SMAR 2026

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

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Book of abstracts

Yvonne Ciupack, Silke Scheerer, Steffen Marx (eds.)

TUDIAS BILDUNG . SPRACHE . GEMEINSCHAFT

Technische Universität Dresden

Empa Materials Science and Technology

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

BOOK OF ABSTRACTS

Editors:

Prof. Dr.-Ing. Yvonne Ciupack (TU Darmstadt)

Dr.-Ing. Silke Scheerer (TU Dresden)

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PREFACE

It is our great pleasure to welcome you to the 8th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR 2026) in Dresden, Germany.

Over the past years, SMAR has established itself as one of the leading international forums for researchers, engineers and practitioners working in the fields of structural health monitoring, assessment, maintenance and rehabilitation of civil infrastructure. The conference provides an excellent opportunity to exchange ideas, discuss recent scientific advances and strengthen collaborations between academia and industry.

Dresden offers a particularly inspiring setting for this year's conference. With its outstanding engineering tradition, internationally renowned research institutions and numerous landmark structures, the city represents an ideal venue for scientific exchange. At the same time, the recent collapse of the Carolabrücke has highlighted the societal importance of reliable structural assessment, monitoring and resilient infrastructure management, making the topics of SMAR 2026 more relevant than ever.

The scientific program brings together keynote lectures by internationally recognized experts, 32 Mini Symposia, parallel technical sessions and numerous opportunities for discussion and networking. We sincerely hope that these days will inspire new ideas, foster collaborations and contribute to further advances in research and engineering practice.

A conference of this scale would not be possible without the commitment and support of many people. We would like to express our sincere gratitude to the Honorary Chairs, the International Scientific Committee, the Mini Symposia organizers, session chairs, reviewers, sponsors, exhibitors and all members of the Local Organizing Committee for their invaluable contributions. We also thank all authors and participants whose enthusiasm and scientific excellence make SMAR 2026 possible.

We wish you an inspiring conference, stimulating discussions and an enjoyable stay in Dresden.

Prof. Dr.-Ing. Steffen Marx Prof. Dr. Moslem Shahverdi
Conference Chairs, SMAR 2026

Prof. Dr.-Ing. Yvonne Ciupack
Head of International Scientific Committee, SMAR 2026

TABLE OF CONTENTS

MS31: Wave-based monitoring techniques for structural engineering **410**

MS32: Crowdsourced and indirect approaches to structural health monitoring **420**

PARALLEL SESSIONS **424**

PS01: Structural health monitoring and damage detection **425**

PS02: Digital methods for structural assessment **437**

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

Keynote Lectures

Keynote Lecture 1

Digital twin-enabled SHM for real-time performance assessment of smart structures

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Abstract

Structural health and usage monitoring of engineering assets has long relied on conservative, fleet- or population-level assumptions that fail to capture the true operational variability between individual structures. This paper presents a generic Digital Twin (DT) framework for real-time structural health management (SHM) that transitions asset management from population-level to individual-level assessment, enabling condition-based, predictive operational and maintenance strategies across a broad class of engineering structures. The framework integrates three tightly coupled components: a physical sensing system providing continuous in situ measurement of structural response; a virtual system combining physics-based models with probabilistic machine learning for real-time damage diagnosis and remaining useful life prognosis; and a secure data communication platform linking physical and virtual systems through on-asset and cloud-based processing. The framework is designed to be generic and scalable, applicable to any structure for which real-time strain, load, and response data can be acquired and coupled with high-fidelity analytical models. Its applicability spans metallic structures under safe-life and fail-safe design philosophies, and composite structures under damage-tolerant design. The framework is demonstrated through its application to aerospace structures within the H2020 AVATAR project, where an IoT sensing skin, physics-informed virtual models, and advanced analytics are integrated into a full life-cycle DT for transformative air vehicles. Results illustrate how individual-level usage monitoring can extend service life, reduce operational costs, and enhance safety beyond what is achievable under conventional fleet-level management.

Keywords: Digital twin; SHM; smart structures; fatigue & damage assessment; real-time monitoring; IoT sensing skin

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Keynote Lecture 2

Transforming structural fire safety with intelligent sensing for advanced materials

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Abstract

The increasing integration of advanced construction materials such as ultra-high-performance concrete (UHPC) introduces new challenges for monitoring structural behaviour under extreme environmental conditions, including high temperatures and fire exposure. This paper provides an overview of recent advances in sensing technologies for structural monitoring, with particular emphasis on digital image correlation (DIC) and distributed fibre optic sensing (DFOS). The capabilities and limitations of these techniques for measuring strain, displacement, and crack development in cementitious materials are discussed based on recent experimental studies. Examples from the literature are presented to illustrate the effectiveness of DIC for measuring deformation and crack localization at elevated temperatures, as well as the application of DFOS systems for distributed strain and temperature sensing in reinforced concrete and UHPC specimens. The challenges associated with fibre optic sensors at high temperatures, including fibre coatings, signal stability, and temperature–strain cross-sensitivity, are also reviewed. In addition, recent developments in data processing strategies for optical sensing systems are discussed, with particular attention to the potential role of artificial intelligence (AI) and machine learning methods for improving signal interpretation, noise reduction, and parameter identification in distributed sensing systems. The paper highlights how the integration of advanced sensing technologies and AI-based data analysis can support improved experimental investigation of advanced construction materials under extreme conditions. Attention is given to ongoing efforts to apply these approaches to UHPC, a material that still presents significant uncertainties regarding its behaviour at high temperatures

Keywords: Sensing; fire; concrete; fibre reinforced polymers; ultra-high-performance concrete; distributed fibre optic sensors

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

Keynote Lecture 3

Monitoring, assessment and rehabilitation of road infrastructure – a precondition for a sustainable future

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Monitoring, assessment and rehabilitation of road infrastructure – a precondition for a sustainable future

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Keywords: Data overload; different perspectives with AI

1. Introduction

Infrastructure inspection plays a central role in the management of civil structures. Bridges, tunnels and other structural assets are periodically assessed to document their condition, detect deterioration mechanisms and support maintenance planning. These inspections generate large volumes of qualitative descriptions, technical observations and professional judgments.

At the level of an individual structure, expert judgment is both necessary and appropriate. However, when decisions must be taken at portfolio scale, consistency becomes critical. Investment prioritization, risk allocation and long-term planning depend not only on the condition of each asset, but also on the comparability of assessments across many structures.

In practice, two structural challenges emerge. First, the evaluation of damage severity is influenced by human variability. Even under shared standards and guidelines, different engineers may assign different degrees of urgency to comparable observations. Second, inspection reports often exhibit heterogeneous documentation quality, including telegraphic language, implicit assumptions, incomplete localization of defects or missing quantification.

These factors introduce dispersion into the decision-making process. While such variability is not problematic at the level of isolated inspections, it may distort prioritization and resource allocation at portfolio scale.

This paper explores how artificial intelligence can assist in reducing variability and improving consistency in inspection documentation and severity assessment — not by replacing expert judgment, but by supporting it through structured and repeatable processes.

2. Variability of severity assessment

The assessment of structural damage inherently involves professional judgment. Inspection guidelines and condition rating systems provide a structured framework, yet they cannot eliminate interpretative variability. In the Swiss national road context, for example, FEDRO's KUBA 5.1 guide for inspectors of civil engineering structures defines a standardized procedure for the recording of inspections and supports a uniform assessment of observations, damage groups, extents and deterioration processes across FEDRO regional branches. Nevertheless, engineers evaluate observed defects based on their training, experience, risk perception and understanding of deterioration mechanisms.

Even when observing comparable phenomena — for example cracking patterns, corrosion traces or spalling — different inspectors may attribute different levels of severity or urgency. Such differences do not necessarily reflect errors; rather, they illustrate the discretionary space that exists within qualitative assessment processes.

At the level of a single structure, this variability is often manageable. However, at portfolio scale, dispersion in severity attribution can accumulate. When maintenance prioritization depends on condition ratings, inconsistent interpretation may influence investment sequencing, budget allocation and risk management strategies.

The challenge therefore lies not in eliminating expert judgment, but in reducing unnecessary variability while preserving technical responsibility. A more consistent translation of observed conditions into structured severity levels becomes essential when decisions extend beyond individual assets and affect entire infrastructure networks.

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3. Heterogeneity of inspection reports

Beyond variability in severity assessment, another structural challenge concerns the quality and consistency of inspection documentation. Field observations are frequently recorded under time constraints and later completed in office environments. As a result, inspection reports may contain heterogeneous linguistic styles and varying levels of detail.

In practice, descriptions often include telegraphic formulations, personal abbreviations, implicit assumptions or locally understood terminology. Defects may be described without precise localization within the structural element, without quantitative estimation of extent, or without explicit linkage to predefined damage categories. In some cases, causal interpretations remain implicit rather than explicitly stated.

While such documentation may be fully understandable to the original inspector, it reduces the clarity and comparability of information when processed at portfolio scale. Ambiguity complicates data structuring, limits reproducibility of assessments and increases dependency on individual interpretation during later decision stages.

The issue is therefore not the absence of technical expertise, but the absence of structured and standardized transcription. When qualitative descriptions form the basis for digital databases and prioritization models, inconsistencies at acquisition stage propagate through the entire decision chain.

Improving documentation quality at the moment of data capture thus becomes a decisive factor for reliable monitoring, assessment and rehabilitation planning.

4. Proposed AI-assisted framework

The framework described in this paper is currently at prototype stage. It is being tested by armasuisse in collaboration with the Swiss Federal Roads Office FEDRO on concrete infrastructure-related use cases. The purpose of this phase is to assess the technical feasibility and practical relevance of the approach before considering a broader implementation. As the prototype is still under evaluation, no dedicated public documentation is available at this stage.

4.1. AI as semantic normalizer

The first component of the proposed framework addresses documentation quality at the stage of data acquisition. Rather than replacing inspection activity, artificial intelligence is introduced as a structured linguistic and semantic assistant.

Inspection observations are typically expressed in free-text form. These descriptions contain valuable technical information, but may vary significantly in wording, precision and completeness. The proposed AI module analyses the textual input and performs several support functions.

First, it reformulates telegraphic or abbreviated expressions into structured and standardized language aligned with predefined terminology. This does not alter the meaning of the observation; instead, it ensures that descriptions become explicit and compatible with digital data models.

Second, the system checks the internal completeness of the description. It can detect missing localization (e.g. structural element not clearly identified), absence of quantification (extent, width, area or intensity of damage), or ambiguous causal interpretation. In such cases, the system prompts the inspector to provide clarification.

Third, the AI compares the description against available damage catalogues and inspection standards. If inconsistencies or undefined terms are detected, the system signals this to the user without automatically correcting the content.

The inspector remains responsible for validation. All reformulations and suggestions must be confirmed before integration into the official inspection record. The objective is not to guide the engineer toward a predefined conclusion, but to ensure clarity, traceability and alignment with established standards.

By improving linguistic precision and structural consistency at the moment of documentation, the semantic normalization process strengthens the reliability of downstream analyses and portfolio-level evaluations.

4.2. AI as consistent severity engine

The second component of the framework addresses the translation of qualitative observations into structured severity levels. While inspection standards often define condition classes or damage categories, their practical interpretation remains partly dependent on professional discretion.

The proposed AI module applies a consistent evaluation logic to documented defects. Based on predefined criteria, weighting schemes and reference thresholds, qualitative descriptions are transformed into structured severity indicators. The objective is not to replace expert assessment, but to ensure that similar descriptions are processed according to the same analytical logic.

In this context, the value of the algorithm does not lie in absolute accuracy, but in repeatability. A human evaluation may be highly precise in an individual case, yet variable across different inspectors. An algorithmic approach may not eliminate uncertainty, but it applies the same reasoning structure to every comparable input.

This consistency becomes particularly relevant at portfolio scale. When prioritization of maintenance interventions depends on condition indicators, dispersion in severity attribution can significantly influence investment sequencing. A harmonized severity engine reduces interpretative noise and strengthens comparability across assets.

Importantly, the AI-generated severity output remains transparent and traceable. The underlying criteria and weighting logic must be explicitly defined and accessible. Engineers retain the ability to review and, where justified, adjust the proposed classification.

By combining semantic normalization with consistent severity processing, the framework supports both improved data acquisition and more robust portfolio-level prioritization.

5. Governance principle

The integration of artificial intelligence into inspection processes requires a clear governance framework. In the current prototype and testing phase, the proposed system is being evaluated as a decision-support tool, not as an autonomous evaluator. Technical responsibility remains fully with the inspecting engineer and the responsible authority.

All AI-generated reformulations, completeness checks and severity classifications are subject to explicit human validation before becoming part of the official record. The system may identify inconsistencies or indicate when a description lacks sufficient precision, localization or quantification to enable unambiguous interpretation. It does not guide, suggest or influence the inspector's severity assessment, which remains exclusively under the inspector's professional responsibility.

Transparency is a fundamental requirement. The evaluation logic, weighting criteria and reference thresholds used by the severity engine must be documented and accessible. This ensures traceability and allows expert review of the algorithmic reasoning process.

Furthermore, the framework is conceived to support, rather than constrain, professional expertise. The objective is not to reduce discretionary judgment, but to reduce unintended variability and documentation inconsistency. Engineers retain the authority to override or refine AI-supported outputs where justified by contextual considerations.

By embedding AI within a clearly defined governance structure, the approach aims to strengthen reliability, comparability and accountability in infrastructure assessment, without undermining expert responsibility.

6. Expected impact at portfolio level

The combined use of semantic normalization and consistent severity processing is expected to generate measurable improvements at portfolio scale.

First, increased documentation clarity enhances data reliability. Structured and standardized descriptions reduce ambiguity and facilitate digital integration into asset management systems. This improves the reproducibility of analyses and strengthens long-term traceability of condition evolution.

Second, the reduction of interpretative dispersion supports more robust prioritization mechanisms. When comparable defects are processed under a consistent analytical framework, maintenance sequencing becomes less sensitive to individual variability. Investment decisions can therefore rely on more stable condition indicators across the portfolio.

Third, the approach enables improved cross-asset comparability. Harmonized severity levels facilitate benchmarking between structures, regions or asset categories. This is particularly relevant for large public infrastructure networks, where transparent allocation of limited financial resources is essential.

Finally, the framework contributes to a more structured interaction between monitoring, assessment and rehabilitation planning. By strengthening consistency at the stage of data acquisition and interpretation, downstream planning processes benefit from clearer and more comparable inputs.

The proposed AI-assisted methodology therefore aims not at increasing automation, but at enhancing coherence and decision robustness in infrastructure portfolio management.

7. Conclusion

Infrastructure inspection generates valuable expert knowledge, yet portfolio-level decision-making requires more than isolated professional judgment. Consistency, comparability and documentation quality become decisive factors when managing large networks of civil structures.

This paper proposes an AI-assisted framework that operates at two complementary levels: semantic normalization of inspection documentation and consistent translation of qualitative observations into structured severity indicators. The approach does not seek to replace human expertise, but to support it through repeatable and transparent processes.

By reducing unintended variability and strengthening data clarity at the point of acquisition, the methodology enhances robustness in prioritization and rehabilitation planning. In this perspective, the value of artificial intelligence lies not in autonomy, but in coherence — enabling infrastructure managers to make more stable and accountable decisions across entire portfolios.

References

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Keynote Lecture 4

The evolution of structural health monitoring from qualitative observation to digital twin

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Abstract

A modern definition of structural health monitoring (SHM) is the general process of making an assessment, based on appropriate analyses of in-situ measured data (which may include fused human inspection data), about the current ability of a structural component or system to perform its intended design function(s) successfully. Damage prognosis (DP) extends this SHM process by considering how this current state assessment, when combined with probabilistic models of future loading conditions, degradation evolution, and uncertainty quantification due to sources of variability, may be used to forecast metrics of system performance useful to the owner/managers, e.g., remaining useful life. The evolution of SHM/DP through time is characterized by large paradigm or capability shifts including digital computing, the internet, and artificial intelligence. The result of these shifts has resulted in "digital twin" architectures whereby a cybermodel of a structure or system is built that can perform several efficient duties ranging across SHM/DP and even optimal life cycle management. This paper considers the evolution of SHM/DP over time and concludes with discussion of some ongoing challenges.

Keywords: Structural health monitoring; digital twin; nondestructive evaluation; value of information

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

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Keynote Lecture 5

Vibration-based SHM of bridges: experiences at Politecnico di Milano

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Abstract

Structural Health Monitoring (SHM) is generally defined as a multi-disciplinary process involving the repeated or continuous acquisition of structural data through arrays of appropriate sensors, the extraction from measured data of features which are representative of the health condition and the classification of those features to detect any "novelty" or abnormal change in the investigated system. The sequence of data acquisition, feature extraction and statistical modelling for feature classification constitutes the well-known Statistical Pattern Recognition (SPR) paradigm.
In the last few years, the feature extraction based on operational modal analysis (OMA, i.e. the identification of modal parameters using only the vibration response) has received increasing attention especially in the field of Bridge Engineering and many dynamic monitoring systems have been installed on bridges all over the world.
Within the framework of vibration-based SHM, the paper summarizes the SPR paradigm involving: (a) data acquisition; (b) automated identification of modal parameters and tracking; (c) minimization of environmental and operational variability and (d) novelty analysis for anomaly detection/localization. Taking advantage of a research program between the author's University and the government of Lombardy Region, the OMA-based SPR paradigm was implemented in a new stand-alone software package, denoted to as DYMoND (DYnamic MOnitoring and Novelty Detection) and initially developed in the MATLAB environment.
Subsequently, among the structures and infrastructures monitored by the author and his research group in Politecnico di Milano, the paper exemplifies the application of OMA-based SHM through the DYMOND software on two bridges: an arch bridge dating back to 1917 (5 years of collected data) and a long-span steel-concrete composite bridge (3 years of collected data).

Keywords: Environmental and operational variability, modal identification, novelty detection, statistical pattern recognition, structural health monitoring

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Keynote Lecture 6

Preserving structures with carbon reinforced concrete: today and tomorrow

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Abstract

The construction industry is one of the largest contributors to global CO_2 emissions and resource consumption. Against this background, there is a growing need to make construction practices more sustainable. One particularly effective strategy is to preserve existing structures rather than demolishing them and replacing them with new buildings.

One possible approach is the strengthening of existing concrete structures using carbon reinforced concrete. This paper presents the concept of carbon reinforced concrete strengthening and selected strengthening projects carried out in recent years, demonstrating the current capabilities of carbon reinforced concrete strengthening in building construction, both for interior and exterior applications, as well as for bridge structures. In addition, current research needs are identified and future development potentials are discussed.

Keywords: Carbon reinforced concrete; preservation; strengthening; sustainability; projects

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

Mini Symposia

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MS01: Structural health monitoring and assessment of aging railway infrastructures

Organizers:
Chao Wang (Luleå University of Technology, Sweden)
Zhanchong Shi (Politecnico di Milano, Italy)
Jaime Gonzalez-Libreros (Luleå University of Technology, Sweden)
Gabriel Sas (Luleå University of Technology, Sweden)

ABSTRACT

Aging railway infrastructures increasingly suffer from fatigue, corrosion and cracking as a result of prolonged service, harsh environments and growing traffic loads. This Mini Symposium invites researchers and industry practitioners to explore state-of-the-art structural health monitoring (SHM) and assessment strategies tailored to these vulnerable systems. The aim is to drive scalable, sustainable solutions to extend infrastructure life, enhance safety, and optimize rail network management.
Key topics are advanced sensing technologies (fiber-optic, wireless networks, UAV-based inspection); data analytics and machine-learning diagnostics; digital twins and life-cycle assessment models; predictive and condition-based maintenance strategies; integration of multi-sensor data and standards development; real-world case studies and implementation challenges; and risk assessment and decision-support tools.

Methods of indirect monitoring of deflection, load, and stress on bridges

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Abstract

The subject of this paper is the current findings and insights of the SRIMS – TM05000045 Smart Railway Infrastructure Monitoring System project. The analysis of railway administration needs is described, and possibilities for long-term monitoring of degradation or damage to certain structures in railway infrastructure are presented. The proposed concept of affordable and widely applicable measurement of shifts in the supporting structure in the area of bearings is described, working with the possibility of correlating deflections and stress oscillations in the middle of the span with shifts in the bearing. Findings from experiments conducted with the aim of compiling stress spectra and monitoring damage accumulation are presented.

Keywords: Bridge; railway; monitoring; fatigue

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

Operational applications of continuous strain monitoring on prestressed beam-girder bridges

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Abstract

Concrete beam-girder decks prestressed by post-tensioning are a widely used typology of structure for road bridges. In Europe, many of them were built between the 1960' and 1980' and now reach the theoretical lifetime they were designed for. In addition, this typology of bridge decks undergoes specific ageing effects which can weaken their loading capacity, like loss of prestress load, prestress cable corrosion, and concrete cracking and spalling. To address the issue of maintaining this wide asset portfolio in operation while keeping the failure risk minimal, Structural Health Monitoring (SHM) including alert systems and the release of synthetic health indices is gaining interest nowadays, since the reliability of the sensors and the anomaly detection methods have become mature. This contribution describes the feedback of SHM carried out from continuous strain measurements on post-tensioned prestress beam-girder road bridges on some recent case studies in France and Italy. The useful information obtained by the asset managers from the SHM and the related methodologies are presented, including operational results like Bridge-Weigh-in-Motion (B-WIM) to assess the real level of traffic loads, health indices from statistical analysis of large quantities of measurement data, and anomaly assessment on one example of a damaged bridge.

Keywords: Structural health monitoring; weigh-in-motion; prestressed concrete; data analysis

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

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From data to insight: anomaly detection with 6D monitoring for bridge bearings

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Keywords: structural health monitoring; bridge bearing; 6D sensor; anomaly detection; PELT segmentation; machine learning

1. Introduction

To ensure long-term safety and functionality of bridges, smart and cost-efficient monitoring solutions are needed. Our innovative 6D monitoring approach combines multi-axis sensing with anomaly detection to enable continuous and intelligent observation of bridge bearing behavior, thereby extending the lifespan of existing infrastructure and advancing the state of the art in Structural Health Monitoring (SHM).

The monitoring of bridge bearings as key structural elements provides valuable insight into the overall structural condition, particularly in bridges already exhibiting irregularities. The SuessCo 6D sensor, based on the patented method by Windl (2024), offers a unique advantage for this application: by measuring three displacements and three rotations simultaneously with integrated temperature measurement, it allows direct correlation between thermal effects and mechanical response – an essential factor in understanding bridge bearing performance.

However, this comprehensive sensing capability results in a large volume of complex data. Interpreting these datasets is time-consuming, as it requires detailed knowledge of the sensor orientation, the mounting configuration, and the expected temperature-dependent movement patterns. This complexity often limits the practical usability of such monitoring systems, as identifying relevant anomalies under operational conditions remains a significant challenge.

To address this challenge, we propose a two-step approach combining conventional data analysis with AI-based methods. In the first step, a classical correlation technique is applied to establish a baseline relationship between displacement and temperature over a defined observation period. The resulting envelope yields reliable detection of significant anomalies, but it cannot capture temporal disturbances, the relationship between the measured sensor temperature and the slower-reacting component temperature, or correlations between the measured sensor axes. In the second step, AI-based methods are introduced which can model these complex temperature correlations and inter-axis relationships far more effectively. However, sensor remounting or maintenance interruptions can cause problems for AI algorithm training and evaluation, prolonging the required training period and triggering false alarms. To overcome this, a PELT-based data partitioning is applied to normalize the anomaly score after such disturbances.

