

SMAR 2026



SMAR 2026 - 8th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

MS20: Earth observation and other remote sensing methods for infrastructure monitoring

Organizers:

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ABSTRACT

Over the past decades the importance of remote sensing methods, particularly those based on earth observation techniques, has steadily increased for the monitoring of civil infrastructure. Due to the technological progress important aspects such as accuracy, temporal and spatial resolution or affordability have improved significantly, thus opening the path for ever more applications. The Mini Symposium wishes to showcase the wide range of possibilities offered by remote sensing for the structural health monitoring (SHM) of civil infrastructure. Contributions on remote sensing techniques, field applications, data processing, new approaches or technologies are invited. Some core topics include methods such as InSAR, LiDAR, terrestrial laser scanning, GNSS, thermal radiometry or hyperspectral imaging. The aim is to bring experts in this quickly developing field in SHM together to share their insights and experiences, to exchange ideas and promote the far-reaching opportunities offered by remote sensing methods for civil infrastructure.

BBD-V: a national, transport-focused ground motion monitoring service in Germany

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Abstract

Transport infrastructure is vulnerable to ground motion caused by natural or anthropogenic processes. Monitoring ground motion from space through multi-temporal interferometric synthetic aperture radar (MT-InSAR) is less resource-intensive than traditional methods. It allows for an increased data comparability on large spatial extent, the transferability of approaches between different linear transportation infrastructure - roads, rail-, and waterways - and processing consistency across Germany. The BBD-V (*germ.* Bodenbewegungsdienst für den Verkehrssektor) is a currently developed transport-focused and Sentinel-1 MT-InSAR-based ground motion service for Germany. By tailoring monitoring to the transport sector, it aims at increasing the applicability of the approach to linear infrastructure in terms of usage, process adaptation, and user-targeted communication of results.

Keywords: Ground motion; MT-InSAR; infrastructure monitoring; Copernicus; BBD-V; Germany

* The full paper is open access available in the Conference Proceedings. *

Structural health monitoring of flood protection Structures through improved InSAR processing

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Abstract

Interferometric Synthetic Aperture Radar (InSAR) provides an effective means of observing vertical displacements of large-scale civil engineering structures across extensive areas. In this study, InSAR data are investigated with respect to their use for the structural health monitoring of flood protection structures. The focus lies on direct InSAR data processing and on testing strategies to increase the density and reliability of measurement points. Several complementary approaches are considered to address the low availability of natural reflectors in vegetated areas: i) evaluation of persistent versus distributed scatterers, ii) assessment of different radar frequency bands (X-, C-, and L-band) in relation to spatial and temporal resolution, iii) investigation of seasonal effects, where winter acquisitions may yield higher PS densities due to reduced vegetation, and iv) installation of corner reflectors (CRs) on selected flood protection structures. The analysis indicates that PS density is strongly influenced by surface characteristics and object orientation with respect to the satellite line of sight. To address the scarcity of reliable scatterers, CRs show potential for establishing stable reference points. This study highlights both the opportunities and the current limitations of applying advanced InSAR techniques for deformation monitoring in complex natural environments.

Keywords: InSAR; structural health monitoring; persistent scatterer interferometry; corner reflectors; flood protection

* The full paper is open access available in the Conference Proceedings. *

Strategies for monitoring bridge portfolios by radar satellites

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Abstract

Interferometric synthetic aperture radar (InSAR) satellites, with global coverage and free data access plans, such as Sentinel-1, have enabled a paradigm shift in the structural health monitoring (SHM) of civil infrastructure such as bridges. Traditionally, due to its high costs for sensor installation, maintenance, and data acquisition, SHM was generally restricted to a limited number of critical structures, mostly with known defects. Since InSAR operates entirely remotely and covers large areas, it offers an extremely cost-effective way of monitoring entire bridge portfolios within an area simultaneously. Since numerous structures can be monitored in parallel, for the first time an early warning system may be established identifying critical bridges not known before.

Based on the results of a recent research project on the potentials of InSAR for bridge monitoring and their shared experience in SHM, the authors propose a framework which would allow for such a strategy. The paper highlights the potentials of such a concept but also addresses its pre-conditions and limitations. This includes the evaluation of important bridge characteristics which may affect InSAR monitoring such as size, orientation, bridge type, construction material etc. as well as the types of failure modes which are likely to be detected. Furthermore, approaches are described for follow-up investigations if potentially critical structures are detected, that can be supported with the historical data that InSAR provides. The authors trust that the InSAR technology will open a new chapter in the SHM of bridges, and the paper outlines the possible strategies which have become available.

Keywords: Remote sensing; insar; bridges; shm; anomaly detection

* The full paper is open access available in the Conference Proceedings. *

Interpreting InSAR-derived bridge displacements through a calibrated finite element model

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Abstract

Spaceborne Interferometric Synthetic Aperture Radar (InSAR) is increasingly used for the long-term monitoring of civil infrastructures, enabling the reconstruction of displacement time histories over multi-year periods and extended spatial domains, without dedicated on-site instrumentation. However, the structural interpretation of InSAR-derived displacements remains challenging. The reconstruction of displacement components requires combining measurements from different acquisition geometries and adopting simplifying assumptions on structural behaviour, which may introduce uncertainties and potential bias. In addition, structural displacements reflect the combined influence of environmental actions, structural configuration, restraint conditions, and, where present, anomalous ongoing phenomena. This study examines this issue for the A21 Po River Bridge, a prestressed-concrete Gerber viaduct in northern Italy. The InSAR-derived time histories indicate a predominantly thermally driven longitudinal response, with displacement patterns varying along the bridge and influenced by the restraint conditions at the supports. A Finite Element (FE) model was calibrated through experimentally identified modal frequencies and used to simulate the bridge thermal response. The comparison between measured and simulated displacements shows good agreement in terms of spatial distribution and temporal evolution, supporting the proposed interpretation of the InSAR data.

Keywords: Structural health monitoring; InSAR; remote sensing; acceleration; finite element; bridge

* The full paper is open access available in the Conference Proceedings. *

Design and implementation of a multi-channel ultra-low-power IoT-based strain monitoring system with edge computing and precise time synchronization

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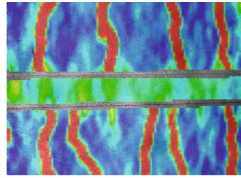
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Abstract

This study presents the design and implementation of a multi-channel ultra-low-power IoT-based strain monitoring system with edge computing and precise time synchronization. The system integrates circuit design, microcontroller technology, digital communication, and IoT frameworks to achieve efficient, real-time structural monitoring. A dedicated circuit has been developed for high-precision dynamic strain measurement, enabling ultra-low-noise excitation of resistive strain gauges and accurate acquisition of minute bridge differential signals for amplification and digitization. At the intelligent node, customized firmware with edge-computing algorithms enables real-time analysis of large-scale dynamic strain data and conversion into meaningful monitoring information. Through the integration of firmware and digital communication protocols, multi-channel synchronization within the millisecond range has been achieved, while maintaining total system power consumption at the milliwatt level. With an ultra-low-power design, the system can operate continuously using a solar module smaller than 100 cm². Furthermore, a cross-platform data exchange framework and an IoT-based strain monitoring server have been developed, allowing seamless integration with existing large-scale structural health monitoring systems. Field experiments conducted on a prestressed girder verified the system's feasibility and demonstrated its capability for real-world bridge health monitoring. The proposed system provides a practical and energy-efficient solution for on-site structural health monitoring applications.

Keywords: Structural health monitoring, electric resistance strain gauge, edge computing

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Raman spectroscopy-based stress monitoring of nuclear containment structures

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Keywords: Raman spectroscopy; stress monitoring; zirconia shim plate (3Y-TZP); prestressed tendon; nuclear containment structure

1. Introduction

Prestressed tendons are critical load-bearing components in nuclear containment structures, and their long-term force retention directly governs structural safety [1]. Conventional tendon-force evaluation has been mainly performed through lift-off testing, which provides a direct estimate of residual tendon force at the anchorage but remains inherently discontinuous, equipment-intensive, and laborious for field inspection [2]. To overcome this discontinuity, prior studies and practical monitoring approaches have adopted embedded or contact-based sensing techniques, including load cells, strain gauges, and vibration-based tendon assessment [3]. However, such contact-based sensors are highly vulnerable to installation errors, construction-induced damage, signal drift, and long-term durability degradation [4]. Furthermore, once embedded in the structure, they are nearly impossible to repair or replace [5]. To address the fundamental vulnerabilities of these contact-based and embedded sensors, this study proposes a non-contact, Raman spectroscopy-based stress monitoring system. The core of this system is a 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) shim plate integrated directly into the tendon anchorage, which functions simultaneously as a photoluminescence-active piezo-spectroscopic transducer and a load-bearing structural element. Designed as a drop-in replacement for the conventional shim plate, the proposed 3Y-TZP component preserves the original load-transfer mechanism without requiring modifications to the existing anchorage configuration. Based on the proposed non-contact stress monitoring system, a Physics-Guided Neural Network (PGNN) framework is developed to estimate stress from remotely acquired Raman spectral signals. By leveraging large-scale, physics-derived synthetic datasets to capture fundamental thermo-mechanical behaviors, the PGNN inherently decouples thermal fluctuations from stress-induced peak shifts. This physics-guided approach is subsequently fine-tuned with a limited set of experimental data, ensuring highly accurate stress estimation and robust field adaptability.

2. Non-contact stress monitoring system and PGNN framework

The proposed Raman-based stress monitoring system is configured at the tendon anchorage as shown in Fig. 1. The key sensing element is a ring-type 3Y-TZP shim plate, which serves as a structural replacement for the conventional shim plate installed between the anchor head and the bearing plate. Instead of introducing an additional external sensor, this system enables the 3Y-TZP shim plate itself to function directly as both a load-distributing component and the active sensing medium. This dual functionality allows direct integration into the tendon anchorage without requiring significant geometric modifications or additional installation space. Furthermore, the tendon anchorage is designed with a dual-cap structure. Since the anti-corrosion grease is isolated within the first inner cap, measurement can be efficiently performed simply by removing the second outer protective cap. The Raman spectrometer and a laser source are connected to the probe via fiber-optic cables, facilitating the remote acquisition of Raman signals from the exposed surface of the 3Y-TZP shim plate. These signals are subsequently transferred to a computer and converted into analysis-ready data for stress monitoring.

Based on the spectra acquired through the non-contact measurement, Fig. 2 illustrates the residual-based stress estimation framework. The framework operates in two sequential stages: pre-training on large-scale synthetic data, followed by fine-tuning

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on limited experimental datasets. This dual-stage strategy bridges the gap between idealized physics-based forward modeling and noisy, complex spectral signals acquired in real-world environments, thereby enabling robust domain adaptation.

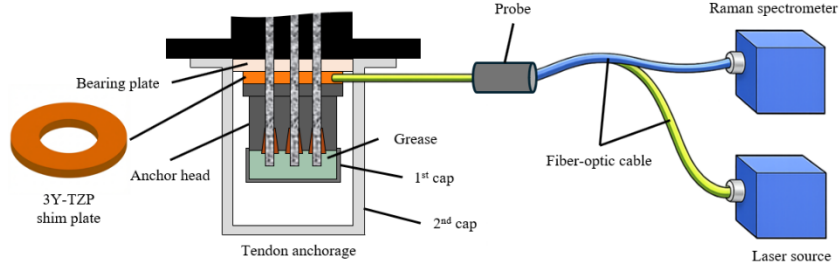


Fig. 1. Measurement configuration at the tendon anchorage.

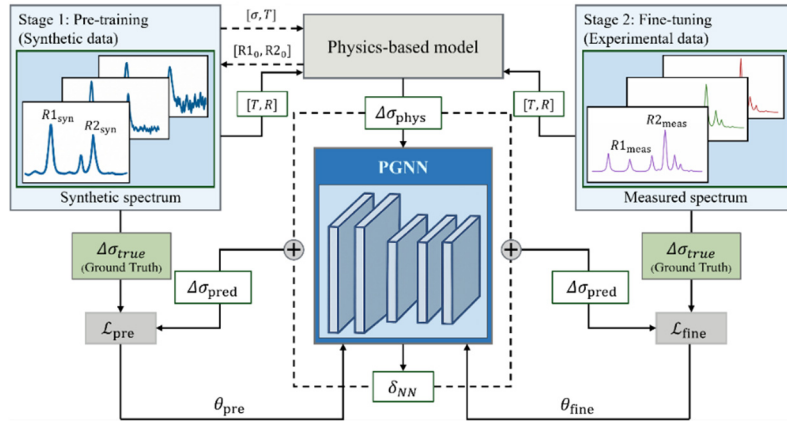


Fig. 2. Physics-guided stress evaluation framework: σ , T : stress and temperature; $R1_0$, $R2_0$: baseline peak positions; $R1_{syn}$, $R2_{syn}$, $R1_{meas}$, $R2_{meas}$: feature peak positions extracted from synthetic and measured spectrum; R : extracted feature peaks; $\Delta\sigma_{phys}$: physics-based stress variation; $\Delta\sigma_{true}$: ground-truth stress variation; $\Delta\sigma_{pred}$: model-predicted stress variation; $\mathcal{L}_{pre}$, $\mathcal{L}_{fine}$: loss functions for pre-training and fine-tuning; θ_{pre} , θ_{fine} : model parameters updated during pre-training and fine-tuning; δ_{NN} : residual term.

In the pre-training stage, temperature (T) and stress (σ) are randomly sampled to determine the reference peak positions ($R1_0$, $R2_0$). Synthetic spectra are then generated using a Voigt profile, and the feature peaks ($R1_{syn}$, $R2_{syn}$) extracted from these spectra are further augmented with Gaussian noise to enhance the framework's robustness before training. For the fine-tuning stage, the raw spectra acquired from the portable Raman device undergo Voigt fitting to compensate for its limited spectral resolution, and the feature peaks ($R1_{meas}$, $R2_{meas}$) were then extracted. The framework combines the PGNN model with a residual corrector. The physics-based model describes the thermo-mechanical relationship among temperature (T), stress (σ), and peak position (R), and takes $[T, R]$ as inputs to compute the physics-based stress variation, $\Delta\sigma_{phys}$. This term serves as a physics-based baseline by intrinsically decoupling thermal effects from the spectral response, while the PGNN predicts the residual term, δ_{NN} , to account for nonlinearities and uncertainties not captured by the analytical model. The final predicted stress variation, $\Delta\sigma_{pred}$, is obtained by the superposition of these two terms. The model parameters (θ) are optimized by minimizing the difference between the predicted stress variation ($\Delta\sigma_{pred}$) and the ground truth ($\Delta\sigma_{true}$). To account for the different data characteristics of each stage, stage-specific loss functions are employed. For the synthetic dataset, the pre-training loss $\mathcal{L}_{pre}$ in Eq. (1) penalizes the residual prediction error with an additional regularization term. N is the number of samples, δ_i and $\hat{\delta}_i$ denote the target and predicted residuals, respectively, and λ_{reg} is the regularization weight. For the fine-tuning stage, the loss $\mathcal{L}_{fine}$ in Eq. (2) introduces a starting-point regularization term to constrain the parameter update around the pre-trained parameters θ_{pre} , where λ_{sp} denotes the regularization coefficient.

$$\mathcal{L}_{pre}(\theta) = \frac{1}{N} \sum_{i=1}^N (\hat{\delta}_i - \delta_i)^2 + \lambda_{reg} \frac{1}{N} \sum_{i=1}^N \hat{\delta}_i^2 \quad (1)$$

$$\mathcal{L}_{fine}(\theta) = \frac{1}{N} \sum_{i=1}^N (\hat{\delta}_i - \delta_i)^2 + \lambda_{sp} \|\theta - \theta_{pre}\|_2^2 \quad (2)$$

3. Experimental validation

The proposed model was established through model pre-training on a set of 3,000 physics-derived synthetic samples and subsequent fine-tuning using 30 experimental measurements. To evaluate the stress estimation performance of the new framework, a mock-up test was conducted (Fig. 3a). A target load of 1,462 kN was applied to the tendon anchorage, corresponding to 80% of the nominal anchoring force in an actual nuclear containment structure. To rigorously evaluate the fine-tuned framework, five

distinct validation scenarios were designed under varying decrement intervals (e.g., 10, 7, and 5% load reductions) combined with different temperature conditions assigned to each step. A representative validation case demonstrating a stepwise load reduction from the initial target load illustrates Fig. 3(b), where points *a* through *e* denote the sequential optical measurement steps. While the loading profile in Fig. 3(b) is controlled and monitored based on the applied load, the quantitative evaluation of the framework is performed in terms of structural stress converted from the calibration setup. The representative stress estimation results corresponding to the sequential steps (*a* to *e*) in this validation scenario are summarized in Table 1. As presented there, the estimated stress values closely match the ground-truth stress levels across the entire decompression path. Starting from the first load-loss step after the initial target load, the prediction error between the true applied stress and the estimated stress was rigorously evaluated, yielding a high average stress estimation accuracy of 98.71% over the sequential steps. Across all five evaluated scenarios, the proposed framework consistently maintained an average stress estimation accuracy exceeding 95%. This demonstrates a highly robust and reliable monitoring performance under complex, coupled thermo-mechanical environmental conditions.

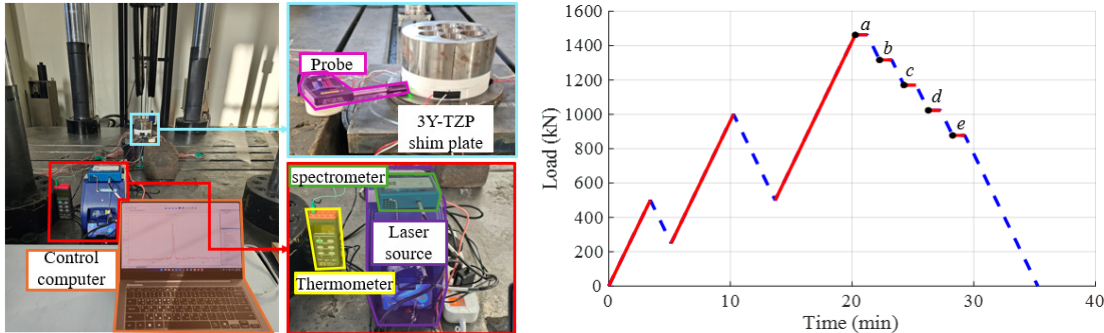


Fig. 3. (a) Mock-up test setup; (b) time-load curve.

Table 1. Representative stress estimation results under the representative validation scenario.

Ground-truth stress estimated stress (MPa)	194.4 194.6	175 174.9	155.6 149.0	136.0 135.9	116.6 119
Accuracy (%)	99.9	99.94	95.76	99.93	97.94

4. Conclusion

This study developed a non-contact Raman spectroscopy-based stress monitoring system for nuclear containment tendons. By utilizing the 3Y-TZP shim plate integrated into the anchorage, the system overcomes the durability and maintenance limitations of conventional embedded sensors. Remotely acquired optical signals are processed by the proposed physics-guided framework, which decouples thermal fluctuations from stress-induced peak shifts. Validation under complex thermo-mechanical scenarios demonstrated a stress prediction accuracy exceeding 95%, confirming the framework's reliability as a non-invasive structural health monitoring solution. However, during practical data acquisition, minor temperature fluctuations ranging between 0.1 °C to 0.5 °C were observed within a span of a few minutes. These rapid thermal variations represent a potential error source that can affect the baseline stability of the spectral peaks. Therefore, these results provide a critical basis for future full-scale validation and emphasize the need for further characterization of temporal temperature variations. Future research will focus on upgrading and advancing the temperature compensation algorithm to effectively eliminate such transient thermal effects, thereby ensuring the long-term robustness and reliability of tendon force monitoring under complex field conditions.

Acknowledgements

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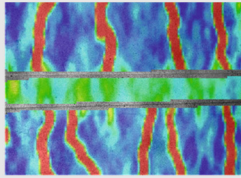
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SMAR 2026



SMAR 2026 - 8th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

MS21: Bio-based materials for seismic retrofit of existing structures – enhancing structural performance and environmental sustainability

Organizers:

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ABSTRACT

This Mini Symposium focuses on the development and application of sustainable materials and techniques for seismic retrofit of existing buildings. The growing interest in low-impact reinforcement solutions — such as natural fiber composites, bio-based matrices, and recycled or low-carbon systems — requires rigorous assessment of their structural performance, durability, and compatibility with existing construction materials.

The session invites contributions presenting experimental investigations, numerical modeling, or integrated approaches aimed at evaluating mechanical behavior, interface properties, long-term performance, and environmental impact.

Topics include (but are not limited to): sustainable reinforcement systems; bio-based or recycled materials; bond behavior and substrate compatibility; durability under mechanical and environmental actions; life cycle assessment (LCA) and sustainability metrics; design strategies for structural retrofitting; applications to heritage and contemporary structures; and hybrid or multi-material reinforcement systems.

The session aims to provide a technical framework for the validation and optimization of sustainable solutions within modern structural engineering practice.

Re-engineering traditional binders: CO₂-driven transformation of nano-enhanced lime mortars

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Abstract

Non-hydraulic lime mortars are widely used in heritage conservation due to their compatibility with historical masonry; however, their relatively low mechanical strength limits structural applications. This study investigates the mechanical performance of nano-modified aerial lime mortars incorporating nano-silica (NS) and nano-alumina (NA) combined with accelerated CO₂ curing. Twenty mortar formulations were produced using different NS and NA contents while maintaining a constant binder–aggregate ratio. A total of 120 specimens were tested to evaluate compressive and flexural behavior under normal curing and carbonation curing conditions. The results show that nano-additives improve the lime matrix through pozzolanic and micro-filler effects, while accelerated carbonation significantly enhances strength development by promoting rapid formation of calcium carbonate. A clear synergistic effect was observed when nano-particles and CO₂ curing were combined, producing compressive strengths above 7 MPa. The findings demonstrate the potential of nano-modified lime mortars as sustainable, high-performance materials for conservation and low-carbon construction.

Keywords: Non-hydraulic lime; mechanical properties; nano-particles

* The full paper is open access available in the Conference Proceedings. *

Mechanical response of masonry walls strengthened by hybrid natural textile reinforced mortar

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Abstract

Nowadays, the construction sector accounts for approximately 11% of the global environmental footprint. Research is facing an important challenge in finding more sustainable materials. This study aims to investigate the use of natural fibers as a low environmental impact alternative for building reinforcement, replacing conventional synthetic fibers. The research focuses on a composite system composed of flax textile-reinforced mortar combined with short jute fibers. Mechanical performance was derived through four-point bending tests on the composite material, selected instead of classical tensile tests to better capture the ability of short fibers to control crack formation and propagation. Additionally, diagonal compression tests were performed on masonry walls reinforced with the hybrid composite to evaluate mechanical improvements. Toughness was also calculated, integrating the post-peak curve, to quantify the energy dissipation capacity of the system. This value shows a significant increase compared to unreinforced materials. The experimental results demonstrate the promising potential of natural fiber composites in enhancing both mechanical strength and sustainability in construction applications. These findings support the transition toward more sustainable building practices by promoting materials that could reduce environmental impact.

Keywords: Natural fibres, diagonal compression test, flax fibres, short fibres, textile reinforced mortar

* The full paper is open access available in the Conference Proceedings. *

Diagonal compression tests on masonry walls strengthened with natural TRM: scale effects and retrofitting efficiency

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Abstract

This contribution presents the results of a comprehensive experimental campaign consisting of 36 diagonal compression tests on unreinforced and reinforced masonry walls. Two geometries were examined—120×120 cm and 60×60 cm—to assess the influence of scale on shear response and failure mechanisms. Strengthening systems included jute diaton and a bidirectional Flax Fiber net embedded in a lime-based mortar, developed within the IntegraTRM PRIN project. Test results highlight the effectiveness of both reinforcement configurations in enhancing shear strength and deformation capacity, while offering insights into scale-dependent behaviour and the mechanical efficiency of natural-fiber TRM strengthening. The work contributes to the development of sustainable seismic-retrofitting systems based on bio-based components, providing experimental evidence useful for future analytical modelling and for establishing performance-oriented design criteria tailored to natural-fiber composites. Moreover, the results allow a deeper understanding of the interaction between the flax-based textiles and the masonry substrate, clarifying failure modes, crack patterns, and load-transfer mechanisms. These findings support the feasibility of natural-fiber TRM as a low-carbon, cost-effective alternative for strengthening existing masonry structures.

Keywords: Sustainability, jute, flax, masonry structures

* The full paper is open access available in the Conference Proceedings. *

Durability of jute fiber-reinforced mortars in masonry panels under natural weathering

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Abstract

An experimental study was proposed to evaluate the mechanical and physical conditions of jute fiber-reinforced mortars applied to masonry panels exposed to weathering for 730 days (2 years), subjected to heat and rain in the natural environment. It is important to highlight that the evaluated coating mortars were composed of 30% metakaolin and 20% fly ash as partial replacements for cement. The experimental investigation consisted of reusing the panels previously tested in diagonal compression, which remained exposed outdoors after testing. Cubic and cylindrical specimens were extracted for compressive and flexural testing, and microstructural analyses. The results showed that the jute fiber-reinforced mortars exhibited a positive mechanical impact, provided by the increase in both compressive strength and flexural strength. The strength gain indicated that hydration reactions continued and that microstructural improvement occurred. Pore refinement, Ca(OH)₂ consumption, and water absorption stability are desirable for the durability of masonry structures and coatings, as they provide favorable conditions for preserving the fibrous reinforcement, allowing jute fibers to remain intact and contributing to the mechanical performance of reinforced masonry under natural weathering.

Keywords: Sustainability; natural fibers; reinforced mortars; diagonal compression test

* The full paper is open access available in the Conference Proceedings. *

Performance-based seismic retrofit of RC buildings using self-centering rocking frames

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Abstract

This study proposes an innovative Performance-Spectra (P-Spectra) framework for the seismic strengthening of reinforced concrete (RC) buildings using self-centering exoskeleton systems. These exoskeletons—external steel frames mechanically linked to the existing structure—provide a reversible, non-invasive retrofit strategy that enhances seismic safety while promoting structural sustainability. The integration of self-centering mechanisms effectively limits damage, reduces residual drifts, and enables rapid post-earthquake re-occupancy, a critical aspect for essential and strategic facilities. In contrast to traditional iterative retrofit methods, the P-Spectra approach directly correlates target performance objectives with the mechanical characteristics of self-centering braces and rocking joints. By translating structural response parameters - such as displacement, acceleration, and energy dissipation - into equivalent single-degree-of-freedom (SDOF) spectra, the method facilitates the rational and efficient sizing of exoskeleton components. The proposed methodology is applied to the seismic retrofit of a representative RC school building. Results from nonlinear time-history analyses under spectrum-compatible ground motions reveal notable reductions in interstory drifts and peak floor accelerations, as well as enhanced re-centering behavior. The findings demonstrate that self-centering exoskeletons designed through the P-Spectra framework provide an effective, resilient, and sustainable solution for upgrading existing RC buildings in line with modern performance-based seismic design principles.

Keywords: Steel exoskeletons; self-centering; seismic retrofit

* The full paper is open access available in the Conference Proceedings. *

Seismic resilience assessment of buildings using a fuzzy set approach

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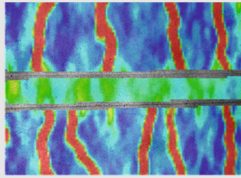
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Abstract

Seismic resilience - the ability of structures to withstand, absorb, and recover from earthquake-induced disruptions - is a fundamental aspect of disaster risk reduction and performance-based design. However, conventional probabilistic approaches to resilience assessment often fail to capture epistemic uncertainties and vague expert judgments inherent in real-world decision-making. This study presents a novel fuzzy set-based framework for quantifying the seismic resilience of buildings, integrating key performance indicators such as residual functionality, recovery time, and the probability of exceedance within a unified inference system. By defining appropriate membership functions and rule sets, the proposed model translates imprecise input data into a quantitative resilience index through a Mamdani fuzzy inference system. The methodology is validated through an application to a case-study hospital building, and the results are compared against traditional probabilistic methods under various seismic hazard levels. Findings demonstrate that the fuzzy approach produces resilience estimates with comparable accuracy but significantly enhanced flexibility, computational efficiency, and robustness to uncertain input data. This research highlights the potential of fuzzy logic to support more realistic, adaptable, and decision-oriented seismic resilience evaluations, offering a valuable tool for engineers, stakeholders, and policymakers involved in earthquake risk mitigation.

Keywords: Seismic resilience; earthquake engineering; fuzzy set theory; structural vulnerability assessment; residual functionality; disaster risk reduction

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SMAR 2026 - 8th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

MS22: Advances in fiber optic sensing solutions for infrastructure, geotechnics, and earth sciences

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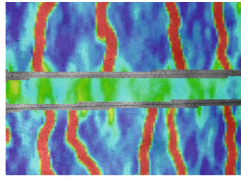
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ABSTRACT

Nowadays, fiber optic sensing is reliably employed in numerous applications in smart structure monitoring, geotechnical surveys, hydrogeological assessments, and geophysical exploration.

The symposium examines real-world case studies, testing methods, and the integration of fiber optics sensing with traditional monitoring techniques, IoT, and modern data analytics. Key topics are cutting-edge advancements in fiber optic sensing technology, applications in smart civil structure monitoring and assessment, geotechnical monitoring for safer construction and infrastructure, hydrogeological insights through fiber optic sensors, and geophysical applications for subsurface exploration.



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Characterizing footstep-induced strain in pavement fibers with distributed acoustic sensing

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Keywords: Distributed acoustic sensing, roadway monitoring, pedestrian footsteps, surface wave propagation, fiber-road coupling

1. Introduction

Distributed Acoustic Sensing (DAS) is increasingly being explored for near-surface monitoring (Lindsey et al. 2020; Liu et al., 2025). Among potential applications, pedestrian detection and tracking is an emerging application area in traffic monitoring (Saw et al., 2025). However, the characteristics of footstep-induced wavefields and their variability across different cable deployments remain underexplored. Footstep-induced signals may vary substantially depending on fiber-ground coupling, offset between the source and the fiber, and the relative contributions of localized deformation and propagating wave energy.

This study compares pedestrian signals recorded by two DAS cable configurations deployed along the same experimental roadway: (1) a tightly buffered cable embedded within the asphalt pavement and (2) a loose-tube cable buried in a shallow roadside trench. Controlled pedestrian experiments were conducted to examine the spatio-temporal characteristics of footstep-induced strain, as well as their frequency-wavenumber (f-k) (Yilmaz, 2001) and frequency-band energy (FBE) representations.

2. Experimental setup

Experiments were performed on an instrumented experimental roadway featuring two distinct deployment conditions: a tightly buffered cable embedded within the asphalt pavement and a loose-tube cable buried in a shallow trench adjacent to the pavement (Hubbard et al., 2022). The DAS interrogator (OptaSense ODH4) was configured with 1.02 m channel spacing, 2.04 m gauge length, and a sampling rate of 20 kHz. Pedestrians walked across the pavement while strain data recorded continuously along the fiber. The recorded data were first bandpass filtered within 1-100 Hz, then analyzed using f-k transform to characterize spectral content and propagating waves, followed by FBE computation to visualize the spatiotemporal distribution of band-limited energy.

3. Analysis and results

The spatio-temporal strain distribution and corresponding f-k spectra for an example footstep event are shown in Fig. 1. For the pavement-embedded, tightly buffered cable (Fig. 1, top), the strain response is dominated by strong, localized deformation near the impact location. This is evident as a horizontally concentrated, high-amplitude band in the spatio-temporal plot, with comparatively weak and less coherent propagating features. The corresponding f-k spectrum shows greater energy concentrated at low frequencies and near-zero wavenumbers, with broad and diffuse spectral content. This indicates that the measured response is dominated by near-field signals, which may obscure the identification of propagating wave modes.

The trench-buried, loose-tube cable (Fig. 1, bottom) exhibits a different response. The spatio-temporal strain distribution displays a clear V-shaped pattern, indicating wavefronts propagating away from a localized source along the fiber. This propagation behavior is further supported by the f-k spectrum, which shows distinct energy lobes at finite wavenumbers, particularly in the approximate 20-40 Hz range. These features are characteristic of coherent wave propagation with identifiable apparent velocities.

For example, energy concentrated near $f \approx 25$ Hz and $k \approx \pm 0.1$ m⁻¹ gives an estimated apparent velocity of 250 m/s, which is likely to be a guided or surface wave mode.

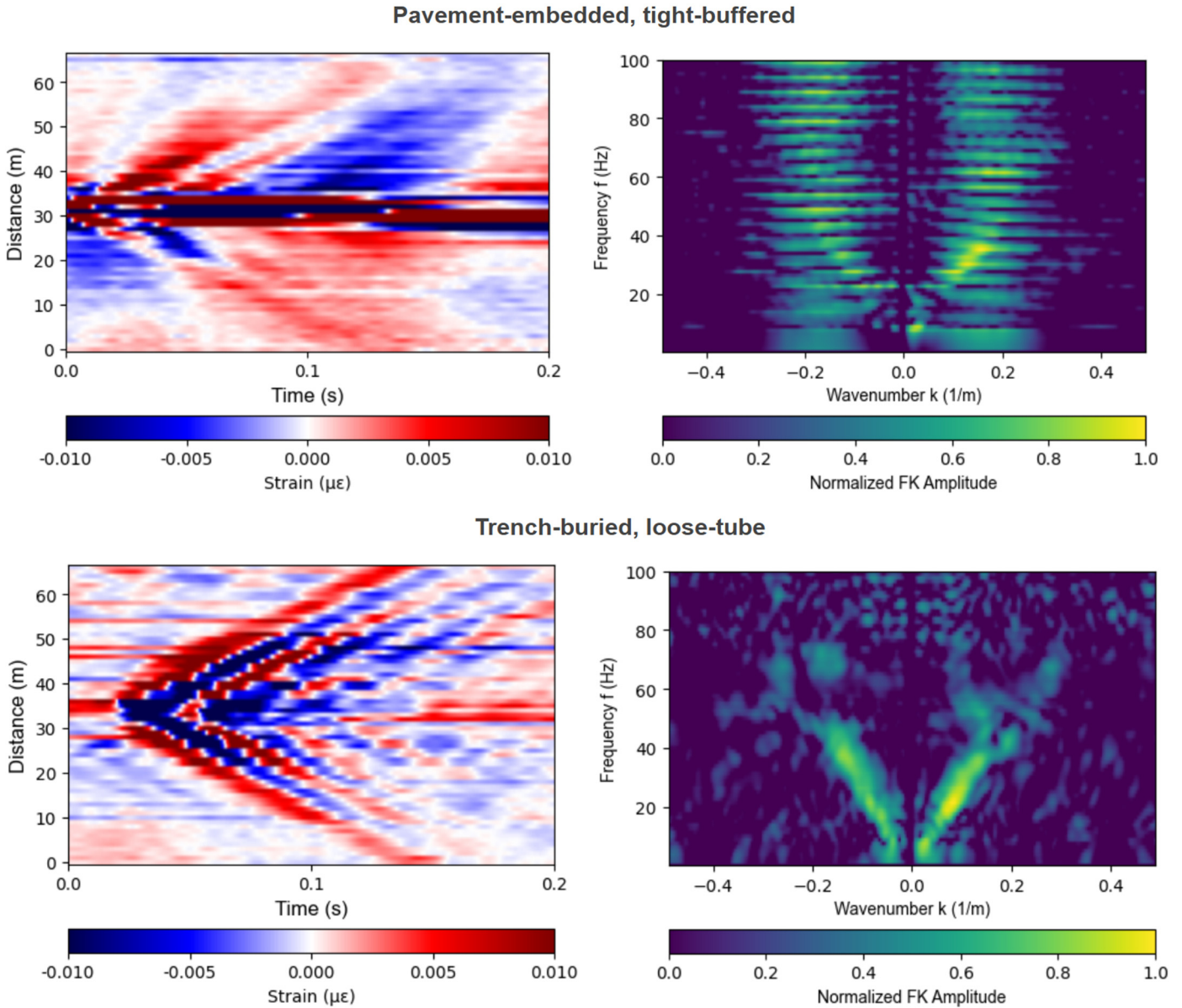


Fig. 1. Individual footstep examined through spatio-temporal distribution of strain (left) and f-k spectra (right); (top) pavement-embedded, tightly buffered cable; (bottom) trench-buried, loose-tube cable.

To further examine propagation behavior, FBE was computed in the 10-50 Hz range using a sliding-window (length of 256 samples) short-time FFT with overlap of 50%. For each channel, the power spectral density was estimated and averaged over the selected frequency band, and expressed in dB, yielding a time-varying representation of band-limited energy along the fiber.

The FBE plots (Fig. 2) show repeated impulsive events corresponding to individual footsteps, each forming symmetric wavefronts propagating along the fiber in opposite directions away from the impact point. This symmetry arises because the footstep acts as a localized source that excites waves traveling along the fiber in both directions. The slopes of these wavefronts in the time-distance domain correspond to apparent propagation velocities.

In the embedded, tightly buffered configuration (Fig. 2, top), the lines are sharper and two distinct propagation modes are observed: a primary mode with an apparent velocity of approximately 175 m/s and a secondary mode of approximately 350 m/s. The secondary wavefronts are weaker and less continuous but remain consistently observable across multiple events, indicating that they represent a physically meaningful propagation mode rather than noise. Slight asymmetries in wavefront amplitudes are also observed, where the primary mode is more consistently observed compared to the secondary mode. The presence of these multiple velocities suggests that footstep loading excites multiple wave modes within the pavement-soil system, potentially including surface or guided waves within the pavement layer and additional modes influenced by subsurface structure. In contrast, the trench-buried, loose-tube configuration shows more dispersive wave modes, and the two distinct propagation modes are not clearly resolved.

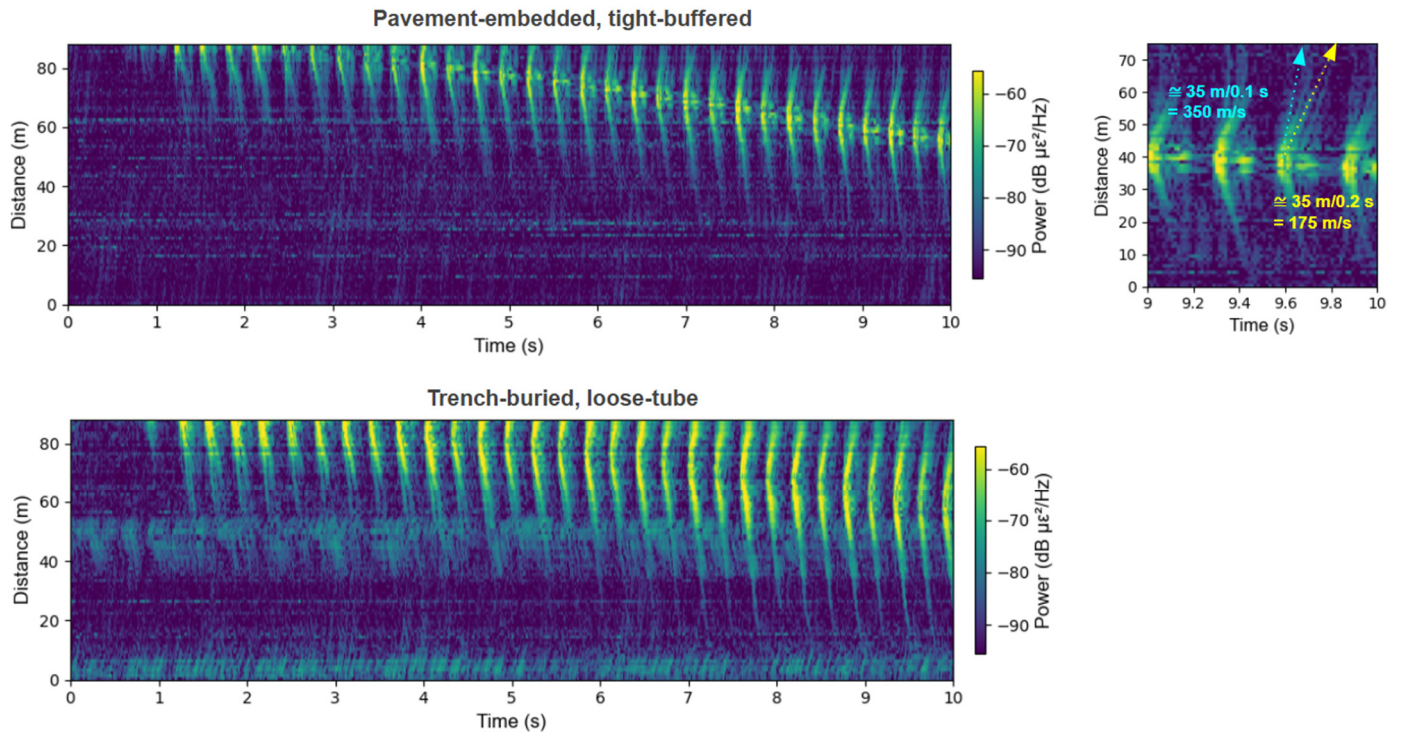


Fig. 2. Footstep sequence examined using FBE. (Top) Pavement-embedded, tightly buffered cable with a 1-second window delineating the two propagation modes; (Bottom) trench-buried, loose-tube cable.

4. Conclusions

The results indicate that the two installations emphasize different aspects of the footstep-induced wavefield. The embedded fiber provides stronger coupling and higher response amplitudes, but this stronger coupling also introduces substantial near-field deformation that can obscure simple propagation geometry in both the strain and f-k domains. The trench fiber produces weaker signals overall, but it more cleanly captures the propagating component of the wavefield, yielding a clearer V-shape in the strain response and more distinct finite-wavenumber features in the f-k spectrum. However, individual propagation modes are more clearly resolved in the embedded configuration.

These findings demonstrate that the DAS deployment configuration affects not only signal amplitude but also the relative visibility of localized vs. propagating wave phenomena, which provides important implications for signal interpretation and pedestrian detection methodologies.

Acknowledgements

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Earth structures with embedded fibre optic sensors: from the lab to the field

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Abstract

Distributed fibre optic sensing (DFOS) is increasingly recognised as a versatile tool not only in laboratory research but also in real engineering practice. Its ability to provide continuous measurements of strain and temperature along the entire length of an optical fibre makes it particularly valuable for the monitoring of earth structures, where conventional point sensors may fail to capture localised effects. This article discusses practical aspects of embedding and operating distributed fibre optic sensors in both small-scale laboratory models and full-scale field applications. Special attention is given to methods of sensor installation. Examples with real-life data highlight the challenges that arise when transferring methodologies from controlled conditions to complex field environments, including, for instance, the necessity of applying appropriate thermal compensation. Selected case studies are presented to demonstrate the performance of DFOS in capturing the behaviour of earth structures of different scales under various conditions. The paper thus bridges experimental research and field implementation, showing how DFOS can enhance the diagnostic and monitoring capabilities available to geotechnical and civil engineers.

Keywords: Distributed Sensors; Earth structures; Measurements; Strains; Displacements

* The full paper is open access available in the Conference Proceedings. *

Integration of distributed fiber-optic sensing in pile foundations and civil structures

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Abstract

This paper presents a field study on the use of distributed fiber-optic sensing (DFOS) for monitoring negative skin friction and downdrag in steel pile foundations at Project Kaj 16, a 78-m-high mass-timber office building under construction in Lilla Bommen, Gothenburg, Sweden. The site is characterized by soft clay layers exceeding 100 meters in depth, where ongoing creep settlements generate significant long-term downdrag loads on the friction piles. Four open-ended steel piles, 220 mm in diameter and 78 m long, were instrumented with Brillouin-based distributed strain sensing (DSS) cables fixed to the pile exterior using custom-made mechanical clamps at 2-m intervals. Measurements were taken at three time points spanning two years of construction, capturing the progressive build-up of strain along the pile length as the superstructure was erected. The results reveal a clear negative skin friction pattern, with peak strains occurring at 15–30 m depth depending on pile location, and show differences in downdrag magnitude between perimeter and interior piles consistent with finite element predictions from PLAXIS 3D. The study demonstrates that DFOS technology provides high-resolution, spatially continuous strain data that offers new insight into pile load distribution — data that would be impractical to obtain with conventional discrete sensor systems — while also highlighting the need for improved protection of sensing cable during construction.

Keywords: distributed fiber-optic sensing; DFOS; pile foundation; negative skin friction; downdrag; Brillouin DTSS; geotechnical monitoring

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DFOS for pull-out testing of self-drilling passive anchors in port reinforcement works

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Abstract

Port infrastructures undergoing deepening or dredging works often require structural reinforcement to withstand the increased earth pressures acting on quay walls. In such contexts, self-drilling passive anchors are increasingly replacing traditional active tie rods, due to their faster installation, higher durability, and reduced maintenance requirements. However, their design and validation demand accurate testing methods capable to describe the full load-transfer mechanism along the bar. Conventional pull-out tests instrumented with strain gages provide reliable strain measurements but only at discrete locations. Distributed Fiber Optic Sensing (DFOS) technology overcomes this limitation by enabling continuous, high-resolution strain measurements along the entire anchor length. This work presents results of a full-scale pull-out test on a passive self-drilling anchor used to reinforce a quay wall within a port area. The test was instrumented with both conventional strain gages and DFOS cables integrated along the steel bar, allowing a direct comparison between the two measurement systems. The distributed strain profiles allowed the progressive mobilization of bond stresses along the anchor to be clearly identified, providing a more comprehensive description of the mechanical response of the anchor compared with traditional strain gages. The results demonstrate the potential of DFOS as a powerful tool for the experimental validation and future monitoring of geotechnical reinforcement systems in marine infrastructures.

Keywords: Distributed fiber optic sensor; smart monitoring; strain gages; self-drilling anchor; pull-out test

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Distributed fibre optic monitoring of a repaired concrete tunnel lining at CERN

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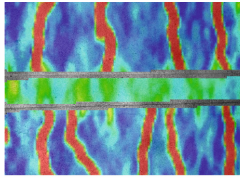
Abstract

In 2023, a routine visual inspection revealed the development of critical cracks in the concrete lining of a section of the Super Proton Synchrotron (SPS) ring tunnel at the European Laboratory for Particle Physics (CERN). The pattern of the observed cracks indicated that this section of tunnel was undergoing deformation, with a critical mechanism such as vertical elongation. Following an extensive investigation, emergency repair works were carried out to stabilize the tunnel lining and prevent further deformation. As part of the long-term mitigation measures put in place, a permanent distributed fibre optic sensing (DFOS) system was installed on the surface of the repaired tunnel lining to enable its continuous monitoring.

The DFOS monitoring system, which has been in operation since April 2024, has allowed the asset owners to track the performance of the tunnel structure in real-time. The data acquired so far indicate that, although the repair works have been effective in stabilizing most of the affected tunnel area, a small section of the lining is still exhibiting vertical elongation, with the magnitude of the deformation evidently increasing with time.

Keywords: Distributed fiber optic sensing; distributed temperature and strain sensing; Brillouin sensing; long-term monitoring; tunnel lining

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Fiber optic strain telemetry with mid-range OFDR for viaduct structural monitoring

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Keywords: Telemetry; OFDR; viaduct; distributed fiber optic sensing; strain

1. Introduction

Distributed fiber optic sensing (DFOS) has become an essential monitoring method for bridge and tunnel construction management. Bridge structural health monitoring supports safety management during renewal work and after construction through the evaluation of the dynamic strain response to vehicle live loads and the long-term trend of residual strain. During tunnel construction, support stress and ground heave are monitored to manage the construction quality. Therefore, a high-precision, rapid DFOS is expected to be useful for construction work. Optical frequency domain reflectometry (OFDR) is known as a promising short-range sensing method. Recently, we have developed an OFDR-based novel DFOS analyzer that extends the measurement distance to 1 km. However, when monitoring viaducts or mountain tunnels, it is necessary to measure with optical fiber sensors via long transmission fiber cables due to the restriction of monitor placement. In such situations, the effective measurement distance becomes shorter, and the application is limited. In this study, we propose a novel fiber optic strain telemetry for selective remote area monitoring and demonstrate this technology on viaduct structural monitoring. Normally, a distributed strain sensing system starts the data recording from the analyzer output port, but this proposed method acquires distant fiber sensor area data from an arbitrary sensor position defined as the measurement origin point. In this testing, optical fiber sensors installed on the main girder of the viaduct were remotely measured via a 1 km transmission cable, and the dynamic strain response to a running vehicle was evaluated. Strain sensing data from transmission cables not fixed to civil structures is uncertain, so a telemetry method that skips the transmission cable area is also practical for sensor data management. This telemetry suggests that it will significantly expand the applicability of high-spatial-resolution OFDR for civil infrastructure sensing.

2. Fiber optic strain telemetry with mid-range OFDR

2.1. Mid-range OFDR

OFDR, which can measure static and dynamic strain with high spatial resolution, is widely used in structural monitoring. However, despite its excellent sensing performance, OFDR has been limited to structural health monitoring applications because the sensing distance is constrained by the temporal coherence of the laser source. Since the sensing distance is generally less than 100 m, OFDR has been widely used for laboratory use in civil engineering. On the other hand, in the field of telecommunications, a PNC (phase noise compensation) algorithm for correcting the laser source's coherence has already been verified, and PNC-OFDR, which implements the PNC algorithm in OFDR, has successfully measured the reflectivity of backscattered light over a distance of 40 km. Although this PNC-OFDR has not been confirmed for strain sensing, the authors expected that PNC-OFDR would be a practical sensing technology for on-site structural health monitoring and developed a mid-range OFDR analyzer. The table in Fig. 1 shows the specifications of the PNC-OFDR based strain sensing system. Currently, this system can measure over a 1 km range and is suitable for short and medium-scale structural monitoring. In addition, a key feature is its extremely short measurement time

of 2ms. Sample rate, which corresponds to the time interval in strain sensing, reaches 150 Hz. According to the Nyquist theorem, the maximum discriminable frequency is 75 Hz, making it possible to evaluate dynamic strain in monitoring bridges and roads where low-frequency vibrations occur.

Sensing distance	1km
Strain resolution	1×10^{-6}
Spatial resolution	1~10cm
Measurement time	2msec./shot
Strain range	$\sim4000\times10^{-6}$ (Typ.)
Sample rate	DC~150Hz

Fig. 1. Specifications of PNC-OFDR based strain sensing system.

2.2. Fiber optic strain telemetry

Fig. 2 shows the configuration of fiber optic strain telemetry employing mid-range OFDR. When measuring from the analyzer to the fiber end, the total length of the transmission cable and sensing section must be within the distance determined by the detector bandwidth. Therefore, the longer the transmission fiber, the shorter the measurable section range becomes. In OFDR, which measures the interference between a reference light and scattered light from a sensing fiber, the difference in length between the reference fiber connected into the analyzer and the sensing fiber is defined as the distance. Applying this principle, OFDR allows us to set the sensing start position at any arbitrary point where the optical path difference is zero by adding a sensing-section adjustment fiber to the reference fiber. Incidentally, the light that has passed through the delay fiber is returned to the reference fiber by a fiber mirror. As a result, a 1 km sensing section can be monitored remotely regardless of the length of the transmission fiber. Since the starting position is determined by the length of the sensing section adjustment fiber, when applying this method on-site, the transmission fiber length should be checked in advance. When a delay fiber of the same length as the transmission fiber is installed, the connection point with the sensing fiber becomes the sensing starting position. And there's another factor to consider when implementing this fiber optic strain telemetry. This telemetry is interfered with by the detection of backscattered light from both the transmission and sensing fibers. We prepared the optical path shown in Fig. 2(b) using two transmission fibers and optical circulators. Our detection system is designed to separate the optical paths of the input light and the backscattered light from a sensing fiber. Backscattered light from the transmission fiber is blocked by the optical circulator, and the analyzer detects only the backscattered light from the sensing fiber.

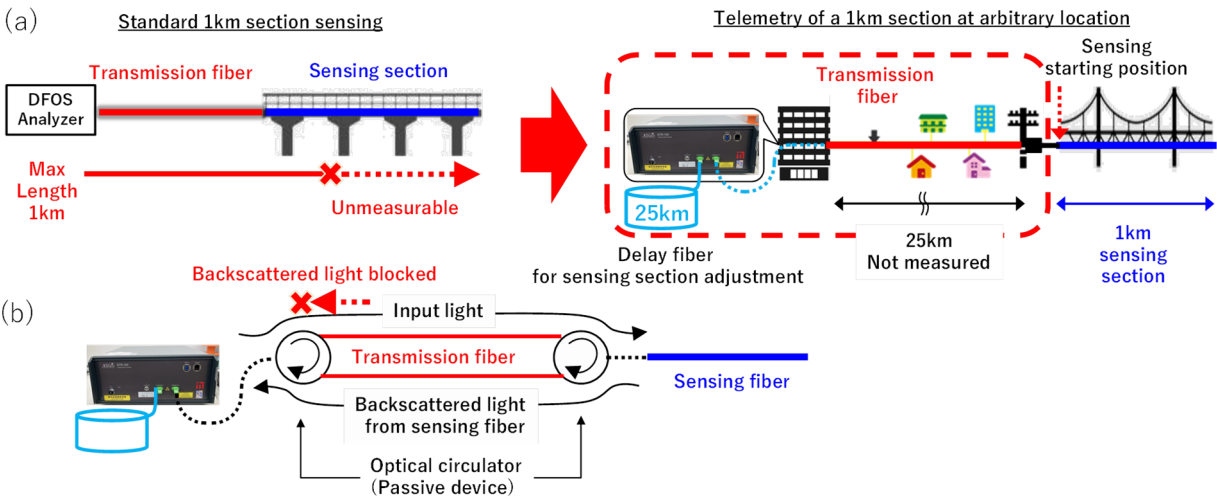


Fig. 2. (a) Schematic diagram of fiber optic strain telemetry employing mid-range OFDR; (b) Transmission path diagram implemented in telemetry.

Verification of fiber optic strain telemetry in viaduct structural monitoring

To demonstrate the proposed telemetry, main girder deflection monitoring of the viaduct was conducted. Fig. 3 shows the implementation of the optical fiber sensor at the monitoring site. The analyzer was set in a prefabricated hut on the ground, and an 1100 m transmission fiber cable was laid to connect to an 180m optical fiber sensor installed on mounted to the top surface of the bottom steel flange. The transmission fiber cable was routed from the elevated deck along temporary stairs to the ground and connected to the DFOS analyzer to construct a fiber optic strain telemetry setup. Fig. 4 shows the dynamic strain response of the main girder acquired during a truck running at 60 km/h. The distance indicates the length of the fiber sensor deployed along the

main girder. The sampling rate was set to 5 Hz, the spatial resolution to 10cm, and the acquired strain distribution is shown at 0.4-second intervals for clarity. The deflection of the main girder due to live load is captured as tensile strain, and the deflection position shifts from 40 to 75 m as the truck runs. The 50 m and 62 m points, where strain decreases, are locations where the flanges are connected with splice plates, and the increased plate thickness results in smaller strain. Viaduct monitoring via a 1 km transmission fiber cable was verified by proposed fiber optic telemetry.



Fig. 3. Optical fiber sensor installation on the viaduct; left: Fiber cable layout from DFOS analyzer to fiber sensor; center: transmission and sensing fibers connected in the fiber junction box installed on the upper deck; right: optical fiber sensor mounted to the top surface of the bottom flange.

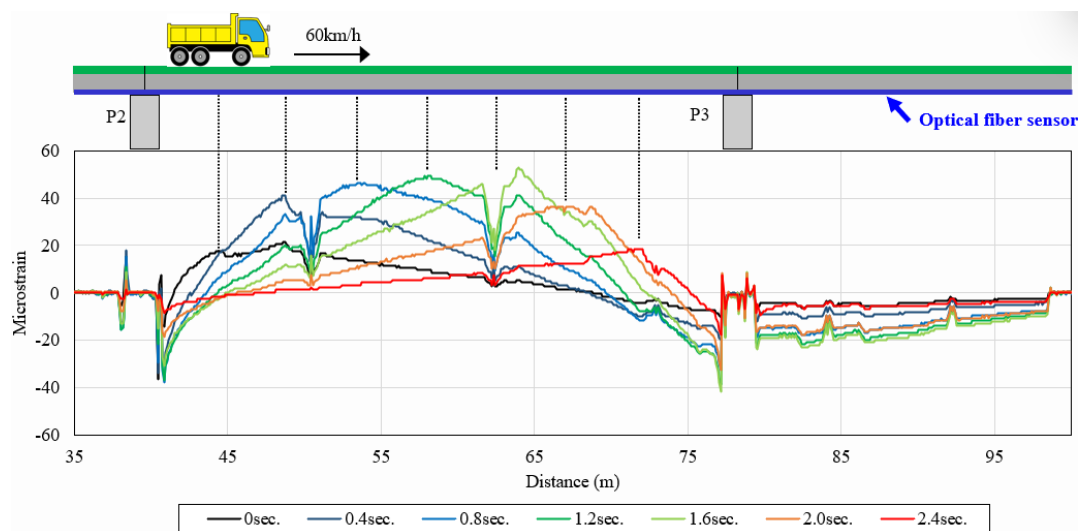


Fig. 4. Dynamic strain distribution during a truck running at 60 km/h.

Conclusion

We proposed a fiber optic strain telemetry employing mid-range OFDR and verified the applicability through an application to viaduct structural monitoring. We will continue to develop PNC-OFDR so that it will become a sensing technology necessary for the quantitative evaluation of civil engineering structures, such as bridges, dams, and mountain tunnels.

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Damage localization in the openLAB research bridge using fiber segment interferometry

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Abstract

We demonstrate a novel approach to detection and localization of structural damages using Fiber Segment Interferometry (FSI). FSI is a long-gauge optical sensing technology for the measurement of elongation, characterized by nano-strain resolution and high sampling rate. This paper shows that low-amplitude transient strain changes caused by acoustic emissions can be measured with FSI and used to pinpoint the origin of events. This work examines results from tests conducted on the openLAB research bridge. During the experiment, several wires from the prestressing tendons were cut, creating damage along the central span of the bridge, and causing acoustic events. The 15 m central span of the bridge was instrumented with three FSI strain-sensing fibers, each 800 mm in length, bonded directly to the concrete surface in a linear arrangement along the girder. Each fiber contained five reflectors, forming four contiguous measurement segments. In FSI, the measurement corresponds to the change in elongation of the segment between adjacent reflectors. When a wire is severed, the event will propagate to each fiber and segment with a delay. A comparison of the differential delay can be used to triangulate the location of the damage. Of the 38 events nominally reported, 84% were successfully detected using FSI technology. Considering all measurement locations, we observed an average event amplitude of 717 ± 513 nε, well above the signal noise level of 34 ± 13 nε. Localization of the events was also successful, with an average absolute deviation from nominal damage location of 84 ± 43 mm and a maximum deviation of 175 mm. These results provide a strong indication of the potential of FSI for damage localization. Future development will extend this line of research to other sources of damage detectable with dynamic strain measurements.

Keywords: Fiber segment interferometry; openLAB research bridge; acoustic emissions; dynamic strain

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Smart road monitoring: fibre optic sensor integration for traffic and structural analysis

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Abstract

This study explores advanced fibre optic sensing technologies for continuous, high-resolution monitoring of road structures to enhance infrastructure safety and maintenance. The primary objective of this work is to evaluate the capability of distributed dynamic strain sensing (DDSS) for quantitative monitoring of traffic-induced pavement responses under controlled and operational traffic loading. Traditional methods often lack the ability to provide real-time data on mechanical and thermal conditions, limiting effective decision-making. In a pilot application, nearly 1 km of highway pavement was embedded with fibre optic cables, enabling simultaneous Distributed Temperature Sensing (DTS) and Distributed Dynamic Strain Sensing (DDSS). This innovative setup facilitated detailed spatial and temporal data collection, capturing pavement deformation caused by individual vehicle axles, as well as temperature variations throughout construction and operation phases. The high-resolution DDSS data allowed for vehicle detection, speed estimation, and classification based on wheelbase measurements, as well as the monitoring of driving behaviors such as overtaking and braking. Quantitative analysis of deformation curves enabled estimates of axle loads, supporting potential weigh-in-motion applications. Furthermore, the system recorded vibrations before and after vehicle passage, enriching the understanding of dynamic loading effects. The integration of these sensors provides insights into the mechanical properties of asphalt structures, which are crucial for assessing structural integrity and planning maintenance strategies.

This research demonstrates that fibre optic sensing offers a promising solution for real-time infrastructure monitoring, facilitating more accurate condition assessments and proactive maintenance planning. The observed correlation between measured strain and applied load highlights the potential of the technology for pavement assessment, traffic monitoring, and future weigh-in-motion systems. Ongoing work focuses on refining load-strain calibration relationships and quantitative evaluation methods for road engineering applications.

Keywords: Fibre optic sensors; structural health monitoring; traffic assessment; distributed dynamic strain sensing (DDSS)

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EDF's feedback on the operation of fiber optic monitoring systems for hydraulic structures

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Abstract

EDF (Electricité de France) is the owner and operator of approximately 500 km of long linear hydraulic embankment structures (levees and canal embankments) in France. Considering that certain problems that these structures could face, such as internal erosion or risks related to the formation of cavities in the foundations, could not be detected effectively by conventional monitoring methods, EDF began developing fiber optic distributed measurement methods in 2001. The initial developments focused on methods for analyzing temperature data using fiber optics in order to locate and characterize leakage flows through the embankment body or its shallow foundation. First, initial experience was gained in the implementation and operation of fiber optic temperature-based leak detection systems on actual EDF facilities but used for research and development purposes between 2001 and 2007. Then, the rehabilitation of the Curbans canal waterproofing in 2010-2011 provided an opportunity to install the first EDF industrial-grade fiber optic-based monitoring system, with 2 x 5 km of fiber optic cable for temperature measurement and 2 km of cable for strain measurement. This installation has now been in operation for over 14 years and, thanks to distributed strain measurements, provides important information on the development and potential presence of cavities under the canal invert. EDF, together with its partner geophyConsult, has to date designed, supervised the implementation, commissioned and then operated or provided training in the operation of fiber optic monitoring systems for levees and canal embankments in France, comprising 106 km of cables acting as measurement sensors. This article presents the main principles of the fiber optic data analysis methods developed by EDF, the general methodology for designing installations for the early detection of internal erosion risk, and the lessons learned from more than 10 years of operating these installations. It also presents several new requirements for monitoring levees and canal embankments, where innovative fiber optic measurements could prove very useful.

Keywords: Fibre optic distributed temperature and strain measurements; internal erosion monitoring; tunnel monitoring

* The full paper is open access available in the Conference Proceedings. *

Distributed fiber-optic temperature monitoring and PCA–ICA analysis for near-real-time seepage detection in river levees

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Abstract

Smart monitoring of geotechnical structures increasingly relies on distributed fiber-optic sensing (DFOS) to provide continuous, high-resolution measurements of temperature, strain, or pressure over long distances. Such systems enable the early identification of local anomalies that may compromise structural integrity under variable conditions. This study presents a methodology for the early detection of seepage anomalies in river levees by combining distributed temperature sensing (DTS) with multivariate statistical processing. The proposed framework integrates principal component analysis (PCA) to reduce data dimensionality and identify dominant thermal patterns, followed by independent component analysis (ICA) to isolate statistically independent signals associated with seepage-induced advective heat transport. The methodology was applied to a levee section along the Adige River (Northern Italy), where DTS monitoring was implemented together with conventional pressure and temperature sensors. During a flood event, the approach successfully identified transient thermal anomalies consistent with visually observed seepage zones and corresponding pore-pressure responses. The algorithm was further evaluated under near-real-time conditions by progressively analyzing partial datasets, demonstrating the capability to detect anomalies within a few hours after their onset. The results highlight the potential of integrating DFOS-based monitoring with advanced statistical data processing to support automated and scalable assessment of levee behavior, contributing to proactive flood-risk management and smart monitoring of hydraulic infrastructures.

Keywords: Smart monitoring; distributed fiber-optic; seepage detection; principal component analysis; independent component analysis

* The full paper is open access available in the Conference Proceedings. *

DOFS for an integrated landslide monitoring setup during tunnel excavation

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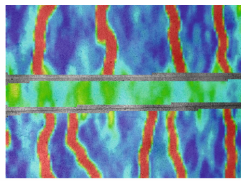
Abstract

The use of distributed optical fiber sensors (DOFS) as an emerging technology for deformation monitoring is becoming increasingly widespread, especially in structural health monitoring and slope engineering, thanks to their ability to provide continuous, stand-alone, real-time measurements even in hard-to-reach locations. These characteristics make them attractive for developing improved monitoring and early-warning systems for geohazards that can threaten human lives.

In this context, characterized by a high-risk scenario where a deep-seated landslide is interested by tunnelling excavation in an urbanized area, a 60 m-long optical fiber Smart Extenso-Inclinometer (SEI), based on the Brillouin scattering phenomenon, was installed to monitor ground deformation along a suitably selected vertical section during the works. The preliminary results are presented in this paper. Among other findings, the SEI's ability to measure settlement trends across progressive excavation phases exceeds that of traditional inclinometers. It underscores the significant potential of DOFS to enhance the effectiveness of conventional monitoring techniques and devices in such complex scenarios.

Keywords: DFOS extenso-inclinometer; innovative technologies; landslide monitoring

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Experimental investigation of debris flow monitoring using DAS in a large-scale physical model

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Keywords: DAS; debris flow; optical fiber sensing

1. Introduction

Debris flows are rapid, gravity-driven movements of water-saturated sediments that pose significant risks to infrastructure and human safety. Their unpredictability and fast evolution challenge traditional monitoring systems, which often rely on spatially limited point sensors. To overcome these limitations, this study investigates the application of Distributed Acoustic Sensing (DAS) for continuous, large-scale debris-flow monitoring. A fiber-optic cable was integrated into a large-scale soil flume to simulate debris flows under controlled conditions. The experimental setup, methodological challenges, and preliminary results are presented, demonstrating the feasibility and potential of DAS to improve real-time detection and characterization of debris-flow dynamics.

2. Experimental setup

The physical model of this work is a large-scale earth flume, shown in Fig. 1, consisting of a channel dug into an artificial embankment, with a 28.6% slope relative to the horizontal, a total length of 10.5 m, and a width of 2.24 m. The channel bed is reinforced to prevent erosion, thereby facilitating the runout of the flowing material. Moreover, a non-woven fabric is laid over the embankment surface as a base layer, and a sand blanket is then placed along the channel borders for the deployment of the optical fiber. The central part of the channel, where the debris is released, is protected by a green artificial mattress, designed to both prevent channel bed erosion and support a guided, repeatable flow path. The top of the embankment is equipped to allow controlled material release during the experiments: at the crest, we installed a 300 L concrete hopper bucket on a 5.9 by 4.2 m platform, which ensures controlled, repeatable debris release. An additional chute between the hopper and the channel is added to direct the discharged material into the channel and prevent unwanted impacts at the release point.

The optical fiber cable was installed at the channel's borders and then covered with an additional layer of sand. However, applying Distributed Acoustic Sensing (DAS) to physical-model experiments presents specific challenges not encountered in typical field deployments. In physical models, the monitored domain typically spans only a few meters, while the processes of interest evolve on short spatial and temporal scales, requiring very fine spatial resolution and high sampling rates to be properly captured. Such demanding requirements often exceed the nominal capabilities of commercially available DAS interrogators, which are generally optimized for tens of kilometers of sensing fiber and some-meter-scale spatial resolutions (Hartog, 2017). State-of-the-art solutions to improve spatial resolution to the cm scale at km range have been proposed so far (Soriano- Amat et al., 2021); however, they are limited to a few tens of Hz, which is insufficient for debris-flow monitoring. Alternatively, authors have proposed that proper fiber arrangements can enhance spatial resolution; for example, by deploying the fiber in loops, with or without a

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supporting mandrel, to implement daisy-chained arrays of coils (Hussel et al., 2019). In this scenario, the fiber can be wound with a large excess, and this excess length can be used to improve sensitivity by employing a longer gauge length in DAS measurements or by properly stacking the signals collected at different positions within the same coil. This improved sensitivity, which corresponds to a higher SNR of the raw measurements, can also lead to better accuracy in the derived measurements.

Here we followed that approach: we created two arrays of 13 coils each, which we deployed on the shoulders of the channel. Each coil consists of approximately 15 meters of cable wound in a Yin-Yang spiral configuration. In this Yin-Yang configuration, the cable is coiled into a spiral with a central “S”-shaped path, allowing both ends of the coil to be accessible from the outer layer, and therefore, enabling easier handling, daisy-chaining, and integration. The cable we used here contains two bend-insensitive, inexpensive, commercially available single-mode telecom-grade fibers (G657.A1) that offer low attenuation at the operating wavelength of 1550 nm and allow twice the fiber length within the same coil. In each coil, the two fibers from one free end of the cable have been spliced together to form a loop; in contrast, the two fibers from the other free end have been daisy-chained with other coils. Therefore, for every meter of cable, we can simultaneously interrogate 2 meters of fiber, thereby doubling the data collected. The final topology of the cable deployment, showing the path of the fiber from the interrogator to the array of coils, is shown in Fig. 1(b). Overall, we deployed approximately 430 m of cable (860 m of fiber) into the physical flume. To precisely locate the seismic signals relative to the physical flume, we mapped the acoustic sensor's position on the flume to the corresponding linear coordinate along the optical path from the interrogator port. The physical flume is interrogated using a commercial DAS with a gauge length of 3 m, a sample spacing of 1 m, and a repetition rate of 50 kHz, thereby improving robustness against saturation. The final acoustic bandwidth, after downsampling, is set to a prudent value of 1 kHz, more than twice the value typically addressed with standard sensors (i.e., less than 350 Hz).

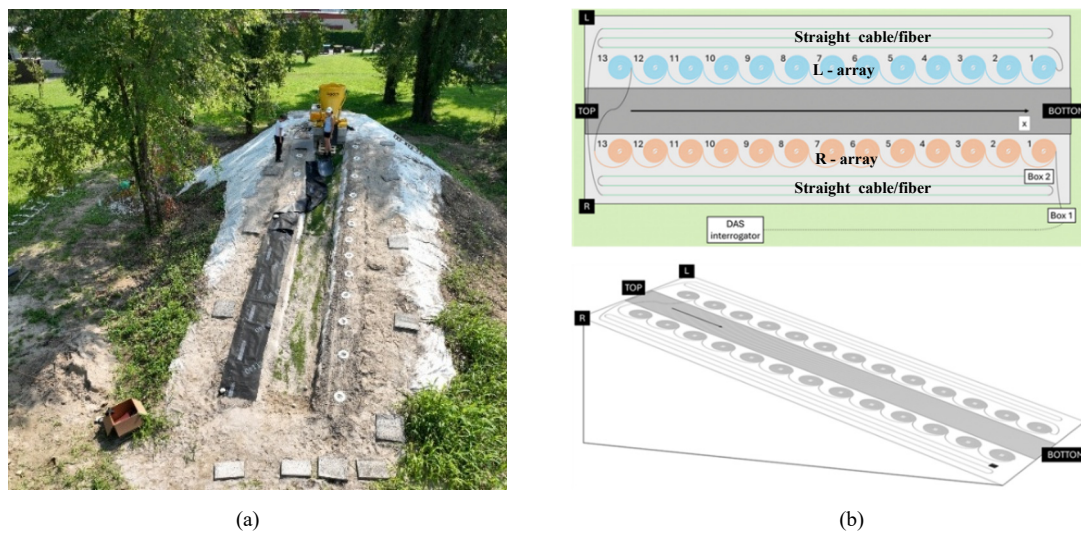


Fig. 1. (a) Aerial photo of the large-scale physical model during construction: it is possible to distinguish the channel, identified by the green artificial mattress, the hooper bucket used for the controlled release of material at the crest of the embankment, and the coil arrays of white cable at the sides of the channel. (b) Top view of the flume (from the top) with the corresponding 3D representation (from the side), with a schematic view of the cable deployment. The material released on the top side falls towards the bottom along the flume indicated by the grey area.

3. Results

Fig. 2 shows the waterfall plot of the seismic signal generated by a single polygenic clast stone (10 x 15 x 25 cm), used to calibrate the system, released from the top of the flume within a short time frame of less than 0.5 seconds. During this period, the stone bounces three times, creating a characteristic inverted “V” shape in the plot (highlighted with dashed green curves), with the apex indicating the coil closest to the impact point (shown with white-filled green circles in the picture). By tracking the time of impact, we can estimate the stone's velocity. In contrast, the slopes of the V-arms indicate the speed of the waves generated by the impacts, which was estimated to be 130-200 m/s for all tests; this range is consistent with loose, dry sand or partially compacted soil (Oelze et al. 2002).

Fig. 3(a) shows an example of the waterfall plot for the release of more than 100 kg of mixed boulders with a maximum diameter not larger than 15 cm. The x-axis is limited to the portion of fiber in the right array: the vertical checkerboard structure of the waterfall, with uniform bands 15 meters long, is due to the coiled deployment. As an example of the analysis enabled by the system, Fig. 3(b) shows the power spectral density of the stacked signals collected at the coils number 12, 9, 7, 5, 3, 1 which are located at 0.47, 1.28, 2.35, 3.41, 4.21 and 4.77 m from the crest of the flume, where the debris have been released. The PSDs show a clear evolution from the crest to the lower part of the flume. Near the crest, the spectra are broader and more energetic, with a pronounced low-frequency peak and some energy at intermediate frequencies, consistent with intense, multiscale debris-flow fluctuations. As one moves downslope, the spectra become progressively smoother, while the intermediate- and high-frequency components gradually disappear. In the lowest sections of the flume, the signal is increasingly dominated by low-frequency components, suggesting progressive dissipation of small-scale dynamics and a downstream stabilization of the flow.