2. Envelope method – baseline correlation analysis

In the first step, a baseline relationship between movement in all axes and temperature is established from one year of reference data. For each displacement component, the observed values are binned by temperature, and an envelope is computed as the minimum and maximum displacement per bin with an additional safety margin. New measurements falling outside this envelope are flagged as potential anomalies. To reduce false positives from isolated outliers, only violations occurring in sequences of at least 12 consecutive hours, usually 12 measurements, are reported. This simple, interpretable method provides a first-level screening that is computationally inexpensive and easy to communicate to bridge operators.

Figure 1 illustrates the envelope method applied to the x-displacement of a sensor on a Danube bridge over four consecutive years. Figure 1 on the left shows the displacement–temperature relationship with the reference envelope (green area); points outside the envelope are flagged as outliers. Figure 1(b) displays the same data over time, highlighting 91 consecutive outliers. All other

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events are single or short-term outliers. Reasons for outliers may include temporary shading or direct sunlight given that the measured temperature is in the sensor, not in the bridge structure.

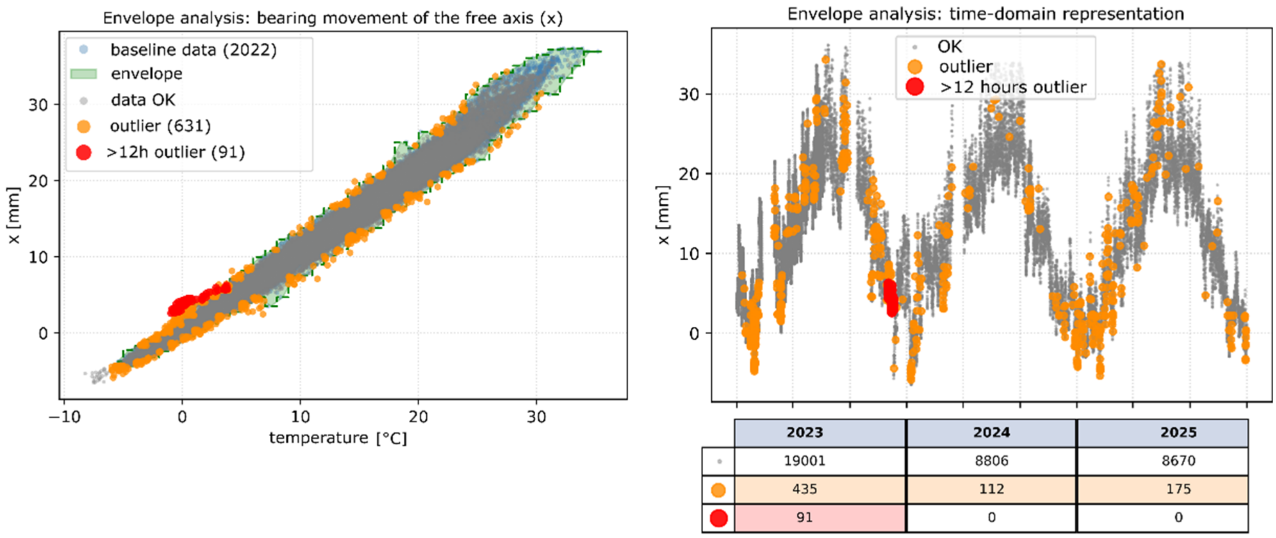

Fig. 1. Envelope method for bridge bearing with the freely moving axis (x-displacement). Left: Displacement vs. temperature during the first year as baseline (blue) with its envelope (green) and detected outliers in the following years. Outliers lasting more than 12 hours are marked in red, short time outliers in orange. Right: Displacement vs. time showing sequences of consecutive envelope violations (91 total).

While the envelope method successfully detects significant changes, it has inherent limitations: each measurement is evaluated in isolation against the temperature bin, ignoring temporal context. It cannot capture the thermal inertia between the rapidly changing sensor temperature and the slowly responding structural component temperature. Furthermore, quick changes or stops of movement in the sensor's usual over-year range as well as correlations between the sensor's measurement axes (lateral movements x, y, z, as well as the Euler angles α, β, γ) are not considered.

3. AI-based anomaly detection

To overcome these limitations, AI-based methods are employed in the second step. We use the Regression-Based Thermal Response Prediction Method (RBTRPM), following the approach of Wedel and Marx (2025a, 2025b). For each displacement component, a Multi-Layer Perceptron (MLP) is trained to predict the expected displacement solely from temperature history. The input features consist of the current temperature plus lagged values over a 24-hour backward window, thereby capturing the thermal inertia between sensor temperature and structural temperature. Anomaly scores are computed as the moving-window mean squared error (MSE) between measured and predicted displacement. Multi-scale windows (4 h, 12 h, 24 h, 72 h) enable detection of both sudden shifts and gradual drifts that would remain undetected by the envelope method. The detection threshold is determined automatically using Peaks-Over-Threshold (POT) extreme-value statistics, eliminating the need for manual calibration. Uncertainty quantification is provided through MC Dropout: multiple stochastic forward passes yield prediction confidence intervals.

4. PELT-based data partitioning

Real-world sensor data frequently contains discontinuities from sensor remounting, bearing maintenance or accidental displacement of the sensor. These offset jumps corrupt the learned temperature–displacement relationship and can significantly increase the required AI training period or trigger persistent false alarms after a disturbance. To address this, we employ the Pruned Exact Linear Time (PELT) algorithm introduced by Killick et al. (2012) for automatic change-point detection. PELT uses dynamic programming with cost pruning. Our implementation extends PELT with time-weighted statistics for irregular sampling intervals, multivariate cost functions combining all displacement components, and a BIC-based penalty scaled by data dimensionality as proposed by Lei et al. (2023). For evaluation, four classes of synthetic anomalies were injected into the signal at varying magnitudes and on different axes: sudden shifts, oscillations, gradual drifts with four-week periods, and trend changes (i.e., slope shifts).

Figure 2 demonstrates the decisive effect of PELT partitioning on anomaly scores. Without partitioning, offset jumps caused by sensor remounting in the learning period degrade the score signal or can mask the synthetic anomaly. PELT partitioning resets the baseline after each such disturbance, restoring the score's sensitivity and yielding a clear, high-confidence detection.

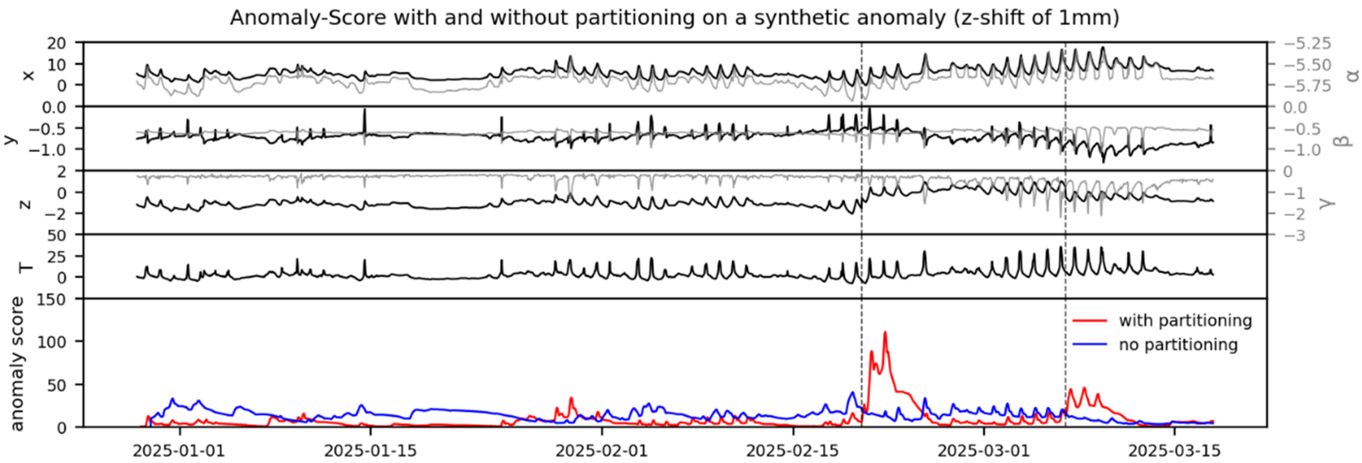

Fig. 2. Measurement data and anomaly scores for a bridge bearing sensor with and without PELT-based data partitioning on a synthetic anomaly (marked with vertical lines) of a sudden shift in z axis of 1 mm. Without partitioning, scores cannot detect the shown anomaly. Furthermore, with PELT partitioning, the scores are renormalized more effectively.

5. Summary and outlook

The proposed framework was validated on two steel bridges comprising a total of eight monitored bearings, each providing four years of continuous measurement data. The results demonstrate that the PELT-based partitioning algorithm substantially reduces the persistently elevated baseline of anomaly scores caused by offset jumps after sensor remounting, thereby improving the contrast between background and true anomalies across the majority of the evaluated datasets. However, the algorithm does not yet perform consistently across all bearings, indicating that further refinement of the segmentation parameters or cost functions is required for certain boundary conditions. The evaluation further confirms that the AI-based approach generalizes well to bridges with differing sensor placements and orientations, as the MLP independently learns the thermal response characteristics for each displacement component without prior knowledge of the mounting configuration. By combining multi-axis sensing with intelligent data analysis, bridge monitoring is thus transformed from a data-rich to an information-rich process, enabling early fault detection, reducing maintenance effort, and supporting data-driven decisions for safer and longer-lasting infrastructure.

Future work will focus on extending the sensor network by integrating complementary measurement technologies, such as strain gauges and accelerometers, to provide a more comprehensive characterization of structural behavior and to further improve the robustness of the anomaly detection framework.

Acknowledgements

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Pressure distribution at the ballast–concrete interface in a full scale RC trough bridge

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Abstract

In ballasted reinforced concrete bridges, the way loads are transmitted through the ballast to the concrete slab plays a critical role in structural performance. However, most current design standards assume a simplified uniform load distribution, which does not accurately reflect real conditions. Past studies mainly focused on sleeper-ballast or ballast-sub-ballast interfaces, leaving the load transfer at the ballast-concrete interface poorly understood. This paper addresses the gap by testing a full-scale reinforced concrete trough bridge, a typical structural type found along European railway lines. The bridge was subjected to controlled static and cyclic loading, simulating real railway traffic in the Iron Ore Line which connects Luleå, Sweden to Narvik, Norway. Custom load plates were installed at the ballast-concrete interface to directly measure contact pressures. The results presented focus on the influence of ballast compaction, represented here in terms of the number of simulated load cycles, on pressure distribution. The data collected is analyzed to evaluate existing distribution models. Main findings highlight that ballast compaction and cumulative repeated loading influence pressure distribution, emphasizing the importance of detailed monitoring and further experimental research to incorporate evolving patterns on structural condition assessment and design of ballasted bridges.

Keywords: Reinforced concrete; railway bridges; ballast; pressure distribution; design models

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

SMAR 2026

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Condition assessment of steel bridges – experimental and numerical procedures

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Keywords: Condition and structural assessment; repair and strengthening; structural health monitoring; modeling optimization

1. Introduction

The present study focuses on the condition assessment of three bridges (Figure 1), a through type single span open web girder bridge (truss bridge number 139A) on the Torangallu - Hospet section and two plate girder bridges (number 3) in Toranagallu and the Castle Rock Kulum Section (number 102) section of the Southwestern Railway zone. The bridges were part of a meter gauge line that underwent gauge conversion to broad gauge (1.67 m) and formed the primary line for the transport of iron ore. Over the years, freight traffic has increased in this section. The axle load until a few years ago was classified as 18-ton axle load has undergone an upward revision to 22-ton axle based on an in-house assessment of the Indian Railways.

Fig. 1. Bridge 139A, Bridge 3, and Bridge 102, respectively.

The condition assessment of the bridges in this section has been initiated with a view to understanding the present state of the bridge and the ramifications of increasing the payload on the bridge to 25-ton axle with or without any intervention for structural enhancement. In this study, details of field measurements undertaken at the bridge under ambient and design train traffic and analytical work based on static and dynamic finite element analysis is presented. The study concludes with some remarks on the state of the bridge within the framework of the information available and inferred.

2. Methodology

2.1. Field study

A multi-channel data acquisition system was used to acquire strains (electrical strain gauges SG and vibrating wire VW), displacements (LVDT), accelerations (BK and CB type), tilt (in pier and abutment), and temperature at various locations in the

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bridge girders, bearings and sub-structure (Figure 2). The test protocol employed in the field ranged from a suite of static tests that included loading the span with a gradual increase in load (LD test) in the form of additional sleepers in a pre-positioned wagon (formation 1); an influence line test (ILD) with known loads (formation 2) applied at a point on the bridge and monitoring the traversal across the span(formation 2 consisting of two WDG4 locomotives, followed by two BFR wagons (each carrying 200 PSC sleepers), two BOXN wagons (carrying loads of 96.3 t and 97.3 t*,* respectively) and a brake van); speed tests with known loads (formation 2 train) to assess dynamic augment in loads, tractive effort studies through starting or braking the train formation on the bridge (formation 2 train). Speed tests were conducted using two formations*, a* formation 2 train and *a* formation 3 train (consisting of two WDG4 engines, 58 goods wagons (BOXNEL), each loaded with 22.78 t/axle load (CC+8+2) and a guard van at the end). The objective of the tests was to assess the load demands on bridge member elements, the bearings, and the sub-structure. The results of the speed tests were also employed to estimate the system natural frequencies achieved by considering the Fourier transformation of the accelerometer data that was captured in the free vibration of the bridge following the exit of the train from the bridge.

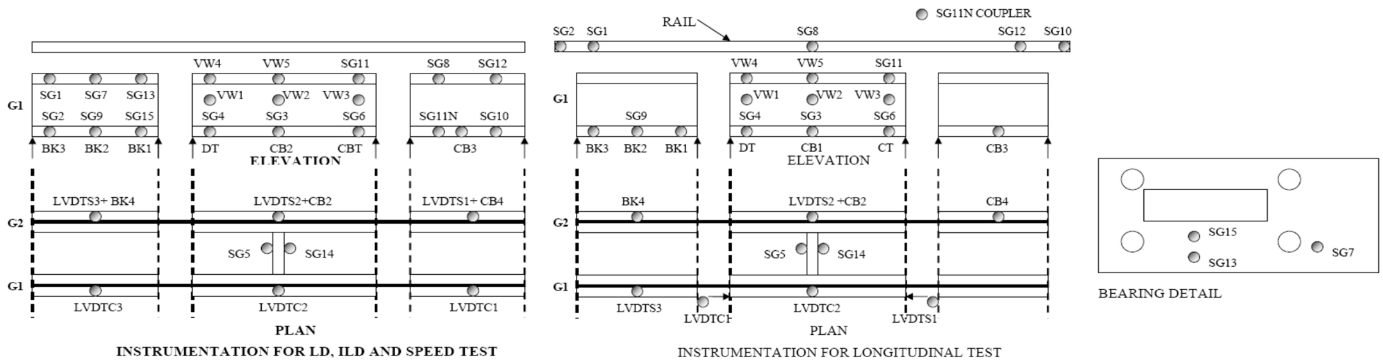

Fig. 2. Layout of sensors for Bridge 3 (plan and elevation over 3 spans and bearings) for different tests.

2.2. Numerical simulation

In the finite element analysis model, the steel girder bridge has been idealized as composed of an isotropic homogeneous material, namely, steel resting on strip support. The pier and abutments have not been explicitly modeled. A three-dimensional model of the bridge has been developed in an ANSYS FE platform. The girder, sleepers, and rails were modelled ensuring proper connectivity of the member using multipoint constraint capabilities to correctly represent the kinematics and the loads placed as per the field test loading scenarios were applied at the same position as in the experiment and corresponding measurements recovered from the model for needed comparison. Comparison between field measurements and the simulations provided good agreement, a validation of the current bridge condition, offering room for axle load enhancement**.**

3. Results and discussion

The static test with sleeper loads being increased gradually yielded deflection measurements at the center of the lattice girder bridge that showed deflections of 2.81mm and 2.36mm in the field measurement and finite element model prediction for a 100 sleeper weight that gradually increased to 4.87mm and 4.73mm in the field measurement and finite element prediction for a 200 sleeper payload (Table 1). This provided a measure of confidence that the modelling of the open web lattice girder bridge (number 139a) was reasonably accurate. Similar validation in measurements from field studies and corresponding finite element predictions were also obtained for the plate girder bridges (bridge 3 and bridge 102).

Table 1. Load versus vertical deflection Bridge 139A.

Load	Field measurement(mm)	Finite element prediction (mm)
100 Sleepers	2.81	2.36
120 Sleepers	3.09	2.84
140 Sleepers	3.44	3.31
160 Sleepers	3.98	3.78
180 Sleepers	4.38	4.26
200 Sleepers	4.87	4.73

The pseudo static moving load analysis deflection measurements and the corresponding finite element deflection prediction provided similar close agreements in deflection measurements across the three bridges (number 3, number 102 and 139A). Further a free vibration analysis indicated the first fifty modes were between 3HZ and 16 HZ and agreed closely with the finite element predictions. The speed test indicated that for bridge 139 A (truss bridge) the stresses ranged from 1.7MPa to 41 MPa across different truss members for speeds varying from 4 to 50 kmph.

According to the railway code**,** the coefficient of dynamic augment (CDA) applicable up to speed of 160 kmph on broad gauge and single track is obtained using the relation equation 1.

$$CDA = 0.15 + 8/(6 + L) \tag{1}$$

where L is the loaded length of span in meters for the position of the train giving the maximum stress in the member under consideration. For the present bridge, assuming L to be 33 meters, the CDA works out to be 0.36. The strains recorded on the bearings are high during the starting and stopping tests of formation 3 (maximum tractive effort in formation 3 having two engines and 58 wagons with axle loads of 22.5t) shown in Table 2. The cross section of the abutment is experiencing tensile stresses and so the abutment is unsafe against cracking. Therefore, periodic monitoring and caution against applying high tractive forces through braking or acceleration on the bridge is advised.

Table 2: Values of horizontal forces transferred to the rails in the longitudinal load test (formation 3); remark: Maximum values reported are at different time instances and should not be algebraic ally added.

Test type	Tractive force applied by loco (t)	Force at coupler as measured (t)	Force transferred to rails (t)				Force on bearings (t)[&]	
			Approach[#]		On bridge (top of bearing)[$]			
			H-end	T-end	H-end	T-end	H-end	T-end
Coupler test LT9	47T × 2 = 94[*]	71.1	25.14 66.40	8.06 12.36	59.87	25.56	16.28	84.13 6.41
Service brake test (LT4)	51.3 × 2 = 102.6[*]	Not measured	22.9 62.27	96.42	74.37	80.14	259.35	121.91 20.90
Brake binding test (LT32)	51.7 × 2 = 103.4[*]	Not measured	9.61 61.85	86.77	57.27	77.62	132.30	235.62 27.41
Stopping test LT1	20.0 × 2 = 40.0[*]	Not measured	15.71 64.45	79.84	46.88	79.77	274.37	205.53 17.54
Accelerating test (LT3)	23.0 × 2 = 46.0[*]	Not measured	19.62 74.07	87.33	60.26	78.74	293.06	224.53 22.79

[#] Two values reported for each test in this column correspond to strain gages SG1 and SG12 at Hospet-end and SG11 and SG15 at Toranagallu-end

[$] Values reported in this column correspond to strain gages SG7 (H-end) and SG14 (T-end).

[&] Values reported in this column corresponds to strain gages, SG10 at H-end and SG8 and SG9 at T-end

Nondestructive tests using rebound hammer and Pandit were carried out on the bridge substructure (abutment and piers) to assess adequacy. Based on the stress method, highest stress observed in the bridge over a passage of a single train is about 7.5 kg/mm^2 (75 MPa) and assuming a stress range of σ_{max} = +75 MPa and σ_{min} = –75 MPa, the factor of safety is computed to be 1.9 for one million cycles. Here, each cycle corresponds to the passage of one train. Assuming ten trains passing on the bridge per day, this translates to about 520 years (1x10^6 X 1.9/3650). Results of field studies carried out on bridge 139a (truss bridge) and bridge 3 and 102 (girder bridges) showed similar trends.

4. Conclusions

From the field measurements it was seen that the load versus deflection in each of the three bridges exhibited a linear relationship. From the study of amplitude of Fourier transform of free vibration response following the exit of moving formations, it is inferred that the dominant modes of vibration lie in the range of 5–60 Hz. The highest dynamic amplification factor for the displacements was observed to be 1.12 (formation 2) and for strain (and hence possibly for stresses) in the girder of 1.4 (formation 2). These trends were seen in all three bridges. The strains recorded on the bearings are high during the starting and stopping tests of formation 3 (2 locomotives with 58 wagons of 22.5-ton axle). The cross section of the abutment is experiencing tensile stresses and so the abutment is unsafe against cracking. Therefore, periodic monitoring and caution against applying high tractive forces through braking or acceleration on the bridge is advised. The finite element model can predict static and dynamic responses corresponding to the field studies quite well. The fatigue life estimate of the bridge members is obtained using stress method to be about 520 years. The rapidly evolving field of AI ML offers opportunity to combine data with physics to develop improved insights in the health of these bridges.

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Fatigue assessment of railway noise barriers based on field monitoring, ML-driven stress prediction and numerical modeling

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Abstract

Railway noise barriers are frequently subjected to train-induced aerodynamic loads during long-term service, which may lead to fatigue problems at the welded base of steel posts. Conventional fatigue assessment methods often fail to account for the complex operational and environmental conditions experienced by real structures. To address this issue, this study proposes a fatigue evaluation framework that integrates long-term field monitoring data with machine learning (ML) and numerical simulation. Based on a field test database, a data-driven calculation model was developed to predict the stress responses of barrier steel posts under actual operational and environmental conditions. A finite element (FE) model validated by field data was further used to establish a quantitative relationship between the monitored stress responses and the maximum stress at the steel post base. Fatigue life for weld toe and weld root failure modes was evaluated using Palmgren-Miner linear damage rule and the nominal stress method in the Eurocode. Results show that weld root failure governs the fatigue performance of the steel post base, with significantly shorter fatigue lives than weld toe failure. Nose waves dominate fatigue damage, while tail waves still contribute about 14–23%. The fatigue life is also strongly influenced by train operating speeds and train type distribution, highlighting the importance of considering realistic train operating conditions in fatigue assessment and design. The proposed framework provides a practical and scalable tool for fatigue assessment and lifecycle maintenance planning of railway noise barrier systems.

Keywords: Fatigue assessment; interpretable machine learning; long-term monitoring; numerical simulation, railway noise barriers

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

Network-level uncertainty-aware deterioration onset model for concrete railway bridges on Sweden's Iron Ore Line

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Abstract

Sweden's Iron Ore Line transports over 30 million tons of iron ore annually and depends on a corridor of ageing concrete railway bridges exposed to heavy axle loads and severe climate. Sparse and stepwise inspections make it difficult to identify deterioration consistently and prioritize intervention across the bridge stock. This paper presents a family-based, uncertainty-aware deterioration onset framework for concrete railway bridges on the line. Superstructure and substructure behavior are modelled separately using family-specific time origins, allowing onset to be analyzed in a more physically meaningful way than bridge-level aggregation. Inspection records are transformed into interval-based bridge-family histories while preserving the distinction between observed states and assumed-no-report states. Deterioration onset is defined as the first transition from Good (TK0) to Fair or worse (TK1+) and is analyzed using family-based survival methods with uncertainty propagated through 300 Monte Carlo reruns sampling onset timing, censoring windows, and engineering input variation. For the primary superstructure family, an exploratory Cox proportional-hazards model links onset timing to load-capacity margin and remaining fatigue life, though the association is directional only given the sample size. The results show substantially earlier onset in the two superstructure families than in the substructure family, indicating that the current reinforced-concrete superstructure generation has entered its main onset window while the supporting structure remains on a slower onset trajectory. The study should be read as a corridor-scale proof-of-concept for sparse bridge archives and as an onset-oriented screening tool rather than a full multistate deterioration or failure model.

Keywords: Deterioration onset; survival analysis; bridge asset management; network-level screening; structural health monitoring

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Self-sensing functionalisation of UHPC

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Keywords: UHPC; smart; piezoresistivity; carbon nanotubes; recycled carbon fibres

1. Introduction

Ultra-High Performance (Fibre-Reinforced) Concrete (UHPC) has been well established as a cementitious composite material with exceptional mechanical properties, durability, and self-healing attributes, both for new construction and retrofitting applications. The integration of self-sensing functionalities into UHPC could further unlock real-time structural health monitoring (SHM) and timely intervention in critical infrastructures, alleviating costs arising from more complex monitoring systems.

However, the scientific literature about the smart functionalization of UHPC, through the incorporation of conductive fillers, is still in its infancy, especially when more sustainable UHPC formulations are employed. Despite the presence of short, dispersed steel fibres, conventional UHPC does not exhibit a piezoresistive behaviour (You et al. 2017). Encouraging evidence has been provided that integrating nano- and micro-carbon black into UHPC enhances signal stability by balancing matrix densification and conductive network formation (Xu et al., 2025), whereas carbon fibres (CF) can additionally serve as bridges between conductive pathways (Li et al. 2024). A recent review has also highlighted the superior capability of multi-walled carbon nanotubes (MWCNT) in endowing high self-sensing functionalities in both compressive and tensile loading (Guo et al. 2024). It can be therefore surmised that multi-scale fillers in hybrid combinations (e.g. micro-fibres and/or nano-materials) are needed to achieve optimal sensitivity and repeatability, yet their synergy is not comprehensively understood.

This paper presents preliminary results on the separate and synergistic effect of carbon nanotubes and recycled carbon fibres on the self-sensing and mechanical performance of UHPC, paving the way for hybrid UHPC formulations in smart applications.

2. Materials and experimental programme

Four different UHPC mixes were developed, comprising CEM IV and pozzolan as main binder, a water/binder ratio equal to 0.2 and 2 % vol. of steel fibres having 20 mm length and 0.2 mm diameter. Recycled CF (0.25 % vol.) of 6 mm in length and 0.7 mm in diameter, and MWCNT (0.1% wt. binder) were incorporated either individually or in combination. A UHPC mix without any additional conductive filler was also produced, serving as reference. The selected filler contents were based on recommendations from existing literature (Trochoutsou et al. 2025, Maglogianni et al. 2025). Where included, MWCNT were first dispersed in an aqueous solution containing an anti-foaming admixture using ultrasonication. Mechanical characterisation tests were conducted after 28 days following EN1015-11, and the self-sensing performance was assessed on 160×40×40 mm^3 prisms provided with solid copper tapes as sensing electrodes, through cyclic compression tests up to 30 % and 50 % of the ultimate strength. Three replicate specimens were tested for each mix design. During testing, the impedance was continuously monitored using a Hioki IM3536 LCR meter, by injecting a low amplitude, high frequency AC excitation, using the four-wire method. The conductive filler materials and experimental test setup, along with the loading protocol, are shown in Fig. 1.

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Fig. 1. Conductive filler materials and experimental test set-up for electro-mechanical testing of UHPC.

3. Preliminary results

All UHPC formulations were characterised by a 28-day compressive strength higher than 120 MPa, satisfying the classification of the concrete material as UHPC according to ASTM C1856 (2024) and the Canadian Standard Association (2014). Overall, the incorporation of CNT improved the compressive strength by approximately 8 % on average, while a minimal reduction of 5 % was recorded in the presence of recycled CF, possibly due to fibre agglomerations and reduced workability. It should be noted that the dosage of superplasticizer remained constant across the mixes.

Table 1. Compressive strength of reference and functionalised UHPC – coefficient of variation values in parentheses.

Property\UHPC mix	Reference	with recycled CF	with MWCNT	with recycled CF & MWCNT
Compressive strength (MPa)	134.9 (2 %)	127.8 (7 %)	147.2 (3 %)	144.4 (5 %)

Results from the electro-mechanical testing are presented in terms of fractional change of electrical resistance (FCR), calculated as $\Delta R/R_o$, plotted against time (Fig. 2). ΔR is the difference between the real part of the impedance (i.e., the resistance) measured during the test and the initial resistance R_o. Upon compression and as the specimen undergoes elastic deformations, resistance is expected to decrease as the conductive fillers reach maximal proximity, thus enhancing the conductivity of the composite material; the opposite holds true during unloading. The magnitude of FCR depends on both contacting and tunnelling conduction between the fillers (Lee et al. 2019). From the analysis of Fig. 2, it is confirmed that the reference UHPC showed minimal sensitivity to an applied stress corresponding to 30 % of the ultimate strength, and significantly higher FCR values were recorded at higher levels of stress, albeit exhibiting a nonlinear correlation with the applied load, possibly due to the germination of micro-cracks. Improved self-sensing performance was achieved with the incorporation of recycled CF (Fig. 2b) at both the examined stress levels, as highlighted by the higher reversibility of the FCR versus time response, indicating the beneficial action of the fibres in further bridging internal electrical discontinuities. The incorporation of MWCNT further enhanced the piezoresistive response too (Fig. 2c), particularly in terms of linearity at higher stress levels. This may be attributed to the more uniform dispersion of the nanomaterials within the UHPC matrix as opposed to their fibre-based counterparts, where fibre agglomeration may have compromised the sensitivity.

The triphasic UHPC formulation (i.e. with macro steel fibres, recycled micro CF and MWCNT) exhibited the best self-sensing performance, including sensitivity, reversibility, linearity and repeatability of the piezoresistive behaviour across the cycles, highlighting the synergy of fibres in effectively controlling micro-crack development and the ability of MWCNT in densifying the mortar matrix. The peak value of FCR reached 11 % and the corresponding average gauge factor (GF), calculated as the ratio of FCR to the applied strain, was found equal to 14.8. It should be noted that higher FCR and GF values indicate higher self-sensing capability; structural materials with FCR values > 5 % can be considered to be good piezoresistive sensors (Konsta-Gdoutos and Aza, 2014), provided that linearity and repeatability can be guaranteed.

4. Conclusions

This study presented the preliminary results on the electro-mechanical performance of UHPC, functionalized with respect to self-sensing. The following conclusions can be drawn:

- Incorporation of only 2 % vol. of steel fibres was insufficient to impart piezoresistivity to UHPC.
- The best self-sensing performance was achieved with multi-phasic UHPC formulations, including 2 % vol. steel fibres, 0.1 % wt. multi-walled carbon nanotubes and 0.25 % vol. recycled carbon fibres. The resulting composites exhibited a reversible and linear piezoresistive response, with GF equal to approximately 15 and a maximum FCR up to 11 %.
- Higher sensitivity was typically attained at higher stress levels of the elastic regime (50 % of ultimate strength).
- The lack of uniform distribution of fibre-type fillers may have compromised the self-sensing sensitivity in the absence of carbon nanotubes.

More research is needed towards the optimisation of smart UHPC through the exploration of different filler types and contents, inclusion of higher contents of supplementary cementitious materials, as well as dispersion procedures. The investigation of the size effect on the self-sensing performance of UHPC subjected to realistic loading conditions, should be also prioritised.

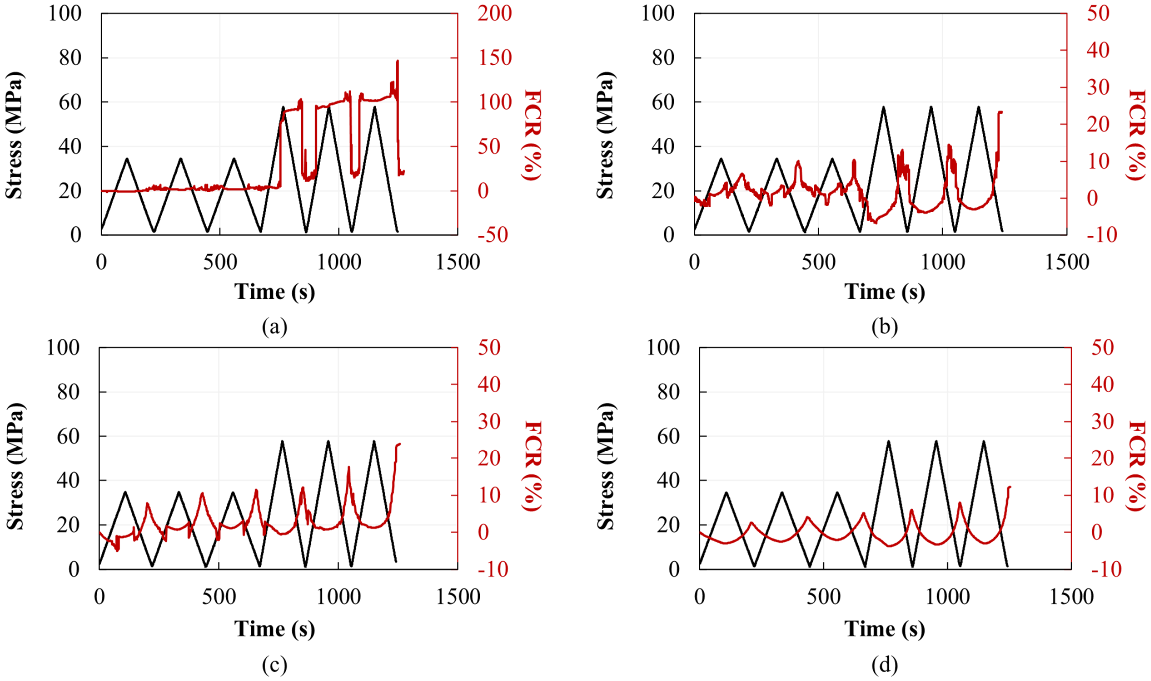

Fig. 2. Electro-mechanical response of UHPC: (a) reference mix; (b) with recycled CF; (c) with MWCNT, and (d) with recycled CF and MWCNT. Note: the secondary (right) vertical axis is different only in the case of reference UHPC.

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

MS02: Innovative bonded solutions for steel structure repair and retrofit

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ABSTRACT

Bonded reinforcement techniques are gaining increasing attention as effective, minimally invasive, and material-efficient solutions for the strengthening and repair of existing steel structures. By relying on adhesive bonding, these methods enable the integration of a wide range of reinforcement materials and allow for tailored interventions that preserve the integrity of the original structure. This Mini Symposium invites contributions that address advances in design approaches, material behavior, durability assessment, long-term performance, and challenges in practical application. Topics may include experimental investigations, numerical modeling, hybrid strengthening systems, monitoring strategies, and case studies from both laboratory and field implementations. With its focus on structural safety, service life extension, and sustainable rehabilitation, the symposium aligns closely with the core themes of SMAR 2026 and aims to foster interdisciplinary dialogue between researchers, engineers, and stakeholders involved in infrastructure preservation and innovation.

Meta-analysis of fatigue performance of centrally notched steel plates strengthened with CFRP

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Abstract

The strengthening of steel structures using adhesively bonded carbon fibre-reinforced polymers (CFRP) has emerged as a promising technique to enhance fatigue resistance, particularly in aging infrastructure. However, the wide variation in experimental setups, material systems, and application strategies has limited the comparability of available data. This study presents a meta-analysis of approximately 250 fatigue tests on centrally notched steel specimens strengthened with CFRP under constant amplitude loading. By systematically harmonizing the data, five key parameters governing the effectiveness of CFRP strengthening are identified: application type (single- or double-sided), relative positioning to the fatigue crack, pre-damage level of the steel, stiffness ratio between CFRP and steel, and degree of prestress. The analysis shows that fatigue life can be significantly increased through optimized combinations of these parameters, with double-sided application and full crack coverage proving particularly effective. The results highlight both the potential and limitations of CFRP-based fatigue strengthening and provide a foundation for the development of a structured research database. This enables improved comparability of future studies and supports the practical implementation of CFRP systems in fatigue-critical steel components, such as those found in bridges and other civil infrastructure.

Keywords: CFRP strengthening; centrally notched steel specimens; fatigue life; adhesive bonding

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

Static behavior of damaged steel beams repaired with CFRP plates bonded with toughened adhesives: experimental and analytical study

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Abstract

The use of externally bonded Carbon Fiber Reinforced Polymer (CFRP) plates has emerged as an effective technique to restore the structural capacity of deteriorated steel members. In bonded solutions, however, the performance of the strengthening system is often limited by debonding of the CFRP plates. Toughened adhesives, characterized by enhanced ductility and fracture resistance, represent a promising alternative to traditional brittle epoxy, although limited research is currently available on their performance in full-scale applications. This paper investigates the static behavior of damaged steel beams repaired with pultruded CFRP plate bonded using a toughened epoxy. An analytical model is developed for a typical central cracked I-beam under four-point bending loading configuration and reinforced using a bonded CFRP strip. A cohesive zone model is used to study the full-range intermediate reinforcement debonding. Closed form solution is developed for the reinforcement strain, interface slip and debonded length. Direct shear tests are then performed, and results are used to calibrate the parameters of the bond-slip law of the toughened epoxy. Results from an experimental campaign on CFRP reinforced cracked I-steel beam are then adopted to validate the bond-slip law proposed. Finally, the intermediate strain distribution along the CFRP strip is evaluated using the proposed analytical model.

Keywords: Repair; externally bonded CFRP; cohesive model; bond

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

Numerical investigation of the fatigue behavior of CFRP reinforced cracked steel beams

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Abstract

Among the different techniques adopted to retrofit steel structures, that had become inadequate under cyclic loadings, the use of carbon fiber reinforced composite materials (CFRP) has gained more popularity for their relevant properties such as high strength to weight ratio and excellent corrosion resistance. However, debonding of the CFRP lamina from the substrate represents the main failure mechanism which may prevent the achievement of the full load bearing capacity of the reinforced element. In this paper, a numerical method is proposed able to follow the full range behavior of a cracked steel beam, externally strengthened using CFRP strips bonded with an epoxy adhesive, under force-controlled cyclic loading. Debonding of the CFRP lamina from the steel substrate is considered adopting a cyclic cohesive zone model, while crack propagation in the steel section is modelled through a modified version of the Paris law. The method is first validated by benchmarking experimental results and then exploited to perform parametric analyses to point out the effect of fatigue damage occurring at the interface due to cyclic loading.

Keywords: Steel beam; CFRP reinforcement; fatigue loading; numerical modelling

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

Adhesively bonded steel patches for retrofitting orthotropic bridge decks

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Abstract

Since the 1950s, many wide-span bridges in Germany – mostly river bridges, e.g. over the Rhine – have been constructed using orthotropic steel structures due to their favorable load-bearing-capacity-to-weight ratio. However, the design and execution of the decks that were built until the end of the 1970s often reveal material and construction faults, which, combined with a sharp increase in traffic intensity and axle loads, have in many cases led to considerable fatigue damage to the bridge structures.
Several research projects have developed solutions with bonded steel patches to cover cracks in steel structures and thus repair them. For this purpose, structural, two-component epoxy resin or polyurethane adhesives are used. Previous investigations were carried out on small and medium-scale bonded samples, but the Institute of Steel Construction at RWTH Aachen University now has several bridge sections from dismantled bridges available for large-scale, 1:1 tests. This contribution covers the tests carried out on such a section of the Cologne-Mülheim Rhine bridge.
The bridge element was strengthened at six critical points with bonded steel patches, to investigate different steel patch geometries. Static tests on the bridge section element before and after the application of the patches proved the strengthening effect of the steel patches, by measuring the stress changes at the surrounding notch locations, which revealed a significant reduction in notch stresses. In addition, cyclic tests were carried out. The steel patches retained their structural integrity even under large deformations, thus permanently relieving the notch stresses around the patches. Now, bridge elements of the Leverkusen Rhine bridge with bonded patches are also being tested to demonstrate the transferability of the strengthening method to other bridge geometries.

Keywords: Orthotropic steel bridges; adhesive bonding; retrofitting; strengthening; FEA; structural analysis

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Influence of physical, creep, humid and coupled ageing on the evolution of the mechanical properties of a steel-to-steel bonded assembly in mode II

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Abstract

The use of adhesively bonded joint provides an interesting connecting solution for existing steel structures in order to reinforce them, or to adapt them to new constraints/usage (bonded fasteners, bonded steel or composite reinforcements, etc.). Yet, there is still a lack of knowledge regarding the long-term durability of such assemblies, especially in humid environments and under combined mechanical and environmental loading. The presented work aims at studying the behavior of ageing steel-to-steel bonded assembly under different conditions (immersion in water, sustained mechanical loading and a coupled case combining both moisture exposure and creep). The objective is to better understand the contribution of each studied phenomena and to determine whether coupling effects exist between them. Focusing on mode II fracture behavior, four ageing conditions were investigated on an identical bonded joint: (1) physical ageing, (2) mechanical ageing under constant load (creep), (3) humid ageing (immersion in water) and (4) coupled hygro-mechanical ageing conditions. The first part will present the bonded joint geometry, the applied ageing conditions, and the used characterization techniques. The second part will detail the main experimental results in terms of failure modes, mode II toughness, and cohesive laws. Finally, a discussion will be provided regarding the influence of each ageing condition and the existence or not of coupling effects.

Keywords: Adhesively bonded joints; ageing; mode II fracture; creep; moisture; cohesive law

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Use of fiber optic sensors (FOS) for the monitoring of adhesively bonded steel laminates

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Abstract

Adhesively bonded steel patches on repaired welds present a novel approach to strengthen fatigue cracked steel bridges or similar structures. Unfortunately, this covers the weld permanently and therefore any form of direct, visual inspection is no longer possible.

Fiber optic sensors (FOS) using Rayleigh backscatter offer a spatial distributed strain measurement from which a deformation profile can be generated. This deformation profile allows to determine the load distribution between patch and structure and can be used to monitor possible changes, which can represent a change in the mechanical properties and therefore a possible defect. Having not only the information about the absolute value of the strain but also its distribution, the expected damage can be located and measured. In a practical approach, the establishment of the FOS on a patch under real conditions is demonstrated using the example of the box girder of a motorway bridge. This section addresses the critical practical issues involved in using sensitive measurement technology in harsh environments and the preparatory measures required for these operating conditions. Similarly, measurements are shown on bonded patches on a defined bending beam at laboratory scale, which allow for a defined load introduction and the corresponding response in the measurement. In the next step, reinforcements on parts of a dismantled bridge under quasi-static and oscillating loads was examined and the quality of the FOS measurements was evaluated. By doing this, e.g. a localized failure of the adhesive layer was detectable via the FOS attached to the patch.

Keywords: Repair; reinforcement; steel patches; monitoring; FOS

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TFC Booster – accelerated controlled CFRP curing process for rapid return to service

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Abstract

Concerning strengthening existing structures with externally bonding Composite Fibers Reinforced Polymers (CFRP), especially concrete bridges, the bond capacity of the composite is critical, and the bridge cannot be reopened to traffic until a sufficient bond strength is reached. When reinforcement works are carried out during night-time traffic interruptions or restrictions, with low ambient temperatures, traffic may only be reopened if the work area is confined and heated for at least 24 hours. To reduce the time required to return the bridge to service, a special process named Foreva TFC Booster based on Joule effect was developed to accelerate the curing of the adhesive resin, allowing it to harden within maximum two hours and achieve the required bond capacity. The process is based on a precise controlled heating of carbon sheets with thermal sensor and IR camera analysis, tailored to the section and length of the carbon strips, ensuring uniform curing of the resin and critical bond capacity in maximum two hours. The effectiveness of the process was assessed for different geometries on a real concrete beam taken from an old bridge. Laboratory tests on concrete beams reinforced with the process also demonstrated the performance of the system.

Keywords: Concrete reinforcement; CFRP; durability; process; temperature monitoring

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Experimental development of a self-sensing steel reinforced polymer system with fiber Bragg grating sensors

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Abstract

The effective protection of the building stock requires continuous monitoring of structural safety to enable timely, targeted, and cost-efficient maintenance interventions. For the upgrade of existing structures, smart solutions can be achieved by combining strengthening systems with structural health monitoring (SHM) sensor networks. This work presents a novel integrated technology in which Fibre Bragg Grating (FBG) sensors are embedded in Steel Reinforced Polymer (SRP) composites. SRP systems consist of Ultra High Tensile Strength Steel (UHTSS) micro-cords embedded in epoxy resin and have been developed for upgrading reinforced concrete and masonry structures. A dedicated procedure was defined for the preparation and application of FBG sensors to the textile, addressing the challenges of installing optical fibres on the rough surface of the micro-cords while ensuring accurate axial strain measurement and protection. A PEEK coating was adopted both to act as a deformation transducer and to protect the sensor during handling and installation. SRP-FBG prismatic specimens were manufactured using two textiles with different cord densities (12 cords/inch and 21 cords/inch) and tested under direct tensile cyclic loading. The strains recorded by the embedded FBG sensors were validated against those obtained through Digital Image Correlation. The proposed SRP-FBG integrated system proved reliable and demonstrated significant potential for combined strengthening and SHM applications.

Keywords: Strengthening, monitoring; optical fibres; tensile test; digital image correlation

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

Memory-steel for fatigue strengthening of a steel bridge in Germany

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Keywords: Iron-based shape memory alloy (Fe-SMA), fatigue strengthening, bridge strengthening, bonded repair, lifetime extension

1. Extended abstract

A significant number of steel bridges worldwide require strengthening due to fatigue loading and the progressive aging of infrastructure. Many of these structures have already reached or even exceeded their intended service life. As a consequence, replacement for numerous bridges is currently being planned. However, the long planning and construction periods associated with such critical infrastructure often leads to partial or complete restrictions for heavy traffic even before replacement works begin.

In many cases, the remaining service life of existing bridges is governed by fatigue-critical details. These include connection details that were not originally designed for fatigue resistance (e.g., stiffeners in orthotropic bridge decks) as well as local stress concentrations of structural components.

To significantly extend the remaining service life of such structures, ensure unrestricted traffic during planning phases, and potentially prolong these planning periods, effective local strengthening methods are highly desirable. In Germany, various approaches for extending the service life of bridge structures are currently under investigation. Among these, prestressed strengthening techniques are particularly promising. Unlike conventional strengthening methods, they not only counteract service loads but can also partially compensate for dead loads. This enables an effective redistribution of stresses and reduction of local stress concentrations. In particular, for cracked components with limited residual life, the introduction of compressive stresses through prestressing can significantly reduce or even arrest crack propagation. By shifting the stress state at the crack tip partly or even total into compression, the fatigue life can be substantially increased, allowing critical components to remain unproblematic over the remaining service life of the structure.