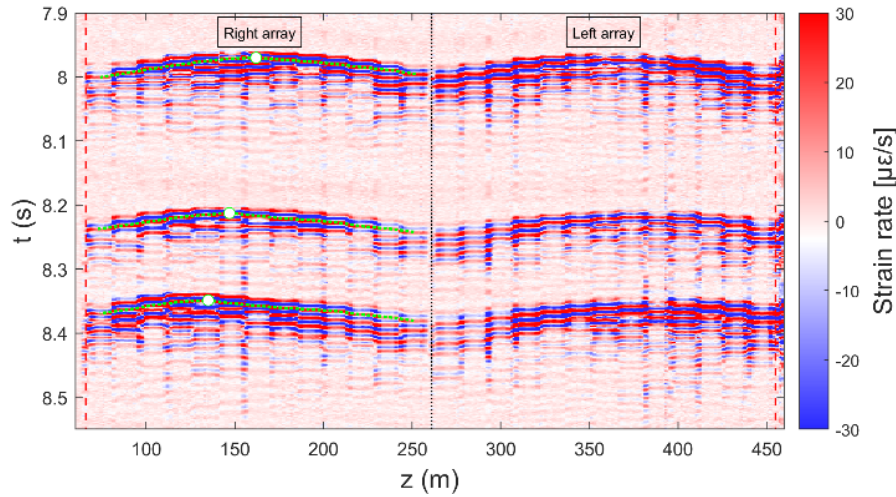


Fig. 2. Waterfall plot corresponding to the deployment of the cable on the flume. The labels identify the fiber path and its corresponding position with respect to the physical model.

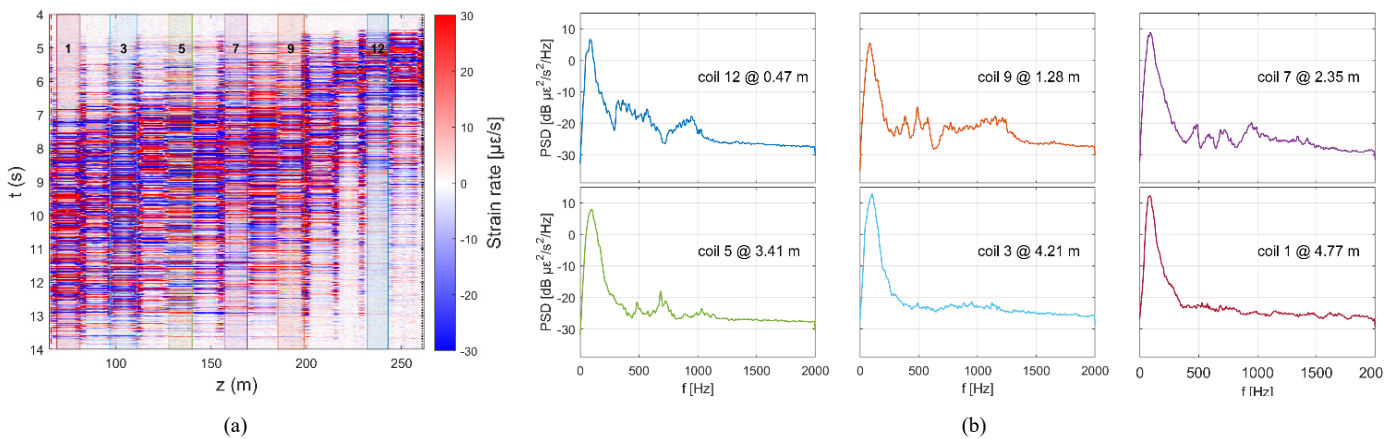


Fig. 3. (a) Waterfall plot, limited to the right coils array, of a simulated debris flow consisting of more than 100 kg of mixed boulders (shaded areas identify the portion of fiber corresponding to six coils in the right array analyzed in the right plots). (b) PSD spectra of the stacked signals measured at the six coils (color and labels are consistent with the shaded area of the left waterfall plot).

4. Conclusions

The preliminary results shown here confirm the potential of DAS as an effective tool for the distributed monitoring of debris flows. The system, applied to a large-scale physical model, has been shown to effectively track and measure spatial and temporal variations in the flow, confirming the potential of this technology for high-spatial-resolution characterization of debris-flow dynamics. DAS technology represents a promising solution for developing high-resolution monitoring systems, suitable for physical models and for future early-warning and land-monitoring systems.

Acknowledgements

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Integrating economic and innovation aspects for improved landslide risk mitigation

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Abstract

Since 2025, the EU's Stability and Growth Pact 'National Escape Clause' (NEC) enables member states to temporarily exceed strict fiscal limits to support strategic spending. This significant economic flexibility supports, e.g., investments in innovative monitoring technologies for natural hazards. In slope engineering, distributed fiber optic sensors have advanced landslide monitoring by providing continuous, real-time data on soil deformation. The new smart hybrid transducer (NSHT), based on Brillouin scattering, offers significant advantages over traditional instruments by accurately measuring the strain of soil or structural elements to which it is connected. The smart extenso-inclinometer, based on NSHT, also offers significant advantages over traditional devices by accurately measuring both vertical and horizontal strains of subsoil, even under rapid or complex ground movements, such as shallow fast-moving or deep-seated landslides. Such precise monitoring enhances landslide risk management by enabling timely, targeted interventions to protect structures, infrastructure, and communities. The large-scale implementation of these sensors facilitates the acquisition of precise, real-time data. This vast dataset has the potential to serve as an essential 'oracle' for blockchain systems, enabling the integration of substantial data on real-world assets (e.g., real estate or infrastructure) that would otherwise remain inaccessible to blockchain environments, which are inherently isolated from external physical events.

Keywords: Landslide risk mitigation; innovative technologies; landslide monitoring; Oracle; RWA Tokenisation Web 3.0

* The full paper is open access available in the Conference Proceedings. *

Distributed fiber-optic sensing and 3D laser scanning in an underground mine towards development of a digital twin

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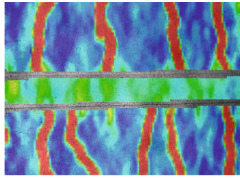
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Abstract

This study presents the installation and evaluation of a distributed fiber optic sensing (DFOS) system in an underground lab located in the research and education mine "Forschungs- und Lehrbergwerk (FLB) Reiche Zeche" at TU Bergakademie Freiberg, Germany. The target of the study is to support the development of a digital twin for mining environments. DFOS-based strain and temperature sensing cables were installed along a 60 m section of a mine drift and spatially referenced using a high-resolution SLAM-derived 3D point cloud. Continuous monitoring over 647 epochs captured temperature variations consistent with seasonal cooling and revealed several localized zones of significant strain change. On-site inspection showed that these zones corresponded primarily to joints, weathering features, and areas of tight cable bending, with only one location affected by partial mortar detachment. The combined DFOS–3D point cloud acquisition workflow proved effective for linking distributed measurements to complex underground geometries, enabling detailed interpretation of geological and environmental processes. The results demonstrate the suitability of integrated DFOS and 3D mapping approaches for long-term monitoring and form an essential step towards a digital twin of the underground mine.

Keywords: fiber-optic sensing; 3D point cloud; digital twin; underground mining

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From DFOS measurements to engineering insights – the role of custom software solutions

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Keywords: DFOS; distributed fibre optic sensing; automation; software solutions

1. Introduction

Distributed fiber optic sensing (DFOS) based on Brillouin, Rayleigh, and Raman backscattering delivers continuous strain, temperature, and vibration profiles along kilometers of fiber with sub-millimeter to meter-scale spatial resolution. Commercial interrogators and robust sensors have reached a high level of maturity, yet DFOS adoption in routine infrastructure management remains limited. The primary bottleneck is now commonly identified as the software pipeline that transforms raw optical signals into engineering insights and supports decisions, either with engineering insights or machine-learning-supported data processing. Commercial interrogator software covers raw signal processing and basic visualization, but the path to engineering insight, that is project-specific calibration, automated damage detection, contextual interpretation, and reporting, must largely be built from scratch. This paper surveys algorithms, open-source tools, and commercial software for DFOS evaluation in civil infrastructure, identifies critical gaps, and illustrates the need for custom solutions based on practical experience with high-resolution strain measurements using Luna ODiSI Interrogator.

2. The DFOS data processing pipeline: from laser signal to engineering decisions

2.1. Three-layer pipeline

The transformation of raw DFOS data into engineering decisions can be conceptualized as a three-layer pipeline. Layer (a): raw signal processing involves sampling, filtering, and denoising. Layer (b): physical quantity extraction covers strain/temperature calibration, while Layer (c): engineering interpretation includes the transition from strain values to structural interpretations and currently represents the largest methodological and software gap.

2.2. Open-source and commercial software tools

The recent software landscape can be divided into open-source research ecosystems and commercial monitoring platforms. On the open-source side, a relatively mature ecosystem of frameworks exists for distributed acoustic sensing (DAS) and distributed temperature sensing (DTS), having been developed mainly by researchers: DASCORE (Spica et al., 2024), DASPy (Hu et al., 2024), PhaseNet-DAS (Zhu et al., 2023), and dtscalibration for Raman DTS. The asymmetry relative to distributed strain sensing (DSS) is clearly visible – for distributed strain sensing, the most significant open-source tool is *fosanalysis* (github.com/TUD-IMB/fosanalysis), a Python framework from TU Dresden for automated crack detection and width calculation from OFDR data, with pre-processing for strain anomalies (Richter et al., 2024a, 2024b). It stands essentially alone as a dedicated open-source framework for distributed strain interpretation. At RWTH Aachen University a FOS Evaluator tool is being developed and public

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release was stated as planned (Janiak et al., 2023). A promising framework combining DFOS data with augmented reality and digital twin integration has been demonstrated recently (Fernandez et al., 2025). Multiple studies present flowcharts and approaches to specific challenges, such as removing the strain reading anomalies (Bado et al. 2020), yet these still remain largely individual research contributions, not reusable platforms.

Commercial software solutions from manufacturers of the measurement devices, such as Luna (ODiSI), Neubrex (NEUBREGATE), fibrisTerre (fTView/fTScope), FEBUS (FOGrid), AP Sensing (SmartVision) or Omnisens, provide powerful acquisition and visualization but primarily address layers (a) and (b). Engineering-level interpretations, crack width calculations, multi-sensor fusion and visualization of multiple measuring sessions, using more complicated offset and reversing functions, fall outside their scope. A thorough asset management integration remains unsolved.

A major challenge is therefore not the lack of signal-processing tools per se, but the lack of reusable software frameworks that connect processed DFOS signals to engineering interpretation in a transparent and validated manner.

2.3. The role of custom software solutions

For structural and infrastructure applications, the value of custom software lies in its ability to turn dense sensing data into interpretable condition information. In real-world DFOS installations involve often complex sensor routing, mapping measurement positions to physical locations and maintaining this mapping across campaigns, what requires dedicated tools. Furthermore, in concrete structures, distributed strain measurements can be transformed into indicators of crack initiation, localization, and width. The critical outcome is therefore not a plot of the raw data, but a reduced and interpretable set of indicators that engineers can act upon. Custom software organizes the signal chains, embeds engineering assumptions, and makes the output available in formats that can be integrated into inspection workflows, maintenance planning, or operational alarm systems.

Custom software solutions are also essential because DFOS evaluation rarely follows a universal workflow. One of the important topics is automated quality control and preprocessing. Here, custom software enables repeatable handling of noise, drift, outliers, missing data, spatial artefacts, and sensor-specific disturbances. Another task is calibration, compensation, and feature extraction from the pre-processed data, which may include also the topic of temperature-strain decoupling. The final task of custom software is data interpretation and integration. This is where raw or processed signals can become engineering outputs such as damage indicators, crack maps, alarms, or even digital twin updates. This step requires more than visualization, it requires combined domain knowledge embedded in the structural behavior, rules, thresholds, models, and reporting logic. In this sense, custom software is the mechanism through which project-specific engineering meaning is encoded. The most robust architecture separates data ingestion, metadata handling, quality control and calibration, feature extraction, and insight generation.

3. Practical experience: FOlens custom software

To support the transition from raw DFOS measurements to actionable engineering information, the authors developed FOlens, a desktop, no-code application for the analysis and interpretation of distributed fiber optic sensing data (Fig. 1). FOlens provides an integrated workflow for processing measurements in both the spatial and temporal domains, covering data import, offset correction, anomaly detection and removal, advanced filtering, peak and discontinuity detection, as well as the joining and comparison of multiple measurement sessions and sensors. The software also enables automated crack detection and crack width calculation for concrete structures using a scientifically referenced strain-integration approach, linking measured strain profiles directly to engineering performance indicators. By replacing ad hoc spreadsheet workflows and custom scripts with a consistent, traceable, and reproducible pipeline, FOlens facilitates efficient DFOS data evaluation for structural health monitoring, laboratory investigations, and infrastructure diagnostics.

FOlens is conceived as a desktop, no-code environment for DFOS data evaluation. The frontend is based on Vue.js and the Quasar Framework, while the backend is implemented using .NET microservices. Additional optimizations in memory management were introduced to improve charting performance for large datasets. The introduction of .folens project files, which store imported file paths and analysis settings, facilitates data retrieval and the integration of results from repeated measurement campaigns. The software was developed to provide engineers and researchers with a versatile environment for rapid visualization, interpretation, and comparison of acquired data. The integrated visualization of multiple sessions in a single view in the length and time domains has proven particularly valuable for periodic monitoring, where engineers need to identify trends and changes relative to a reference state.

Considering practical deployment and performance in multi-campaign monitoring scenarios, projects routinely accumulate multiple GB of raw data across several measurement sessions. To address performance constraints associated with large DFOS datasets, FOlens incorporates an optimized data handling strategy combining on-disk storage with in-memory caching of preprocessed data. Frequently accessed and already processed data segments are selectively loaded into memory, significantly reducing latency during interactive analysis and enabling smooth visualization even for multi-gigabyte measurement campaigns.

In addition to its desktop-based user interface, FOlens is built on a service-oriented architecture leveraging .NET-based microservices, enabling modularization of data processing, version control, and system management functionalities. This multi-platform architecture provides a foundation for scalable and extensible deployment scenarios, including future integration with cloud-based infrastructures. Beyond data processing, the software architecture includes a flexible licensing and version management system that supports collaborative use across teams. Combined with an automatic update system, this enables rapid

distribution of new features, algorithm improvements, and project-specific extensions, ensuring a consistent and up-to-date software environment across all users.

FOlens leverages also a flexible communication architecture that adapts to different performance and integration requirements. Depending on the use case, the system utilizes REST APIs for standard interactions, WebSocket-based communication for real-time data exchange, and gRPC for efficient, low-latency service-to-service communication. This multi-protocol approach enables seamless integration across heterogeneous environments and lays a foundation for a future-oriented software solution.



Fig. 1. FOlens desktop application for postprocessing of DFOS-data: (left top) length-domain analysis with strain results and crack width calculation, (left bottom) time-domain view showing strain evolution at selected gage positions during a load test, (right) FOlens system architecture.

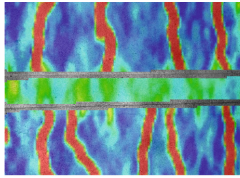
4. Conclusions and outlook

In conclusion, the path from DFOS measurements to engineering insight is fundamentally a software problem as much as it is a sensing problem. The most promising direction lies in custom software solutions that integrate data standards, robust preprocessing, quality control, automated interpretation, and application-specific engineering knowledge. Custom software is the key enabler that turns high-resolution sensing into usable, trustworthy engineering information. Broader adoption of DFOS in infrastructure management will depend not only on sensor performance but on transparent, validated software workflows that enable repeatable interpretation across projects, operators, and asset types.

Looking ahead, machine learning methods for automated anomaly detection and pattern classification offer the potential to further reduce manual interpretation effort. A transition from desktop toward cloud-based or hybrid deployment would enable remote access, collaborative analysis, and scalability. The DFOS community would also benefit from standardized data exchange formats facilitating interoperability between interrogator software, evaluation tools, and asset management systems, an area requiring coordination with broader SHM standardization efforts. Finally, coupling DFOS evaluation software with BIM, VR, and digital twin frameworks represents a promising path toward embedding continuous sensing data into lifecycle models of infrastructure assets.

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Fiber optic strain sensing of a solar PV single-axis tracking system under wind loads

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Keywords: Distributed fiber optic strain sensing; modal analysis; single-axis solar tracker

1. Introduction

Wind-induced dynamic response remains a critical challenge for utility-scale solar photovoltaic (PV) tracking systems (Bao et al., 2023), particularly for single-axis configurations that are susceptible to torsional deformation and aeroelastic effects. These systems are increasingly deployed in regions with complex wind environments, where both quasi-static and dynamic loading can govern structural performance and long-term durability.

Conventional structural health monitoring (SHM) approaches rely on discrete sensors such as strain gauges and accelerometers. While effective for localized measurements, these sensors provide limited spatial resolution and may not adequately capture distributed deformation patterns or global system behavior. In particular, accelerometer measurements are often dominated by local panel vibration modes, which may obscure system-level response characteristics.

Fiber optic sensing (FOS), including distributed strain sensing (DSS) and fiber Bragg grating (FBG) sensors, offers a promising alternative by enabling dense spatial measurements with high durability and multiplexing capability (Liu et al., 2021; Mariñelarena et al., 2019; Zhang et al., 2022). This study investigates the application of FOS for capturing distributed structural response and identifying modal characteristics of a full-scale solar PV tracking system under wind loading. Laboratory validation tests and field measurements are combined with system identification techniques to evaluate the effectiveness of this approach.

2. Experimental overview

A full-scale single-axis solar tracker at the Michigan Solar Regional Test Center was instrumented with fiber optic sensors and conventional sensors (Fig. 1). The sensing configuration included multiplexed FBG strain sensors distributed along the torque tube, DSS cables for continuous strain measurements, accelerometers for comparison, and anemometers for wind characterization.

Prior to field deployment, laboratory tests were conducted to validate sensor performance under controlled bending and torsional loading conditions. In particular, torsion tests confirmed that fiber optic sensors mounted at 45° relative to the tube axis effectively capture torsional strain response.

Field validation included both static torsion tests and dynamic impact tests. Hammer impact excitation produced clear vibration signatures in both strain and acceleration measurements, providing a basis for comparing sensing modalities.

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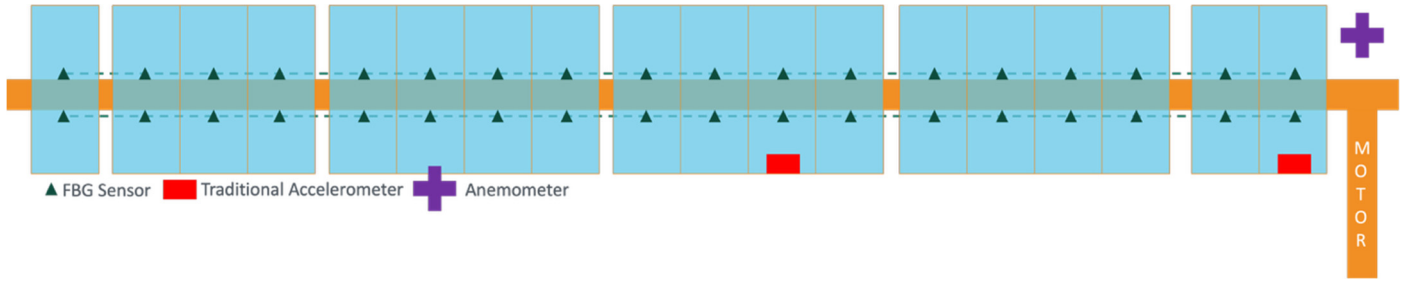


Fig. 1. Schematic diagram of sensors attachment per row.

3. Modal Identification using distributed strain data

Dynamic response data from the FBG sensor network were analyzed using frequency domain decomposition (FDD). By constructing and decomposing the cross-power spectral density matrix of the multi-sensor strain measurements, dominant structural modes were identified while suppressing incoherent noise.

The resulting singular value spectra revealed distinct modal peaks, with a dominant frequency observed near 4–5 Hz (Fig. 2), corresponding to the fundamental torsional mode of the tracker system. Additional higher-frequency modes were also identified, associated with localized structural behavior.

Compared to conventional FFT analysis of individual sensors, the FDD approach provides clearer and more stable identification of modal frequencies by leveraging spatial coherence across the distributed sensor network.

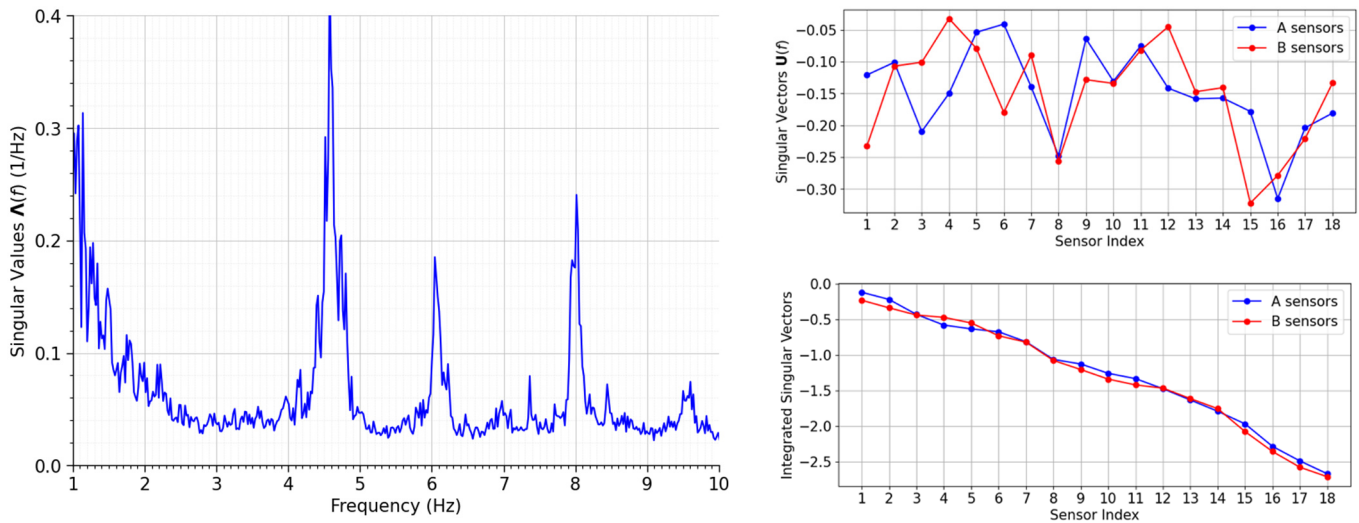


Fig. 2. Modal identification (FDD method) using the FBG data.

4. Response under ambient wind loading

Continuous monitoring under natural wind conditions demonstrated that fiber optic sensors capture measurable strain fluctuations even at low wind speeds (Fig. 3). A sliding-window FDD approach was used to evaluate the temporal evolution of modal energy within the primary frequency band.

Periods of increased wind intensity were generally associated with elevated modal response, indicating that the fundamental torsional mode is actively excited by ambient wind loading. In contrast, accelerometer measurements were dominated by local panel vibration modes and showed weaker correlation with wind speed.

These observations suggest that distributed strain sensing is more effective in capturing global structural behavior and system-level dynamic response compared to discrete acceleration measurements.

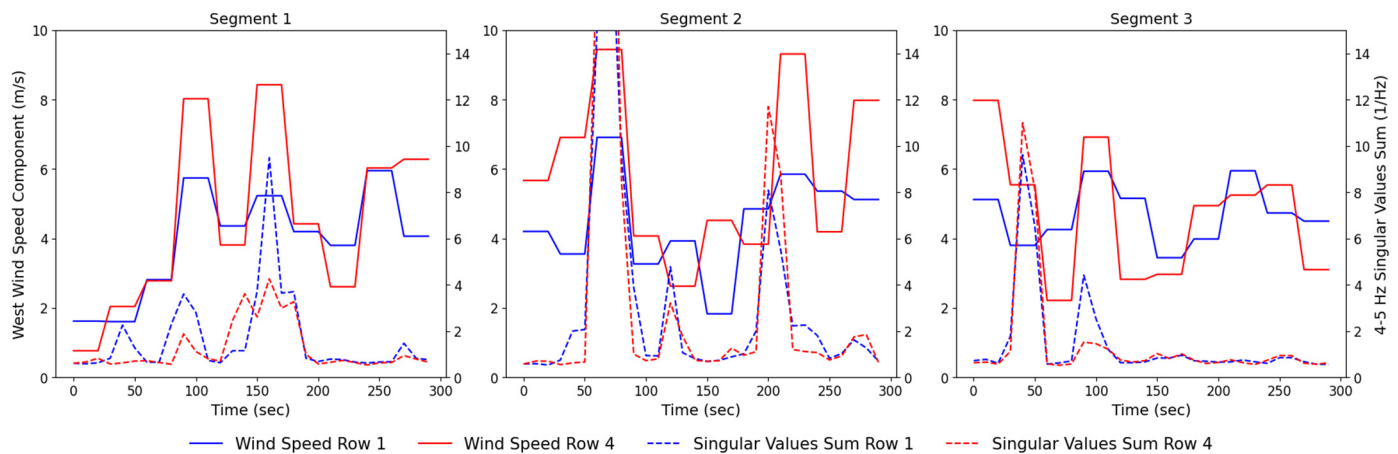


Fig. 3. Wind speed versus singular values sum (obtained from FDD) within 4–5 Hz.

5. Conclusions

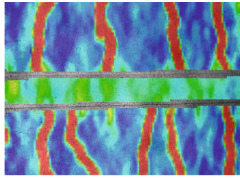
This study demonstrates the effectiveness of fiber optic sensing for monitoring distributed structural response and identifying modal characteristics of solar PV tracking systems under wind loading.

Fiber optic sensors provide spatially continuous strain measurements that capture torsional deformation patterns and enable robust modal identification using multi-channel analysis techniques. The results highlight the limitations of traditional accelerometer-based approaches for system-level monitoring and demonstrate the advantages of distributed sensing for capturing global structural behavior.

The findings support the use of fiber optic sensing as a scalable and robust SHM solution for wind-sensitive renewable energy infrastructure.

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Sensors for detecting stress in steel reinforcements of infrastructure

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Abstract

To date, destructive testing methods have generally been used to determine strains in reinforcing and prestressing steel in existing structures. In contrast, non-destructive testing methods (NDT) used to date can only detect changes in strain. The initial state (e.g. existing residual stresses or stresses from the dead weight) cannot be recorded with these methods. Reliable, practical non-destructive testing methods (NDT) for recording the stresses or strains (residual stresses and stress changes due to load) of reinforcing or prestressing steel are not available. Laser Speckle Photometry (LSP) and Barkhausen Noise (BN) are non-destructive testing methods that can quickly and reliably determine residual stress and stress changes in concrete and prestressing steel reinforcement. The development of a sensor based on both methods and an associated database represents an important tool for the future evaluation of existing structures. This paper demonstrates the possibility of obtaining the necessary information on the stress state non-destructively by optically recording the strain (by LSP) and the change in the magnetic properties (by BN) of the steel of the steel reinforcement. In addition, the results of the investigations of stress and stress changes in other load-bearing structures in Saxony's coal mining industry are shown here.

Keywords: Laser-speckle-photometrie; Barkhausen noise; steel reinforcement; state of stress

Note: Full paper

1. Introduction

Aging infrastructure presents a major challenge. Many bridges and civil engineering structures are approaching or exceeding their intended service life. This results in limited accessibility or even collapses, such as the recent collapse of the Carola bridge in Dresden [1,2]. Due to limited financial, temporal, and personnel resources, complete replacement of deteriorated structures is not feasible in the near future. Therefore, responsible management of existing infrastructure is essential to ensure operational safety and availability.

Most bridges in highway networks consist of reinforced and prestressed concrete. Knowledge of the actual condition and stress state in reinforcing and prestressing steel is a crucial basis for assessing structural safety and remaining service life. Traditionally, destructive testing methods, such as strain recovery measurements using applied strain gauges [3,4], have been employed to determine stresses in embedded reinforcement. These methods require local intervention and partial removal of material, which can compromise structural integrity and are unsuitable for routine inspections.

In contrast, non-destructive testing (NDT) methods such as strain gauges or digital image correlation (DIC) can only measure changes in strain. They do not provide information about the state of absolute stress, including residual stresses or stresses resulting from critical loads. Consequently, there is a significant need for reliable, practical NDT methods capable of determining absolute stresses and stress variations in reinforcing and prestressing steel directly on the structure.

This study addresses this gap by combining two complementary measurement principles: Laser Speckle Photometry (LSP) for optical strain detection and Barkhausen Noise (BN) analysis for magnetic characterization of stress states.

2. Combined sensor concept

2.1. Stress-strain relationship

For linear elastic material behavior, stress and strain are related by Hooke's law:

$$\sigma = E \cdot \varepsilon \quad (1)$$

where σ = normal stress, E = Young's modulus, ε = strain. In reinforcing steel, residual stresses σ_r may be superimposed with externally applied stresses σ_L :

$$\sigma_{tot} = \sigma_r + \sigma_L \quad (2)$$

2.2. Fundamentals of laser-speckle-photometry and experimental equipment

The measurement equipment of Laser-Speckle-Photometry (LSP) is depicted in **Fehler! Verweisquelle konnte nicht gefunden werden.** The experimental technique consists mainly of three groups of components: illumination, heating and speckle movement detecting. The illumination on the sample is carried out by the irradiation of the surface with coherent light. The laser speckles are generated by this process. Laser speckles are a phenomenon of an optical rough surface illuminated by highly coherent laser source. They are formed by the interference of coherent wavelength with different phases from several elements of the specimen surface and have a random –looking pattern.

The surface change due to strain influences the interference pattern and leads to characteristic changes in the speckle pattern. This results in a coding of the strain state in the speckle pattern. These stochastic speckle patterns are used to measure absolute stress and stress changes. If the surface is elongated, the scattering centers of speckle patterns shift. These minimal changes influence the path of the spherical waves of the reflected or scattered light, so that the interference pattern changes [5]. Speckles become brighter or darker or are extinguished or newly created. The LSP measures the spatial dynamics of the speckle, caused by the change in intensity of each individual pixel of the camera sensor. A mathematical function can be used to establish the correlation between speckle dynamics and the strain change of the sample [6].

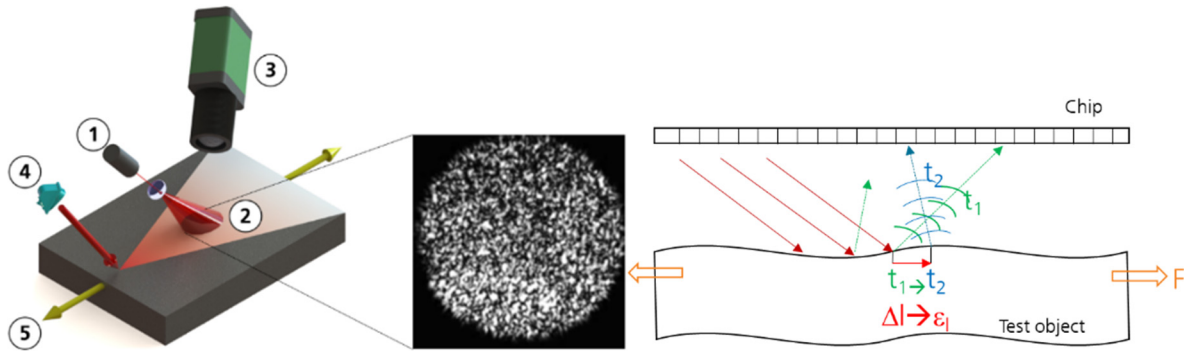


Fig. 1. Left: LSP experimental setup: Coherent light from a laser (1) is reflected from the surface and forms a speckle pattern (2), which is recorded by a camera (3). With thermal (4) or mechanical (5) excitation, the speckle pattern changes and a correlation to the excitation can be derived. Right: Schematic representation of the formation of a speckle image and its change due to surface deformations ($\Delta l \rightarrow \varepsilon_l$ = Elongation by mechanical activation causes the deformation of the test object, which presents in stochastic superposition of wavefronts respectively in stochastic change of the speckle pattern, so called dynamic speckle).

When coherent laser light illuminates a rough metallic surface, an interference pattern (speckle pattern) is generated. Surface deformation causes displacement of the speckle pattern. The lateral elongation ε_l causes the displacement field $u(x, y)$ that can be calculated using correlation between two recorded speckle images. The strain is derived from spatial displacement gradients:

$$\varepsilon_x = \frac{\partial u_x}{\partial x}; \varepsilon_y = \frac{\partial u_y}{\partial y} \quad (3)$$

The measured strain change $\Delta \varepsilon$ bei LSP is related to stress change via:

$$\Delta \sigma = E \cdot \Delta \varepsilon \quad (4)$$

2.3. Fundamentals of Barkhausen noise analysis and experimental equipment

Barkhausen Noise is a magnetic phenomenon observed in ferromagnetic materials such as steel. When a varying magnetic field is applied, magnetic domain walls move discontinuously due to microstructural obstacles. These abrupt movements generate measurable voltage pulses known as BN. The intensity and distribution of BN signals depend on residual stress state, applied mechanical stress, microstructure and hardness and material composition.

Ferromagnetic materials consist of magnetic domains separated by domain walls. Under an alternating magnetic field $H(t)$, discontinuous domain wall movement produces voltage pulses measurable as Barkhausen Noise.

The induced voltage signal $V(t)$ is proportional to the rate of change of magnetic flux:

$$V(t) \propto \frac{dB}{dt} \quad (5)$$

where B is magnetic flux density.

Tensile and compressive stresses influence magnetic domain wall motion differently, allowing stress-dependent signal evaluation.

Mechanical stress alters magnetic anisotropy energy E_a in ferromagnetic materials.

$$E_a = \frac{3}{2} \lambda_s \sigma \cos \theta^2 \quad (6)$$

Where λ_s = magnetostriction constant, σ = applied stress, θ = angle between stress and magnetization.

The RMS value of the Barkhausen Noise signal:

$$BN_{RMS} = \sqrt{\frac{1}{T} \int_0^T V^2(t) dt} \quad (7)$$

correlates with stress state after calibration.

By calibrating the BN signal against known stress states, quantitative relationships between magnetic response and stress can be established. It is possible to record stress measurements without knowing the initial state of the material or requiring calibration samples [7,8]. Unlike optical methods, BN analysis provides information about residual stresses σ_r and absolute stress states in near-surface regions.

Authors has many years of experience in various novel approaches in the field of BN [9], e.g. in the development of application-oriented measurement technology, sensor concepts and algorithms [10,11].

2.4. Combined evaluation approach

The combined method determines the residual stress σ_r via BN calibration and stress change $\Delta\sigma$ via LSP, where the total stress σ_{tot} equals:

$$\sigma_{tot} = \sigma_r + E \cdot \Delta\varepsilon \quad (8)$$

Data fusion of LSP and BN analysis enhances measurement reliability and compensates for the inherent limitations of the individual techniques. The innovative contribution of this research lies in the integration of both measurement principles into a single hybrid sensor system, enabling comprehensive stress state characterization.

LSP provides high spatial resolution measurements of strain changes by optically detecting surface deformation. In contrast, BN analysis delivers information on residual stresses and absolute stress levels based on stress-dependent micromagnetic behavior of ferromagnetic materials. The complementary nature of these methods allows determination of the initial residual stress state, continuous monitoring of load-induced stress variations under operational conditions, and cross-validation of optical and magnetic measurement data. This integrated approach significantly improves the robustness and reliability of structural assessment.

3. Experimental investigations

3.1. Experimental setup

The LSP setup [12] used in this study was implemented by applying a laser wavelength of 650 nm in combination with an area camera equipped with a CMOS sensor. The recorded image resolution was 700 px × 1000 px, corresponding to a physical measurement area of approximately 3.85 mm × 5.5 mm on the specimen surface, see Fig. 1.

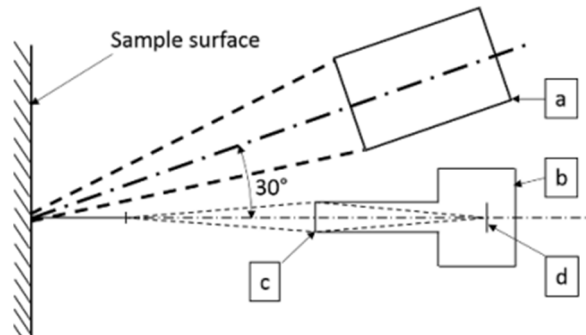


Fig. 1. Schematic structure of the laser speckle photometry setup: (a) – Laser Diode (LD), (b) – camera system, (c) – optics and (d) –sensor.

For the acquisition of BN signals, a FracDim device was used. The associated test head of this device contains a magnetic yoke with a corresponding winding that is supplied by the device generator. To ensure good coupling between the ferromagnetic material and the test surface, the magnetic flux is guided to the measuring point with the aid of ferritic poles. The size of the contact surface

is approximately 8 mm². In the space between the poles, a movable ferritic test probe with a fine measuring coil is located, which detects the noise signals.

The remagnetization field was applied at a frequency of 60 Hz. The magnetic noise was selectively recorded in the frequency range of 30–200 kHz, corresponding to a penetration depth of approximately 0.5 mm.

Dynamic LSP and BN measurements were carried out during the loading of the steel reinforcement using a tensile testing machine. The tensile tests were performed within the elastic stress range between 50 MPa and 500 MPa.

In total, four LSP and BN measurement series were conducted. One series was used for calibration purposes (Experiment 3 and 4), while three independent series were used for evaluation and validation of the repeated stress determination (Experiment 1 and 2). Stress determination was performed using static LSP parameters derived from the correlation analysis of the speckle images.

For the detection of two-dimensional stress using the BN technique, measurements were performed with the magnetic field applied in different orientations. Two measurements were carried out with the magnetic field applied in the tensile direction (parallel to the applied load), and two measurements were performed with the magnetic field applied perpendicular to the tensile direction. In each orientation, one measurement was used for calibration and one for evaluation.

3.2. Samples

A reinforcing steel bar with a diameter of 16 mm, representative of typical bridge construction applications, was selected as the test specimen. The reinforcement bar was clamped at both ends in the tensile testing machine.

For BN measurements, the measurement location was mechanically prepared in order to improve the contact between the BN sensor and the specimen surface. In contrast, the LSP measurements were performed on the untreated specimen surface.

Fig. 2 shows the reinforcing steel specimen on which parallel stress measurements using LSP and BN were conducted. The positions of the two signal acquisition locations are indicated: the BN measurement position is located on the left side of the specimen, while the LSP measurement position is located on the right side.

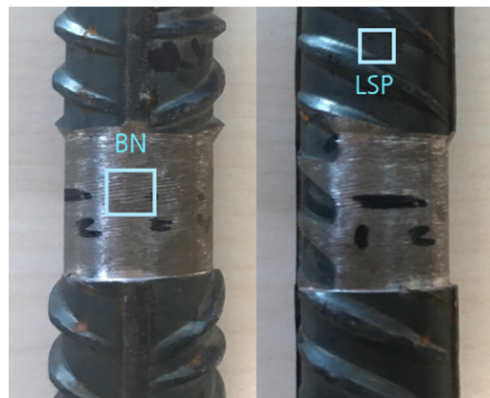


Fig. 2. Sample from the reinforcing steel on which the parallel recording of the spanning was carried out using LSP and BN. The sampling positions of the two types of sigla are marked, left for BN and right for LSP.

4. Results

Within this study, the nondestructive testing (NDT) methods LSP and BN are investigated with regard to their feasibility for the measurement of absolute stresses in steel reinforcement. The objective is the development of a calibration methodology based on a unified fundamental principle for stress determination, thereby extending the current state of the art by introducing a novel measurement approach.

The results of the parallel LSP and BN stress measurements performed on the specimen shown in Fig. 3 during tensile loading are presented in Fig. 3. In this figure, the differential stress reaches a maximum value of 500 MPa, which approaches the upper limit of the elastic stress range of the material.

A clear correlation between the LSP and BN techniques was observed for the reinforcing steel specimens, indicating promising potential for the detection of residual stresses in inhomogeneous material structures (Experiments 1 and 2, blue and green data points). Both methods exhibited linear calibration behavior in Experiments 3 and 4, which is consistent with the theoretical relationship described by Hooke's law (red dashed line).

In the calibration experiments, linear regression analysis demonstrated that characteristic LSP and BN parameters can be used for the quantitative determination of the stress state of the specimen. The combined evaluation of LSP and BN data allowed a correlation between optically determined strain variations and magnetically derived stress parameters, thereby forming the basis for the subsequent data fusion approach.

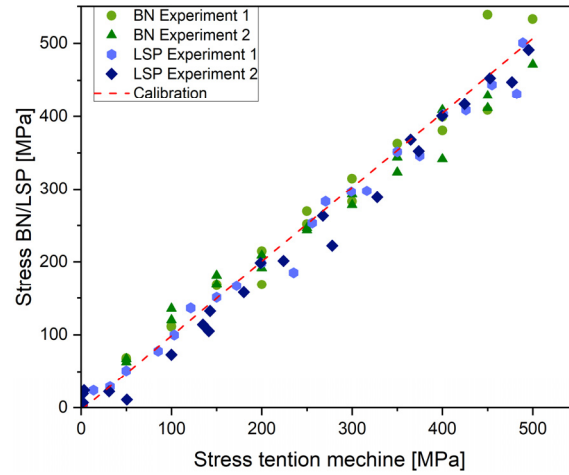


Fig. 3. Stress determined during a tensile test using the combined LSP/BN measurement technique. The stress determined by the LSP and BN sensors is compared with the stress determined on the samples from the tensile test; shown are the last two tests determined from the calibration procedure (experiments 1 and 2).

An example of the transfer of the calibration results obtained from the combined sensor approach is presented in the following field application:

Both methods (LSP and BN as combined sensors) were tested under field conditions on an overburden conveyor bridge used in opencast lignite mining. The measurements were carried out at the so-called tension head of the bridge structure. At this measurement location, the stress state strongly depends on the extension and the inclination angle of the bridge during operation.

The placement of the LSP measurement system is shown on the left side of Fig. 5. The evolution of the measured stress indicates that the maximum stress at the measurement location reaches approximately 75 MPa when the bridge is in its maximum extended position and at the largest inclination angle (black curve in the diagram). After retracting the bridge, the measured stress at the measurement point does not return to the initial value within the observation period (blue curve in the diagram), indicating the presence of residual stress effects.

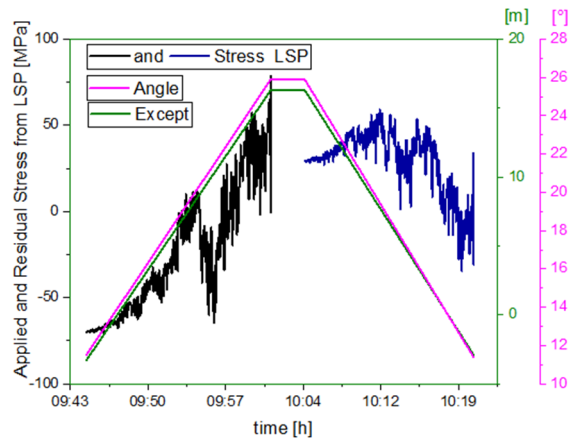


Fig. 4: Left: Placement of the LSP sensor system in the vicinity of the tension head of the overburden conveyor bridge. The measurement locations for the BN and LSP techniques are identical. Right: Total stress determined from the combined evaluation of both measurement methods during the extension of the bridge and the variation of its inclination angle. The BN technique was used to determine the initial value of the absolute stress, while the LSP method was applied to monitor the subsequent stress variations during the change in bridge position.

5. Discussion

Extensive monitoring of evolving material stresses was performed using the combined LSP and BN sensing approach. The motivation for this work arises from the increasing demand in industry for improved evaluation of stress states and damage development in structural components. In particular, nondestructive and preferably contactless measurement techniques are of significant interest as alternatives to conventional inspection methods.

The presented approach combines optical speckle-based strain measurements with magnetic BN analysis. The optical LSP method enables high-resolution detection of strain variations on the material surface, whereas the BN technique provides sensitivity to both residual and applied stresses through magnetic domain wall interactions. The combination of both measurement principles therefore allows the determination of absolute stress states as well as their evolution during loading.

The laboratory experiments on reinforcing steel specimens demonstrated a clear correlation between the characteristic parameters of both methods and the applied stress within the elastic range. The calibration experiments showed a linear relationship between the evaluated LSP and BN parameters and the applied stress, which is consistent with the theoretical expectations derived

from Hooke's law. This confirms that both techniques are suitable for quantitative stress evaluation when appropriate calibration procedures are applied.

The field measurements performed on the overburden conveyor bridge in an opencast mine further demonstrated the applicability of the combined measurement approach under realistic industrial conditions. At the investigated measurement location near the tension head of the bridge, the stress state was strongly influenced by the operational configuration of the structure, particularly by the bridge extension and the inclination angle. The results showed that the BN method can be used to determine the initial absolute stress state, while the LSP measurements allow continuous monitoring of stress variations during structural movement. The maximum measured stress of approximately 75 MPa occurred at the largest bridge extension and inclination angle.

An important observation is that the measured stress did not return to its initial value after retracting the bridge, indicating the presence of residual stress effects or local structural relaxation phenomena. This behavior highlights the importance of distinguishing between load-induced and residual stresses in large structural components.

Overall, the results demonstrate several advantages of the combined measurement concept:

- reliable detection of strain changes using LSP,
- high sensitivity of BN measurements to residual and applied stresses,
- improved accuracy and robustness through the combined evaluation of both data sets.

However, several limitations must also be considered. The BN technique requires sufficient magnetic coupling to the material surface, which may necessitate local surface preparation. In addition, the calibration parameters depend on material properties and microstructural conditions, which may vary between different steel grades and manufacturing processes.

6. Conclusions

This study demonstrates the feasibility of a combine nondestructive sensing approach for determining absolute and load-induced stresses in reinforcing steel by combining LSP analysis with BN measurements.

The developed prototype sensor system enables in-situ stress monitoring of reinforcing steel and large structural components. The integration of optical and magnetic sensing therefore represents a promising strategy for advanced structural health monitoring of aging infrastructure.

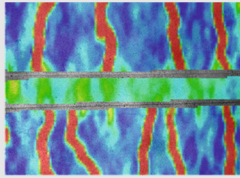
Future work will therefore focus on improving the robustness and usability of the sensor system, including automated signal evaluation, sensor miniaturization, and the extension of the methodology to prestressing tendons and other high-strength structural components.

Acknowledgements

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MS23: Considering defects and damage effects on the safety of civil engineering structures

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ABSTRACT

Due to the topography, the existing (road and rail) infrastructure is formed by a large number of civil engineering structures. These will reach the end of their service life in the foreseeable future or will be adversely affected by a variety of influences. The assessment of such effects is one of the challenging tasks that will be faced by inspection personnel and engineers in the future. The planned symposium intends to highlight current possibilities and developments in this interdisciplinary field of engineering and, above all, to consider them from a practical point of view.

Info4Infra – including geotechnical and structural information into the inspection process

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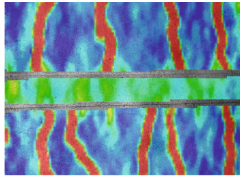
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Abstract

Austria's infrastructure network comprises 127,000 km of roads and 5,600 km of railways, which are, next to bridges and tunnels, supported by numerous geotechnical structures such as retaining walls and anchored systems. The increasing age of these assets, rising traffic loads, insufficient maintenance and climate change highlight the need for more efficient and reliable inspection processes. Current practices are often limited by fragmented information and rely strongly on expert judgement to assess damage patterns and their structural implications. This paper presents an integrated digital workflow that connects inspection processes with structural and geotechnical information as well as relevant failure mechanisms. By integrating digital models (e.g. point clouds, BIM models and geometric reconstructions) with analytical or numerical validation methods, the workflow enables a direct link between observed damages and structural load-bearing behavior. This approach is demonstrated through case studies on existing structures, highlighting its applicability, benefits and limitations. By consolidating all relevant information in a single model – one single source of truth – the workflow enables more systematic and reliable infrastructure inspections and contributes to data-driven and more resilient infrastructure management.

Keywords: Infrastructure inspection; digital workflow; geotechnical structures; assessment

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Real-time damage annotation and damage development using 3D inspection models

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Keywords: safety assessment, inspection, digital inspection, 3D-models

1. Austrian road assets and safety assessment

With approximately 14 m of road per inhabitant (VCÖ, 2024), Austria has a road network density that is high by European standards, comprising both major transportation routes (2,275 km of highways and expressways; see ASFINAG, 2024) and an extensive secondary road network (see BMK, 2023). Austria's mountainous terrain, with an elevation difference of approximately 2,390m between its highest and lowest point, places high demands on the alignment of roads. Considering requirements for routing, property rights and existing routes, the construction of road infrastructure is often only possible through the use of engineering structures such as bridges, tunnels, and retaining walls. To ensure their availability and safety, continuous maintenance, inspection and monitoring are required in addition to an appropriate design. The goal of maintenance in the case of inspection is to identify damage and defects at an early stage and to determine appropriate corrective actions to fulfill safety standards and availability of as well as the longest possible service-life to promote a cost-effective operation. In Austria, these requirements are implemented in practice through the RVS-guidelines, specifically the series RVS 13.03, governing quality assurance in inspection.

In any case, periodic, visual and hands-on inspection activities are required, through which the condition of the structure is continuously assessed. The goal is to give the infrastructure provider (i. e. the structures owner from a legal point of view) the opportunity to rectify defects at an early stage, before significant economic loss occurs or traffic safety is compromised (see RVS 13.03.21, 2022). Conducting such inspections typically involves significant on-site personnel and time resources, as well as corresponding follow-up work to determine the structures condition – the state-of-conservation. Together with these timely restrictions, the current process in inspection is highly personal-dependent to ensure damage assessments and condition evaluations to be made.

In addition to the natural aging of structures and the effects of climate change, demographic shifts will pose a growing challenge in managing infrastructure. The age-related leave of experienced professionals leads to a loss of knowledge, particularly in the field on-site activities such as inspection. At the same time, the shortage of skilled workers complicates the performance of labor-intensive inspection activities and poses a risk to the long-term maintenance of infrastructure. However, digitalization can lead to increase the availability of technical tools in the infrastructure sector. For structural inspection tasks, it is crucial to recognize that a digital transformation is not merely about the use of new technologies, but rather about the systematic integration of data, modeling, and engineering analysis. Although digital tools are increasingly being used, in practice, they often serve merely as electronic substitutes for analog documentation methods. Digital inspection in a strict sense however, requires the structured integration of geometric data, condition information, as-built documentation, and engineering expertise within a consistent data environment. The goal of a digitalized inspection process must therefore be not just a simple replication of existing analog processes, but rather to conceptually advance the inspection process.

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2. Digital inspection, damage annotation and 3D models

In both analog and digital inspection, the collection, processing, and provision of structural data is a key task. This includes, on the one hand, basic information such as the identification of the structure, its location, year of construction, or type of construction and materials used. On the other hand, it encompasses more detailed documentation, such as design assumptions, as-built documentation from construction as well as repairs and changes carried out during its operational life, records of previous inspections, and monitoring data. In many cases, this information is (at least partially) already stored in existing database systems (RVS 13.04.01, 2009). This is often supplemented by condition assessments, information on inspection intervals, and details regarding planned or already implemented maintenance measures providing structured information that allows for the initiation of inspections by qualified and trained personnel. However, it is important to note, that the mere existence of a database or any other structure to store this information does not guarantee a consistent data structure with respect to integrated digital structural documentation. Data has often accumulated over time, exists in various formats, and is only partially linked to each other. While geometric information, condition data, maintenance histories, and monitoring data exist in parallel, they do not necessarily form a logically coherent structure. Therefore, and to create a robust foundation for inspection, it is essential to ensure that analog data is converted into digital form in a high-quality and meaningful manner. The goal is to implement a digital utilization of the data, such as model-based condition documentation or the systematic linking of damage information with geometric data.

A key factor distinguishing digital structural inspections from analog or semi-digital ones is the collection of all information related to the structure using exclusively digital methods. Consequently, the use of analog data sources such as plans or other documents should be minimized as much as possible to ensure a fully digital process. Digital devices capable of processing this information are an integral part of such an approach. Furthermore, the captured information must be geolocated and referenced to identify the location of damaged areas in the structure and draw conclusions about their effects and progression over time. The following figure illustrates a possible implementation of such a process.

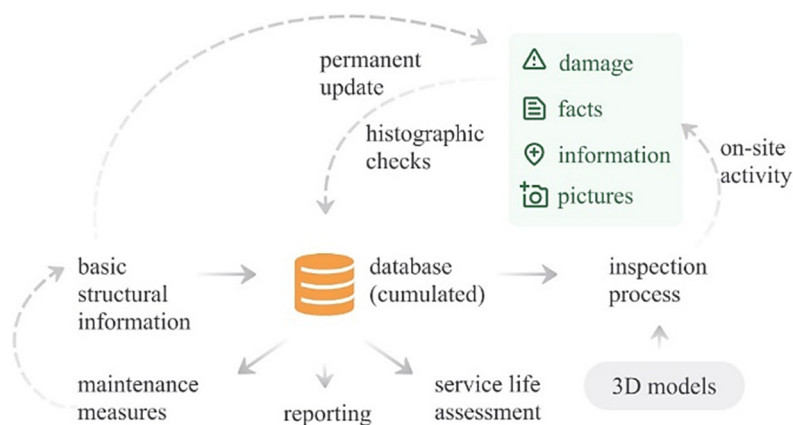


Fig. 1. Illustration of a digital workflow for inspection.

Prior to the inspection - especially during an initial (first) inspection - the process must begin with the review and preparation of existing information and data. This includes construction plans, calculations, design documentation, previous inspection reports, and results from special inspections (AP33), and can further be supplemented by monitoring data. Many of these documents are often available only in an analog form or as unstructured documents. Yet their content forms the basis for a data base, which can be seen as a “single source of truth” and offers a cumulative data and information space. Each inspection process gets back to this data and generates new information that may include images, their location, facts about the state-of-conservation, or supplementary information. Through a closed-loop cycle, a central database can continuously be expanded and updated. In addition, a control mechanism can be incorporated into this process enabling the comparison of current images and information with existing data, thereby providing both a time-saving and information-related advantage for the inspection.

3D models form a valid and useful basis for this process, as data, information, and images can be linked to them. A variety of methods and approaches can be used to create such models. Terrestrial laser scanning (TLS) captures the surrounding environment by measuring angles and distances via a rotating mirror, thereby generating coordinates in a local coordinate system. The linking of multiple measurement points (registration) and the transformation into a higher-level coordinate system (georeferencing) are performed using control points. Such points are established in advance, using satellite-based methods (GNSS) or classic surveying methods. A key advantage of this method is its high predictability due to the fact, that the quality of the point cloud is reliably in the millimeter-to-centimeter range and can be accurately estimated in advance, even for large areas, provided that the fundamental principles of surveying are followed by qualified personnel. Further, kinematic systems and mobile mapping (Kalenjuk, 2024) allow for data collection while in motion. The carrier platforms for this range from motor vehicles to drones and robots to handheld systems. This method is particularly valuable when used on autonomous or remotely controlled platforms, such as drones, enabling the safe and efficient surveying of hazardous areas from a distance. Due to the complex system calibration and data processing, the operation of professional kinematic systems is usually reserved for experts. In addition, modern smartphones are often equipped

with high-performance cameras and LiDAR sensors that can be used for documentation and model generation. Using known control points, the models reconstructed from images can be transformed into a higher-level system while LiDAR sensors, use the time-of-flight method to map the immediate surroundings.

3. Conclusions and outlook

This paper illustrates that the use of digital solutions - particularly through the integration of data sets and models - can yield significant advantages in the inspection process of civil engineering structures. However, this implicitly assumes, that the inspection process would merely be digitally mapped, meaning that analog or semi-digital workflows existing would be replaced by digitally ones. The most relevant added value of such a method for inspection can be the incorporation of geometric data capture through the integration of raw data (e.g., point clouds) with contextual information such as inspection reports, as-built data, and structural models. This can result in a consistent, updatable data set that functions as a comprehensive digital inspection model, providing its worth through a consistent availability and expandability. Furthermore, the complete implementation of information and data into a holistic model offers the possibility to be used and addressed both in the office and on-site. For the later one, it serves as a central data basis and gives a valid source of information while on-site, as availability on mobile devices for precise orientation is given and it enables comparison with the as-built condition as well as the immediate digital location of findings.

Therefore, such a workflow facilitates a “single-source-of-truth” (SSOT – Grubinger, 2023) offering up to date information on a structure that additionally incorporates all information available on an object. However, this can lead to new approaches or opportunities arising specifically from digitization such as directly including design and construction information into the model, evince the genesis of damage and incorporate methods such as augmented and virtual reality.

In particular, the use of 3D models preferably generated using photogrammetry can create significant added value in this context. With improved data quality and a significant simplification in the creation of such models, a valid database can be established. On the one hand, as-built models can be generated and, on the other hand, this enables automatic damage detection and annotation based on Artificial Intelligence (Mondal and Chen, 2022; Chung, Hong and Kim, 2023, Chordhury and Kaiser, 2024). This can subsequently contribute to a significant reduction in labor, especially by segmenting the structure and performing an automated initial assessment of damage. In addition, automatic detection allows for a comparison with previous inspection activities offering a major advantage, particularly in the processing of inspections, as it enables a reduction in effort by focusing solely on the essential inspection content- newly developed damage, its progression and trends emerging.

A digital workflow such described in Fig. 1 can support inspection personnel in several ways. The key benefit lies in the on-site inspection process itself, since, basic structural information is already available, and existing damage records can be referenced, meaning that only changes or new damage need to be recorded. Furthermore, digital processing offers the potential for simultaneous use by multiple inspectors. In addition, digital preparation can be carried out in advance, which subsequently enables post-processing of the inspection results. As with any digital process, care must be taken to ensure that digitization does not merely replicate an existing or semi-digital approach, but that the advantages of such a process are also integrated. In the approach presented, this is achieved by including 3D models and is ensured through the implementation of the inspection model as a single source of truth (SSoT) for recurring inspection activities.

Acknowledgements

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Advancing structural diagnostics: computed tomography of a full-scale historical building component

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Abstract

As part of the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) Major Research Instrumentation Program, the Gulliver tomography portal is nearing completion – a novel experimental facility that extends computed tomography (CT) to full-scale building components under load. Its purpose is to enable a deeper understanding of the behavior of load-bearing structural elements during damage progression under increasing load. Imaging techniques such as CT enable three-dimensional, high-resolution visualization inside objects to examine materials and structural conditions. For reinforced concrete components, Gulliver provides detailed analysis of internal structures, including embedded reinforcement elements and the surrounding concrete matrix. It also enables precise detection and evaluation of internal damage such as cracks as small as approximately 0.1 mm in width and their spatial and temporal evolution under increasing load. This paper presents the design and functionality of Gulliver and demonstrates its potential for new non-destructive applications in structural engineering. The possibilities for detailed geometric characterization of internal structures such as rebars are illustrated through investigations of a concrete-cast glass church window from a historical building. Using this example, the study demonstrates novel methods for the precise spatial localization of irregularly distributed reinforcing bars and for determining their diameter and the thickness of the concrete cover along their length.

Keywords: Computed tomography (CT), non-destructive testing (NDT), reinforced concrete (RC), cultural heritage, Gulliver, cracks

* The full paper is open access available in the Conference Proceedings. *

Sensitivity analysis of a peridynamic model for alkali-activated materials based on μ -CT-derived pore structure

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Abstract

Alkali-activated materials can significantly reduce carbon emissions and exhibit considerable potential for practical applications. Their superior performance is primarily attributed to their dense gel structure. Micro-computed tomography (μ -CT) enables the characterization of microscale pore structures, and a peridynamic (PD) model can be established based on three-dimensional reconstruction to investigate the mechanical behavior and damage evolution of the material. During model construction, to improve computational efficiency, the PD grid spacing is set to 5–7 times that of the μ -CT resolution. To minimize discrepancies arising from resolution differences, this study investigates the sensitivity of the PD model to grid spacing and particle classification. The results indicate that larger grid spacing leads to increased averaging of internal defects, resulting in higher apparent strength. In contrast, the particle classification has a negligible effect on the mechanical properties of the material.

Keywords: μ -CT; peridynamics; sensitivity analysis; alkali-activated materials

* The full paper is open access available in the Conference Proceedings. *

Static characterization and damage localization in prestressed concrete beams

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Abstract

This study investigates the static response of prestressed concrete (PC) beams subjected to localized tendon-cut scenarios. A laboratory campaign was carried out under service- and ultimate-level loads and using a comprehensive measurement system comprising MEMS/PCB accelerometers, biaxial inclinometers, lasers, and LVDT sensors. Structural behavior was investigated through deflection profiles reconstructed from tilt measurements, which were cross-validated with LVDT and laser data. This method enabled accurate localization of tendon-cut positions and tracking of damage progression. Accelerometer data supported anomaly detection procedures via operational modal analysis, i.e., shifts in natural frequencies and changes in mode-shape characteristics. To interpret the observed trends and evaluate safety implications, a finite-element model was developed in SAP2000. This high-fidelity FE model incorporates staged construction, prestress losses, diaphragm effects, and realistic boundary conditions. Although the monitoring system includes static and dynamic sensors, this work concentrates on static findings, demonstrating how a tilt-based monitoring approach can provide valuable diagnostic support. Results indicate that inclinometer-derived deflection profiles provide clear, repeatable localization of tendon-cut positions and agree with laser and LVDT measurements. Cross-validation between FEM simulation reproduces the main static and dynamic trends, with residual differences minimized through boundary-stiffness adjustments. In summary, the results confirm the effectiveness of tilt-based monitoring for reliable damage detection and long-term tracking.

Keywords: Prestressed concrete beams; bonded tendons; tilt deflection profiles; structural health monitoring; finite-element

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Multi-sensor detection of controlled prestress release in an existing continuous post-tensioned bridge

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Abstract

Time-dependent prestress losses significantly influence the long-term performance of prestressed concrete bridges, yet full-scale validation of monitoring techniques under real structural conditions remains rare. This study presents a controlled prestress release experiment conducted on a 62-year-old post-tensioned concrete bridge to experimentally verify the detection and quantification of controlled prestress release in a continuous bridge system. Individual prestressing wires were sequentially cut, generating measurable stress reduction events. The rupture events were monitored using acoustic emission (AE), strain gauges installed directly on prestressing wires, and a MEMS (Micro-Electro-Mechanical Systems)-based inclination sensor installed at the support. AE monitoring detected individual wire fractures and clearly distinguished rupture signals from operational noise. Strain gauges quantified the immediate local stress release associated with each severed wire, enabling estimation of residual prestress levels at the time of testing. The MEMS system captured distinct stepwise inclination increments temporally consistent with the rupture events, demonstrating that localized prestress loss produced measurable global structural response in the continuous bridge system. Despite differences in temporal resolution, the sequence of rupture detection, local stress drop, and global rotation confirms a consistent multi-scale response. The results demonstrate that integrated multi-sensor monitoring can reliably detect and quantify controlled prestress reduction in a full-scale post-tensioned bridge under real field conditions.

Keywords: Prestressed concrete bridges; prestress loss detection; tendon cutting; structural health monitoring; acoustic emission monitoring

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Condition assessment and structural behavior of prototype bridge deck slabs

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Abstract

Bridges are essential element of transportation infrastructure, yet their durability and serviceability are continually challenged by environmental exposure, material degradation, and traffic-induced stresses. This study focuses on the condition assessment of prototype bridge deck slabs, with the objective of evaluating their long-term structural performance under vehicular loading. The study integrates both experimental and analytical approaches to assess structural behavior. The methodology combined visual inspections, crack width measurements, and deflection monitoring with advanced numerical modelling using ETABS software. Experimental work involved applying controlled static vehicular loads to a prototype bridge deck slab, while monitoring responses with a Linear Variable Differential Transformer (LVDT), Laser Distance Meter (LDM), and crack width measuring systems. Findings indicate progressive crack propagation and significant increases in deflection. The results highlight the onset of material fatigue and gradual loss of stiffness, signaling long-term risks of serviceability reduction and potential structural failure if left unaddressed. The study concludes that continuous monitoring, preventive maintenance, and timely interventions are essential to extend the service life of bridge deck slabs, leading to the development of more resilient and sustainable bridge infrastructure.

Keywords: Condition assessment; bridge deck slabs; performance; monitoring; maintenance

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Effect of defects on stress concentration factors in pipes under bending

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Abstract

This study proposes a dimensionless analytical framework for predicting the residual strength of vertically oriented steel pipes with the lower end fixed and containing rectangular geometric defects. The model incorporates defect size parameters, stress concentration factors (SCFs), and classical Bernoulli-Euler beam theory to establish a relationship between defect geometry and structural performance. A dimensionless expression for residual bending strength is derived, enabling generalized assessment across various defect scenarios. Finite element simulations are conducted to validate the proposed framework. Results demonstrate strong agreement between theoretical predictions and simulation data. The proposed approach offers a simplified yet effective tool for evaluating the structural integrity of steel pipe with defects.

Keywords: Stress concentration factor; Bernoulli Euler beam theory; steel pipe; finite element simulation

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Durability and corrosion of micropiles: insights from a multi-year field study

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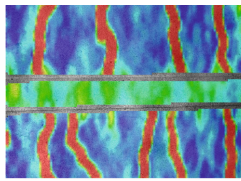
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Abstract

Micropiles are commonly used in geotechnical engineering to direct compressive as well as tensile forces from superstructures such as buildings or retaining systems into the ground. The transfer of tensile forces requires reinforcement in the concrete micropiles. For permanent micropiles, corrosion protection systems with different levels, depending on the corrosion risk, are needed. A high-level corrosion protection as given in the Swisscodes (SIA) consists of an inner injection surrounding the steel-reinforcement, followed by a ribbed plastic tube as well as an outer injection surrounding the plastic tube (double corrosion protection). In case of couplings, the inner injection cannot be applied as the steel-reinforcements are connected with screwed joints. These couplings are therefore considered weak points in the overall corrosion protection of micropiles. Four double-protected micropiles – with well-defined defects (small scratches in the protective tube as well as missing outer injection) and instrumented with various sensors for continuous monitoring to measure potential corrosion along the steel-reinforcement and the couplings. The micropiles have been installed in the ground on two different sites in the greater area of Lucerne (Switzerland). This contribution first reviews the common corrosion protection system and typical defects that might occur during micropile installation. Subsequently, monitoring results acquired over the last 5 years are presented with lessons learnt.

Keywords: Damage of micropiles; corrosion; monitoring of geotechnical structures

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Damaged anchored structures: geotechnical and structural assessment using numerical analysis

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Keywords: Anchored structure; safety; ground anchor; anchor failure; load redistribution; soil-structure interaction; numerical analysis

1. Introduction

Anchored structures serve as a cost-effective solution for the permanent stabilization of deep cuts and steep slopes along transport corridors, ensuring infrastructure safety and availability. Pre-stressed ground anchors enable more slender designs compared to conventional solutions such as gravity walls. However, they require more extensive inspection and maintenance, leading to periodic closures of road or railway infrastructure and consequently high life-cycle costs.

During inspections, various damage mechanisms of both geotechnical and structural origin can be observed. Corrosion of ground anchors is among the most critical, as it reduces the tendon cross-section and thus the load-bearing capacity. This may lead to stress concentrations exceeding the residual capacity of the anchor and ultimately to failure.

Anchor failure induces a three-dimensional redistribution of loads within the retaining wall, the remaining anchors, and the surrounding soil. This may result in overstressing of structural components, potentially triggering secondary failures or even progressive collapse. Therefore, accurately capturing these mechanisms is essential for assessing the long-term safety of anchored structures and requires three-dimensional numerical analyses of soil-structure interaction. Existing design and assessment approaches typically rely on simplified two-dimensional or uncoupled analyses, which are limited in their ability to capture three-dimensional load redistribution effects following local anchor failures.

This paper investigates load redistribution in anchored retaining structures following anchor failure within the research project Safety and Risk of Anchored Structures (SaRAS; VÖBU, 2025). The novelty of this work lies in the systematic comparison between a coupled geotechnical–structural modelling approach and a computationally efficient decoupled strategy. The aim of the study is to evaluate the accuracy and practical applicability of both approaches for engineering assessment.

The results show that the coupled approach does not provide satisfactory agreement while remaining computationally intensive. In contrast, the decoupled approach enables an efficient and sufficiently accurate analysis, despite limitations in representing interaction effects. These findings support the development of a simplified assessment procedure for anchored retaining structures under damage scenarios.

2. Numerical analyses

2.1. Coupled geotechnical and structural framework

From a theoretical perspective, coupling of geotechnical and structural models enables a consistent load distribution between soil and structure. This was implemented by transferring nodal displacements between identical finite element meshes combined with feedback-based adjustment of element stiffnesses.

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Displacements calculated in PLAXIS 3D (Seequent/Bentley Systems, 2024) were imposed on the corresponding SOFiSTiK (SOFiSTiK AG, 2023) model, while stiffness reductions from the structural analysis were reassigned to the geotechnical model. The resulting deformations were iteratively reintroduced into the structural analysis, and the procedure was extended to include construction stages and targeted anchor failure.

In practice, however, satisfactory convergence was not achieved. Despite multiple iterations, significant variations in anchor forces persisted. Given the high computational demand and limited improvements in results, further iterations were deemed inefficient. The approach nevertheless provides valuable insight into the governing parameters of load transfer (e.g., relative stiffnesses) and the limitations of coupled modelling strategies, thereby motivating the adoption of a decoupled modelling approach.

2.2. Numerical investigations from a geotechnical perspective

Within the geotechnical numerical investigations, a three-dimensional finite element model of the anchored retaining system was developed using PLAXIS 3D to capture soil-structure interaction (Fig. 1, left). The model comprises a homogeneous soil body ($140 \times 60 \times 25$ m). The initial geometry consists of a 20° inclined slope with a height of 14.49 m, without groundwater.

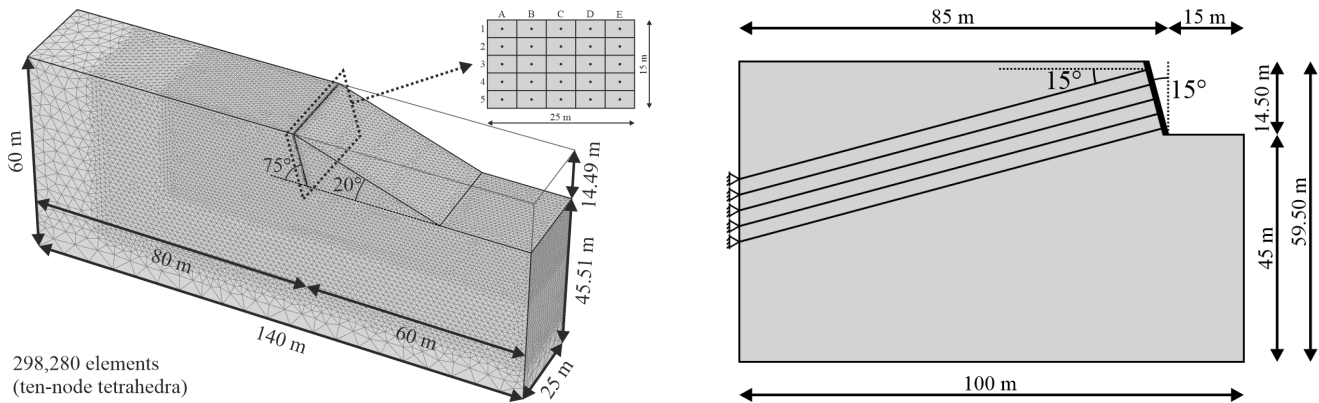


Fig. 1. (left) geotechnical three-dimensional finite element model; (right) side view of the structural three-dimensional finite element model.

The construction process is simulated in five excavation stages, in which the slope is progressively replaced by a retaining wall inclined at 15° and supported by five rows of anchors. The retaining wall is discretized into a 5×5 grid of plate elements (5×3 m each), resulting in a wall area of 25 m by 15 m. Each plate is centrally supported by one ground anchor, leading to a regular spacing of 5 m horizontally and 3 m vertically. The wall thickness is 0.60 m. Anchors are inclined at 15° to the horizontal, consist of a 20 m free length and a 6 m bonded length, and are arranged in a grid from A to E (horizontal) and 1 to 5 (vertical).

The soil is modelled as a homogeneous medium using the Hardening Soil model with small-strain stiffness (Schanz, 1998; Benz, 2007), the retaining wall as linear elastic plate elements. Soil-structure interaction is accounted for using zero-thickness interface elements (Stastny and Tschuchnigg, 2023). The anchors are modelled using elastoplastic node-to-node elements for the free length and linear elastic embedded beam elements (Granitzer and Tschuchnigg, 2021; Granitzer et al., 2024) for the bonded length.