One promising approach for the prestressed reinforcement of fatigue cracks is the use of so-called Memory-Steel patches. These patches utilize the shape memory effect of iron-based shape memory alloys (Fe-SMA) to introduce compressive stresses into the parent structure, thereby promoting crack closure and preventing further crack growth. A key advantage of this material lies in the simplicity of prestress application. After pre-straining, the material is activated by moderate heating, which induces recovery stress. When the material is bonded to a structural component, this recovery stress generates prestressing forces within the structure. For local fatigue strengthening, adhesive bonding of Fe-SMA patches enables efficient reinforcement with minimal intervention in the existing structure and negligible spatial constraints.

The development of reliable strengthening solutions requires not only theoretical understanding but also validation through real-world pilot applications. This study presents the first application of prestressed Fe-SMA patches on an in-service bridge in Germany.

The investigated structure in this study is a steel highway bridge located in Duisburg (Germany), a key traffic hub in the Ruhr region. Due to its high traffic relevance and its current structural condition, the bridge is subject to regular inspections. Fatigue cracks have been identified at redundant connection details between longitudinal stiffeners and cross beams. Previously, these

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cracked details were conservatively repaired using bolted steel plates. In some cases, this approach did not successfully arrest crack propagation, and additional stop-holes were introduced. However, this method is considered critical, as drilling holes leads to local cross-sectional weakening and stress concentrations, which may themselves become fatigue-critical. Furthermore, there is inherent uncertainty in ensuring that the crack tip has been fully removed, as it is not always clearly visible, allowing cracks to potentially propagate beyond the stop-hole.

To address these limitations, a strengthening concept using adhesively bonded Fe-SMA patches was developed. The patches were applied on both sides of the longitudinal stiffener at the crack location and have dimensions of 1.5 mm in thickness, 130 mm in length, and 70 mm in width. They were positioned centrally over the crack, enabling an effective crack-bridging mechanism. The application process included surface preparation of the steel detail using a handheld grinder to remove the coating and ensure sufficient surface roughness for bonding. Subsequently, the surface was cleaned using acetone and wipes, and the adhesive (SikaPower®-1277) was applied. The Fe-SMA patches were then positioned using a magnetic fixture and cured in accordance with the manufacturer's specifications.

Prior to strengthening, the structural detail was instrumented with multiple strain gauges and crack gauges to monitor crack opening and local strains (to infer corresponding stresses) in both the unstrengthened and strengthened states. After curing, the central region of each patch, over a length of 50 mm, was activated at a temperature of approximately 180 °C to induce prestress. The activation was performed using a gas torch, while the temperature was controlled using a handheld measurement device. The measurements show that the maximum crack opening amplitude is reduced by approximately 50 % solely due to the bonding of the patches, as a result of the increased stiffness. Furthermore, activation of the patches introduces compressive stresses exceeding 20 MPa in the critical region above the stop-hole, effectively strengthen the fatigue-critical area. This prestressing leads to a noticeable reduction in crack opening and partial crack closure. Long-term monitoring confirms the sustained presence of the introduced compressive stress over time.

Overall, the results demonstrate that the activation of Fe-SMA patches leads to both crack closure and the introduction of beneficial compressive stresses in the critical region. While the unactivated bonded patches already reduce the crack opening range due to their added stiffness, activation significantly enhances the strengthening effect by directly influencing the crack behavior.

Acknowledgements

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Shear performance of timber-steel hybrid beams: experimental investigation

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Abstract

The building sector accounts for approximately 40 % of global CO_2 emissions, setting the demand for efficient and resource-efficient structural systems. Timber structures offer significant sustainability advantages but exhibit mechanical limitations, particularly regarding shear strength and stiffness. Steel-based strengthening therefore represents a promising strategy to improve the structural performance of timber elements while maintaining a high percentage of the renewable material timber.
This study investigates a strengthening approach for timber beams using slender steel profiles that are adhesively bonded into the timber cross-section. Three-point bending tests with a span of 0.74 m were conducted to generate shear-dominated loading conditions. Strengthened beams were compared with timber reference beams of identical geometry using two material combinations: GL 24h with S355 and LVL 48p with S420. The strengthening significantly improves structural performance. The load-carrying capacity increases by 99 % for GL 24h and 77 % for LVL, while the shear stiffness increases by factors of 5.7 and 4.0, respectively. Whereas the timber reference beams fail in a brittle shear mode, the strengthened beams exhibit a more ductile response due to plastic deformation of the steel profiles combined with timber failure. The results demonstrate the high potential of steel-based strengthening for shear-critical timber members.

Keywords: Hybrid; timber; steel; adhesive; shear stiffness

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

Strengthening cross-laminated timber with CFRP for structural reuse

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Abstract

According to the UN Environment Programme, 34% of global CO_2 emissions and 32% of energy use are attributable to the construction sector, making it a significant contributor to climate change. Greenhouse emissions are caused by operational carbon emissions from energy use during the service life of a building and embodied carbon emissions in the building materials used for construction. Although operational emissions have decreased, further advancements are required in the form of sustainable materials and strengthening techniques to prolong the service life of existing structures and to allow structural reuse. Mass timber products, such as glued-laminated timber (glulam) and cross-laminated timber (CLT), are low-carbon alternatives to steel and concrete. Although carbon fiber-reinforced polymer (CFRP) strengthening has been thoroughly researched for conventional building materials such as concrete, its application to mass timber products remains largely unexplored, highlighting the need for further research. This study investigates the application of CFRP sheets for strengthening damaged cross-laminated timber beams experimentally. A comparison between the strengthened damaged beams and intact specimens demonstrates the effectiveness of this method, as the strengthened beams exhibited comparable peak loads and stiffness, higher deflections at peak load, and, in some cases, increased ultimate load capacity. These findings offer insights into the strengthening effect of CFRP retrofits and support the design of mass timber structures for the circular economy.

Keywords: Cross-laminated timber; carbon fiber reinforced polymer; strengthening; timber; structural reuse

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

Effect of mineral-bonded protective layers under impact loading

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Abstract

Protective layers on reinforced concrete components on the impact-facing side can provide very effective subsequent protection of existing structures. A load-distributing cover layer and a low-strength energy-absorbing damping layer can achieve a significant reduction in impact energy. For a detailed investigation of the effectiveness of the strengthening layer, impact experiments on plain and strengthened reinforced concrete (RC) cuboids of dimensions 49 × 49 × 30 cm³ were conducted in the drop tower of the Otto-Mohr-Laboratory at TU Dresden. The specimens were protected with a layered protective system consisting of an infra-lightweight concrete (ILC) sub-layer of different thicknesses and an additional 1 cm cover layer of strain-hardening cementitious composite (SHCC). The ILC, acting as the damping layer, consist of porous aggregates that crush under impact load, which effectively decreases the peak load resulting in reduced damage of the RC-cuboid underneath. The basic mechanism has already been described in Leicht (2024). To assess the effectiveness of this strengthening system, a solid steel impactor was accelerated onto the specimens and the resulting structural response was monitored. This experimental study focuses on quantifying the observed damping effect by showing the dependency on the thickness of the layers and the impact energy.

Keywords: Impact loading; drop tower; protective layer; structural protection

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MS03: Railway track monitoring – an essential basis for the optimization of railway infrastructure

Organizers:
Marc Wenner (MKP GmbH, Weimar, Germany)
Günther Grunert (DB InfraGO AG, Germany)

ABSTRACT

The railway network plays a vital role in achieving climate targets by shifting both passenger and freight transport from road to rail. To support this transition, railway infrastructure must be reliable, robust, and highly available. Monitoring is key to understanding existing systems and guiding the development of improved ones.

This Mini Symposium will explore both trackside and onboard (vehicle-side) monitoring approaches. Topics include track behavior under dynamic loads, resistance to buckling, structural responses on bridges, and emerging trends in continuous monitoring via regular passenger trains.

A special focus is placed on fostering interdisciplinary exchange across domains that are currently only loosely connected, but where strong synergies are possible. The symposium aims to bring together experts from research, industry, and operations to inspire collaboration and drive innovation in monitoring technologies for the railways of the future.

Smart instrumented test track for advanced railway superstructure evaluation

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Abstract

To advance the systematic development, validation, and comparison of modern railway superstructure systems, a fully instrumented 54 m test track has been constructed at the voestalpine Rail Technology site in Donawitz. Embedded in a reinforced concrete trough to ensure constant and repeatable boundary conditions, the facility comprises three 18 m sections equipped with under-ballast mats (UBMs) of systematically varied stiffness. The track integrates a multi-layer sensor architecture enabling high-resolution measurement of wheel–rail forces, rail–sleeper interaction, sleeper dynamics, ballast stress distributions, and load transfer into the substructure. In cooperation with TU Graz, the first measurement campaign focused on the systematic investigation of lateral track resistance after tamping and following the application of a Dynamic Track Stabilizer (DTS). The measured responses not only confirm established ballast mechanical behaviours but also provide unprecedented spatial and temporal fidelity, enabling deeper insights into load redistribution processes. These data form a robust basis for numerical model calibration, component benchmarking, and the validation of concepts supporting high-availability track designs.

Keywords: Railway; instrumented test track; superstructure evaluation; smart monitoring; lateral track resistance

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

Experimental DAS, FBG and DFOS based monitoring system of the rail track in high-speed train loading

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Abstract

Railway structures face numerous threats to their structural integrity. Climate change accelerates the degradation of earth structures, while concrete supports and bridges continue to age. At the same time, the introduction of high-speed trains puts additional stress on existing infrastructure. Together, these factors increase the risk of transportation failures that may result in enormous economic losses and, most importantly, endanger human lives. In this article, the authors present an innovative approach to monitoring aging railway infrastructure. The project aimed to support certification of the increasing of the maximum admissible speed from 160 km/h to 250 km/h on a railway line built in the 1970s, which remains a crucial connection between Poland's capital and the industrial region of Silesia. Multiple advanced fibre optic sensing techniques were applied to monitor the physical parameters of the track. The results were validated against classical measurement methods, confirming the reliability and accuracy of the approach. Surveys were executed throughout the year to check influence of seasonal conditions on the dynamic behavior of the track.

Keywords: DFOS, DAS, railway, track, FBG

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

Piezoresistive sensors for smart monitoring applications in railway infrastructure

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Abstract

Increasing traffic demand, higher axle loads, and rising train speeds impose significant stresses on railway infrastructure, requiring advanced maintenance strategies. In critical zones such as turnouts and track discontinuities, conventional inspection methods mainly capture geometric and kinematic parameters and fail to represent the load interactions governing deterioration. Continuous monitoring of loads is therefore essential for predictive maintenance. This study investigates the applicability of piezoresistive sensors for load monitoring in railway infrastructure, focusing on their integration into rail pads. Experimental tests using piezoresistive sensors were conducted under static and dynamic loading, considering frequencies between 1–20 Hz, temperatures from −20 °C to +40 °C, and long-term behaviour up to 300,000 load cycles. Both individual sensors and sensor-integrated rail pads (SIRP) were evaluated, including simulated train passage scenarios. The results show a clear frequency dependency with decreasing sensitivity at higher frequencies. Temperature effects were moderate at low temperature changes but reasonable at higher temperatures changes. Long-term tests revealed drift and sensitivity degradation over time. Despite these effects, good agreement with reference measurements was achieved, and reliable performance was demonstrated for the SIRP. The findings indicate that piezoresistive sensors are a promising solution for measuring load transfer in railway infrastructure. However, their application requires consideration of frequency effects, temperature dependency, and long-term drift, as well as appropriate calibration strategies to ensure reliable performance under field conditions.

Keywords: Piezoresistive sensors, smart railway monitoring, load measurement

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

Mission profiling of railway bridges using low-power smart MEMS sensors

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Abstract

Structural health monitoring of railway infrastructure, particularly bridges, is essential for ensuring long-term safety, reliability, and cost-effective maintenance. Traditional monitoring systems often rely on wired or high-power sensors, which limits large-scale deployment and long-term operation. Recent advancements in low-power micro-electro-mechanical systems (MEMS) sensors enable a new generation of smart, autonomous monitoring solutions tailored for mission profiling of railway bridges. By capturing acceleration data over extended periods, these sensors can provide insights into the cumulative loading patterns and degradation processes of bridges. Smart MEMS-based sensing networks enable energy-efficient data acquisition for improved prediction of the remaining useful lifetime of railway infrastructures, helping to reduce the need for frequent maintenance and manual inspections. Typically, for infrastructure monitoring at remote locations, external power supply is often unavailable and low power communication is required. Complex time series data must be evaluated and compressed locally on the sensor or edge device to reduce overall energy consumption and data traffic. This paper analyzes field data from railway bridges in the Czech Republic and demonstrates how key parameters like train passage, speed, length and number of wagons and axles can be extracted from acceleration data using signal processing methods. In addition, a low-power MEMS sensor system is investigated and evaluated by means of in-lab reproduction of field data. Suitable algorithms are developed with respect to the limited resources of such devices. Overall, this approach supports predictive maintenance strategies and enhances the understanding of load-induced structural behavior, contributing to safer and more sustainable railway infrastructure management.

Keywords: Structural health monitoring; railway infrastructure; mission profiling; smart sensors; MEMS accelerometer

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

Continuous track monitoring (CTM) for condition-based maintenance of railway bridges

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Abstract

A large number of railway bridges in Germany are approaching or have already exceeded their intended design life, yet resources for manual inspection remain limited. This paper investigates the use of Continuous Track Monitoring (CTM) data, specifically the D0 signal, a bandpass-filtered track geometry signal for wavelengths of 1–5 m, for condition-based monitoring of bridges and their transition zones. Unlike the established 3-point chord signal (3p), the D0 signal provides a true representation of short-wavelength irregularities and is largely independent of vehicle speed. Two field examples are presented: a deteriorating bridge transition zone and a bridge with a defective bearing. For both cases, the growth rate and variance of the D0 signal are shown to distinguish effectively between intact and damaged conditions. The results provide an initial basis for future normative development of assessment criteria in the short-wavelength range.

Keywords: Condition-based maintenance; structural health; indirect monitoring; drive-by-monitoring; railway bridges

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

Track geometry prediction method – development and practice at DB InfraGO

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Abstract

Track geometry behavior is strongly influenced by locally varying boundary conditions and therefore cannot be described by a uniform deterioration law. DB InfraGO has developed a prediction method for track geometry that analyzes the inspection data in the course of time and forecasts the track geometry parameters for the next years. Automated track geometry prediction forms the basis for optimizing the planning of maintenance work with new opportunities for locally adaptable maintenance, earlier planning and scheduling, efficient employment of maintenance machines and track blocking times and bundling of maintenance measures and related works. Linking the track geometry history and prediction with data of structures, track alignment, speed profiles, loading, etc., enables a better understanding of the relationships and of the root causes for track geometry defects.The prediction method is currently being implemented at DB InfraGO in the regular decision-making process for tamping maintenance work. In EU project IAM4RAIL, the prediction method serves as the basis for the development of new tools for more efficient planning of maintenance machine shifts and of traffic coordination during maintenance.

Keywords: Track geometry; deterioration; prediction; tamping maintenance; maintenance planning

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Longitudinal displacement of ballast track with rail expansion joints during traction and braking

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Abstract

Rail expansion joints are used to separate continuously welded rails, with the aim of minimizing additional longitudinal rail stresses, which are usually caused by displacements of bridges under traffic loads and temperature influences. However, rail expansion joints lead to a discontinuity in the contact area between the rail and the wheel, which has a negative impact on driving dynamics. The increased dynamic load resulting from this often necessitates extensive and costly maintenance work. Depending on the length and type of bridge, it could be useful to investigate whether rail expansion joints can be avoided. The proof of rail stress, which determines the need for such a design, is based on design parameters that no longer correspond to the current technical standard. This includes longitudinal rail deformation at the ends of bridges with rail expansion joints, for example, which can be caused by trains traction and braking. According to the current German railway regulations, a length change of up to 30 mm is permitted when rail expansion joints are arranged on both sides. This publication presents a study in which short-term measurement was carried out in 2023 on a bridge chain with rail expansion joints on both sides, to determine the actual longitudinal deformation caused by the traction and braking of freight trains; however, measurements were taken at only one rail expansion joint. The focus of this work is on the relative displacements of the tongue rail and stock rail caused by the traction and braking of, as well as the passage of, freight trains over the rail expansion joint. A specific measurement concept and evaluation methodology are developed.

Keywords: Longitudinal displacement, ballast superstructure, rail expansion joints, longitudinal rail stress, longitudinal load distribution

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Track–bridge interaction for a railway bridge with longitudinally movable track

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Abstract

As part of the upgrading of a freight railway line involving increased axle loads and train speeds, the ballasted track on a 73.5 m long existing bridge had to be modified in order to avoid an increase in longitudinal forces at the fixed bearing of the superstructure. To reduce additional rail stresses caused by track–bridge interaction (TBI), longitudinally movable rails installed on synthetic sleepers were implemented. A two-year monitoring campaign was carried out to validate the assumptions of the project-specific rail stress analysis and to derive practical conclusions for design and maintenance. For this type of rail system, neither design approaches nor experimentally validated resistance parameters for TBI calculations are currently available in literature or standards. The presented investigation provides one of the first comprehensive field studies on the behaviour of longitudinally movable running rails in ballasted track. By combining numerical modelling with long-term monitoring under operational traffic, the study improves understanding of governing interaction mechanisms, quantifies the activated longitudinal resistance, and provides recommendations for the calculation and assessment of TBI effects on existing railway bridges.

Keywords: Track-bridge interaction; rail stresses; bridge; ballasted track; simulation; monitoring; zero longitudinal restraint

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Track-bridge interaction – preliminary experimental results about the behavior of ballasted track on bridges

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Abstract

The "TraBI" (Track-Bridge-Interaction) research project aims to develop a future-proof and universal verification method for track-bridge interaction across various track construction types. Current validation methods defined in Ril 804.3401 and DIN EN 1991-2 are limited to standard track configurations and do not account for frequently occurring deviations in railway infrastructure. To close this gap, the German Centre for Rail Traffic Research (DZSF) initiated TraBI to investigate longitudinal force transmission in additional track scenarios and curve radii. Running from February 2025 to January 2028, the project combines theoretical and experimental studies, including in-situ tests on a representative railway bridge in Elsterwerda, Germany. Extensive monitoring is being conducted to investigate the behaviour of the ballasted track under different loading conditions, while laboratory experiments evaluate critical track resistance parameters. The results will support the development of an enhanced computational model for track-bridge interaction covering a broader range of track configurations. A key objective is the preparation of a practical guideline for modelling, calculation, and load case superposition, providing the basis for future extensions of current railway standards.

Keywords: Railway bridges, track-bridge interaction

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High-speed testing of a tied arch railway bridge vehicle-bridge interaction at resonance

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Abstract

Seeing an entire railway bridge visually deflect and feeling the dynamic movement is an impressive sensation and a notable display of resonance effects introduced by train crossings. Substantial dynamic vibrations are to be prevented in normal operation, since they pose excessive risks for the structural integrity and durability of both bridge and railway track. During high-speed trials, resonant oscillations were intentionally excited to validate a new high-speed train by demonstrating acceptable dynamic behavior. This paper presents results from monitoring train, bridge and track reactions. Further evaluation of the numerical multi-body model provides insight into the underlying dynamic mechanism. Computational analysis of bridges at resonance has become more common in recent years, but in situ measurements reaching severe amplitudes have rarely been published. These findings contribute to the discussion on how to enable the incorporation of vehicle-bridge interaction effects in dynamic analysis.

Keywords: Resonance; high-speed trials; vehicle-bridge interaction; tied arch railway bridge; multi-body model

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SMAR 2026

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Sensor-based load–response correlation for monitoring railway bridge condition

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Keywords: Railway bridge monitoring; condition monitoring; structural health monitoring; axle-load measurement; structural responses

1. Introduction

Railway bridges can achieve service lives of more than 100 years when they are properly maintained. However, operational demands and environmental conditions may change over time. For instance, an unexpected increase in load cycles or rising rail temperatures can accelerate the deterioration of the railway bridge stock. It is therefore essential to implement long-term monitoring systems on various bridge types to collect robust and meaningful data. In this context, the research project “Monitoring Stations for Engineering Structures in the Open Digital Test Field of the German Centre for Rail Traffic Research” offers a valuable data foundation for analyzing the long-term structural behavior of railway bridges under operational and environmental conditions. In addition to a wide range of equipment for monitoring the structural behavior of the bridge superstructure, a special focus is set on studying track behavior while accounting for climatic influences. The project includes comprehensive sensor instrumentation on two prestressed concrete bridges and one filler-beam bridge. Each prestressed concrete bridge is equipped with around 300 sensors, approximately one-third of which are located within the track area, while the filler-beam bridge contains more than 150 sensors. The three monitoring stations began operation in April 2025. A key aspect of the monitoring systems design is that not only the structural and track responses are measured, but also axle loads and environmental parameters. This integrated approach enables detailed analysis of the relationships among these different data types. This contribution presents an overview of the project and discusses initial results that show potential applications of condition monitoring of railway bridges based on feature-based correlations between structural responses and axle-load measurements.

2. Measurement set-up and analysis of results

A total of three railway bridges are being monitored extensively within the project. They are located within the Open Digital Test Field, a geographic space between the German cities of Halle (Saale), Cottbus, and Niesky. The selection of the bridges to be monitored was based on different criteria. Besides the consideration of structural parameters, also railway-specific and operational criteria played an important role. Two railway bridges serve as river crossings, the third one crosses a street. Two bridges follow a straight line; the other one exhibits a curved trace. All railway tracks are doubled-tracked, electrified, with a permissible train speed ranging between 120 km/h and 200 km/h. The same measurement setup was used for the measurements on the three bridges in “Open Digital Test Field of the German Centre for Rail Traffic Research”. Different sensor systems are employed to correlate the effects of traffic with the bridge's response. Strain measurements on the rails are used to measure the effects in the form of axle load measurements. These measurements are automatically calibrated by known vehicles, and the strain data is then used to classify the trains according to their type. The structural and track responses are recorded by a comprehensive number of sensors installed on the superstructure and at the track level; these include displacements, temperature, accelerations and strains. **Fehler!**

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Verweisquelle konnte nicht gefunden werden. 1 shows the typical installation of the sensors, which were used for all three bridges whereas the sensor positions on a representative cross-section of the superstructure are shown in Fig. 2a. The classification of trains is subject to an automated process to evaluate the train parameters in detail. Based on these parameters, a graphic as shown in Fig. 2b can be created for each train. This data is stored in a database, allowing filter and section the data. There are no limits to the selection process, train crossings can be selected based on track, speed, train configuration, etc. For the following explanations, the ICE1/2 trains are selected from the classified trains, which normally travel across the bridge at an average speed of 160 km/h.

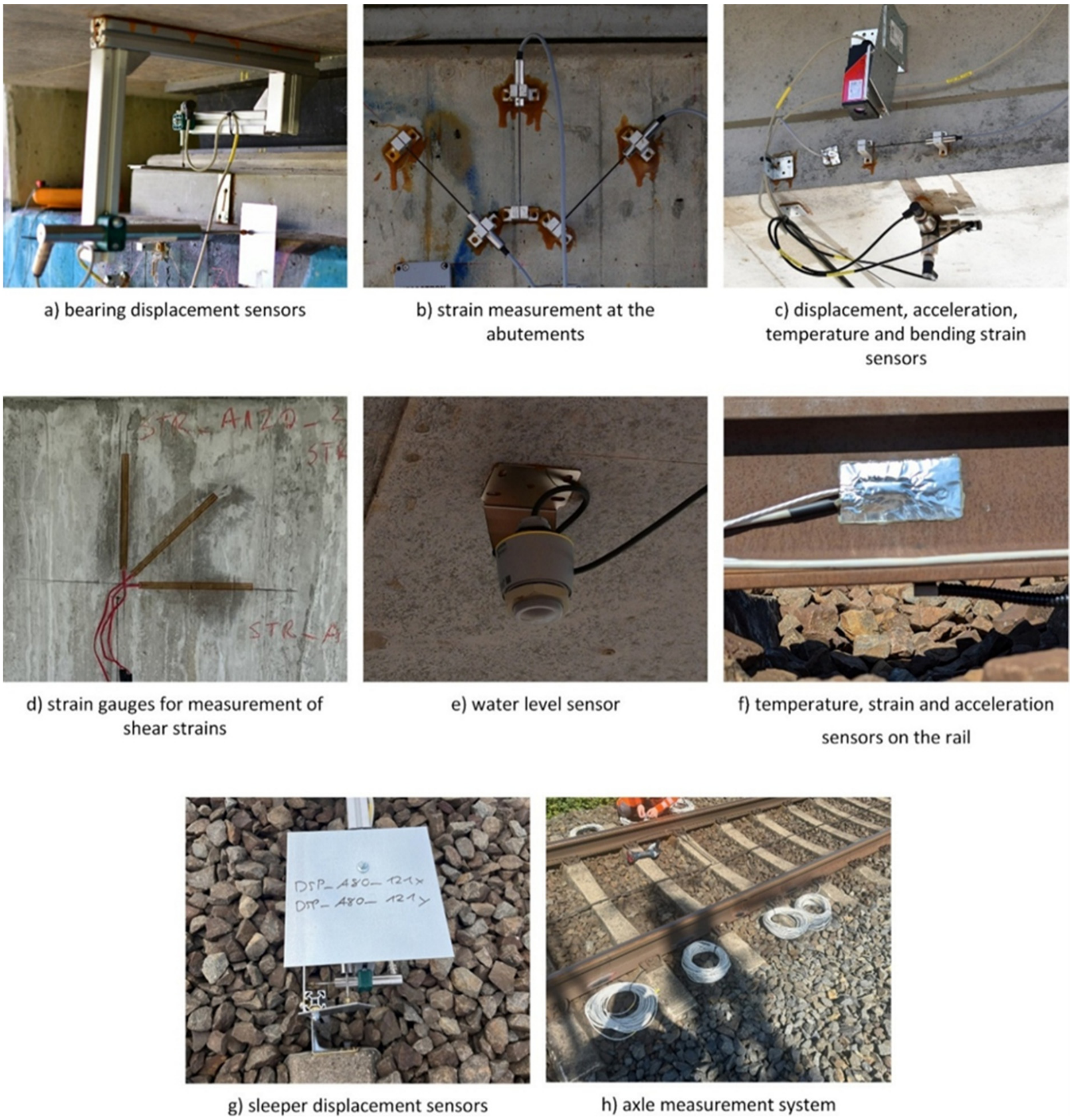

Fig. 1. Typical sensor installation.

For each train pass and sensor, the data is sampled at sampling rates between 250 and 1000 Hz to adequately resolve the loads depending on the area of influence. This means that during crossings lasting only a few seconds, a very large number of data points are generated which must be summarized into meaningful metrics in order to enable feature-based correlations. A very straight forward approach to feature engineering is the use of statistical quantities such as extreme values. In the case of physical sensor data, these quantities typically correspond to the position of the train relative to the sensor position that causes the biggest strain or deflection amplitude when a train passes the bridge. If the data selection is based on the same train configuration, the extreme values should always be of approximately the same size.

Such a representation is shown in Fig. 2c for the deflection of the second span of a continuous system. The deflections always reach an approximately equal magnitude of 1.5 mm vertically in the z-direction of gravity and –0.8 mm against it. The deflections occur within this range (Δ = 2.3 mm) when an ICE 1/2 train crosses the bridge. The same is shown for the strains in the longitudinal x-direction in Fig. 2d. What can also be observed here is that the extreme values for each train crossing occur at two different levels.

This clearly illustrates that the strain gauges are significantly more sensitive in distinguishing between a crossing on track 1 and track 2. In this evaluation of the sensor readings from track 1, the extreme values are considerably higher than when the train crosses track 2. The strain range for a train passing on track 1 is 26 µm/m and 18 µm/m for a passing on track 2.

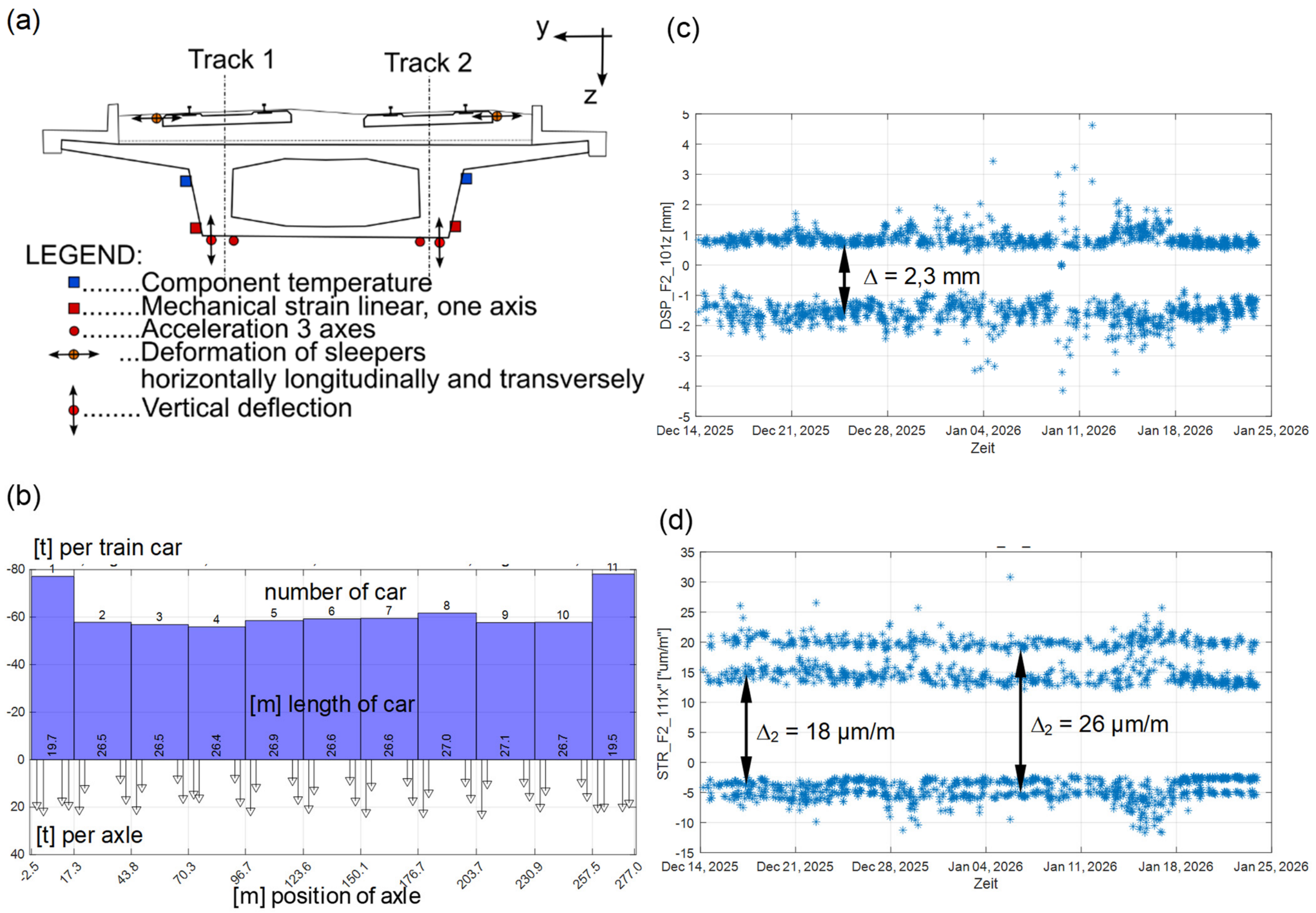

Fig. 2. (a) Representative bridge cross-section in the center of the field showing the sensor positions, (b) configuration of ICE1/2, (c) Min/Max values due to ICE1/2 passing for the vertical deflection sensor on track 1 and (d) Min/Max values due to ICE1/2 passing for the longitudinal strain sensor on track 1.

The selected period covers approximately 1 month from December 2025 to the end of January 2026 and basically shows a very constant trend except for four days between January 12th and 16th, 2026. These deviations in amplitude are evident for both deflection (Fig. 2c) and strain (Fig. 2d). These deviations do not constitute an exceptional situation, but they do indicate operational changes. The data analysis shows no changes in train crossings, e.g., due to a change in operational speed, but rather a significant increase in component temperatures for the superstructure from –9°C to +2°C during this period. It is assumed that the sharp temperature increase creates stresses that affect the stiffness of the structure and are then reduced until the expected structural response is restored.

3. Conclusions

The present contribution gives a brief overview of a large-scale railway bridge monitoring project within Open Digital Test Field of the German Centre for Rail Traffic Research. Selected analyzed data emphasizes the potential of a combined load–response analysis of the measurement data for monitoring railway bridge condition by means of trend-based evaluation. In this context, it is to be mentioned that this combined analysis has to be carefully performed and should consider to distinguish between critical and non-critical effects, such as environmental related changes.

Acknowledgements

The authors would like to express their gratitude to DB InfraGO (Network Cottbus and Network Leipzig) and to BB-Konrad GmbH, Leipzig, for their support. It is only through the successful collaboration between contractors, clients, the infrastructure operator, and third parties that the collection of cross-sector data has been made possible. This project represents the first infrastructure-related project within the Open Digital Test Field of the German Centre for Rail Traffic Research.

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Take it to the bridge – drive-by monitoring to assess railway bridge and track dynamics

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Keywords: Drive-by monitoring; bridge accelerations; bridge transitions; track geometry; digital shadows

1. Introduction

Vehicle-based track monitoring systems such as the Continuous Track Monitoring system (CTM 2.0), developed by DB Systemtechnik GmbH, have been successfully deployed for over two decades. Using axle box accelerometers on scheduled trains, they continuously assess track geometry across the network according to DIN EN 13848. However, bridges represent neuralgic points for railway infrastructure: their transition zones are particularly susceptible to ballast deterioration and differential settlement, with maintenance frequencies up to eight times higher than on open track (Wang and Markine, 2019). At the same time, increasing axle loads and new train configurations place growing dynamic demands on aging bridge structures (Karimi, 2020, Firus et al., 2018). With an average age of 122 years (Knapp, 2019), many of these structures are operating close to their expected service life and design limits. Drive-by monitoring, in which sensors on passing vehicles are used to assess infrastructure condition (Yang et al., 2004), offers a scalable approach to address both challenges.

This raises the question of whether measurements already collected on trains, can be leveraged more effectively, not only for track geometry but also for assessing bridge dynamics and monitoring the condition of bridge transition zones. This contribution presents recent advances in two complementary directions that address this question: (i) the indirect monitoring of bridge transition zones using CTM 2.0 data (Rupp et al., 2024), and (ii) code compliance checks, such as the estimation of maximum bridge accelerations, from on-board axle box measurements (Lorenzen et al., 2024). Building on these results, an outlook is given on a DFG-funded project that integrates drive-by monitoring into digital shadow models for the prediction of bridge responses across different train types.

2. Monitoring bridge transitions with existing track measurements

The CTM 2.0 system was originally designed for track quality assessment, but as bridges represent critical points within the track system, the question arises whether the same measurements can capture deterioration in bridge transition areas. A case study on a tied-arch steel bridge (span 77.5 m) demonstrated that this is indeed the case. No hardware modifications to the CTM system were necessary (Rupp et al., 2024).

In the transition area of this bridge, a white spot caused by defective drainage was identified during an on-site visit. The spot was monitored both directly, using a sleeper-mounted accelerometer recording over 85,000 train crossings, and indirectly, through 71 CTM crossings in the affected direction. The max-min spans of vertical track geometry, extracted from the CTM data, showed a clear increase over time interrupted by step-wise improvements after tamping operations. Both the time span between tamping cycles (slightly more than one year) and the magnitude of deterioration (approximately a factor of 3) were consistently captured by the indirect CTM monitoring and the direct sleeper measurement. This demonstrates that the existing track monitoring infrastructure can serve a dual purpose: assessing track geometry and detecting bridge transition deterioration at network scale.

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3. From track geometry to bridge accelerations

While the CTM system effectively captures track geometry changes at bridge transitions, assessing the dynamic response of the bridge structure itself requires a different approach. To ensure ballast stability, the Eurocode limits maximum vertical bridge accelerations to 3.5 m/s². Monitoring compliance with this limit across the network using bridge-mounted sensors would be impractical; a vehicle-based approach is therefore desirable.

Extracting bridge response quantities from on-board measurements is, however, not straightforward. Vertical displacements inferred from vehicle measurements are very small in magnitude for typical short- and medium-span bridges, making them difficult to use as a stand-alone monitoring criterion. Accelerations are considerably more sensitive to the bridge’s dynamic behaviour, but they are inherently affected by speed-dependent track irregularity effects: the same track defect produces different acceleration amplitudes at different speeds, masking the bridge’s own response.

The key to isolating the bridge contribution lies in using residual signals derived from two axles. Because both axles experience the same track irregularities at the same speed, subtracting the phase-shifted signal of a preceding axle from the current axle’s signal effectively cancels the common track input. The residual then predominantly contains the bridge's dynamic response, which differs between axles due to the evolving vibration state of the structure. The field experiments presented here show that already a single additional instrumented axle significantly extends the analytical capabilities beyond what current single-axle CTM configurations can provide, enabling bridge acceleration estimation alongside track geometry assessment.

The methodology was initially validated in two field campaigns on steel trough bridges (spans of 19.5 m and 16.4 m) with a 12-car ICE 4 (52 crossings) and a 4-car ICE TD (12 crossings), respectively. In both cases, synchronized accelerations were recorded on the bridge and on the train, allowing direct comparison. The results show that the estimation error of the residual-based approach decreases with increasing bridge acceleration amplitude. At resonance-inducing speeds, where accelerations are highest and thus most relevant for code compliance, mean absolute percentage errors of approximately 22 to 24% were achieved (Lorenzen et al., 2024). This is promising for screening applications, as the critical states near the regulatory threshold are captured with acceptable accuracy.

4. Outlook: towards comprehensive vehicle-based bridge monitoring

Beyond the two initial field campaigns, further experiments have been conducted with in total three instrumented ICE trains (ICE 4, ICE TD, and ICE L) on a total of five bridges covering two structural types: two tied-arch bridges and three steel trough bridges. These datasets, which capture a range of span lengths, structural behaviours, and train configurations, form the experimental basis for a current DFG-funded project.

In this project, resonance information identified from drive-by measurements is used to calibrate and update bridge models, constructing digital shadows of individual structures. These digital shadows then enable the prediction of structural responses for different train types, supporting the assessment of new rolling stock, verification of acceleration limits, and long-term maintenance planning.

A key requirement emerging from this work is the availability of acceleration data from at least two axles per bogie. Current track monitoring systems typically instrument only a single axle box, which is sufficient for track geometry assessment but does not allow the formation of residual signals needed for bridge acceleration estimation. Notably, many modern rolling stock vehicles are already equipped with axle box accelerometers on multiple or even all axles for vehicle control and running gear diagnostics purposes. These sensors are, however, generally not utilised for infrastructure monitoring. Unlocking this existing sensor infrastructure for bridge monitoring would be a cost-effective path towards comprehensive, fleet-wide assessment of bridge dynamics during regular train operations, turning every suitably instrumented train into a mobile bridge monitoring system.

5. Conclusion

This contribution has shown that vehicle-based measurements, already established for track geometry monitoring, can be extended to address two critical aspects of railway bridge management. First, the existing CTM 2.0 system can reliably detect ballast deterioration in bridge transition zones without any system modifications. Second, residual signals formed from two instrumented axles enable the estimation of bridge accelerations with sufficient accuracy for screening purposes, particularly in the critical high-amplitude regime. With field data from five bridges and three ICE train types now available, the ongoing DFG-funded project builds on a broad experimental foundation to develop digital shadow models of the railway bridge network. Ultimately, existing multi-axle sensor installations on modern rolling stock could enable fleet-wide bridge monitoring, complementing established track geometry assessment with structural dynamics evaluation at network scale.

Acknowledgements

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MS04: Load testing of bridges

Organizers:
Gregor Schacht (MKP GmbH, Dresden, Germany)
Oliver Mosig (MKP GmbH, Dresden, Germany)
Eva Lantsoght (Delft University of Technology, Netherlands)

ABSTRACT

The use of load testing to prove the bearing capacity of structures is as old as the humankind and played an important role in the early years of bridge construction. Loading tests proofed the bearing strength obviously for everybody and therefore they were likely used to convince the people of the bearing capability of bridges. With the development of static calculations and of acceptable design rules, load testing became unnecessary for new structures. Since the evaluation of existing structures becomes more and more important the advantages of experimental assessments are used. Load testing is today and effective tool for the evaluation of the bearing safety of older bridges. This Mini Symposium shall determine the state of the Art of load testing and show the potential of an experimental evaluation for the structural reliability.

Advancing SHM of bridges: the deformation and strain area difference methods

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Abstract

The safety and serviceability of bridge infrastructure are increasingly challenged by aging structures, rising traffic demands, and limited maintenance resources. Structural Health Monitoring (SHM) provides a data-driven framework to address these issues, yet many established methods face limitations in precision, cost-efficiency, or scalability. This paper summarizes recent research on advancing static load-based SHM through the Deformation Area Difference (DAD) method and its extensions. The DAD method detects damage by comparing the measured deformation line under static loading to an undamaged reference supported by finite element reference models. Through parametric analyses and field studies, this work identifies key limitations related to deflection magnitudes, noise sensitivity, and measurement point density, introducing the concept of Damage Detection Range (DDR) to quantify applicability. To overcome noise constraints and low-deflection scenarios, the Strain Area Difference (SAD) method is proposed, leveraging curvature analysis calculated from measured strains. Laboratory experiments and bridge-scale case studies confirm its robustness and precision. Finally, the integration of model updating techniques enables assessment not only of damage location but also of severity, extending SHM capabilities toward predictive maintenance. Field validations on steel and composite bridges demonstrate the applicability of these methods using modern measurement technologies, including UAV-based photogrammetry. Collectively, these contributions establish a reliable and scalable SHM framework that bridges the gap between academic methods and practical infrastructure monitoring.

Keywords: Structural health monitoring (SHM), bridges, deformation area difference (DAD), strain area difference (SAD), model updating, levels of SHM

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

Integration of IoT-based SHM in bridge load testing: field applications in Italy

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Abstract

Bridge load testing involves the application of controlled actions on a structure, providing essential support for design verification and analytical model validation to evaluate its performance. Structural Health Monitoring (SHM) systems play a crucial role by enabling continuous and synchronized measurements of structural response both static and dynamic through distributed sensor networks. This paper presents the industrial implementation of continuous IoT-based data acquisition using a network principally composed by MEMS accelerometers and clinometers applied to different bridges throughout the structural life cycle. Several real-world applications, located in northern and central Italy, are discussed to demonstrate the SHM and IoT technologies combined for practical bridge assessment. The first case study examines a proof loading test conducted on a newly constructed steel-concrete composite single-cell box girder bridge comprising 21 spans. In this case, the structure is continuously monitored from the construction phase. A second group of case studies explores the systematic use of diagnostic load testing across a network of more than 50 existing concrete bridges. Automated procedures, mobile applications, and algorithmic data processing were employed to guide on-site operations and to develop model updating procedures in nonlinear FEMs through the simulation of damage scenarios and model-driven thresholds definition. Finally, an additional case study addresses the partial demolition of a carriageway of a PRC bridge with reinforcing steel arches. Diagnostic load tests were performed both before and after the intervention to verify the static and dynamic response of the remaining structure, still open to traffic. The results show how the continuous SHM, IoT network and automated analytical tools enable a more efficient and reliable structural evaluation.

Keywords: SHM; bridge; continuous monitoring; proof loading test; diagnostic load test; model updating; MEMS

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Static distributed fiber optic measurements on prestressed concrete bridges

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Keywords: distributed fiber optic strain sensor; prestressed concrete structure; structural health monitoring; Rayleigh scattering; wire break

1. Motivation

The integration of distributed fiber optic sensors (DFOSs) into prestressed concrete bridges represents a promising advancement in infrastructure monitoring. DFOSs provide continuous, high-resolution, and spatially resolved measurements of strain and temperature, making them particularly suitable for monitoring critical components in prestressed systems. They can be seamlessly integrated into new bridge constructions at relatively low additional cost, enabling structural monitoring to begin as early as the construction phase. Furthermore, DFOSs offer the unique ability to detect and localize damage that remains invisible to conventional visual inspection methods. These advantages position DFOSs as a valuable technology for enhancing the long-term safety, reliability, and digitalization of bridge infrastructure.

This research demonstrates the potential of static distributed fiber optic strain measurements conducted along DFOSs embedded in newly constructed prestressed concrete bridges. The applications include load testing and controlled damage induction of the prestressing strands.

The measurement results presented herein provide insights into the application-specific sensitivity of Rayleigh-based measurement methods, with consideration of the position and configuration of the embedded DFOSs.

2. Methodology

The analysis of the measurement results in this study focuses on key findings from a representative subset of DFOSs embedded in two prestressed concrete bridges, with their layouts and spatial arrangement schematically shown in Fig. 1 and Fig. 2a.

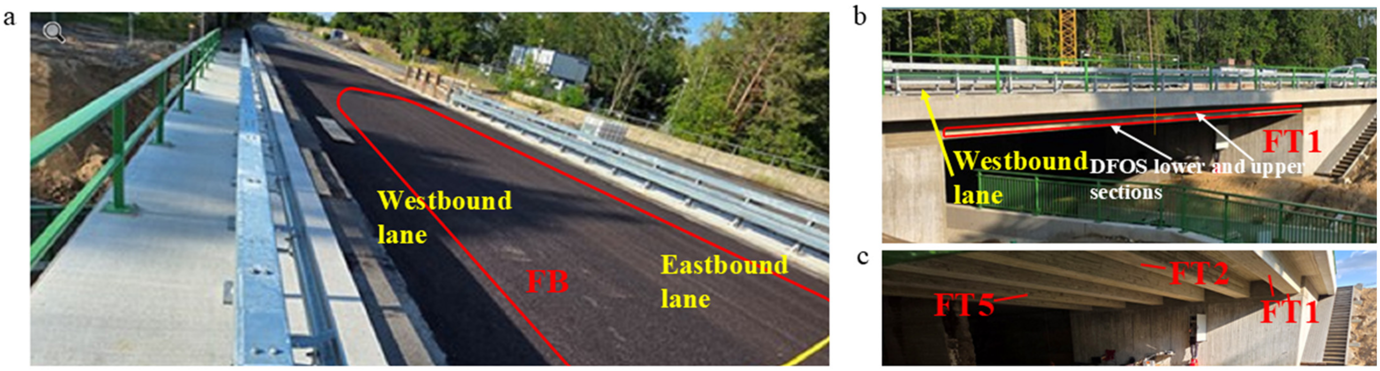

Fig. 1. Hubertus bridge showing the schematic placement of the selected sensing cable loops embedded (a) in the deck slab (b) and in the precast girder FT1; (c) Location of the girders with sensing cable loops selected for the load test.