The finite element mesh consists of approximately 298,000 ten-node tetrahedral elements, providing a second-order spatial discretisation of the model. The analysis simulates construction, service conditions, and selected anchor failure scenarios using a staged construction procedure with twelve phases. Phase 0 establishes the initial stress state via gravity loading, followed by a plastic nil step in Phase 1. Excavation, wall installation, anchor activation, and pre-stressing (500 kN per anchor) are carried out in subsequent phases until the final state in Phase 11. Additional phases starting from the final state investigate anchor or anchor group deactivation to assess failure scenarios and resulting load redistribution.

2.3. Numerical investigations from a structural perspective

The structural numerical investigations, conducted in close coordination with the geotechnical analyses, show that a fully detailed representation of soil behavior within the structural model is very difficult to achieve. The complexity of advanced geotechnical models, combined with uncertainties in parameter calibration, results in outputs that are difficult to interpret in terms of stress and internal force distribution within the reinforced concrete structure. For this reason, a simplified modelling approach was adopted to analyze the structural response of the concrete wall. The analyses were performed using SOFiSTiK. The soil domain differs from that used in the geotechnical model and measures 100 m in width, 59.50 m in height, and 25 m in depth (Fig. 1, right). The geometry of the retaining wall is identical to that in Subsection 2.2.

In the structural model, anchors are idealized as fixed supports at the model boundary. Their bond length is represented by an engineering-based adjustment of anchor stiffness to account for the effective anchor length. This assumption is based on the premise that failure is governed by the anchor head or free length rather than the grout body; grout failure is therefore not considered in the structural analysis.

The construction process is divided into four phases: Phase 0 establishes the initial stress state; Phase 1 includes installation of the structure and anchors; Phase 2 applies anchor pre-stressing; and Phase 3 simulates excavation in a single step.

3. Results

The numerical results demonstrate how different modelling strategies influence the representation of soil-structure interaction. Although a comprehensive coupled approach was initially adopted, including the transfer of geotechnically-derived deformations to the structural model, this did not yield satisfactory results or achieve the required level of agreement for engineering applications. Consequently, a simplified structural engineering model was employed.

Within this framework, the analysis of the reinforced concrete structure after the final construction stage indicates that bending moment distributions differ only marginally between linear and nonlinear approaches. This suggests that there is no significant redistribution of internal forces due to cracking or plastic deformations. Following anchor failure, bending moments increase compared to the final construction stage; however, they remain below the cracking moment for a cross-section thickness of 0.60 m. Accordingly, no substantial additional force redistribution due to nonlinear material behavior is observed.

It can therefore be concluded that a reduction in bending stiffness is not required for subsequent structural and geotechnical analyses, supporting the use of a linear elastic concrete structure within the geotechnical model.

The geotechnical investigations indicate that anchor failure results in only limited load redistribution to the remaining anchors. Instead, most of the load is transferred to the retaining wall — reflected in significant changes in bending moments — and to the surrounding soil, without exceeding their respective capacities. This behavior is illustrated in Fig. 2, which shows the change in bending moment distribution following failure of the central anchor C3 (left) and the entire anchor row 3 (right) relative to the final construction phase. In addition, the absolute and percentage changes in anchor forces are indicated at each anchor position. Even in the case of complete failure of anchor row 3, the maximum force increase in adjacent anchors is 26 kN (5%). Despite this limited force redistribution, the bending moment distribution changes significantly. This response is attributed to sufficient reserve capacity of the remaining anchors, which prevents the development of secondary failures. If this reserve capacity is insufficient, the load redistribution pattern changes markedly and may lead to secondary failures.

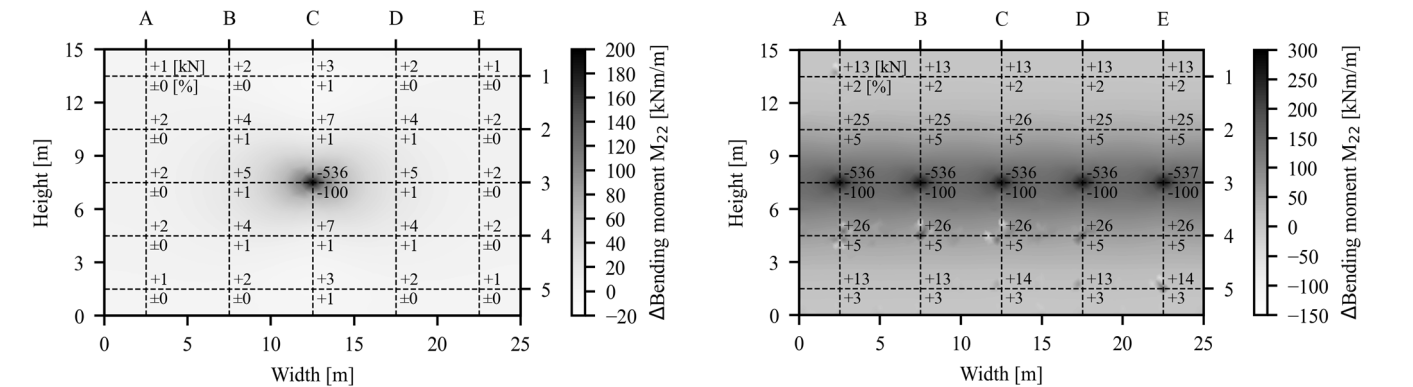


Fig. 2. Change in bending moment distribution M_{22} ; (left) failure of central anchor C3; (right) failure of the entire anchor row 3.

Acknowledgements

The work presented in this paper was conducted as part of the research project Safety and Risk of Anchored Structures (SaRAS), supported by the Austrian Research Promotion Agency (FFG). The authors gratefully acknowledge the funding provided by FFG.

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Condition assessment and rehabilitation of ageing large concrete water reservoirs: South African case studies

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Abstract

This paper presents a monitoring and remedial assessment of two ageing reservoirs (Benoni No.3 (B3) and Meyers Hill (MH)) owned by Rand Water, South Africa's largest water utility company. Reservoir B3, a 122 Mℓ rectangular reinforced concrete (RC) structure completed in 1987, showed severe cracking in 19 out of 200 RC column pedestals, with crack widths ranging between 0.7 and 3.5 mm. Visual inspection, reinforcement scanning, concrete testing, and structural analysis confirmed compromised concrete integrity. Cracking is attributed primarily to thermal gradient effects during the mass concrete pour, possibly aggravated by alkali-silica reaction (ASR). The remedial design involves propping the roof, followed by demolition and reconstruction of the severely cracked bases. Reservoir MH, a 273 Mℓ cylindrical concrete structure completed in 1956, exhibited extensive cracking and seepage. A comprehensive geotechnical and structural investigation revealed that poorly compacted backfill contributed to differential settlement and severe structural distress, with extensive internal cracking, efflorescence, and shear failure of construction joint keys. Poorly compacted fill material (abundant boulders in a loose sandy matrix) contributed to strain incompatibility (ARQ Consulting Engineers, 2023), rendering rehabilitation to full capacity unfeasible. Consequently, demolition and replacement was recommended. These case studies demonstrate the critical importance of rigorous, periodic dam safety evaluations (DSEs) in managing ageing water infrastructure, guiding decisions ranging from targeted remedial interventions to decommissioning.

Keywords: Dam safety evaluation;rand water reservoirs;structural health monitoring;ageing concrete water reservoirs;structural failure

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Secant stiffness and failure modes of EBF frames using castellated beams

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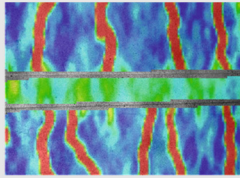
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Abstract

One structural system that meets the requirements for earthquake-resistant design is the steel Eccentrically Braced Frame (EBF) system. The concept of EBF earthquake-resistant design is that link elements are designed to undergo damage and dissipate energy, while other elements outside the link are expected to remain elastic. Castellated steel beams are alternative materials for link elements because their greater moment of inertia provides higher stiffness than conventional steel beams. In this study, three castellated link test specimens were tested with link lengths of 450 mm, 650 mm, and 870 mm. The steel beam used was IWF 150,75,7.5,5, which was transformed into a castellated steel beam. The test showed that, once the specimens reached the initial yielding state, each exhibited different behavior, resulting in different secant stiffness values. This difference indicates that variation in link length affects the secant stiffness, reflecting differences in the specimens' ability to resist deformation after passing through the elastic phase, thereby impacting the overall structural response. The failure mode at yield was characterized by the formation of a significant inelastic rotation angle upon deformation. Each specimen exhibited a different failure mode. The CL-450 test specimen failed at the connection between the beam and the column; the CL-650 test specimen failed at both the beam-link connection and the beam-column connection. The CL-870 test specimen failed in the link area.

Keywords: EBF; castellated beam; failure mechanism

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SMAR 2026 - 8th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

MS24: Non-destructive testing and monitoring of timber structures

Organizers:

Cristoforo Demartino (Roma Tre University, Italy)

Michele Mirra (TU Delft, Netherlands)

Vittoria Borghese (TNO, Netherlands)

Angelo Aloisio (Università degli Studi dell'Aquila, Italy)

Martina Sciomenta (Università degli Studi dell'Aquila, Italy)

Antonio Sandoli (University of Molise, Italy)

Mariapaola Riggio (Oregon State University, USA)

ABSTRACT

The structural assessment of existing timber elements, particularly in historical buildings, poses significant challenges due to its natural variability, its anisotropic behavior, and the presence of degradation phenomena. These complexities are compounded by the need for minimally invasive diagnostics, as destructive testing (DT) is often not permitted in heritage contexts.

This Mini Symposium explores advanced strategies for the reliable assessment and monitoring of timber structures, combining non-destructive testing (NDT) methods to calibrate and validate diagnostic data.

Particular focus will be placed on: correlation models between NDT results and physical-mechanical properties; integration with long-term monitoring systems for moisture, deformation, and crack propagation; insights from visual grading for preliminary analyses; digital tools and machine learning algorithms for reliability assessment and property prediction under uncertainty; and sustainability metrics in structural interventions.

The MS welcomes contributions on historic timber structures and contemporary engineered wood systems, especially those addressing life-cycle extension, preventive maintenance, and risk-informed decision-making.

Knowledge gaps and fire behavior of deadwood

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Abstract

The reuse of salvaged and deadwood timber represents a promising yet challenging opportunity within a circular construction framework. Deadwood is an abundant resource whose mechanical and thermal responses are significantly affected by ageing, environmental degradation, and prior exposure conditions. These factors may alter density, moisture transport, and chemical composition, leading to fire behavior that differs markedly from that of new timber. Moreover, reclaimed wood is frequently subjected to conditioning or stabilization treatments, such as drying, hydrothermal vaporization, or saline impregnation, whose implications for fire resistance are still poorly understood. This paper reviews the current state of knowledge on the thermo-mechanical behavior of aged and treated wood under fire exposure, with a particular focus on the mechanisms governing ignition, charring, and post-fire strength degradation. The work highlights the scientific and technological gaps that must be addressed to ensure safe and reliable reuse of salvaged timber in structural applications. By mapping available data and identifying research priorities, this study aims to establish a foundation for future experimental and modelling investigations supporting the sustainable valorization of deadwood in a sustainable built environment.

Keywords: Salvaged timber; deadwood; fire performance; thermo-mechanical properties; circular economy

* The full paper is open access available in the Conference Proceedings. *

Structural assessment and service life modeling of historic timber foundations in Amsterdam

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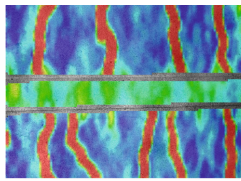
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Abstract

The historic city center of Amsterdam (NL) is renowned for the system of bridges and quay walls built along its canals. These structures are supported by millions of wooden foundation piles having a service life of 100 to 300 years, submerged below the water table, and thus subjected to bacterial decay in anaerobic environment. Assessing their condition, mechanical properties, and remaining service life, is of paramount importance, as foundation failure could have catastrophic consequences. This work describes an integrated methodology for evaluating the piles' structural integrity and remaining load-carrying capacity. The approach firstly involved biological degradation analysis and mechanical testing to support and validate on-site non-destructive monitoring, based on underwater micro-drilling. A comprehensive experimental campaign consistently correlated micro-drilling profiles with density, strength, and stiffness variations in sound and degraded piles, proving the reliability of this technique for an on-site assessment of wood quality, as well as decay extent and severity. Secondly, a nonlinear damage accumulation model was developed, accounting for bacterial decay evolution over time and mechanical degradation due to long-term loading: this finally enables the assessment of the remaining load-carrying capacity and service life of the piles. This research offers a robust framework for structural health assessment, monitoring, maintenance, and preservation strategies of historic timber foundations.

Keywords: Wooden foundations; bacterial decay; micro-drilling; service life modeling

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Integrated seismic assessment of a 19th century timber gate structure in Japan

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Keywords: Historic timber gate; seismic assessment; building information modeling; long-term monitoring; ambient vibration testing

1. Introduction

The Akamon Gate, also known as the red gate of the University of Tokyo, constructed in 1827, is a timber-structured gate designated as an Important Cultural Property by the Japanese national government. Due to concerns regarding its seismic performance, the gate has been closed since 2021. Since 2020, our research team has conducted a series of investigations on the gate, including on-site investigation, ambient vibration tests, and long-term monitoring. The collected data have also been integrated within a BIM model to support a comprehensive seismic assessment.

2. Preliminary investigation

2.1. Scale and configuration

The gate faces slightly south of west with four front columns and three door openings. The total span between the outermost columns is 8.06 m. In section, the structure comprises a single bay supported by two parallel rows of columns, with a spacing of 3.27 m and the ridge height reaches 9.0 m. More importantly, the gate is a typical *yakuimon* (a gate style), with a deliberate offset between the roof ridge and the supporting frame, enhancing its visual monumentality. However, this asymmetric mass distribution may increase the tendency for overturning under horizontal load.

2.2. Investigation and BIM-based integration of structural information

The Akamon Gate features a traditional hon-gawara-buki (Japanese pan-and-cover clay tile) roofing system with a soil bedding layer. As a result, the roofing system is estimated to weigh approximately 24.6 tons, which elevates the center of gravity of the structure. Joints in timber structures can also significantly affect the global seismic performance. For the Akamon Gate, three main types of concealed joints were identified at the column head, beam-column interface, and column base (netsu-gi), although their influence on the global structural response remains unclear. Partial 3D laser scanning was conducted on retained replaced timber members to document their geometry. Based on archival drawings and site measurements, an initial Revit model was developed as a component-level data backbone, in which joint types, sensor locations, measurement records, and derived indicators were linked through a consistent ID system for traceable visualization and subsequent model-based assessment.

3. Ambient vibration tests

Ambient vibration measurements were conducted on the Akamon Gate in 2020, 2022 and 2024, to identify natural frequencies and to obtain modal shapes (see Fig. 1a). Table 1 presents the main results of the three test campaigns. First, the gate exhibits potential seasonal variations. The fundamental frequency decreased from about 3.07 Hz (X) and 1.80–1.82 Hz (Y) in summer to

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2.66 Hz (X) and 1.50–1.68 Hz (Y) in winter, with an overall reduction of roughly 10–20%. The spring results fell mostly between the two, consistent with seasonal trends. In addition, the structure exhibits clear direction-dependent behavior. The natural frequencies in the X direction are significantly higher than those in the Y direction, indicating stiffness differences along the two axes. In the Y direction, the fundamental response differs noticeably between the northern and southern sides. The corresponding in-plane mode shapes also show clear spatial variations in both amplitude and phase among measurement points (see Fig. 1b).

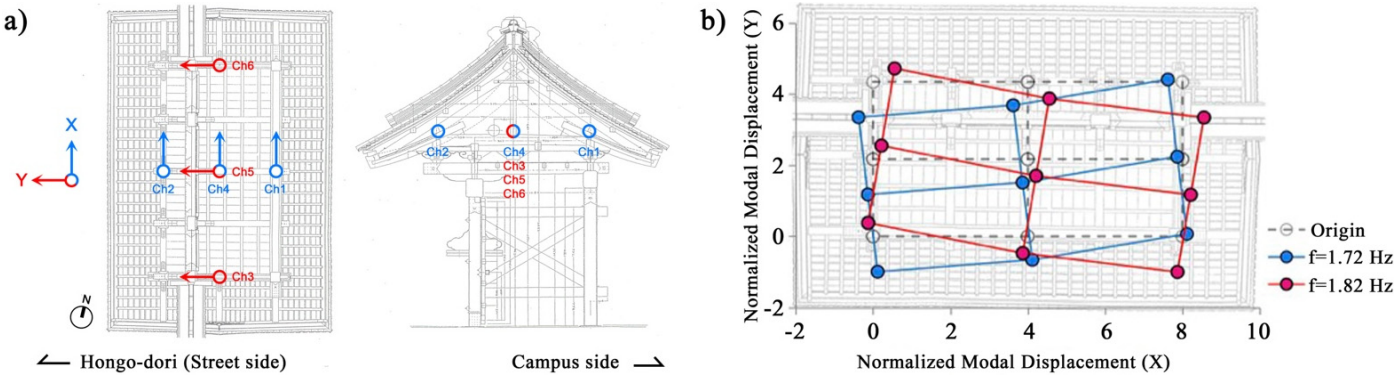


Fig. 1. (a) Sensor layout for the ambient vibration tests, (b) in-plane mode shape distribution in the Y direction.

Table 1. Results of three measurements.

Test date	Temperature (°C)	Relative humidity (%)	X direction natural frequency (Hz)		Y direction natural frequency (Hz)		
			First mode	Second mode	First mode (north)	First mode (south)	Second mode
2020/7/7	27.5	81	3.07	6.66	1.82	1.8	4.79
2022/2/2	10.4	39	2.66	6.56	1.68	1.5	4.76
2025/4/2	13.2	82	2.83	6.62	1.82	1.72	4.9

4. Long-term monitoring analysis

4.1. Recorded events

Long-term structural monitoring of the Akamon Gate was initiated in June 2022 to evaluate its dynamic response to external excitations such as earthquakes and strong winds. Recording was automatically triggered when the roof response acceleration exceeded 4 cm/s². Between June 2022 and December 2024, 45 valid events were recorded. Of these events, 43 were clearly associated with earthquakes according to Japan Meteorological Agency (JMA) records.

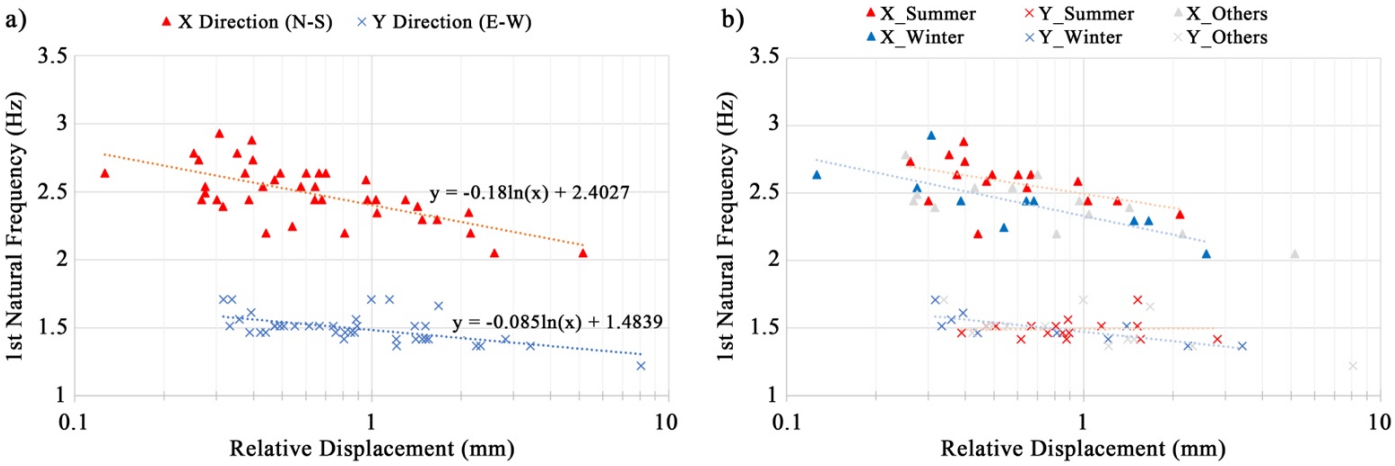


Fig. 2. (a) 1st natural frequency vs. roof-to-ground relative displacement; (b) seasonal comparison of 1st natural frequency vs. relative displacement.

4.2. Dynamic characteristics analysis

For each valid event, the fundamental frequency was identified from the roof-to-ground spectral ratio, and the maximum relative displacement was derived by double integration of the corrected acceleration records. A log-linear relationship is then observed between the two variables (see Fig. 2a). Notably, the fitted regression line is steeper in the X direction than in the Y direction,

indicating greater sensitivity to vibration intensity. A seasonal comparison then suggests that natural frequencies in winter are generally lower than those in summer (see Fig. 2b). Statistical analysis further shows that the natural frequency in the X direction decreases by approximately 6% between the two seasons, whereas no significant change is observed in the Y direction. This suggests greater environmental sensitivity of the dynamic characteristics in the X direction.

4.3. Strong motion record analysis

The record from May 11, 2023, is selected for further analysis. Peak ground accelerations were 20.0 cm/s^2 in the X direction and 44.7 cm/s^2 in the Y direction, where the corresponding peak roof accelerations were 43.2 cm/s^2 and 51.8 cm/s^2 . During the event, the first natural frequencies decreased to 2.02 Hz (X) and 1.25 Hz (Y). Correspondingly, the equivalent stiffness was estimated to decrease by approximately 42% (X) and 31% (Y). The maximum displacements are estimated as 0.51 cm and 0.81 cm in two directions, giving drift angles of about $1/1333 \text{ rad}$ and $1/840 \text{ rad}$ at the sensor height of 6.8 m, both within the elastic range of traditional Japanese timber structures (typically $1/200$ – $1/120 \text{ rad}$). To examine temporal variation, the vibration record was divided into eight segments using two time-window lengths (20.48 s and 40.96 s) and the peak frequency in each segment was identified (see Fig. 3). The results show that, in both directions, the peak frequency dropped rapidly with the arrival of strong shaking and gradually recovered as the vibration amplitude decreased, eventually returning close to the pre-event level.

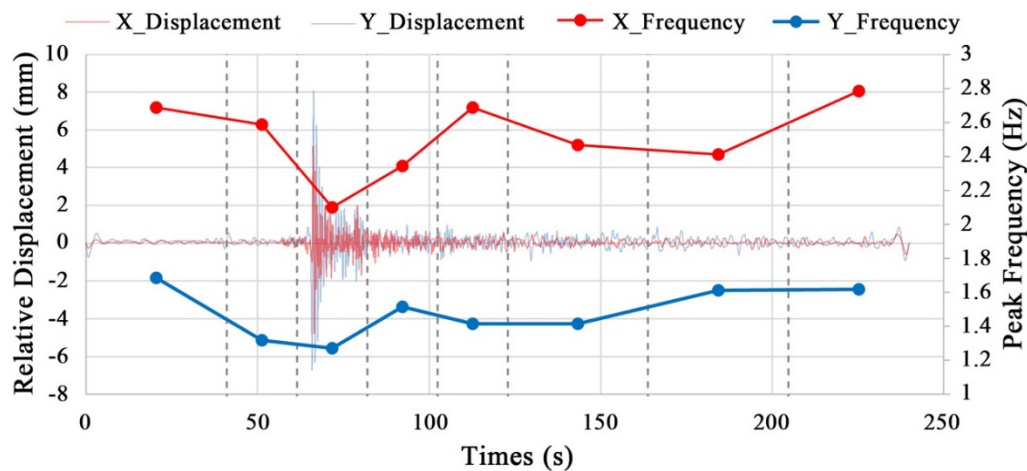


Fig. 3. Peak natural frequency and relative displacement in each time window.

5. Discussion and conclusion

These investigations clarify the seismic behavior of the Akamon Gate. The lower fundamental frequency in the Y direction indicates lower effective lateral stiffness, while modal splitting and in-plane amplitude asymmetry suggest non-negligible torsional participation. Considering the elevated center of mass and the eccentric roof configuration, horizontal excitation is more likely to imply potentially higher vulnerability in the Y direction. In contrast, the X direction exhibits stronger frequency sensitivity to both seasonal variation and vibration intensity, likely reflecting joint-related effects rather than uniform material change. In addition, this study proposes an integrated workflow combining on-site survey, BIM-based data integration, vibration testing, and long-term monitoring to support model-based evaluation and maintenance of timber heritage structures.

Acknowledgements

The authors gratefully acknowledge Shimizu Corporation for its support during the on-site investigation, Professor Koichi Kusunoki for providing the earthquake monitoring device, the Shisetsu-bu of the University of Tokyo for its support and the University of Tokyo Foundation “Center of Engineering Timber Architectural Heritage” (Kaori Fujita) for financial support. This work was also supported by JST SPRING, Grant Number JPMJSP2108.

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Non-destructive assessment of secondary and virgin timber

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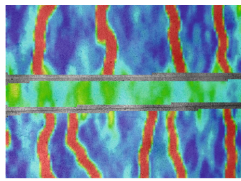
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Abstract

This study investigates the mechanical properties and grading accuracy of secondary timber, comparing it to virgin timber through both non-destructive testing (NDT) and destructive testing. Secondary timber beams, sourced from demolition sites with unknown origins and service histories, were evaluated alongside virgin beams using stress wave measurements and four-point bending tests. Results indicate that secondary timber exhibits comparable, and sometimes superior, stiffness and strength relative to virgin timber, suggesting its viability for structural reuse. However, current grading standards and calibration curves, designed for virgin timber, are less reliable for secondary timber due to the lack of service history and physical feature data. The integration of X-ray computed tomography (CT) scanning allows for detailed visualization and quantification of knots and cracks, enhancing grading precision. The results highlight the need to refine NDT methods and develop calibration curves tailored to secondary timber, incorporating CT scan data to improve reliability. Advancing these assessment techniques will support sustainable construction practices by facilitating the safe and efficient reuse of secondary timber, making it essential to unlocking the full potential of secondary timber in modern construction

Keywords: Secondary timber; X-ray computed tomography (CT); quality assessment; strength grading; non-destructive testing (NDT)

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Non-destructive testing of thermal-density properties in chestnut wood

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Keywords: Active infrared thermography; timber diagnostics; wood density estimation; non-destructive testing; chestnut timber; moisture content; heritage timber conservation; timber reuse.

1. Introduction

Timber is an orthotropic and highly variable material whose physical and mechanical behaviour is strongly influenced by moisture exchange, anatomical direction, and local degradation. This variability makes the assessment of existing members, especially in historical structures, more complex than for more homogeneous construction materials, and often discourages preservation and reuse. As a result, reliable non-destructive procedures are needed to estimate relevant properties without altering the original element. In this context, density is a key parameter because it is closely related to both structural performance and conservation state. However, surface-based measurements alone may be insufficient, particularly in reused timber, where previous treatments and ageing may affect local response. For this reason, recent research has explored the combined use of penetrometric testing and infrared thermography to improve the interpretation of density-related properties in wood (Posta and Dolejs, 2015; Kucharska and Jaskowska-Lemańska, 2021; Xin et al., 2021). Building on this background, the present study proposes a preliminary experimental approach to investigate the correlation between thermal response and density in chestnut timber elements, with the broader aim of supporting conservation-oriented and reuse-oriented diagnostic protocols.

2. Methodology

The experimental program was conceived as a preliminary non-destructive protocol for relating timber density to thermal response in preserved and reused wooden elements. Eight specimens were examined, including seven chestnut samples and one oak sample, selected to represent both newly produced material and reused timber subjected to different treatments such as vaporization, drying, and salification. The workflow combined visual inspection, surface density estimation, moisture measurements, and active infrared thermography, with the final aim of comparing the outputs of the different techniques within a conservation-oriented assessment strategy. Visual grading was carried out in accordance with UNI 11119:2004, which was used to document geometry, visible defects, and indicative mechanical classification before the instrumental tests. Surface density was estimated through Woodpecker penetrometric testing, a modified Schmidt hammer equipped with a 2.5 mm steel needle. A regular grid with 30 mm spacing was marked on each specimen so that penetration depth, hygrometric measurements, and thermographic data could be compared at corresponding locations. Moisture content was measured on the same grid using a surface hygrometer, under controlled indoor conditions. Active lock-in thermography was then performed by coating the timber surface with a thin black opaque paint layer to standardize emissivity, setting the emissivity value to 0.96, and applying cyclic heating with two 500 W halogen lamps positioned 400 mm from the specimen. Each heating stage lasted 30 s and was followed by 60 s of cooling, repeated over three cycles. Thermal acquisition was performed with a FLIR A6751sc infrared camera placed 2000 mm from the surface, and the recorded thermograms were processed into phase maps through frequency-domain analysis. This combined setup

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allowed the authors to investigate whether spatial variations in thermal phase patterns could be associated with local density and moisture distributions in timber.

3. Results and discussion

The experimental results indicate that the two non-destructive techniques provide complementary information on the physical condition of the timber specimens. Woodpecker measurements systematically underestimated the actual density, which the authors attribute to the calibration of the device for new timber and to the influence of superficial degradation. Nevertheless, after excluding one outlier specimen, a clear positive linear relationship was found between measured density and penetrometric density estimation, with a Pearson correlation coefficient of $r = 0.98$. This suggests that surface penetration data can still be used as a meaningful proxy for density, provided that the results are interpreted with appropriate caution and calibration.

Active thermography confirmed that the thermal response of the specimens is strongly affected by both testing conditions and material heterogeneity. Among the investigated excitation periods, 30 s provided the most informative phase maps, offering the best compromise between thermal-wave penetration and image clarity. The results also showed that surface coating alters the thermal signature, since painted specimens exhibited less distinct patterns than uncoated ones, while increasing the distance of the heating source reduced spatial resolution and the visibility of local features. When phase maps were compared with density and humidity distributions, the thermographic patterns were found to follow the timber fiber arrangement and to reflect both density-related and moisture-related variations. In particular, lower humidity values tended to occur in denser regions, dried specimens showed a more uniform moisture distribution, and salified samples displayed larger spatial variability and higher average humidity. Overall, the results support a qualitative correlation between thermal response, density, and moisture, while also showing that the intrinsic heterogeneity of timber still limits a fully quantitative interpretation.

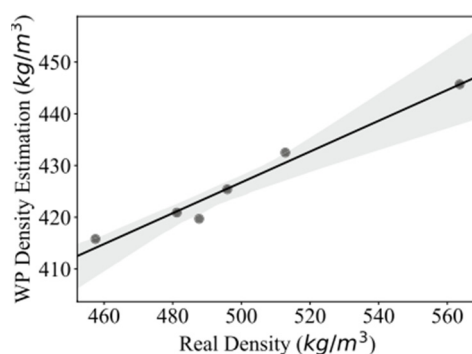


Fig. 1. Scatter plot illustrating the correlation between real timber density and WP density estimation.

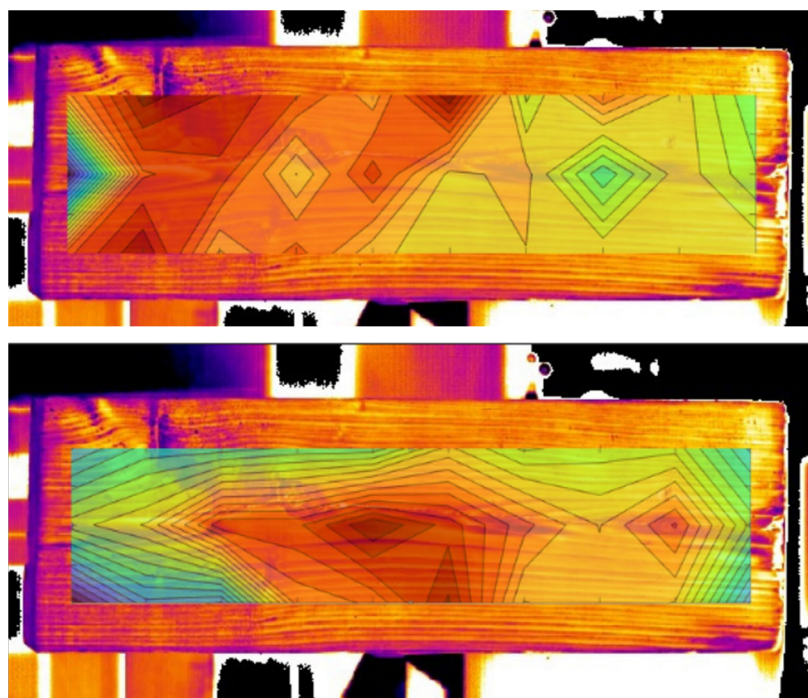


Fig. 2. False-color phase maps of timber sample 2 in relation to density (top) and humidity (bottom); red/orange tones correspond to higher phase values, green tones to intermediate values, and blue/cyan tones to lower phase values.

Table 1. Sample dimensions, strength classes given by the visual grading, and comparison between real and estimated density.

Sample	Process	Strength class	Density [kg/m ³]	WP density estimation [kg/m ³]
1	Standard	I	495.9	425.4
2	Vaporized	I	487.7	419.7
3	Standard	I	498.6	473.6
4	Standard	I	447.3	428.9
5	Dried	I	457.5	415.8
6	Salified	I	563.6	445.7
7	Vaporized	I	512.8	432.5
8	Salified	I	481.2	420.9

4. Future research

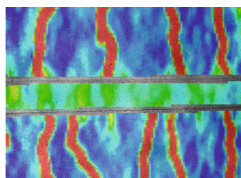
Future research should extend the present X-ray CT-based workflow from proof-of-concept applications toward a robust and scalable pipeline for the industrial reuse of secondary timber. First, the dimension-determination algorithm should be further improved for highly irregular cross-sections, particularly window and door profiles, and translated from MATLAB into Python to ensure full compatibility with the other automated routines. Second, the metal characterization procedure should be validated on a larger and more diverse dataset and integrated with robotic removal strategies, so that the extracted geometric parameters of each fastener can directly guide the choice between pulling, milling, or sawing, depending on wood species, fastener geometry, and local timber quality. Third, the current knot characterization approach should be expanded into a complete strength re-grading framework by incorporating additional defect classes, such as cracks, cavities, fungal decay, and other density anomalies visible in CT scans. This would allow the internal features identified through tomography to be linked more directly to existing visual grading rules and to broader reliability-based assessment strategies for reclaimed timber (Riggio et al., 2018; Piazza and Riggio, 2008; Qu et al., 2020). Finally, future work should focus on large-scale validation, algorithm refinement for complex geometries, and the development of standardized digital decision protocols capable of combining geometry, fastener contamination, and timber quality into practical reuse recommendations. In this way, X-ray CT could evolve from an advanced diagnostic tool into a key enabling technology for safe, automated, and high-value secondary timber reuse (Vonk, 2024).

5. Conclusions

This study proposed a preliminary non-destructive methodology for investigating the relationship between density, moisture, and thermal response in timber elements intended for conservation and reuse assessment. The results showed that penetrometric testing and active infrared thermography provide complementary information: the former offers a useful surface-based proxy for density, while the latter captures spatial thermal patterns influenced by both material heterogeneity and moisture distribution. Although a promising correlation between thermal response and density was observed, the results also confirmed that the intrinsic variability of timber and the sensitivity of the measurements to surface condition and testing setup still limit a fully quantitative interpretation. For this reason, the proposed approach should currently be regarded as a diagnostic support tool rather than a stand-alone predictive method. Future developments should therefore focus on improving calibration and validation by comparing surface-based measurements with volumetric reference techniques such as X-ray computed tomography, with the aim of increasing the reliability of non-destructive assessment protocols for existing timber members.

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Gamma irradiation of timber: safety and mechanical effects

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Keywords: Gamma ray; structural timber; non-destructive testing (NDT); cellulose and lignin degradation; biodeterogen eradication

1. Introduction and research motivation

Gamma irradiation from ^{60}Co is increasingly considered as a promising tool for wood treatment to provide sterilization without significantly modify the lignocellulosic microstructure. In wood, cellulose is the main load-bearing constituent, embedded in a matrix of hemicelluloses and lignin. Under ionizing radiation, these polymers undergo radical-mediated reactions, including chain scission, oxidation, and, to a lesser extent, cross-linking. The balance between the absorbed dose and these mechanisms governs the resulting changes in stiffness, strength, and durability. Previous studies showed that moderate doses may preserve the bulk mechanical response, whereas higher doses reduce cellulose degree of polymerization, alter crystallinity, and increase brittleness (Despot et al., 2012; Aoki et al., 1977; Kasprzyk and Wichlacz, 2004).

Moreover, biological studies in agreement with the European Standard EN 113 (CEN, 1996) guidelines confirm the effectiveness of gamma irradiation at sterilization-relevant doses to completely eradicate a variety of biodeterogen species, maintaining the structural features of wood acceptable for conservation purposes (Hasan et al., 2008; Severiano et al., 2010). Despite this background, structural-scale evidence based on consistent static bending tests is still limited. For this reason, the present study investigates the effect of γ -irradiation on the bending behaviour of Norway spruce, birch, and beech, with the aim of identifying mechanically acceptable dose levels for structural applications.

2. Materials and methods

Gamma irradiation was carried out at Calliope γ -irradiation Facility at the ENEA R.C. in Rome. Calliope is a pool-type irradiation plant, equipped with a ^{60}Co radio-isotopic source operating with a mean photon energy of about 1.25 MeV. Dose delivery and uniformity were controlled through standard dosimetric procedures based on Fricke, and alanine/ESR systems, in accordance with international radiation-testing practice (Baccaro et al., 2019; ISO/ASTM 51026, 2015; ISO/ASTM 51276, 2010; ISO/ASTM 51607, 2012; IEC 60544-1, 2013).

The experimental campaign was designed to assess the effect of γ -irradiation on the static bending response of clear wood from three commercially relevant species: Norway spruce (*Picea abies*), birch (*Betula* sp.), and beech (*Fagus sylvatica*). Defect-free and straight-grained boards were selected, and all specimens were conditioned to a moisture content of $12 \pm 1\%$ before testing. Rectangular samples with a cross-section of $20 \times 20\text{mm}^2$ and a total length of 400 mm were prepared for four-point bending tests.

The adopted geometry consisted of an outer span of 360 mm and an inner loading span of 120 mm. For each species, 100 specimens were prepared and divided into five groups of 20 specimens each, including one untreated reference configuration and four irradiated configurations at different nominal absorbed doses.

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For each species, untreated reference specimens were compared with irradiated specimens exposed to nominal total absorbed doses of 8 kGy and 106 kGy. Static four-point bending tests were carried out to determine the modulus of elasticity and bending strength in accordance with ISO 3349:1975 and ISO 3133:1975, respectively. Load-displacement curves were continuously recorded to evaluate both the linear elastic response and the peak load at failure. In addition, selected specimens were examined through complementary techniques, including FTIR, XRD, degree of polymerization assessment, SEM, and color measurements, to relate the mechanical response to possible radiation-induced changes in cellulose structure and wood micro morphology.

3. Main results

The bending response showed a clear dose-dependent trend across all investigated species. At the lower irradiation level (8 kGy), the stress-displacement curves of spruce, birch, and beech remained broadly comparable to those of the untreated reference specimens. In particular, the initial linear portion of the curves, which reflects the effective bending stiffness, showed substantial overlap between irradiated and non-irradiated samples, indicating that low-dose irradiation did not produce a measurable modification of the elastic response. Differences in maximum bending stress were limited and remained within the intrinsic scatter of the material. One-way ANOVA confirmed that the effect of 8 kGy irradiation on bending strength was not statistically significant for spruce, birch, or beech, with small effect sizes in all cases (Fig. 1).

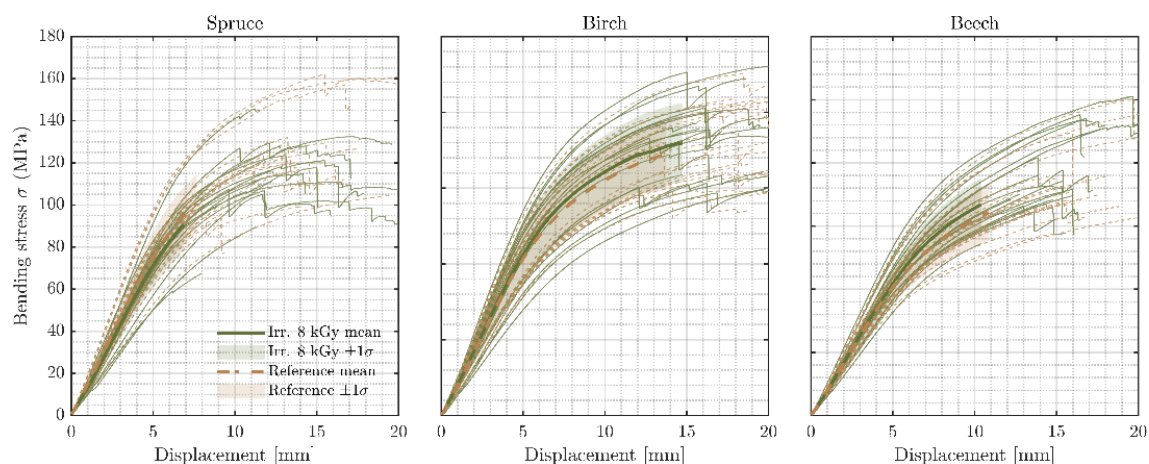


Fig. 1. Bending stress–displacement responses obtained from four-point bending tests on clear-wood specimens of spruce (*Picea abies*), birch (*Betula*), and beech (*Fagus sylvatica*). For each species, individual curves are shown together with the mean response and the $\pm\sigma$ band for untreated reference specimens and for specimens irradiated at an absorbed dose of 8 kGy.

By contrast, irradiation at 106 kGy produced a consistent reduction in bending strength for all three species (Fig. 2). The mean modulus of rupture decreased by about 16.6% in spruce, 11.9% in birch, and 18.3% in beech, and these reductions were statistically significant. This result indicates that high-dose irradiation causes a clear degradation of load-carrying capacity, despite some species-dependent variability in the absolute values of strength. Visual inspection of failed specimens did not reveal a change in the dominant failure mode, which remained governed by tensile rupture in bending, although irradiated samples tended to show slightly more diffuse fracture surfaces, suggesting a progressive weakening of the lignocellulosic matrix rather than a macroscopic change in failure mechanism.

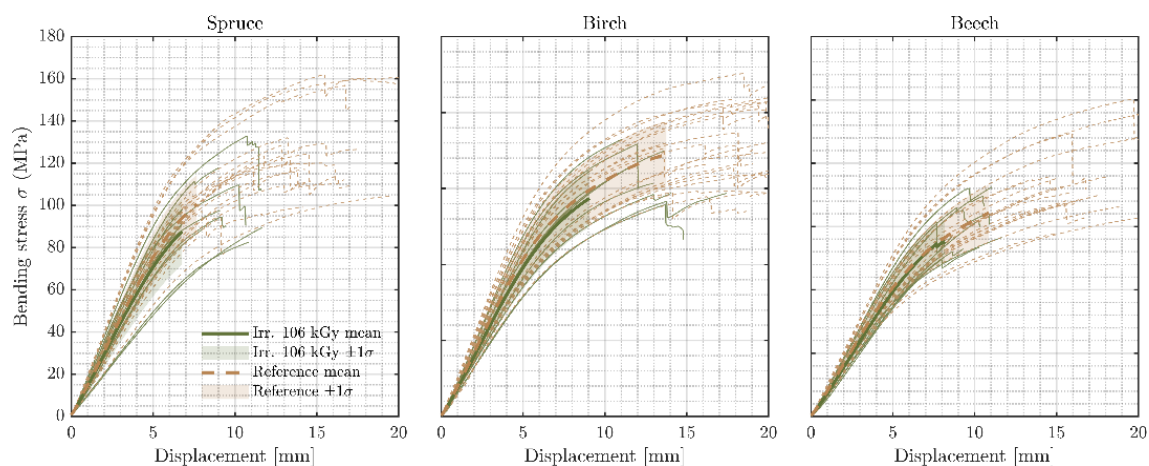


Fig. 2. Bending stress–displacement responses obtained from four-point bending tests on clear-wood specimens of spruce (*Picea abies*), birch (*Betula*), and beech (*Fagus sylvatica*). For each species, individual curves are shown together with the mean response and the $\pm\sigma$ band for untreated reference specimens and for specimens irradiated at an absorbed dose of 106 kGy.

A different trend was observed for stiffness. The modulus of elasticity showed only limited variations after irradiation, and no statistically significant changes were detected at either 8 kGy or 106 kGy for any of the considered species (Tab. 1). Overall, the statistical analysis confirms that species was the main source of variability in bending behavior, whereas irradiation affected strength only at the higher dose. These findings suggest that low-dose gamma treatment may be mechanically acceptable for structural wood, while high-dose exposure leads to a significant loss of bending resistance.

Table 1. Summary of four-point bending results for spruce, birch, and beech, comparing untreated specimens with wood irradiated at 8 and 106 kGy. (sistemare la tabella per renderla più leggibile e descrivere nel dettaglio nel testo il significato dei singoli parametri riportati.).

Species	Treatment	n	Mean (MPa)	SD (MPa)	CoV (%)	Δ (%)	p / η^2
Spruce	Reference	20	120.24	20.91	17.39	—	—
Spruce	8 kGy	20	112.58	17.55	15.59	-6.37	0.217 / 0.040
Spruce	106 kGy	10	100.25	15.43	15.40	-16.63	0.0124 / 0.203
Birch	Reference	20	181.58	23.99	13.21	—	—
Birch	8 kGy	20	186.04	24.75	13.30	+2.46	0.566 / 0.009
Birch	106 kGy	10	159.99	14.99	9.37	-11.89	0.0150 / 0.193
Beech	Reference	20	184.69	28.51	15.44	—	—
Beech	8 kGy	20	192.74	32.10	16.65	+4.36	0.407 / 0.018
Beech	106 kGy	10	150.89	19.40	12.86	-18.30	0.0022 / 0.288

4. Conclusions

The results indicate that the mechanical effect of γ -irradiation on structural wood is strongly dose-dependent. At 8 kGy, no statistically significant changes were observed in either bending strength or modulus of elasticity for spruce, birch, and beech, suggesting that low-dose treatment can be applied without measurable loss of structural performance. By contrast, irradiation at 106 kGy produced a consistent reduction in bending strength in all species, while stiffness remained substantially unchanged. This difference suggests that strength is more sensitive than elastic response to radiation-induced damage, likely due to the effects produced by the irradiation on the chemico-physical properties of the polysaccharides species within the wood matrix. Overall, the findings support the existence of a mechanically acceptable low-dose window for sterilization-oriented applications, while higher doses appear unsuitable for structural use due to their detrimental effect on load-carrying capacity. Further correlation with FTIR, XRD, degree of polymerization, and SEM observations will help clarify the link between macroscopic behavior and microstructural degradation.

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Pre-grading of structural timber boards by means of non-destructive dynamic testing

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Abstract

Timber constructions are rapidly gaining popularity due to their strong performance and environmental sustainability. However, certain stages of the structural timber production process, such as drying, are energy-intensive and have a significant environmental impact. Additionally, many wood species suffer from low yield. For this reason, assessing the quality of the green (freshly sawn) material before it undergoes the most costly and impactful production steps is crucial. This study investigates the variation in the dynamic modulus of elasticity (MOE_{dyn}), a key parameter used in mechanical grading of structural timber, as a function of moisture content during the drying process of Sardinian maritime pine boards intended for laminated timber production. The MOE_{dyn} was derived from the measurement of the natural frequency corresponding to the first vibration mode of the timber boards, constrained in a cantilever configuration. The measurements were carried out through a dynamic test involving the mechanical excitation of the boards and the use of accelerometers to detect the parameters of interest. The findings demonstrate that the dry MOE_{dyn} can be reliably estimated from the dynamic test performed on green boards. This provides a foundation for implementing a pre-grading system for Sardinian maritime pine, which could lead to reduced manufacturing costs, lower environmental impact, and improved yield of structurally graded timber.

Keywords: Structural timber; green timber grading; non-destructive dynamic testing; dynamic modulus of elasticity

* The full paper is open access available in the Conference Proceedings. *

Non-destructive field tests and FEA modeling of a timber wharf building in Norway from 1767

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Abstract

Non-destructive field measurement campaign consisting of two parts: (1) dynamic identification tests and (2) timber elements assessment, was conducted on the 18th century timber wharf building made of Norway Spruce in Trondheim, Norway. Currently, the building is undergoing restoration, and the goal of the field measurement campaign is to carefully assess the structural condition of the building while restoring it as closely as possible to sufficient strength for adaptive reuse. Dynamic identification was conducted by measuring ambient vibrations of the wharf using wireless tri-axial accelerometers and a wireless gateway for sensor synchronization and data aggregation. Stochastic subspace identification was used to determine the modal properties of the building: the natural frequencies and mode shapes. Non-destructive tests of selected beams were carried out using ultrasound time-of-flight, experimental modal analysis, and sound wave time-of-flight methods to estimate local material properties, i.e., dynamic elastic modulus. In addition, a resistograph was employed for in-situ density estimation, while a LIDAR scan was used to determine the volume of the structural elements. The results of the field measurements were used to develop the numerical model of the wharf in FEA software Abaqus. The mechanical properties estimated through the non-destructive testing were used for timber material model. The identified natural frequencies and mode shapes of the building were subsequently compared with those from the numerical model of the wharf building. Historic timber buildings possess not only important cultural value but are also benchmarks for gathering information about the future adaptive reuse of buildings, where assessment of existing mechanical properties is important to allow for service life extension with minimum intervention and costs.

Keywords: NDT; historic timber; existing timber; Norway spruce; dynamic identification

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Structural assessment of a decade-old severely degraded glulam roof

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Abstract

The on-site structural assessment of timber members is becoming increasingly widespread and significant for preserving both existing constructions, often belonging to the architectural heritage of a specific territory, and new buildings whose detailing, monitoring, and maintenance have not always been properly conceived and planned. As a consequence, certain timber members might exhibit degradation phenomena within a much lower time frame than the envisaged lifespan of the structure, meaning that a timely assessment of decay and subsequent retrofit of the elements can prove vital to avoid further damage, or even collapse, and ensure their durability. In this framework, the present work discusses an interesting case study of a relatively new glued laminated timber roof structure, having a service life of one decade, and exhibiting extensive fungal decay. After describing the building involved in this study, the structural assessment of the roof is presented: this involved the collection of small samples, their material characterization and observation under the microscope, as well as the identification of the potential causes of the observed degradation. Finally, interventions to restore the load-carrying capacity and structural health of the roof are proposed.

Keywords: Timber; decay; structural assessment; durability

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Non-destructive evaluation of the elastic properties of CLT floors by vibration techniques

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Abstract

Cross-laminated timber (CLT) panels are increasingly used as structural flooring solutions in buildings. However, its vibratory performance is a very sensitive issue for users, so it must be monitored periodically. This paper presents the results of the non-destructive evaluation of the elastic properties of CLT floors and their connections in a building prototype. The floor evaluated has dimensions of 4.04 m by 6.44 m and is composed of five 165 mm-thick radiata pine CLT panels. The evaluation was carried out in two stages. In the first stage, modal impact tests were performed on the floor. The floor was instrumented with uniaxial accelerometers and excited with a modal impact hammer. The floor's dynamic response enabled identification of three vertical modal shapes, vibration frequencies and damping ratios. Then, in the second stage, a finite element model of the floor was generated, including the orthotropic elastic properties of the CLT panels and the rotational elastic stiffnesses of the slab-to-slab and slab-to-wall connections. Five relevant parameters of the finite element model were calibrated to minimize differences between measured and simulated dynamic properties. The model calibration was performed through successive applications of regional sensitivity analysis techniques. The results obtained in the calibrated parameters of the CLT floor demonstrate its good structural health and excellent vibratory performance. Finally, the non-destructive methodology used in this work is projected as a powerful alternative for determining the structural health of CLT panels and their connections in existing buildings.

Keywords: Massive timber floors; experimental modal analysis; model updating

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Bayesian vibration-based identification of CLT mechanical properties and connection stiffness

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Abstract

A vibration-based non-destructive testing methodology is proposed for identifying the mechanical properties and connection stiffness of a panelized cross-laminated timber (CLT) building under ambient vibration. The framework proposed integrates ambient-vibration measurements, finite-element modelling, and Bayesian inference to quantify uncertainties and update mechanical parameters. A 3D FE model with orthotropic panels and discrete connections was developed, considering 14 uncertain parameters, representing the mechanical properties of the panels (modulus of elasticity parallel to the grain), density, and connection stiffnesses (angle brackets, hold down, screws, etc.). A surrogate artificial-neural-network model was trained using 1000 nonlinear finite-element runs, achieving a high predictive accuracy ($R^2 \approx 0.99$ and $MSE \approx 1e-3$) and enabling large-scale Bayesian sampling. Bayesian updating was performed using experimentally identified modal frequencies obtained from operational modal analysis. The results show that the updated model reproduces the identified frequencies with errors below 0.5%. Furthermore, uncertainty propagation through the surrogate model reveals a substantial reduction in the predictive uncertainty of the fundamental frequencies after updating. The proposed methodology shows the potential of combining vibration-based testing, surrogate modeling, and Bayesian inference. This combination allows for the probabilistic identification and updating of models for Cross-Laminated Timber (CLT) buildings

Keywords: Cross-laminated timber (CLT); operational modal analysis (OMA); finite element model

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Microwave measurements – methods for non-destructive condition assessment of timber structures

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Abstract

The preservation and reliable condition assessment of timber engineering structures necessitate effective non-destructive testing (NDT) methods. Prior laboratory studies have demonstrated that Ground Penetrating Radar (GPR) is fundamentally capable of detecting defects such as metallic connectors and moisture zones in timber components. However, the method's effectiveness is highly dependent on material properties, measurement setups, and external interferences, while manual evaluation remains time-intensive and experience-dependent.

The objective of this study is to enhance microwave-based methods for NDT of timber structures and evaluate its potential for qualitative anomaly detection under laboratory and field conditions. Initially, existing research and preliminary findings are reviewed to identify strengths and limitations of the methodologies. Microwave measurements will be conducted and analyzed to assess the detectability of typical damage patterns, including moisture zones, biological degradation, and metallic connectors.

Finally, the outcomes will be discussed regarding GPR's potential and constraints in timber structure diagnostics. Future perspectives for methodological advancements, particularly involving automated processes and intelligent algorithms, will be outlined to guide further developments in NDT for civil engineering.

Keywords: Non-destructive testing; GPR; microwave; timber structures

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Climate monitoring of roof structures with punched metal plate fasteners

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Abstract

Roof structures consisting of timber trusses with punched metal plate fasteners have been successfully used for decades. Inspections of such structures have revealed cases of nail backout – i.e. the detachment of punched metal plate fasteners from the timber surface. Several factors may contribute to this phenomenon. In addition to improper pressing during manufacturing process, additional loads and stresses occurring during transport and assembly, as well as variations in climatic conditions throughout the service life may also play a significant role. Despite these potential influences, there is a knowledge gap regarding the actual climatic conditions affecting roof structures in Central Europe, and particularly in Germany. To evaluate the climatic factors influencing timber structures with punched metal plate fasteners, MiTek Industries GmbH and RWTH Aachen University conducted a three-year climate monitoring campaign on various roof construction types. This paper describes the climate monitoring methodology, the post-processing of the collected data, and a discussion with regard to changes in timber moisture content and classification according to service classes.

Keywords: Climate monitoring, roof structures, punched metal plate fasteners

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Monitoring of curved long-span timber structures through satellite interferometry

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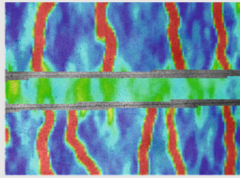
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Abstract

Structural Health Monitoring of timber structures represents a challenging task in the field of structural engineering. With respect to other materials, timber is particularly affected by degradation phenomena, due to environmental thermal-hygrometric variations, insect and biological attacks or durability issues. Consequently, a decay of the material properties and connections are expected, modifying the structural response. In this field, the monitoring through satellite interferometry data can represent an interesting emerging technology in the field of timber structures because of its potentialities related to monitor long-term displacements, thus following the time degradation of the structures. This paper presents an overview on the potentialities offered by the interferometric monitoring applied to long-span roof timber structures having simple or double curvature, interested by displacement causes due to environmental and/or long-term actions. Nevertheless, the curvature of these structures, together with the main orientation of the structure with respect to the satellite travelling orbits, make available measures extrapolated associated with a single dataset (ascending or descending) distributed on different surfaces of the structure separately. Therefore, spatial resampling issues arise in the displacement measures, making the measured displacements related to environmental and long-term factors affected by uncertainties. These issues are discussed with reference to some selected case of curved timber roofs characterized by long-spans, subjected to displacement causes related to environmental and long-term effects.

Keywords: Satellite monitoring, timber structures, temperature, creep

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MS25: Advancements in risk, reliability, and resilience assessment of existing structures

Organizers:

Edward Steeves (Dalhousie University, Canada)

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ABSTRACT

The health and safety of modern communities depend on reliable and resilient infrastructure – qualities that are vital for addressing the challenges of aging infrastructure, including material degradation, damage induced by mechanical or environmental loading, and lack of code-compliance. Advancements in risk, reliability, and resilience assessment are therefore needed to provide practical and science-driven tools for the evaluation and repair of existing structures facing these challenges. For learning outcomes, audience members attending this session will be exposed to:

- (A) new methods or tools in measuring the risk, reliability, or resilience of existing structures;
- (B) new methods or tools in enhancing the reliability or resilience of existing structures;
- (C) case studies demonstrating the application of (A) or (B) to structures affected by various forms of damage.

Fragility assessment of existing reinforced concrete buildings under ground-settlement and seismic action

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Abstract

The seismic evaluation of reinforced concrete (RC) buildings is often conducted without considering possible pre-existing damage caused by other factors, such as ground-settlements. In recent years, significant attention has been devoted by researchers to properly addressing multi-hazard interactions and their combined influence on structural behavior, rather than following a simplified single-hazard approach, to improve the accuracy of numerical models used for seismic vulnerability assessment. These combined effects are becoming increasingly relevant, as many existing structures have reached or surpassed their original design service life. In this study, three representative three-dimensional RC buildings, including infill panels, are modeled and designed for gravity loads. The numerical modeling of structural elements was first defined, including the characterization of nonlinear behavior to be considered in the calculations. Subsequently, analyses under gravity loads were performed using a force-controlled procedure to verify the global stability of the structure. The effects of imposed settlements were then simulated through force-controlled analyses, enabling the assessment of damage induced by differential ground movements. Lateral load analyses were conducted using a displacement-controlled approach, to evaluate the seismic performance and derive the structure's global capacity. Nonlinear dynamic analyses on the single degree of freedom associated system were performed and a fragility curves comparison highlighted the differences in the building's safety condition in both cases, with and without considering the prior effects.

Keywords: Fragility curves; multi-risk; seismic risk; ground settlements

* The full paper is open access available in the Conference Proceedings. *

Fast seismic risk assessment of highway bridges using artificial neural networks

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Abstract

Bridges represent fundamental elements of transportation networks, whose reliability and operational efficiency are crucial for economic growth, public safety, and emergency management. Given the rising occurrence of structural failures caused by extreme events, data-driven approaches have gained importance as effective tools for supporting risk evaluation and maintenance prioritization, especially in scenarios with constrained resources. This work enhances a previously developed framework based on artificial neural networks, originally conceived to estimate the structural deterioration and the risk level associated with traffic loads of existing bridges in accordance with the new Italian Guidelines for Risk Classification. The improved framework incorporates the assessment of seismic risk, enabling the rapid estimation of the seismic risk of existing bridges by employing only a limited number of easily obtainable parameters. The extended framework is applied to a case study involving 95 bridges along the Italian state highway network, allowing for the prediction of seismic risk for each structure. The outcomes are then represented through GIS-based analyses to investigate the spatial distribution of risk, identifying clusters and territorial trends. The results provide a practical and scalable decision-support tool for inspection prioritization and risk mitigation planning within large-scale bridge management systems, fostering more effective and informed infrastructure management under seismic hazard

Keyword: Existing bridges; seismic risk assessment; artificial neural network; GIS-based risk mapping; retrofit prioritization

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SEISMic risk and URBA resilience in historical environments: the case study of Molfetta, Italy

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Abstract

The Italian building stock is highly heterogeneous, encompassing historic, transitional, and modern structures that coexist within the same urban fabric. A large portion of this heritage consists of masonry buildings lacking seismic design criteria and frequently modified through uncontrolled interventions, which significantly compromise their structural integrity. Moreover, many reinforced concrete buildings constructed during the post-war period show deficiencies related to inadequate design, poor material quality, and the absence of effective seismic regulations at the time of their construction. These factors collectively contribute to a high level of seismic vulnerability across Italian cities. This paper proposes an integrated approach to seismic risk assessment and resilient spatial planning, applicable to different built environments. By combining a taxonomic classification of buildings with data on seismic hazard and structural vulnerability, the methodology enables a multi-scale evaluation of seismic risk within a Geographic Information System (GIS) framework. The GIS-based environment supports the spatial analysis and visualization of risk patterns, enhancing decision-making for prevention and preparedness. The expected outcomes include the identification of effective strategies for risk mitigation, the prioritization of interventions on vulnerable structures, and the development of tools to support emergency management and the long-term resilience of the built environment. The methodology has been applied to the historical city center of Molfetta, Italy

Keywords: Seismic risk, territorial scale, resilient spatial planning, GIS

* The full paper is open access available in the Conference Proceedings. *

Rocking and wobbling of dry-jointed masonry elements: a sensitivity analysis using DEM

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Abstract

The structural modeling and analysis of ancient dry-jointed masonry structures composed of large stone blocks pose a particularly demanding challenge, especially in archaeological contexts under seismic excitation. Their seismic behavior is mainly governed by the interaction among discrete stone blocks, as the absence of mortar or binding materials makes the rigid-body assumption particularly suitable for analyzing their response to lateral loads. In this study, a numerical investigation is carried out using the Distinct Element Method (DEM) to simulate rigid block-based masonry systems, with particular attention to the dynamic response of column-like elements (i.e., rocking, sliding, and wobbling phenomena). As a representative case, a circular stone masonry column located within the archaeological site of Pietrabbondante (Molise Region, Italy) was selected for the analyses. The numerical models were developed using 3DEC software, and some key parameters influencing the dynamic response - namely block-face discretization, interface stiffnesses, and friction angle - were investigated. In this context, the paper addresses typical challenges associated with the numerical modeling of the dynamic response of masonry columns. The insights gained contribute to enhancing the reliability of DEM-based simulations for dry-jointed masonry structures under dynamic loading.

Keywords: Distinct element method (DEM); rocking; wobbling; dry-joint masonry; sensitivity analysis

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Capacity prediction of existing concrete structures based on limited field testing using Bayesian compressive sampling and random finite element

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Abstract

Accurate assessment of the resistance of existing structures is vital for safety evaluation. In practice, uncertainty in capacity prediction arises when in-situ material properties are estimated from field testing, due to testing reliability, limited sampling, and accessibility constraints. The method integrates advanced Bayesian compressive sampling (ABCS) and random fields (RF) to reconstruct probabilistic spatial material properties from sparse data and propagate them into structural analysis. It is demonstrated on a 33-feet decommissioned bridge girder built in the 1970s and tested to assess flexural capacity, focusing on variability in concrete compressive strength. Three scenarios with varying sampling densities and accessibility were examined. Results show that the bias factor (ratio of actual-to-predicted) for yield and ultimate loads remained close to unity (0.97–1.10) with low COV (< 6%), whereas ultimate displacement showed higher mean (1.23–1.42) and COV (7.2–31.9%). Reducing accessibility from 0.50 to 0.25 of girder length increased the COV by up to seven times, whereas reducing sampling density led to slightly less conservative results. The framework provides a practical tool for improving reliability in structural assessment using limited field data.

Keywords: Existing structures; Bayesian compressive sampling; non-destructive testing; semi-destructive testing; reliability

* The full paper is open access available in the Conference Proceedings. *

Updating the reliability of sheet pile walls – 3D scans for a load-deflection curve approximation

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Abstract

The aging of German quay wall infrastructure poses increasing challenges for maintenance and structural safety, requiring improved assessment approaches for steel sheet pile walls. The concepts are based on a semi-probabilistic safety format defined in Eurocode 0, which often relies on limited or uncertain input data, particularly for underwater conditions. This contribution explores the integration of high-resolution 3D underwater scan data obtained by the HydroMapper system into reliability-based safety assessments of steel sheet pile walls. HydroMapper data were validated against inclinometer measurements and conventional numerical models. The comparison shows good agreement, confirming the potential of underwater scans for quantifying deformations and the resulting structural response. Monte Carlo simulations were applied to evaluate the influence of point cloud data on the reliability index β . The results demonstrate that precise monitoring data significantly reduces uncertainties, enabling an update of reliability indices and a more realistic estimation of residual service life. The approach supports more realistic residual service life assessments. This integration can strengthen the link between theory and practice in civil engineering while contributing to more sustainable infrastructure management.

Keywords: Sheet pile walls; Sonar; 3D scans; reliability analysis; structural monitoring

* The full paper is open access available in the Conference Proceedings. *

Practical evaluation procedure for structural robustness assessments of steel truss bridges

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Abstract

Robustness, and by extension redundancy, are intrinsic structural properties that ensure a bridge is able to maintain a level of safety after damage or overloading, respectively. Albeit the Canadian Highway Bridge Design Code (CSA S6:25) does not provide quantitative measures of robustness, structural evaluations of existing bridges should consider robustness and redundancy assessments to ensure the bridge can withstand a reasonable level of environmental or mechanical damage and achieve a system reliability higher than the reliability of any of its members. In response, the authors formulated new holistic structural robustness and structural redundancy indices specifically for steel truss bridges that are simple, expressive, and calculable through a user-friendly framework of analysis. However, the indices have only been applied to truss bridges subjected to corrosion damage under generic gravity loading. Furthermore, a review of the current indices and framework of analysis has highlighted practical limitations that reduce the relevance and significance of these evaluations. Therefore, the objective of this paper is to provide a practical evaluation procedure for structural robustness assessments of steel truss bridges using the same indices and analysis framework with practical modifications targeted for use by engineers in industry. The evaluation procedure will be showcased through a practical application of a steel truss bridge based off a real-life structure located in the province of Nova Scotia, Canada, subjected to mechanical damage and three different loading conditions. Robustness and redundancy indices within an informative evaluation procedure are significant advancements towards successful technology transfer to industry.

Keywords: Robustness; redundancy; practical; evaluation; steel truss bridge

* The full paper is open access available in the Conference Proceedings. *

Damage affecting the stability of anchored structures – a new research approach

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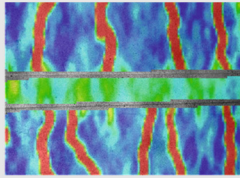
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Abstract

Civil engineering structures, such as bridges, tunnels and retaining walls are characteristic features along infrastructure routes in the Alpine region. The latter type usually includes gravity and cantilever walls as well as anchored structures, which increasingly pose challenges for inspection and maintenance. In particular, aging and the growing prevalence of corrosion-related damage in tension elements have a significant impact on the structure's reliability. This paper presents a method for evaluating the effects of damage on the stability of anchored structures using established analytical approaches by separating the geotechnical and structural aspects of the problem. The objective is to determine the load transfer potential independently of the structural components, such as concrete facings and tension elements. Subsequently, by assessing the redistribution potential in adjacent, undamaged or non-critical tension elements, the overall stability of the structure can be evaluated. By combining this approach with inspection data, the degree of damage to anchored structures can be determined. Although this does not represent a fully accurate structural analysis, it provides a basis for decision-making, particularly for operators. Moreover, the method can be used to illustrate the consequences of damage, enabling more targeted interventions and highlighting the need for maintenance. Furthermore, using this simplified approach climate change related effects can be considered, making it a tool to determine the resilience of structures.

Keywords: Anchored structures; existing structures; safety assessment; damage; simplified safety assessment

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MS26: Retrofitting, strengthening and strategies to extend the service life for concrete and masonry structures

Organizers:

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ABSTRACT

The retrofitting, strengthening, and repair of concrete and masonry structures is becoming increasingly important to ensure the safety of existing buildings and infrastructure. Instead of opting for demolition, resource-efficient solutions are essential to extend service life and preserve structural heritage. Innovative materials and methods, possibly supported by structural health monitoring (SHM), open new possibilities for sustainable interventions that enhance both performance and durability.

This Mini Symposium invites contributions that address solutions for preserving existing structures by applying advanced materials, design strategies, construction methods and monitoring approaches. Topics may include experimental investigations, theoretical approaches, and numerical simulations that provide insights into structural behavior, durability, and effectiveness. By fostering discussion and presenting cutting-edge research, the session aims to highlight the role of retrofitting and repair for solid construction in ensuring safe, sustainable, and resource-conscious use of our built environment.

Numerical investigation of brittle failure and tensile strength scatter in CRC systems

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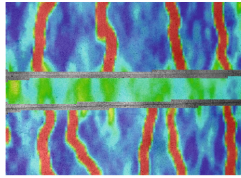
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Abstract

Extending the service life of existing concrete and masonry structures requires advanced strengthening systems that combine durability and high mechanical efficiency. Carbon reinforced concrete (CRC) has great potential for preserving existing building stock. However, to fully exploit its potential and establish its use, especially for additional fields of application, the load-bearing behavior of carbon reinforcement, particularly in connection with existing structures, must be clearly understood under all loading scenarios. To better capture this behavior beyond experimental investigations, numerical simulations are essential. Nevertheless, the complex load-bearing behavior of carbon reinforcement, in combination with the bond behavior to concrete and the interaction with the existing structure, poses a significant challenge. To establish a consistent simulation foundation, a stepwise finite element (FE) modeling framework is being developed in Ansys Parametric Design Language (APDL). The research begins at the material scale with a detailed tensile test simulation of a single carbon fiber strand, incorporating brittle failure and statistical scatter, based on preliminary investigations of anisotropic material behavior, to reproduce experimentally observed stress-strain behavior. Calibration against experimental data confirms the ability of the model to capture stiffness, strength, and failure variability. The long-term objective is therefore to create a robust simulation framework that links fiber-level properties to the global response of retrofitted elements, enabling performance-based design and durability assessment of CRC-strengthened concrete structures.

Keywords: Brittle failure; statistical scatter; tensile test simulation; FE modeling; APDL

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Lap-splice analysis of carbon-reinforced concrete strengthening with DFOS

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Keywords: Flexural strengthening; carbon-reinforced concrete (CRC); textile reinforced concrete (TRC); retrofitting; distributed fiber-optic sensors (DFOS)

1. Introduction

Carbon-reinforced concrete (CRC) represents an innovative and highly efficient method for flexural strengthening of reinforced concrete members, as demonstrated by Zhang et al. (2022). With only a few millimeters of added material, the load-bearing capacity of structural elements such as slabs, beams, and even bridges can be significantly enhanced, as shown by Guo et al. (2021).

The integration of distributed fiber optic sensors (DFOS) into the strengthening layer by attaching them to the carbon reinforcement enables spatially and temporally quasi-continuous monitoring of strain development and structural performance in both laboratory specimens and full-scale structures, see Becks et al. (2022).

In this study, DFOS provided detailed insight into the structural behavior of a lap splice, capturing localized tensile force transfer within the carbon reinforcement, including bond and cracking behavior, as well as stress redistribution within the cross-section. The sensors were applied in a large-scale four-point bending test on a three-meter-long reinforced concrete slab with a cross-section of $0.50 \times 0.12 \text{ m}^2$, strengthened with CRC.

2. Specimens and test setup

The slab specimen had dimensions of $3.00 \times 0.50 \times 0.12 \text{ m}^3$ for the steel-reinforced concrete (RC) member, see Fig. 1. The specimen was tested under 4-point-bending with an effective span of $l_{ef} = 2.7 \text{ m}$ and a distance of $a = 0.8 \text{ m}$ from the supports to the load introduction points on each side. The total steel reinforcement area was $A_s = 141.4 \text{ mm}^2$ with a rebar diameter of $\phi 6 \text{ mm}$. Cylinder tests yielded a mean concrete compressive strength of $f_{cm} = 27.8 \text{ MPa}$ and a Young's Modulus of $E_{cm} = 28233 \text{ MPa}$. The bottom surface of the RC member was roughened to prepare the composite interface for the strengthening layer. In accordance with Deutsches Institut für Bautechnik DIBt (2023), a surface roughness of more than 1 mm was achieved.

The strengthening layer was applied in the tension zone using shotcrete with a total thickness of 10 mm and consisted of a uniaxial carbon textile grid embedded centrally in a fine-grained concrete matrix (maximum aggregate size 1 mm). Two carbon grid segments with a length of 1.75 m each were installed in direct contact with each other, forming a lap splice at midspan with a length of $l_b = 500 \text{ mm}$. The carbon grid featured a grid spacing of 12.7 mm in the warp direction (main load-bearing direction) with a total cross-sectional area per fiber strand of $a_{f,mm} = 70.2 \text{ mm}^2$. The mean tensile strength $f_{t,mm,m} = 3039.2 \text{ MPa}$ and the corresponding ultimate strain $\varepsilon_{nm,u} = 14.9 \text{ ‰}$ were determined in accordance with Deutscher Ausschuss für Stahlbeton [DAfStb] (2024). The Young's modulus was $E_{f,mm,m} = 203,973 \text{ MPa}$.