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The first bridge (see Fig. 1) is the BW2, known as the Hubertus bridge, located along the A117 motorway at the southeastern border between Berlin and Brandenburg. The second bridge (see Fig. 2) is the openLAB research bridge constructed within the IDA-KI research project, with its structural details presented by Herbers et al. (2024).

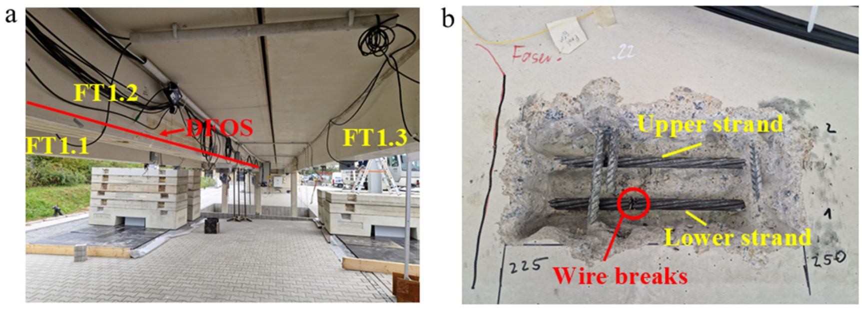

Fig. 2. (a) Underside view of the openLAB bridge with the DFOS embedded centrally at the bottom of the middle girder FT1.2; (b) Wire breaks in the lower strand on the side of FT1.2 not visible in view (a) – position O1.

The first part of the measurement results presented in Section 3 refers to a load test carried out with a 36-ton mobile crane on the Hubertus bridge, which applied a static load at three positions on westbound lane - at one quarter of the bridge length (Position 1/4), at mid span (Position 2/4), and at three quarters of the bridge length (Position 3/4). The load-induced strain response of the bridge structure was recorded as high-resolution distributed strain profiles along the sensing fibers using a frequency-domain optical backscatter reflectometer, following the measurement principle described by Samiec (2012). Since predictive maintenance, as mentioned by Wimmer and Braml (2023), requires data from the very beginning of a bridge structure's lifetime, these measurements constitute an initial basis for long-term monitoring.

The remaining results presented below pertain to destructive tests in which prestressing strands were cut at two positions on either side of the FT1.2, with a longitudinal offset of 1.5 m. In this case, the distributed structural strain response was measured using the tunable-wavelength coherent optical time-domain reflectometry (TW-COTDR) method, which is detailed by Delepine-Lesoille et al. (2013).

3. Findings and key outcomes

Fig. 3 shows the development of strain profiles under static loading at the previously described bridge locations, obtained from sensor loops embedded within different structural components.

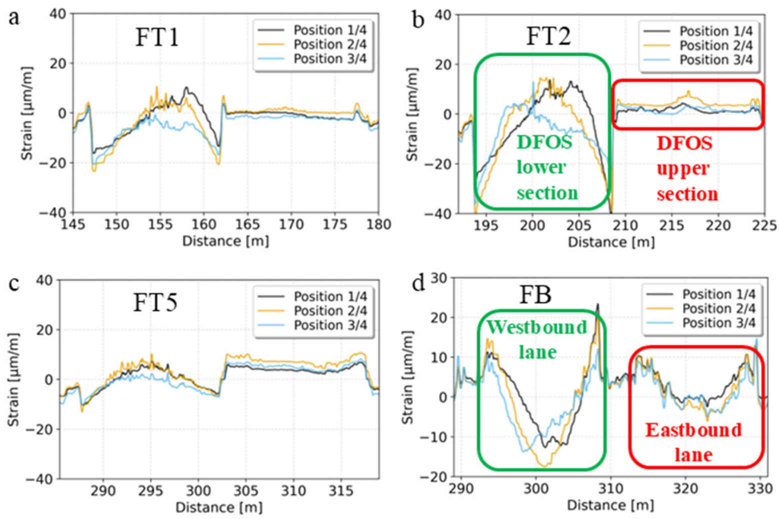

Fig. 3. Load-induced strain profiles measured by DFOSs in (a-c) the girders (d) and the deck slab.

Fig. 3(a-c) depict how sensor sensitivity varies with their placement in different girders. Across all girders, the load-induced strain response of the DFOSs shows sufficient sensitivity in the respective installation-induced prestressed lower sensor section (cf. Fig. 1(b)), even though this section is located roughly 60 cm farther from the load application points than the upper sensor section. Fig. 3 (d) illustrates the capability to accurately localize the point of load application when sensing cables are embedded in the deck slab in proximity to the loading area, here the westbound lane. All measured strain profiles presented in Fig. 3 demonstrate a distinct correlation between the recorded strain values and the horizontal distance between the embedded DFOSs and the load application location.

Fig. 4 shows the evolution of the strain profiles along the DFOS during the progressive cutting of the prestressing strands, as summarized by the events listed in Table 1. All damage-inducing events were clearly detected and accurately localized.

Table 1. Overview of the damage events applied to the openLAB bridge at their respective measurement times in chronological order

	Structural condition of the openLAB bridge during measurement
meas1	After cutting all seven wires in the lower strand at position O1 (see Fig.2(b))
meas2	After further cutting of all seven wires in the upper strand at position O1
meas3	After further cutting of all seven wires in the upper strand at position O2
meas4	After further cutting 3 of the 7 wires in the lower strand at position O2
meas5	After further cutting of the remaining four wires in the lower strand at position O2

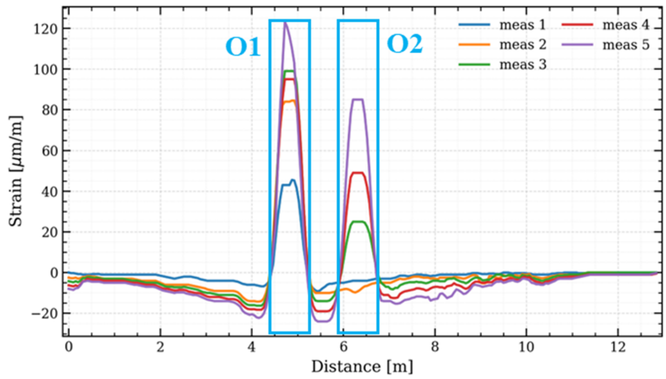

Fig. 4 Strain response observed during the destructive cutting of the prestressing strands.

4. Conclusion

The functionality of DFOSs, employing two correlation-based techniques that analyze Rayleigh backscatter fingerprints for distributed strain sensing, has been demonstrated in identifying and localizing static load conditions on a real bridge as well as in the detection of wire breaks. Both Rayleigh-based measurement methods demonstrate sufficient strain sensitivity and can be used interchangeably, depending on the desired trade-off between sensing range, spatial resolution and measurement duration, according to their characteristics as summarized in Table 1 by Monsberger and Lienhart (2021). Accordingly, DFOSs represent an alternative for measuring structural deformations compared to conventional methods such as digital image correlation discussed by Pirskawetz et al. (2023), offering advantages in terms of robustness and long-term monitoring.

Acknowledgements

The authors would like to acknowledge the financial support offered by the Federal Ministry of Transport (BMV), Germany, within the mFUND funding program for the research project 'FOSsure' (grant no. 19FS2075D).

The authors gratefully acknowledge Autobahn GmbH des Bundes for their trust and for commissioning the research activities on the integration and evaluation of sensor systems (DFOS, RFID, Coda Wave Interferometry) as part of the replacement construction of bridge structure BW2 along the A117. The current work places particular emphasis on cost-effectiveness analysis, durability, ease of installation, and data management.

We extend our sincere thanks to Company Hentschke Bau GmbH for their organizational and technical support in conducting the measurements on both bridges. We also thank the Institute of Concrete Structures at TU Dresden for planning and coordinating the destructive tests on the openLAB bridge.

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SMAR 2026

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Assessment of applied tension on high strength steels by X-ray diffraction (XRD) and magnetic Barkhausen (MBN)

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Keywords: Post-tensioned cables, non-destructive methods, X-Ray diffraction, Barkhausen noise, stress measurement, special inspections

1. Introduction

Prestressed reinforced concrete structures may be subject to reduction of their bearing capacity and safety with the progressive degradation of the prestressing system, either determined by decay of the prestressing state or by corrosion. Therefore, measurement of the existing stress state is an important information in structural condition assessment. The measurement of the actual state of stress is, up to date, carried out mainly using destructive techniques such as stress release by wire cutting that, however, cannot be extensively or periodically used, Zanini et al. (2022). This technique was used to assess the stress state of decks at La Guardia Airport in 1996. It was considered very promising, but difficult to use in the civil engineering field due to the instrumental dimensions, Carfagno et al. (1996). In 2021, as part of the initiatives undertaken in Italy following the collapse of the Morandi Bridge in Genoa, evaluation tests of the XRD technique were conducted both in laboratories and onsite at selected bridges, Gennari Santori et al. (2024), Chiaia et al. (2023), Zanini et al. (2022), Mazzatura et al. (2023).

XRD, as recommended method to assess stress state, is already mentioned in some Italian national protocols, such as: https://www.piarc-italia.it/wp-content/uploads/2023/12/Quaderno-CT-4.2-127-pp.pdf
www.mit.gov.it/nfsmitgov/files/media/normativa/2020-12/8_All_D_Scheda_ispezione_speciale.pdf

Due to the necessity to have a more compact system to optimize measurement in bridges, a project was subsequently commissioned to further miniaturize the instrument for field use. SPIDER EDGE P miniaturized XRD has been used for the tests reported in this work and is currently in use by some Companies in field measurements, Gennari Santori et al. (2024), Chiaia et al. (2023), Zanini et al. (2022), Mazzatura et al. (2023). Even if XRD has to be considered as the preferential method to assess the stress state, to overcome some limitations due to the use of ionizing radiations and measurement speed, an alternative method based on Barkhausen Noise, Rautiohao et al. (1994), Behleda (2021) is being evaluated, verifying its agreement with XRD readings both in laboratory and in field measurements.

2. X-ray diffraction (XRD)

X-ray diffraction (XRD) is a non-destructive technique used to measure residual stresses in polycrystalline materials by using the crystal lattice as an internal strain gauge and it is based on Bragg's law (1). This law states that when a material is under stress, the inter-planar spacing of atoms d changes. An X-ray beam of wavelength λ incident with angle θ undergoes constructive interference when, being n an arbitrary integer,

$$n\,\lambda = 2\,d\,\sin(\theta) \quad (1)$$

The change in d-spacing causes a shift in the diffraction angle θ.

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XRD measures θ corresponding to constructive interference and determines the inter-planar spacing d. By measuring the shift in the diffraction angle compared to a stress-free sample (e.g. iron powder with inter-planar spacing of atoms d_0) the variation $d - d_0$ can be measured and the strain ε can be calculated by

$$\varepsilon = \frac{d - d_0}{d_0} = \frac{\Delta d}{d_0} \quad (2)$$

Knowing the Young's modulus and Poisson's ratio of the material under test, it is possible to determine the corresponding stress. The output of XRD is the stress in the material, that includes both applied mechanical stress and fabrication residual stress.

3. Barkhausen effect

Barkhausen effect is the phenomenon of discontinuous, stepwise changes in the magnetization of a ferromagnetic material when subjected to a slowly changing external magnetic field. Internal mechanical stresses significantly influence the Barkhausen effect through magnetoelastic coupling (or magnetostriction), which alters how magnetic domains respond to an external magnetic field. For materials with positive magnetostriction, like low carbon steels, the domain walls move more easily along the stress direction in case of tensile stress, increasing the signal amplitude and energy. In case of compressive stress, a decrease in signal amplitude and energy is observed.

Opposite behaviour is observed in case of pearlitic steels / high eutectoid steels like harmonic steel normally used for pre- and post-tensioning. For these steels, having negative magnetostriction, the signal decreases with the increment of the applied load. R. Rautiohao et al. (1994); Neslušan et al. (2019).

4. Experimental tests

To illustrate typical XRD readings, a 7 wires strand 15.2 mm of diameter was mounted on a tensile machine and loaded at different incremental loads. XRD measurements were done holding the load constant during the measurements. Results are reported in Table 1, where plain XRD readings is reported along whith the reading depurated from residual fabrication stress. The residual fabrication stress can be either known for the steel under testing or can be measured by XRD either on a mechanically unloaded sample or by varying the applied stress in the linear material range and measuring the observed offset from the expected linear stress-strain relation as reported in the following. In the sample of Table 1 and Fig. 1 the residual manufacturing stress RS is equal to 170 MPa.

Table 1: Applied stress vs. XRD readings and XRD readings minus residual fabrication stress RS.

Applied stress (MPa)	XRD measured (MPa)	XRD – RS (MPa)
0.0	177	0
65.5	189	12
363.8	421	244
727.6	690	513
1091.3	897	720
1273.2	1062	885

a

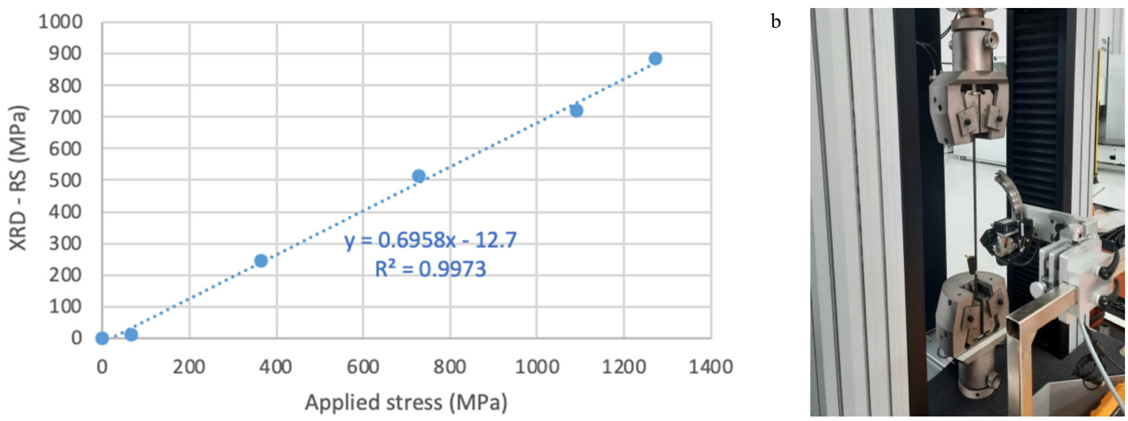

Fig. 1. (a) XRD readings versus applied stress; (b) instrumental setup.

The correlation between applied and measures stress by XRD is reported in Fig. 1. It can be noticed that the expected linear trend is very well captured although an increasing difference of the applied vs. measured stress is observed when loading is increased. This aspect is under investigation, but can easily accounted for in measurements due to the perfectly linear correlation.

Several test measurements by MBN have been performed on wires of different diameter and a 7 wires strand in order to validate this technique in the measurement of known stress states. Measurements have been done using a MAGSTRESS 5 Barkhausen noise instrument specifically designed for Stress measurements. By varying the applied stress, a nearly linear correlation has been observed between stress and MBN INT value (integral of the measured Barkhausen noise signal). To illustrate a typical correlation, Fig. 2a plots experimental results obtained on single wires of different diameter.

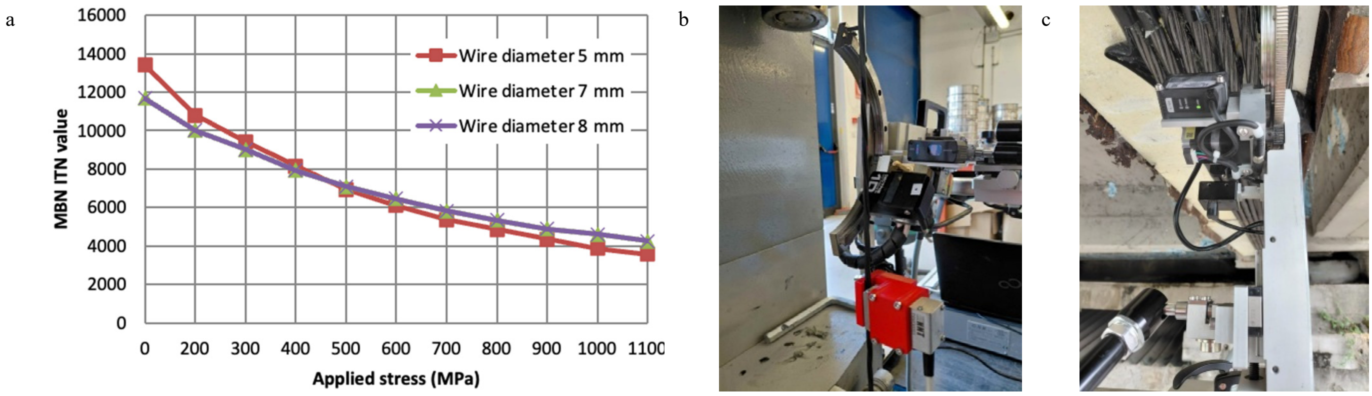

Fig. 2. (a) MBN readings vs. applied stress; (b) laboratory test setup for MBN and XRD; (c) XRD and MBN field setup.

Following the promising laboratory test results, field measurements have been successfully conducted and others planned in a near future using both methods. A field measurement setup is reported in Fig.2b.

5. Conclusions

While the use of XRD is a proven methodology for measuring existing tensile stress in prestressing steel, an experimental campaign has proven that MBN, properly calibrated, can yield results of the same accuracy level as XRD. The two methodologies can therefore find a very good synergy, where XRD data are used for MBN calibration, but then, thanks to the incomparable higher speed of MBN measurements, a very high number of measurements can be taken. Typical applications foresee the rapid assessment of the stress state of many parallel or twisted wires and the periodic check of external prestressing systems against stress decay in time.

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Residual prestressing evaluation in HISCC-prone bridges: full-scale loading at Lingelbach

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Abstract

Hydrogen-induced stress corrosion cracking (HISCC), identified as the primary cause of the 2024 Carola Bridge collapse, underscores the urgent need for advanced assessment methods for aging prestressed concrete structures. For the Lingelbach Bridge in Hessen – containing HISCC-susceptible prestressing steel – analyses showed that the 'crack-before-break' criterion of the German HISCC guideline could not be satisfied due to the bridge's high stiffness-to-span ratio and the resulting high cracking moments. A full-scale loading test was therefore planned to experimentally determine the residual prestressing reinforcement. The test concept involved incrementally increasing loads using self-propelled modular transporters (SPMTs), while the measuring concept consisted of fibre-optic sensors (FOS) attached to the bridge to monitor strain development and any onset of cracking throughout the structure. The experimentally derived prestressing reinforcement was intended to serve as the basis for a probabilistic verification of the 'crack-before-break' criterion. However, in-situ material investigations revealed an unexpectedly high concrete tensile strength, implying that cracking would only occur at substantially higher load levels than anticipated. To avoid potential structural or equipment damage, the planned loading test was ultimately cancelled. Despite this outcome, the methodology demonstrates the considerable potential of integrating analytical, probabilistic and experimental approaches and offers valuable insights for the assessment of complex, safety-critical bridge structures.

Keywords: Residual prestressing reinforcement; hydrogen induced stress corrosion creacking (HISCC); full-scale bridge loading

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

Load test on the Elbe bridge Bad Schandau

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Abstract

After the collapse of the Carola Bridge in September 2024, similar bridges were subjected to special inspections. As a result, the Elbe bridge Bad Schandau was closed due to the detection of cracks and the use of susceptible to stress corrosion cracking prestressed steel. Extensive diagnostic and structural analyses were carried out, and comprehensive monitoring measures were installed to observe the behavior of the bridge and possible deterioration processes, including acoustic emission monitoring (AEM) and distributed fiber optic sensors (DFOS).
A load test was carried out to evaluate the resistance of the bridge and to determine the remaining prestressing force. The structural reactions were recorded and evaluated. None of the limit criteria were reached during the test. The evaluation showed sufficient load-bearing capacity, so that the bridge could be approved for compensated traffic.

Keywords: Prestressed concrete; stress corrosion cracking; load test; DFOS; AEM

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

Hybrid monitoring approach for structural assessment of the Nibelungen Bridge (Worms)

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Abstract

The Nibelungen Bridge in Worms is one of the earliest prestressed concrete bridges constructed using the balanced cantilever method. As part of a digital preservation strategy, a hybrid monitoring system and a load-testing campaign were implemented to support service-life extension. The paper presents selected results from load tests focusing on global structural behavior and the integrity of shear-critical regions. The monitoring concept combines a hydrostatic leveling system, total station measurements, and distributed fiber optic sensing. The measured deformed shape agrees well with the expected structural response. Measured displacements were smaller than predicted by the nonlinear FE model at low load levels and approached the calculated values with increasing load, indicating a stiffer structural behavior. Distributed strain measurements confirmed the absence of relevant cracking in the web regions. The results are a basis for FE model calibration and contribute to the bridge's ongoing service-life extension.

Keywords: Bridge load test; civil structural health monitoring; distributed fiber optic sensing; shear monitoring

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

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Experimental study of ambient vibration based structural health monitoring of bridge girder

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Keywords: Ambient vibration; modal vectors; operational modal analysis

1. Introduction

Civil engineering infrastructure is generally designed for a service life of 50-100 years, during which structural integrity, stability, and functionality must be maintained. However, increasing traffic demands, infrastructure expansion, industrialization, population growth, and the growing frequency of extreme environmental events associated with climate change subject these structures to higher stress cycles than originally anticipated. The accumulation of damage over time can significantly reduce structural durability, reliability, and service life, potentially leading to unexpected failures. Consequently, Structural Health Monitoring (SHM) has emerged as an indispensable tool for ensuring the safety, durability, and long-term performance of civil engineering infrastructure through timely detection of deterioration and the implementation of appropriate maintenance strategies.

Fig. 1. (a), (b) Catastrophic failure of bridges; (c) distress in bridge deck.

SHM provides a systematic framework for evaluating structural condition by continuously monitoring changes in dynamic characteristics, particularly stiffness and damping, whose degradation often indicates damage caused by fatigue, material aging, or environmental effects. In bridge engineering, SHM facilitates early identification of structural anomalies, enabling preventive maintenance and minimizing the risk of catastrophic failure. Among the available dynamic assessment techniques, Ambient Vibration Testing (AVT) combined with Operational Modal Analysis (OMA) has gained recognition as a reliable, non-destructive approach for identifying modal parameters under operational conditions without interrupting service. The present study investigates the dynamic response of a reinforced concrete (RCC) T-girder bridge subjected to repetitive cyclic loading under laboratory conditions. Variations in natural frequencies and mode shapes extracted through OMA are used to evaluate structural degradation. The findings demonstrate AVT-based OMA effectively detects structural damage and demonstrates practical applicability.

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2. Methodology and experimental study

The experimental investigation may be divided four parts as follows:

- Dynamic testing of the RCC T-girder to acquire response data in time domain with AVT adopting roving accelerometer.
- Post processing of the acquired data in frequency domain for Frequency Domain Decomposition (FDD).
- Extraction of modal data by curve fitting from FDD in the OMA Platform.
- To assess the subsequent effect of cyclic loading on the extracted modal parameters.

The deflection controlled cyclic loading is applied to the RCC T-girder using hydraulic press (HEICO make) after it is securely placed on loading platform using a chain-pulley system. Dynamic testing of the RCC T-girder by ambient vibration technique using the roving accelerometer (Brüel & Kjær make) setup to determine its natural frequency, mode shapes using OMA (Brüel & Kjær).

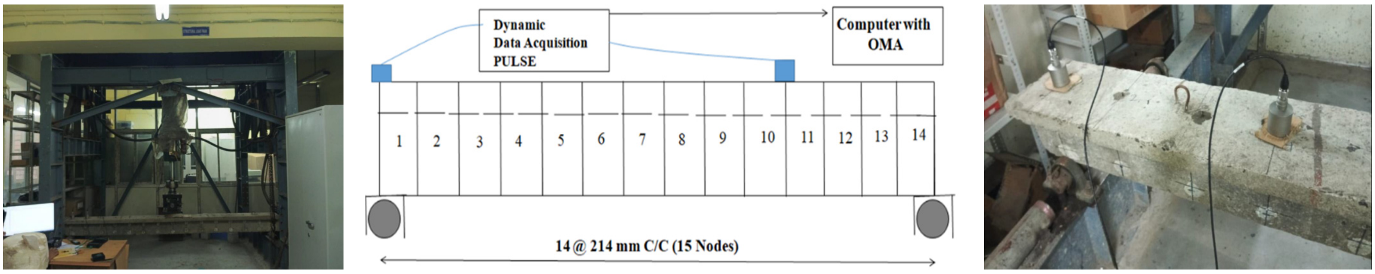
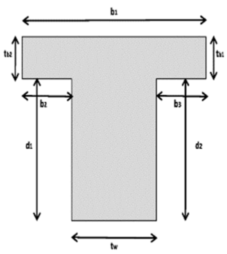


Fig. 2. (a) Experimental Set-up of cyclic load on the T Girder; (b) accelerometer locations for OMA; (c) data acquisition through seismic accelerometers.

The RCC T-girder is made up of M30 grade of concrete and Fe500 grade of steel; resting over two MS pipes and one edge of the beam is supported on hinge support made up of a cut piece channel and other end is placed initially on a plate later on freely horizontally movable channel to simulate the roller support. The beam is of 3000 mm length between the supports and 100 mm as overhangs at both sides. The span is discretized into 15 nos. of equidistant points to place the accelerometers for testing. All the details of the RCC T-girder specimen are presented below:

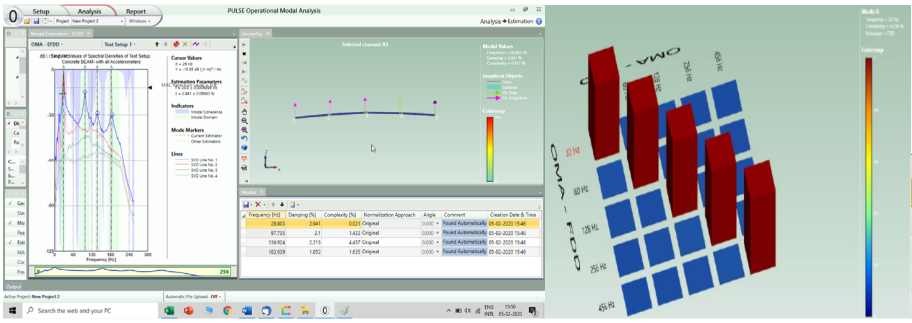


Node	B1(mm)	B2(mm)	B3(mm)	Tb1(mm)	Tb2(mm)	D1(mm)	D2(mm)	tw(mm)
1	255	60	63	53	53	172	170	127
5	257	62	64	50	53	173	173	124
6	256	60	62	50	54	175	175	123
8	260	62	61	49	55	170	174	122
14	260	61	62	51	55	170	174	125
15	257	60	65	50	52	170	175	124
Avg.	258	61	63	50	53	172	174	124

Fig. 3. (a) Cross-section of RCC T-girder; (b) measurement of dimensions of the T girder; (c) tuned roller support.

3. Extraction and interpretation of modal parameters

The extraction and interpretation of experimental data play a crucial role in ensuring the accuracy and reliability for a successful experimental study. The main steps for this study are as follows: i) Collection and preprocessing of Acceleration Time-History Data, ii) Application of the Enhanced Frequency Domain Decomposition (EFDD) technique in OMA Software, and iii) Modal Parameters Extraction. Subsequently, the identified modal characteristics are systematically compared between the undamaged and various damaged states of the structure to evaluate the influence of progressive damage on the dynamic response as shown below.



Frequency [Hz]	Complexity [%]	Normalization Approach	Angle	Comment
36	0.207	Original	0.000	
252.001	4.353	Original	0.000	Found Automatically
452.001	2.01	Original	0.000	Found Automatically
668.002	3.805	Original	0.000	Found Automatically
936.002	3.826	Original	0.000	

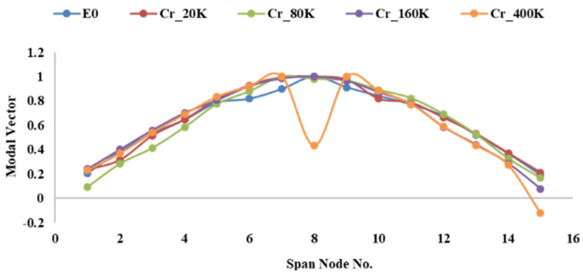
Fig. 4. (a) Modal Frequency Extraction using OMA software; (b) Checking for Modal Assurance Criterion; (c) typical table of extracted modal parameters.

4. Results and discussions

One RCC T-girder is subjected to strain-controlled cyclic loading, and its modal parameters are extracted using OMA based on AVT. Modal testing is performed after every 20,000 loading cycles under a two-point loading arrangement to produce a pure bending condition. Cyclic loading is applied using a servo-controlled actuator equipped with a load cell and LVDT. The loading amplitude is maintained at 1.5 mm deflection up to 220,000 cycles, followed by 2.0 mm up to 280,000 cycles, 2.5 mm up to 340,000 cycles, and 3.0 mm up to 400,000 cycles to induce progressive material deterioration. The first mode shapes at different loading stages (Fig. 5 (a)) exhibit an overall consistent pattern, indicating stable global structural behaviour. However, slight deviations become evident with increasing loading cycles, particularly near the mid-span after 400,000 cycles, suggesting the onset of internal deterioration. These variations may also result from measurement uncertainties, boundary condition imperfections, and experimental limitations. To quantify these changes, the variance of the first modal vectors with respect to the initial undamaged state is computed (Table 1). Despite a scatter is arising from uncertainties in OMA, AVT, and experimental boundary conditions; the overall trend (Fig. 5(b)) shows a progressive increase in modal variance with cyclic loading. The widening envelope between peak and trough values indicates nonlinear accumulation of structural deterioration. These findings confirm the sensitivity of first-mode modal parameters for detecting progressive damage in RCC T-girder bridges.

Table 1. Summary of the variance of modal vectors with the increasing of cyclic loading.

Cyclic Load	Mode Shape-1
20000	0.03361
80000	0.06541
160000	0.06163
240000	0.14000
400000	0.47984



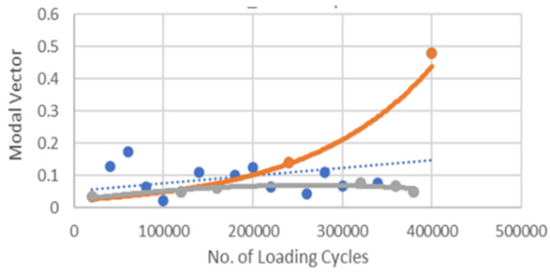


Fig. 5. (a) First mode shapes of RCC T-girder: undamaged and damaged states; (b) variance of 1st-mode experimental modal vectors under cyclic loading.

5. Conclusions

The variance of the modal vectors with respect to the initial unloaded condition effectively captures the influence of increasing cyclic loading. Although some randomness is observed due to uncertainties in the structural model, time-domain measurements, and modal parameter extraction using Operational Modal Analysis (OMA), the overall trend demonstrates a progressive increase in modal parameter variance with loading cycles. Minor fluctuations in the trend curves may also arise from measurement errors and variations in boundary conditions during testing. The lower vibration modes exhibit greater sensitivity to structural deterioration, indicating their suitability for detecting damage. The progressive increase in mode shape variance reflects the accumulation of stresses and the associated degradation of the RCC T-girder under repetitive loading. These observations confirm that mode shape characteristics successfully capture the changing dynamic behavior of the structure. This study demonstrates the effectiveness of Ambient Vibration Testing (AVT) combined with OMA as a reliable, non-destructive technique for structural health monitoring and damage assessment of bridge structures subjected to fatigue loading.

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

MS05: Research on shape memory alloys in Germany

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ABSTRACT

This Mini Symposium (MS) will highlight current research in Germany on shape memory alloys (SMA) with a focus on their microstructural behaviour and application potential. The first part will address the importance of microstructural-level studies, as the functional and mechanical properties of SMAs, such as damping behaviour, pre-stress magnitudes, and transformation-induced relaxation resistance, are strongly governed by features like grain size, precipitate distribution, and phase morphology. Tailoring these characteristics enables the design of SMAs suited for specific applications. The second part will focus on application-oriented research, showcasing how these microstructural insights are being translated into real-world uses. A special emphasis will be placed on the construction sector, where Fe-based SMAs are being investigated for innovative uses such as pre-stressing in civil engineering structures and damping applications, with additional attention to emerging uses in the medical field. This symposium aims to connect fundamental research with practical implementation, encouraging collaboration across academia, engineering, and infrastructure development. Although the MS is mainly targeting the research and development of SMAs in Germany, it also welcomes other international contributions and presentations to target a broader audience worldwide.

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

Recent research and applications of Fe-SMA in Germany and Europe

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Keywords: Fe-SMA; construction; Germany; applications in Europe; sustainability

Extended abstract

Iron-based shape memory alloys (Fe-SMAs), also known as Memory-Steel, have emerged as a highly promising class of smart construction materials for strengthening, prestressing, and rehabilitating civil infrastructure (Hilscher et al. 2025). Owing to their shape memory effect, Fe-SMA elements can be pre-strained and subsequently activated by heating under restraint, thereby generating recovery stress and introducing prestress into an existing structural member. In contrast to conventional prestressing systems, this enables comparatively simple and compact strengthening solutions, particularly attractive for rehabilitation of aging infrastructure and for interventions in geometrically restricted conditions. Fe-SMAs are cost-effective and fatigue-resistant technology with strong relevance to structural engineering in Germany and Europe.

Over the last decade, research activities across Europe have significantly advanced the understanding and application of Fe-SMAs in construction. Recent studies have addressed material development, thermomechanical characterization, constitutive understanding, activation strategies, and system-level implementation in concrete (Harmanci et al., 2024; Tabrizikahou et al., 2025), steel (Wang et al., 2021; Wang et al., 2024), composite (Qiang et al, 2026), and glass (Silvestru et al., 2022) structures. A major driver of this progress has been the development of Fe-Mn-Si-Cr-Ni-based alloys tailored for civil engineering, combining practical activation temperatures with high recovery stress and good compatibility with conventional steel construction. These material features, together with relatively low material and processing costs compared with other SMAs, have contributed to the increasing interest in Fe-SMAs as a structural strengthening material.

A particularly important line of research in Europe concerns strengthening systems for metallic and bridge structures. Mechanically anchored Fe-SMA strips and bars have been successfully applied to improve fatigue performance, reduce tensile stresses, and extend the service life of existing structures. Notably, field applications on bridges have demonstrated the practical feasibility of the technology, including the strengthening of a 113-year-old steel bridge (Vůjtěch et al., 2021) and a deficient steel–concrete composite bridge (Vůjtěch et al., 2025). These projects showed measurable reductions in tensile stress and deflection and confirmed the suitability of Fe-SMAs for real infrastructure under service conditions. In parallel, bonded Fe-SMA strengthening systems have gained increasing attention. Experimental studies on bonded Fe-SMA strips for steel beams and cracked metallic members showed stable prestressing action, effective force transfer, and even the potential for fatigue crack arrest (Wang et al., 2023).

Beyond steel structures, Fe-SMAs have also been investigated for reinforced concrete members, steel–concrete composite systems, and glass applications. Near-surface mounted and embedded Fe-SMA bars have shown strong potential for crack closure, flexural strengthening, and prestressing of concrete elements. In glass structures, bonded Fe-SMA strips have opened new possibilities for prestressed retrofitting, though temperature sensitivity of adhesive systems remains an important design consideration. Furthermore, emerging topics such as Fe-SMA couplers and the integration of Fe-SMAs into adaptive and additively manufactured systems indicate that the field is evolving from proof-of-concept studies toward multifunctional structural solutions.

Despite this progress, several research needs remain before broad implementation can be achieved. Among the most important are long-term durability under combined environmental and cyclic loading, prestress retention over the service life, corrosion and

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possible stress-corrosion effects, reliable modelling of the complex thermomechanical material response, and further standardization for design and execution. Addressing these challenges is essential for scaling Fe-SMA technologies from innovative case studies to routine engineering practice. Overall, recent developments in Germany and Europe demonstrate that Fe-SMAs are not only scientifically attractive but also increasingly practical for strengthening and lifetime extension of civil infrastructure. They therefore represent a promising pathway toward more resilient, adaptive, and sustainable construction.

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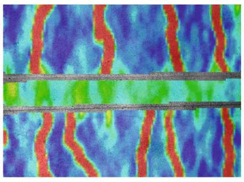

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Effect of pre-strain on recovery stress and its stability in Fe-Mn-Si-Cr-Ni-VC shape memory alloys

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Keywords: Iron-based SMAs; martensitic transformation; pre-straining; recovery strain; recovery stress; stress relaxation, cyclic loading

Preliminary note: *The results presented in this conference contribution are based on (Bauer et al., 2026).*

Shape memory alloys (SMAs) can recover their original shape after undergoing large deformation when heated above the transformation temperature. If this shape recovery is constrained, e.g., by a fixed anchorage of the SMA to a parent structure, stresses are introduced in the material that are referred to as recovery stress. The level of recovery stress determines the force transferred to the parent structure and therefore the prestressing effect that can be achieved. Iron-based shape memory alloys, particularly Fe-17Mn-5Si-10Cr-4Ni-1(V,C) (wt.%), therefore offer high potential for use as prestressing elements for the reinforcement and retrofitting of concrete and steel structures in civil engineering. For prestressing applications, both the magnitude of recovery stress and its stability under cyclic loading are of crucial importance. Previous studies have shown that activation temperature and pre-strain influence recovery stress formation, but most investigations have been limited to moderate pre-strain levels. In addition, the influence of pre-strain level, activation temperature, and initial recovery stress on stress relaxation under cyclic loading has not yet been systematically investigated.

To address this gap, the present study investigates the influence of pre-strain on transformation behavior, recovery stress formation, and its stability under cyclic loading in Fe-17Mn-5Si-10Cr-4Ni-1(V,C) shape memory alloys. Pre-strain levels between 1.6 % and 19.7 % and activation temperatures ranging from 160 °C to 400 °C were examined. The microstructural evolution with increasing pre-strain was analyzed using electron backscatter diffraction (EBSD). Recovery stress formation was studied for different activation temperatures, and strain-controlled cyclic loading was applied over 10,000 cycles to evaluate the stability of the recovery stress depending on pre-strain, activation temperature, and initial stress level. In addition, the reversibility of recovery stress losses was assessed by repeated thermal reactivation.

The results demonstrate that the final recovery stress is not solely determined by the extent of reverse transformation (hcp-ε to fcc-γ) during heating. Instead, recovery stress formation is significantly influenced by the transformation and plastic deformation processes that occur during cooling after activation. The critical factors limiting the maximum achievable recovery stress were identified as the resistance of the austenitic phase present at the activation temperature against renewed stress-induced martensitic forward transformation upon cooling, as well as the resistance to dislocation activity.

At low activation temperatures between 160 °C and 250 °C, recovery stress was almost independent of the pre-strain level and reached a plateau at moderate pre-strain levels around 6.6 %. However, as the activation temperature increased, the influence of the pre-strain level became more pronounced. Recovery stress increased by 43 % for a pre-strain level of 6.6 % and by up to 78 % for a pre-strain level of 19.7 %, corresponding to an increase from approximately 350 MPa at 160 °C to 625 MPa at 400 °C.

Higher pre-strain levels were also found to significantly improve recovery stress stability during cyclic loading, irrespective of the initial recovery stress level. Stress relaxation decreased from approximately 13 % at a pre-strain level of 1.6 % to about 7 % at 19.7 % pre-strain after 10,000 load cycles. Notably, similar relaxation behavior was observed for the 19.7 % pre-strained condition after activation at 160 °C and 400 °C, despite substantially different initial recovery stresses. Complementary EBSD analyses revealed an increased fraction of ε-martensite and higher kernel average misorientation values with increasing pre-strain, indicating

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an increased local dislocation density. The increased local phase stability associated with these dislocations is therefore identified as a key factor enabling higher recovery stresses while simultaneously enhancing their stability under cyclic loading.

Reactivation after 10,000 load cycles fully restored the initial recovery stress in all cases, independent of the pre-strain level, activation temperature, initial recovery stress, or extent of stress loss.

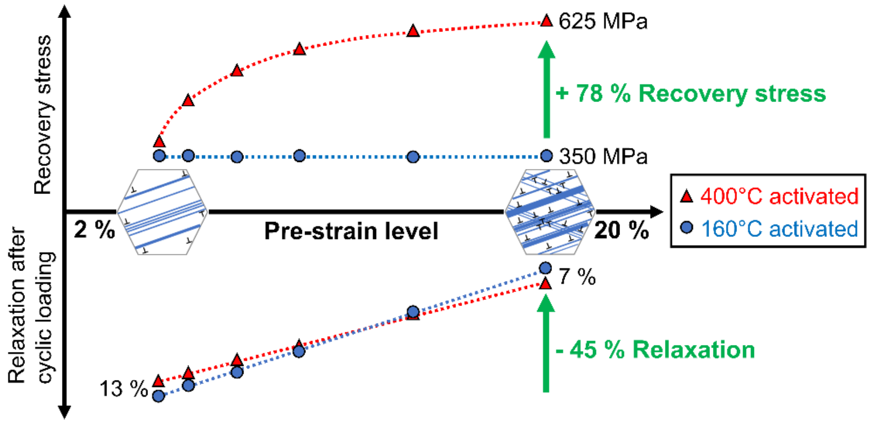

Fig. 1. Schematic illustration summarizing the effect of pre-strain on microstructural evolution, recovery stress formation, and recovery stress stability in Fe-17Mn-5Si-10Cr-4Ni-1(V,C) shape memory alloys.

From an application-oriented perspective, the results allow specific recommendations regarding the selection of pre-strain levels depending on the available activation temperature. If the activation temperature is limited to approximately 250 °C or below, moderate pre-strain levels around 6.6 % are sufficient, providing the highest recovery strain and nearly maximal recovery stress. Under these conditions, higher pre-strain levels mainly improve the stability of the recovery stress. If the activation temperature is not restricted, for example in steel constructions or coupling systems, higher pre-strain levels of up to approximately 20 % offer substantial benefits, enabling significantly higher and more stable recovery stresses. Moreover, the prestressing force can be further increased after initial installation through reactivation at higher temperatures, opening up new possibilities for smart adaptive structural systems.

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Influence of recovery stress level and loading amplitude on the fatigue behavior in iron-based shape memory alloys

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Keywords: Iron-based shape memory alloy, recovery stress, fatigue, pre-stressing

Extended abstract

Preliminary note*: The results presented in this conference contribution are based on (Bauer et al., 2026).*

Iron-based shape memory alloys (Fe-SMAs) are increasingly used in civil engineering applications to introduce prestressing forces into existing structures such as reinforced concrete or steel members. The prestress is generated through thermally activated recovery stress, enabling a highly efficient and installation-friendly strengthening technique. In practical applications, Fe-SMA elements can be subjected to cyclic service loading while maintaining a high mean stress level originating from the recovery stress. As a result, relatively large stress ratios can occur, often reaching values up to $R \approx 0.7$. Recent developments have demonstrated that recovery stress levels can be significantly increased, in some cases exceeding 600 MPa. While this enhances the achievable prestressing effect, it simultaneously increases the mean stress level and thus alters the fatigue-relevant loading conditions. Despite the growing interest in maximizing recovery stress, the interaction between prestress level, cyclic loading and fatigue behavior remains insufficiently understood.

This ongoing study addresses this gap by systematically investigating the influence of cyclic strain range and pre-strain level on the evolution of recovery stress under fatigue loading. By linking cyclic stress response and relaxation behavior, the work provides insights relevant for the fatigue design of prestressed Fe-SMA elements.

Thermomechanical tests were performed using a servo-hydraulic testing system equipped with a high-temperature extensometer. Specimens were pre-strained to different levels (1.6 %, 4.9 %, and 19.7 %) prior to activation. After unloading, thermal activation was carried out under strain-controlled conditions to generate recovery stress. A constant preload was applied to ensure stable boundary conditions during heating. Activation temperatures of 160 °C, 300 °C and 400 °C were investigated. Heating and cooling were performed at constant rates, and temperature was monitored directly at the specimen surface. Following activation, strain-controlled cyclic loading was applied with strain ranges between 0.055 % and 0.165 % for up to 10,000 cycles. These loading conditions correspond to stress ranges and mean stress levels representative of prestressed Fe-SMA elements subjected to service loads.

Thermal activation resulted in recovery stress levels strongly dependent on the applied pre-strain and activation temperature. For high pre-strain levels, recovery stresses approaching the upper range relevant for structural applications were achieved. The resulting stress state after activation corresponds to a high mean stress level, which forms the baseline for subsequent cyclic loading. This directly defines the effective stress ratio during service loading and highlights the importance of recovery stress stability for fatigue design.

Under strain-controlled cyclic loading, a pronounced reduction in recovery stress was observed during the initial loading phase. For all investigated strain ranges, the majority of the stress loss occurred within approximately the first 100 cycles, after which the stress level stabilized. A clear and systematic dependency on the applied cyclic strain range was identified. Increasing the strain

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range from 0.055 % to 0.165 % resulted in a nearly proportional increase in the initial recovery stress drop. The absolute stress loss within the first 100 cycles ranged approximately from:

- ~40–50 MPa for $\Delta\varepsilon = 0.055$ %
- ~70–90 MPa for $\Delta\varepsilon = 0.11$ %
- ~100–130 MPa for $\Delta\varepsilon = 0.165$ %

This indicates a quasi-linear relationship between cyclic strain range and initial recovery stress loss, suggesting that the early-stage relaxation is primarily governed by strain-controlled microstructural accommodation processes. Despite the differences in initial stress drop, the subsequent relaxation rate beyond the first 100 cycles was found to be largely independent of the applied strain range. The stress level remained nearly constant up to 10,000 cycles, indicating a stable cyclic response. In addition, the resulting cyclic stress range increased approximately linearly with the imposed strain amplitude, reaching values of up to ~150–175 MPa at the highest investigated strain range. This confirms that the cyclic response is predominantly controlled by the applied strain amplitude rather than by progressive degradation mechanisms. From a fatigue perspective, these results imply that both the effective stress range and the initial mean stress reduction scale with the imposed strain amplitude, while long-term cyclic stability is largely unaffected by further cycling.