On each of the overlapping carbon grids, one DFOS with Ormocer-coating was installed directly on the carbon grid using epoxy resin at mid-depth of the cross-section. Further details on the DFOS installation on carbon reinforcement are provided in Sandmann et al. (2025), while data pre-processing followed the procedures described by Richter et al. (2024). For reasons related to robust and reliable installation, including protective components such as pigtails, splice protection, and terminations, the sensors did not cover the full specimen length of 3.0 m , but extended from 0.26 m to 2.61 m . For the same reason, the sensors did not cover the full lap splice length, terminating approximately 50 mm before the ends of the overlap.

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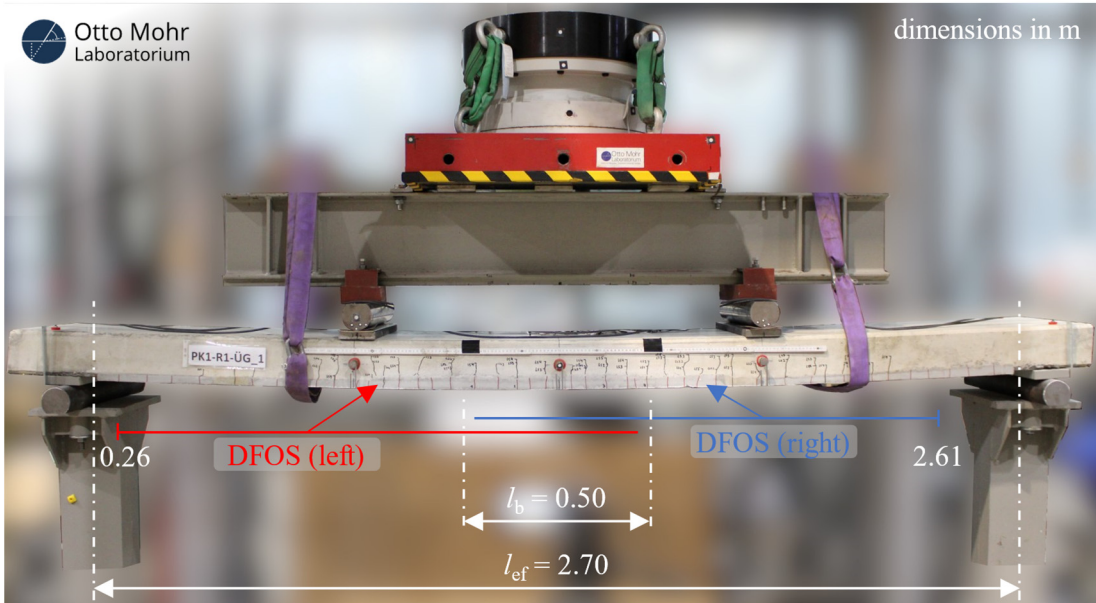


Fig. 1. Test setup of the slab specimen with centered lap-splice.

3. Lap-splice analysis

Fig. 2 shows the DFOS strain profile of the two sensors on the carbon grid as strain values along the specimen length, presented both as the raw, pre-processed data (grey curve in the background) and as averaged curves (red and blue). Peaks in the strain profile indicate cracks in the CRC layer. Between adjacent cracks, tensile forces in the carbon reinforcement were transferred by bond into the fine-grained concrete and subsequently across the interface into the RC member.

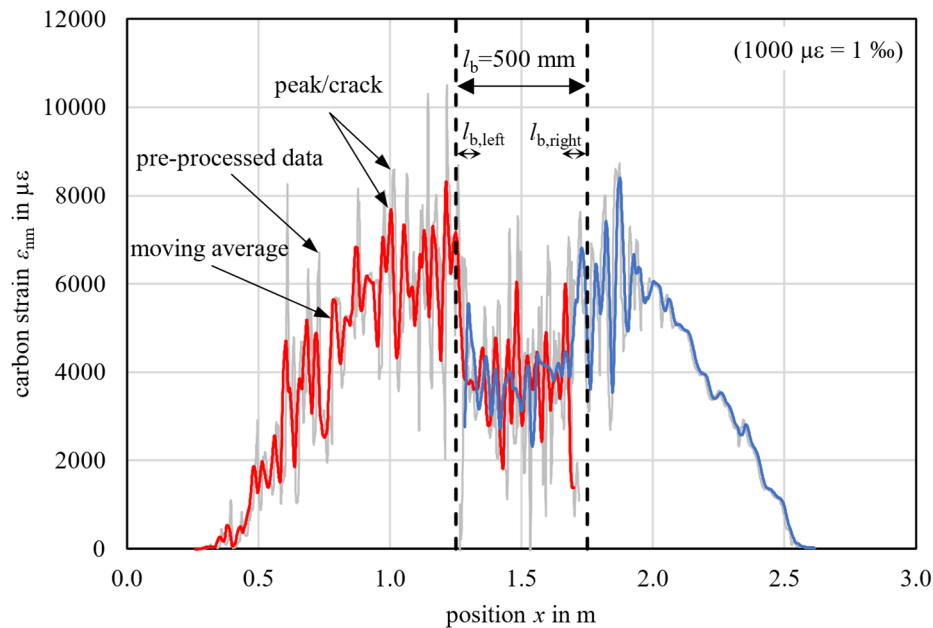


Fig. 2. DFOS strain-profile of the carbon grid with lap-splice, raw data and moving average curve.

Notably, contrary to common assumptions, the tensile forces between the overlapping carbon grids were not transferred linearly along the entire lap splice length. Instead, force transfer was concentrated within comparatively short regions at the entry zones of each grid into the lap splice, with transfer lengths of approximately $l_{b, \text{left}} = 80$ mm (left side) and $l_{b, \text{right}} = 70$ mm (right side) at the considered load level. Along the remaining length towards the center, the strain profile was approximately constant. This behavior highlights the excellent bond properties of the carbon reinforcement, as also reported in Sandmann and Marx (2024).

The curves presented in Fig. 2 illustrate the behavior of the carbon grid up to sensor breakage shortly before failure at a bending moment of $M = 20.5$ kNm. Final failure occurred a few seconds later due to sudden rupture of the lap splice at $M_u = 24.5$ kNm (including the dead load (DL) of $M_{DL} = 1.4$ kNm). At this stage, the carbon grid reached only about 60% of its ultimate strain (based on peaks of the pre-processed data, not averaged curves), which is unexpected since the full capacity of the lap splice was not mobilized. This behavior can be attributed to imperfect alignment of the carbon grids within the lap splice and insufficient concrete

cover. Two carbon grids, each 1.5 mm thick, were embedded in a 10 mm concrete layer without spacing between them, resulted in a concrete cover of only 3.5 mm.

In the averaged curves, the lap splice region is clearly identifiable by a significantly lower strain level of approximately $\varepsilon_{nm} = 4400 \mu\epsilon$ (4.4 ‰; peak values in the cracks), compared to approximately $\varepsilon_{nm} = 7400 \mu\epsilon$ (7.4 ‰) at the edges of the lap splice. The presence of two carbon grid layers therefore did not result in a halving of the tensile strain. This can be attributed to stress redistributions within the cross-section: owing to its stiffer bond behavior, a higher Young's modulus and larger structural depth compared to the steel reinforcement, the carbon grid attracts a disproportionately high share of tensile forces relative to the assumption of plane sections according to the Bernoulli hypothesis, see also Steinbock (2021) and Hägle et al. (2025).

4. Conclusions and outlook

Distributed fiber-optic sensors are well suited for precisely capturing the local strain distribution in carbon reinforcement, as demonstrated by their application in the carbon-reinforced concrete strengthening layer of the presented flexural test. This enabled further insights into the bond and anchorage behavior within the lap splice. Contrary to common assumptions, load transfer between the overlapping carbon grids did not occur linearly along the entire lap splice but was localized near its entry zones, with a transfer length of less than 100 mm at the considered load level. The observed behavior could be plausibly explained and thus provides a sound basis for further investigations into the development of load transfer within the lap splice under increasing load and quasi-static load cycles, as well as its influence on lap splice performance. Additionally, the cracking pattern within the lap splice was significantly more finely distributed than in other regions of the carbon-reinforced concrete layer. This will be examined in more detail using DFOS data in future studies.

Acknowledgements

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A simplified design approach for CRC strengthening using a single ω -table

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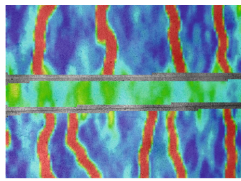
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Abstract

The strengthening of existing reinforced concrete structures is becoming increasingly important for extending service life and reducing the environmental impact associated with replacement and reconstruction. Carbon-reinforced concrete (CRC) has emerged as an efficient strengthening solution due to its high tensile strength, corrosion resistance, and the possibility of applying thin strengthening layers. The design of CRC strengthening systems is commonly performed using dimensionless design tables (ω -tables) derived from strain compatibility analysis. However, the reinforcement demand depends on the ultimate strain capacity of the non-metallic reinforcement, requiring separate ω -tables for different reinforcement materials. This study presents a simplified and generalized design approach that enables the determination of the required reinforcement area using a single reference ω -table. Two coefficients are introduced: k , relating the required reinforcement area at any ultimate strain to a reference case, and c , defined as the ratio of mechanical reinforcement ratios, which alone is sufficient to estimate the reinforcement area directly. Based on the observed relationships, regression-based polynomial formulations are developed to estimate the coefficients directly from the governing design parameters. The proposed formulations were validated against reference calculations obtained from ω -tables developed for multiple ultimate strain capacities. The proposed approach significantly simplifies the design procedure and provides a practical tool for the design of CRC strengthening systems using different non-metallic reinforcement materials while requiring only a single reference ω -table.

Keywords: Carbon-reinforced concrete; non-metallic reinforcement; structural strengthening; simplified design; ω -table; ultimate strain

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Numerical investigation of the influence of a CRC waterproofing layer on the structural behavior of masonry arch bridges

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Keywords: Carbon-reinforced concrete (CRC); masonry arch bridge; waterproofing layer; finite element method (FEM); interface modeling

1. Introduction

Masonry arch bridges represent a significant part of modern infrastructure, valued for their robustness and cultural heritage. Approximately 25% of railway bridges in Germany are masonry arches, with an average service life of over 135 years. Despite their durability, these structures face challenges due to aging and modern traffic loads. However, aging and modern traffic loads pose challenges, particularly due to the degradation of waterproofing layers, which typically last about 50 years. This leads to water penetration, frost-thaw damage, and structural issues.

In this study, carbon-reinforced concrete (CRC) is evaluated as a novel waterproofing solution. CRC offers a longer service life of up to 100 years and superior mechanical properties such as higher stiffness and compressive strength, enhanced crack distribution due to the carbon grid reinforcement, and better resistance to environmental factors compared to traditional membranes, see Wagner et al. (2022) and Steinbock et al. (2021). However, its higher stiffness may interact with the structural behavior of masonry arches, necessitating a detailed investigation. This work systematically evaluates the influence of CRC waterproofing layers on masonry arch bridges using finite element modeling (FEM), incorporating experimental data for material and interface properties. The aim of this research is to evaluate the feasibility and structural impact of applying CRC waterproofing layers to masonry arch bridges. The study examines the load-bearing behavior of arches with and without CRC, investigates CRC-masonry interface properties using experimental data, and analyzes stress distribution, thrust lines, and interface stresses under various loads.

2. Methodology

A parametric study was carried out using the finite element software ATENA, developed by Červenka (2022), which enables advanced modeling of masonry structures and interface behavior. Two different masonry arch geometries were considered: a steep arch (span-to-rise ratio of $f/L > 0.45$) and a shallow arch ($f/L < 0.27$) (Keßler et al. (2024)). The investigated arches are shown in Fig. 1. Each geometry was analyzed in two configurations, both with and without a CRC waterproofing layer. The CRC waterproofing layer consists of a 3 cm thick mortar layer reinforced with a centrally placed carbon grid. The interface between the masonry and the CRC layer was modeled using nonlinear zero-thickness elements, incorporating experimentally determined tensile, shear, and stiffness properties. The study was structured in several steps. First, material testing was performed to determine the mechanical properties of CRC and the interface between CRC and mortar. Tensile and shear strengths were obtained through pull-off and shear tests, while the young's modulus and compressive strength of CRC were also characterized. Subsequently, finite element models were developed, representing the arches as one-meter-wide strips with ballast, masonry, and CRC modeled as separate domains. Interface elements were introduced to realistically simulate the bond behavior between masonry and CRC. Finally, different load cases were applied based on Deutsche Bahn guideline Ril 805.0203, see DB Netz AG (2010), including full-load and half-load scenarios for railway traffic. In addition, extreme load cases were considered to evaluate the structural performance beyond standard service conditions. Additionally, load cases were investigated in which the applied loads were twice

as high as those specified by guideline Ril 805.0203, see DB Netz AG (2010). The evaluation was carried out by comparing the stresses in the masonry arch and its thrust lines with and without CRC waterproofing layer. Fig. 2 shows the setup of the FE model, including its boundary conditions and monitoring points used to measure loads and deformations.

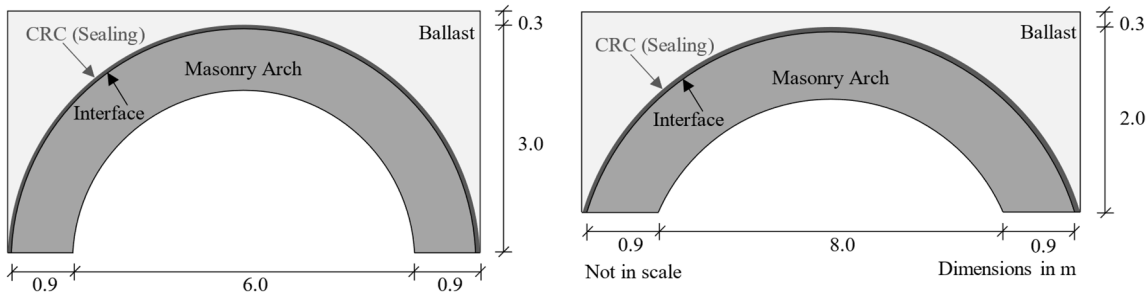


Fig. 1. Geometry of the selected bridge cross-sections with CRC layer.

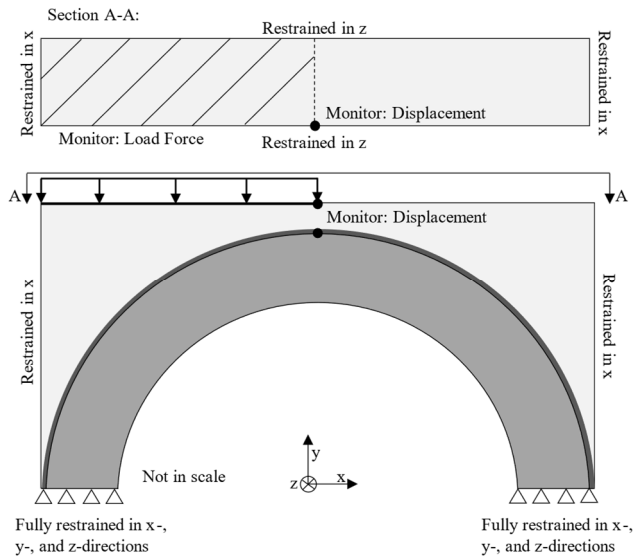


Fig. 2. Steep arch under half load with support conditions and monitoring points.

3. Results and Discussion

The finite element simulations indicate that CRC waterproofing layers have only a minor influence on the structural behavior of masonry arch bridges under service load conditions. Overall, the results demonstrate that the application of CRC does not adversely affect the load-bearing performance of the arches.

- With regard to thrust line behavior, the thrust line remained within the allowable limits ($d/9$ of the cross-section according to Ril 805.0203) for both arch geometries under full-load and half-load scenarios. In the case of the steep arch under half-load conditions, the presence of the CRC layer showed a beneficial effect, as it attracted load in the crown region, thereby reducing eccentricity and leading to a more favorable stress distribution. Fig. 3 illustrates the thrust line of the very shallow arch and the steep arch under half and full load, as well as how it changes when a CRC layer is applied.
- In terms of stress distribution, the simulations revealed slight reductions in both compressive and tensile stresses for arches with CRC layers under half-load conditions, indicating a modest but positive redistribution of internal forces. For instance, in the shallow arch under half-load, the maximum compressive stress decreased from -0.960 MPa (without CRC) to -0.435 MPa (with CRC), while tensile stresses were also marginally reduced.
- The analysis of interface stresses showed that the stresses between the CRC layer and the masonry remained low in both normal and tangential directions. Maximum values of 0.054 MPa (normal) and 0.151 MPa (tangential) were observed, which are significantly below the experimentally determined strength limits of the interface. Furthermore, variations in interface stiffness and strength parameters within realistic ranges had negligible impact on the overall structural response.
- Under higher loading conditions exceeding twice the design loads, a slight increase in thrust line eccentricity was observed in the shallow arch, reaching 36.1 cm at the quarter point and thus exceeding the $d/9$ limit (35 cm). Nevertheless, this consideration shows that even under higher loads, the influence of the CRC layer remains small.
- Finally, an increase in the stiffness of the CRC–masonry interface to unrealistically high values did not lead to critical changes in thrust line behavior or interface stresses, confirming the robustness of the system. Overall, the CRC layer primarily acts as a

protective measure and does not significantly alter load redistribution between masonry and ballast under service conditions, while maintaining the structural integrity of the arch.

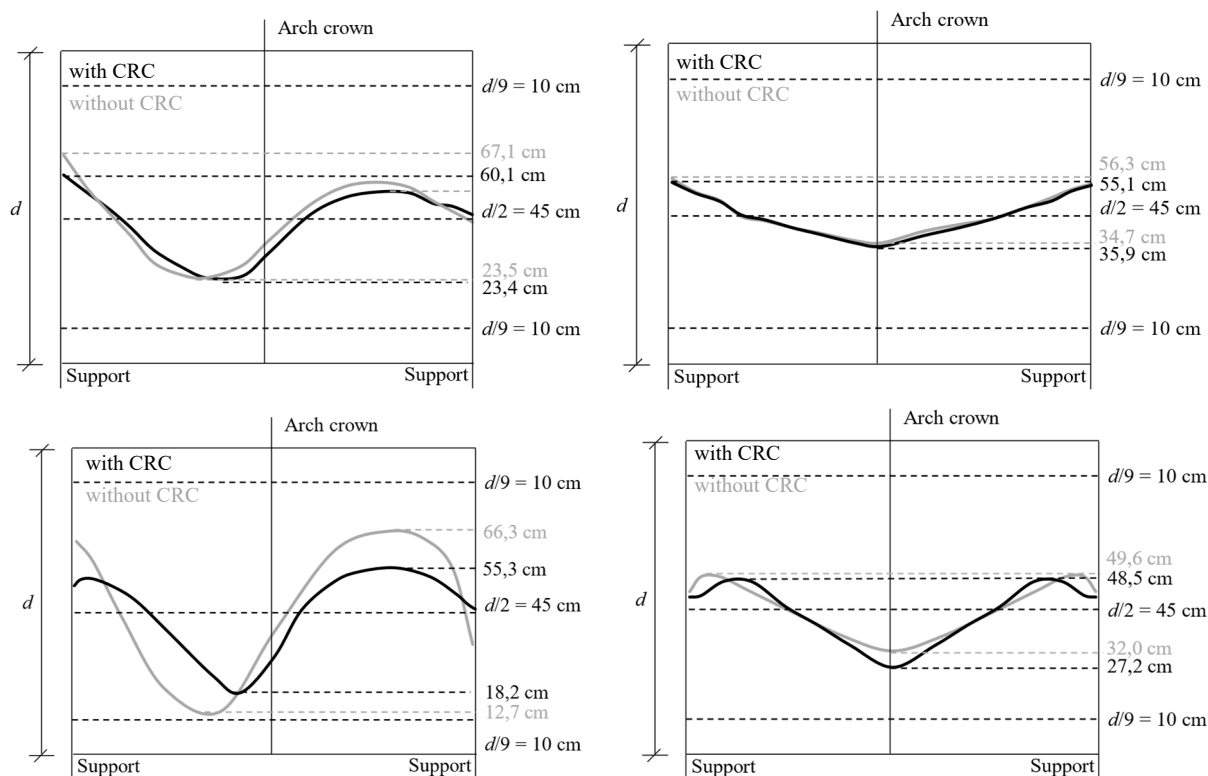


Fig. 3. Thrust lines; very shallow (top) and steep arch (bottom) under half (left) and full load (right).

The results of the FE analysis indicate that the use of a CRC waterproofing layer does not cause any critical redistribution of the thrust line. Due to its enhanced mechanical properties, CRC represents a durable and sustainable alternative to conventional waterproofing systems. However, under extreme load conditions far beyond service requirements, its high stiffness could lead to minor adverse effects, such as increased eccentricity. The study also underscores the importance of accurate modeling of the CRC-masonry interface. The interface stresses remained low even when interface properties were varied, indicating that the system is not highly sensitive to minor variations in material properties. This robustness simplifies the practical implementation of CRC layers in rehabilitation projects.

4. Conclusion

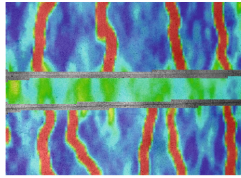
This research demonstrates that CRC waterproofing layers are a feasible and sustainable alternative for masonry arch bridges. They provide enhanced durability without significantly influencing structural behavior under typical service loads. Even under extreme loading conditions, the effect of CRC remains in the range of the critical limits specified by Ril 805.2023 ($d/9$), see DB Netz AG (2010). The combination of experimental determination of the properties of the CRC layer and the interface between the arch and CRC, together with advanced finite element modeling, provides a reliable framework for assessing the impact of novel materials like CRC on existing infrastructure. Future work will include large-scale validation tests and field implementation to further validate these findings and refine the design process.

Acknowledgements

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Influence of Fe-SMA embedment under semi-cyclic loading and multiple activations

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Keywords: Iron-based shape memory alloys (Fe-SMA), prestressing reinforcement, Fe-SMA embedment, semi-cyclic loading, multiple activation

1. Introduction

The strengthening of reinforced concrete (RC) structures has become a major challenge in civil engineering due to aging infrastructure and increasing service demands. Among emerging technologies, iron-based shape memory alloys (Fe-SMAs) have attracted considerable attention as active reinforcement materials for prestressing applications due to the shape memory effect (Cladera et al. 2014). This effect refers to the ability of these materials to return to their original shape after deformation upon activation (heating followed by natural air cooling). This property allows Fe-SMA elements to introduce prestressing into RC members without the need for complex mechanical anchorage systems. Recent studies have shown that Fe-SMA elements can effectively be used to strengthen concrete structures, with ongoing developments exploring new methods for flexural strengthening (Lemos et al. 2026). However, the activation process is multiphysical and strongly influenced by the Fe-SMA embedment material (Saeedi et al. 2025). In addition, semi-cyclic loading may reduce the benefits of Fe-SMA reinforcement due to recovery stress losses induced by these loads, although reactivation can partially restore the recovery stress, at least at the material level, as reported by Mir et al. (2025). Therefore, this paper investigates the influence of conventional concrete and a high-strength cementitious grout as embedment materials for Fe-SMA rebars in RC beams subjected to semi-cyclic loading and multiple activations.

2. Description of the experimental campaign

Manufacturing process. Eight beam specimens were manufactured with dimensions of 100 × 200 × 3550 mm and a span of 1890 mm (Fig. 1a). The tensile reinforcement consisted of a pre-strained (4%) Fe-SMA rebar, with four specimens reinforced with Ø16 mm and four with Ø11 mm rebar. The Fe-SMA bars were supplied by the Swiss company re-fer AG. Their detailed testing procedures and stress-strain curves are reported in Mir et al. (2025) where the bars identified as S1-Ø11 and S2-Ø16 correspond to those used in the present work. Each beam included a Ø10 mm B500SD rebar in the compression zone to control cracking during Fe-SMA activation.

The beams were manufactured in two phases. First, the specimens were cast upside down, with the Fe-SMA tensile reinforcement placed at the top. In the central test zone (see Fig. 1a), the Fe-SMA was left uncovered to allow activation. After the initial activation, the test zone was covered with conventional concrete in four specimens and with SikaGrout-340 in the remaining four specimens. No surface treatment was applied to the first concrete cast before the second casting; only humidification of the interface was carried out, while the concrete surface was left with its natural roughness.

The specimens were designated as *Sx-ØD-yz*, where *Sx* identifies the specimen number, *ØD* indicates the Fe-SMA diameter (11 or 16 mm), *y* denotes the embedment material used in the second casting (C for conventional concrete and S for SikaGrout-340), and *z* indicates the activation condition during the first structural testing (A for activated and P for as-provided).

Test setup. The experimental campaign consisted of three stages. First, in four of the eight specimens, the Fe-SMA rebars were heated to 250 °C using an industrial torch with the Fe-SMA positioned at the top (Fig. 1a), generating recovery stresses that acted as prestressing. Second, all specimens, regardless of whether they had been initially activated, were subjected to semi-cyclic loading without sign inversion with the Fe-SMA positioned at the bottom (Fig. 1b). Beams reinforced with Ø16 mm Fe-SMA rebars were loaded through seven incremental load levels, increasing by 5 kN after each set of three semi-cyclic cycles, reaching a maximum

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load of 35.5 kN (from 0.5 kN to 35.5 kN), as shown in Fig. 1c. Beams reinforced with Ø11 mm Fe-SMA rebars were loaded through three incremental load levels of 5 kN, reaching a maximum load of 15.5 kN (from 0.5 kN to 15.5 kN) (Fig. 1d). Third, after the semi-cyclic loading test, the Fe-SMA rebars were electrically heated to 160 °C. During the tests, mid-span deflection, support displacements, strains in the B500SD and Fe-SMA rebars were monitored, and three HD cameras recorded images for Digital Image Correlation (DIC) analysis.

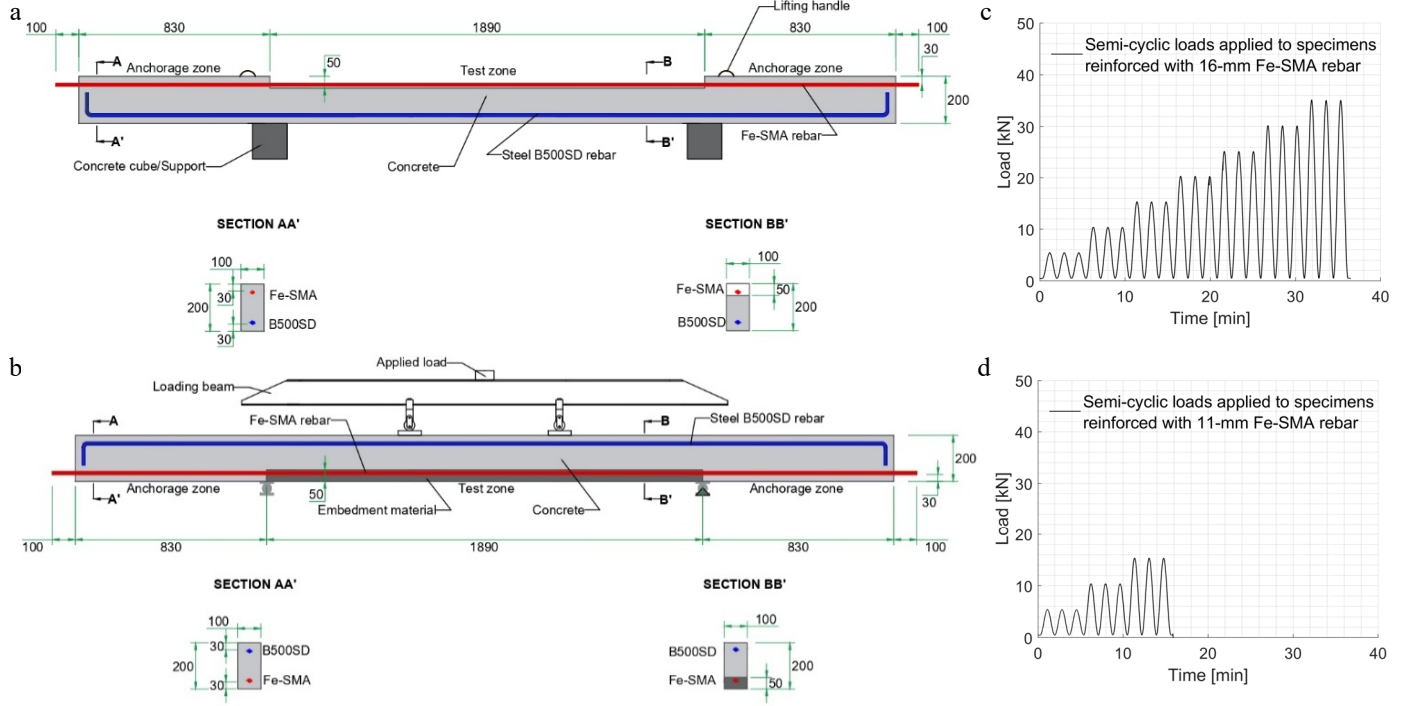


Fig. 1. Specimen design and test setup for the experimental campaign: (a) first activation; (b) semi-cyclic loading test and subsequent activation; semi-cyclic loading protocol for specimens with (c) 16-mm Fe-SMA and (d) 11-mm Fe-SMA rebar.

Concrete properties and embedment material. The concrete used for the major part of the beam, including the anchorage zones, had a mean compressive strength f_{cm} of 26.4 MPa and a splitting tensile strength f_{sp} of 2.4 MPa measured on the first activation day. Two different materials were used for the cover: concrete with f_{cm} of 32.3 MPa and f_{sp} of 2.2 MPa for four beams, and SikaGrout-340 for the other four beams, achieving f_{cm} of 55 MPa (all measured on the semi-cyclic loading test day). According to the manufacturer, the grout modulus of elasticity E_c is 38 GPa, while for both concrete batches it was estimated to range between 28 and 30 GPa using EC2 formulation.

3. Results and discussion

First activation. The first activation, performed prior to semi-cyclic loading and without Fe-SMA cover in the test zone, was applied to specimens S2-Ø16-CA, S4-Ø16-SA, S6-Ø11-CA, and S8-Ø11-SA. At this stage, the test-zone cross section was 100 × 150 mm. This activation generated a precamber of 7.8 mm and a prestressing stress (σ_p), estimated from the mid-span deflection according to del-Río-Bonnín et al. 2026, of 166 MPa in the 16-mm Fe-SMA rebars. For the 11-mm Fe-SMA rebars, the corresponding precamber and prestressing stress were 5.33 mm and 320 MPa, respectively.

Semi-cyclic loading tests. Specimens with cementitious grout as the embedment material showed lower peak and residual deflections than those with conventional concrete, indicating a stiffer structural response. This behavior is attributed to the higher strength, modulus of elasticity, and improved bond performance of the grout. Deflection reductions of about 30% were observed in beams reinforced with 16-mm Fe-SMA rebars and about 20% in those reinforced with 11-mm rebars. Specimens with conventional concrete exhibited earlier bond loss between the Fe-SMA cover and the beam concrete than those with grout. Although this early bond loss limited crack propagation into the beam web, the stronger bond provided by the grout allowed greater crack development, leading to shear failure in specimen S3-Ø16-SP (Fig. 2b). Furthermore, early bond loss (Fig. 2a) promoted an arch-action mechanism, where a compressive strut formed between the load application point and the support while the Fe-SMA rebar acted as a tensile tie. This mechanism likely increased the Ultimate Limit State capacity but resulted in poorer performance at the Service Limit State.

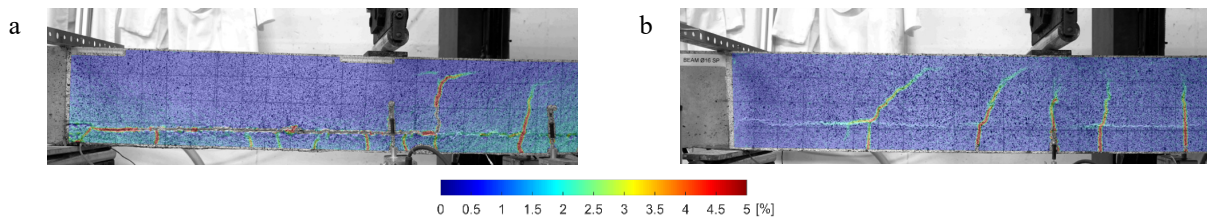


Fig. 2. Crack propagation at maximum load in: (a) S1-Ø16-CP; (b) S3-Ø16-SP.

Activation after the semi-cyclic loading test. Specimens with grout embedment developed lower precamber than those with conventional concrete due to the higher stiffness of the grout (Fig. 3). For beams S1-Ø16-CP and S2-Ø16-CA, the average σ_p was 210 MPa, whereas specimen S4-Ø16-SA, embedded in grout, developed a σ_p of 145 MPa. Although the σ_p was only about 30% lower in specimens with grout embedment, the precamber was considerably higher in specimens S1-Ø16-CP and S2-Ø16-CA. This indicates that grout requires greater σ_p to produce comparable precamber because of its higher stiffness. For S5-Ø11-CP to S8-Ø11-SA, significant precamber was observed only in specimens that were not initially activated, reaching 1.18 mm when embedded in concrete and 0.63 mm when embedded in grout, with corresponding mean σ_p values of 326 MPa and 373 MPa, respectively.

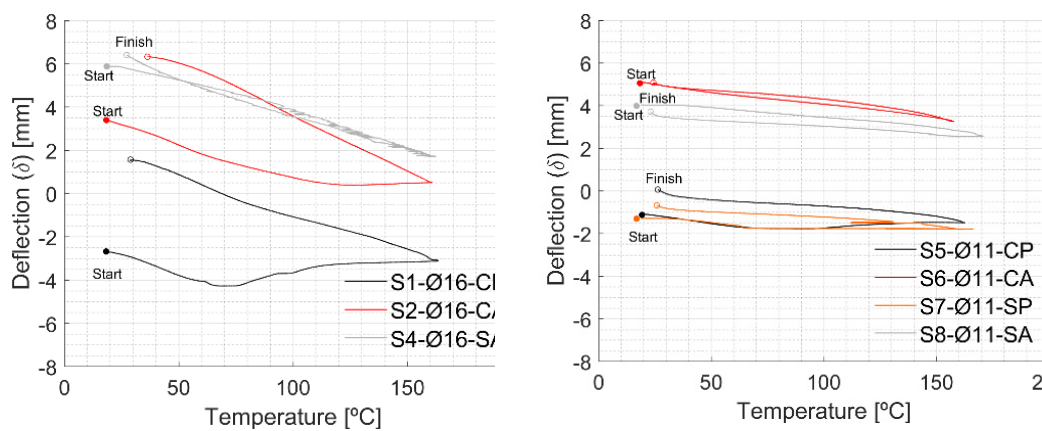


Fig. 3. Evolution of precamber during activation after the semi-cyclic loading test.

4. Conclusions

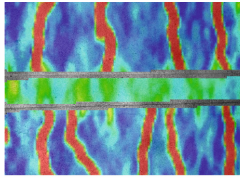
Specimens with Fe-SMA rebars embedded in SikaGrout-340 showed lower deflections during semi-cyclic loading than those with conventional concrete due to the higher strength, stiffness, and improved bond performance of the grout. The stronger bond maintained beam action, allowing the development of the cracks in the beam web, leading to shear failure in specimen S3-Ø16-SP. In contrast, early bond loss in specimens with concrete embedment limited crack propagation along the beam web and promoted arch action, resulting in poorer serviceability performance. Overall, for practice-oriented applications, grout showed improved behavior when activation was carried out before service, whereas conventional concrete improved the effects of the 2nd activation.

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Recovery stress behavior of Fe-SMA under cooling and semi-cyclic loading

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Keywords: Iron-based shape memory alloys (Fe-SMA); martensitic transformation; transformation temperatures; semi-cyclic loading; prestress losses

1. Introduction

Iron-based shape memory alloys (Fe-SMAs) are promising materials with significant potential to enhance the durability and service life of civil engineering structures. Their ability to recover a predefined shape after deformation through activation (heating followed by cooling), known as the shape memory effect (SME), is governed by the reverse phase transformation from martensite to austenite of previously mechanically induced martensite. This phenomenon enables their use as prestressing reinforcement when deformation is restrained. Under these conditions, as the material attempts to shorten during heating, tensile stress develops due to the imposed restraint, thereby generating recovery stresses (σ_{rec}). In addition, Fe-SMAs offer advantages such as simple manufacturing processes and ease of installation (Cladera et al. 2014). However, uncertainties remain regarding the long-term prestress stability, which has recently been investigated by Harmanci et al. (2024), as well as the behavior of Fe-SMAs under semi-cyclic loading scenarios (Mir et al. 2025).

This paper presents an experimental campaign investigating potential σ_{rec} reductions in Fe-SMA rebars after activation when exposed to cooling. Recent findings by Kustov et al. (2024) indicate that some Fe-SMA samples exhibit martensite start temperatures (M_s) close to ambient conditions, which may trigger undesired phase transformations in cold environments and lead to stress losses. For structural applications, lower M_s values are preferable, as they help maintain the austenitic phase under service conditions. Furthermore, the study examines whether cooling-induced stress reductions accelerate stress losses under semi-cyclic loading.

2. Experimental campaign

2.1. Material

Two 11-mm Fe-SMA rebars supplied by re-fer AG were studied, both with a nominal composition of Fe-17Mn-5Si-10Cr-4Ni-1(V, C) (mass%). The S1-Ø11 samples, purchased in 2022, were initially prestrained by the manufacturer to 4%, whereas the S3-Ø11 samples, purchased in 2019, were prestrained between 2% and 4%. Although both samples shared the same nominal composition, they exhibited different transformation temperatures at the zero-stress state. The M_s was 17 °C for S1-Ø11, as reported by Kustov et al. 2024, which can be considered too close to ambient conditions for enhanced Fe-SMA structural applications, and -53 °C for S3-Ø11, a value generally considered adequate for such applications. The austenite start temperature (A_s) was 87 °C for S1-Ø11 and 93 °C for S3-Ø11, while the austenite finish temperature (A_f) was higher for S1-Ø11 (127 °C) than for S3-Ø11 (117 °C). This higher A_f suggests that S1-Ø11 could benefit from higher activation temperatures to achieve greater σ_{rec} , as the reverse transformation from martensite to austenite occurs over a broader temperature range. The mechanical properties of both samples are reported in Mir et al. 2025.

2.2. Recovery-stress generation, cooling and semi-cyclic loading test

The tests were conducted using a Zwick Universal Testing Machine equipped with a 100 kN load cell (Fig. 1a and 1b). First, an initial preload of 60 MPa, in grey in Fig. 2, was applied to prevent compression and potential buckling during heating due to thermal

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expansion. Fig. 3 also includes the initial preload; however, it is not clearly visible due to the superposition of the recovery stress curve. Second, the Fe-SMA rebars were heated to 200 °C using a heat gun under restrained strain to generate σ_{rec} , shown in red in Fig. 2, and cooled to room temperature. Third, the specimen was cooled to approximately -10 °C using a freezer spray (Fig. 1c) and subsequently allowed to return to ambient temperature to evaluate potential reductions in σ_{rec} , represented in blue in Fig. 2, resulting from crossing the M_s temperature under stress. Fourth, starting from the stress level obtained after cooling, five load–unload cycles without sign reversal were applied, with strain increments of 0.1% per cycle up to a total strain of 0.5%, plotted in black in Fig. 3. These loads, referred to as semi-cyclic loading, are known to cause significant stress losses when applied after activation, as reported in Mir et al. 2025.

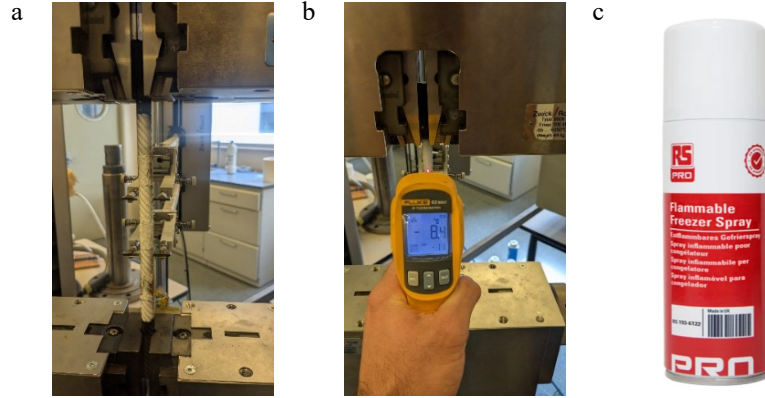


Fig. 1. (a) and (b) Fe-SMA cooling; (c) freezer spray applied.

3. Results and discussion

3.1. Cooling response

The S1-Ø11 and S3-Ø11 samples were activated at 200 °C, achieving mean σ_{rec} values (green dots in Fig. 2) of 364 MPa and 303 MPa, respectively. Upon cooling to a mean temperature of -8 °C, a reduction of approximately 20–25% in σ_{rec} was observed for both samples after the specimens returned to room temperature (cyan dots in Fig. 2).

Cooling with the freezer spray causes the restrained Fe-SMA to contract, leading to an increase in σ_{rec} . However, as the temperature drops below the martensite start temperature under the concomitant stress, part of the austenite transforms into martensite. As the material returns to ambient temperature, thermal expansion reduces stress; however, the newly generated martensite may remain, preventing going back to the previous stress state. Assuming an M_s of 17 °C at the zero-stress state for the S1-Ø11 sample, the slope of the M_s curve can be cautiously estimated to be approximately 5.5 MPa/°C. In contrast, for S3-Ø11 a slope of about 1.5 MPa/°C was estimated, which is consistent with the value of 1.15 MPa/°C reported by Mir et al. (2025) for a 16-mm Fe-SMA rebar and with other studies reporting M_s slopes in the range of 1–2 MPa/°C (Lee et al. 2013).

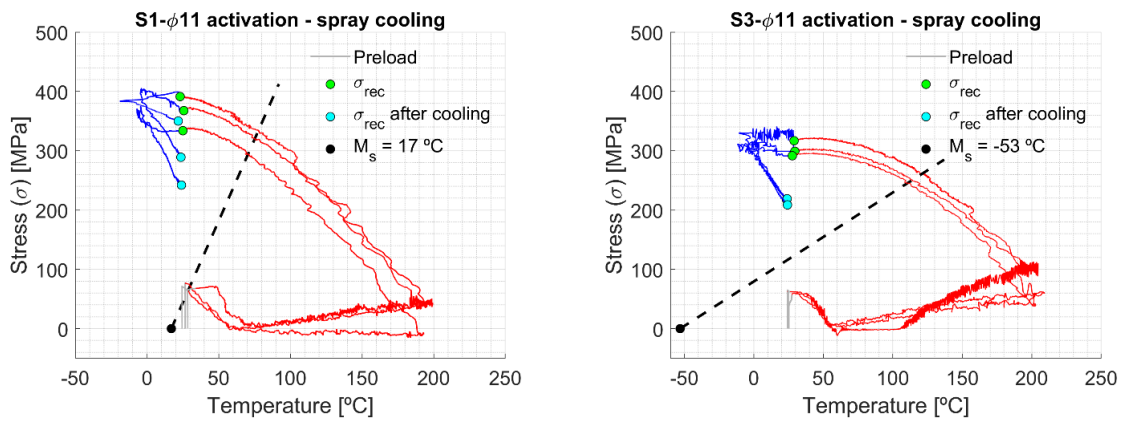


Fig.2. Activation of S1-Ø11 and S3-Ø11 Fe-SMA samples followed by cooling to low temperatures.

3.2. Semi-cyclic loading response

Both S1-Ø11 and S3-Ø11 exhibited complete stress loss after the full semi-cyclic loading sequence (Fig. 3). However, for small strain increments (0.1%), the stress loss was substantially lower than those reported for specimens without prior Fe-SMA cooling: mean stress losses of 14% and 11% were obtained for S1-Ø11 and S3-Ø11, respectively, compared to previously reported results

by Mir et al. (2025) that showed mean stress losses of 29% for S1-Ø11 and 40% for S3-Ø11 for the same 0.1% strain increment. Although complete stress losses due to semi-cyclic loading were not prevented, the stress reductions induced by cooling did not accelerate subsequent losses associated with semi-cyclic loading, reported by Mir et al. (2025).

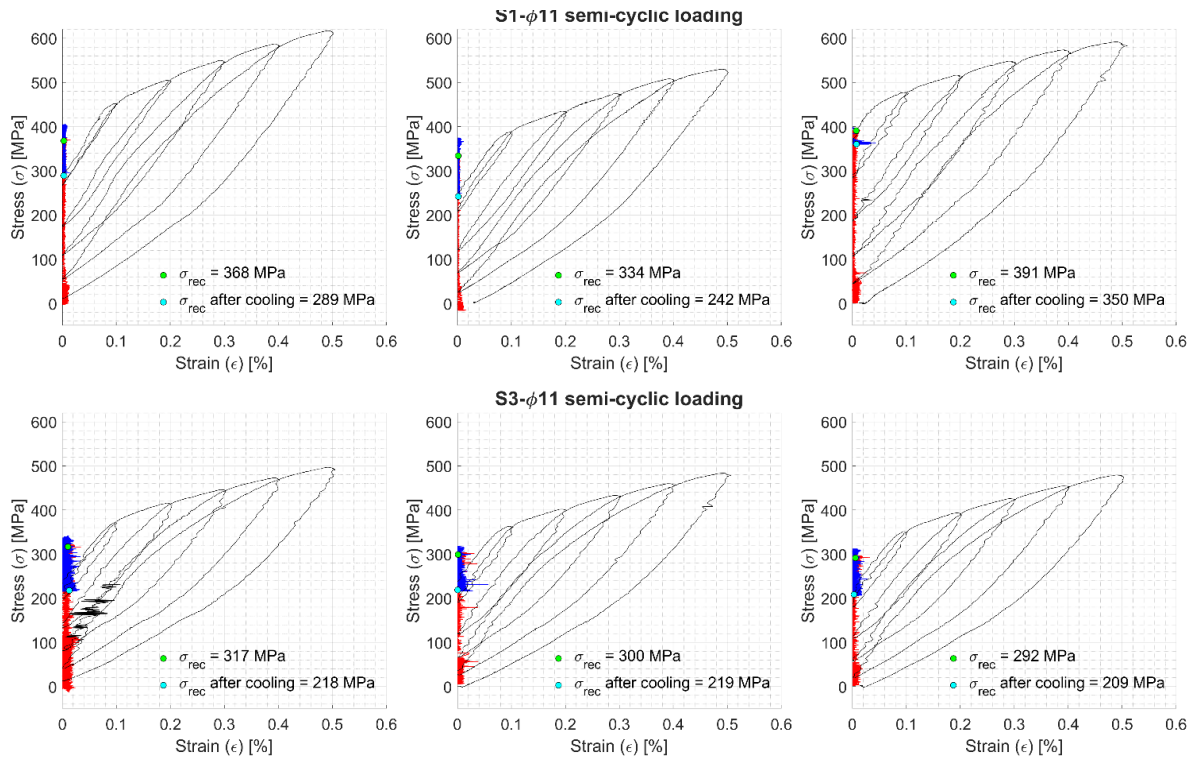


Fig. 3. Semi-cyclic loading test after Fe-SMA activation and cooling.

4. Conclusions

An experimental campaign was conducted to evaluate potential stress losses in 11-mm Fe-SMA rebars subjected to cooling to negative temperatures ($\approx -10\text{ }^{\circ}\text{C}$) after activation, to assess the influence of a M_s close to ambient conditions. The results showed that cooling led to stress losses of approximately 20–25% in both Fe-SMA samples, suggesting that prestress reductions may occur in Fe-SMA reinforced concrete (RC) elements under service conditions when certain low-temperature thresholds are reached. Notably, such stress reductions were observed even for the S3-Ø11 sample, which exhibits an M_s of $-53\text{ }^{\circ}\text{C}$ and is generally considered adequate for Fe-SMA structural applications. However, despite this stress reduction, the cooling-induced losses did not accelerate those associated with semi-cyclic loading, as complete loss of recovery stress at a strain level of 0.5% has also been reported in previous studies without prior Fe-SMA cooling. Further research is required to determine whether these stress reductions significantly affect the behavior of Fe-SMA RC elements.

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Flexural rehabilitation of damaged RC balconies using Fe-SMA bars

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Abstract

Carbon fiber-reinforced polymer (CFRP) bar systems installed using hybrid near-surface-mounted (NSM) and embedded through-section (ETS) techniques have proven effective in enhancing the stiffness and load-carrying capacity of reinforced concrete (RC) balconies under flexural loading. However, these systems function passively and cannot self-induce prestress, unlike iron-based shape-memory alloy (Fe-SMA) bars. This study investigated the feasibility of rehabilitating full-scale, previously tested, and damaged RC balconies using ribbed Fe-SMA bars installed in a hybrid NSM–ETS configuration. Upon thermal activation, the Fe-SMA bars generated recovery stresses that introduced a self-prestressing effect, leading to reduced crack opening, decreased residual deformation, and improved post-cracking stiffness. The bars were anchored using a cementitious grout with adequate thermal resistance to ensure compatibility during activation and effective stress transfer. The experimental results indicate that the Fe-SMA strengthening system enhances the post-cracking stiffness, increases the load-carrying capacity, and provides a more stable post-peak response compared with the previously failed CFRP system, demonstrating the potential of Fe-SMA as a promising approach for the rehabilitation of damaged RC structures.

Keywords: Fe-SMA; RC balconies; hybrid ETS–NSM strengthening; flexural strengthening; self-prestressing; smart materials

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Shear strengthening mechanism and analytical model for Fe-SMA-retrofitted masonry walls

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Abstract

Conventional bed-joint strengthening techniques can improve the shear performance of masonry walls; however, their effectiveness is often limited by delayed stress transfer and the passive nature of the reinforcement. To overcome these limitations, this paper proposes a bed-joint strengthening approach based on the self-prestressing effect of iron-based shape memory alloy (Fe-SMA) wires embedded in horizontal joints. The shear strengthening mechanism is examined by tracing the load-transfer paths within the wall and clarifying the development and contribution of prestress induced by Fe-SMA activation. On this basis, a simplified analytical model is established, in which the effects of prestress level and strengthening configuration are explicitly incorporated. The proposed framework aims to provide a rational interpretation of the shear resistance enhancement achieved by Fe-SMA-based strengthening. Representative diagonal compression tests on masonry walls are employed to assess the validity of the analytical model. The results indicate that Fe-SMA self-prestressing bed-joint strengthening can effectively increase the shear capacity and energy dissipation of masonry walls, while the analytical predictions are able to reasonably capture the influence of prestress level on shear behavior. The study offers useful insights for the engineering application and preliminary design of Fe-SMA-based shear strengthening schemes for masonry structures.

Keywords: Fe-SMA; masonry wall; shear strengthening; self-prestressing; analytical model

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Electromagnetic quality assessment of fiber orientation in cement-based composites

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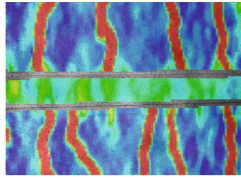
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Abstract

This research presents a non-destructive method for detecting the orientation and content of fibers in real structural elements made of cement-based composites with ferromagnetic fibers. The study focuses on the use of the quality factor (Q) measurement to determine fiber orientation and distribution without damaging the examined element. The method is based on measuring the quality factor (Q) of an electrical coil, whose electromagnetic response changes depending on the amount and preferential orientation of nearby steel fibers. The measurement principle is comparative rather than absolute, and the interpretation of Q-values depends on the geometry of the measured element, fiber content, and measuring configuration. Under controlled measuring conditions, variations in Q-values can therefore be used to evaluate either local fiber volume concentration or preferential fiber orientation. Spatial variations of Q-values within an element indicate differences in local fiber concentration and distribution, while directional measurements performed in multiple axes provide information about preferential fiber orientation. The method was verified on beam-like elements and thin-walled slabs produced under realistic prefabrication conditions. It can easily identify issues such as fiber settlement in thin-walled components and confirm targeted fiber alignment achieved during manufacturing. The results confirm that electromagnetic measurements accurately detect variations in fiber content, orientation, and possible material defects in large concrete elements, showing strong correlation with destructive testing.

Keywords: UHPFRC; inductive method; non-destructive measurement; fibers

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Distribution patterns of surface tensile strength in low-strength concrete slabs

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Keywords: Low-strength concrete; surface tensile strength; strengthening; basic evaluation; Zechenhaus Brieske

1. Introduction

Reinforced concrete components dating from before 1943 often have very low and highly variable material properties (Weber & Thiele 2016). Surface tensile strength is a key design parameter for planning strengthening measures, especially for systems based on adhesive bonding (DAfStb 2012, Finckh 2024). Particularly in the case of low-strength concrete components, concrete classification according to (TR-IH 2020) depends on the typically low surface tensile strength. The following practical example illustrates the distribution of surface tensile strength across two low-strength reinforced concrete slabs and examines the correlation between the measured concrete compressive and splitting tensile strengths and the surface tensile strength.

The investigations were carried out at the Zechenhaus Brieske (Germany), which was constructed between 1911 and 1913. All slabs were constructed using reinforced concrete in accordance with the Prussian regulations of 1907 that were in force at the time. In an initial investigation program, large sections of the slabs were classified as old concrete class A1 according to (TR-IH 2020) due to insufficient surface tensile strength. In Germany, old concrete class A1 means that repairs are not regulated by standards. In practice, the reconstruction of these components is a common consequence.

In cooperation with the district of Oberspreewald-Lausitz (Germany) and the engineering firm KREBS+KIEFER Dresden, two slabs were then examined in detail by the University of Applied Sciences (HTW) in Dresden, Germany.

2. Determination of the measurement fields

The surface tensile strength of the two A1-classified reinforced concrete slabs was examined with a measurement grid of $30 \times 30 \text{ cm}^2$ on the upper and lower sides, resulting in four measurement fields (see Table 1). Accompanying core samples were taken to determine the concrete compressive strength and splitting tensile strength ($l/d = 75/75 \text{ mm}$). The concrete was carbonated to a depth of approximately 20–40 mm. The varying number of measurement points is due to the geometry of the measurement fields and their accessibility.

Table 1. Examination matrix for measurement fields.

Measurement field	Slab panel 1		Slab panel 2	
	1.1 (top)	1.2 (bottom)	2.1 (top)	2.2 (bottom)
Slab geometry	$2,5 \times 6,8 \times 0,09 \text{ m}^3$		$15,0 \times 4,8 \times 0,09 \text{ m}^3$	
Number of surface tensile strength tests	12	129	114	10
(Area in $\text{m} \times \text{m}$)	($0,9 \times 1,2$)	($1,8 \times 5,7$)	($4,8 \times 1,8$)	(distributed)
Number of core samples (compressive strength)		4		5
Number of core samples (splitting tensile strength)		9		9

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3. Determination of concrete strengths

3.1. Concrete compressive strength

The compressive strength in the slabs was determined by direct sampling in accordance with DIN EN 13791:2020 and amendment A20:2022. Due to the low slab thickness of approximately 9 cm and the maximum grain size of 16 mm, core samples with a diameter of 75 mm were taken using the wet drilling method. In summary, a characteristic concrete compressive strength of $f_{ck, is, cyl, 1} = 16,8 \text{ N/mm}^2$ ($v_{fc, 1} = 0,15$) was determined for slab 1 and $f_{ck, is, cyl, 2} = 20,5 \text{ N/mm}^2$ ($v_{fc, 2} = 0,10$) for slab 2.

3.2. Splitting tensile strength

Because the compressive and tensile strengths in historic concrete components often do not correlate according to the ratio described in DIN EN 1992-1-1 (Thiele and Weber 2019), the axial tensile strength was also derived from the splitting tensile strength. The core samples were taken as described in 3.1. In summary, a characteristic splitting tensile strength of $f_{ctk, sp, 1} = 1,60 \text{ N/mm}^2$ ($v_{fct, sp, 1} = 0,19$) was determined for slab 1 and $f_{ctk, sp, 2} = 2,00 \text{ N/mm}^2$ ($v_{fct, sp, 2} = 0,10$) for slab 2.

3.3. Surface tensile strength

The surface tensile strength was determined in accordance with DIN EN 1542:1999 and with reference to further information in DAfStb booklet 638 and (Momber and Schulz 2006). Using a measurement grid of $30 \times 30 \text{ cm}^2$, the measuring points were ground to a depth of approximately 3–4 mm and provided with a ring groove approximately 5–10 mm deep. This was produced using a dry drilling method. Contrary to some expert opinions, our own comparative studies of wet and dry drilling on low-strength concrete slabs showed no lower results for dry-drilled ring grooves. The stamp ($d = 50 \text{ mm}$) was glued on with a fast-reacting polyurethane-based adhesive and fixed to the underside of the slab with masonry anchors. After the adhesive had hardened, the measurement was carried out using the DY-206 device from Proceq at a tensile speed of 98 N/s. The results are summarized in Table 2. To ensure comparability of the results, the characteristic surface tensile strength $f_{ctk, surf}$ was derived according to DIN EN 1990 based on a statistical evaluation assuming an unknown coefficient of variation of the population v_x . The failure occurred almost entirely in the concrete (cylinder stump).

Table 2. Surface tensile strengths in measurement fields.

	Slab 1		Slab 2	
Measurement field	1.1 (top)	1.2 (bottom)	2.1 (top)	2.2 (bottom)
Mean value $[\text{N/mm}^2]$	1,61	1,08	1,38	1,32
Standard deviation $s_{x, fct, surf} [\text{N/mm}^2]$	0,40	0,49	0,48	0,49
Coefficient of variation $v_{fct, surf} [-]$	0,25	0,45	0,35	0,37
Characteristic surface tensile strength $f_{ctk(surf)} [\text{N/mm}^2]$	0,83	0,28	0,59	0,38

4. Evaluation of the results

4.1. Correlation of concrete strengths

The characteristic axial tensile strength f_{ctk} can be determined using empirical correlations from the compressive and splitting tensile strength in accordance with DIN EN 1992-1-1. These correlations are based on (Heilmann et al. 1969) and (Rüsch 1975) and were determined for normal-strength concrete aged 28 days. The axial tensile strength in the concrete edge zone can be derived from the surface tensile strength according to (Finckh 2024) using the coefficient k_{surf} depending on the direction of concreting. The comparisons of the respective derived characteristic concrete tensile strengths are summarized in Table 3.

Table 3. Calculated concrete tensile strengths.

	Slab 1		Slab 2	
measurement field	1.1 (top)	1.2 (bottom)	2.1 (top)	2.2 (bottom)
Char. axial tensile strengths $f_{ctk(cyl)}$ from compressive strength $[\text{N/mm}^2]$		1,38		1,57
Char. axial tensile strengths $f_{ctk(sp)}$ from splitting tensile strengths $[\text{N/mm}^2]$		1,60		2,00
Char. axial tensile strengths $f_{ctk(surf)}$ from surface tensile strengths $[\text{N/mm}^2]$	0,82	0,28	0,59	0,38
Comparison of $f_{ctk(cyl)}$ to $f_{ctk(surf)}$ [%]	167	491	266	413
Comparison of $f_{ctk(sp)}$ to $f_{ctk(surf)}$ [%]	193	569	339	527

Table 3 clearly shows that the derived char. tensile strength $f_{ctk(cyl)}$ is about 13–22 % lower than that derived from $f_{ctk(sp)}$. However, the comparison of $f_{ctk(surf)}$ with $f_{ctk(cyl)}$ and $f_{ctk(sp)}$ is particularly noticeable. The char. tensile strengths determined in the concrete edge

zone of the slabs are 2–6 times lower than the results derived from the compressive and splitting tensile strength according to the standard. The main reason for this is the significant statistical reduction of $f_{ctk(surf)}$ due to the very high scatter.

4.2. Distribution of surface strengths

Heatmaps were produced to visualize the distribution of the measured values of the surface tensile strength (see Fig. 1 for measurement field 2.1 exemplarily). For reasons of clarity, only every third measurement point is shown. Intermediate values were interpolated. The results show a significant scatter with a tendency toward clustered and distinct distributions of lower and higher strength areas.

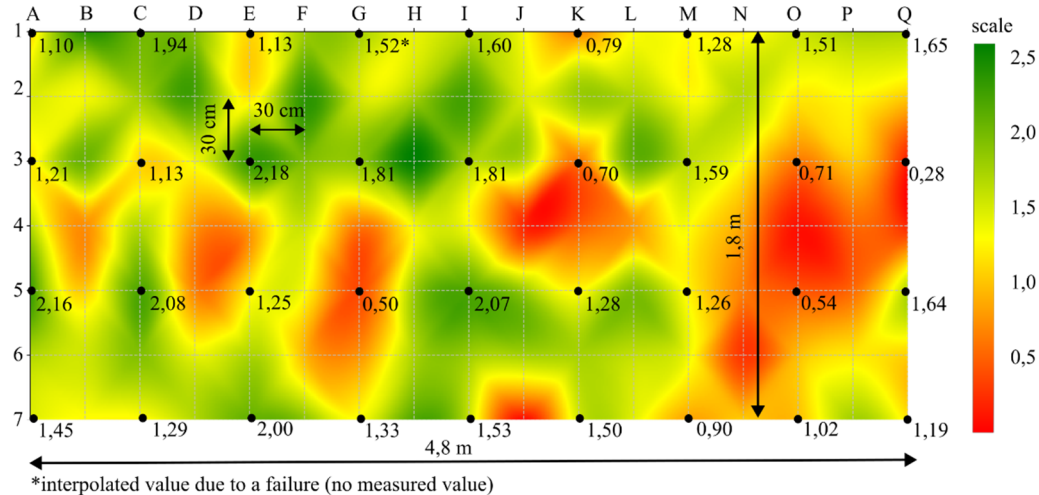


Fig. 1. Heat map of the surface tensile strengths in N/mm²: measurement field 2.1.

5. Recommendations and conclusion

The variation in surface tensile strength across low-strength slabs can be significant. However, measurements taken at points directly next to each other rarely differ substantially at 30 cm, meaning that a larger grid size, e.g., $50 \times 50 \text{ cm}^2$, appears sufficient for a detailed assessment. Areas that stand out should be examined in greater detail. For bonded joints, structurally relevant areas should be identified in advance in order to limit the extent of the required measurement areas. In the case of strengthening of single-span beams, the support regions are of primary interest. For continuous systems, the relevant measurement areas shift towards the midspan.

Intensive investigations of the two slab panels in the Zechehaus Brieske showed that a normative correlation between concrete compressive strength and concrete splitting strength via the axial tensile strength to the surface tensile strength cannot be assumed and can lead to overestimations. Further details on the investigations presented here are published in (Berger et al. 2026).

For further investigations, additional existing low-strength slabs in Forst (Lausitz, Germany), Berlin, and low-strength slab specimens reproduced at HTW Dresden were examined. The results are presently under evaluation and will later be compared with the findings presented in this study.

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The role of bond, friction and hook-bearing on anchor pull-out in low-strength concrete: experiments and design implications

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Abstract

This study presents a comprehensive experimental program to evaluate the behavior of unheaded straight and bent-bar anchors with J-hook details, which were embedded in 15 MPa concrete representative of existing industrial pedestals. The program is structured to isolate resistance of bent part of the anchor, quantify the contribution of surface friction, examine the limits of bond mobilization, and evaluate mechanisms under controlled boundary conditions. The results demonstrate bearing of bent part of the anchor and surface friction provide measurable contributions to pullout resistance, and that current pullout predictions are conservative for the investigated conditions. The findings establish a rational basis for reassessing anchor performance in low-strength industrial concrete and support refinement of evaluation methodologies without compromising safety.

Keywords: Anchorage; bearing; bond; friction; pull-out

* The full paper is open access available in the Conference Proceedings. *

Experimental study on the creep behavior of old, preloaded concrete

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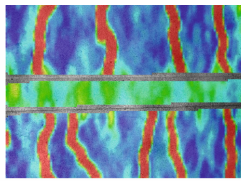
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Abstract

When existing concrete structures no longer meet current or future service requirements, engineers should resort to conversion or strengthening. Such interventions often introduce additional loads, thereby generating additional compressive stresses in the aged concrete. Each new stress induces additional creep deformations, which must be considered to predict prestressing losses, deflections, redistribution of internal forces, and other deformation-related effects. Current normative creep-prediction models—e.g., the Model Code 2020—are based on tests performed on relatively young, previously unloaded concrete. Consequently, their applicability to existing structures that have been subjected to sustained loads for decades remains uncertain. To address this knowledge gap, creep tests were carried out on unsealed drill core specimens extracted from three dismantled prestressed-concrete bridges, both in the longitudinal and transverse directions to the preload. The cores, aged 43–57 years, were loaded to sustained stresses corresponding to 35 %–50 % of their current compressive strength for periods ranging from 90 to 182 days. Despite their high age and the preload, the specimens exhibited pronounced creep. After 90 days, the measured creep coefficients ranged from $\varphi_{90d} \approx 0.3$ to 0.6, and the observed creep strains were up to 146% higher than the values predicted by the Model Code 2020 creep model. Therefore, the model is deemed insufficient for predicting the behavior of highly aged, previously loaded concrete.

Keywords: Creep tests; prediction models; prestressed concrete; concrete; existing structures

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Smart sensing of restrained shrinkage in UHPC overlays using DFOS

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Abstract

Ultra-high performance concrete (UHPC) overlays are used to strengthen and extend the service life of bridge decks. Restrained shrinkage in such bonded overlays can induce internal stresses, leading to surface cracking and interface debonding. Although the transition from normal concrete (NC) to UHPC overlays has mitigated several performance issues in repaired systems, the development of restrained shrinkage in UHPC-NC composites remains insufficiently understood.

To address this gap, the present study investigates the evolution of restrained shrinkage in UHPC-NC composites and the associated potential failure modes. Composite specimens measuring $180 \times 75 \times 15 \text{ cm}^3$ were fabricated and instrumented with distributed fiber optic sensors (DFOS) featuring a novel embedment layout to capture time-dependent deformations within the bonded UHPC overlays. The experimental program systematically examined the influence of key overlay parameters. The collected data provided firsthand information on the magnitude and spatial distribution of restrained shrinkage in the UHPC-NC composites over time. By characterizing the restrained shrinkage through advanced methods, the findings of this study are expected to provide deeper insight into the performance of UHPC overlays.

Keywords: Ultra-high performance concrete; restrained shrinkage; distributed fiber optic sensing; retrofitting, overlay

1. Introduction

Ultra-high performance concrete (UHPC) is characterized by a very low water-to-binder ratio (0.15-0.25), high particle packing density, and fiber reinforcement, resulting in exceptional mechanical strength, durability, and near-impermeability compared to normal concrete (Graybeal (2006), Fehling et al. (2015)). These properties make UHPC particularly suitable for thin bonded overlays used to strengthen and protect infrastructure such as bridges and pavements, enhancing structural capacity and service life while offering potential sustainability benefits through optimized mix design (Denarié and Brühwiler (2006)). However, UHPC is prone to significant autogenous shrinkage due to rapid self-desiccation during hydration, especially within the first month, which can induce tensile stresses, cracking, and interface debonding in restrained systems like bonded overlays (Wu et al. (2017)). Characterizing this time-dependent behavior is challenging, as conventional measurement techniques often lack the spatial resolution and continuity required for thin UHPC overlays. Distributed fiber optic sensing (DFOS) is a promising technology for monitoring large-scale composite systems (Villalba and Casas (2013)). To address existing research gaps, this study employed DFOS as an advanced monitoring technique to capture high-resolution, continuous strain data in UHPC overlays, a domain where its application has been limited. A comprehensive experimental campaign was performed to investigate the impacts of UHPC properties on restrained shrinkage behavior and associated failure mechanisms.

2. Methodology

To investigate the effects of overlay characteristics, three non-proprietary UHPC mixtures were developed. The first mixture serves as a reference UHPC without fibers. The second is a fiber-reinforced UHPC (UHPC-F) incorporating hybrid steel and PVA fibers. The third is a fiber-reinforced recycled UHPC (UHPC-FR), which includes hybrid steel-PVA fibers and 30% cement

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replacement with a recycled cementitious binder. To achieve a comprehensive spatial characterization of strain within UHPC overlays, a distributed fiber optic sensing (DFOS) layout was developed, consisting of seven transverse (T1-T7) and three longitudinal (L1-L3) sensing sections arranged in continuous fiber paths. All transverse sections were positioned at mid-depth (2.5 cm below the surface) with 30 cm spacing, while longitudinal sections included one near the edge at shallow depth (1 cm) and two along the centerline at shallow (1 cm) and deeper (4 cm) levels. This configuration enabled detailed monitoring of both in-plane and through-thickness strain variations. Using this layout, a continuous optical fiber with a length of 18.5 m was prepared and spliced for each composite slab. For installation, the optical fiber was passed through side holes of the overlay formwork, anchored, and eventually pre-stressed (through hand tightening).

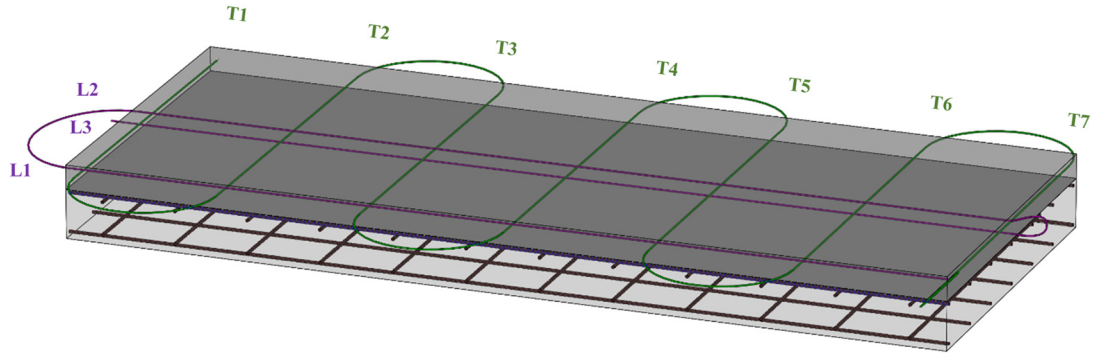


Fig. 1. 3D schematic of the optical fiber layout embedded in UHPC overlay. The normal concrete (NC) substrate is 10 cm thick reinforced with double-layer steel mesh (6mm bars) with 20 cm spacing.

3. Results

The strain development was monitored and analyzed over a period of six months, starting from the time of casting. Figure 2 exemplarily show the strain history inside the UHPC overlay. Given the layout presented in Figure 1, the position of measurement points along the optical fiber and their corresponding strain data were categorized into embedded transverse (green) and longitudinal (purple). The external sections included the loops designed to maintain the continuity of the optical fibers, and were not included in the analysis. The strain was expressed as negative or positive, capturing compression or tension, respectively, in reference to zero reading. The negative strains indicate shrinkage inside the UHPC overlay, while positive strains, which typically emerged as sharp and localized peaks, correspond to cracks formed inside the overlay. Comparing the strain profile patterns in all selected sections, an uneven distribution strain in the form of a camel hump is noticeable for most sections. Specifically, the absolute value of shrinkage was found lowest in the center part, while it increased toward the edges in each section. This was noted to be consistent with the (relatively) low restraint conditions near the overlay's edges.

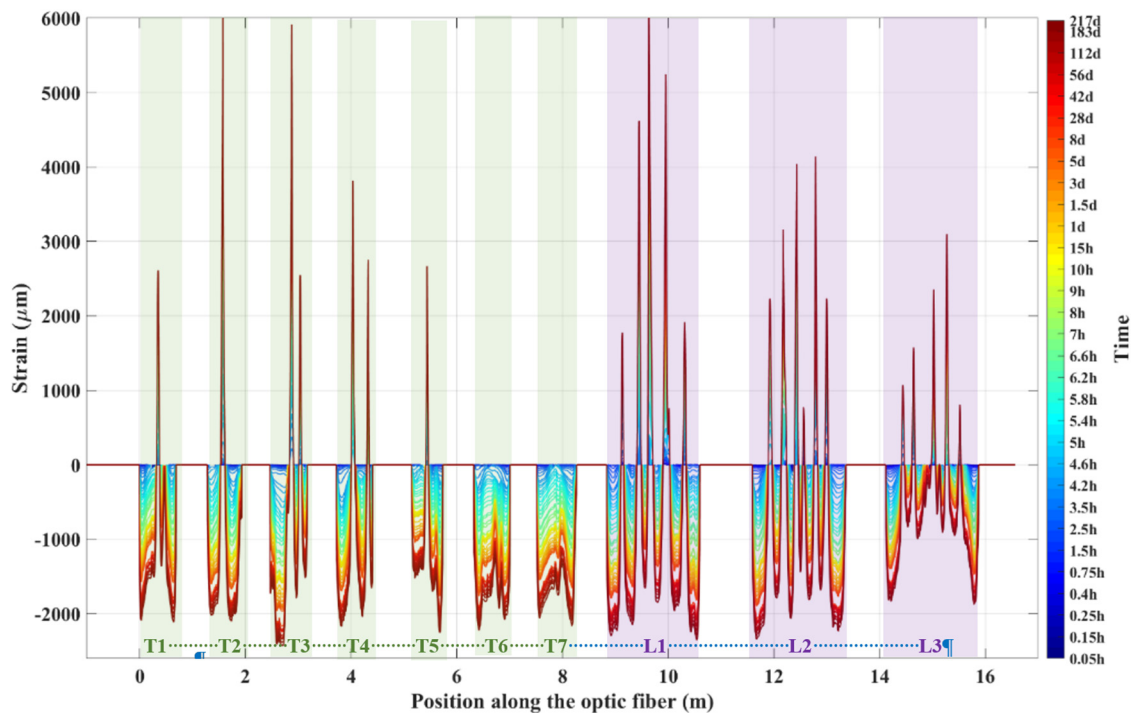


Fig. 2. Example of strain profile developed inside the UHPC overlay

The shrinkage strain values were averaged over sections. Figure 3.(a) presents the evolution of average shrinkage strain in various overlays. After six months, the flat UHPC overlay reached an average shrinkage strain of $-1,716 \mu\epsilon$, while the UHPC-F and UHPC-FR overlays exhibited much lower overall shrinkage, with average shrinkage strain values of -942 and $-869 \mu\epsilon$, respectively. This reduction is attributed to the effective internal restraint provided by the fibers, which enhances resistance to deformation and promote internal pore connectivity through their bridging effect. The average shrinkage was found to decrease by 8% upon replacing the OPC with the developed recycled binder in UHPC-FR. The reduced shrinkage in the UHPC-FR overlays can be due to the internal curing effect as such recycled cementitious materials absorb free water during mixing and subsequently release it to alleviate the self-desiccation effect caused by cement hydration. Additionally, the lower shrinkage observed in UHPC-FR overlays results from the reduced cement content, which decreases and delays the hydration process. Given the average shrinkage in selected sections (Figure 3.(b)), no significant differences were observed among the longitudinal as well as the transverse sections embedded at the same depth, indicating a seemingly uniform stain development between the cross-sectional points in these directions.

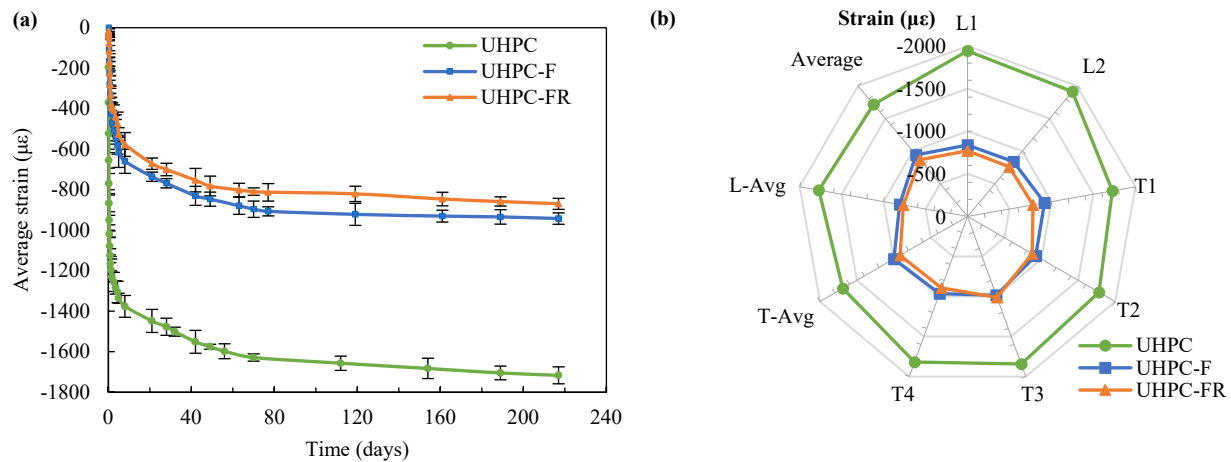


Fig. 3. (a) Comparison of the evolution of average shrinkage strain in overlays. The error bars represent standard deviation. (b) The average shrinkage strain across selected sections after six months. The terms T-avg, L-avg, and Average refer to the mean values of shrinkage across transverse, longitudinal, and all sections.

4. Conclusion

This study leveraged the capabilities of distributed fiber optic sensing (DFOS) technology in the UHPC-NC investigation domain. By implementing a novel sensor embedment layout, the results provide both qualitative and quantitative insights into the time-dependent response, strain distribution, and cracking potential of the UHPC overlay. The findings demonstrate that the UHPC composition significantly influences overall performance, highlighting the necessity of an appropriately designed mix to ensure the long-term durability of UHPC overlays. This advanced characterization approach enabled a comprehensive assessment of the magnitude and spatial distribution of restrained shrinkage, as well as the associated risk of crack formation in UHPC-NC composites over time. By addressing the challenges related to controlling the overlay's time-dependent properties, this study contributes to advancing the knowledge and application of thin-bonded UHPC overlays, contributing to the proper use of this emerging overlay choice.

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Higher-order multivariate environmental influences in structural health monitoring

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Abstract

System outputs such as eigenfrequencies or strain data, often used in structural health monitoring (SHM), not only react to damage but also depend on environmental conditions. When trying to correct for these confounding effects, it is often (at least implicitly) assumed that only the expected, i.e., mean, output values are affected by environmental conditions. However, the evaluation of real-world SHM data indicates that environmental conditions may influence not only the mean output but also higher-order statistical moments, particularly the variances of and the covariances and correlations between the output quantities, such as eigenfrequencies of different modes or strain sensors at different locations. To address these issues, we discuss two approaches for identifying and quantifying multivariate confounding effects on output covariances and correlations: a random forest (RF) and a nonparametric, kernel-based approach. We compare the two competing methods on both artificial and real-world SHM data, finding that the kernel-based approach achieves higher accuracy, but the RF produces estimates that are more robust and sometimes easier to interpret.

Keywords: Conditional covariance; machine learning; nonparametric statistics; random forest; temperature removal

* The full paper is open access available in the Conference Proceedings. *

Seismic retrofit of RC structures using hybrid SMA-stainless steel jackets

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Abstract

A widely used strengthening technique for existing Reinforced Concrete (RC) structures is jacketing with conventional steel reinforcement embedded. This study presents a numerical investigation of the performance of an existing RC structure with shear-deficient beams using externally applied jackets employing superelastic Shape Memory Alloys (SMAs) and Stainless Steel (SS) as reinforcement instead of conventional steel. SMAs are known for the superelastic effect they exhibit and their self-centering capability, while SS provides high strength, ductility, durability and corrosion resistance. To evaluate the influence of jacket configuration and material behavior, non-linear analyses (pushover and dynamic time-history) were conducted under significant earthquakes that have occurred in Greece. Results demonstrate that the proposed hybrid jackets significantly improve the seismic performance and deformation capacity of the structure. This numerical study highlights the potential of SMA-SS composite jackets as an effective and innovative retrofit scheme for enhancing the seismic resilience of existing RC structures, offering a promising solution for sustainable, durable, and resilient retrofit strategies.

Keywords: Seismic retrofit; shape memory alloys; stainless steel; reinforced concrete structures

* The full paper is open access available in the Conference Proceedings. *

Self-centering SE-SMA core BRBs for seismic resilience

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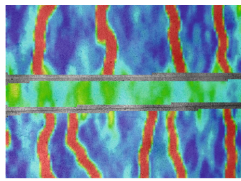
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Abstract

Older reinforced-concrete frames often require seismic retrofit to improve performance and support rapid re-occupancy. This study reports bare-brace experimental testing of a buckling-restrained brace (BRB) that replaces the typical steel core with a superelastic shape-memory-alloy (SE-SMA) core, adding self-centering while maintaining lateral strength. The proposed BRB also provides full-length core restraint and end elements that accommodate smooth cores, minimizing machining of SE-SMA bars. To enable objective comparisons, three core materials (SE-SMA, stainless steel, and low-carbon steel) were tested under identical displacement-controlled cyclic loading referencing AISC 341-22 BRB qualification. This study quantifies force–displacement hysteresis response, tension–compression strength symmetry, and residual displacement. Results illustrate that the SE-SMA core produced stable, flag-shaped hysteresis with minimal residual displacements, while steel-core braces exhibited stable, symmetric loops but accumulated considerable residual displacements. The core restraint and unbonded layer prevented local buckling in all BRB braces. To relate the test results to resilience, the residual displacements were mapped to re-occupancy thresholds. Findings indicate SE-SMA-core BRBs preserve lateral capacity and reduce expected downtime by limiting permanent displacement and supporting reliable functional recovery.

Keywords: Self-centering BRBs; superelastic shape-memory alloys (SE-SMA); residual deformation reduction; seismic resilience

* The full paper is open access available in the Conference Proceedings. *



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Effect of masonry infills on seismic retrofitting of existing RC frames with steel exoskeletons

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Keywords: Pushover analysis; nonlinear dynamic analysis; masonry infills; reinforced concrete; steel exoskeletons

1. Introduction

As outlined by the European Environmental Agency (2020), modern government policies are increasingly promoting the reuse of existing buildings, making the seismic retrofitting of RC frames a growing concern for structural engineers. Moreover, since several existing reinforced concrete (RC) frame structures do not comply with current seismic safety standards, structure-level strengthening techniques, e.g. steel exoskeletons (external steel bracing systems), can improve the safety of existing buildings while minimizing disruption to their occupancy and potentially providing integration with systems improving the energy efficiency of the building, as highlighted by Cao et al. (2022) and Nigro et al. (2023).

Accordingly, this paper presents a performance assessment of an archetype Italian RC frame building (ideally located in a high seismic hazard area) retrofitted with steel exoskeletons. Two retrofit configurations were examined, assessing the efficiency of the seismic upgrading interventions with respect to different performance levels: one ensuring structural serviceability and the other preventing collapse. Furthermore, the study focuses on the influence of masonry infill panels on the overall efficiency of the steel bracing system. To this end, nonlinear static (pushover) and incremental dynamic analyses (IDAs) were performed, highlighting the key performance indicators characterizing both the bare and the infilled frame configurations and emphasizing the efficiency of the steel exoskeletons for various intensity levels of ground motion.

2. The archetype structure and the steel exoskeletons

2.1. The archetype RC structure

The case-study building corresponds to the 6-storey residential RC frame widely documented by De Risi et al (2025) for pre-code Italian structures. It features a regular rectangular layout with five bays in the X-direction and three bays in the Y-direction, and storey heights of 3.40 m (ground floor) and 3.05 m (upper floors). The structure was designed according to the Italian code in force at the time of construction.

A nonlinear lumped-plasticity numerical model was developed, adopting zero-length hinges governed by empirical backbone relations calibrated for RC members with plain bars, as outlined by De Risi et al. (2023). Two as-built configurations were analyzed: the bare frame (BF) and the infilled frame (IF), the latter including masonry panels following widely adopted modelling criteria for Italian pre-code buildings, discussed in detail by Di Domenico et al. (2023).

Further details about the existing RC structural models are omitted herein for the sake of brevity, but they have been discussed in detail by De Risi et al. (2023), Di Domenico et al. (2023) and Nigro et al. (2026b).

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2.2. The designed steel exoskeletons

The retrofit layout consists of four external braced towers located at the building corners, each equipped with a single concentric diagonal brace per bay, as outlined in Fig. 1.

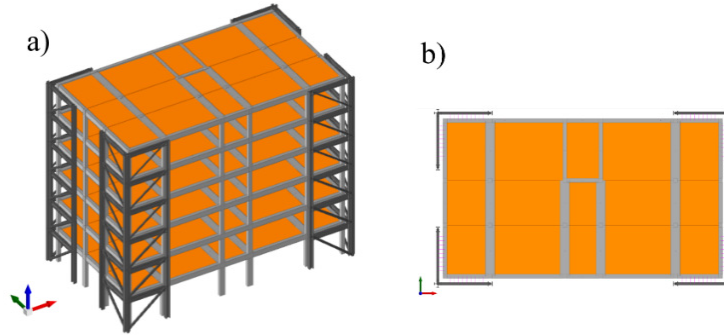


Fig. 1. (a) 3D layout of the structural model; (b) Plan layout of the structural model.

Two retrofit configurations were conceived adopting a force-based design philosophy. In the *Strong Exoskeleton* configuration, the new bracing system is assumed to resist the entire seismic base shear of the upgraded structure. Conversely, in the *Weak Exoskeleton* configuration, the design base shear is halved to approximate partial force sharing with the existing RC frame.

Further details about the steel exoskeletons and their nonlinear Finite Element models are omitted herein for the sake of brevity, but they have been discussed by Nigro et al. (2026a, 2026b).

3. Nonlinear analyses and discussion of results

3.1. Comparative assessment based on pushover response analysis

The pushover analyses run for the various structural models highlight substantial gains in global stiffness, strength, and displacement capacity for both retrofit configurations, although they are omitted herein due to space constraints.

Fig. 2a and Fig. 2b respectively highlight the ratio between the “safety index” ζ_E of the upgraded structure and the one of the existing structure. As given by the Italian Technical Code (DM 17/01/2018), the index represents the capacity-to-demand ratio in terms of Peak Ground Acceleration (PGA) for Severe Damage Limit State (SD-LS).

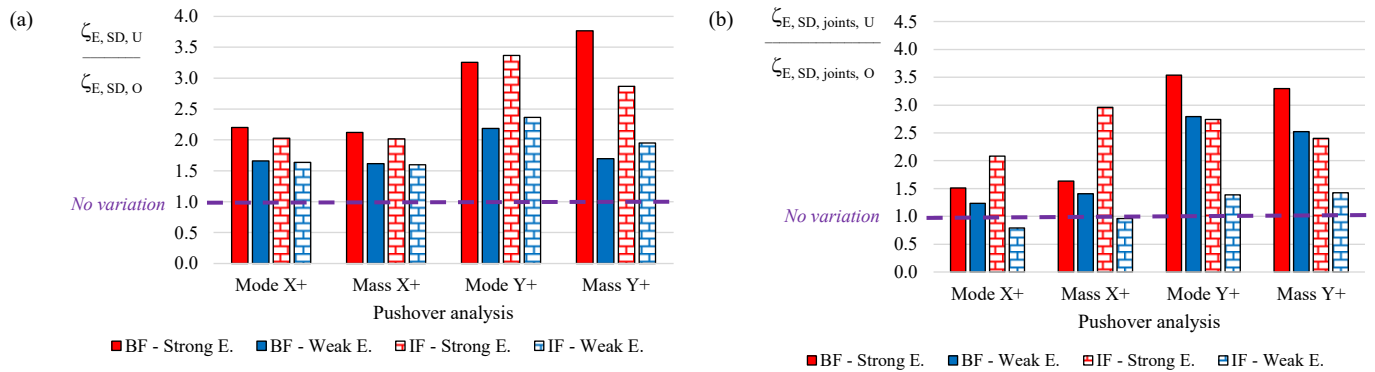


Fig. 2. Ratio of safety indices for the upgraded and original structures: ductile failures at SD-LS (a) and brittle failure of RC joints at SD-LS (b).

More specifically, Fig. 2a focuses on ductile failure mechanisms: the *Strong Exoskeleton* configuration provides a safety index increase of at least 2 for the X direction and 3 for the Y direction (which is the less stiff for the existing structure), whereas the *Weak Exoskeleton* structural model is characterized by safety index increases of 1.5 along X and of 2 along Y.

Conversely, Fig. 2b reports the ratio evaluated for brittle failure of existing beam-column joints: in this circumstance, the exoskeletons improve the joint shear capacities, though to a lower extent than for ductile responses. Indeed, for the *Weak Exoskeleton* -especially in the IF configuration- the gains for shear-critical components remain modest. These findings indicate that, while the retrofit provides substantial improvements in global collapse safety, additional local strengthening may still be necessary to address residual vulnerabilities depending on the lack in seismic detailing of existing RC structures.

A more detailed representation of the performance variation, including the pushover curves has been provided by Nigro et al. (2026a, 2026b).

3.2. Comparative assessment based on dynamic response analysis

Multiple-stripe analyses were carried out using ten intensity stripes, each including 20 bidirectional ground motions scaled with respect to a spectral pseudo-acceleration at $T = 1.0$ s. The assessment was performed considering two performance levels, as done by De Risi et al. (2025) on the BF and IF structural models of the sole existing structure.

The first level, Usability-Preventing Damage (UPD), corresponds to the onset of extensive non-structural damage, assumed to occur when the peak inter-storey drift ratio reaches 0.5%, consistent with Italian provisions for brittle infills. The second level, Global Collapse (GC), reflects a condition of structural instability; for the reference RC building, these drift limits amounted to 2.70% and 2.12% in the X- and Y-directions.

Hence, the failure rate λ_F was evaluated according to a well-established methodology provided by Baraschino et al. (2020). Table 1 shows that steel exoskeletons can prevent premature infill degradation, as the *IF - Weak Exoskeleton* exhibits a UPD-level failure rate almost equal to the one observed for the *Strong Exoskeleton* structural models. Moreover, at the GC level, the retrofit effectiveness is so pronounced that no meaningful failure rate can be computed for all the upgraded structures.

Further details about the outcomes of the Multiple-Stripe Analyses have been provided by Nigro et al. (2026b).

Table 1. Failure rates of the considered structural models.

Structural model	λ_F for usability preventing damage	λ_F for global collapse
BF - Existing	$7.7 \cdot 10^{-3}$	$8.7 \cdot 10^{-4}$
BF - <i>Strong Exoskeleton</i>	$2.2 \cdot 10^{-6}$	-
BF - <i>Weak Exoskeleton</i>	$1.7 \cdot 10^{-4}$	-
IF - Existing	$5.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$
IF - <i>Strong Exoskeleton</i>	$2.2 \cdot 10^{-6}$	-
IF - <i>Weak Exoskeleton</i>	$3.8 \cdot 10^{-5}$	-

4. Concluding remarks

This study examined key aspects related to the seismic upgrading of existing RC frame structures through steel exoskeletons, with particular focus on the role of infill walls. Two force-based retrofit strategies - *Strong* and *Weak Exoskeletons* - were assessed. The results show that steel exoskeletons generally eliminate ductile failure modes and markedly reduce brittle failure modes, although some local strengthening may still be required, even with the *Strong Exoskeleton*.

Dynamic analyses indicated that the exoskeletons substantially mitigate damage to the masonry infill walls, significantly lowering the likelihood of damage occurrence. The influence of infill panels was proved to be negligible for the *Strong Exoskeleton* cases, while some interaction effects emerged for the *Weak* configuration.

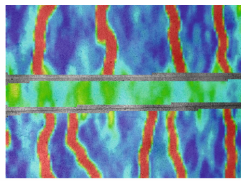
Overall, the exoskeletons greatly enhanced global collapse performance, eliminating collapse occurrences even for the weaker solution at high seismic intensities, although further studies on buildings with more irregular infill distributions are recommended to extend these conclusions.

Acknowledgements

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Optimal design of retrofit interventions for existing RC frames through genetic algorithm

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Keywords: Seismic retrofit; reinforced concrete structures; genetic algorithm; multi-objective optimization; life cycle assessment

1. Introduction

The seismic retrofit of existing reinforced concrete (RC) buildings is supposed to induce lower economic and environmental impacts than the total replacement of the construction, as demonstrated by Alba-Rodríguez et al. (2017).

However, selecting an efficient retrofit strategy usually results to be a complex task due to the wide range of available strengthening techniques, each associated with specific performance, cost, and environmental implications. Hence, this problem is usually solved through traditional trial-and-error approaches that are usually inefficient and based on subjective judgement, rather than on objective criteria, which, as shown by Falcone et al. (2020) and by Lima et al. (2023), can lead to the choice of more effective solutions.

To address these limitations, this study employs a Genetic Algorithm (GA) based optimisation framework capable of systematically exploring large design spaces and identifying retrofit configurations that satisfy seismic performance requirements while minimising economic or environmental impact. The methodology, discussed by Nigro and Martinelli (2023, 2024) combines local (member-level) and global (structure-level) interventions, as defined by the *fib* bulletin 24 (Fardis et al., 2003), within a unified computational approach, enabling a balanced assessment of alternative strategies and their synergistic effects.

Overall, the proposed GA-assisted procedure provides a rational, transparent, and reproducible tool for performance-based seismic retrofit design, supporting practitioners (in the early stage of intervention design) in selecting interventions that efficiently enhance safety while optimising resource use.

2. Definition of the constrained optimisation problem

2.1. Intervention encoding

As reported by Nigro and Martinelli (2023, 2024), each candidate retrofit configuration is represented by an “individual” in the GA population.

Coherently with the Genetic Algorithm syntax, the “individual” consists of a set of design variables describing local interventions (number of FRP layers for confinement of column end regions) and global interventions (indicating the type and location of steel CHS braces, installed within perimeter bays).

The Finite Element model of the structure incorporates FRP confined columns, following the *fib* bulletin 35 provisions (Balázs et al., 2006), jacketing of columns adjacent to braces, and nonlinear force-based elements with distributed plasticity. Brace buckling is captured through initial geometric imperfections consistent with Eurocode 3 recommendations (EN 1993-1-1, 2005).

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2.2. Objective functions

The considered objective function (to be minimised) is evaluated according to Equation 1, as the sum of the cost of local and global (C_{loc} and C_{glob}) interventions are summed to the cost of potential foundation upgrading (C_{found}) and to the cost needed to prevent brittle failures ($C_{brittle}$). Finally, a “penalty” cost (Φ_{pen}) is applied to the solutions that result to be unfeasible under the engineering standpoint, based on Code requirements (DM 17/01/2018; EN 1998-3, 2005) and estimating the seismic demand through the N2-method (Fajfar, 1999).

$$f(x) = C_{loc}(x) + C_{glob}(x) + C_{found}(x) + C_{brittle}(x) + \Phi_{pen}(x) \quad (1)$$

In the present study, two separate objective functions are considered: economic optimisation, minimising the initial cost of interventions, based on unit costs consistent with a regional pricing list (*Prezzario Campania LL.PP.*, 2022) and the environmental impact accounting for the Global Warming Potential (GWP) of materials according to cradle to gate indicators from literature (Hart et al., 2021; Tait and Cheung, 2016).

2.3. Algorithm workflow

The optimisation begins with the seismic assessment of the as built structure to identify all relevant design variables. A population of randomly generated retrofit solutions is then evaluated through nonlinear static analyses in the OpenSees-Py framework (Zhu, 2018). In order to reduce computational time, parallel computing is employed. Indeed, the procedure has been debugged and tested through the Arizona State University “Sol” Supercomputer (Jennewein et al., 2023)

The so-called “genetic operators” (selection, multi point crossover, and mutation) are iteratively applied to evolve the population toward more efficient solutions while avoiding local minima. For the sake of brevity, further details are omitted herein, although a clearer explanation of the procedure has been given by Nigro and Martinelli (2023, 2024).

3. Applications of the optimisation procedure

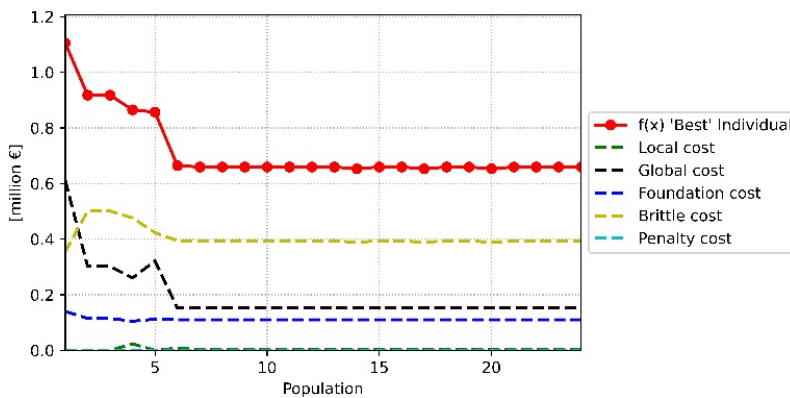
The proposed GA was applied to a four storey RC frame structure designed for gravity loads only, according to outdated seismic design codes (RD 16/11/1939), located in an Italian region characterised by very high seismic hazard. The present section summarises the outcomes of the procedure considering different objective functions.

3.1. Optimisation of the initial economic cost of the seismic upgrading interventions

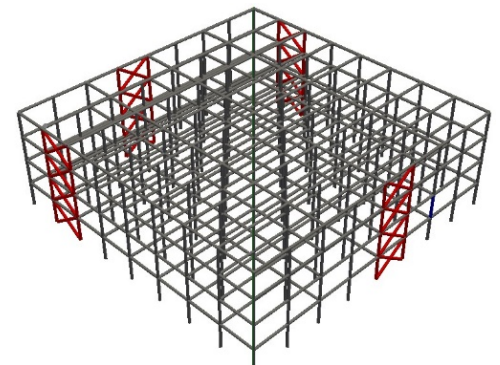
Fig. 1a reports the evolution of the objective function (economic cost of interventions, evaluated according to Equation 1) during the optimisation process and Fig. 1b illustrates the layout of the ‘optimal’ solution highlighting the braced bays in red.

The results consistently show a rapid reduction of the objective function in the early iterations and convergence toward solutions involving a limited number of brace locations (typically 4 bays consisting in 2 bays for each plan direction), combined with local strengthening to prevent brittle failures.

Indeed, the global intervention cost dominates the optimisation process, reflecting the significant stiffness and strength increase necessary to meet the seismic demand. Foundation interventions appear only weakly coupled with the total cost, whereas costs associated with brittle-failure mitigation are inversely related to the extent of global strengthening.



(a)



(b)

Fig. 1. Minimisation of the economic cost as objective function (a); layout of interventions for the ‘optimal’ solution (b).

3.2. Optimisation of the environmental impact of the seismic upgrading interventions

Fig. 2a reports the evolution of the objective function (GWP associated with the interventions, evaluated according to Equation 1) during the optimization process, while Fig. 2b illustrates the layout of the ‘optimal’ solution highlighting the braced bays in red.

When minimising the GWP, the algorithm identifies solutions with reduced use of concrete for the foundation interventions, making some braced bays adjacent in the corner of the structure.

Nonetheless, global interventions together with local strengthening to mitigate brittle failures remain essential to achieve the targeted performance levels.

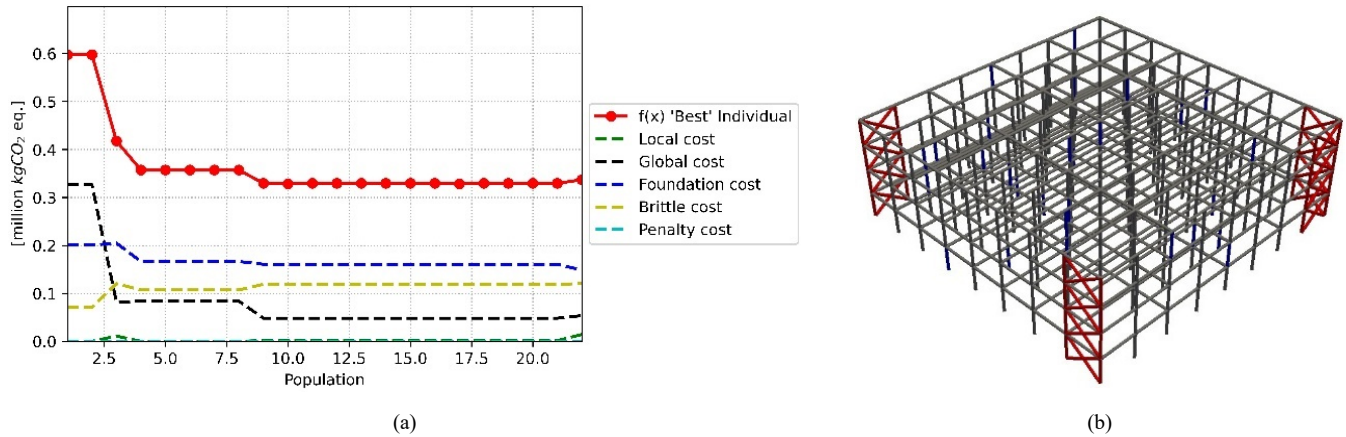


Fig. 2. Minimisation of the environmental cost as objective function (a); layout of interventions for the ‘optimal’ solution (b).

4. Concluding remarks

The present study demonstrated the capability of a GA-based framework to support the design of seismic retrofit interventions for existing RC frame structures. By simultaneously exploring local and global strengthening options, the optimisation procedure identifies feasible retrofit configurations that comply with code-based performance requirements while minimising either the initial economic cost or the environmental impact of the interventions. In both cases, the algorithm suggested that global and local measures should act synergistically to ensure satisfactory seismic performance. Future developments will extend the current single-objective approach toward a comprehensive multi-objective optimisation framework, enabling a balanced assessment of economic, environmental, and structural performance criteria within a unified decision-support tool for retrofit design.

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Fatigue tests on large-scale prestressed concrete beams with a dry ground joint

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Abstract

With the increasing deployment of wind energy, hybrid towers have become an established structural concept, particularly for large onshore wind turbines. Hybrid towers consist of a lower part made of prefabricated concrete segments and an upper part made of steel, with an adapter segment at the transition zone. The prefabricated concrete segments are stacked on top of each other and externally prestressed together, featuring dry ground joints between the segments. For the structural safety of these towers, fatigue resistance plays a key role, as high cyclic bending stresses caused by wind loads occur. While initial findings exist on the fatigue behavior of large-scale prestressed concrete members under bending resulting in a linear stress distribution within the cross-section, the influence of horizontal dry joints between concrete segments subjected to bending loads on the fatigue behavior and stress distribution remains largely unexplored. To address this gap, experimental fatigue tests were conducted on five large-scale prestressed concrete beams with a dry joint at midspan and two continuous reference beams, all subjected to bending loads. The results reveal that load transfer across the dry joint is ensured, indicating good stability of the connection between the two prestressed beam halves under cyclic loading. Although the joint appears to have only a limited influence on the fatigue performance, the specimens with dry joints exhibited earlier spalling at the joint, slightly lower numbers of load cycles to failure, and higher strain rates compared to the continuous reference beams, indicating a faster degradation of the concrete.

Keywords: Concrete fatigue; dry ground joint; material degradation; large-scale testing; experimental testing

* The full paper is open access available in the Conference Proceedings. *

Numerical investigation of a cushion-protected bridge girder subjected to hard-body impact

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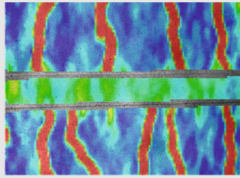
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Abstract

This study presents a numerical investigation of a bridge girder subjected to hard-body impact loading using an explicit finite element model developed in LS-DYNA. The model incorporates nonlinear material behaviour, strain-rate effects, and contact interactions to accurately capture the impact response and is validated against experimental impact tests conducted by the authors, showing good agreement in peak impact force and damage patterns. The effectiveness of an energy-absorbing cushioning system is also evaluated by comparing unprotected and protected configurations under similar impact conditions. The results show that the cushioning system significantly increases the impact duration and dissipates a large portion of the collision energy, reducing the peak impact force from 1065 kN to 324 kN (69.6% reduction) and limiting the extent of structural damage. These findings improve understanding of impact-induced failure mechanisms and demonstrate the potential of cushioning systems to enhance the resilience of bridge girders subjected to hard-body collisions.

Keywords: Bridge girder; LS-DYNA; hard-body impact; localized damage

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SMAR 2026



SMAR 2026 - 8th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

MS27: Machine learning methodologies for structural health monitoring

Organizers:

Yunus Emre Harmanci (Empa, Switzerland)

Panagiotis Martakis (irmos technologies AG, Switzerland)

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ABSTRACT

Advances in sensing technologies has enabled the collection of vast amounts of data on the performance and condition of civil infrastructure. However, extracting actionable information from large, complex, and often noisy datasets continues to pose significant challenges. Machine learning (ML) techniques offer powerful tools for feature extraction, anomaly detection, forecasting, and decision support in structural health monitoring (SHM) and pave the path towards predictive maintenance schemes. This Mini Symposium brings together researchers and practitioners to discuss recent developments and open challenges at the intersection of ML and SHM. Topics of interest include but are not limited to supervised and unsupervised learning for damage detection and condition assessment, deep learning for time series forecasting, computer vision-based monitoring, physics-informed ML approaches, strategies for handling sparse or heterogeneous data, and data-based maintenance decision-making.

Uncertainty-aware prognosis using polynomial chaos expansion: insights from case studies

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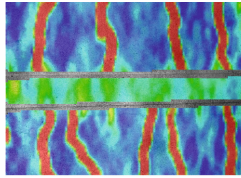
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Abstract

Accurate prediction of structural behavior remains a demanding task due to the combined influence of operationally driven changes, environmental variability, and the intrinsic complexity of real-world systems, factors that are often difficult to capture adequately using conventional physics-based models. In this context, data-driven approaches leveraging long-term monitoring data offer a complementary framework for describing structural response, particularly for complex structures where simplifying model assumptions may limit interpretability. This paper presents the application of the polynomial chaos expansion (PCE) method in a ML- fashion for the development of prognostic models aimed at the continuous monitoring of engineering structures. The approach establishes baseline representations of structural behavior by linking measured response quantities with environmental and operational parameters. Its performance is illustrated through full-scale case studies of a concrete dam and an industrial steel chimney. The study explores the behavior of the PCE-based models under practical constraints in long-term monitoring applications, including incomplete training data and output statistical transformations scenarios. The PCE formulation is kept simple, with the aim of highlighting its transparency, ease of implementation, and straightforward re-adaptation for different structures and monitoring configurations. The results demonstrate that PCE models can capture long-term behaviour and detect operational variability changes, supporting their use in autonomous assessment and long-term monitoring, provided that representative data and an engineering-informed understanding of the environmental and operational envelope are in place.

Keywords: Structural health monitoring; polynomial chaos expansion; uncertainty; forecasting; machine learning

* The full paper is open access available in the Conference Proceedings. *



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Residual-PCA similarity for robust missing-sensor prediction in Schwindegg Bridge

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Keywords: Structural health monitoring; neural networks; principal component analysis; strain sensors; bridge monitoring.

1. Introduction

Bridge owners increasingly rely on permanent structural health monitoring (SHM) systems to support condition assessment and digital-twin applications, particularly in the context of ageing infrastructure and limited resources for manual inspection. The operational value of monitoring data depends not only on sensor coverage but also on data continuity and plausibility. The Isen bridge in Schwindegg (Germany) is a representative municipal bridge equipped during construction with an extensive sensor network (≈ 140 physical sensors providing ≈ 170 measured channels), intended as a field test for digital-twin concepts and long-term monitoring strategies (Wimmer and Braml 2023). However, real monitoring datasets routinely contain gaps from sensor malfunction, transmission issues, maintenance periods, or automated quality screening. A dedicated plausibility check on the Schwindegg bridge measurements demonstrates that a subset of sensors can produce non-responsive or implausible signals under expected stimuli, motivating the exclusion of those channels and increasing the need for robust data reconstruction (Mediel-Cuadra et al. 2025).

Missing-channel reconstruction in SHM has been approached through sparse and low-rank recovery (Yang and Nagarajaiah 2016), probabilistic multi-task learning (Wan and Ni 2019), and more recently deep meta-learning methods (Zhao et al. 2025). In bridge engineering this task is often framed as *virtual sensing*: estimating responses at unmeasured or inaccessible locations from a limited set of measured channels (Tchemodanova et al. 2021). The novelty of this contribution lies in treating predictor selection itself as the central virtual-sensing problem: an interpretable residual-PCA similarity score ranks candidate sensors relative to a target channel, and its effect is isolated through high- versus low-similarity control models on real bridge monitoring data.

2. Methodology

All analyses use minute-aggregated monitoring data from the Schwindegg bridge covering the period 2024-07-09 to 2024-07-31 (31,681 samples), with the target channel being strain gauge DMS-P10B-2B (strain transducer installed in concrete – sensor position at bored pile head). Data were split chronologically into 80% for training, 10% for validation, and 10% for testing, reflecting how a reconstruction model would be deployed in a live SHM pipeline and preventing information leakage from future conditions. All predictor channels were z-score standardised and sensors identified as non-responsive or implausible in the prior plausibility screening (Mediel-Cuadra et al. 2025) were excluded from the candidate set.

Bridge monitoring data contain strong common-mode effects, most notably temperature-driven trends, that inflate inter-sensor correlations and mask more informative local structural relationships. To isolate sensor-specific behaviour, similarity between sensors is therefore computed in a PCA residual subspace rather than in the raw time-series domain. PCA is fitted to the standardised sensor matrix, the first principal component capturing the dominant global trend is excluded, and the subsequent components explaining more than 90% of the remaining variance define the residual subspace. Each sensor is then represented by its normalised loading vector in this subspace, and pairwise similarity to the target is quantified using sign-invariant cosine similarity to remove

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ambiguity from both PCA sign indeterminacy and possible physical sensor orientation differences. Sensors are ranked by descending similarity, producing a shortlist of candidate predictors. The full pipeline is illustrated in Fig. 1.

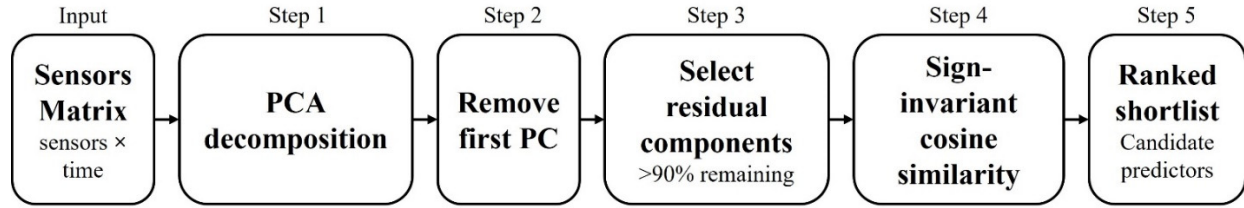


Fig. 1. Processing pipeline for sensor similarity ranking.

Five reconstruction models of increasing complexity were trained and evaluated on the same chronological splits, as summarised in Table 1. The single-sensor offset model reconstructs the target as the value of the near-duplicate reference sensor plus a constant offset, defined as the difference between the training-period means of the target and reference channels. This favourable case is not representative of most virtual-sensing deployments, where a colocated or functionally equivalent backup channel is unavailable; it is therefore used only as an interpretable upper-bound benchmark. The remaining models are designed to test whether the target can be reconstructed accurately without relying on a near-duplicate sensor. A ridge regression model was trained on the four highest-ranked non-duplicate sensors using lagged features spanning a full 24 hours to capture diurnal thermo-mechanical patterns. A Long Short-Term Memory (LSTM) network was trained on short multivariate sequences of five minutes to assess whether recurrent nonlinear dynamics improve reconstruction. Two feed-forward neural networks (FFNN) were trained on a 24-hour flattened input window: one using the same four top-ranked sensors as the ridge model, and one using the full set of valid sensors excluding the near-duplicate and plausibility-failed channels, to contrast similarity-guided selection against a broad-input approach. To quantify the influence of predictor ranking on reconstruction quality, a complementary set of control models was trained using the same architectures (ridge regression, LSTM, and FFNN) but replacing the four highest-ranked non-duplicate sensors with the four lowest-ranked sensors that still passed the plausibility screening. This substitution isolates the effect of PCA-residual similarity from the effect of model capacity, providing a direct experimental control for the sensor selection hypothesis.

Table 1. Configuration of the reconstruction models. Models labelled "(low)" use the four lowest-ranked plausible sensors as a control group for the similarity-based selection. All models were evaluated on the same chronological train / validation / test splits.

Model	Predictor	Context	Architecture
Single sensor offset	One near-duplicate reference sensor	-	Constant offset (training period mean difference)
Ridge regression	Four top-ranked non-duplicate sensors	24 h lagged features	Linear (L2 regularisation)
Ridge regression (low)	Four lowest-ranked plausible sensors	24 h lagged features	Linear (L2 regularisation)
LSTM	Four top-ranked non-duplicate sensors	5 min sequences	Recurrent neural network
LSTM (low)	Four lowest-ranked plausible sensors	5 min sequences	Recurrent neural network
FFNN	Four top-ranked non-duplicate sensors	24 h flattened window	Feed-forward neural network
FFNN (low)	Four lowest-ranked plausible sensors	24 h flattened window	Feed-forward neural network
FFNN (all sensors)	All valid sensors (excl. near duplicate & failed sensors)	24 h flattened window	Feed-forward neural network

3. Results and discussion

The residual PCA analysis produced a physically plausible neighbourhood around DMS-P10B-2B, with sensors sharing non-global structural behaviour clustering tightly around the target. Importantly, the ranking immediately exposed one near-duplicate neighbour, a sensor colocated and functionally equivalent to the target, which is retained as an upper-bound baseline but excluded from the main predictor set to test genuine generalisation.

The reconstruction models exhibit a clear and consistent pattern, summarised in Table 2. The single-sensor offset model achieves $R^2 \approx 0.961$, confirming strong redundancy with the near-duplicate neighbour, but this strategy is fragile: if that sensor fails, reconstruction collapses entirely. Excluding it, the ridge regression with 24-hour lagged features reaches $R^2 \approx 0.984$, demonstrating that a linear model with similarity-guided sensor selection and sufficient historical context captures most of the target channel's behaviour. The LSTM performed poorly regardless of sequence length, achieving $R^2 \approx 0.894$ with 5-minute sequences and degrading further as the window was extended, suggesting that the recurrent architecture does not suit this type of slowly varying, multivariate strain data well. The compact FFNN trained on a 24-hour flattened window of the four top-ranked sensors achieves the best overall test performance ($R^2 \approx 0.989$, $RMSE \approx 0.149 \mu\text{m/m}$, $MAE \approx 0.122 \mu\text{m/m}$, Pearson $r \approx 0.995$), indicating that a feed-forward architecture with an explicit large input context is more effective than recurrence for this problem.

Expanding the FFNN to all valid sensors produced a counter-intuitive result: test accuracy decreased to $R^2 \approx 0.971$, despite the larger input set. This indicates that adding more channels introduces spurious correlations and noisy variables that reduce out-of-sample generalisation, a risk amplified by the short, seasonally homogeneous training window covering a single summer month. The similarity-based four-sensor shortlist effectively acts as a feature selection regulariser, concentrating the model on the structurally most informative relationships. The control experiment with the four lowest-ranked sensors reinforces this conclusion decisively. When the same ridge regression architecture that achieved $R^2 \approx 0.984$ with similarity-selected predictors is supplied with the most structurally dissimilar sensors, performance collapses to $R^2 \approx -0.050$, indicating that the model fails to explain any target variance beyond the training-period mean. The LSTM trained on the same distant sensors reaches only $R^2 \approx 0.390$, and even the FFNN, the most flexible architecture, attains $R^2 \approx 0.779$, a substantial degradation from its similarity-guided counterpart ($R^2 \approx 0.989$). Notably, the high Pearson correlation coefficients observed for the low-ranked ridge and FFNN models alongside poor R^2 values indicate that these models capture the gross temporal trend driven by shared environmental loading but fail to reproduce the amplitude and local structural response of the target channel. This decoupling between correlation and coefficient of determination highlights that Pearson r alone is an insufficient performance metric for virtual sensing applications and that R^2 and RMSE provide a more faithful assessment of reconstruction fidelity. The magnitude of the performance gap confirms that sensor selection is a first-order driver of reconstruction quality, not merely a marginal refinement. These findings suggest that a similarity-driven shortlist can provide an automated and interpretable basis for predictor selection for other target channels in the network, although target-wise validation remains necessary. Among reconstruction approaches, the ridge regression with lag features offers high accuracy, transparency, and low computational cost, making it a strong candidate for operational deployment, while the FFNN achieves the best accuracy at the cost of requiring careful regularisation and broader validation before production use.

Table 2. Performance comparison of reconstruction models for target sensor DMS-P10B-2B on the test set. R^2 : coefficient of determination; RMSE: root mean square error; MAE: mean absolute error. Models are ordered by complexity. Best test-set values shown in bold.

Model	R^2	RMSE	MAE	Pearson r
Single sensor offset	0.961	0.302	0.249	0.991
Ridge regression	0.984	0.185	0.149	0.992
Ridge regression (low)	-0.050	1.478	1.452	0.989
LSTM	0.894	0.495	0.380	0.959
LSTM (low)	0.390	1.190	1.071	0.948
FFNN	0.989	0.149	0.122	0.995
FFNN (low)	0.779	0.678	0.584	0.996
FFNN (all sensors)	0.971	0.247	0.181	0.991

4. Conclusion

This paper presents a workflow for missing-sensor reconstruction in a densely instrumented bridge monitoring system. A sign-invariant PCA residual cosine similarity ranks sensors by structural proximity to a target channel, providing a principled and automated basis for predictor selection. Applied to strain gauge DMS-P10B-2B on the Schwindegg bridge, similarity-guided selection of four non-duplicate sensors enabled accurate reconstruction across all tested models, with the best model achieving $R^2 \approx 0.989$ and $RMSE \approx 0.149 \mu\text{m/m}$ on the held-out test period. Two complementary findings underscore the centrality of predictor selection. First, expanding the predictor set beyond the similarity-ranked shortlist to all valid sensors degraded test performance. Second, substituting the four highest-ranked sensors with the four lowest-ranked plausible sensors caused reconstruction quality to collapse across all architectures, with the ridge regression R^2 dropping from 0.984 to -0.050 and the FFNN R^2 falling from 0.989 to 0.779. Together, these results demonstrate that PCA-residual similarity ranking is a first-order determinant of reconstruction accuracy, not merely a convenience for reducing input dimensionality. Future work will assess additional target channels, out-of-season periods such as winter data, and periodic re-training and domain-adaptation strategies.

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Machine learning-aided seasonal normalization of modal frequencies in timber buildings

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Abstract

Environmental and operational variations influence dynamic behavior of timber buildings, often leading to fluctuations in modal frequencies that may obscure true structural anomalies. This study compares and develops two machine learning models for supervised and unsupervised normalization based on artificial neural networks. The supervised data normalizer is based on a deep regression neural network (DRNN) that utilizes both environmental/operational data and structural responses. In contrast, the unsupervised data normalizer is developed from a variational autoencoder (VAE) that only employs structural responses for data normalization. This model is proposed to use as a supplementary approach for supervised normalization when the correlation between the measured environmental/operational and response data is weak. An eight-story timber building located in Växjö, Sweden is used to assess the performance of the supervised and unsupervised data normalizers. Results indicate that VAE outperforms DRNN due to weak correlations between the collected environmental factors and the building modal frequencies.

Keywords: Vibration monitoring; modal frequency; environmental variability; timber building; machine learning

* The full paper is open access available in the Conference Proceedings. *

Machine learning-based prediction of wind-induced bridge acceleration using long-term structural health monitoring data

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Abstract

This study investigates the use of machine learning techniques to predict wind-induced bridge acceleration using monitoring data from the Hardanger Bridge in Norway. Environmental variables, including wind speed, turbulence intensity, wind direction, and temperature, were used as input features, while bridge acceleration (RMS) was considered as the target response. Several regression models, including Linear Regression, Random Forest, Gradient Boosting, and Artificial Neural Networks, were developed and evaluated. The results show that nonlinear machine learning approaches outperform the linear model, with the Random Forest algorithm achieving the highest prediction accuracy. Feature importance analysis indicates that wind-related variables, particularly wind speed and turbulence, play a dominant role in predicting bridge acceleration, consistent with the physical behavior of the structure. In contrast, temperature exhibits a limited direct relationship with the structural response and may reflect indirect environmental influences present in the dataset. The findings demonstrate the potential of data-driven approaches for analysing large-scale SHM datasets and improving the understanding of wind-induced bridge dynamics.

Keywords: Structural health monitoring; wind-induced bridge vibrations; machine learning; Hardanger Bridge

* The full paper is open access available in the Conference Proceedings. *

Leveraging transfer learning for SHM: domain adaptation across Italian real bridges

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Abstract

A large number of existing bridge structures are reaching the end of their service life, making continuous structural health monitoring (SHM) a key tool for ensuring safety and optimizing maintenance strategies. When monitoring is extended to an entire network of bridges, such as in the case of a highway administrator, the management of large-scale SHM becomes complex. This complexity arises from the high resources required to comprehensively characterize each structure and from the scarcity of labeled data under anomalous conditions. Machine learning techniques offer valuable support in this context, and among them, transfer learning represents a powerful approach to overcome data limitations. In transfer learning, the structure selected as the source domain, for which extensive data is available, is used to train the model, which is then adapted to one or more target domains, i.e., other structures with similar characteristics, through domain adaptation techniques.

This paper applies transfer learning to real-world Italian bridges monitored via MEMS sensors. The approach is validated across two scenarios: heterogeneous structures and identical spans of twin viaducts. In both cases, spans with complete monitoring histories serve as source domains to establish baselines for target spans in early-monitoring stages. Results demonstrate that leveraging network-wide data enables effective large-scale SHM. While the framework successfully identifies simulated and real structural damage, the findings also highlight challenges regarding seasonal domain shifts, providing a foundation for efficient knowledge transfer and data-informed infrastructure management.

Keywords: SHM; transfer learning; big data; bridges; MEMS

* The full paper is open access available in the Conference Proceedings. *

Two-stage deep learning framework for bridge traffic characterization using DAS

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Abstract

Distributed Acoustic Sensing (DAS) is an important tool for nondestructive evaluation and structural health monitoring, providing distributed dynamic strain measurements along fiber optic cables. Recent studies show that DAS can detect vehicle traffic, yet translating the observed strain data into reliable traffic loading information remains a challenge. This study develops a two-stage deep learning framework to extract traffic and loading parameters from DAS data collected on a bridge in rural Dane County, Wisconsin. The first stage focuses on signal denoising to improve data quality. A U-Net model is trained using five-second DAS patches as input, with detrended, bandpass, and frequency-wavenumber (f-k) filtered versions serving as training targets. The trained model reconstructs clean DAS responses and highlights vehicle-induced patterns along the fiber. The second stage uses denoised data to infer traffic characteristics with two specialized models. First, a Dual-Head Transformer predicts vehicle counts and classifications to quantify traffic flow. Second, a Peak-Strain Weight convolutional neural network (CNN) extracts maximum absolute strain features to estimate vehicle weights, which serve as a practical index for dynamic structural loading. Experimental results demonstrate that the two-stage framework successfully isolates vehicle signals from complex background noise, accurately counts and classifies traffic in a proof-of-concept setting, and provides representative structural load estimates for scalable bridge monitoring.

Keywords: Distributed acoustic sensing (DAS), structural health monitoring, deep learning, traffic characterization, bridge monitoring

* The full paper is open access available in the Conference Proceedings. *

Graph neural networks for structural damage detection on the Hell Bridge Test Arena

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Abstract

Structural Health Monitoring (SHM) is critical for the lifecycle management of aging steel bridges. The Hell Bridge Test Arena (HBTA) dataset provides a unique full-scale benchmark with controlled damage scenarios, making it an ideal platform for validating data-driven algorithms. Previous studies using the HBTA dataset have primarily relied on manual feature extraction and classical machine learning techniques. These approaches typically treat sensor data as independent vectors, neglecting the physical connectivity of the truss structure and the spatial dependencies inherent to vibration propagation. This study proposes a Geometric Deep Learning framework that explicitly incorporates these spatial relationships. A Graph Neural Network (GNN) is developed for supervised damage identification by representing the sensor network as a graph aligned with the bridge topology. In addition, a Graph Neural Network Autoencoder is trained exclusively on undamaged data to evaluate its capability for damage localization.

The performance of the proposed models is benchmarked against classical approaches, including Support Vector Machine (SVM) and Multi-Layer Perceptron (MLP). Results demonstrate that the GNN significantly improves damage identification accuracy by leveraging structural topology, highlighting the benefits of physics-informed geometric deep learning for real-world SHM applications.

Keywords: Graph neural networks; damage detection; bridge assessment

* The full paper is open access available in the Conference Proceedings. *

Machine-learning-based damage detection in beam-column connections using modal features

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Abstract

This paper presents a comparative study of machine-learning-based damage detection in connections and low-rise frames using modal response features. It examines whether natural frequencies alone are sufficient for damage localization and whether normalized mode shapes improve prediction accuracy. Two case studies are considered: a three-degree-of-freedom benchmark with approximately 13% first-story damage, and a three-story, two-bay semi-rigid frame with 12 connection damage variables. Frequency-only predictors are sensitive to stiffness degradation but may produce non-unique localization, while adding mode shapes improves the predicted first-story damage to approximately 12%. Artificial neural networks (ANN) provide the closest damage-vector estimate, and support vector machines (SVM) achieve the best benchmark test-set accuracy. In the numerical frame study, combined frequency and mode-shape features are used to train ANN, SVM, random forests (RF), and least-squares boosting (LSBoost). RF achieves the best overall performance, followed by LSBoost and ANN, while linear SVM provides the fastest baseline. The results show that natural frequencies are useful global indicators, but mode-shape information is necessary for reliable localization and connection-level damage prediction.

Keywords: Damage detection; machine learning; semi-rigid connections; moment-resisting frames

* The full paper is open access available in the Conference Proceedings. *

Damage identification of bridge girders using limited strain data and stacked machine learning

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Abstract

Traditional bridge assessment relies heavily on subjective visual inspections or costly, dense sensor networks that are difficult to maintain. To address these limitations, this study introduces an automated physics-informed augmented stacking ensemble designed to identify structural damage using a limited number of strain sensors. The methodology was evaluated using a non-linear finite element model of a 70 m two-span continuous reinforced concrete bridge developed in SAP2000. The proposed framework transforms raw strain data from eight discrete sensors into 15 high-level, physics-informed features, including cross-sectional curvature and spatially integrated parameters like AreaC (representing accumulated rotation). These features feed into a multi-layered machine learning architecture where a "committee" of Level-0 base models (Random Forest, KNN, AdaBoost, and GPR) provides initial assessments that are then arbitrated by a Level-1 Random Forest Meta-Model. Results indicate that the meta-model significantly outperforms standalone base models, achieving a True Positive Rate (TPR) of 84.1% for identifying unsafe states during testing. Furthermore, the system demonstrates strong load invariance, maintaining a 72.2% TPR when subjected to complex multi-point loading configurations that were entirely unseen during training. Robustness tests confirmed that the framework remains "safety-conservative" even at 10% operational noise, identifying genuine structural compromise with 75% accuracy.

Keywords: Damage detection; structural health monitoring; strain, stacked machine learning; bridge

* The full paper is open access available in the Conference Proceedings. *

Automated seismic damage assessment using limited strain data and machine learning

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Abstract

Rapidly assessing the structural safety and occupancy status of critical infrastructure immediately after a major earthquake is essential for effective emergency response. Conventional assessments rely on expert visual inspections, which are time-consuming and highly dependent on individual experience, while traditional global structural health monitoring often requires dense, cost-prohibitive sensor networks. This study introduces an automated machine learning framework that utilizes strategically limited local strain data to classify post-earthquake structural conditions into two actionable safety states: Occupiable and Evacuate. The methodology integrates numerical pushover analysis for model training with experimental strain data from a scaled two-story, single-bay reinforced concrete (RC) frame for validation. Two algorithms, Random Forest (RF) and Support Vector Machine (SVM), were evaluated using both a four-sensor array and a minimal two-sensor array located strictly at the ground-floor columns. While current error rates necessitate further refinement for critical deployment, these findings demonstrate the fundamental viability of coupling ML classifiers with strictly limited strain arrays, evidenced by the Support Vector Machine maintaining a 78.2% accuracy and 0.91% recall using only two sensors. This study serves as a foundational first step toward developing a robust, cost-effective diagnostic framework for rapid post-earthquake safety evaluation.

Keywords: Damage detection; structural health monitoring; strain; seismic damage; machine learning

* The full paper is open access available in the Conference Proceedings. *

Vibration-based assessment of a historic railway bridge using convolutional autoencoder networks

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Abstract

The use of dynamic monitoring methods integrated with Convolutional Auto-Encoder (CAE) networks is exemplified in the paper with the aim of detecting and localizing structural anomalies. The presented methodology is specifically based on the use of short time histories associated with the transit of trains on railway bridges (so that the assumption of linear time invariant structural system is not guaranteed). Furthermore, one single CAE network is defined and trained with the signals simultaneously collected from several sensors. Once the network has been established in the baseline condition of the structure, it can accurately reconstruct the newly acquired responses as long as the structure remains unchanged. When anomalies or structural changes occur, appropriate indicators (i.e., the reconstruction errors) allow to detect and localize the onset of deviations from the baseline condition. After a concise background on CAE networks and the description of the adopted strategy of data analysis, the effectiveness and accuracy of the proposed CAE-based procedure of damage assessment is demonstrated using data collected in the continuous dynamic monitoring of the historic San Michele bridge (1889), crossing the Adda River about 50 km far from Milan and being used as a combined road and railway bridge.

Keywords: Auto-encoder; dynamic monitoring; historic iron-bridge; novelty detection

* The full paper is open access available in the Conference Proceedings. *

Deep learning-based structural health monitoring for CFRP-strengthened RC slabs

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Abstract

The increased deployment of sensors in structural engineering has resulted in significant volumes of data from infrastructure assets. However, these datasets remain largely underutilized, as traditional analysis methods fail to extract their full potential. Deep learning (DL) algorithms can uncover complex temporal patterns within such datasets and enable the detection of subtle structural anomalies that would otherwise remain hidden in the noise of environmental variations. This study provides an evaluation of DL architectures for strain-based structural health monitoring with a dataset obtained from full-scale reinforced concrete slabs strengthened with carbon fiber-reinforced polymer (CFRP) strips under sustained loading and environmental conditions. The collected data exhibited non-stationarity from concrete creep behavior and superimposed daily temperature cycles and seasonal variations. To this end, four DL architectures, namely Feedforward Neural Networks (FFNN), Recurrent Neural Networks (RNN), Long Short-Term Memory networks (LSTM), and Transformers, have been implemented and systematically compared against baseline approaches. Damage detection is achieved through the Z scores and Mahalanobis distance applied to model prediction residuals. Incorporating exogenous environmental inputs was found to significantly enhance model performance across all architectures. LSTM networks demonstrated superior performance and deemed suitable for real-time monitoring applications. These findings aim to provide quantitative guidance for practitioners implementing DL-based structural health monitoring systems.

Keywords: Structural health monitoring; deep learning; CFRP; non-stationary time series forecasting; anomaly detection

* The full paper is open access available in the Conference Proceedings. *

Satellite-based, territorial-scale screening and maintenance prioritization of river-crossing bridges via interferometry

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Abstract

Ageing bridge stocks and constrained maintenance budgets demand scalable, objective tools to triage inspections and prioritize surveys. This brief contribution presents a territorial-scale screening of 24 river-crossing bridges, all located across the Municipality of Turin. The proposed methodology uses multi-temporal Interferometric SAR (InSAR) from COSMO-SkyMed, applied to a 460-image archive, which was processed via Advanced Differential Interferometry Synthetic Aperture Radar (A-DInSAR) to extract stable Permanent Scatterers (PSs) on bridge decks. Datasets from both orbits were decomposed into Up-Down (UD) and East-West (EW) components. Then, priority rankings were defined, intentionally relying on the UD component for its better observability and cross-asset comparability. Two-level statistical framework produced rankable indicators for bridges: (i) mean vertical velocity (global vs local thresholds) and (ii) differential-settlement indices derived from cumulative vertical displacement (length-normalized and separation-distance-normalized). Scores from the two levels were combined to yield an overall priority ranking that highlights structures with persistent trends and/or pronounced intra-deck gradients, while automatically accounting for bridge size through a normalization step. This research work's outcomes underscore the critical role of satellite interferometry as an efficient, non-invasive first diagnostic layer.

Keywords: Satellite health monitoring, infrastructures network

* The full paper is open access available in the Conference Proceedings. *

A deep learning and ray casting framework for bridge inspection

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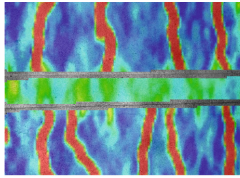
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Abstract

Bridge structures deteriorate over time due to environmental and mechanical stresses, a process increasingly aggravated by the effects of climate change, which accelerate material degradation and structural aging. Regular inspections are therefore essential to ensure safety and serviceability. Conventional inspection methods are often labor-intensive, subjective, and limited by accessibility, motivating the development of more automated remote solutions. This study presents an AI-driven framework for detecting and mapping surface damage on reinforced concrete bridges through the integration of deep learning and 3D projection techniques. A YOLO11-seg-based instance segmentation model was trained to identify common defects such as cracks, efflorescences, and exposed reinforcement in high-resolution inspection images. The detected damage was then projected onto 3D models using a ray-casting algorithm based on the camera's intrinsic and extrinsic parameters, enabling accurate spatial localization and visualization within the bridge geometry. The model achieved a mean Average Precision (mAP50) of 61%, demonstrating strong potential for semi-automated inspection workflows. The combined approach provides a coherent pipeline from 2D image detection to 3D damage mapping, enhancing accuracy, consistency, and interpretability. The methodology was successfully applied to a roadway bridge located in the northern region of Portugal, highlighting the feasibility of integrating artificial intelligence with spatial modeling to support safer, more efficient, and objective bridge condition assessment.

Keywords: Deep learning, ray casting, damage detection, 3D mapping, bridge inspection

* The full paper is open access available in the Conference Proceedings. *



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SLAM-based drone inspection and damage detection for underground rainwater tunnels

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Keywords: SLAM-based drone inspection, underground rainwater tunnel, structural damage detection, point cloud and image fusion

1. Introduction

Recent advances in UAV-based inspection and computer vision have enabled automated structural damage detection using image and point cloud data (Yu et al., 2024). UAVs equipped with cameras and LiDAR can efficiently acquire visual and spatial information, while deep learning methods show strong performance in crack detection. Point cloud data further provide geometric information for accurate damage localization and quantification. However, most existing approaches focus on open environments like bridges and buildings under controlled conditions (Xiao et al., 2024; Lee et al., 2026).

To overcome these limitations, recent studies have integrated image and point cloud data through 3D projection to improve defect visualization. Nevertheless, applying these to underground environments remains challenging due to confined spaces, low illumination, and GPS-denied conditions. Moreover, current manual inspections pose safety risks and lack precise spatial referencing for documented defects.

In this study, a SLAM-based UAV inspection framework is proposed for structural damage detection and spatial localization in underground rainwater tunnels. Compared to conventional methods, this system offers substantial added value by eliminating human hazards and enabling high-precision, automated 3D localization of concrete cracks. The framework integrates trajectory estimation, sensor fusion, and deep learning-based detection to enable automated inspection in complex environments.

The main contributions of this study are as follows:

- Development of a SLAM-based UAV inspection framework for underground environments,
- Integration of image and point cloud data for spatial damage localization,
- Application of deep learning-based crack detection using UAV-acquired data,
- Experimental validation under low-illumination conditions.

2. Introduction

2.1. Overall framework

The proposed framework consists of UAV-based data acquisition, SLAM-based pose estimation, image extraction, damage detection, and 3D mapping. A UAV platform (Elios 3) equipped with LiDAR and camera sensors is used to collect point cloud and video data in underground environments. The acquired data are processed to estimate the UAV trajectory, extract image frames, detect structural damage, and map the results onto a 3D point cloud.

The overall framework of the proposed UAV-based inspection system is illustrated in Fig. 1. The process consists of five main stages: data acquisition, LiDAR-IMU fusion, pose estimation, video-based damage analysis, and damage classification.

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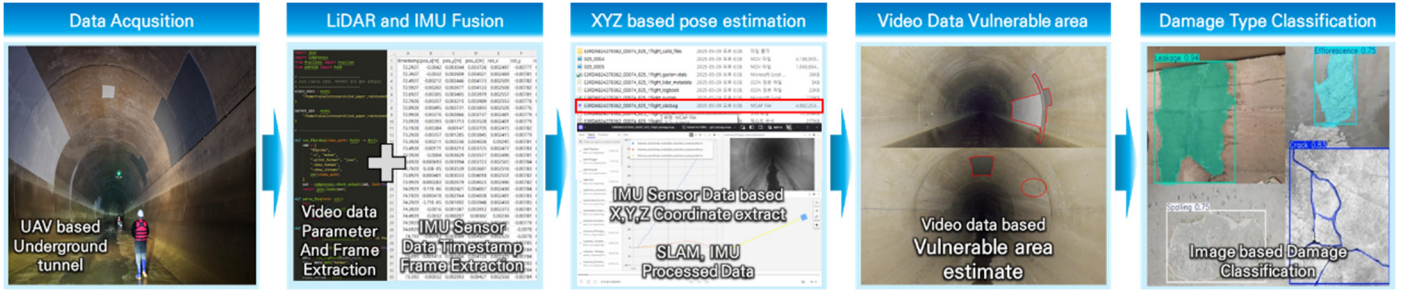


Fig. 1. Overall framework of the proposed SLAM-based UAV inspection system.

First, a UAV (Elios 3) is deployed to collect video and point cloud data in an underground tunnel environment. The acquired video data are processed to extract frame information, while IMU sensor data with timestamps are obtained simultaneously.

Next, LiDAR and IMU data are integrated to estimate the UAV trajectory in a unified coordinate system. Based on the synchronized timestamps, the UAV pose is estimated in the XYZ coordinate system.

The extracted video frames are then used to identify vulnerable areas of the tunnel structure. Finally, a deep learning-based model is applied to classify structural damage, such as cracks and surface deterioration, from the image data.

2.2. SLAM-based pose estimation

The UAV provides IMU-based pose data with timestamps, which are used to estimate the trajectory in a GPS-denied environment. The pose information is aligned with the point cloud coordinate system to determine the spatial position of the UAV during data acquisition.

Additionally, the temporal consistency between sensor data is maintained to ensure accurate trajectory estimation, and the resulting pose information serves as a reference for subsequent data fusion processes.

2.3. Video–point cloud fusion

To enable spatial localization of damage, image and point cloud data are integrated through timestamp synchronization. Each image frame is associated with the corresponding UAV pose, and its spatial position is estimated. Using camera intrinsic parameters obtained from checkerboard calibration, the image frames are projected onto the 3D point cloud, allowing the mapping of visual information into spatial coordinates.

This fusion process enables direct correspondence between detected damage in images and its location in 3D space, facilitating intuitive visualization and spatial analysis.

2.4. Damage detection

Structural damage is detected using a hybrid CNN–Transformer-based crack segmentation network. The model identifies defects such as cracks from the extracted image frames, and the detected results are mapped onto the corresponding locations in the 3D point cloud.

The model leverages both local feature extraction and global contextual information to improve detection robustness under low-illumination conditions commonly found in underground environments.

3. Results and discussion

3.1. Experimental setup

To validate the feasibility of damage detection, experiments were conducted in an indoor laboratory environment under low-illumination conditions simulating underground tunnels. A UAV (Elios 3) was used to capture image data from concrete specimens with induced cracks. The specimens had dimensions of $1500 \times 120 \times 135$ mm, and cracks with a width of approximately 0.3 mm were generated through loading tests. The UAV maintained a distance of approximately 3 m during data acquisition.

3.2. Damage detection results

Fig. 2 shows the crack detection results obtained from UAV-acquired images. The hybrid CNN–Transformer-based model successfully detected cracks on the concrete surface, even under low-illumination conditions. The results demonstrate that cracks with a width of approximately 0.3 mm can be identified from images captured at a distance of 3 m.

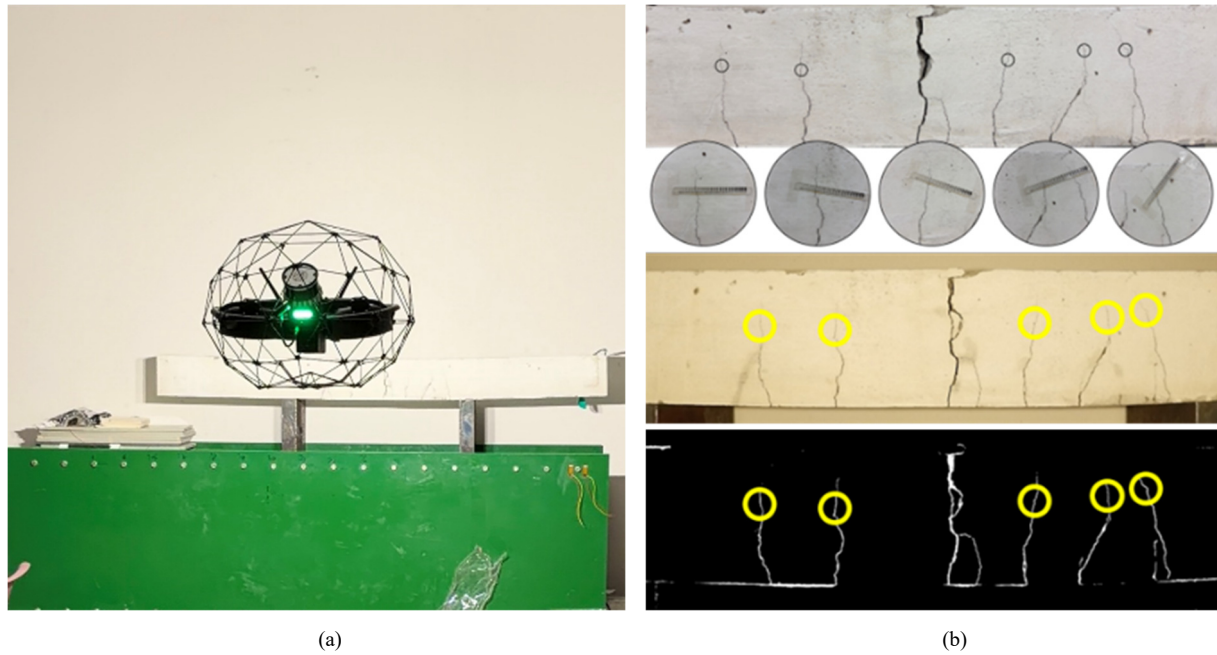


Fig. 2. (a) Indoor UAV-specimen setting, (b) proposed model indoor test result.

3.3. Discussion

The experimental results confirm the feasibility of applying UAV-based vision systems for structural damage detection in underground environments. The proposed model shows robustness under low-light conditions and demonstrates potential for practical inspection scenarios. However, the current study is limited to laboratory-scale experiments. In real tunnels, environmental factors such as water reflections and severe spatial constraints may induce data noise and aerodynamic disturbances. Therefore, further validation in operational tunnel environments is required. In addition, quantitative evaluation of detection performance will be addressed in future work.

4. Conclusion

This study proposed a SLAM-based UAV inspection framework for automated structural damage detection and 3D spatial localization in underground rainwater tunnels. The system successfully integrated trajectory estimation, sensor fusion, and deep learning-based crack detection into a unified pipeline.

Experimental validation confirmed that the proposed framework can effectively identify fine cracks under low-illumination conditions, demonstrating its feasibility for contact-free underground infrastructure inspection. Based on these findings, future work will focus on acquiring data from real underground rainwater tunnels to validate the framework under real-world operating conditions. This is expected to pave the way for practical applications in automated tunnel maintenance.

Acknowledgements

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Pi-MFLNet: a DFL-based raster-scan MFL imaging system for structural monitoring

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Abstract

This study proposes a velocity-aware deep feature learning (DFL) framework for magnetic flux leakage (MFL)-based structural monitoring using a multi-channel raster-scan acquisition strategy and a Raspberry Pi-enhanced sensor network. A parametric numerical investigation was conducted to evaluate the influence of defect morphology, scanning trajectory, and motion-induced electromagnetic effects on leakage-field behavior, considering curved crack depths of 1–5 mm and inspection velocities between 3.6 and 10 km/h. The simulation results revealed pronounced directional flux perturbations and velocity-dependent redistribution patterns associated with defect geometry and relative sensor motion.

An experimental inspection prototype was implemented for steel Circular and scaffolding structures containing artificial discontinuities. The platform enables synchronized magnetization, real-time multi-channel acquisition, edge-level preprocessing, and wireless data transmission. Statistical flux characterization using extreme-value modelling and adaptive thresholding was applied to establish robust anomaly limits. While conventional machine learning classifiers exhibited limited robustness to velocity-induced distortion, a one-dimensional convolutional neural network demonstrated superior generalization by learning spatiotemporal leakage patterns. Furthermore, rasterized MFL image synthesis supported YOLOv5-based defect localization with high detection accuracy providing scalable and reliable solution for intelligent SHM.

Keywords: Sensor-based inspection; deep feature learning; structural damage detection; MFL imaging

* The full paper is open access available in the Conference Proceedings. *

A semantic workflow linking image-based concrete damage segmentation to ontology-driven knowledge graphs for digital twin integration and automated structural diagnostics

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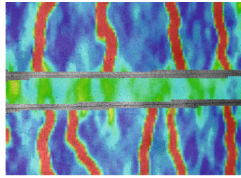
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Abstract

Reliable detection and interpretation of damage in reinforced concrete structures are essential for maintenance planning and structural health monitoring. While annotated damage datasets have enabled automated assessment through computer vision and machine learning, a consistent semantic framework is needed to connect pixel-level predictions with knowledge-based reasoning and digital inspection workflows. This paper presents an extension of the Concrete Damage Ontology (CDO), derived from the Damage Topology Ontology (DOT), to incorporate reinforced concrete damage classes in a structured format. We standardize damage quantification by defining core measurement attributes for damage types such as cracking, spalling, and efflorescence. Using the Damage Classification 10k (DACL10k) dataset, segmentation models are trained and evaluated across 19 damage categories. Model predictions are encoded as ontology-aligned templates, and integrated into a knowledge graph to enable automated population of damage instances, representation of spatial information through topological relations, and efficient querying across inspections. The proposed methodology establishes a reproducible workflow from pixel-level damage detection to ontology-aligned knowledge graphs, supporting integration with digital twins and automated decision-support systems for infrastructure diagnostics and lifecycle management.

Keywords: Structural health monitoring, semantic segmentation, DACL dataset, concrete damage ontology, knowledge graph

* The full paper is open access available in the Conference Proceedings. *



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Synthetic data generation for visual damage recognition of aging bridge structures using 3D engine-based simulation

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Keywords: Aging bridge; synthetic data; visual damage recognition; 3D engine simulation; object detection

1. Introduction

Recent advances in artificial intelligence (AI) have enabled automated structural damage assessment in post-disaster environments. However, AI-based inspection models require large-scale annotated datasets, which are difficult to obtain for aging bridge structures because damaged sites are unsafe, access is limited, and manual annotation is costly. As a result, available datasets are often insufficient and imbalanced, limiting model generalization. To address this issue, synthetic data generation using virtual simulation has emerged as a practical alternative. In this study, the target use case is visual damage recognition of aging bridge structures, including bridge decks, piers, girders, and connection regions, under disaster or extreme loading scenarios such as earthquakes, floods, vehicle impact, ground weakening, and extreme rainfall. The considered damage features include cracks, local fracture, spalling, and debris. This study develops a 3D engine-based simulation framework for synthetic bridge damage data generation. Physics-based damage simulation is used to generate damage patterns, and Unreal Engine is used to render synthetic images under varying viewpoints, lighting conditions, and camera distances. A SAM2-assisted annotation process and YOLO-based object detection model are then used to evaluate the feasibility of synthetic data for visual damage recognition. Vision-language models (VLMs) are discussed as a future extension for semantic disaster-scene interpretation.

The main contributions of this study are as follows:

- Development of a 3D engine-based synthetic data generation pipeline for aging bridge damage scenarios,
- Preliminary validation of SAM2-assisted YOLO-based damage recognition using real, synthetic, and mixed datasets,
- Discussion of VLM integration as a future extension for semantic disaster-scene interpretation.

2. Methodology

2.1. Overall framework

This study proposes a 3D engine-based framework for generating synthetic bridge damage data and training a visual damage recognition model. As shown in Fig. 1, the proposed pipeline consists of three stages: physics-based damage simulation, synthetic image generation, and damage detection model training. First, damage patterns such as cracks, local fracture, and debris are generated using Houdini by assigning material properties and applying physics-based simulation. Second, the simulated damage models are imported into Unreal Engine, where synthetic images are rendered under different viewpoints, lighting conditions, camera distances, and environmental backgrounds. Third, the generated images are annotated with SAM2-assisted refinement and used to train a YOLO-based object detection model for visual damage recognition.

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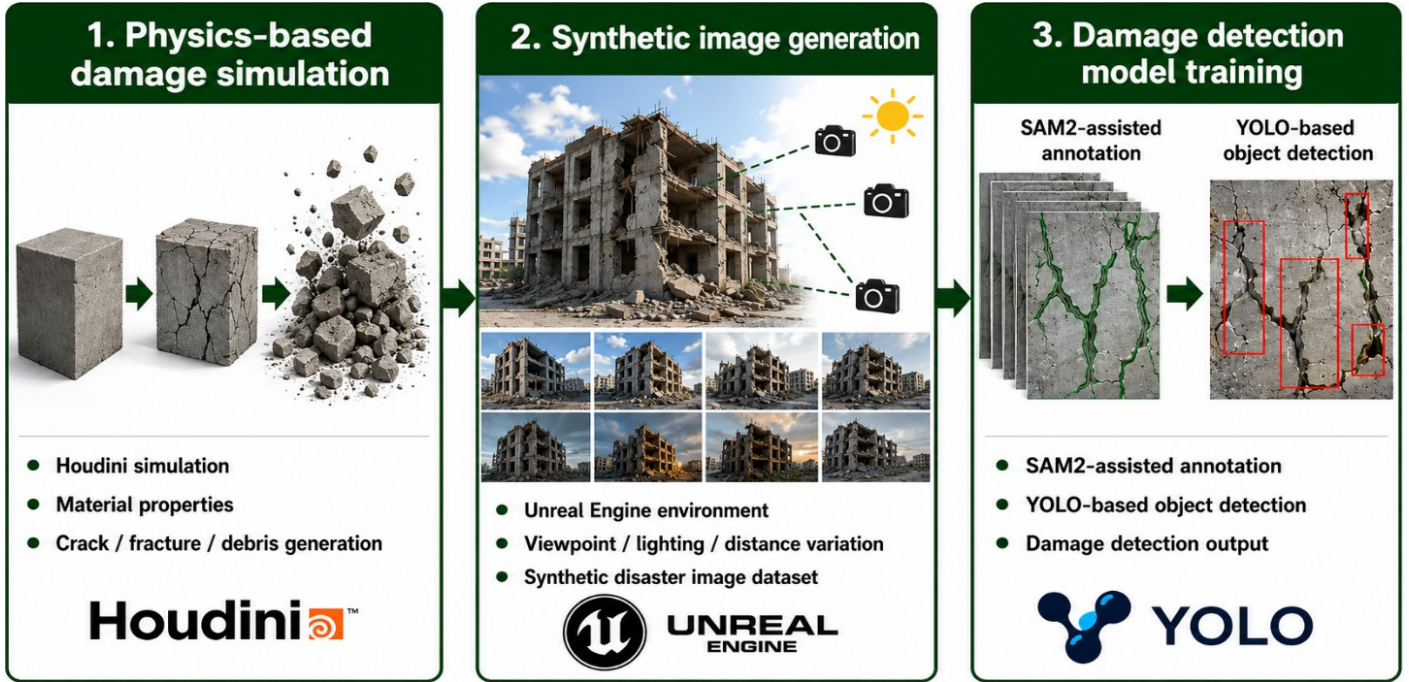


Fig. 1. Overall pipeline of 3D engine-based synthetic data generation and visual damage detection. The representative virtual disaster scene illustrates the simulation-to-detection workflow, which is designed for aging bridge damage recognition.

2.2. Synthetic dataset generation

Synthetic images are generated by capturing bridge damage scenarios from the virtual environment under varying visual conditions. The target damage features include cracks, local fracture, spalling, and debris on aging bridge components such as decks, piers, girders, and connection regions. The simulation environment allows repeated image acquisition from different camera viewpoints and lighting conditions, which helps increase dataset diversity while reducing manual data collection efforts.

For model training and validation, three dataset settings were prepared: real-only, real-plus-simulation, and simulation-only. Each setting contains 12,000 images with a resolution of 720×640 pixels, divided into 10,000 training images and 2,000 validation images. The real-plus-simulation setting contains an equal proportion of real and synthetic images. This comparison was designed to evaluate the feasibility of synthetic data as a training source when real post-disaster bridge data are limited.

2.3. Structural damage recognition

A SAM2-assisted annotation process was used to refine damage labels before training. The refined annotations were used to train an Ultralytics YOLOv8-based object detection model to identify visual damage features. The model was trained for 50 epochs with a batch size of 16. Training and testing were performed on a Windows 10 Pro workstation equipped with an Intel i5-11500 CPU, an RTX 3060 GPU, and 16 GB RAM.

2.4. Potential integration of vision-language models

Although this study focuses on visual damage detection, VLM integration is considered as a future extension for semantic disaster-scene interpretation. In future work, the detection results can be linked with natural-language descriptions to support automated reporting and decision-making for bridge disaster response.

3. Results and discussion

Table 1 compares the performance of the SAM2-assisted YOLO-based visual damage detection models trained using three dataset settings: real-only, real-plus-simulation, and simulation-only data. The comparison was conducted to examine whether synthetic images generated from the proposed 3D engine-based simulation framework can provide useful training data for visual damage recognition of aging bridge structures.

In the current validation setting, the simulation-only model achieved the highest Precision of 63.72%, Recall of 74.95%, F1-score of 68.61%, Accuracy of 96.2%, and mIoU of 51.83%. This result indicates that synthetic data can provide consistent and controllable training signals when real post-disaster bridge images are scarce. The representative detection outputs included in Fig. 1 qualitatively illustrate that the trained model can localize crack-like damage regions from visual inputs, supporting the feasibility of the proposed synthetic data generation pipeline.

Table 1. Performance comparison of SAM2-assisted YOLOv8-based visual damage detection models trained with different datasets.

Model	Metrics (%)				
	P	R	F1	Acc	mIoU
A: Real	59.52	69.95	63.96	89.7	49.73
B: Real + Simulation	60.63	71.32	65.35	91.6	48.98
C: Simulation	63.72	74.95	68.61	96.2	51.83

However, this result should be interpreted with caution. The higher performance of the simulation-only model does not necessarily mean that synthetic data are superior to real-world data. It may be affected by the controlled visual distribution, consistent annotation quality, and reduced background noise of the simulation dataset. In addition, Accuracy alone may overestimate model performance when damaged regions occupy only a small portion of the image. Therefore, F1-score and mIoU should be considered together for evaluating damage detection performance.

The current evaluation is a preliminary validation rather than a complete demonstration of real-world generalization. Since real bridge inspection images may include complex backgrounds, weather effects, shadows, sensor noise, material deterioration, and irregular crack patterns, further cross-domain validation using independent real-world bridge images is required. Future work will focus on reducing the simulation-to-real domain gap and expanding the dataset to include more bridge components, damage types, and environmental conditions.

4. Conclusion

This study proposed a 3D engine-based synthetic data generation framework for visual damage recognition of aging bridge structures. The proposed pipeline consists of physics-based damage simulation, Unreal Engine-based synthetic image generation, SAM2-assisted annotation refinement, and YOLO-based object detection model training. The framework was designed to generate damage images under varying viewpoints, lighting conditions, camera distances, and environmental backgrounds.

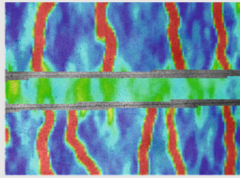
The experimental comparison using real-only, real-plus-simulation, and simulation-only datasets showed that synthetic data can support AI-based visual damage recognition when real post-disaster bridge data are limited. Nevertheless, the present results should be regarded as preliminary feasibility evidence, because independent real-world bridge validation has not yet been fully conducted. Future work will focus on cross-domain evaluation, simulation-to-real domain adaptation, expansion to additional bridge components and damage types, and VLM-based semantic interpretation for automated disaster-scene reporting.

Acknowledgements

This research was supported by the National Research Foundation of Korea (NRF) grants funded by the Korean government (MSIT) (RS-2024-00336270) and (RS-2025-02223612). In addition, this research was supported by Korea Environment Industry & Technology Institute (KEITI) through Climate Resilient R&D Project for Water-Related Disaster Management, funded by Korea Ministry of Climate, Energy, Environment (MCEE)(RS-2024-00335526).

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MS28: Impact of climate change on infrastructure

Organizer:

Julian Unglaub (TU Braunschweig, Germany)

ABSTRACT

The accelerating pace of climate change is reshaping the risk to infrastructures worldwide. Extreme temperature spikes, intensified precipitation, sea-level rise and an increased frequency of wind and flood events are already compromising the serviceability and safety of bridges, tunnels, railways, and other lifeline assets. While traditional design codes rely on historical climate envelopes, the emerging reality demands a proactive, data-driven approach that couples real-time condition assessment with adaptation and mitigation strategies. Key topics include: impact scenarios based on climate-change projections; quantifying climate-induced degradation; infrastructure management frameworks; SHM-based asset-management to promote proactive retrofitting; decision support under uncertain conditions; and adaptive structural design solutions.

Inspection of rail and road infrastructure considering climate change related effects

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Abstract

Advancements in geotechnical design and construction between 1950 and the late 1980s expanded transport infrastructure into alpine regions with complex geological conditions. Today, the long-term operation of these assets is increasingly challenged by structural aging, natural hazards, and climate change. Current inspection practices rely on regular visual assessments and reactive adaptations but lack the proactive integration of environmental data necessary to address accelerating climatic variability. The research project MORICE addresses these challenges by investigating climate-induced damage processes and integrating remote sensing with hydro-chemical in-situ diagnostics into traditional inspection strategies. By leveraging spatial statistics, the project links climate simulations with infrastructure networks to identify high-risk areas and propose remote-sensing-based methods for monitoring terrain stability. Field investigations demonstrate that altered water chemistry - often exacerbated by the application of de-icing agents - triggers complex ion exchange reactions that accelerate mineral scaling and clay neoformation, leading to systematic drainage clogging. Furthermore, this study presents methods for adapting asset management, particularly structural and geotechnical assessments, to enable the identification and evaluation of climate-related impacts. These approaches provide a framework for the early detection of climate-induced damage, supporting resilient hazard management and informing future national inspection standards.

Keywords: Infrastructure asset management; inspection; climate resilient; climate change; natural hazards

* The full paper is open access available in the Conference Proceedings. *

Climate change effects on the durability and reliability of reinforced concrete structures

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Abstract

Climate change is posing new challenges for the design of civil engineering structures both in terms of accelerated material degradation processes and shifts in the frequency and intensity of climate extremes. Traditional design approaches based on stationary climate conditions are currently discussed and time dependent reliability analysis is gaining attention. The paper presents a method to quantify the effects of global warming on the service life and long-term reliability of reinforced concrete structures designed according to the Eurocodes and exposed to chloride induced corrosion. The proposed probabilistic approach considered all the uncertainties related to material properties and kinetics of corrosion processes, combined with those related to climate variability and scenarios. The effect of non-stationarities on service life and ultimate limit state is examined with reference to a benchmark reinforced concrete slab designed according to the second generation of structural Eurocodes. Reliability levels are evaluated for XS exposure conditions considering different cement types of cement (ordinary Portland, fly-ash and slag) and accounting for the expected temperature variations predicted by downscaled, high-resolution climate projections for Italy from the new generation of Shared Socioeconomic Pathways (SSP) climate scenarios. These first outcomes suggest that the impact of climate change on the service life limit state induced by chlorides is relatively limited. At the same time, the findings confirm the need to integrate climate-change considerations into structural design to ensure target reliability levels over time, particularly in the case of reinforced concrete structures built with Ordinary Portland Cement (OPC).

Keywords: Reinforced concrete, durability, reliability, climate change.

* The full paper is open access available in the Conference Proceedings. *

Alternative evaluation approach to determine the chloride migration coefficient

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Abstract

One element in achieving climate targets in the construction sector is the modification and development of new binders to reduce the carbon footprint of concrete. In this context, alternative binders are currently being developed, such as Ordinary Portland Cement (OPC) based composite cements with alternative additives as well as calcium sulfoaluminate cements and alkali-activated materials. Performance tests have been carried out to characterize the performance of these new building materials. With regard to the resistance of concrete towards chloride penetration, experiences show that determining this resistance by using the chloride migration test can be challenging in some cases, as the indicator used in the test evaluation does not provide a significant color change for some binders. The paper presents alternative evaluation options for the chloride migration coefficient that do not require the application of an indicator and thus enable the determination even for building materials for which the indicator produces no significant color change. Two evaluation options by directly using the information from chloride ingress data are presented. The alternative methods show good agreement with the conventional approach, although larger deviations may be observed for one method when using binders with a higher chloride-binding capacity.

Keywords: durability; chloride ingress; chloride migration test

* The full paper is open access available in the Conference Proceedings. *

The use of hyperspectral imaging for chloride detection in concrete in the presence of chloride-induced steel corrosion and protective coatings

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Abstract

Concrete is a widely used construction material; however, it is prone to environmental deterioration. Chloride penetrates the concrete and causes chloride-induced corrosion of embedded steel reinforcement, compromising the integrity and service life of concrete. Therefore, early detection of chloride ingress is critical in durability assessment. This work investigates the application of hyperspectral imaging (HSI) in the short-wave infrared (SWIR) as a non-destructive, non-contact technique for detecting chloride intrusion in the near-surface zone of concrete structures. This study aims at chloride detection on the concrete surface, further evaluates the influence of corrosion products accumulating at the surface, and the effect of common protective coating on the measured spectral response and the detection accuracy. Two paint systems were used in this study, including acrylic-based water-repellent coating and pigmented polyurethane paint. Different chloride concentrations (0%, 3.5%, and 7%) were used to simulate different exposure scenarios. Our findings show that rusty colors do not affect the spectral measurements in the SWIR range but affect the Red-Green-Blue (RGB) reflectance. In addition, the electromagnetic signals of light were observed to fully penetrate transparent sealer, whereas pigmented paint systems can prevent the penetration of light. This will enable early chloride detection in the near-surface zone, improving durability assessment of concrete structures exposed to harsh environments.

Keywords: Chloride detection; concrete protective coating; spectroscopy imaging; reinforced concrete; structural assessment

* The full paper is open access available in the Conference Proceedings. *

Towards system identification of degraded prestressed concrete bridges

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Abstract

Prestressed concrete bridges from the mid-20th century form a critical part of Germany's infrastructure, now facing accelerated degradation due to increased loads and extreme climate conditions. Internal tendon corrosion compromises residual capacity, while conventional non-destructive testing remains ineffective for early detection. Acoustic emission can signal cracking but lacks quantification.

This study presents an inverse system identification framework combining a high-fidelity finite-element model with adjoint-based sensitivity analysis to localize and quantify tendon and concrete damage. The model is parameterized element-wise by concrete's Young's modulus and tendon's cross-sectional area. A gradient-based optimization algorithm identifies these parameters using only sparse displacement or strain measurements. Gradients of the discrepancy between simulated and measured structural responses are computed efficiently via the adjoint method. This framework not only advances structural health monitoring under intensified climatic loading but also informs maintenance planning, thereby enhancing the safety of aging prestressed concrete bridges

Keywords: Prestressed concrete; structural health monitoring; system identification; digital twin; adjoint method; damage localization

* The full paper is open access available in the Conference Proceedings. *

From inspection to maintenance: an AI-driven tool to optimize maintenance and its planning

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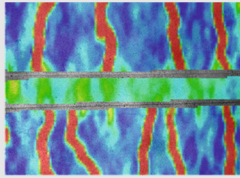
Abstract

This presentation highlights the use of the Civil Engineering Assistant (CEA) platform, developed by KnowCE and adopted by DiMoRe, for the digital inspection. The innovative application has been tested on a full-scale pilot bridge project in Italy. Starting from a 3D model built from thousands of high-resolution images, the platform identifies and analyzes concrete defects as well as possible causes and evaluates them in accordance with the Italian Bridge Inspection Guidelines.

AI algorithms, validated by human experts, support the detection and classification of each defect, along with the automatic calculation of k_1 , k_2 , G , and a priority index. Structural assessments of both individual components and the overall structure are generated automatically. The platform also produces a final report including all key indexes and the necessary data to assign the "Attention Class" for engineering evaluation. The software comprises also of a newly developed maintenance module to support the efficient planning of restoration interventions. The aim of this contribution is to demonstrate the customizability of the CEA platform originally developed for different national regulations and assessment standards for bridge inspections like Italy and Austria.

Keywords: Digital inspections; bridges; defects; maintenance; assessment

* The full paper is open access available in the Conference Proceedings. *



SMAR 2026



SMAR 2026 - 8th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

MS29: Distributed acoustic sensing (DAS) in civil engineering

Organizers:

Katarzyna Zdanowicz (FOLAB GmbH, Germany)

Christos Karapanagiotis (BAM, Berlin, Germany)

Bertram Richter (TU Dresden, Germany)

ABSTRACT

Distributed Acoustic Sensing (DAS) is an emerging technology in structural health monitoring, transforming conventional optical fibers into dense arrays of high-resolution vibration sensors. This mini-symposium will bring together academics and practitioners to highlight recent advances in DAS-based monitoring in civil engineering. Contributions are invited that demonstrate how DAS enables (i) vehicle-induced load assessment on bridges, (ii) real-time recording of vibrations for various monitoring purposes, and (iii) early warning of tendon failures, cracking or other damage mechanisms in prestressed and reinforced concrete structures. Case studies illustrating practical deployments, AI-enhanced signal processing or multi-parameter (DAS + DTS/DSS) approaches are particularly welcome. By showcasing field data and monitoring strategies or concepts, the session will contribute to a roadmap towards resilient, data-driven infrastructure management and foster collaboration between the civil engineering and fiber-optic communities.

Development towards a high frequency acoustic emission distributed acoustic sensing system

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Abstract

Distributed Acoustic Sensing (DAS) has become an established technique in civil, geophysical and geotechnical engineering during the last decades. Its capabilities to cover a large region of interest by a single optical fiber with a relatively high spatial and temporal sampling has unlocked applications and data processing strategies which are limited almost exclusively by the amount of data. Acoustic emission monitoring (AE) for structural health monitoring (SHM) is another well-suited application, especially for large structures where conventional multi-channel systems become uneconomical. So far, promising results regarding the monitoring of high energy emissions in the lower kilohertz range were provided. However, current commercially available DAS systems lack in comparison to conventional AE systems in terms of Signal-Noise-Ratio (SNR) and waveform retrieval capabilities, especially for high frequency and low energy emissions. In those cases, the trade-off between gauge length and SNR in combination with the fiber arrangement often leads to destructive interference falsifying the waveform till complete undetectability. In this work we propose fiber arrangement and signal processing strategies to overcome those issues on the example of acoustic emission measurements on a steel pipe. The strategies are validated by analytical model and experimental lab data, measured with two different DAS and one conventional AE system.

Keywords: Acoustic emission waveform retrieval; structural health monitoring; guided elastic waves; ultrasonic guided waves

* The full paper is open access available in the Conference Proceedings. *

Distributed acoustic sensing for detection and localization of steel wire breaks

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Abstract

A common form of suspension bridge cable deterioration is the loss of cross-sectional area due to wire failures. Buried among tens of thousands of identical wires in the cable, broken wires are difficult to detect comprehensively by visual inspection. Repairing these breaks is generally infeasible, with full re-cabling being prohibitively expensive and disruptive. It is therefore imperative that bridge owners take an active role in managing cable health. A key tool for maintenance decision making is acoustic emission (AE) monitoring, where sensors are used to detect the elastic stress waves emitted as wires fail. Conventionally, by using multiple AE point sensors the position of the break along the cable is often estimated along its length. The alternative investigated here, distributed acoustic sensing (DAS), is a form of fiber optic sensing which can surpass spatial density limitations of traditional point sensors while still sampling the observed wavefield at kHz-range sampling rates. These advantages offer an opportunity to improve event detection reliability and, with multiple fibers, enable three-dimensional localization of failure sites. Two experiments were conducted to validate the proposed ability of DAS to detect and localize wire failures. In the first experiment, a braided steel rope was tensioned and individual wires cut while recording with the DAS system. The data clearly shows AE wave propagation along the cable. To localize the wire break from the DAS data, an algorithm was developed using an iterative wavefront refitting procedure. The proposed method, applied to DAS data taken at a sampling rate of 100 kHz, is shown to be capable of localizing wire breaks with sub-meter resolution, below the spatial resolution of the DAS system. In a second experiment, six steel wires were positioned within a 3.60 m long grout specimen with fiber optic cables epoxied externally. The cross-section of each wire was reduced beforehand at a known location to induce spatially controlled failures within the specimen. Each wire was then individually tensioned to failure. The data again clearly shows AE wave propagation. The resulting wavefield is then investigated using various signal processing approaches; the clarity of the wave front arrival is heavily influenced by filtering, as expected.

Keywords: Acoustic emission; structural health monitoring; fiber optic sensing; distributed acoustic sensing; bridge monitoring

* The full paper is open access available in the Conference Proceedings. *

Distributed acoustic sensing for bridges – from traffic monitoring to damage detection

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Abstract

The continuous monitoring of bridge structures is essential to ensure their structural safety, serviceability, and long-term durability. In addition to conventional sensing systems, fibre-optic measurement technologies, collectively known as Distributed Fibre Optic Sensing (DFOS), have been gaining increasing attention as a robust and scalable alternative. Among these, Distributed Acoustic Sensing (DAS) provides unique capabilities for dynamic measurements by enabling acquisition of vibrations and sudden acoustic events along an optical fibre with high temporal and spatial resolution. This study explores the application of DAS for structural health monitoring (SHM) of bridge structures, with a focus on its potential to capture traffic-induced dynamic responses and damage-related phenomena. DAS measurements allow for the detection and characterization of vehicle passages in road and railway bridges, as well as the early recognition of critical events such as tendon failures caused by stress corrosion cracking. The distributed sensing approach provides quasi-continuous coverage of large structures without the need for discrete sensor installation. Practical examples from full-scale bridge measurements in Germany are presented to demonstrate the performance and challenges of DAS in real-world conditions. The results highlight the potential of DAS to complement and enhance existing monitoring strategies, paving the way for its integration as a key technology in the next generation of structural health monitoring systems

Keywords: Distributed acoustic sensing; bridges; structural health monitoring; traffic monitoring; damage detection

* The full paper is open access available in the Conference Proceedings. *

Simultaneous assessment of bridge traffic and bridge response with distributed acoustic sensing

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Abstract

Distributed Acoustic Sensing (DAS) enables continuous, spatially distributed vibration measurements along the full length of optical fibers. This setting offers a scalable alternative to conventional sensing in structural health monitoring. A single interrogator can monitor tens of kilometers with meter-scale spatial resolution and kilohertz sampling rates. Although over the last decade DAS has been used increasingly for seismic monitoring, traffic surveillance, and Third Party Intrusion (TPI) detection, its application to civil structural monitoring particularly for separating excitation sources from structural response remains limited. This paper reports a case study where DAS captured the dynamic response of a bridge induced by traffic. A sensing cable originally installed for Distributed Strain Sensing (DSS) was mounted along one girder of a single-span bridge. Data was collected under normal operation, capturing heterogeneous traffic scenarios including buses, trucks, and passenger vehicles. A signal processing framework through filtering and dedicated processing is proposed to separate traffic-induced excitation from intrinsic structural response. The results demonstrate reliable separation of excitation and response components. Enabling simultaneous tracking of traffic activity and structural frequency characteristics.

Keywords: DFOS; DAS; distributed acoustic sensing; traffic monitoring; bridge monitoring

* The full paper is open access available in the Conference Proceedings. *

Bridge traffic load monitoring using distributed acoustic sensing and machine learning

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Abstract

In this paper, we report on traffic load monitoring on a frame bridge instrumented with embedded optical fibers using distributed acoustic sensing (DAS) assisted by machine learning and computer vision algorithms. Specifically, we demonstrate that our DAS system can capture vehicle flows along the bridge, including a) the number of vehicles, b) their velocities and c) the number of axles. Vehicle detection was performed using a pretrained convolutional neural network (CNN)-based state-of-the-art object detection model (YOLOv8), achieving a true positive rate of 100 % (165 out of 165 vehicles successfully detected). Furthermore, the model achieved a high precision score of 98.2 %, highlighting its robustness. Vehicle velocities were calculated using a computer vision technique based on gradient-based structure tensor analysis. In addition, the number of axles and the spacing between them were calculated using a peak detection algorithm. The accuracy of the axle spacing calculation was evaluated through experiments involving a vehicle with a known axle configuration. Our results show that the use of DAS can enable data-driven and reliable traffic load modeling for road bridges, thereby contributing to the digital transformation of infrastructure monitoring and quality assurance.

Keywords: Distributed fiber optic sensing; distributed acoustic sensing; structural health monitoring; machine learning; traffic models

* The full paper is open access available in the Conference Proceedings. *

Vehicle weigh-in-motion (WIM) along roadways with distributed acoustic sensing (DAS)

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Abstract

Vehicle weigh-in-motion (WIM) using distributed acoustic sensing (DAS) deployed on fiber optic cables along roadways offers unique potential to fill the gaps between discrete traditional WIM sensors and provide continuous WIM coverage. However, the direct contribution of vehicle weight and speed to the DAS-measured signal remains uncharacterized, often masked by fiber installation conditions and vehicle-to-vehicle variability. This study addresses this gap by deploying DAS on a fiber optic cable-instrumented roadway to investigate DAS measurement sensitivity to vehicle weight and speed. Controlled experiments were conducted using a cargo vehicle with known empty weight, driven along the roadway with various additional loads (0%, 35%, and 70% of maximum allowable vehicle load) at multiple speeds (8, 16, and 32 km/h). The influence of fiber optic cable installation location (asphalt pavement-embedded vs. trench-buried) and cable type (tight-buffered vs. loose-tube) was assessed. Findings demonstrate two dominant trends in the DAS-measured strain at the measurement point along the fiber closest to the passing vehicle: increased vehicle weight leads to increased strain waveform amplitude, and increased vehicle speed results in shortened strain waveform duration. Notably, trench-buried fiber optic cables, which are representative of existing roadside telecom fiber, also demonstrated sensitivity to vehicle axle-specific load characteristics. This study presents a reproducible framework for DAS system deployment and signal processing for WIM applications under field conditions.

Keywords: Distributed acoustic sensing (DAS), weigh-in-motion (WIM), roadway vehicle monitoring

* The full paper is open access available in the Conference Proceedings. *

Crack detection on road surfaces using distributed acoustic sensing (DAS)

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Abstract

Crack detection on road surfaces using distributed acoustic sensing (DAS) offers a promising approach for the continuous, long-distance monitoring of road infrastructure, complementing the limitations of conventional visual and image-based inspection methods. While the main focus of previous distributed fiber-optic sensing studies was pipeline monitoring or vehicle-induced responses, walking-induced dynamic DAS signals for pavement crack detection remain underexplored. This study examines how pavement surface cracks affect strain transfer to pavement-embedded fiber-optic cables by analyzing DAS responses from controlled pedestrian walking on a smart road containing wide cracks, small cracks, and intact sections. The responses were evaluated using frequency-band energy (FBE) and strain-based metrics. The results indicate that wide surface cracks cause pronounced attenuation of the strain transfer to the embedded fibers, whereas sections with small or no visible cracking exhibit comparable responses regardless of the walking route or position. This attenuation persists after normalization by body weight and is consistently observed across multiple metrics, indicating a crack-induced mechanical origin rather than geometric edge effects or inter-subject variability. These results highlight the potential of DAS as a low-cost, complementary tool for detecting pavement crack degradation under low-amplitude, quasi-static loading.

Keywords: Distributed acoustic sensing (DAS); pavement cracking; structural health monitoring; fiber optic sensing; road infrastructure

* The full paper is open access available in the Conference Proceedings. *

Monitoring of long-distance structures with DAS: from local tests to 70 km remote interrogation

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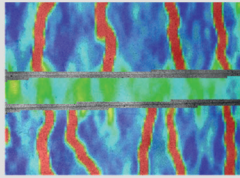
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Abstract

Long-distance structures pose significant engineering challenges not only during construction but also in terms of long-term maintenance. Many of these structures are located in remote, hard-to-access areas with poor cellular reception. However, most of them - such as pipelines - are equipped with fibre-optic cables. These networks can be utilized to connect fibre-optic sensors and develop Structural Health Monitoring (SHM) systems in the parts of the structures most exposed to risk. When combined with Distributed Acoustic Sensing (DAS), such systems can become highly robust, enabling a central interrogation unit to monitor hundreds of kilometres of structure from a single remote location. In this paper, the authors present the results of tests carried out first locally and then from a connection centre located 70 km away. A series of experiments was executed in order to establish the response of the fibre to the dynamic events. The locally and remotely measured signals were compared in order to determine whether and how distance influences signal quality.

Keywords: DAS, pipelines, SHM, geotechnics, sensing

* The full paper is open access available in the Conference Proceedings. *



SMAR 2026



SMAR 2026 - 8th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

MS30: Video-based and imaging techniques for structural monitoring

Organizers:

Ivan Roselli (ENEA, Italy)

Stefano De Santis (Roma Tre University, Italy)

Marialuigia Sangirardi (University of Oxford, UK)

Alessandro Zona (University of Camerino, Italy)

ABSTRACT

Video-based and imaging techniques are promising tools for structural monitoring as both complementary or alternative methods to conventional ones, which require contact sensors to be physically located in measurement points. This represents a crucial issue, particularly for structural parts not easily or safely accessible, as well as in case of delicate and vulnerable historical constructions, which require minimal invasiveness. In laboratory experiments, the application of video-based and imaging techniques has also recently shown several advantages. A major advantage is that such methods generally require instruments easier and cheaper than those employed in traditional setups.

The Mini Symposium seeks to explore the latest advancements in this field with particular emphasis on: advances in digital image correlation applications to experimental tests; motion capture techniques for laboratory and real-field applications to structural monitoring; video-based methods and processing; image processing for structural monitoring; and applications to case studies.

Analysis of algorithms for real-time dynamic structural monitoring through computer-vision

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Abstract

Vision-based techniques are increasingly adopted in Structural Health Monitoring (SHM) to measure displacements without physical contact. Since the magnitude of structural motions is often small compared with the pixel size of video cameras, many vision-based approaches rely on subpixel estimation algorithms to improve measurement resolution. Several algorithms have been proposed in the literature, often based on interpolation or refinement procedures, and their performance may differ in terms of accuracy, robustness, and computational cost. This study aims to compare a set of commonly adopted subpixel displacement estimation algorithms in order to highlight their main strengths and limitations. Particular attention is devoted to the presence of systematic errors that may arise from the interpolation procedures. To perform a controlled and objective comparison, the analysis is conducted using computer-generated video sequences with exactly known imposed motion. In addition, controlled perturbations such as dynamic range reduction and digital noise are introduced to reproduce typical conditions encountered in practical video analysis and to examine how these factors influence the resulting displacement estimates. The algorithms are assessed in terms of accuracy, robustness, and computational efficiency under progressively more demanding conditions.

Keywords: Structural monitoring; bridge monitoring; computer-vision; systematic error; algorithm evaluation

* The full paper is open access available in the Conference Proceedings. *

Internal and external cameras for vision-based monitoring of buildings during shake-table tests

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Abstract

This paper presents a configuration combining internal and external cameras for monitoring absolute and inter-story displacements of multi-story buildings during full-scale shake-table testing. The internal and external cameras are arranged to work in a complementary configuration that enhances measurement accuracy and reliability through redundancy and noise compensation. The internal camera, mounted on the roof and pointing downward, captures the motion of multiple targets distributed along the building height, while the external camera provides an independent reference by tracking the roof displacement. Advanced computer-vision algorithms enable the extraction of high-resolution displacement time histories even under strong dynamic excitations and environmental disturbances. The methodology was validated during the testing of a full-scale six-story mass timber building on the Large High-Performance Outdoor Shake Table (LHPOST6) at the University of California San Diego. Results confirm the capability of the proposed approach to provide precise, redundant, and scalable displacement measurements, supporting its use in dynamic testing and structural health monitoring applications.

Keywords: Absolute displacements; inter-story displacements; shake-table testing; structural health monitoring; vision-based monitoring

* The full paper is open access available in the Conference Proceedings. *

Modal identification by phase-based motion magnification and comparison with classical methods

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Abstract

The analysis of natural frequencies and modal parameters plays a key role in assessing structural vulnerability, monitoring performance over time, and planning targeted strengthening or retrofitting interventions. Nowadays, modal identification techniques mainly rely on dedicated instrumentation which provide accurate measurements but are often expensive, complex to install, and difficult to apply—especially in historical or hard-to-access contexts. Within this framework, the Phase-Based Motion Magnification (PBMM) technique offers a video-based approach capable of amplifying imperceptible motions and visualizing subtle deformations, effectively transforming each pixel into a potential virtual sensor. The present work aims to validate the use of PBMM for the modal identification of real structures, evaluating its reliability and reproducibility under different operational conditions. Three case studies of varying typology and complexity were analyzed—the Quirino Majorana school building (Rieti), the bell tower of the Cathedral of Santa Maria Assunta (Rieti) and the Temple of Apollo Sosianus (Rome)—comparing video-based results with conventional instrumental measurements and finite element models. Dedicated MATLAB processing tools were developed, and two distinct approaches for spectral analysis based on selected Regions of Interest (ROI) were tested, defining operational criteria for parameter selection and result validation. In addition to confirming the capability of PBMM to identify modal frequencies with limited errors, the study highlights the most favorable acquisition conditions, the main sources of uncertainty, and practical strategies for its reliable application. The results outline a framework in which PBMM, despite its current limitations, emerges as a promising tool for non-invasive dynamic analysis of structures.

Keywords: Phase-based motion magnification; video-based modal analysis; structural monitoring; non-destructive evaluation; heritage structures

* The full paper is open access available in the Conference Proceedings. *

Insights into the dynamic behavior of an elevated water tank from computer vision-based SHM

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Abstract

The structural health monitoring (SHM) of ageing infrastructure is critical to ensure safety, prioritize maintenance, and preserve existing building stock. Elevated water tanks represent a particularly challenging class of structures due to their slender geometry, complex boundary conditions, susceptibility to material deterioration, and seismic vulnerability. Traditional vibration-based SHM relies on accelerometric data to detect changes in dynamic properties, but installation costs, maintenance requirements, and limited sensor coverage restrict its applicability. Recent advances in computer vision have introduced contactless, video-based techniques as a cost-efficient and non-invasive alternative. In this study, a reinforced concrete elevated water tank was investigated through a combined approach: simplified analytical and numerical predictions, accelerometric measurements, and computer-vision-based monitoring. Video data, processed via phase-based motion magnification and principal component analysis, enabled the extraction of fundamental frequencies and modal properties. The results demonstrated strong agreement with accelerometer-based measurements, while offering additional insight into structural response thanks to full-field, pixel-level tracking. This work highlights the potential of video-based monitoring to validate and complement standard techniques, providing a powerful tool for the dynamic identification and SHM of complex geometries.

Keywords: Computer vision; monitoring; modal identification; structural health monitoring; motion magnification

* The full paper is open access available in the Conference Proceedings. *

Structural health monitoring of civil infrastructure with neuromorphic cameras

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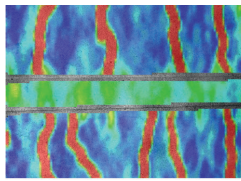
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Abstract

Structural vibrations can provide valuable insights from their fundamental dynamic characteristics, and detected changes in modal parameters can be an indicator of modifications in the structure's physical properties, possibly caused by damage or deterioration. Structural Health Monitoring is therefore crucial for early damage detection and assessment. Vibration analysis is mainly performed using physically installed sensors, a mature and reliable technology that offers high-precision data and an optimal signal-to-noise ratio but requires physical mounting, often in difficult access areas and, over time, maintenance and sensor calibration directly onto the structure, with time-consuming, costly, and potentially disruptive processes. In contrast, non-contact techniques work without physical installations, can monitor wide areas or multiple points simultaneously, and are often easier to set up or adapt to different structures, although with limitations in precision, temporal resolution, sensitivity under low light conditions, and/or data throughput. This work introduces a vision-based framework for non-contact modal analysis using neuromorphic cameras, a novel class of visual sensors that asynchronously record pixel-level brightness changes. The proposed method is validated in both controlled laboratory experiments on a cantilever beam and on a real-scale bridge specimen subjected to traffic-induced vibrations. The results demonstrate the feasibility and effectiveness of neuromorphic camera-based vibration monitoring for structural health assessment in real-world scenarios.

Keywords: Neuromorphic cameras, time surface, image processing, robust estimation, structural health monitoring

* The full paper is open access available in the Conference Proceedings. *



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Using motion capture and DIC for the monitoring of masonry structures under testing

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Keywords: Masonry structures; full-scale testing; motion capture; digital image correlation

1. Introduction

Stone and brick masonry structures are widespread in many countries. They represent half of the French heritage of bridges and retaining walls. As they age and face changing conditions (like pier settlement or heavier traffic loads), they require increasing preservation efforts. Testing models at various scales is a valuable way to better understand the behavior of this heterogeneous and anisotropic material, provided that the relevant measurement methods are used. As Boothby et al. (1998) demonstrate, contact sensors such as LVDTs have historically been widely used due to their simplicity and reliability. However, since they provide only unidirectional measurements at a single location and require significant installation effort, they are now supplemented by image-based measurement methods, as did Liu et al. (2024) on their brick bridge model.

Here, two image-based measurement methods, Digital Image Correlation (DIC) and Motion Capture (MoCap), will be tested on masonry structures. Although these methods are well established, their application to the monitoring of outdoor constructions remains rare. An overview of the experimental results obtained by applying DIC and MoCap to three masonry structures will be presented: 1) a full-scale experimental dry-stone curved retaining wall, 2) an 19th-century bridge, and 3) a half-scale experimental stone bridge, subjected to pier settlement. This feedback will enable better use of these techniques in future tests.

2. Description of DIC and MoCap

DIC is a method for automatically tracking the position of subsets of pixels across a series of successive images, leading to a two-dimensional displacement or deformation field of the surface of the studied structure (Jones et al., 2025). It relies on the use of a camera with sufficient spatial resolution to capture the displacements, and on the presence of sufficient contrast on the surface of the structure. Artificial speckles are used when necessary. This method is now well established in the field of structural monitoring, as it allows for great flexibility in post-processing and dense measurements. However, more experience is needed under outdoor conditions, specifically on large-scale structures exposed to changing weather conditions.

MoCap is a technology designed to track the 3D position of an object in space and time (Menolotto et al., 2020). A MoCap system is composed of several infrared cameras positioned around the object being tracked, and of spherical reflective markers attached to this object. Once the position of each camera is known thanks to a calibration process, triangulation is used to determine the position of the markers in real time. Unlike DIC, this method is much less commonly used in civil engineering. There are only a few examples of its use on construction models. For instance, Park et al. (2015) used it on a small-scale model of a three-story building for a free-vibration test, and Roselli et al. (2019) on a full-scale model of a masonry cross vault for shaking table tests. MoCap is particularly relevant for assessing the movement of masonry structures: by attaching three reflective markers to a single masonry block, its three-dimensional movement as a rigid body can be accurately determined. Since this system is particularly sensitive to changes in sunlight, using it outdoors remains a challenge.

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3. Application to large-scale tests

3.1. Dry-stone curved wall

In 2022, to assess the strength of a future retaining wall, an experimental curved dry-stone wall, 6 m long and 1.8 m high, was tested (Fig. 1.). After being filled with gravel, a jack applied a load to the surface of the filling until the wall failed. The displacement of the wall was followed by MoCap and laser tracker. The OptiTrack MoCap system consisted of 10 infrared cameras (Prime 17W and Prime X22) and 129 markers, glued in groups of three to the stones of the wall.

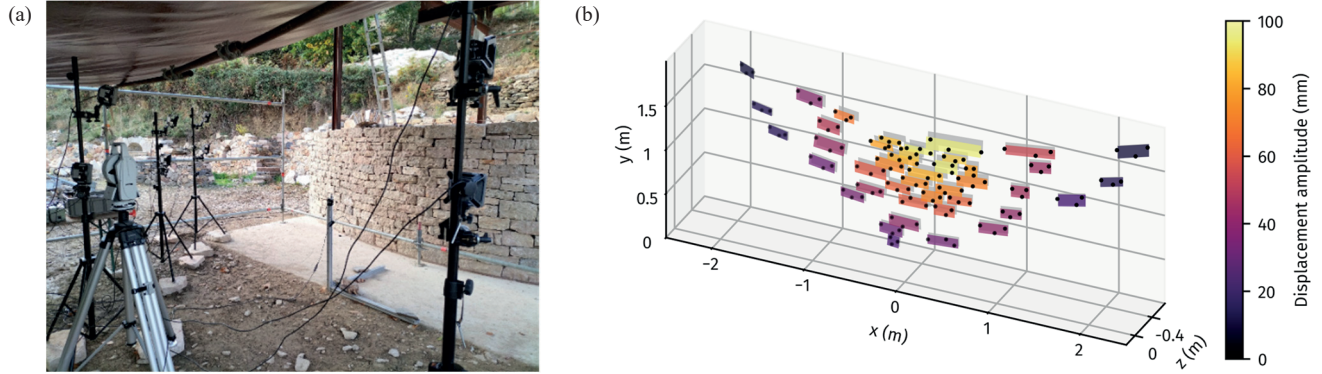


Fig. 1. (a) Monitoring setup in front of the dry-stone curved wall: MoCap cameras (in black) and laser tracker; (b) 3D displacements of the monitored stones at the end of the loading. Black dots represent the markers, grey rectangles the initial position of the stones, and colored ones their final position.

The data obtained were immediately usable after signal smoothing. Comparison with the laser tracker validated the 3D displacements obtained, and rigid-body (group of three markers on the same stone) analysis allowed the kinematics of the wall to be represented. In particular, the formation of a joint opening in the center of the wall was quantified from the displacements of the markers located on either side of the crack. This level of detail is possible thanks to the large number of markers that the MoCap system can track. Given the current accuracy of numerical models for masonry, having precise 3D information on joint openings is highly relevant for their validation.

3.2. Osserain ridge

Constructed in 1880 and located in the French region of Pyrénées-Atlantiques, the Osserain bridge was scheduled for demolition in 2023 as it had been replaced by a concrete bridge (Fig. 2.). As part of the national project DOLMEN (2021), numerous partners collaborated to take advantage of this opportunity to test measurement methods on masonry. The bridge was extensively instrumented, subjected to a load of 360 t, and then dismantled. Among the various measurement methods used, DIC and MoCap were implemented. A Vieworks VC-151MX-M6H00 high-definition camera (151 MP), was set up in front of the loaded arch, along with 10 OptiTrack infrared cameras and 141 markers screwed onto the bridge.

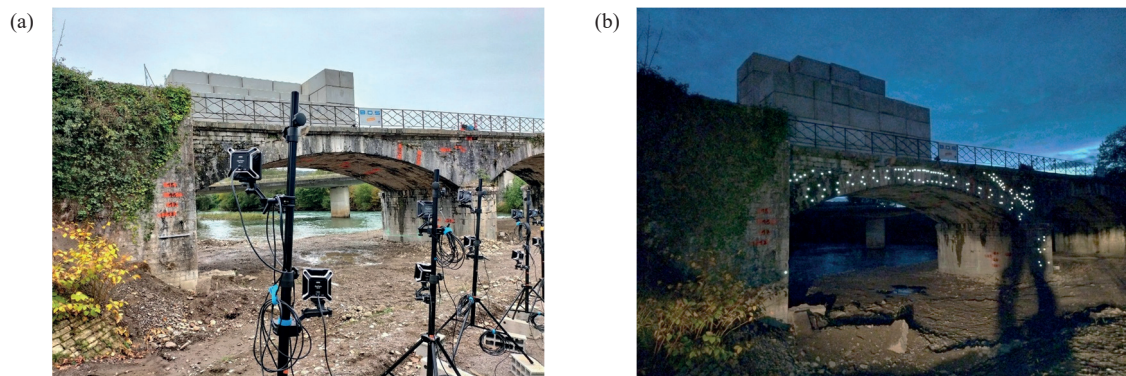


Fig. 2. (a) MoCap cameras in front of the left arch of the Osserain bridge; the concrete blocks laid on the bridge constitute the loading; (b) night view of the reflective markers on the bridge.

The cameras were set up on a temporary embankment that was not ideally positioned: they were far from the bridge and close to each other, which amplified the triangulation errors. Autumnal rain and variable illumination further complicated the OptiTrack system calibration and marker detection, necessitating more extensive post-processing than for the wall tests. Minor movements of the high-definition camera were corrected following Yoneyama et al. (2012). The resulting displacements were compared with

each other and with other measurement methods, allowing to identify the areas of the bridge where MoCap measurements were reliable. The natural surface texture of the bridge provided sufficient contrast for DIC, which proved more robust to weather-induced variability and effectively revealed the deformation mechanism of the bridge.

3.3. Model of a stone bridge subject to pier settlement

As part of an ongoing experimental campaign, DIC and MoCap are used to instrument an experimental 5-meter-long stone arch bridge undergoing central-pier settlement and loaded by a jack (Fig. 3.). Several configurations are tested: with or without spandrel walls and filling, and with or without mortar. The tests are conducted outdoors, and protective tarps are set up to protect against light fluctuations and rain. About a hundred markers are screwed into the stones, and an artificial speckled pattern is painted onto the bridge using a paint roller. In addition to the 10 infrared cameras and the high-definition camera, two more cameras are installed in front of the structure to enable stereovision. Two cable sensors and load cells are also included. Preliminary results from this campaign show a high degree of agreement among the various measurement systems. The versatility of image-based measurements opens the door to a wide range of post-processing applications, including block rotation, joint opening, and sliding.

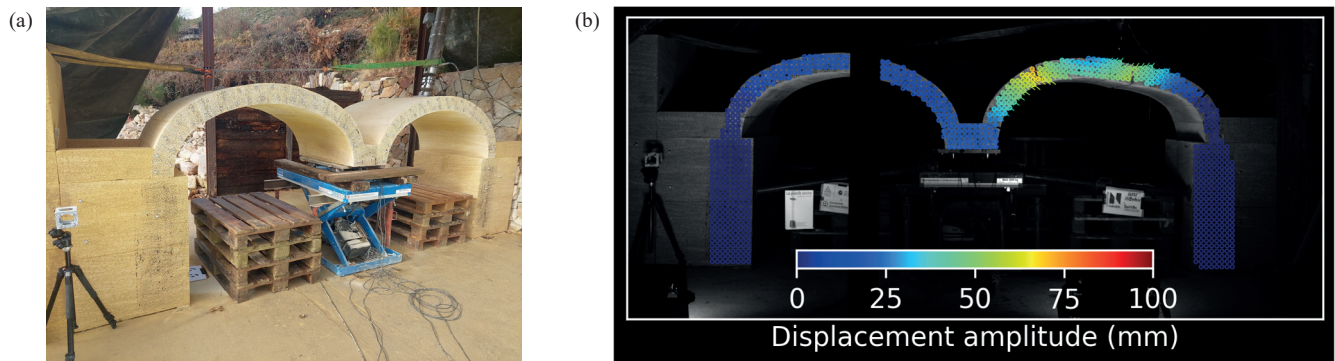


Fig. 3. (a) Arch bridge model with reflective markers and artificial speckle pattern; (b) displacement field of the settled bridge after the jack loading.

4. Conclusion

The various tests on masonry structures presented show that, provided they are properly installed and protected from adverse weather conditions, DIC and MoCap systems provide reliable and comprehensive measurements of the displacements of a structure. DIC requires more post-processing, and the algorithms can be somewhat time-consuming when applied to large images. However, the data obtained allows for a very thorough analysis of the tests, enabling a better understanding of the mechanical behavior of masonry. MoCap requires more setup and calibration work, but the data obtained consists directly of 3D displacements. Treating groups of three markers as rigid bodies makes it easier to understand a material in which the blocks can be considered rigid. Under the right conditions, these methods are therefore very useful tools for comprehensive contactless monitoring of masonry structures.

Acknowledgements

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Using in-situ computer tomography for crack development inside carbon-reinforced hollow core beams – comparison with DIC

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Abstract

Computed Tomography at the Gulliver portal at RPTU Kaiserslautern-Landau enables the investigation of cracks while loading a specimen (in-situ). Carbon fiber reinforced polymers (CFRP) placed inside concrete show a finer crack pattern than steel-reinforced concrete. Understanding the bearing behavior of carbon reinforced structures, which can be built with thinner cross-sections due to the corrosion resistance of CFRP, is an important step for new principles in carbon-reinforced concrete (CRC). In the present study, a hollow core beam of CRC was studied by crack analysis with the help of digital image correlation. The digital volume correlation of this specimen is presented in detail within another paper at this conference. The so-called alternating carbon-fiber reinforcement is a load-adaptive reinforcement, presented here in detail.

Keywords: Computer tomography, digital image correlation, carbon-reinforced concrete, hollow core beam, thin-walled structures

* The full paper is open access available in the Conference Proceedings. *

Sensitivity of DIC-based tensile modulus of elasticity evaluation in ultra-high-performance concrete at low strain levels

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Abstract

Digital image correlation (DIC) is becoming more common for measuring strain in ultra-high performance concrete (UHPC). However, evaluating low elastic strains remains challenging. The high stiffness of UHPC means that elastic strains are often close to the noise level of DIC, making the results highly sensitive to the evaluation strategy chosen. This study investigates how the DIC-based evaluation methods influence the determination of elastic strains in direct tensile tests on UHPC. The effects of virtual gauge length, cut position, region-of-interest definition and smoothing strategies are quantified. The results demonstrate that elastic strains derived from DIC can vary significantly depending on the evaluation parameters, even within the linear elastic range. A sensitivity analysis is conducted and recommendations are made to enable the tensile modulus of elasticity (MOE) of UHPC to be determined robustly at low strain levels. The analysis underlines the importance of evaluating the stress-strain behavior at multiple load levels and with a maximum virtual gauge length that excludes the peripheral areas. The MOE can be determined using the secant modulus or trend line slope, provided that the dispersion of the strain values remains limited.

Keywords: Digital image correlation (DIC); modulus of elasticity (MOE); ultra-high-performance concrete (UHPC); low strain levels

* The full paper is open access available in the Conference Proceedings. *

AI-based RC infilled frame cracks analysis by 3D motion capture displacements in shake table tests

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Abstract

Analyzing the relative displacements between markers of a high-speed vision-based system the behavior of the arising cracks, as well as the deformations and the development of kinematics and collapse mechanisms, of a structure specimen during seismic tests on shaking table tests were investigated. In this context, artificial intelligence (AI) can contribute to analyze the displacements time histories to identify and classify the fissures behavior. This study explored an AI procedure applied to a 2/3 scaled two-story reinforced concrete (RC) frame subjected to shaking table tests. The tested specimen has conventional infill walls with different connection conditions. The seismic shakes were based on recordings of the L'Aquila earthquake, 2009, with increasing scaling factors up to the collapse of the worst connected infill walls. A 3D motion capture system was used with particular focus on the relative displacements at the connections between RC frame and infill walls. A total of 136 markers covered with retro-reflecting coating tape were located at the most critical positions on the tested specimen. The tracking accuracy of the markers positions was assessed and utilized to estimate the cracks arising. The cracks identification was improved by an AI procedure.

Keywords: Artificial intelligence (AI), 3D optical motion capture, crack monitoring, damage, shaking table testing, RC frame, infill walls

* The full paper is open access available in the Conference Proceedings. *

Multitemporal and multimodal SHM for targeted tunnel inspection

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Abstract

Proactive, data driven tunnel maintenance is essential for reliable operation and cost-efficient asset management. This study advances image- and geometry based structural health monitoring by integrating multitemporal and multimodal data to produce decision ready indicators for inspection and renovation. The approach is demonstrated on a two-lane highway tunnel where structural defects were mapped over eight years using high-resolution, co-registered scans of the full tunnel surface. Beside structure from laser scanning and photogrammetry, we leveraged a compact multispectral descriptor set comprising high resolution visible cameras for surface sampling, thermal infrared imagery for temperature information, and laser intensity values for damage analysis. The multispectral dataset maps a high-resolution regular grid onto the orthorectified tunnel surface and is analyzed with advanced image analytics, complemented by geometry-based metrics. Targeted defect types were cracks, delamination, spalling, and voids or cavities. Results include defect maps, change detection maps highlighting deterioration patterns, hotspot regions, and quantitative evidence on the sensitivity and reliability of different modalities for defect localization and characterization.

Keywords: Tunnel SHM; inspection; change detection; sensor fusion; defect mapping

* The full paper is open access available in the Conference Proceedings. *

Integrated 360-degree imaging and digital forms: complementing dam visual inspections

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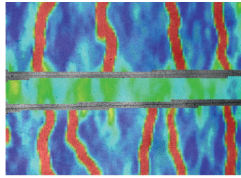
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Abstract

Traditional visual inspection of hydraulic structures, while crucial for maintaining dam safety and ensuring structural integrity, is often labour-intensive, time-consuming, and reliant on subjective manual documentation. This reliance on paper forms and disparate photographic evidence frequently results in data inconsistency, poor traceability, and reduced accessibility of critical historical condition records. This paper presents a novel and integrated methodology designed to complement and enhance essential on-site dam inspection protocols by combining high-resolution 360-degree panoramic imaging with custom-built digital inspection form systems. The proposed system utilises specialised 360-degree cameras to capture comprehensive, georeferenced visual records of the entire dam structure and its immediate environment. These immersive images serve as the foundation for the digital forms, allowing inspectors to accurately localise and annotate defects directly onto the visual data with precise spatial context. The digital forms enforce mandatory fields and standardise defect categorisation, significantly improving objectivity and consistency in documentation compared to traditional methods. Key findings demonstrate that this integrated solution considerably reduces on-site inspection time while simultaneously enhancing the quality, completeness, and auditability of the documented defects. Furthermore, the resulting 360-degree visual archive provides a permanent, easily navigable baseline for remote expert review and quantitative historical comparison, thereby improving collaboration and long-term asset management. This framework offers a safer, more efficient, and robust support tool for dam safety engineers, paving the way for the future integration of machine learning algorithms for automated defect detection and predictive maintenance planning

Keywords: Dam inspection; 360-degree imaging; digital forms; defect localization; asset management

* The full paper is open access available in the Conference Proceedings. *



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Distance-based fire risk classification on construction sites with Unreal Engine simulation validation

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Keywords: Fire risk classification, construction site safety, deep learning, Unreal Engine simulation

1. Introduction

Fire accidents at construction sites frequently arise from situations that develop prior to ignition, such as welding sparks, combustible material accumulation, and improper handling of heat sources. Because construction environments are highly dynamic and congested, once a fire ignites, it can spread rapidly, leading to severe casualties and substantial property damage. Recently, there have been advancements in virtual environments capable of simulating these dynamic and congested conditions, as illustrated by the virtual construction environment and fire simulation in Figure 1 (a) and (b). However, conventional fire detection systems primarily focus on identifying flames or smoke after ignition, which limits their effectiveness for early prevention and proactive safety management, as shown in Figure 2 (a) and (b). To address this limitation, this study proposes a pre-fire risk detection framework designed to identify risk situations before ignition.



Fig. 1. (a) Example of Unreal Engine environment (construction site); (b) example of Unreal Engine environment (fire simulation).

- First, the study introduces the concept of pre-fire risk detection, which focuses on recognizing visual indicators associated with potential fire ignition during construction activities.
- Second, a fire risk grading scheme is proposed to classify risk situations according to their severity and likelihood of fire occurrence.
- Third, to verify the practical feasibility of the proposed approach, a virtual construction environment is developed using Unreal Engine, where various fire-risk scenarios are simulated and evaluated.

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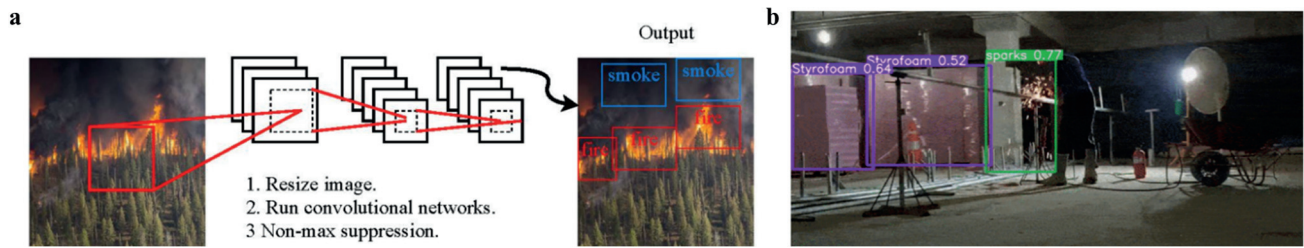


Fig. 2. (a) Architecture of a fire detection system using deep learning methods; (b) Example of fire risk detection at a construction site.

2. Pre-fire risk situations framework and results

This study introduces a National Fire Protection Association (NFPA) 51B-based pre-fire risk detection framework that recognizes visual indicators associated with potential ignition sources during construction activities, as shown in Figure 3 (a) and (b). The framework utilizes deep learning-based object detection to identify sparks (ignition sources), styrofoam (combustible materials), construction workers, and preventive measures. Because welding sparks typically occur near workers during hot work, the system uses the worker's location as a reference point to calculate the Euclidean distance to combustible materials, classifying fire risk levels in real time. The proposed distance-based risk levels are defined as follows:

- **Negligible Risk:** No critical risk situation is detected, or preventive measures are present.
- **Low Risk:** The distance between construction workers and combustible materials exceeds 11 m, satisfying the recommended safety clearance under NFPA 51B.
- **Medium Risk:** The distance is between 5 m and 11 m inclusive, indicating that combustible materials are located within the safety radius and require close monitoring.
- **High Risk:** The distance is less than 5 m, indicating a critical risk with a high likelihood of immediate ignition.

Direct empirical experiments involving fire scenarios during hot work at actual construction sites are highly restricted due to the risk of casualties and property damage. To overcome these limitations, this study developed a high-resolution 3D virtual construction environment based on Unreal Engine to reproduce fire-risk situations in a safe, controlled, and repeatable manner.

Figure 4 visualizes the intermediate outputs of the first two stages of the proposed framework. Figure 4(a) shows the 2D object detection results, while Figure 4(b) presents the depth map generated for 3D coordinate calculation. By integrating these processes, the system produces the final risk assessment results, as shown in Figure 5.

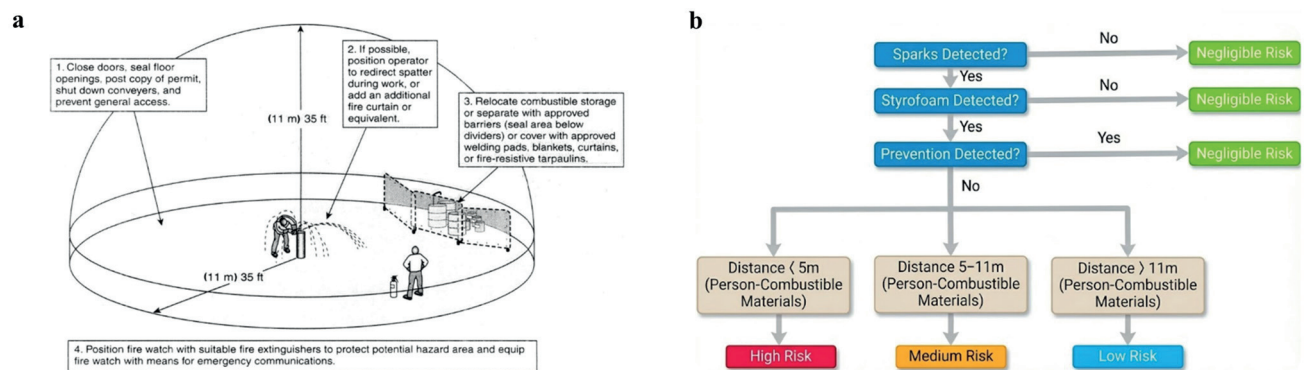


Fig. 3. (a) Fire safety perimeter requirements under NFPA 51B; (b) pre-fire risk situations framework.

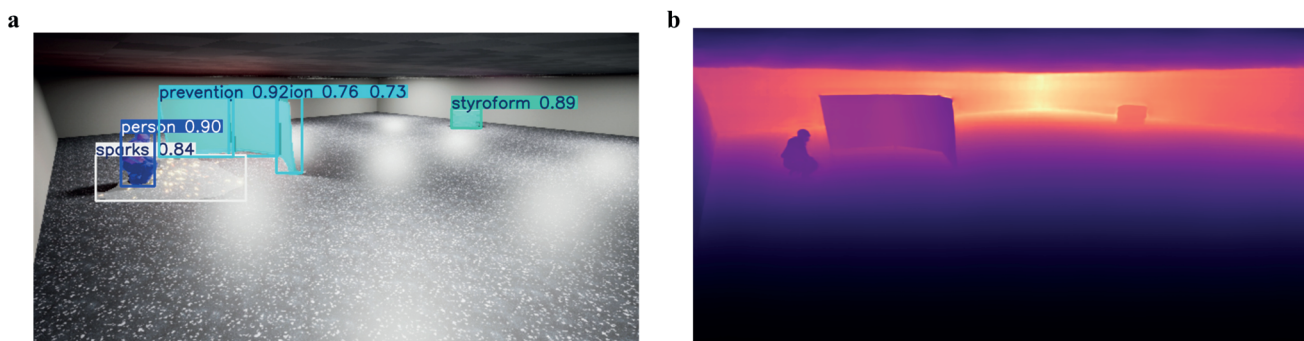


Fig. 4. (a) Object detection results for key elements; (b) depth estimation for 3D coordinate calculation.

Figure 5(a) illustrates a case in which the distance between a worker and a combustible material was estimated at 9.88 m in a virtual test scenario, resulting in a Medium Risk classification. In contrast, Figure 5(b) shows that, even under comparable distance conditions, the detection of a preventive measure near the worker led the system to downgrade the risk level to Negligible Risk. Because the preventive measure was incorporated into the risk assessment, the system classified the situation as safe, and the distance annotation was omitted in the final visualization. These results demonstrate that the proposed framework does not merely measure geometric distance but also supports contextual fire risk assessment.

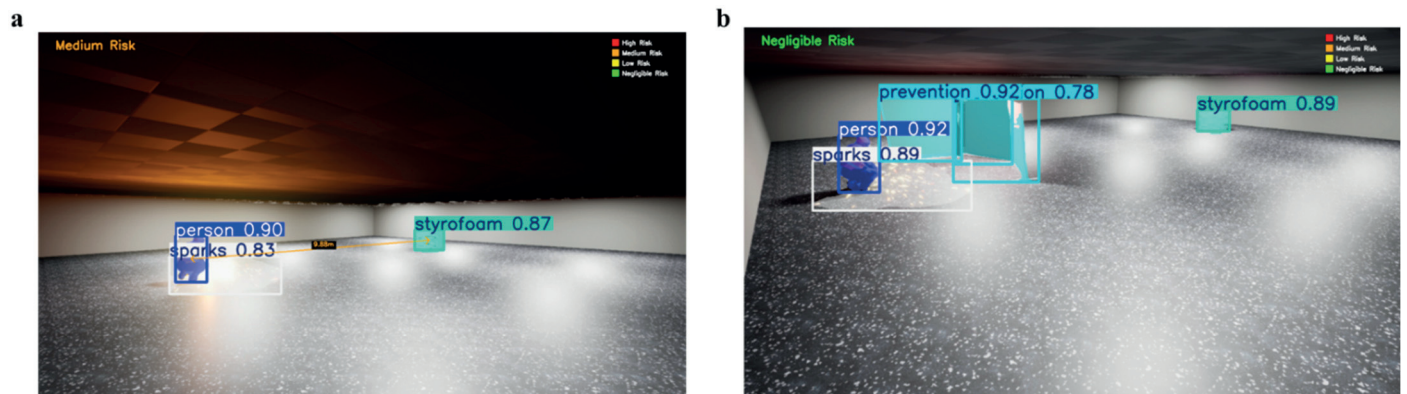


Fig. 5. (a) Medium risk (distance = 9.88 m); (b) negligible risk (preventive measure detected).

3. Conclusion

This study proposes a framework for detecting pre-fire risk situations in construction environments. Unlike conventional fire detection systems that identify flames or smoke after ignition, the proposed approach focuses on recognizing risk situations that may lead to fire incidents before ignition occurs. By shifting the focus from post-fire detection to pre-fire risk recognition, the framework supports proactive safety management at construction sites. In addition, a fire risk grading scheme was introduced to classify risk situations according to their severity, thereby supporting systematic interpretation and prioritized safety responses in complex construction environments. To evaluate the practical applicability of the proposed approach, a virtual construction environment was implemented using Unreal Engine. The simulation results demonstrate that the proposed framework can evaluate risk situations reproduced in a controlled virtual environment.

Nevertheless, the proposed framework presents several limitations. First, the current validation was primarily conducted in an Unreal Engine-based virtual environment. Discrepancies with real-world environments — such as sensor noise and lighting variations — limit the generalizability of the results. Thus, further validation of using actual construction site footage is required. Second, the current distance-based risk classification is effective only when objects are fully unobstructed. In real-world scenarios, occlusions caused by on-site structures or object overlapping within the 2D image plane can significantly amplify detection and distance estimation errors. Addressing this occlusion and overlap challenges remains a critical direction for future research.

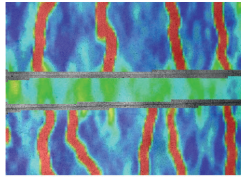
The simulation videos used in this study are publicly available at <https://doi.org/10.5281/zenodo.20175389>.

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Multi-view RGB-to-3D distance reasoning for construction site safety

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Keywords: construction safety monitoring; UAV mapping; CCTV; 3D localization; digital twin

1. Introduction

Construction sites remain hazardous because workers and heavy equipment interact in dense and rapidly changing spaces. Despite progress in computer vision, many practical monitoring systems still operate on isolated 2D camera views, which limits direct reasoning about distance, height, occlusion, and worker-equipment proximity across the site Cheng et al. (2022) improved worker re-identification and PPE compliance monitoring, while Jeon et al. (2024) advanced multi-camera motion prediction. In addition, Sun et al. (2025) and Jeon et al. (2025) explored site reconstruction using surveillance imagery and NeRF-BIM integration. Saif et al. (2024) demonstrated the value of integrated spatial monitoring in digital-twin safety systems, but these approaches often require wearable sensors or additional tracking infrastructure. Therefore, a practical gap still remains between low-cost vision-only sensing and site-wide 3D safety reasoning on active construction projects.

To address this gap, this study proposes a framework that combines drone-based 3D mapping and fixed CCTV monitoring in one global coordinate system. The contribution is not limited to 2D object detection; rather, the framework establishes a shared 3D spatial reference in which workers and equipment observed from multiple cameras can be interpreted consistently. This enables a practical basis for future proximity analysis, hazardous-zone intrusion detection, and spatially informed digital-twin applications.

2. Methodology

The workflow consists of three stages. First, multi-view drone imagery is used to reconstruct a global 3D site map. Building on recent advances in visual geometry learning reported by Wang et al. (2025), the present implementation uses a VGGT-based geometry estimation pipeline together with complementary reconstruction and refinement steps to recover camera parameters, depth-related geometry, and a dense site representation. The reconstructed model serves as the global spatial reference for downstream monitoring.

Second, each fixed CCTV is re-localized into the drone-derived global frame. This step estimates the pose of every CCTV relative to the site model so that separate camera views can be interpreted in one coordinate system rather than as isolated image streams.

Third, workers and equipment are detected in CCTV frames using a YOLO-based detector. The resulting 2D detections are back-projected into 3D using the estimated camera intrinsics, extrinsics, and depth information. Each detected entity can therefore be represented in global coordinates, which makes site-level spatial reasoning possible.

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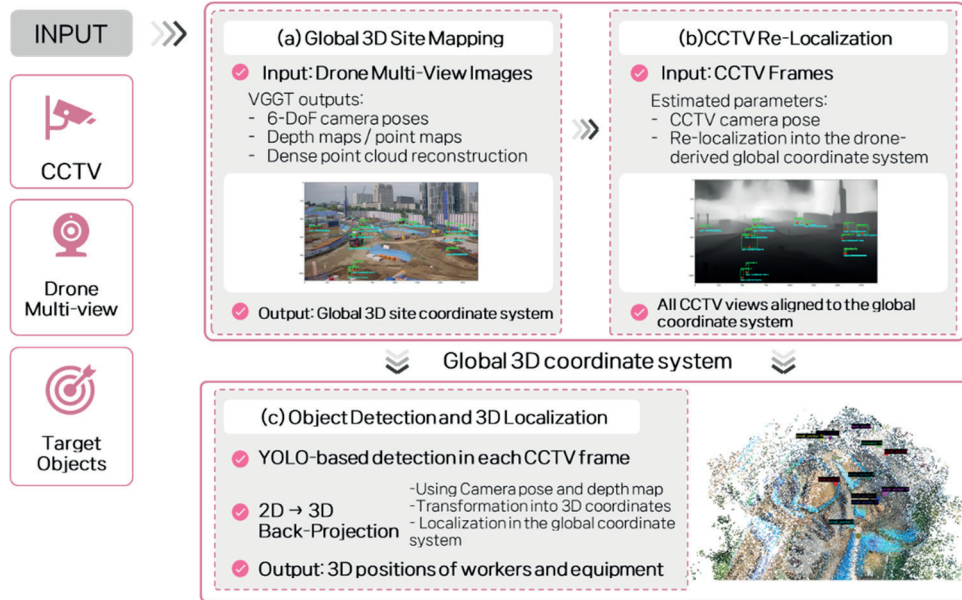


Fig. 1. Overview of the proposed vision-only 3D safety monitoring framework.

3. Field deployment

The framework was deployed at the Seocho Seoripul mixed-use construction site in Seoul, Republic of Korea. Drone data were collected between 1 and 15 September 2025, producing approximately 3,200 4K images captured at altitudes of 50-100 m. These images were used to reconstruct the global site geometry.

Three fixed CCTV cameras were installed to maximize overlap, reduce blind spots, and focus on a high-risk work zone where workers and heavy equipment frequently coexisted. The CCTV dataset comprised approximately 280,000 full-HD frames. This combination of periodic drone mapping and continuous camera observation balances site-scale spatial context with practical on-site deploy ability.

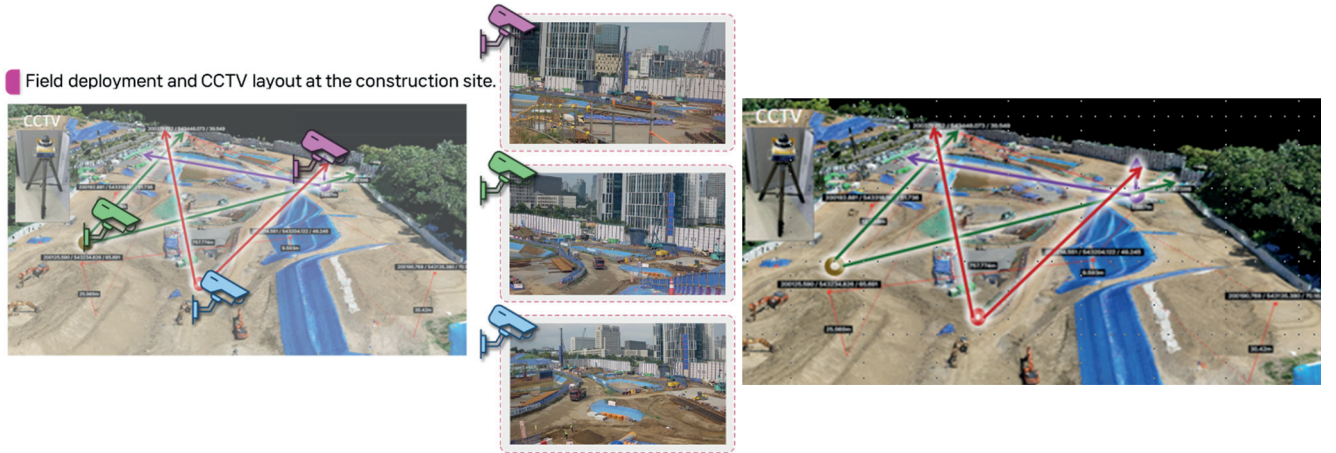


Fig. 2. Field deployment and sensor configuration at the construction site.

4. Results and discussion

For 2D detection, the trained YOLO model achieved 80.2% mAP@0.5, 81.2% precision, and 73.3% recall on site CCTV data. Given the challenging visual conditions of construction scenes, including small distant targets, clutter, partial occlusion, and variable lighting, these results indicate sufficient robustness for downstream spatial localization.

Qualitative results show that the proposed pipeline can generate a global 3D site map from drone imagery and can reproject workers and equipment detected from multiple CCTVs into the same global coordinate system. Instead of producing only per-camera safety events, the framework forms a site-level spatial layer in which dynamic entities can be interpreted together. This is particularly relevant for future applications involving worker-equipment proximity analysis and hazardous-zone intrusion monitoring.

The present study should nevertheless be interpreted as a feasibility study rather than a fully validated real-time warning system. Ground-truth 3D positions of workers and equipment were not available during the field campaign, so the current evaluation is stronger in 2D detection and qualitative spatial consistency than in quantitative localization accuracy. Even so, the framework demonstrates a meaningful trade-off between deployability and spatial intelligence because it relies primarily on drone imagery and existing CCTV infrastructure rather than LiDAR, RTLS, or wearable devices.

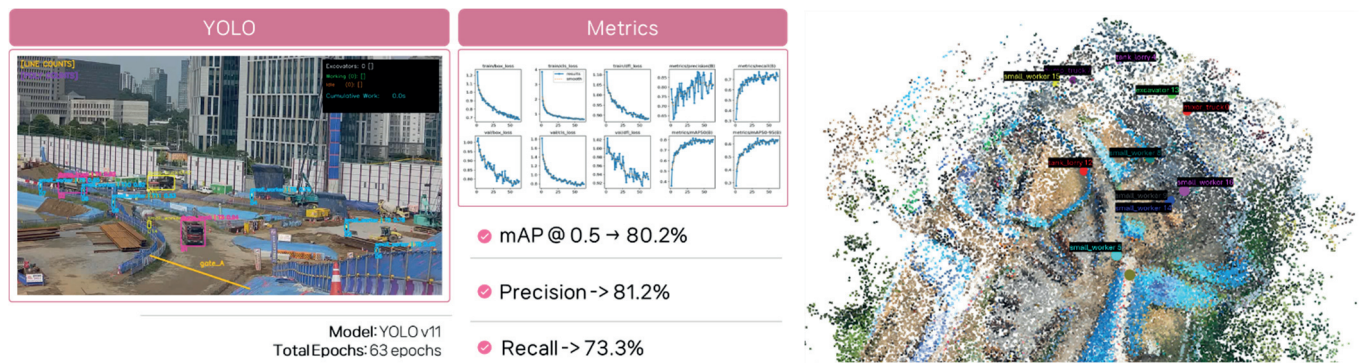


Fig. 3. Qualitative results of multi-camera 3D localization in the shared global map.

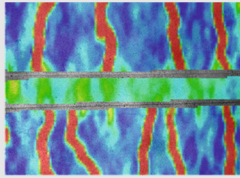
5. Conclusions

This study presented a vision-only framework that combines drone-based 3D mapping and fixed CCTV data fusion for spatial safety monitoring on construction sites. By reconstructing a global site model, re-localizing CCTVs, and back-projecting 2D detections into 3D, the method establishes a shared spatial basis for interpreting worker and equipment interactions at site scale. The field deployment indicates that this approach is technically feasible with relatively low additional hardware cost.

Future work should focus on quantitative 3D localization validation using RTK-GNSS, UWB, total stations, or comparable ground-truth methods; temporal multi-camera association and trajectory smoothing; integration of rule-based or learning-based risk scoring; and computational acceleration toward near-real-time deployment.

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MS31: Wave-based monitoring techniques for structural engineering

Organizers:

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ABSTRACT

Wave-based monitoring methods are gaining increasing attention as powerful tools for assessing the integrity and durability of civil infrastructure, e.g. for bridges or offshore structures. Techniques such as acoustic emission, guided waves, and related approaches enable the detection, localization, and characterization of damage at early stages, thus supporting proactive maintenance strategies. This Mini Symposium brings together recent advances in wave-based monitoring for a broad range of structural materials, including wood, steel, and concrete. Contributions will highlight both fundamental research and practical applications, covering signal processing, sensing technologies, and innovative implementations for structural health monitoring and rehabilitation. Bringing together researchers and practitioners, the session aims to advance the state of the art in wave-based techniques and promote their integration into smart infrastructure systems.

Non-destructive wave-based detection of delamination in corroded RC panels

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Abstract

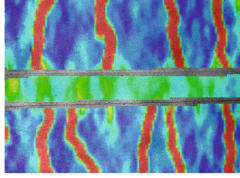
Corrosion in reinforced concrete (RC) not only degrades the embedded steel, but also induces cracking, spalling and delamination of the concrete cover, the latter of which may not be visible at the surface. Therefore, corrosion threatens the integrity of existing infrastructure and hinders the reuse of RC elements in circular construction. To improve the long-term durability of civil infrastructure, reliable detection of hidden corrosion damage is essential.

This study investigates the effectiveness of wave-based non-destructive testing (NDT) techniques for identifying and characterizing delamination in corroded RC panels. Two concrete panels ($0.8 \times 0.8 \times 0.12 \text{ m}^3$) were cast with a dense reinforcement layout to facilitate delamination, both with different concrete cover thickness. Thereafter, they were subjected to an accelerated corrosion process. To assess the resulting damage, four NDT methods were employed: impact-echo (IE), ultrasonic pulse velocity (UPV), infrared thermography (IRT) and acoustic emission (AE). IE, UPV and AE each analyze the propagation of elastic waves across different frequency ranges, wave modes, emitting sources and sensor setups, while IRT captures surface temperature variations through infrared wave responses. Therefore, they each offer distinct information about the condition of the delaminated RC elements.

While previous studies report successful delamination detection for artificial voids, the present results show that identification of more realistic, corrosion-induced delamination is challenging with IE, UPV and IRT. AE, on the other hand, provided real-time information on the location of corrosion propagation, offering clearer insight into the development of corrosion damage.

Keywords: Non-destructive testing; delamination; reinforced concrete; corrosion

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Non-destructive measurements for assessing concrete material in underwater conditions

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Keywords: Non-destructive testing, ultrasound, underwater, concrete

1. Introduction

Worldwide, numerous infrastructural buildings approach their projected lifespans. Therefore, the assessment of the current condition is a crucial point for decision-making processes. Depending on the outcome, upon further use, the renovation or the demolition and reconstruction is decided. One of the key means of communication is by sea, which also includes transport on rivers. In addition, this pertains to ship locks.

Investigations of concrete structures below the water surface are initiated at this juncture. The purpose of this research is to evaluate the condition of the object using non-destructive measurement tools. As a starting point, laboratory experiments are conducted on a concrete block, where ultrasound sensors are applied. During the experiment the water saturation of the concrete material is changing. The measurement results are compared and merged to create a comprehensive picture of the object. The objective is to enhance comprehension of the preliminary state of the research item.

2. Methods

Changes in temperature and water content, progressing damage or stress redistribution alter the ultrasonic wave propagation inside concrete structures. For frequencies above roughly 100 kHz the wavelength reaches the same order as the aggregate size of the concrete and waves will be scattered multiple times on the path between transmitter and receiver. The initial part of the measured signal is composed of weakly scattered waves, but as time progresses, the wave path length and accordingly the number of scattering events increases. If the wave velocity is slightly perturbed, the reference signal and the perturbed signal will lose correlation with increasing time. This is why the tail of the recorded signal, called “coda”, is very sensitive to any structural changes, that could alter wave propagation between transmitter and receiver. Considering the scattering medium as a sort of interferometer, the method was introduced under the name “Coda Wave Interferometry” (CWI) by Snieder et. al. in 2002.

The amount of decorrelation is evaluated with the cross correlation (CC), which quantifies the similarity of two signals. The reference signal s_r is shifted in time by t_s with respect to the perturbed signal s_p to maximize the correlation coefficient $R^{(t,T)}$, which is computed on an interval of width T and central time t according to

$$R^{(t,T)}(t_s) = \frac{\int_{t-T}^{t+T} s_r(t' + t_s) s_p(t') dt'}{\sqrt{\int_{t-T}^{t+T} s_r^2(t' + t_s) dt' \int_{t-T}^{t+T} s_p^2(t') dt'}} \in [-1, 1]. \quad (1)$$

Under the assumption that t_s is much smaller than the dominant wave period and that $T \ll t$, the maximizing time shift can be related to an average relative shift in wave velocity

$$t_s/t = -\delta v/v. \quad (2)$$

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An alternative approach used by e.g. Sens-Schönfelder and Wegler (2006), which neglects these assumptions, stretches the time scale of s_r with a factor $(1 + \epsilon)$ instead of shifting it with a constant t_s . In the integral of eq. (1) the term $(t' + t_s)$ is substituted with $t'(1 + \epsilon)$ and the time interval can be extended to a larger part of the signal. The velocity shift is then determined using the argument maximizing $R^{(t,T)}(\epsilon)$ in the altered version of eq. (2)

$$\epsilon = -\delta v/v. \quad (3)$$

When a large part of the signal is considered, this value will relate to an average velocity shift in the whole monitored volume. However, different parts of the coda signal correspond to different path lengths. As time progresses, sub waves will have more time to diffuse through the medium and correspondingly the size of the halo, where these waves concentrate, increases with $\sqrt{t}$ (Planès et al. 2014). Utilizing a probabilistic description of the wave propagation in the form of sensitivity kernels, it is possible to infer on the location of the perturbation inside the structure. This was applied to localize e.g. drill holes in concrete by Larose et al. (2010).

3. Experiment

We established two different measurement setups for investigating the changes in ultrasonic wave speed, as water saturation increases non-uniformly within the concrete. Setup 1 is shown at the left of Fig. 1, a small concrete block (10 x 10 x 15 cm) was measured in transmission. Between measurements the top face was exposed to a water reservoir and the block was weighed for saturation calculations. In setup 2 on the right a larger block (40 x 20 x 16 cm) was completely submerged into water and sensors were positioned on the top face for measurements. Both specimens are made from identical concrete mixtures with a density of 2.2 g/cm³ and a maximum grain size of 16 mm. They were brought into first contact with the water with the initial measurement.

For ultrasound generation and measurements, two cylindrical ultrasonic transducers with a center frequency of 450 kHz and a bandwidth of 110 % were operated in pulse echo mode. The transmitter was excited with a 2.5 μ s rectangular pulse generating waves in the multiple scattering regime. For each point in time, the transducers were repositioned to the same marked location ten times and coupled to the concrete surface with water. Between measurements they were removed to allow full water absorption. Ultrasound signals were captured at a sampling rate of 10 MS/s and averaged over 10 pulses. Both air and water temperatures changed by less than 1 °C within the measurement period.

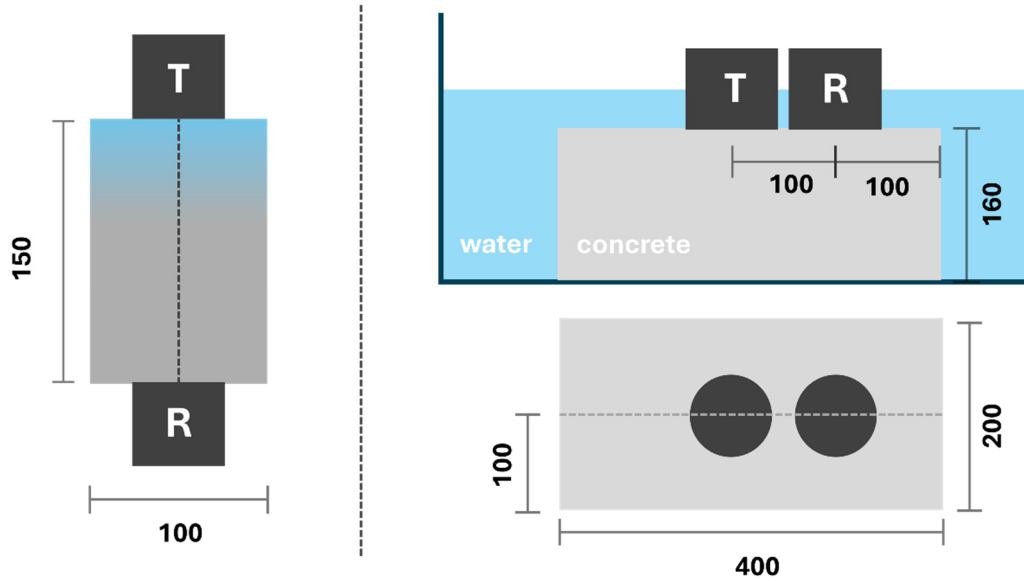


Fig. 1. Experimental geometries for Coda measurements; left: small block transmission setup up, right: big block under water setup.

4. Results and conclusion

The cross correlation analysis described above and the stretching factor used in eq. (3) were used to determine the relative change in ultrasonic wave velocity over time for both setups. The initial ultrasonic pulse velocity was determined at 4400 m/s, based on the arrival time of the backwall reflection peak and the known thickness of the specimen in setup 1. The time window used for the coda analysis was chosen such that the waves would have traveled through the whole specimen several times while still keeping the SNR above 15 dB. The CC was computed for 10 individual pairs of measurements, adding up the velocity shift cumulatively.

In Fig. 2a the determination of the stretching factor ϵ for one measurement pair is shown. It uses signals from the two last time steps measured in setup 2. The maximum of the CC corresponds to the target stretching factor and is indicated with a vertical line. Fig. 2b. shows the relative velocity shifts, which were computed with that procedure for setup 2. The data points show the median and the 25/75% quantile error bars, which on average span a $\delta v/v$ range of 0.1%. The error is expected to arise mainly from small

deviations in the sensor positioning, but possibly also from water movement in the tank. The temporal axis is expressed in terms of the square root of time, consistent with EN ISO 15148, according to which water absorption of porous media is expected to linearly increase with $\sqrt{t}$. The water absorption coefficient of the used concrete was determined previously at a value of $W_w = 1.39 \text{ kg/m}^2 \text{ h}^{0.5}$. In both setups, a decrease of wave speed with increasing time and water content can be observed. The magnitude of the decrease is similar in both setups, even though the specimen size and sensor arrangement are very different. Positive phase shifts for later measurements observed around the first reflection peak reinforce this observation. This is contradictory to many studies, which have shown, that the ultrasonic wave speed increases with water saturation in concrete, such as Ohdaira (2000). We measured a decrease in wave speed of about 30 m/s for an increase in water content of 1.5 %. The magnitude and linear behaviour over root of time is similar to the findings in literature. The latter however usually measured concrete samples with more homogeneous water content distribution compared to the gradients, which are caused in our experimental setups. To investigate frequency dependence, the analysis was repeated with excitation pulses of length 5 and 10 μs and changes were less than 10 %.

These results reinforce the importance of considering temporal as well as spatial variations of the water content, when using CWI for the monitoring of dams or ship locks. The related changes in wave velocity are considerable and might dominate over subtle changes induced by slowly developing structural damage caused by e.g. Alkali-silica reactions. Analytical and numerical models of moistening and drying concrete might support eliminating these contributions in the future.

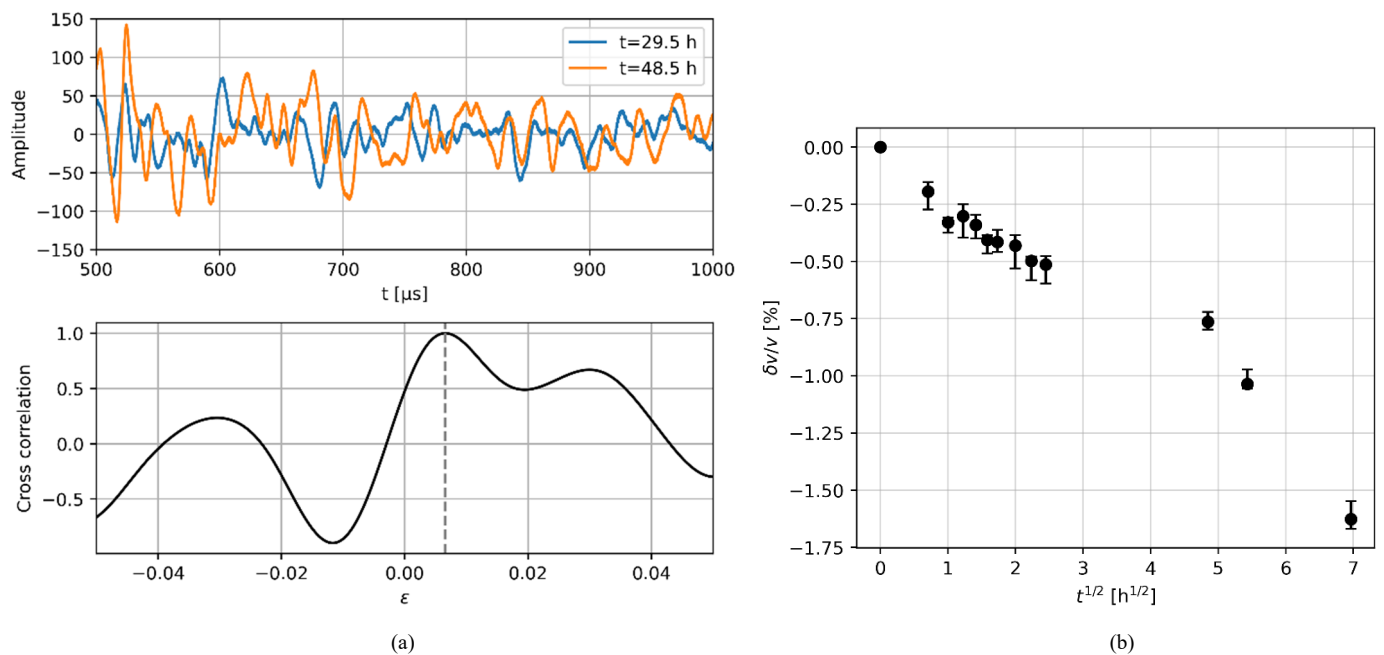


Fig. 2. (a) CC computation for one measurement pair; (b) velocity shift computed with CWI for setup 2.

Acknowledgements

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Field application of acoustic emission during load testing of existing reinforced concrete bridge

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Abstract

Existing concrete structures require effective structural assessment. The Balladelaan Bridge in Amersfoort, the Netherlands, is a reinforced concrete (RC) slab bridge constructed in 1946 and approaching the end of its original design life. However, no design drawings or calculations are available for structural assessment. Therefore, inspection and monitoring is required to provide information on its current condition. In this study, Acoustic Emission (AE) monitoring was performed during controlled loading with a heavy truck to identify potential existing cracks. While AE is promising in crack detection, its application in the field has greater and more complex uncertainties. This study evaluates a few sources of uncertainty in field AE monitoring, including sensor installation inaccuracies (particularly on the hard-to-access underside of the bridge), environmental influences such as rainfall (which both generates noise and affects sensor coupling), and the unknown structural configurations (which challenge the assumptions in wave propagation). The results provide insights into the applicability of AE for the condition assessment of existing RC bridges under field challenges.

Keywords: –

* The full paper is open access available in the Conference Proceedings. *

Acoustic digital twin for prestressed concrete bridges

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Abstract

Among the available monitoring techniques, acoustic emission analysis has proven to one of the most effective and economically viable methods for detecting wire breaks and preventing catastrophic damage of prestressed concrete bridges. The research project “Simulation of Acoustic Wave Propagation in Prestressed Concrete Bridges” utilizes digital twin technologies to evaluate the acoustic behavior of structures and to optimize the design and application of monitoring systems. The integration of simulated wave propagation data with measured acoustic signals from actual wire breaks provides the basis for developing a comprehensive reference database of acoustic emission signals, enabling improved detection algorithms and more reliable structural health monitoring. This paper introduces a workflow for the acoustic digital twin technology, as well as demonstrates its validation and possible application through a case study of an existing bridge structure. The key assumptions for numerical simulation are provided, and the envelope characteristics of simulated and experimentally recorded wire-breakage signals are analyzed and compared. Inverse simulation techniques are applied to estimate the source location, helping the bridge owners make informed decisions. The developed methodology contributes to the safety of bridges at potential risk until their replacement

Keywords: Acoustic emission; bridge monitoring; prestressed concrete; stress corrosion cracking

* The full paper is open access available in the Conference Proceedings. *

Machine learning for wire break detection

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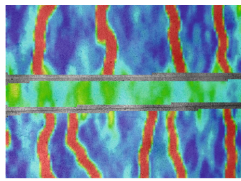
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Abstract

The detection of wire breaks in prestressed concrete structures using acoustic emission (AE) monitoring has become increasingly relevant for the structural health assessment of bridges. While AE systems are capable of capturing fracture events in post-tensioning tendons, practical applications often suffer from false alarms caused by operational noise such as traffic-induced vibrations or electromagnetic interference. This study presents a supervised machine learning approach for the classification of AE signals under realistic bridge conditions. A heterogeneous dataset was compiled, including laboratory wire breaks, quasi-field wire breaks during strand removal, verified in-situ wire break events, and operational noise from twelve bridge structures. A Random Forest classifier was trained and evaluated in two scenarios to investigate the influence of training data composition, particularly the inclusion of real in-situ wire break signals. The results show that increasing the variability of the noise data improves robustness against false positives, but does not substantially improve recall when real in-situ wire break events are absent from training. In contrast, including verified in-situ wire break signals leads to a clear improvement in classification performance, enabling both high recall and high precision. The study highlights the importance of representative real-world data for reliable AE-based wire break detection in practical bridge monitoring.

Keywords: Acoustic emission, structural health monitoring, machine learning

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Acoustic emission monitoring of fatigue damage in a transition piece of a wind turbine tower

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Keywords: Concrete fatigue monitoring; acoustic emission; ultrasound; hybrid wind turbine tower

1. Acoustic emission monitoring of a wind turbine tower

Wind energy plays a substantial role in Germany's energy transition. In 2006, about 1200 wind turbines systems were installed (BWE (2026)) and will soon reach the end of their service life which is typically 20 years (Ziegler et al. (2018)). Extending their operation requires the development of innovative inspection and monitoring strategies. Onshore wind turbine towers are commonly designed as hybrid structures, with a prestressed concrete lower section and a steel tubular upper section. These tall towers are subjected to continuous cyclic loading. Within the joint research initiative WinConFat – Structure, BAM is exploring advanced methods to monitor fatigue damage progression in the concrete segments of hybrid towers. Previous studies, like Thiele and Pirskawetz (2022) and Frei et al. (2024), indicate that combining ultrasonic testing with acoustic emission monitoring can effectively detect critical conditions as concrete approaches its fatigue limit. As a part of WinConFat – Structure, acoustic emission sensors were installed at the base and at the transition zone between concrete and steel of a hybrid tower. Beyond detection of acoustic emission signals, the sensor configuration enables ultrasonic velocity measurements around the circumference. Additional data - such as strain, temperature, inclination, and acceleration - provide insights into operational and environmental influences and their effect on the acoustic properties of concrete. This abstract presents acoustic measurements at the transition piece and correlates them with SCADA data, including active power and wind direction.

1.1. Structure under monitoring

The hybrid tower selected for monitoring is located in Thörlingswerder/Wriezen, about 60 km east of Berlin, Germany. The rotor has a diameter of 116.8 m on a hub height of 141 m. The turbine has a nominal power of 2.4 MW. The initial start-up was in May 2017. The lower part of the tower is 80 height and is constructed of 20 precast concrete ring elements. The tendons of the concrete tower are anchored in the foundation and on the upper concrete element, the transition piece. The steel tower is bolted using bolts that are anchored in the transition piece. This highly loaded concrete element was selected for acoustic emission monitoring.

1.2. Monitoring system

The acoustic emission data associated with fatigue crack formation must be correlated with the applied loads. For this purpose, a supplementary monitoring system was installed on the tower. In addition, the operational data of the turbine are incorporated into the evaluation of the acoustic emission measurements. Fig. 1 provides an overview of the monitoring system installed.

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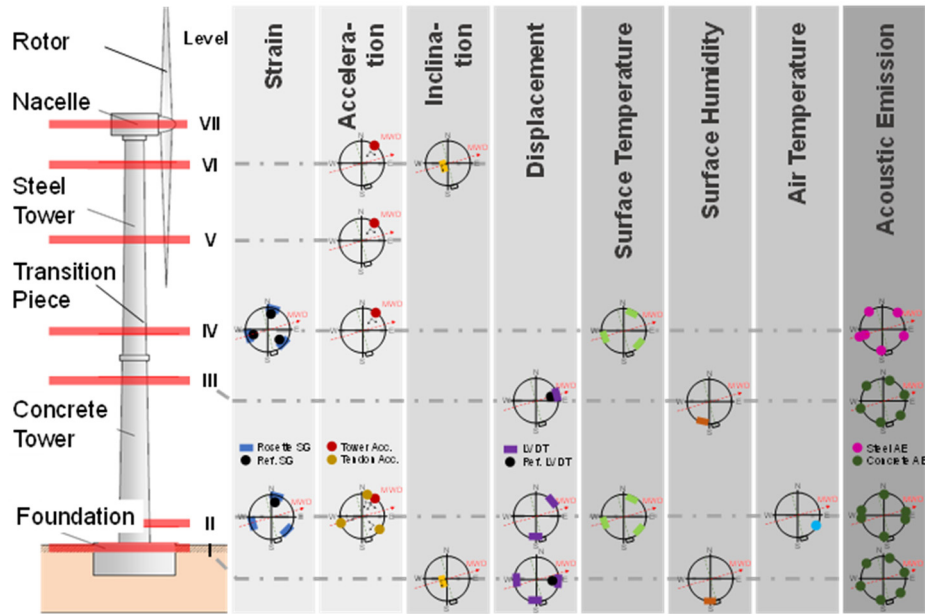


Fig. 1. Positions and types of sensors installed on the wind turbine tower (Pirskawetz et al., 2024).

1.3. Acoustic emission monitoring

The acoustic emission system comprises a total of 23 sensors that are installed in particularly highly loaded areas of the concrete tower. Six sensors are located in the basement and six on the lower concrete segment. The transition piece is monitored by six sensors mounted on the concrete surface and five sensors positioned on the steel flange of the steel tower. The following presentation of the results focuses on the data obtained from the sensors on the flange. The positions of the sensors on the transition piece are shown in Fig. 2.

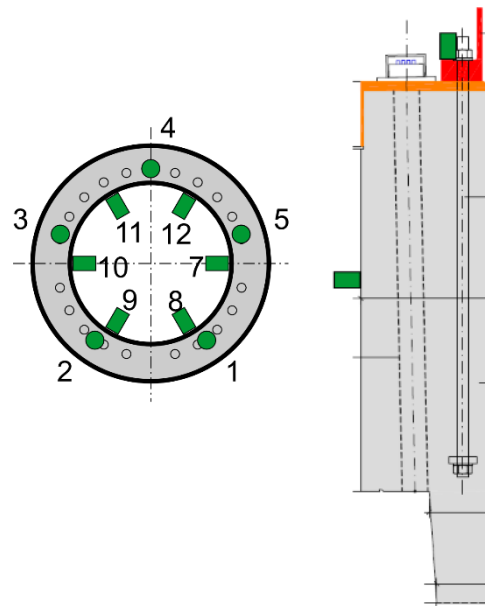


Fig. 2. Positions of acoustic emission sensors on the transition piece; sketch is not drawn to scale.

1.4. Acoustic emission results

The cyclic loading of the transition piece leads to fatigue-induced cracking in the concrete. The initiation and propagation of these cracks can be detected using acoustic emission analysis. The acoustic emission activity therefore corresponds to the evolution of damage. To evaluate the acoustic emission activity, time periods with comparable structural loading must be analyzed. The diagrams in Fig. 3 present the acoustic emission energy per hour and per sensor at a turbine output of 2400–2500 kW. During the analyzed periods, the wind direction—and thus the position of the nacelle—remained nearly constant.

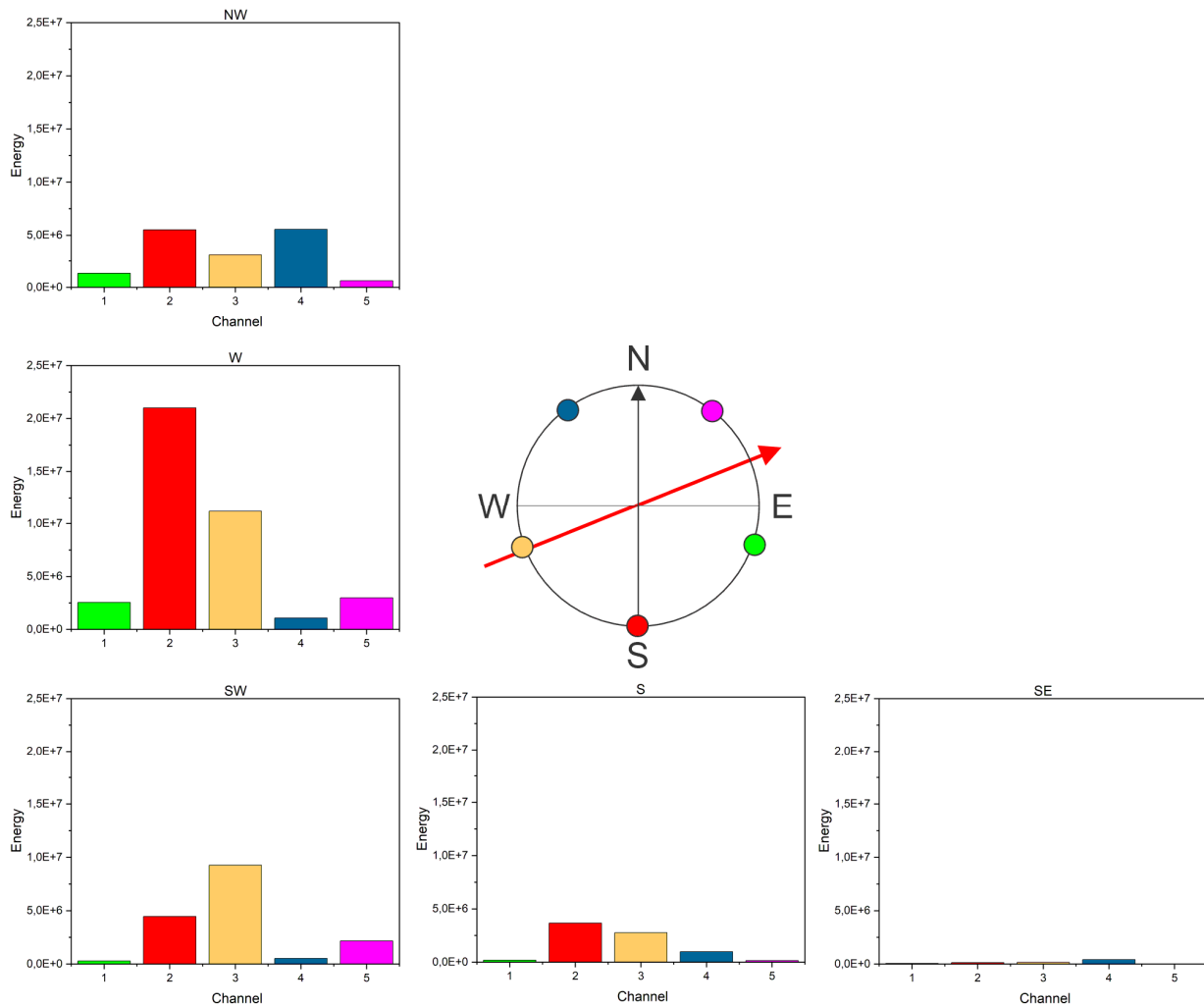


Fig. 3. Acoustic emission energy per sensor and per hour at a turbine power output of 2400-2500 kW. The red arrow in the compass rose indicates the main wind direction.

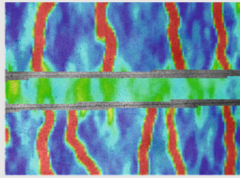
Thus far, too few data have been evaluated to establish reliable statistics. Nevertheless, particularly for sensors 3 (yellow) and 4 (blue), a correlation between wind direction and acoustic emission activity is noticeable. The activity is higher on the windward side. The activity recorded by sensor 2 (red) is conspicuously high. A ladder is installed at this location; it is possible that the connection between the ladder and the tower is subjected to increased loading, especially during westerly winds (the predominant wind direction).

Acknowledgements

The project “Monitoring of damage processes in wind turbines and their joints as well as measurement-based service life assessment” is part of the joint project “Component fatigue of wind turbines made of reinforced concrete and prestressed concrete under highly cyclic loading” (WinConFat-Structure) [4] with Technische Universität Dresden, Leibniz Universität Hannover, RWTH Aachen University as partners. It is funded by the Federal Ministry for Economic Affairs and Climate Action Germany. The associated partners edis.natur and Vallen Systeme GmbH are supporting the project. Additionally, Max Bögl advises the project.

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MS32: Crowdsourced and indirect approaches to structural health monitoring

Organizers:

Maria Pina Limongelli (Politecnico di Milano, Italy)
Thomas Matarazzo (United States Military Academy, USA)
Zhenkun Li (Aalto University, Finland)
Kim Chul-Woo (Kyoto University, Japan)

ABSTRACT

Crowdsensing and indirect monitoring are emerging as powerful complements to conventional structural health monitoring (SHM). By leveraging data from vehicles, smartphones, drones, and other connected devices, these approaches enable scalable and cost-efficient assessments of infrastructure performance, particularly where direct instrumentation is impractical. This Mini Symposium will provide a forum to present advances in drive-by monitoring, smartphone- and wearable-based vibration sensing, drone-enabled inspections, and the integration of heterogeneous data streams. Emphasis will be placed on data analytics, uncertainty quantification, and the use of artificial intelligence to extract actionable insights from large and noisy datasets. Contributions reporting field studies, validation campaigns, and implementation strategies are especially welcome. Bringing together researchers, practitioners, and infrastructure managers, the Mini Symposium will highlight opportunities and challenges of crowdsensing and indirect monitoring, from the evaluation of individual structures to large-scale portfolio-level monitoring and management.

Mobile crowdsensing for structural health monitoring: field validation

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Abstract

A major challenge in bridge Structural Health Monitoring (SHM) is the cost associated with deploying and maintaining sensor systems. Although regular monitoring is essential for ensuring infrastructure safety and longevity, limited financial resources hinder widespread and continuous implementation. In this respect, mobile crowdsensing offers a promising low-cost solution by eliminating the need for dedicated sensing devices and their associated maintenance. Instead, it utilizes data collected from smartphones and other personal devices carried by everyday users. This paper presents a framework for processing crowdsensed vibration data for bridge monitoring applications. The framework incorporates quality-weighted signal processing and bootstrap resampling to extract natural frequency estimates from heterogeneous smartphone recordings. The efficacy and accuracy of the proposed method are demonstrated through application to a real pedestrian bridge, with results validated against a benchmark study conducted on the same structure using professional instrumentation. Overall, this research contributes to the development of a flexible and scalable framework for applying mobile crowdsensing in bridge structural health monitoring.

Keywords: Mobile crowdsensing; footbridges; modal analysis; internet of things (IoT); smartphone

* The full paper is open access available in the Conference Proceedings. *

A hybrid drive-by framework towards integrated bridge health monitoring

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Abstract

Conventional vibration-based bridge monitoring typically relies on fixed and dense sensor networks to capture modal responses and damage-sensitive features such as bridge displacement, rotation angle and strain. Such instrumentation makes bridge monitoring costly and impractical. On the other hand, drive-by inspection employs an instrumented vehicle as a moving sensor, enabling cost-efficient assessments without permanent bridge instrumentation. Nevertheless, vehicle responses are often dominated by vehicle dynamics, road roughness, and environmental noise, which obscure bridge vibrations and limit practical applicability. While bridge measurements from a few sensor locations provide direct but spatially sparse dynamic information, vehicle measurements offer continuous but indirect information along the span while simultaneously exciting and sensing the bridge. Integrating both becomes essential and useful to overcome the limitations of each. Therefore, this study proposes a Hybrid Drive-by Bridge Inspection (HDBI) framework that jointly utilizes bridge and vehicle responses, maximizing the strengths and information from both systems to reconstruct spatial bridge displacement and rotation angle. A two-degree-of-freedom (2DOF) half-car model is employed to simulate the vehicle-bridge interaction and generate coupled dynamic responses. Bridge accelerations from three sensors are processed for band-limited modal state estimation, while low-frequency rotation information is used for quasi-static response augmentation. The vehicle acceleration is used to reconstruct axle forces via a simplified dynamic model. The estimated axle forces are projected into modal force terms and used together with sparse bridge accelerations to reconstruct bridge responses without time integration and with only a few bridge sensors. The results confirm the feasibility of the proposed HDBI framework, demonstrating the potential of the hybrid framework for integrated structural health monitoring.

Keywords: Drive-by bridge inspection; Hybrid approach; Rotation angle; Kalman filter; Vehicle-bridge interaction

* The full paper is open access available in the Conference Proceedings. *

Fleet monitoring of bridges using drive-by operational deflection shapes

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Abstract

Operational deflection shapes (ODS) provide valuable spatial insight into bridge dynamics and can support damage assessment. This study proposes a drive-by framework for estimating ODS-related information using vehicle-mounted accelerations only. A transfer function based approach is used to reconstruct contact-point bridge acceleration, followed by band-pass filtering and Hilbert transform based amplitude extraction to obtain spatial response envelopes along the bridge. The method is evaluated using a coupled vehicle bridge interaction model under both smooth and stochastic Class A road profiles, considering healthy and locally damaged cases. A Monte Carlo study with a fleet of vehicles is conducted to assess robustness to variability in vehicle properties. Results show that the reconstructed responses capture the dominant modal behavior and produce consistent amplitude patterns across the fleet. While differences between healthy and damaged cases are subtle after normalization, combining front and rear axle responses improves stability and repeatability. The findings demonstrate the potential of drive-by monitoring for extracting ODS-related information towards scalable bridge assessment.

Keywords: Operational deflection shape; drive-by monitoring; structural health monitoring; vehicle bridge interaction

* The full paper is open access available in the Conference Proceedings. *

Pavement settlement identification from vehicle vibrations

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Abstract

Pavement settlement is a critical concern that not only compromises driving comfort but also elevates the risk of progressive failure, as it often reflects instability within the underlying soil strata. Furthermore, such a settlement may result from progressive failure of buried infrastructure, including sewage pipelines, which can exacerbate deformation of the overlying roadway. Early identification of small settlements is therefore essential to prevent such catastrophic collapse. This study investigates the feasibility of using a drive-by pavement inspection approach to identify road settlement using moving vehicle vibrations. A quarter-car vehicle model is adopted to simulate the dynamic interaction between the vehicle and the road settlement. The Dynamic Regularized Least Squares (DRLS) minimization method is employed to identify the settlement profile based on the vehicle axle acceleration. Numerical simulations are conducted to examine the influence of vehicle speed, while a parametric study is carried out to evaluate how both settlement characteristics and vehicle speeds affect the accuracy of DRLS in reconstructing the settlement profile. Vehicle speeds ranging from 2.5 to 20 m/s and settlement depth-to-length ratios (D/L) from 0.5% to 2% are considered. The results show that the DRLS method can accurately identify road settlements. At vehicle speeds between 5 and 15 m/s, the estimation from the rear axle showed better accuracy compared to other vehicle axle responses. Larger depth-to-length ratios led to more accurate identification. Given the limited research on this topic, the findings of this study provide a foundation for future experimental validations.

Keywords: Drive-by monitoring; dynamic regularized least squares minimization; pavement settlement identification; vehicle acceleration

* The full paper is open access available in the Conference Proceedings. *

A crowdsensing-based approach for footbridge frequency identification using pedestrian response

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Abstract

Indirect bridge health monitoring methods using vehicle response have attracted growing attention from researchers worldwide. However, due to the load and access restrictions, such vehicle-based methods are generally not applicable to footbridges, which represent a significant portion of modern transportation infrastructure. The primary users of footbridges are pedestrians whose dynamic interactions with the structure provide a potential source of measurable vibration data. This paper proposes a novel crowdsensing-based approach for footbridge frequency identification using response collected from pedestrians performing several activities on the footbridge. It provides a paradigm of using collected signals from humans for structural health monitoring (SHM) purposes via crowdsensing strategies. The paper first introduces the fundamental pedestrian-footbridge interaction models and then details the key processes of the proposed approach, including data collection, data processing, and frequency identification. Numerical simulations are conducted to validate the feasibility and robustness of the method. The results demonstrate that pedestrian-borne data can effectively capture the dynamic properties of footbridges, paving the way for a low-cost, scalable, and human-centric SHM strategy.

Keywords: Structural health monitoring; crowdsensing; pedestrian-structure interaction; frequency identification

* The full paper is open access available in the Conference Proceedings. *

Self-sensing in smart structures through mineral-impregnated carbon fiber reinforcements

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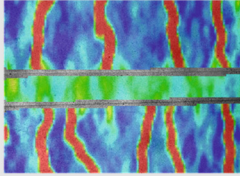
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Abstract

Due to their excellent conductivity, carbon fibers (CFs) show potential for self-heating and structural health monitoring (SHM). The fractional change in resistance (FCR) of CFs varies with factors such as temperature, stress and deformation, enabling self-sensing. However, the intrinsic sensitivity of conventional CFs is limited, hindering their widespread adoption in practical applications. To address this, mineral-impregnated carbon fiber (MCF) was prepared using a limestone calcined clay cement (LC3) suspension. Contact angle measurements evaluated wettability between CF and suspension, followed by flexural tests to measure resistance changes. The FCR and its first derivative (dFCR/dt) were analyzed in-situ. Results show that dFCR/dt provides clearer damage progression patterns than the raw FCR signal. The loading process comprises three stages: pre-peak, peak and post-peak. In the pre-peak stage, a negligible electrical response shows a stable conductive network. At peak load, a clear increase marks crack initiation. In the post-peak stage, dFCR/dt reaches its highest value, reflecting distributed damage and progressive crack propagation. Thus, MCFs can function as self-sensing reinforcing materials, enabling real-time detection of crack initiation and damage evolution. Notably, dFCR/dt fluctuation indicates incipient damage in structures, allowing preventive maintenance before failure, thereby providing a reliable basis for early detection, which enhances the safety and durability of structural systems.

Keywords: Mineral-impregnation; carbon fiber; electrical conductivity; structural health monitoring

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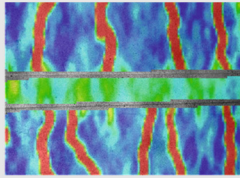


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Parallel Sessions



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Parallel Session 1

Structural health monitoring and damage detection

AI-driven data analysis of monitoring data in natural language

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Abstract

Structural Health Monitoring (SHM) systems enabled by the Internet of Things (IoT) provide valuable insights that facilitate early damage detection, enhance predictive maintenance, and improve overall structural safety. However, the continuous generation of high-volume time-series data often creates an analysis bottleneck, turning valuable information into unused “dark data”. While standard Large Language Models (LLMs) offer intuitive natural language interfaces, their probabilistic nature and tendency to hallucinate are unacceptable risks for safety-critical calculations.

We introduce the Rocket AI framework, a novel Tool-Augmented Generation (TAG) architecture that transforms SHM data analysis into a conversational interaction based on transparent, verifiable logic. Crucially, this system bridges the gap between making complex data analysis accessible to all stakeholders and ensuring the underlying calculations remain rigorously grounded in structural physics and project-specific environmental conditions. Stakeholders without specialized data science or programming skills can now input high-level natural language queries like “Which of my infrastructure needs attention?”, “Provide forecast of crack width”, or “Investigate displacement alert at Pier 3”. The AI autonomously orchestrates multi-step diagnostic workflows by decoupling the semantic reasoning engine from deterministic data processing tools. The framework provides multimodal insights, including text summaries, interactive plots, and downloadable reports or datasets.

We ensure “Verifiable AI”, guaranteeing that users receive answers based on rigorous, mathematically traceable calculations rather than probabilistic text generation. This framework simplifies complex data analysis, dramatically reducing insight time and enabling users to make rapid, trustworthy, and data-driven maintenance decisions.

Keywords: Structural health monitoring; internet of things; ai analytics; natural language; predictive maintenance

* The full paper is open access available in the Conference Proceedings. *

Wire break detection in prestressed concrete bridges: a comparison of broadband accelerometers and ultrasonic transducers for acoustic emission monitoring

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Abstract

Prestressed concrete bridges represent the most prevalent form of bridge construction, accounting for approximately 68 % of the total deck area of German road bridges. Many of these structures are at risk of Stress Corrosion Cracking, which poses a substantial safety hazard, as evidenced by the collapse of the Carola Bridge in 2024. Since an immediate replacement of all at-risk bridges is not feasible, Acoustic Emission Monitoring has gained increasing interest to keep transport infrastructure in operation while ensuring structural safety. This study provides a systematic evaluation of acoustic emission signals recorded during the extraction of prestressing wires from a three-span bridge using both accelerometers with a broadband flat frequency response in the lower audible frequency range and ultrasonic acoustic emission transducers. The results demonstrate that the maximum feasible sensor distance as defined by a German guideline on acoustic emission monitoring of wire breaks is consistently greater if accelerometers are utilized instead of ultrasonic transducers. This is primarily attributed to the significantly lower signal attenuation in the lower frequencies. In fact, for moderate false alarm rates, an increase of the maximum feasible sensor distance of up to 21 meters is observed. Furthermore, wire break events occurring at distances exceeding 50 meters from the closest sensor could be manually identified in the trace of acceleration recordings.

Keywords: Acoustic emission, damage detection, bridge monitoring, stress corrosion cracking

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Millimeter GNSS monitoring of technical objects

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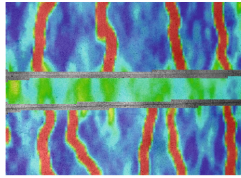
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Abstract

Advances in automated sensing technologies enable precise monitoring of structural deformations in buildings and infrastructure. Modern geodetic methods combined with complementary sensors support reliable deformation analysis, while interest in flexible, open, and configurable monitoring systems continues to grow. Terrestrial and GNSS-based measurements provide positional changes relative to a reference epoch, supported by software for data integration and management. Traditional systems, however, remain costly and hardware intensive. Distributed open geo-sensor networks offer scalable and adaptable alternatives. Selecting an appropriate system requires evaluating reliability, accuracy, and continuous 24/7 operation, with practical projects often revealing the need for customization. This paper presents how these demands can be addressed open, programmable architectures providing rapid adaptability. The practical application of such a low-cost system in pilot application is demonstrated. Selected measurement results of loading test are used to discuss the performance, accuracy, reliability, and limitations of such open monitoring systems to support their application across diverse infrastructure domains.

Keywords: Geodetic monitoring, 3D-position, GNSS, RTK, post-processing, structural health monitoring

* The full paper is open access available in the Conference Proceedings. *



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Applications for maritime monitoring using distributed acoustic sensing (DAS) – opportunities and limitations

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Keywords: Structural health monitoring, hazard detection, underwater acoustic sensor, acoustic emission

1. Abstract

Distributed Acoustic Sensing (DAS) has gained importance for various applications including the detection of acoustic emissions in the marine environment. The technology provides spatially distributed acoustic data via a single fibre optical cable, which offers advantages over conventional techniques in terms of resistance to harsh environmental conditions, electromagnetic shielding and instrumentation costs. Nevertheless, the immense data sets and the reliable interpretation of the data are still challenging for most applications.

Therefore, tests were conducted in the laboratory, in a harbour environment and in an offshore test field to evaluate the potential of optical fibres as underwater receivers for acoustic noise. Several artificial sources were used to generate acoustic subsea signals, and the detectability was evaluated. In addition, a novel coil instrumentation of the optical fibre was used to increase the sensitivity and to ensure detection without a physical connection.

The prospects of such operating modes, particularly for offshore infrastructure monitoring, lie in the use of existing subsea cables with dark fibres as sensor network to detect infrastructure threats like ice and vehicle collisions, submarine landslides and rogue waves to include these data to the residual lifetime models.

2. Introduction

The optical technologies have gained importance during the last decade due to the major improvements of the measurement devices. Used for geophysical applications in the beginning, optical solutions are proposed for a broad variety of infrastructure like bridges, pressure vessels, pipelines, railroads and cables nowadays. The advantages are obvious – only one fiber is needed to cover large areas without cabling individual sensors, the fiber is very cost-sensitive, widely available and used for decades, resistant to external electrical disturbances and last but not least applicable in ex-proof environments, Zhu (2022), Zuyuan (2021), Radet (2024).

Especially in harsh environments like for offshore applications, optical fibres have great advantages compared to conventional testing equipment. Using them for subsea measurements, no measure equipment needs to be installed subsea, only the fibre needs to be installed on the measurement site. The remaining hardware is situated above sea level and is attached to the fibre plug. This is a major advantage. There is no more need for divers or Automated Underwater Vehicle AUV or Remotely operated vehicles ROV during the measurements. Furthermore, the maintenance is significantly simplified.

Nevertheless, challenges remain regarding the data quality, the reliability of the data itself and the reliable interpretability. The devices are still in the high-cost segment and therefore a challenge for monitoring tasks with permanent measurements.

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3. Fundamentals

Using optical fibres for measurements, several scattering types can be used as shown in Fig. 1. The highest amplitude refers to the Rayleigh backscattering which will also be used for the data in this research work. It is an elastic process that is caused by the particles in the fibre and allows for measurements of strain and temperature. Inelastic scattering caused by the interaction with acoustic phonons is the far lower in amplitude Brillouin backscattering which is frequency dependent and therefore causes frequency shifts. It also refers to both temperature and strain measurements. Last but not least, the Raman scattering caused by molecular oscillations measures temperature effects.

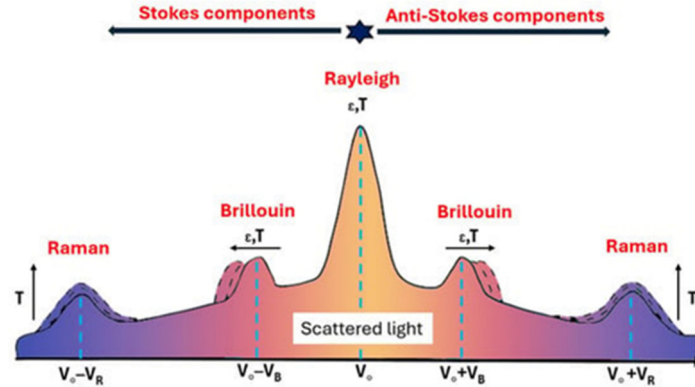


Fig. 1. Possible optical responses for digital fibre optic sensing (DFOS), Rashid (2025).

4. Measurements

4.1. General measurement set-up for permanent measurements

An offshore instrumentation refers to high standards regarding reliability and redundancy. Tab. 1 shows an instrumentation example with the necessary components and some estimated figures regarding the procurement effort. The permanent installation refers to high costs. In order to provide options for broad installation possibilities, the costs for the device and the supplementary equipment need to be reduced significantly.

Component	Cost estimation in €
DAS measurement system	150000-450000
Damping table	5000
Offshore compatible casing	20000-35000
Splitter for connecting several cables	10000-15000
Uninterruptible power supply UPS	2500-3500
Damped data collection hardware	30000-60000
Adapter, plugs etc.	5000
Optic cables	Depending on length
Industrial computer	5000

4.2. Results

First offshore measurements were carried out at the Digital Ocean Lab in Rostock (Germany) in order to test the equipment prior a permanent installation (Fig. 2). A permanently installed optical fibre of 3 km length was used for the measurements and connected to an OptoDAS measurement system from Alcatel Submarine Networks.

Fig. 3 shows the cable on the seabed on the left and the detected noise generated by a Remotely Operated Vehicle (ROV) on the right in yellow. There was no fibre at the right end so that there was no data available there.



Fig. 2. Digital Ocean Lab Rostock (DOL); possibilities – left, subsea optical fibre – middle, offshore platform – right.

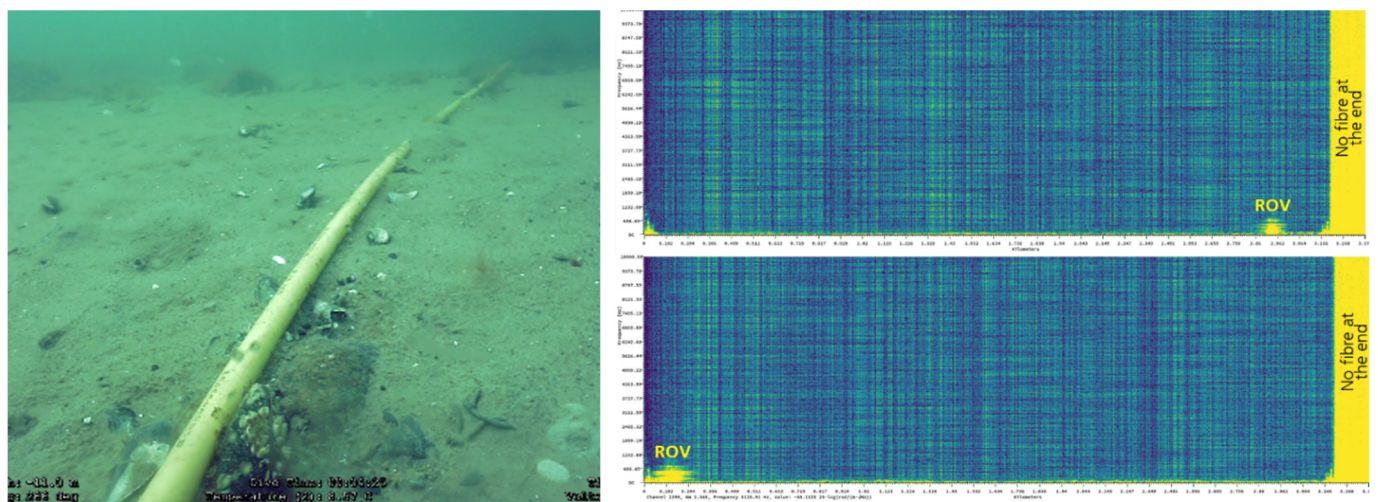


Fig. 3. Offshore testing with a subsea cable as sensor (left) and detection of noise generated with an ROV (right).

5. Conclusions and outlook

The first test in the real offshore environment shows the correct installation of the cable and the detectability of noise in this surrounding. The ROV was clearly detected and localized. As a next step, a permanent installation will be completed and will collect data over a longer period of time. The challenge lies in the amount of data collected and demands for an offshore-safe data storage device.

Generally, DFOS are an excellent opportunity to simplify subsea measurements by having all devices apart from the optical fibre above sealevel. Furthermore, due to the possible measurement length of several kilometers the fibres are well suitable for the monitoring of vast areas like the seabed.

A current drawback is the high related costs. DFOS was first developed for microseismic in oil and gas and for military applications. The manufacturers need to face the challenge to develop a device for infrastructure monitoring and for very specific tasks on the seabed in order to significantly reduce the cost of the measurement devices.

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Crack and reinforcement analysis of a full-scale concrete reinforced beam using CT image data

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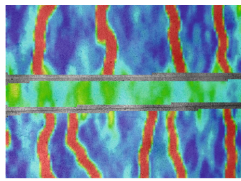
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Abstract

The challenge of improving understanding of crack control in steel-reinforced concrete continues to motivate new research approaches, with the fundamental objective of protecting rebars against corrosion while effectively controlling crack propagation. In particular, accurately analyzing the differences between the observable crack width on the concrete surface and the internal, non-visible crack width at the level of the reinforcing bars remains a significant challenge. To address this, novel methods are required to overcome the inherent difficulty of inspecting the interiors of concrete structures. This paper focuses on the use of one of the most promising non-destructive testing techniques in this context, computed tomography (CT). The study demonstrates the use of CT to analyze crack geometry in a full-scale reinforced concrete beam measuring $30 \times 30 \times 630 \text{ cm}^3$. The adopted methodology for image acquisition and load application, along with relevant findings on the image processing tools and techniques employed, is presented. The crack widths obtained from image data using the spherical granulometry method are compared with those measured on concrete surfaces. Furthermore, the diameter of the steel reinforcement embedded in concrete is obtained using the same algorithm schema with the spherical granulometry method.

Keywords: Computed tomography (CT); reinforced concrete (RC); damage control; non-destructive testing (NDT)

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Strain-based masonry damage detection using neural networks: a numerical study

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Abstract

Structural Health Monitoring is essential for ensuring the safety and resilience of historic masonry structures subjected to seismic events. However, the limited availability of data on damaged conditions hampers the development of reliable predictive models and advanced detection technologies. This work presents an innovative approach that integrates advanced materials, smart sensors, and hybrid modeling for damage assessment and prediction in masonry structures. An archetypal masonry panel is micromechanically modeled using the finite element method to capture local degradation mechanisms, while a realistic façade as a proxy of a real building is represented with a hybrid model, where a micromodelled region is combined with macromodeling of the remaining structure. Both models are subjected to in-plane cyclic loading to simulate earthquake-induced damage at increasing severity levels. Strain data, simulating the response of strain sensitive blocks termed “smart bricks”, are used to train a Domain Adversarial Neural Network on the panel model. The knowledge learned is then transferred to the façade model, enabling accurate damage detection even with limited labeled data. The results demonstrate the potential of this approach as a highly promising technology for intelligent structural monitoring, combining advanced materials, smart sensing, and machine learning to support targeted, continuous interventions. The integration of these technologies paves the way for historic masonry structures that are more resilient, adaptive, and intelligent, aligning with the forefront of structural innovation.

Keywords: Structural health monitoring; smart masonry; numerical modelling; strain measurements; neural network

Note: Full paper

1. Introduction

The built heritage of Italy and Europe is largely composed of masonry structures, many of which are in poor condition due to aging materials and insufficient maintenance. Their location in seismically active zones further amplifies their vulnerability to earthquake-induced damage (Pallarés et al., 2021). The preservation of this irreplaceable architectural heritage is therefore a primary concern for civil engineers and heritage managers alike, making effective and non-invasive monitoring strategies indispensable for their protection.

Structural Health Monitoring (SHM) techniques have progressively established themselves as a key tool for the continuous assessment of masonry buildings, enabling the detection of sensor data anomalies that may indicate changes in structural integrity (Cavalagli et al., 2019; Ramos et al., 2010). Among SHM approaches, vibration-based methods — exploiting operational modal analysis (OMA) and the tracking of natural frequencies — have been widely applied to historic masonry structures, including towers, churches, and monumental buildings (Gigliani et al., 2026; Ubertini et al., 2018). These global techniques provide valuable information on the overall structural state and have demonstrated the ability to detect earthquake-induced damage even when it is not visible from external inspection. However, their sensitivity is limited when damage is localized, and their diagnostic resolution depends heavily on the number and placement of sensors.

To overcome these limitations, recent research has introduced local sensing strategies based on smart masonry, in which structural elements themselves function as distributed sensors (Meoni et al., 2021). This concept encompasses damage-sensitive mortars and strain-sensitive bricks. The present work focuses on smart bricks: piezoresistive clay elements that generate electrical signals proportional to applied mechanical strain (Meoni et al., 2020). When embedded in a masonry assembly, smart bricks can detect strain variations arising from crack formation or environmental changes, providing spatially resolved, real-time insights into the local structural condition. Their distributed placement enables the simultaneous capture of multiple damage mechanisms,

making them particularly well-suited to the post-seismic assessment of historic façades, where damage is often diffuse and difficult to localize from global dynamic signatures alone. To extract maximum diagnostic value from smart brick data, this work leverages Machine Learning (ML) and Artificial Intelligence (AI) techniques. These tools enable the development of intelligent damage classifiers capable of generalizing across different structures. A central challenge in ML-based SHM is the scarcity of labeled data representing damaged conditions in real buildings, where controlled damage experiments are practically prohibited. This limitation is addressed here through Finite Element Models (FEMs) that simulate a comprehensive range of structural scenarios — both undamaged and at multiple damage severity levels — producing a rich synthetic labeled dataset. The classifier trained on simulated data constitutes the source domain model. Transferring this model to real-world cases introduces distributional shifts due to material variability, construction uncertainties, and differences in structural geometry and loading conditions. To bridge this gap, Domain-Adversarial Neural Networks (DANNs) (Ganin and Lempitsky, 2015; Garden et al., 2020; Giglioni et al., 2025) are employed. By learning domain-invariant feature representations through adversarial training, DANNs can adapt classifiers to target-domain data without requiring labeled damage observations from the monitored structure — a major practical advantage for historic heritage.

The present work is composed of different section: section 2 describes the proposed methodology and the DANN architecture; section 3 presents the case study, including the FEM models, the damage scenarios, and the classification results; section 4 discusses outcomes and outlines future research directions.

2. Proposed methodology

2.1. Problem definition

The proposed methodology integrates smart masonry technology with deep learning to assess the structural condition of masonry buildings. A classifier trained on labeled data from an archetypal panel — encompassing healthy and multiple damaged states — is used to predict structural health from strain variations measured by smart bricks. The DANN framework facilitates knowledge transfer from this labeled source domain to the unlabeled target domain of a full masonry façade, enabling reliable damage detection without requiring labeled damage data from the monitored structure. (see Fig. 1).

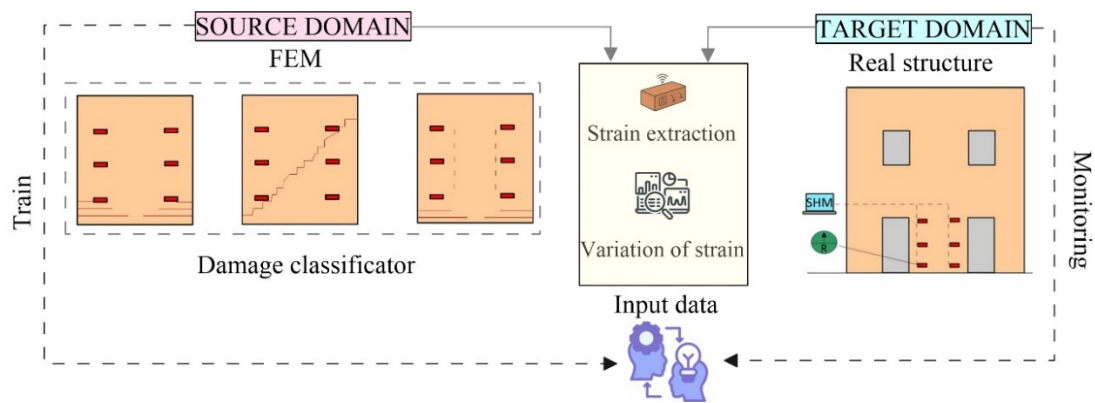


Fig. 1. Proposed methodology of masonry monitoring

2.2. Domain adversarial neural network

Given a source domain D_s and a target domain D_t , with shared feature and label spaces ($X_s=X_t$; $Y_s=Y_t$), but differing probability distributions, domain adaptation improves the target predictive function by exploiting knowledge from the source. A DA-based damage detection approach pursues two goals simultaneously: correctly classifying data within each domain, and identifying cross-domain class similarities (Garden et al., 2020).

DANN requires labeled data exclusively from the source domain and consists of three core components: a feature extractor, a label classifier, and a domain classifier (see Figure 2). The feature extractor processes inputs from both domains and generates domain-invariant representations. A Gradient Reversal Layer (GRL) connects the feature extractor to the domain classifier: during backpropagation, the GRL changes the gradient sign, encouraging the feature extractor to produce representations that confuse the domain classifier. When the domain classifier can no longer distinguish source from target samples, the extracted features are considered effectively domain-invariant.

In the proposed architecture, the feature extractor is implemented as a Spatial Attention Encoder, which combines the strain readings of each sensor with its spatial coordinates on the panel surface. A self-attention mechanism learns the relationships between non-adjacent sensors, capturing the spatial distribution of the strain field. The resulting latent vector feeds two classification heads: the first for binary damage detection, the second for damage type classification. A progressive pseudo-labelling strategy further allows target samples to be gradually incorporated into the training of the second head, reducing the distributional gap between the two domains.

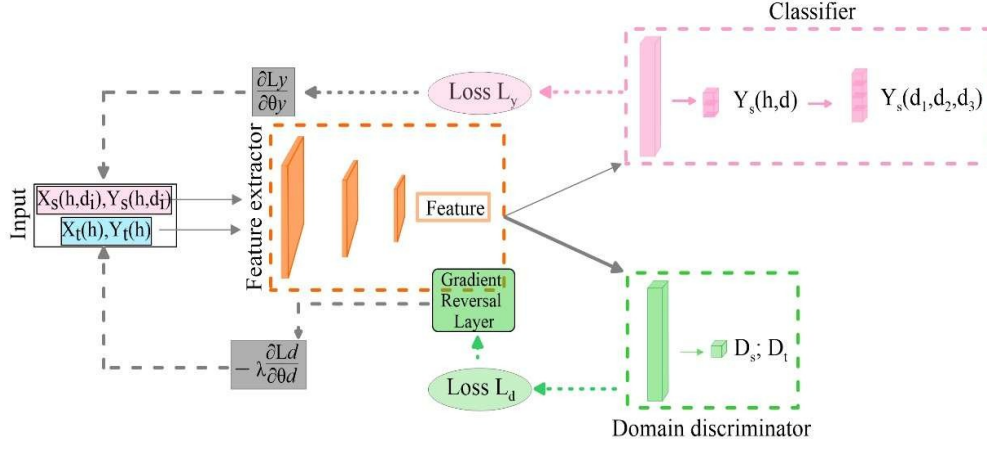


Fig. 2. Domain adversarial neural network.

3. Numerical analysis

To generate the datasets required for training and validating the DANN, finite element models (FEMs) of both an isolated masonry panel and a complete masonry façade were developed in Abaqus. In both cases, a continuous micromechanical modelling approach was adopted, whereby bricks and mortar were represented as distinct material phases without the introduction of explicit interface elements, owing to the lack of detailed experimental characterization data (D’Altri et al., 2018). The masonry assemblage was assumed to consist of M3 mortar and clay bricks with a compressive strength of $f_{cm} = 3$ MPa and $f_{cb} = 35$ MPa, respectively. The Young’s moduli of the constituent materials were estimated according to the empirical relationships reported by Drougkas et al. (2015), corresponding approximately to $700 \times f_{cm}$ for mortar and $300 \times f_{cb}$ for bricks. The mechanical properties adopted in the numerical models are summarized in Table 1.

Table 1. Mechanical parameters of materials.

Element	Density [kg/m ³]	Young's Modulus [MPa]	Poisson's ratio [-]
Brick	1624	10500	0.15
Mortar	1750	2100	0.15
Masonry	1900	2954	0.30
Lintel	700	6500	0.30

The nonlinear behavior of masonry was simulated using the Concrete Damage Plasticity (CDP) model available in Abaqus, which accounts separately for tensile and compressive responses through scalar damage variables ranging from 0 (undamaged material) to 1 (complete stiffness degradation). Tensile damage evolution was defined by assuming a 90% reduction in stiffness at a crack opening displacement of 1 mm. The corresponding fracture energy was calculated as $G_{CM} = (\sigma_{t0} \cdot u_{t0})/2$, following the formulation provided in the ABAQUS Theory Manual (1999). Compressive damage was calibrated assuming a 90% stiffness reduction at the ultimate inelastic deformation, based on the parabolic compressive stress–strain relationship proposed by Drougkas et al. (2015), with a characteristic inelastic displacement $d = G_{CM}/f_c = 1$ mm. The finite element meshes were generated using eight-node linear brick elements with reduced integration (C3D8R).

The masonry panel, arranged in a Gothic bond pattern, measures 1095×1235 mm and is composed of solid clay bricks ($250 \times 120 \times 55$ mm) connected by 10 mm thick cement mortar joints. The façade model, based on a full-scale masonry specimen constructed at the Department of Civil, Chemical, Environmental and Materials Engineering (DICAM) of the University of Bologna (Meoni et al. 2023), measures 4725×4670 mm and shares the same masonry texture, material properties, and sensor layout adopted for the panel (see Fig. 3).

To achieve a balance between modelling accuracy and computational efficiency, a hybrid modelling strategy was adopted for the façade. The instrumented region was represented using a detailed micromechanical approach with explicit brick–mortar discretization, whereas the remaining portions of the structure were modelled as an equivalent homogeneous continuum. The model also includes a timber lintel and two floor diaphragms, represented as distributed non-structural masses to capture their dynamic contribution without altering the global stiffness of the system. Smart brick sensors were positioned following a uniform grid layout covering the entire panel surface, ensuring simultaneous coverage of the regions most susceptible to the three damage mechanisms under investigation. Sensors were placed at locations prone to flexural cracking (base and top of the panel), shear cracking (diagonal band across the mid-height), and compressive crushing (compressed toes), so that each damage type produces a distinctive and spatially identifiable strain signature. The same sensor layout was replicated in the instrumented micromodelled region of the façade model, ensuring consistency between source and target domains. Damage scenarios were generated by simulating the seismic response of the masonry panel through in-plane cyclic displacement-controlled tests applied at the top boundary.

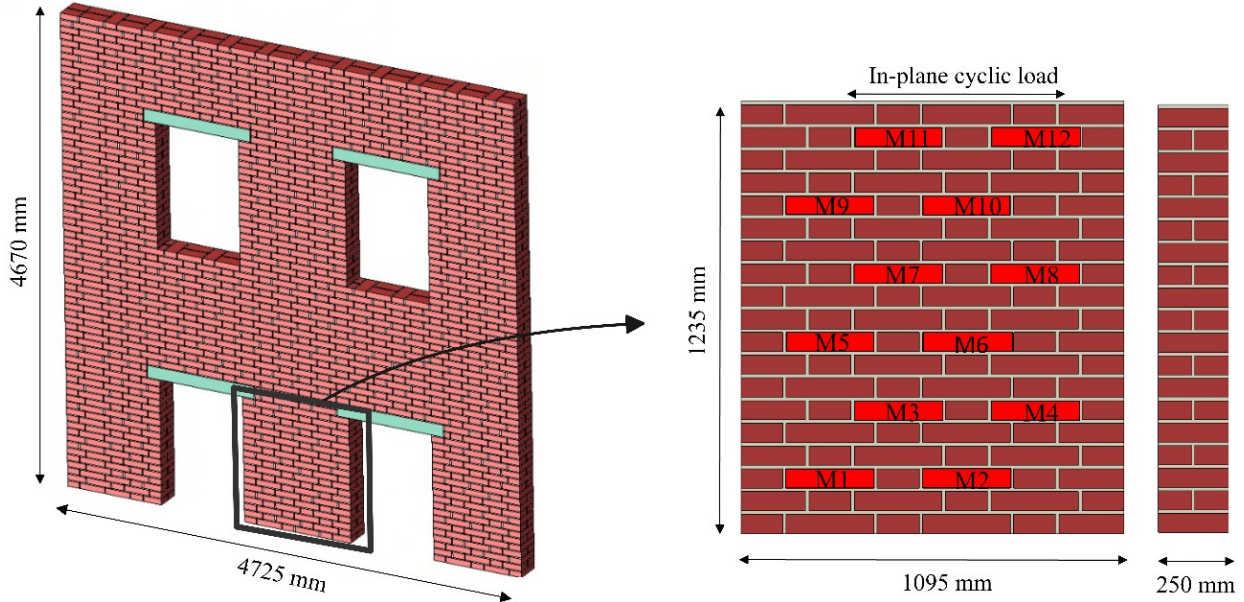


Fig. 3. Geometry of the panel and facade design.

Depending on the level of vertical compressive stress, three distinct damage mechanisms were simulated: flexural cracking (d1), shear cracking (d2), and combined flexural-compressive failure (d3), each at multiple severity levels to expose the classifier to a continuous spectrum of structural degradation. The trained model was subsequently evaluated on the façade, subjected to distributed horizontal inertial forces increasing linearly along the height, according to a linear distribution of pseudo-acceleration reaching 1.2g at the top.

Strain measurements were acquired under permanent loading conditions following the removal of the seismic excitation, thus reproducing a realistic post-earthquake structural health monitoring scenario. To account for measurement uncertainty, additive white Gaussian noise was independently added to each strain measurement. The noise standard deviation was computed according to a prescribed SNR of 40 dB, following a common practice in SHM studies employing synthetic FEM-generated datasets (Al-Qudah et al., 2025). A noise floor of 10^{-6} was imposed to avoid numerical instabilities in the presence of near-zero strain values. The noise was applied independently to each sensor reading in both the healthy and damaged states, prior to computing the relative strain variations used as input features to the classifier. The network was trained using strain variations referenced to the undamaged structural condition, defined. For the healthy state, the strain variation is computed between two consecutive monitoring instants: $\Delta\epsilon_h = (\epsilon_h(t+\Delta t) - \epsilon_h(t))/\epsilon_h(t)$, where $\epsilon_h(t)$ is the strain measured at the current reference instant t , and $\epsilon_h(t + \Delta t)$ is the strain measured at the subsequent instant $t + \Delta t$. For the damaged state, the strain variation is computed with respect to the healthy reference measurement at time t : $\Delta\epsilon_d = (\epsilon_{di} - \epsilon_h(t))/\epsilon_h(t)$ where ϵ_{di} denotes the strain measured under damage condition d_i , with $i \in \{1,2,3\}$ corresponding to flexural, shear, and combined flexural-compressive damage, respectively. Prior to training, all input features were standardised to zero mean and unit variance using a Standard Scaler fitted on the source domain and subsequently applied to the target domain.

Z-score normalization is a well-established preprocessing step in domain adaptation methods, as it reduces the impact of features with large variance and contributes to minimising the distribution shift between domains (Zhang et al., 2023; Poole et al., 2022).

4. Results

The three simulated damage mechanisms produced clearly distinguishable strain signatures. Under low compressive stress (0.25 MPa), flexural cracking (d1) generated horizontal strain concentrations at the base and top of the panel. At intermediate compression (1.0 MPa), shear cracking (d2) produced diagonal patterns across the mid-height, while at high compression (3.0 MPa), combined bending-compressive failure (d3) resulted in toe crushing with co-occurring flexural cracking. In all cases, local stiffness reductions of up to 95% were recorded in the most severely damaged elements. The resulting damage distributions for both the panel and the façade are shown in Fig. 4. For each damage mechanism, strain data were collected upon unloading following four peak displacement levels (3, 5, 7, and 9 mm), corresponding to progressively increasing damage severity. Measurements were acquired under gravity load only. The distribution of the vertical strain component ϵ_{22} was found to vary distinctly across each loading cycle, reflecting the incremental redistribution of internal forces as damage accumulates. This progressive variation confirms that strain measurements carry discriminative information across the full spectrum of damage severity, from slight to severe, and therefore constitute effective input features for the damage classifier. The horizontal inertial forces applied to the façade model induced predominantly flexural damage, consistent with the cantilever-like behaviour of the wall under the linearly increasing acceleration profile. The damage was concentrated in the instrumented micromodelled region, where the detailed brick–mortar discretisation allowed the local degradation to be resolved with sufficient accuracy.

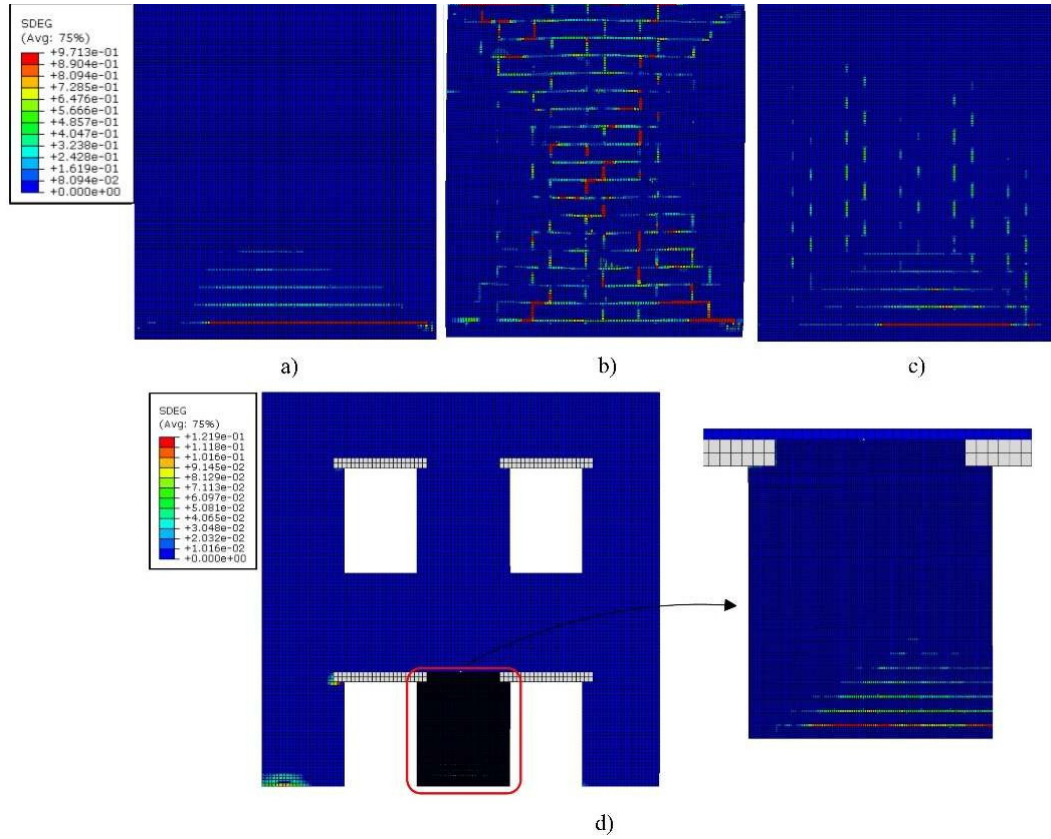


Fig. 4. Damage of the model FEM: (a)–(c) damage of the archetipal panel; (d) damage of the façade.

Regarding sensor selection, all smart bricks embedded in the panel were included as input features, with the exception of sensors M11 and M12. These two sensors are located at the boundary between the micromodelled and macromodelled regions, where the different kinematic constraints between the two models introduce artificial strain discontinuities that are not representative of the true structural response. Their exclusion was found to improve classification accuracy on the façade by removing spurious features that would otherwise confuse the domain classifier. The label classifier, trained exclusively on panel data, achieved near-perfect discrimination among the four structural states (healthy, d1, d2, d3), as confirmed by the confusion matrix. The DANN subsequently transferred this knowledge to the unlabeled façade domain. Despite the differences in geometry, boundary conditions, and loading configuration, the network successfully detected the presence of damage in the façade. The improved training strategy — incorporating a wider range of severity levels and a progressive pseudo-labelling approach — enhanced the alignment between source and target feature distributions, enabling the model to identify low-intensity damage states that were not detectable in the preliminary study. The feature space alignment between source and target domains is illustrated in Fig. 5.

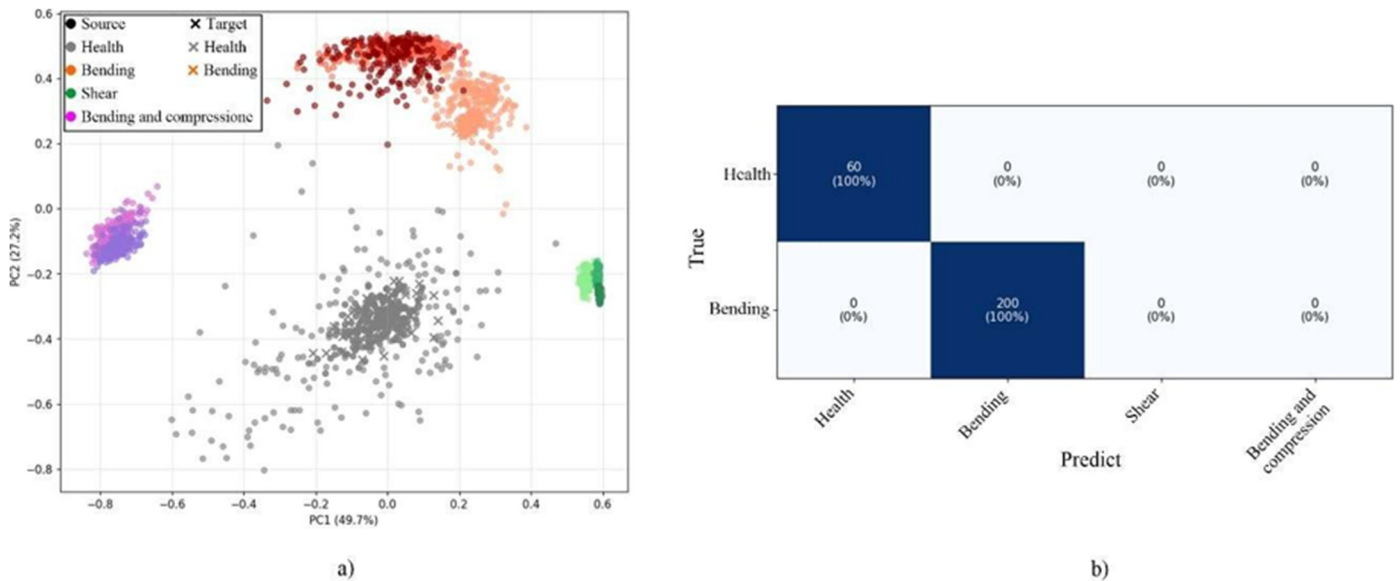


Fig. 5. Result of the transfer learning with DANN.

5. Conclusion

This work presents an extended methodology for SHM of historic masonry structures, integrating smart brick sensor technology, finite element micromechanical modelling, and domain-adversarial neural networks. The dataset encompasses multiple damage scenarios across a wide range of severity levels — corresponding to imposed displacements of 3, 5, 7, and 9 mm — and the DANN training strategy incorporates spatial attention and progressive pseudo-labelling, resulting in high classification accuracy. The damage classifier trained on the archetypal panel achieved near-perfect discrimination among the four structural states: healthy (h), flexural (d1), shear (d2), and combined bending-compressive (d3). The inclusion of multiple severity levels proved essential for capturing the progressive redistribution of the vertical strain field ε_{22} across loading cycles, exposing the classifier to a continuous spectrum of structural degradation and enabling the detection of low-intensity damage states. The DANN successfully transferred the learned knowledge to the unlabeled façade domain, detecting structural anomalies despite significant differences in geometry, boundary conditions, and loading configuration. The exclusion of sensors M11 and M12 — located at the interface between the micromodelled and macromodelled regions — further improved classification accuracy by removing spurious features introduced by kinematic incompatibilities at the model boundary. The improved feature alignment between source and target domains confirms the effectiveness of the domain adaptation strategy when trained on a larger and more diverse dataset.

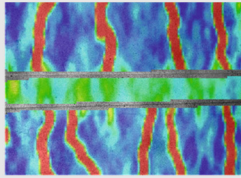
The integration of advanced materials, smart sensing, and machine learning demonstrated here charts a clear pathway toward more resilient, adaptive, and intelligent monitoring of historic masonry structures.

Acknowledgements

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SMAR 2026



SMAR 2026 - 8th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

Parallel Session 2

Digital methods for structural assessment

How effective are LLM-designed optimizers for multilevel thresholding of concrete defects?

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Abstract

Multilevel thresholding is a widely used approach for segmenting concrete surface images in structural health monitoring, where the threshold values are selected by maximizing the Otsu between-class variance. The resulting optimization problem is usually solved with hand-crafted gradient-based or meta-heuristic algorithms, whose design requires considerable expertise and offers no guarantee of being well suited to a given problem size. This study investigates whether a Large Language Model (LLM) can instead design the optimizer automatically. We propose a framework, termed LLM-driven Automated Design of Segmentation optimizers (LADS), in which the DeepSeek model iteratively generates, evaluates, and refines a complete optimization algorithm for the multilevel Otsu problem, guided by an automated objective evaluator and runtime feedback. The framework is tested on five concrete bridge images for threshold counts ranging from 5 to 35 and is benchmarked against two meta-heuristics, Particle Swarm Optimization (PSO) and Genetic Algorithm (GA), and two classical local methods, Sequential Quadratic Programming (SQP) and a Quasi-Newton method. The results show that the LLM-designed optimizer matches the strongest meta-heuristic baselines across the range of thresholds and achieves the best segmentation quality at the highest threshold count, while consistently outperforming the gradient-based methods. These gains come at a markedly higher computational cost. The findings indicate that LLM-driven automated algorithm design transfers effectively from generic benchmarks to a concrete engineering task in structural health monitoring.

Keywords: Large language models; automated algorithm design; defect detection; multilevel thresholding; metaheuristic optimization; structural health monitoring

* The full paper is open access available in the Conference Proceedings. *

Digital volume correlation applied to in-situ tomography data of a hollow core beam

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Abstract

This article presents the application of digital volume correlation for the detection of geometric discrepancies representing cracks in multi-temporal voxel data. The voxel data was obtained with in-situ X-ray tomography of a four-point bending test applied to a carbon-reinforced hollow core concrete beam. The in-situ tests were performed at the large-scale tomography portal Gulliver at Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau. The digital volume correlation data processing chain starts with the definition of a high number of small cuboids (subsets) in the reference voxel dataset under zero-load. These cuboids are tracked in the other datasets of the loaded states (35 kN and 85 kN), resulting in subvoxel-precise 3D displacement fields. Our method continues with the triangulation of the cuboid centers into tetrahedral meshes in each state, where the tetrahedra are analyzed for geometric changes between the datasets. Our mathematical model for brittle material involves a split of the tetrahedron that represents a crack opening and subvoxel-precise deformation vectors are derived as relative movements. The article will show results and visualizations obtained by the DVC technique.

Keywords: Carbon fiber reinforced polymers; deformation measurement; digital volume correlation; hollow core beam

* The full paper is open access available in the Conference Proceedings. *

Assessment of historic cast steel bearings

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Abstract

Historic cast steel bearings pose a particular challenge in terms of structural assessment and remaining service life, since existing design and material documentation is often incomplete or no longer available. This paper presents a comprehensive assessment approach that combines several non-destructive testing (NDT) methods to evaluate the condition of these historic bearings in situ. The process begins with a detailed visual inspection to assess the overall external condition. To detect surface-breaking cracks, magnetic particle testing and dye penetrant testing are applied. For the identification of internal defects such as shrinkage cavities or porosity, ultrasonic testing is supplemented by advanced techniques including phased array ultrasonic testing (PAUT) combined with probability-of-detection-based assessment (POD), providing improved spatial resolution and defect characterization. As an additional component, casting process simulations are used to identify potential defect hot spots prior to inspection, enabling targeted and efficient testing strategies. Furthermore, the chemical composition is determined in situ using mobile, minimally destructive optical emission spectroscopy to verify material properties. The approach is complemented by metallographic investigations performed in place, allowing microstructural analysis to support conclusions regarding heat treatment and corresponding mechanical behavior. The proposed methodology enables a systematic, reproducible, and largely nondestructive assessment of historic cast steel bridge bearings, providing an essential basis for condition evaluation and retrofit strategies in existing infrastructure.

Keywords: Historic cast steel; NDT; PAUT; POD; metallography

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Maintenance and monitoring for the conservation of industrial steel buildings: a review

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Abstract

Industrial steel buildings constitute a significant portion of the built environment and exhibit a high degree of typological variability. Many existing structures, often designed without modern seismic criteria, are affected by degradation phenomena such as corrosion and fatigue, further influenced by operational and environmental conditions. Their conservation therefore requires an integrated approach combining structural assessment, maintenance planning, and monitoring strategies. This review analyzes the structural behavior of these systems with reference to different load-resisting mechanisms, identifying key sources of vulnerability such as insufficient bracing, low-ductility connections, and stability issues. Maintenance strategies are then addressed through BIM-based approaches and their evolution toward Digital Twin frameworks, which enable predictive maintenance by integrating lifecycle information with real-time data. Monitoring techniques are discussed at multiple scales, including local structural health monitoring based on IoT sensors and large-scale satellite observations derived from DInSAR data. The review also proposes a step-by-step process that links preliminary data collection, typological classification, large-scale satellite screening, local monitoring, Digital Twin updating, and risk-based maintenance planning. The results highlight how the integration of digital tools with multiscale monitoring supports early damage detection, prioritization of interventions, and more efficient maintenance planning, fostering a shift toward predictive strategies and improving safety, resilience, and sustainability.

Keywords: Industrial steel buildings, structural monitoring, maintenance, BIM, digital twin, DInSAR

* The full paper is open access available in the Conference Proceedings. *

A rapid post-earthquake loss assessment system for open-pit mines in Taiwan

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Abstract

Taiwan's open-pit mines are frequently exposed to strong seismic shaking, yet rapid post-earthquake loss assessment for mining equipment remains limited. This study develops a Rapid Post-Earthquake Loss Assessment System for open-pit mines in Taiwan, integrating seismic demand estimation, equipment-level fragility modeling, and a pre-simulated earthquake scenario database. Based on field investigations at four representative mines, critical equipment and operational components are identified and evaluated using fragility functions. Once earthquake information is received from the Central Weather Administration, the system automatically matches the event to precomputed scenarios and estimates damage probabilities for monitored equipment. The results are classified into low, moderate, and high risk levels and visualized through an intuitive decision-support interface. By providing rapid, site-specific, and equipment-level risk information, the proposed framework enhances situational awareness, supports inspection prioritization, and facilitates timely emergency response in mining facilities. The system demonstrates a practical approach for applying engineering seismology and fragility-based assessment to industrial seismic risk management.

Keywords: Earthquake loss assessment; open-pit mining; seismic fragility; rapid assessment system; decision support system

* The full paper is open access available in the Conference Proceedings. *

Prediction of unified strain ductility in FRP-confined concrete column using machine learning

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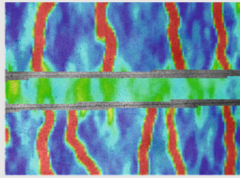
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Abstract

Accurate prediction of the strain ductility of fiber-reinforced polymer (FRP)-confined concrete columns is crucial for understanding and improving their mechanical performance under axial compression. Although several predictive models have been developed, most focus solely on circular cross-section columns and were calibrated using limited experimental databases covering a narrow range of material and geometric parameters. Accordingly, these models exhibit restricted generalization and poor accuracy when applied to non-circular cases. Moreover, the use of machine learning for modeling the ductility behavior of such columns remains rare and insufficiently explored. This study proposes a unified machine learning framework for predicting the strain ductility of fully FRP-confined concrete columns of circular, square and rectangular cross-sections. A comprehensive database of 1866 experimental results were compiled to develop a support vector regression (SVR) model capable of capturing the complex nonlinear interactions between geometric and material parameters influencing ductility. To prevent overfitting, cross-validation with 10 folds was performed throughout the training. The optimal hyperparameter combinations for machine learning was identified during the hyperparameter tuning procedure. The predictive performance of the model was evaluated against the unified strain ductility equation using the root mean square error (RMSE). The SVR model achieved an RMSE of 3.072 for the full dataset, compared with 4.58 for the unified equation, corresponding to an improvement in prediction accuracy of approximately 33%. When applied only to circular columns, the SVR model achieved an RMSE of 2.90, showing a 5.5% improvement compared with the full dataset. The results indicate that machine learning provides improved prediction accuracy for the strain ductility of FRP-confined concrete columns.

Keywords: Unified model; machine learning; strain ductility; fiber-reinforced polymer (FRP) confined concrete column

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Parallel Session 3

Advanced cementitious and composite materials

Effects of chemical admixtures on self-sensing cementitious composites: a review

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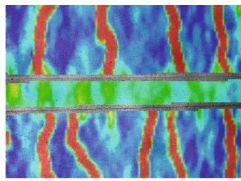
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Abstract

Recent studies have significantly advanced the development of new Self-sensing Cementitious Composites (SSCC) for Structural Health Monitoring (SHM), enabling their application in infrastructures such as bridges, tunnels, roads, dams and high-rise buildings. However, to increase the conductivity of SSCC, electrical materials based on metals or carbon need to be incorporated into the cement matrix, which can affect its properties in the fresh and hardened states. This scenario demands the use of chemical admixtures, such as superplasticizers and water-reducing agents. In this sense, the current research takes a theoretical approach, based on a review, to consolidate the main findings regarding the use of chemical admixtures in cementitious composites and comparing their electrical properties using normalized resistivity. In general, previous studies have shown that admixtures have contributed to the dispersion and homogenization of conductive materials, which improves the formation of electrical networks. While accelerators, corrosion inhibitors and conventional water reducers combined with accelerators generally reduce resistivity by increasing ionic conductivity, shrinkage-reducing, air-entraining, high-range water-reducing, and retarding admixtures tend to increase resistivity due to changes in pore structure and reduced ionic mobility. However, limited data, interactions with conductive fillers, and variability in electrical testing methods restrict direct comparisons, highlighting the need for improved electrochemical characterization and standardized measurement approaches. Therefore, the compilation and analysis of these main findings helped to identify new approaches and challenges that contribute for the improvement of SSCC and its applications in SHM, due to the chemical admixture's effects

Keywords: Smart concrete; SHM; electrical properties; superplasticizers; water-reducer

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Bicomponent PP fibers with chemical surface functionalization for enhanced bonding in cementitious composites

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Keywords: Polypropylene fibers; strain-hardening cementitious composites; fiber surface modification; melt-spinning

1. Introduction

Strain-hardening cementitious composites (SHCC) represent an advanced class of fiber-reinforced cement-based materials that exhibit pseudo-ductile behavior under tensile loading through the formation of multiple microcracks. This behavior is enabled by efficient crack bridging of short discrete fibers that transfer stresses across the crack surfaces while dissipating energy during fiber pullout. The application of thin layers of SHCC offers great potential to improve the impact resistance of existing structures and buildings (Yang & Li, 2010; Li, 2012; Mechtcherine, 2013; Li, 2019). Polypropylene (PP) fibers are commonly used in concrete, e.g., for crack control or fire protection (Lura & Terrasi, 2014). They also demonstrated their potential as a viable, more sustainable and cost-efficient alternative to expensive high-performance fibers in SHCC, like polyvinyl alcohol (PVA) or ultra-high molecular weight polyethylene (UHMW-PE) fibers (Pakravan & Ozbakkaloglu, 2019; Ahmed et al., 2025). Despite their numerous benefits in cement-based composites, they present a significant drawback: poor compatibility and inferior bonding with the cementitious matrix, resulting from their smooth surface with a lack of functional groups (Pakravan & Memariyan, 2017; Wölfel et al., 2021). This not only leads to a reduced composite performance, since the load transfer from matrix to fiber is compromised, but also to problems during mixing, e.g., fiber balling and agglomeration, reducing the threshold for the maximum fiber content percentage.

A viable approach to addressing the insufficient fiber-matrix bond of PP fibers in SHCC is the structural modification of the fiber surface to enhance roughness. Previous studies have shown that the incorporation of calcium carbonate particles in the fiber shell leads to an increased fiber roughness, and, consequently, mechanical interlocking of fiber and matrix during fiber pullout. Therefore, a more efficient energy absorption under tensile loading is possible, multiple cracking is enabled, and pronounced strain-hardening behavior is achieved, while the mechanical integrity of the fiber is maintained by a high-molecular weight PP in the fiber core (Popa et al., 2023; Popa et al., 2025; Popa et al., 2026). While this structural modification approach effectively enhanced mechanical interlocking, the chemical incompatibility between PP and the cementitious matrix still remains and is approached in the ongoing investigations.

The current studies therefore focus on improving the chemical compatibility of the inherently inert PP fibers with the cementitious matrix. Additives based on functionalized polypropylene, such as maleic anhydride grafted PP, are commonly used as compatibilizers between nonpolar polyolefins and more polar materials (Kulkarni & Mahanwar, 2014; Watanabe et al., 2020). However, their relatively lower molecular weight and viscosity can negatively affect spinnability and mechanical fiber properties when used as the main polymer component. Therefore, the design strategy of bicomponent fibers is employed again, which allows for the use of significantly higher additive concentrations without compromising the spinnability and mechanical strength of the fibers. The design concept is depicted in Fig. 1. Fig. 1 a) illustrates the experimental setup for bicomponent spinning at a pilot-spinning line that enables an on-line fiber drawing to achieve enhanced mechanical properties. Fig. 1 b) presents a schematic drawing of the bicomponent fiber, wherein the fiber core is composed of unmodified, high molecular weight PP, while the fiber shell consists of modified PP with functional groups.

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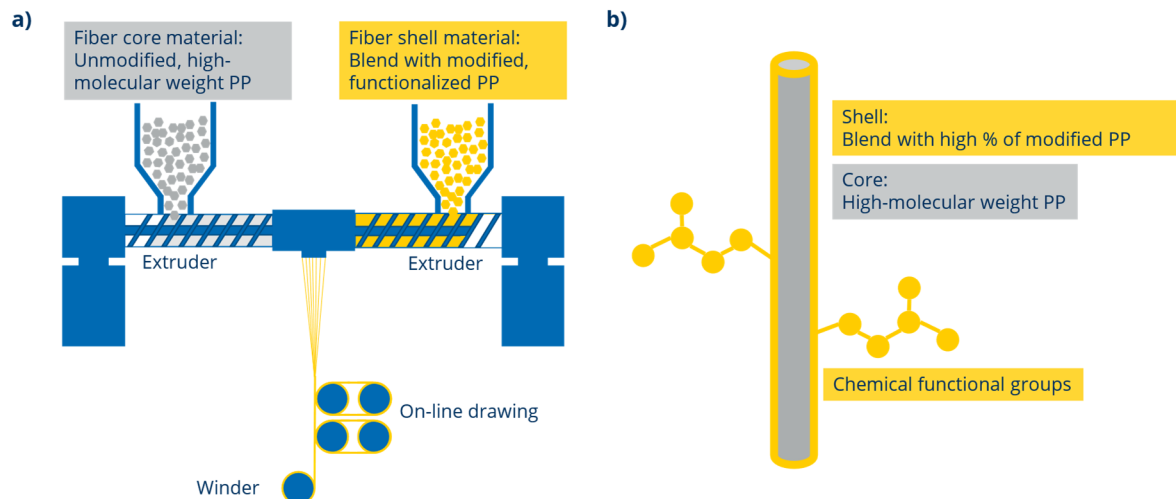


Fig. 1. (a) Setup of the spinning line for bicomponent fiber manufacturing and (b) a schematic drawing of bicomponent fibers with modified fiber shell.

2. Experimental program and analysis methods

As a fiber core material, a high-molecular weight PP for spinning high-strength fibers is used. For the fiber shell material, polymer blends with varying ratios of 2, 10, 20 and 30% are produced. In total, four different chemically functionalized PP types are used. Prior to fiber manufacturing, the spinnability of the polymer systems is assessed through an experimental program (Hübner et al., 2024) that includes rheological characterization, molecular weight analysis, and thermal analysis. Surface properties and potential functionalization effects are investigated using contact angle measurements and infrared spectroscopy.

Initial spinning trials are conducted using a laboratory-scale piston spinning device to determine suitable processing parameters for bicomponent fiber production. With this small-scale setup (~ 10 g per trial), monofilament spinning is possible without an on-line drawing process. Subsequently, the process is upscaled to a pilot spinning line with industry-like scale and conditions, where multifilament fiber spinning is conducted with the application of an on-line drawing step. A fiber core/shell ratio of 80/20 is selected and controlled through the volume throughput during the spinning process. The detailed setup of both spinning lines has been explained in previous studies (ALRahhal et al., 2016; Kühnert et al., 2018).

Subsequently to fiber manufacturing, the influence of the shell modification on fiber-matrix interaction is evaluated using single-fiber pull-out tests under quasi-static and dynamic loading conditions. These micromechanical investigations allow the quantification of pull-out forces and pull-out work, which serve as indicators of fiber-matrix bond performance and crack-bridging capability in SHCC systems. This method has been explained in detail elsewhere (Wölfel et al., 2021). In addition, the influence of the fiber modifications on fiber tensile properties are measured with single fiber tensile testing, according to (Popa et al., 2023).

3. Expected contribution and outlook

The presented study aims to contribute to the existing research gap of chemical fiber surface modification to optimize the fiber-matrix interaction in PP-reinforced SHCC. By exploiting the design flexibility of bicomponent fibers, functional additives can be selectively introduced at the fiber surface while maintaining a high tensile strength and Young's modulus that is required for effective crack bridging.

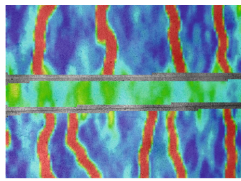
In further studies, this approach will be combined with the previously employed structural modification of PP fibers, with the aim of developing a chemically compatible PP fiber with high roughness for enhanced crack-bridging behavior and energy absorption in SHCC. This approach offers a promising pathway towards scalable and cost-efficient fiber designs for SHCC applications. In combination with alternative low-clinker binder systems, such tailored fibers may contribute to the development of more sustainable and economically viable ductile cementitious composites.

Acknowledgements

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Investigation of bio-inspired layered interphases in carbon fiber-reinforced concrete using μ -CT

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Keywords: Carbon fiber-reinforced concrete; bio-inspired interphases; single fiber pull-out; yarn pull-out; computer tomography

Extended Abstract

Structural rehabilitation offers a sustainable approach to extending the service life of existing infrastructure. Carbon fiber-reinforced concrete (CFRC) is highly suitable for this purpose, offering a wide range of applications, such as shotcrete reinforced with flexible carbon grids (Mechtcherine (2013)). However, a critical challenge remains: the brittle failure mechanisms, particularly the debonding and spalling of the concrete matrix from the carbon-reinforcement due to an insufficient interfacial bonding.

To enhance the interaction between the concrete matrix and carbon reinforcement, Penzel et al. (2022) investigated carbon rovings with a tetrahedral profile. This specific geometry was designed to maximize the mechanical interlock (form fit) by creating significant variations in the roving's cross-section. Other studies used sanded carbon-reinforcement that benefits the crack pattern (width and distance) but not the load bearing capacity (Frenzel et al. (2023)).

Addressing the described limitations of CFRC, a bio-inspired interphase, schematically illustrated in Fig. 1, was developed. By incorporating energy-dissipating mechanisms at the interphase, this approach aims to increase the total fracture energy of the carbon-reinforced system.

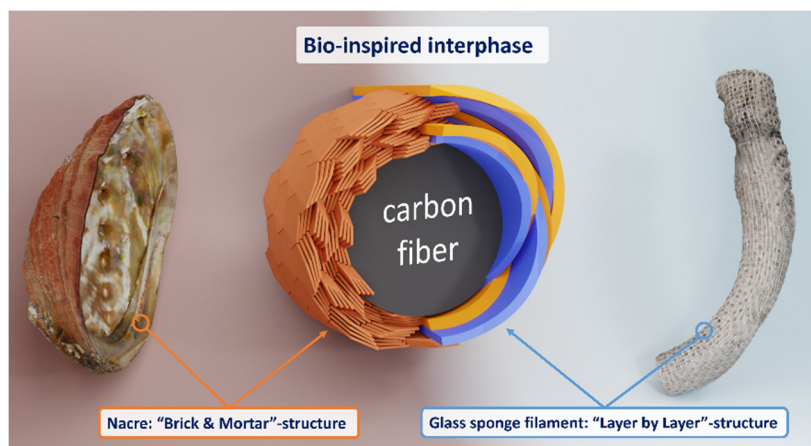


Fig. 1. Schematic illustration of the “Brick & Mortar”-structure (left) and the “Layer by Layer”-structure (right).

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Our approach draws inspiration from natural materials of alternating organic and inorganic layers with exceptional mechanical properties, such as nacre ("Brick and Mortar"-structure, BnM (Wegst et al., 2015)) and glass sponge filaments ("Layer by Layer"-structure, LbL (Woesz et al., 2006)). Self-assembled BnM-structures were produced using mixtures of montmorillonite (MMT) mineral and a polymer. LbL-structures were formed through alternating layers of sodium water-glass (WG) and a polymer.

These structures were applied to single fibers via dip-coating, employing different polymers with varying stiffness (Utech et al. (2024)). In the case of yarns, the impregnation procedure was specifically tailored to account for the internal roving structure and the increased requirements for matrix penetration (Utech et al., 2023). The LbL-approach required multiple treatment steps to achieve the alternating organic and inorganic layers in both cases.

The treated single fibers were embedded in a concrete matrix droplet for single fiber pull-out (SFPO – Utech et al. (2024)) tests, whereas the impregnated yarns were embedded into concrete cubes of varying geometries to ensure both pull-out (small cube) and fixation (larger cube) for the yarn pull-out test (YPO – Utech et al., 2023). Each of these methods, SFPO and YPO, differ in their analytical focus and experimental objectives. SFPO allows for a precise characterization of the interphase between fiber and matrix, whereas YPO encompasses a broader range of effects, such as internal load distribution and the influence of impregnation quality on the overall pull-out resistance.

The SFPO-results showed that LbL interphases with increasing layer count led to a decrease in interfacial shear strength (IFSS) but an increase in the required pull-out work, depending on the polymer stiffness. A BnM-structure with a MMT-to-polymer ratio of 6:4 also exhibited higher pull-out work compared to tests using the single components solely. Scanning electron microscopy (SEM) provided insights onto the self-assembled surface structure and confirmed beneficial bonding at the interphase, evidenced by residues visible on the pulled-out fibers and within the pull-out cavities.

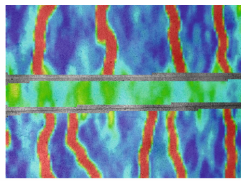
The quality of the yarn impregnation was investigated by micro-computed tomography (μ -CT), which revealed different wetting behaviors resulting in varied yarn and interphase morphologies. YPO tests yielded equally high results for the stiffest polymer as well as for the BnM-structure (9:1 polymer-MMT ratio).

Acknowledgements

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Analysis of concrete penetration into microstructured impregnation of carbon textiles

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Keywords: Carbon-reinforced concrete, interphase, micro-computed tomography, LC3

1. Introduction

Carbon-reinforced concrete (CRC) offers significant advantages over steel-reinforced concrete. These advantages include high tensile strength, corrosion resistance, and a reduced cross-section (Scope et al. 2020). These features make CRC particularly attractive for the rehabilitation existing buildings (Bielak et al. 2021). In order to exploit these advantages, the textile is subjected to impregnation, which offers several benefits: it provides protection for individual filaments, it enhances the handling of textiles during consolidation and it optimizes the transmission of force through the yarn cross-section. Epoxy resins are widely utilized materials in this context. However, this process facilitates a smooth interface to the concrete with no mechanical or chemical bonding, which can result in premature, brittle failure, which in turn impairs both load transfer and durability (Frieese et al. 2022). The interphase is therefore decisive for the overall performance of the composite. Therefore, targeted control of the stress-slip behavior by modifying the interphase is expected to increase the fracture toughness of the reinforced CRC composite.

Previous research has been conducted on sand-coated rovings (e.g. Donnini et al. 2016). Additionally, studies have investigated bio-inspired designs, particularly layer-by-layer and brick-and-mortar structured interphases. For the latter, an increase in fracture toughness was demonstrated in the yarn-pull-out test (Utech et al. 2023).

The primary aim of this project is to develop graded material transitions and promote mechanical interlocking through open-cell interphases formed with a newly developed limestone calcined clay cement matrix (LC³), thereby preventing cleavage-type failure. To achieve this, the sacrificial particle templating method is used in relation to the impregnation of the rovings (Figure 1). The resulting pores must then be penetrable by the concrete matrix in order to achieve the aforementioned effects.

2. Experimental program and analysis methods

48K carbon rovings were impregnated with an epoxy resin. Immediately after impregnation, water-soluble particles of two different size-classes were applied onto the wet rovings so that particles adhered to the resin surface prior to cure. The rovings were then cured under controlled temperature and time conditions to cure the epoxy matrix and fix the particles. Embedded particles were removed by water washing to produce a microstructured open-pore surface. A thin, conformal coating was applied to the rovings as the final step in the procedure. This coating was designed to enhance wettability for the subsequent embedding of the rovings in concrete. A newly developed LC³ matrix, formulated as a self-compacting concrete, was used to cast concrete specimens. After concrete hardening, cores were extracted from the specimens by drilling. All roving-containing samples were labeled to ensure consistent positioning during imaging and to enable later registration across datasets. A roving without particle treatment was included as a control.

Micro-Computed Tomography (μ -CT) scans were acquired at three stages: prior to particle removal, after particle removal, and following concrete embedding. The Procon XPRESS μ -CT was used. The raw X-ray images were used to reconstruct the voxel

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datasets with ca. 9 μm voxel size applying the algorithm of Feldkamp et al. (1984). The voxel datasets were transformed to the same coordinate system by a 3D registration (rigid body transformation).

Quantitative analysis of pore number and pore size after particle removal was carried out using a surface-based determination coupled with a threshold-based floating algorithm for pore segmentation. Penetration of the LC³ matrix into the open-pore surface was assessed by surface registration of the $\mu\text{-CT}$ volumes and by comparative analyses between the regions of interest with and without concrete. Results were processed to quantify infiltrated volume fractions and to correlate pore size with concrete penetration.

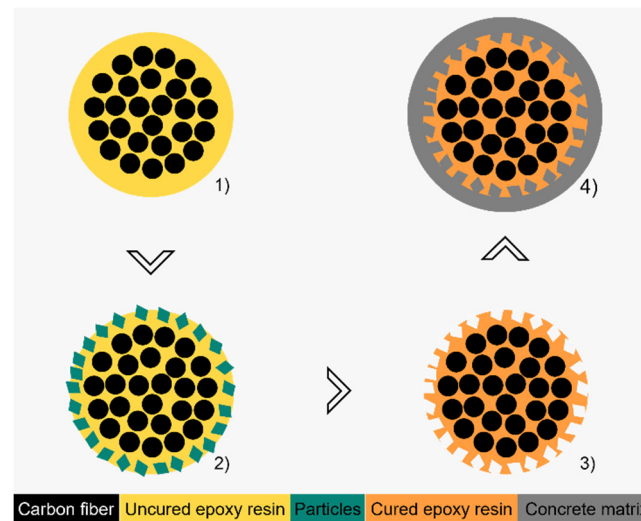


Fig. 1. Schematic representation of the procedure to achieve an open-pore structured surface of an impregnated carbon yarn: 1) impregnation with epoxy resin, 2) application of sacrificial particles, 3) leaching of the particles after curing, 4) penetration of concrete matrix into pores for mechanical interlocking.

3. Expected contribution and outlook

The contribution of the presented approach including the microstructured interphase is aimed at improving the composite performance of carbon-reinforced concrete (CRC), thereby increasing material utilization and long-term durability. Ensuring concrete penetration into the engineered surface porosity is critical, as interfacial air voids not only reduce the effective bond area but also eliminate potential mechanical interlocking. The suitability of micro-computed tomography ($\mu\text{-CT}$) for detecting and quantifying the concrete ingress is therefore being assessed. Beyond the specific CRC application, the employed $\mu\text{-CT}$ workflow is considered transferable to other composite systems in which interfacial porosity governs bonding behavior; in such systems it is equally important to determine how many and which size classes of air pores are present at the interface. Additional to the characterization by visual analysis, the bond behavior of the graded open-cell structured interphase will be studied by yarn pull-out tests.

Acknowledgements

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Machine learning-based prediction of compressive strength in 3D concrete printing: a multi-layer perceptron approach

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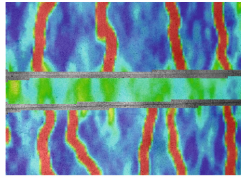
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Abstract

3D concrete printing (3DCP) technology has gained considerable attention within the construction industry due to its significant advantages over conventional casting methods, including reduced material waste, lower transportation costs, elimination of formwork requirements, accelerated construction times, and enhanced design flexibility for complex geometries. Whilst numerous experimental investigations in the literature have examined the mechanical properties of 3DCP elements, their widespread adoption in real-world projects remains limited due to insufficient design guidelines and predictive tools for assessing printed concrete behaviour at the design stage. This study presents an effective application of the Multi-Layer Perceptron (MLP) machine learning algorithm to predict the compressive strength of 3D-printed concrete based on mix design constituents. For this purpose, an experimental dataset has been collected from literature for compressive strength tests of 3D-printed concrete specimens. The performance of the MLP model is optimised through systematic hyperparameter tuning via random search methodology to establish appropriate parameter ranges. Additionally, 10-fold cross-validation is employed to mitigate overfitting risks and enhance model generalisation. The developed MLP model's performance is validated against experimental data, with the objective of providing designers with reliable computational tools to facilitate broader adoption of 3DCP technology in future construction projects. Furthermore, a sensitivity analysis is carried out to explore the influence of mix design components on the strength of 3D printed concrete.

Keywords: 3D concrete printing (3DCP); machine learning; compressive strength

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Designing carbon-reinforced concrete structures using enhanced digital methods, including building information modeling and research information modeling

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Keywords: Carbon-reinforced concrete (CRC); strengthening; retrofitting; design; distributed fiber optic sensing (DFOS); digital twin; building information modeling BIM; research information modeling (RIM)

1. Introduction

Carbon-reinforced concrete (CRC) is a promising composite for resource-efficient construction members. Due to the corrosion resistance of the nonmetallic reinforcement, low concrete cover is required. This opens up the possibility for thin and filigree concrete members as well as for resource-efficient and material-saving constructions. Non-metallic reinforced concrete can be used for both retrofitting or strengthening applications as well as for newly built constructions. For both applications, digital methods can help to transfer key procedures of the engineering process from an individual, specific case into a generalized process system. This article presents digital approaches for integrating measured values, sensor data, and structural information into an information model, both for retrofitting applications and for the design of new structures. The present work brings together an investigation of CRC and digital concepts such as digital twin and building information modeling (BIM). Research information modeling (RIM) as an overarching research modeling system is presented.

2. Investigation of CRC

2.1. Retrofitting and strengthening

Retrofitting and preserving existing buildings saves energy and materials compared to demolition and new construction and thus has the greatest impact on resource conservation and sustainability; examples are given in Sandmann et al. 2023 and Orlowsky 2023. Even thin layers of CRC of about 1 cm in thickness can significantly increase load-bearing capacity due to the high tensile strength and corrosion resistance of the carbon fibers, while adding only a negligible amount to the structure's weight. In addition, the external appearance of the components remains largely unchanged, making this construction method particularly suitable for historic buildings, as shown by Wagner et al. 2022 or Rempel et al. 2018, for example. Numerous theoretical and experimental studies on strengthening with CRC have been conducted. The focus has been primarily on the load-bearing capacity, e. g. Beckmann et al. 2015 or Feix et al. 2023. In contrast, the behavior of these materials under serviceability limit conditions has been studied in Sandmann et al. 2026, including undamaged and pre-damaged steel-reinforced concrete (RC) members strengthened with CRC. Deformations and crack evolution are investigated, whereby measurement techniques such as digital image correlation (DIC), inductive displacement sensor (linear variable differential transformer, LVDT), and distributed fiber optic sensing (DFOS) are used

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(see Sandmann et al. 2026). An enormous amount of sensor data is acquired as a basis for evaluating the structural performance and deformation behavior and to decide on the suitable strengthening approach.

2.2. Newly built construction

When CRC is used for new constructions, a first step of establishing carbon reinforced concrete as a new building composite material, carbon reinforcement has basically served to replace the state-of-the-art steel reinforcement. However, substituting steel with carbon does not allow full utilization of carbon's benefits, while its disadvantageous properties reveal the limits of this approach. Instead, novel design principles are required to meet the material's nature, aiming to appropriately use its beneficial properties, e. g., Curbach et al. 2023. Spartali et al. 2024 and Beckmann et al. 2021 show that designing CRC using existing RC-related concepts leads to either high deformation or low material utilization and that new methods are required to meet both.

To find novel construction principles, on the one hand, several questions regarding material, structure, and production need to be addressed. For example, investigation of buckling (see Giese et al. 2023) becomes more important since the members are more filigree. Furthermore, automated production such as 3D-printing (Goertzen et al. 2025) and extrusion (Morales Cruz et al. 2024) offer new options. On the other hand, the process of designing new construction is of great importance for finding novel construction principles. Against that background, digital models allow for integrated workflow and interrelated data handling.

3. Digital twin and building information modeling

Based on measurement data, digital twins can be used for structural health monitoring and bridge life-cycle management concepts (Kang et al. 2025, Zhang et al. 2025). Building Information Modeling (BIM) is used as a tool for planning, execution, and process modeling in construction. The data model is also used in facility management, for the planning of maintenance measures and the optimization of energy consumption. The virtual model, the digital twin, contains building data such as materials, floor areas, and technical systems. When data on the condition of damage or on structural performance are also integrated into the model, this information can be used to identify measures for retrofitting and strengthening of existing structures.

In the most widely used openBIM model at present, in accordance with ISO 16739, industry foundation classes (IFC) are used. The metadata model, based on IFC, is a holistic product-process model. These IFC models are merely product models that represent the condition of a structure at a certain point in time. Different states of a structure can be represented as model versions (file versions). These model versions are generated at very long intervals, i.e., slowly changing data. Sensor data, sensors, or meters can also be assigned to building products or components (Al Sadoon et al. 2023, Menzel et al. 2022). With internet of things (IoT), changes in the condition of the (physical) building product detected by sensors can be transferred to the digital BIM model in a timely manner or in real time. The change in condition can be represented in a geometric model (e.g., 3D) or, in the simplest case, as a time series assigned to the measurement point.

4. Research information modeling – an overarching information-modeling system

For the design of newly built members, parametric design is a promising approach. As a suitable workflow based on parametric design, a research or design objective is defined together with variable parameters and evaluation criteria. Approved geometry, material, production, and experimental data are retrieved from an overarching meta-system and used in a parametric tool such as programming language Grasshopper in combination with computer-aided design (CAD) Rhinoceros 3D. Design alternatives are generated and evaluated using specialist tools—for example, finite element method (FEM), or optimization software. Results are returned to the system as derived data linked to the exact input configuration, tool version, and evidence. The selected configuration can then be accepted, documented, or used as the starting point for another iteration. Parametric tools can support both design and dimensioning, provided that appropriate calculation and verification methods are connected.

When parametric design is combined in an overarching information-modeling system, this leads to the proposed research information system (RIM). The contribution of the architecture of RIM is to become an organization-controlled Engineering Research Operating System spanning drafts, experiments, parametric design, FEM, optimization, and data processing. Its concrete outcome is a dataflow model based on a parameter registry, protocol-governed containers, versioned configurations, calculation lineage, and governed external-tool writeback. RIM thus combines these functions with one authoritative model of active engineering parameters, exact configurations, permissions, evidence, decisions, and accepted history. The advantage is that parameters no longer remain local sliders or unnamed values inside individual scripts or project files; they receive stable meaning, units, versions, and provenance. Geometry, experiments, material data, calculations, and decisions can therefore refer to the same parameter definitions and exact configuration. In simple terms, RIM effectively scales the Grasshopper canvas from a parametric modeling environment to the level of an entire research workflow. This enables comparison and reconstruction of alternatives, traceability of changes, controlled handover, and identification of results that become outdated after input changes. It also preserves permissions and ownership across the complete workflow rather than separately in every tool. RIM combines versioned Parameters and Protocols; provenance, evidence, and immutable accepted history; ownership and permissions; governed Tools, Macros. Its distinctive feature is not one isolated module, but the governed continuity between all these elements. In RIM, research data provide the evidence, calibration, and validation basis for parametric design. Measurements may define material parameters, boundary conditions, tolerances, uncertainties, or validation targets, while protocols and publications explain how the data were obtained.

RIM can distinguish information that was declared, measured, calculated, reviewed, corrected, or disputed and connect it to its source. Formal structure improves traceability, but qualified researchers remain responsible for scientific interpretation.

Comparing BIM and RIM, both modeling systems structure information around identifiable objects, attributes, relationships, versions, and exchange between specialist tools. BIM is primarily centered on a built asset and its geometric, spatial, technical, and lifecycle description. RIM is centered on the research process: parameters, experiments, measurements, competing configurations, calculation models, evidence, uncertainty, provenance, and decisions. Geometry and BIM models can therefore be governed or referenced inside RIM; it preserves the wider research context in which a BIM model was created and evaluated.

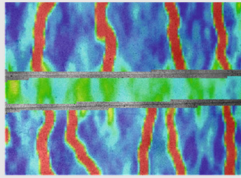
RIM is not exclusively related to CRC, but CRC is especially worth developing in the frame of RIM, since CRC is research-intensive and strongly coupled: matrix composition, carbon reinforcement, bond behavior, geometry, production, durability, structural response, and environmental performance influence one another. Methods, test data, and calculation models continue to evolve, making exact versioning and provenance especially important. CRC also offers a large parametric design space for thin, lightweight, and material-efficient structures, requiring alternatives to be compared simultaneously for structural performance, manufacturability, and environmental impact. RIM makes this potential assessable through its own dataflow and data storage architecture.

Acknowledgements

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Parallel Session 4

Structural behavior and performance of concrete and hybrid structures

Development of a Eurocode 2-compliant model for predicting the flexural behavior of chemically prestressed CTRC plates

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Abstract

Chemical prestressing is a very promising technology to enhance the structural performance of carbon textile reinforced concrete CTRC as shown by experimental evidence previously published by the authors. The technology involves adding an expansive additive to the concrete mixture which causes the swelling of concrete. This swelling leads to stretching of the reinforcement, if enough bond between the concrete and the reinforcement is available, and hence causes the action of prestressing. However, due to the novelty of this technology in its current form, there are currently no established guidelines for the design and analysis of chemically prestressed members. Therefore, this paper aims to develop a Eurocode 2-compliant model for predicting the flexural behaviour of chemically prestressed CTRC plates. For this aim, an empirical model was first developed. Then, the model was validated against previously published test results by the authors. The results have shown that the developed model can predict the flexural behaviour of chemically prestressed CTRC plates accurately.

Keywords: Chemical prestressing; carbon textile reinforced concrete; flexural behavior; Eurocode 2 based model

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A physically-based and code-aligned design method for longitudinal shear of RACCS

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Abstract

Concrete remains a cornerstone of structural engineering, but its production and lifecycle generate significant environmental pressures, primarily due to the extraction of natural aggregates, intensive energy use, and the increasing generation of demolition waste, underscoring the need for circular and sustainable alternatives. Recycled Aggregate Concrete (RCA) from Construction and Demolition Waste (CDW) constitutes a key strategy toward resource efficiency and waste minimization. Nonetheless, its integration into structural members remains challenging due to RCA's inherent heterogeneity, higher porosity, and the consequent alteration of the bond behavior at the steel-concrete interface. This study investigates the longitudinal shear behavior of Recycled Aggregate Concrete Composite Slabs (RACCS) with the aim of extending the applicability of the Eurocode 4 m - k design method to system incorporating recycled aggregates and providing an experimentally supported interpretation of the semi-empirical parameters m and k governing the steel-concrete interface. A dataset of 48 full-scale four-point bending tests covering six RCA replacement ratios (0–100%) and three span lengths was analyzed using linear least-squares regression, to derive the m and k parameters representing mechanical interlock and frictional resistance. Results indicate a non-linear response, with optimal interlock around 30% RCA and degradation beyond this threshold due to ITZ weakening, while frictional effects intensify at higher replacement ratios. A new set of experimentally calibrated correction factors $\alpha(rRCA)$ and $\beta(rRCA)$ was introduced, recalibrating the m - k formulation as a function of the RCA replacement ratio. The proposed formulation is able to reproduce the experimental trend of longitudinal shear resistance across the investigated RCA range, with deviations generally within $\pm 10\%$ compared to the experimental results

Keywords: Sustainability; concrete; recycled concrete aggregate (RCA), composite slabs; longitudinal shear behavior

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Steel plate to concrete connections: comparison of elastic and plastic analysis methods

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Abstract

Connections between steel and concrete structures are frequently made by means of a steel plate with anchors. In Europe the design of such connections should satisfy requirements from two codes: EN 1992-4 and EN 1993-1-8. EN 1992-4 regulates the design of anchorages in concrete, providing basic information and rules to calculate the anchor resistance considering failure modes involving concrete. EN 1992-4 does also propose calculating the forces acting onto a plate anchor using the traditional elasticity-based concrete cross section analysis, which assumes a rigid plate and a linear strain profile. On the contrary, EN 1993-1-8 addresses the design of connections in new steel structures, including column base connections. EN 1993-1-8 is based on the component method, wherein the connection is modelled by means of a rigid bar on multiple springs, with each spring representing a deformation source and including the flexibility of the steel plate. According to EN 1993-1-8, the resistance can be calculated with a plastic analysis, unless failure is due to tensile forces in the anchor bolts, a case where the distribution of the anchor forces is modified to account for the limited force redistribution capability of the connection. Within this context, the paper compares the two analysis methods, first from a conceptual viewpoint, and second from a quantitative perspective using selected sample connections. The paper does also summarize a proposed modification to the current EN 1993-1-8 approach for considering prying forces within plastic analysis of the connection, based on comparisons between the theoretical predictions and results from finite element model simulations

Keywords: Analysis; concrete; connection; model; steel

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Flexural behavior of timber-concrete composite structures with dowel, notch and adhesive connections

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Abstract

To facilitate the timber-concrete composite (TCC) applications in structural systems, this paper investigates the mechanical performance of TCC structures with different connections. The composite elements each comprises a cross-laminated timber (CLT) element topped with concrete, with the investigated connection types including dowel, notch, combined dowel plus notch, and adhesive. The study presents experimental research focusing on the composite behaviors and comparison of the different connection types. Firstly, a series of four-point bending tests were conducted to assess the flexural performance of CLT and TCC members with different connections. Subsequently, the peak load and the corresponding deflection of four types of members with different connection configurations were investigated, and their load–deflection curves were presented. Finally, the crack patterns just beyond the peak load and in the post-failure stage were comparatively analyzed and discussed based on the digital image correlation (DIC) results.

Keywords: Timber-concrete composite; cross-laminated timber; bending; connections

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Experimental study on flexural and shear bearing capacities of naturally corroded RC beams

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Abstract

This study investigates the corrosion states, the flexural and shear bearing capacities of naturally corroded reinforced concrete (RC) beams which were extracted from a RC frame structure that had been exposed to the natural marine environment in Qingdao, China, for fifteen years. Eight beams were systematically divided into twenty-four individual parts and tested under three-point loads. The results revealed that the average corrosion degrees on the windward side of the structure were significantly higher than the ones on the leeward side while the 3D scan results showed that the corrosion of windward reinforcement exhibited more pronounced spatial non-uniformity along the longitudinal direction of steel bars, highlighting the influence of exposure direction during long-term natural corrosion. Furthermore, the failure modes of corroded RC beams varied between bending failure and shear failure, and the ultimate deformation under bending failure tended to be much larger than the one under shear failure. After analyzing the corrosion degrees of longitudinal reinforcements and stirrups, the results showed that there was a complex competition mechanism between the corrosion degrees of longitudinal reinforcements and stirrups, where the weaker one would control the failure mode. These observations will contribute to accurate performance assessment of existing RC structures

Keywords: Corroded reinforced concrete beam; non-uniform corrosion, flexural and shear bearing capacities, natural corrosion, failure mode

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Numerical simulation of torsional behavior of corroded reinforced concrete members

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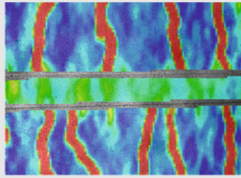
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Abstract

This study investigates the torsional performance degradation of corroded reinforced concrete (RC) members through numerical simulation. To evaluate the mechanical behavior of an RC member under pure torsion at varying corrosion levels, a finite element model (FEM) was developed. The model explicitly incorporates a series of analytical formulations to quantitatively characterize the corrosion-induced deterioration of reinforcement mechanical properties, the degradation of steel-concrete bond performance, and the reduction in the cross-sectional dimensions of the concrete cover. The proposed numerical simulation model was validated against an experimental database comprising 49 published test results to confirm its accuracy and reliability in predicting the residual torsional bearing capacity of an RC member, providing an effective computational method for assessing the torsional performances of corroded RC members.

Keywords: Reinforced concrete member, corrosion, torsional behavior, FEM

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Parallel Session 5

Structural strengthening, retrofit and structural resilience

The impact of macro-synthetic and micro steel fibers on reinforced concrete beam behavior

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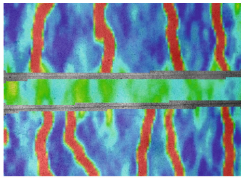
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Abstract

In this study, the impact of macro-synthetic and micro-steel fibers on reinforced concrete beams (RCB) behavior is studied. An experiment with three series of beams of 10 cm x 15 cm and a length of 100 cm was conducted using 1% of micro steel fibers (RCB-S) and macro-synthetic fibers (RCB-P) and without fibers. The results showed that including 1% fibers in the concrete mix increase yielding and ultimate loads ductility in the beams. Rebound hammer test is used to check the in-place concrete quality of reinforced concrete beams after 28 days, and which have been characterized by strength compression (15 cm x 15 cm x 15 cm). The tests were performed on different locations through the height of the beams (upper, medium and lower zones). Results of the compressive strength values derived (D_{fc}) from the rebound hammer test and real compressive strength reveal a variability through the adding of fibers. Based on these results, the reliability of both tests has been discussed.

Keywords: Reinforced concrete beams; compressive strength; rebound hammer test

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Strengthening methods for axially-loaded reinforced concrete columns against impact

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Keywords: Impact load, strengthening, column, textile-reinforced concrete (TRC), strain-hardening limestone calcined clay cement (SHLC³)

1. Background

The retrofitting of structures to withstand specialized dynamic loading conditions, such as earthquakes, impacts, and explosions, represents an economical and environmentally sustainable strategy for improving structural performance without necessitating complete reconstruction. Steel-reinforced concrete (RC) structural elements, including beams, slabs, and columns, are susceptible to such loading conditions during their service life. Among these, certain structural components play a more critical role in maintaining overall stability, as they serve as the primary load-transfer path from the superstructure to the foundation. For instance, building columns and bridge piers, which are essential for structural stability, may be subjected to external forces such as vehicle impacts, rockfalls, seismic activity, or explosive events.

Previous research has explored various methods and materials to enhance the impact resistance of structural elements. A comprehensive review of strengthening techniques for axially loaded RC members has been presented in the literature. (Taheri, et al. (2024)) Among the investigated approaches, materials such as fiber-reinforced polymer (FRP) and short-fiber-reinforced concrete (FRC) have been widely used as strengthening layers for axially loaded RC members subjected to impact loading. (Zhu et al. (2023), Fan et al. (2020)) These studies have demonstrated that the application of such strengthening layers significantly reduces the displacement of structures under impact forces, thereby improving their overall performance and resilience.

However, despite the progress made with FRP and FRC systems, the potential of other advanced strengthening materials, such as textile reinforced concrete, strain-hardening cementitious composites, for enhancing the impact resistance of RC columns remains unexplored. Furthermore, the combined influence of axial load level and strengthening type on the dynamic response of RC columns under impact has not been sufficiently investigated. This study investigates the effectiveness of other strengthening materials and methods for RC columns subjected to impact forces. An overview of the study program, including the experimental setup and initial results, is presented in this report.

2. Design of the study

2.1. Specimens

This study presents a brief overview of an experimental investigation into three distinct material combinations used to enhance the impact resistance of RC columns. The column specimens had a rectangular cross-section of 200 × 300 mm and a total length of 1500 mm (Fig. 1, left). The primary structural concrete was specified as grade C35/45, with B500B longitudinal and shear reinforcing steel. The two prestressing bars (steel Y1050) were used for axial load application. Except for the reference samples, each column specimen was fully encased with a strengthening material, applied to a uniform thickness of 20 mm over the entire cross-section. Three strengthening systems were investigated: textile-reinforced concrete (TRC), strain-hardening limestone calcined clay cement (SHLC³), and a hybrid system made of TRC and SHLC³ (in short: TRC- SHLC³):

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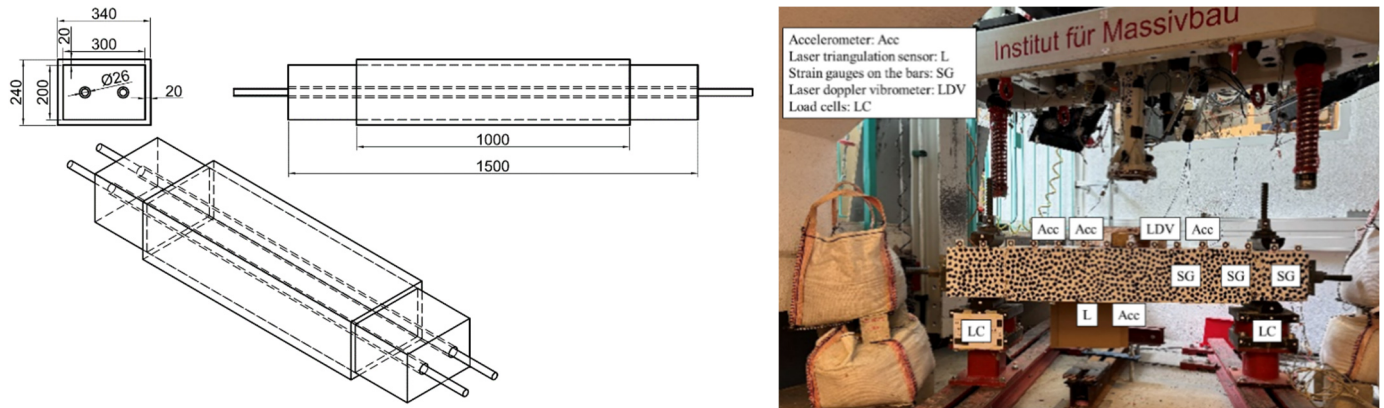


Fig. 1. Column specimen with a 20 mm of strengthening layer in principle (left) and in the drop tower before the test (right).

- TRC specimens: Pagel TF10 (2026), a fine-grain concrete with approximately 80 MPa compressive and circa 8 MPa flexural strength was employed as the matrix, incorporating four L-shaped carbon textile reinforcements (HTC 10/15-80) to wrap the specimen with two layers.
- SHLC³ system: The strengthening material utilized was strain-hardening limestone calcined clay composites. Compared to 'normal' SHLC³, we used a sustainable cementitious composite where 50% of the ordinary Portland cement (OPC) clinker was replaced by a combination of calcined clay and limestone. To achieve strain-hardening behavior, the matrix was reinforced with 1.5 vol-% of 6 mm high-density polyethylene (HDPE) fibers.
- TR- SHLC³ system: This configuration combined the same carbon-fiber textile reinforcement mentioned before within the SHLC³ matrix. This hybrid system leverages the crack-bridging capacity of the short HDPE fibers alongside the high tensile strength of the carbon textile to maximize energy absorption.

Two methodologically distinct application techniques were adopted to achieve the prescribed strengthening configurations: lamination was employed for the fine-grain Pagel TF10, while robotic spraying was utilized for the SHLC³. A robotic arm with 6-axis freedom was utilized to execute a pre-defined spraying path, maintaining a constant standoff distance and perpendicular orientation relative to the column surface. This automated approach allowed for precise control over the 20 mm jacket thickness and minimized material rebound, ensuring a dense and homogenous strengthening layer. The shotcrete process achieved strong bonding, which is a critical factor for the energy dissipation of SHLC³ under high-velocity impact loads. (Nuh et al. (2022), Ivaniuk, et al. (2024)) For the application of SHLC³ to the column specimens the robotic shotcreting was programmed in a single continuous pass to reach a nominal thickness of 20 mm, while for the TR- SHLC³ system the application was executed using a robotic arm in three successive shotcreting passes, with the carbon textile layers interleaved between consecutive matrix depositions to ensure full encapsulation.

2.2. Impact test facility, measurement and test matrix

The aim of the study was to investigate the effects of strengthening RC columns under impact loading using an experimental drop-weight system with different strengthening schemes and axial load levels. The impact experiments were conducted at the drop tower facility of Otto Mohr Laboratory (OML) of TUD Dresden University of Technology (TUD). More information about the facility can be found, e.g., in Just et al. (2015). A rigid Ø100 mm cylindrical steel impactor, 380 mm in length and 21.58 kg in mass, was employed as the projectile. The impactor was accelerated through an 11 m long pipe using compressed-air. Different measurement devices including high speed camera, accelerometers, laser triangulation sensor, laser doppler vibrometer, and strain gauges were used to record various parameters during the impact event. The configuration of the test setup is illustrated in (Fig 1, right).

Table 1 lists four selected experiments that will be discussed in more detail in the following. The columns were subjected to an axial compressive load of 800 kN. One column was unstrengthened as the reference, while the other three were strengthened using the three strengthening systems introduced before. The impactor velocity was approximately 33 m/s in each case.

3. Preliminary results and conclusions

Some preliminary results from the impact experiments are summarized Table 1. The mass of separated concrete fragments generated during impact was measured using a digital scale. In general, the application of strengthening layers significantly reduced debris generation. Strengthened specimens produced almost no debris, whereas unstrengthened specimens exhibited a considerably higher mass of ejected concrete fragments. This observation confirms that the strengthening layers effectively confine the concrete and prevent spalling and scabbing during the impact event.

Table 1. Test matrix and preliminary results.

Specimen	Impactor velocity in m/s	Strengthening material	Strengthening method	Debris in kg	Max. mid-span displacement in mm	Max. impact force in kN	Max. reaction force in kN
C022	32.8	–	–	22.2	17.9	1759.5	177.4
C015	32.9	TRC	lamination	< 1	7.2	2013.9	334.9
C033	33.4	SHLC ³	robotic spraying	0	9.3	1885.4	367.3
C031	33.7	TR-SHLC ³	robotic spraying	0	6.4	2252.8	565.7

The displacement of the unstrengthened specimen was notably higher compared to that of strengthened ones. As shown in Table 1 and Fig 2, the mid-span displacement decreased by more than 48 % when strengthening was applied.

Both the impact force (derived from the high-speed camera analysis) and the reaction forces (recorded by the load cells) were higher in the strengthened specimens compared to the unstrengthened reference, further confirming the increased stiffness provided by the strengthening layers. Among all configurations, TR-SHLC³ exhibited the highest stiffness, attributed to the combined contribution of textile reinforcement and the crack-bridging capability of the SHLC³ matrix.

Among the strengthening materials, the matrix incorporating short fibers (SHLC³) demonstrated superior performance, as the fibers promoted distributed cracking, preventing the formation of a few wide, localized cracks and preserving the integrity of the strengthening layer without debris generation. The combination of textile reinforcement and SHLC³ (TR-SHLC³) yielded the best overall performance, achieving the lowest displacement while avoiding severe damage to both the structural element and the strengthening layer itself.

A comparison between SHLC³- and TR-SHLC³-strengthened specimens further highlighted the advantages of the latter. The inclusion of carbon textile reinforcement in TR-SHLC³ reduced the occurrence of widely opened shrinkage cracks, which were identified as weak points in the solely applied SHLC³. Moreover, the SHLC³-strengthened specimens, in which the strengthening layer was applied in a single shotcreting pass, exhibited weaker bonding between the strengthening layers and the substrate. In contrast, the TR-SHLC³ specimens, applied in three shotcreting passes with textiles interleaved between layers, demonstrated better joint integrity (between shotcreting of adjacent sides of the base specimens in corners) and enhanced overall performance.

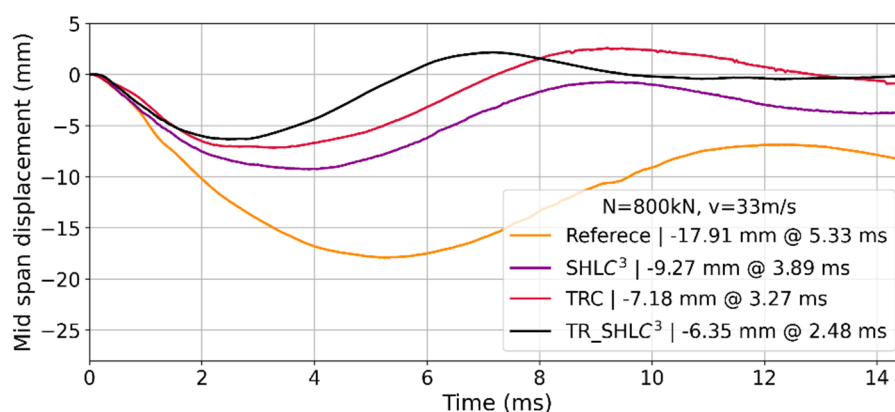


Fig. 2. Displacement-time history of the specimens with 800 kN of axial force under impactor velocity of 33 m/s.

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Seismic retrofit strategy based on self-centering rocking frames

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Abstract

This study investigates the seismic fragility of a pre-code RC school building retrofitted with a self-centering dual-frame rocking exoskeleton. The retrofit system combines post-tensioned elements that provide re-centering capability with energy-dissipating steel fuses designed to control seismic demand and reduce structural damage. The seismic performance of the structure is evaluated through Incremental Dynamic Analysis (IDA) using a set of spectrum-compatible ground motion records. Fragility curves are derived for multiple damage states defined according to HAZUS guidelines, considering inter-story drift ratios as the primary demand parameter. The probabilistic assessment allows comparison between the existing and retrofitted configurations and quantifies the reduction in seismic vulnerability achieved by the proposed intervention. Results show that the rocking exoskeleton significantly improves structural performance, increasing the spectral acceleration thresholds associated with the different damage states and drastically reducing the probability of extensive or complete damage. The retrofit strategy also demonstrates strong self-centering behavior, limiting residual drifts after seismic events. The findings highlight the effectiveness of dissipative rocking exoskeletons as a practical solution for upgrading vulnerable educational buildings in seismic regions.

Keywords: Rocking exoskeleton retrofit; seismic resilience; fragility assessment

* The full paper is open access available in the Conference Proceedings. *

Mitigating progressive collapse in a steel–RC hospital via outrigger-belt truss retrofit

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Abstract

This paper presents a robust and minimally invasive retrofit strategy to mitigate progressive collapse in steel–reinforced concrete (RC) hospital buildings using an outrigger–belt truss system. The proposed solution addresses the limitations of conventional local and global retrofit methods, particularly in operationally critical facilities where construction impact must be minimized. The retrofit system, installed at the roof level, introduces alternative load paths that enhance structural redundancy and robustness without relying on the existing building’s limited catenary capacity. A real-world case study of a hospital in Naples is analyzed using nonlinear static (pushdown) and dynamic simulations, following the Alternate Path Method (APM) as per GSA and UFC guidelines. The as-built structure exhibited insufficient resistance to column loss scenarios, with load factors below unity. After retrofitting, the outrigger–belt truss system successfully redistributed gravity loads, achieving load factors above one and significantly reducing vertical displacements. The effectiveness of this solution is validated through extensive nonlinear static and dynamic push-down analyses conducted on a detailed 3D finite element model of the hospital. The proposed strategy offers a cost-effective, reversible, and operationally compatible solution for enhancing the progressive collapse resistance of essential healthcare infrastructure.

Keywords: Progressive Collapse Retrofit; Steel-RC Building; Outrigger-Belt Truss

* The full paper is open access available in the Conference Proceedings. *

Determination of the stiffness of GFRP under axial compression using digital image correlation (DIC)

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Abstract

The mechanical properties of fiber reinforced polymers under tensile loading are well established in international standards, whereas the stiffness characterization of rod shaped FRP elements under axial compression is still not sufficiently standardized despite its relevance in civil engineering applications. This study develops and validates a digital image correlation-based evaluation methodology to determine the compressive modulus in fiber direction and the transverse contraction coefficient from full field strain data. Compression tests on rod shaped FRP specimens with variations in slenderness, diameter, surface profiling, matrix system, and fiber volume fraction are used to assess typical influences and to benchmark the evaluation procedure.

A secant modulus evaluated between 20 % and 50 % of ultimate load provides stable values of $E_{c,\parallel}$ with low coefficients of variation. The experiments indicate effects of surface condition and fiber volume fraction, with increased compressive modulus for ribbed bars, negligible stiffness contribution from slack helical wrapping, increasing modulus with increasing fiber volume fraction, and decreasing transverse contraction coefficient. The full field strain information enables the selection of representative evaluation zones, supports quality control of boundary conditions, and allows detection of load eccentricities via cross-sectional strain gradients, thereby providing a robust basis for compression stiffness characterization of rod shaped FRPs.

Keywords: Fiber-reinforced polymer (FRP); compression behavior; elastic modulus; Poisson's ratio; digital image correlation (DIC)

* The full paper is open access available in the Conference Proceedings. *

Progressive collapse vulnerability of steel storage racks: insights from testing and FEM analysis

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Abstract

Steel storage racks, commonly used in industrial and commercial facilities, are lightweight yet heavily loaded structures composed of thin-walled cold-formed steel elements. Their vulnerability to progressive collapse arises from semi-rigid connections, asymmetric bracing, and limited ductility. This study investigates the progressive collapse behavior of a braced pallet racking system through a combination of full-scale experimental testing and advanced finite element modeling (FEM). The research, conducted within the PC-RACKS "Progressive Collapse of steel pallet RACKS" research project, funded by the European Union – Next Generation EU, evaluates the performance of beam-to-upright and base-plate connections under combined axial and bending loads. Nonlinear static (pushdown) and dynamic analyses were performed on a real-world five-story rack system subjected to column removal scenarios. The results highlight the critical role of connection detailing and bracing configuration in collapse propagation. While ductile behavior and catenary action were observed in racks with minimal bracing, systems with additional bracing exhibited brittle failure due to constrained deformation paths. The findings underscore the need for performance-based design approaches that account for connection behavior, local buckling, and load redistribution mechanisms to enhance the resilience of steel storage racks against progressive collapse.

Keywords: Steel storage racks; progressive collapse; testing; FEM analysis

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