The results demonstrate that the fatigue-relevant stress state in prestressed Fe-SMA elements is governed by two coupled effects:

- The initial recovery stress, defining the mean stress level
- The cyclic strain amplitude, controlling both initial relaxation and stress range

The observed linear scaling between cyclic strain range and both stress range and initial stress loss enables a simplified interpretation for design purposes. For a given pre-strain condition, the cyclic stress range and the early-stage relaxation can be directly related to the imposed strain amplitude. Importantly, while higher strain amplitudes lead to larger initial reductions in recovery stress, the subsequent stress evolution remains stable. This indicates that the fatigue-relevant loading condition is effectively established during the first cycles and does not significantly deteriorate with further cycling.

Overall, the results demonstrate that Fe-SMA elements can maintain stable prestressing performance under cyclic loading conditions, while the balance between recovery stress and fatigue behavior must be carefully considered in design.

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4D-printed Fe-based shape memory alloy architectures with enhanced recoverability

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Keywords: Fe-based SMA; buckling-induced architected materials; energy dissipation; WAAM

1. Introduction

Additive manufacturing has revolutionized structural design by enabling material-efficient and multifunctional components, allowing rapid prototyping of innovative metal structures (Ford & Despeisse, 2016; Restrepo et al., 2015). Integrating architected meta-structures with smart materials offers extraordinary mechanical properties, such as negative stiffness, negative Poisson's ratio, and exceptional energy absorption, supporting sustainable and high-performance engineering solutions (Chen et al., 2021; Tan et al., 2019). Among these, buckling-induced architected materials (BIAMs) are notable for their superior shock and impact absorption capabilities (Corsi et al., 2022; Frenzel et al., 2016; Rafsanjani et al., 2016; Restrepo et al., 2015). This study introduces buckling-induced architected Fe-based shape memory alloys (BIA Fe-SMAs) as a new class of BIAMs, leveraging the unique pseudo-elasticity and shape memory effect of Fe-SMAs (Jafarabadi et al., 2023). The design can be tuned for mono-stable or bi-stable behavior, offering either self-recoverable or stable post-buckling configurations (Ha et al., 2018; Qiu et al., 2004). The Fe-SMA base material enhances damping through phase transformations between austenite and martensite, generating internal friction and energy dissipation. With their high elastic modulus, strong damping capacity, and cost-effective manufacturability, BIA Fe-SMAs present a promising solution for vibration control, damping, and impact mitigation in large-scale structural and civil engineering applications.

2. Material and methods

2.1. Design of buckling-induced architected structure

In this research, a BIA structure was designed using a single sinusoidal beam unit-cell defined by amplitude (A), wavelength (λ), and thickness (t), as shown in Fig. 1, with stiffening walls to constrain transverse motion and ensure vertical buckling under compression, producing a mono-stable snap-through mechanism that allows recovery upon unloading. Stability is determined by dimensionless ratios ($\pi_1 = t/\lambda$, $\pi_2 = A/\lambda$, and $Q = \pi_2/\pi_1$), where $Q \leq 2.31$ ensures mono-stable behavior, and the maximum buckling strain ($\varepsilon_{max} = 2\pi^2\pi_1\pi_2$) is kept below the material's yield strain to maintain elastic recoverability. Finite element analyses in Abaqus, using steel properties ($E = 200$ GPa, $\nu = 0.3$), were conducted to evaluate buckling and post-buckling behavior, balancing stress minimization and compressive strength. Based on WAAM manufacturability limits, $t = 3$ mm and $\lambda = 250$ mm were selected, and $A = 3.75$ mm was determined through simulations confirming a mono-stable, recoverable response. Linear and nonlinear buckling analyses using imperfection-seeded models with frictionless self-contact and mixed element types validated stable, recoverable buckling under compression, confirming the optimized design for additive manufacturing and structural damping applications.

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2.2. Optimization of WAAM process parameters and material characterization

The main parameters of the WAAM process, including current, voltage, travel speed, and wire feed rate, were analyzed and optimized. The optimal values were determined as follows: wire feed rate of 3 m/min, current of 66 A, travel speed of 5 mm/s, and voltage of 11.7 V. The objective was to stabilize the electric arc, minimize melt pool fluctuations, and enhance the overall quality of layer deposition. In the first step, small wall samples (Fig. 1a) were printed using Fe-SMA wire with a chemical composition of Fe-17Mn-5Si-10Cr-4Ni-1(V,C) (wt.%). These initial prints aimed to identify optimal parameters that yield a defect-free microstructure and favorable mechanical properties. Subsequently, based on the optimized parameters, a large-scale cellular structure was successfully printed (Fig. 1b). It should be noted that the FE simulations identified t and λ as the most critical parameters governing mono-stable behavior. Consequently, the fabrication of the unit cell shown in Fig. 1b prioritized achieving these dimensions accurately, while allowing the remaining dimensions to deviate from the geometric proportions given in Fig. 1b.

To enhance mechanical performance, printed wall specimens were heat-treated via solution annealing at 1100 °C for 2 hours followed by aging at 760 °C for 8 hours. The microstructural evolution was characterized using scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). Tensile specimens extracted from as-built and heat-treated walls were tested up to 4% strain, and the recovery strain of pre-strained samples was measured during heating to 200 °C and subsequent cooling to room temperature.

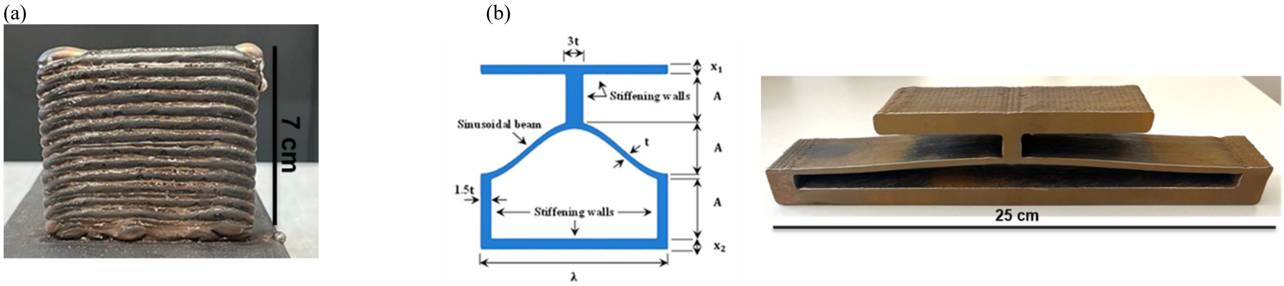

Fig. 1. (a) Fe-SMA wall, (b) schematic view of a BIA unit-cell and printed large-scale cellular structure of carbon steel using WAAM.

3. Results and discussion

Microstructural characterization (Fig. 2) of heat-treated samples revealed a predominantly austenitic phase. However, the heat treatment route significantly influenced grain morphology and precipitation behavior. Solution annealing induced substantial grain coarsening (Fig. 2b), and subsequent aging promoted the precipitation of fine carbides within the austenitic matrix (Fig. 2a). In contrast, direct aging without solution annealing preserved the columnar structure originating from the printing process, though fine carbides still precipitated during aging (Fig. 2c). These carbides were found to critically influence both the mechanical strength and functional behavior of the printed Fe-based samples, emphasizing that tailored post-processing is essential for optimizing the performance of additively manufactured Fe-SMAs.

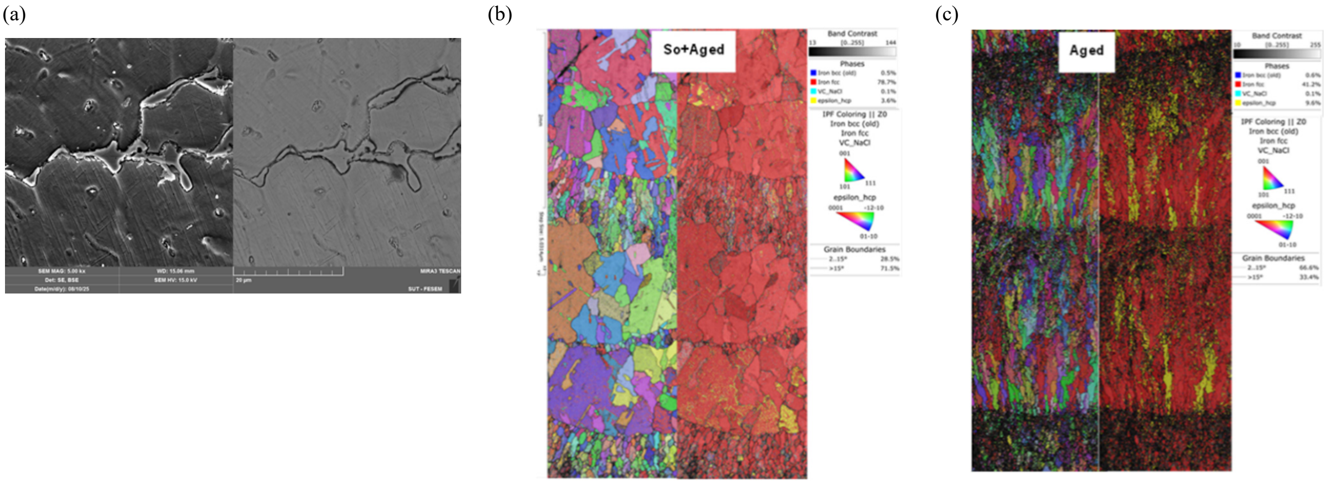

Fig. 2. (a) SEM micrograph of aged samples, EBSD characterization of (b) solution annealed and aged, and (c) aged Fe-SMA samples.

Tensile tests revealed that the as-built samples exhibited brittle behavior, indicating limited ductility (Fig. 3a). In contrast, the heat-treated samples demonstrated a significant improvement in ductility, as shown in Figure 3a. Moreover, the aged specimens displayed the highest pseudo-elasticity and recovery strain (Fig. 3b), confirming that the applied heat treatment effectively enhanced both the mechanical compliance and the functional performance of the printed Fe-SMA structures. The BIA lattices were evaluated through compression testing under multiple loading cycles to assess their deformation and recovery behavior. The maximum measured displacement reached approximately 14 mm. The testing protocol included both monotonic loading and cyclic compression consisting of six loading–unloading cycles at a constant displacement. After each cycle, the Fe-SMA specimens were thermally recovered at 200 °C to restore their original geometry prior to subsequent testing. For comparison, Fe-SMA and carbon steel lattices were each subjected to six compression cycles up to 10 mm displacement. The carbon steel cellular structures exhibited permanent deformation, buckling, and densification after 10 mm compression, indicating irreversible damage and limited reusability. In contrast, the Fe-SMA lattices demonstrated complete recovery—achieved partly through pseudo-elastic deformation and partly via the shape memory effect—without any signs of densification, even at 12 mm displacement (Fig.3c). These results highlight the superior energy dissipation capacity and recoverability of Fe-SMA-based dampers, underscoring their potential for seismic and vibration control applications.

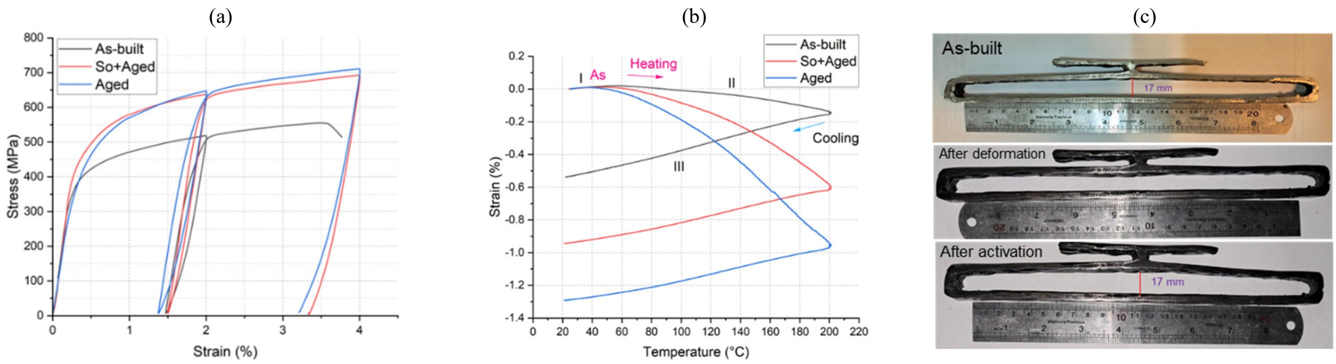

Fig. 3. (a) Stress-strain curves of printed Fe-SMA, (b) Strain recovery vs temperature of as-built and heat-treated samples during activation up to 200 °C, (c) The cross-section images of BIA lattice Fe-SMA before compression, after compression, and after activation at 200 °C.

4. Conclusions

This study successfully developed BIA Fe-SMAs using WAAM, integrating architected geometry, additive manufacturing, and smart material functionality. The optimized sinusoidal lattice design exhibited mono-stable buckling behavior with recoverable deformation under compression, validated by finite element simulations and experiments showing repeated buckling without permanent deformation. Heat treatment produced an austenitic matrix with fine carbides, significantly improving ductility, pseudo-elasticity, and recovery strain. Compression tests confirmed that Fe-SMA lattices achieved full geometric recovery via pseudo-elasticity and the shape memory effect, unlike carbon steel counterparts which showed permanent densification. Overall, this work establishes a 4D printing framework for recoverable metallic systems, opening new pathways toward smart, adaptive, and sustainable structural materials for seismic damping, vibration control, and advanced engineering applications.

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Remote fastening in inaccessible spaces using shape memory alloys

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Abstract

Traditional mechanical fasteners in civil engineering require direct physical access during assembly, restricting design freedom and complicating maintenance procedures, often necessitating additional on-site processing to close access points. Shape Memory Alloys (SMAs), capable of recovering deformation through thermal activation, present a promising approach for remotely actuated fastening in confined or inaccessible locations. This paper investigates the feasibility of SMA-based fasteners for access-independent assembly, with a focus on FeMnSi-based SMAs commonly used in structural applications due to their low cost and good workability, as well as thermoelastic SMAs such as NiTi, which offer enhanced functional performance. The study examines two prototype implementations representing distinct application scenarios: a modular trade-fair wall element requiring rapid and repeatable assembly cycles, and a façade element designed for long-term installation under realistic service conditions. For the modular wall system, the fast response and repeatability of thermoelastic SMA actuators make them the preferred solution. In contrast, the robustness and economic advantages of FeMnSi-based SMAs render them well-suited for the façade application. Experimental results from both prototypes are presented, including validation tests, recovery strain-stress characteristics, and performance under realistic loading. These findings form the basis for evaluating the practicality, reliability, and design implications of SMA-based fastening systems in civil engineering, highlighting their potential to enable new assembly strategies for large structural elements.

Keywords: Civil engineering applications; modular construction; shape memory alloy; remote assembly; constrained assembly

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

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

Influence of Fe-SMA material nonlinearity on the bond-slip and debonding behavior

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Keywords: Iron-based shape memory alloy (Fe-SMA), steel strengthening, bond-slip behavior, bond capacity, cohesive zone model (CZM)

Extended abstract

Iron-based shape memory alloys (Fe-SMA) offer significant potential for the fatigue strengthening of structural components subjected to cyclic loading, particularly in aging steel bridges. The reliability of such strengthening systems strongly depends on the quality of the adhesive bonding interface between the Fe-SMA and the parent structure. Therefore, a thorough understanding of the debonding behavior of this interface is essential for the development of robust and predictable strengthening solutions.

For bonded strengthening systems involving materials with linear elastic behavior, such as carbon fiber reinforced polymers (CFRP), both analytical formulations and numerical simulation frameworks based on cohesive zone modelling (CZM) are well established. The CZM approach is fundamentally based on the bond–slip relationship, which characterizes the behavior of the adhesive interface between the substrate and the strengthening material. The parameters required for CZM are typically derived from experimental investigations, most commonly from lap-shear tests, as Mode II loading represents the dominant condition in bonded joints.

Recent studies have investigated the bond–slip behavior of bonded Fe-SMA and contributed to the development of finite element (FE) models. Building upon these models, the present study provides deeper insight into the underlying debonding mechanisms and examines the influence of material nonlinearity on the debonding process.

Based on experimental lap-shear tests with Fe-SMA and corresponding numerical simulations, this study demonstrates that failure in nonlinear bonded joints (i.e., with nonlinear/toughened adhesive and nonlinear adherends) is governed by a strain-controlled mechanism associated with adhesive interface debonding, rather than by a stress-based failure criterion in the adherend, as commonly assumed for bonded joints with linear adhesives and adherends.

Building on this finding, the conventional processing methodology for deriving bond–slip relationships from experimental data has been revised. The proposed approach extends the established forward processing method and explicitly accounts for debonding of the adhesive layer prior to reaching the maximum stress in the nonlinear material by introducing the concept of a debonding strain. This parameter represents the strain level in the nonlinear adherend at the onset of complete debonding of the bonded interface. To derive full-field displacements and the corresponding bond–slip behavior from experimental investigations, the following procedure is proposed:

- Capture full-field displacement of the top surface of the nonlinear adherend with DIC
- Differentiate the displacement field to obtain the strain distribution up to the debonding strain
- Determine the corresponding stress using the nonlinear stress–strain relationship of the adherend
- Compute the shear stress in the adhesive by differentiating the axial stress and multiplying by the adherend thickness
- Derive the bond–slip relationship by correlating shear stress with relative displacement

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By explicitly accounting for the failure mechanism in nonlinear bonded joints, the proposed method enables an accurate determination of the full-range debonding behavior from experimental lap-shear tests and yields physically consistent bond–slip relationships for nonlinear materials. The improved understanding of the debonding process clarifies the interaction between nonlinear adherends and the bonded interface.

Based on these insights, it becomes feasible to derive analytical solutions for the bond strength of nonlinear bonded joints, which are currently lacking. Furthermore, the derived bond–slip relationships provide a reliable basis for the development of cohesive zone models for the numerical assessment of bonded joints.

Acknowledgements

The authors acknowledge the financial support from the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) with the project number 546183955 and of FOSTA with the project number P 1851 / IGF-Nr. 01IF24731N.

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Recent advances in shear strengthening of concrete structures using self-prestressed Fe-SMA

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Keywords: Concrete T-beam; shear strengthening; Fe-SMA plates; prestressing

1. Introduction

Reinforced concrete (RC) T-beams are widely used in bridge and building structures owing to their efficient load-bearing capacity. However, aging, environmental degradation, and increased service demands often reduce shear performance, creating a need for strengthening interventions (Siddika et al. 2019). Compared with flexural strengthening, improving the shear capacity of T-beams is more challenging because of the brittle and sudden nature of shear failure, which frequently governs the load rating of existing bridges (Holt et al. 2018).

To date, extensive research has demonstrated the effectiveness of Fe-SMA in the flexural strengthening of reinforced concrete members, particularly in terms of recovery-stress generation, crack control, and durability (Hong et al. 2018; Sun et al. 2025; Zheng et al. 2024). In contrast, studies focusing on the shear strengthening of RC beams using Fe-SMA remain relatively limited.

2. Novel Fe-SMA strengthening system

As shown in Fig. 1, the proposed strengthening system consists of Fe-SMA plates welded to duplex stainless-steel end plates and anchored to the concrete web using bolts. Structural adhesive can optionally be applied between the plate and concrete surface to improve bonding performance.

After installation, the Fe-SMA plates are activated through electrical resistance heating. When the material cools, recovery stress is generated, introducing active prestressing into the beam web. This self-prestressing mechanism enhances crack control and shear resistance.

3. Experimental program

A total of fifteen RC T-beam specimens were tested under three-point bending. The main experimental variables included: shear-span ratio (λ = 1.0, 1.5, 2.0); activation temperature (150 °C and 250 °C); Fe-SMA inclination angle (β = 90° or 45°); bonding condition (bonded or unbonded).

The T-beams had a total length of 4600 mm, height of 600 mm, flange width of 480 mm, and web width of 200 mm. Strengthening plates were symmetrically arranged along the shear span. During testing, load, displacement, stirrup strain, and Fe-SMA strain were recorded, and crack development was monitored using digital image correlation (DIC).

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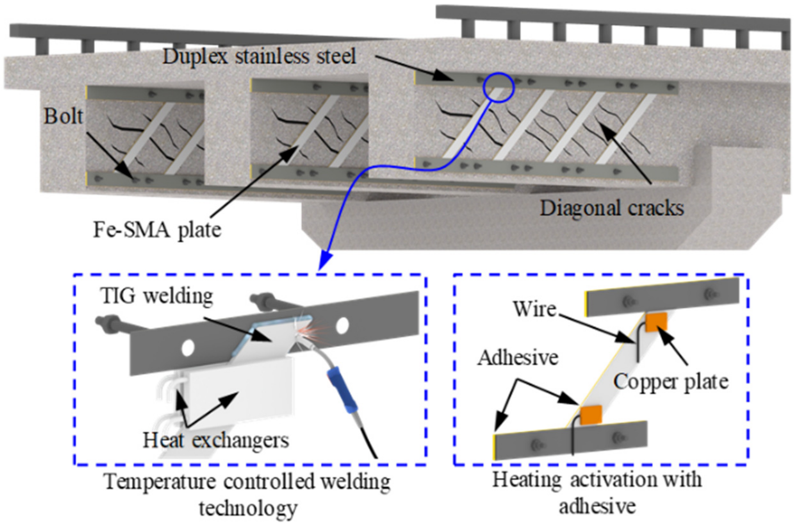

Fig. 1. Design of the proposed shear strengthening system using Fe-SMA plates.

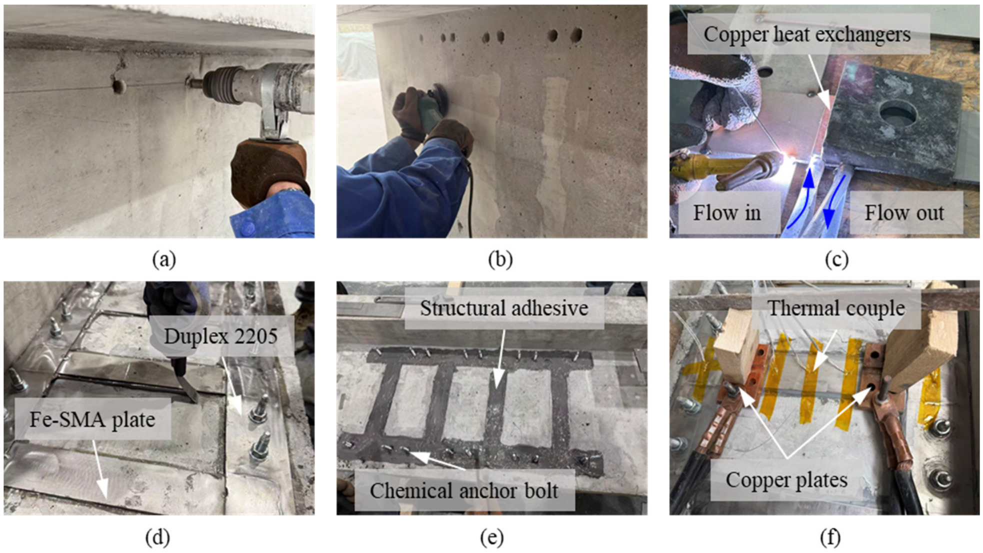

Fig. 2. Strengthening procedure: (a) drilling holes; (b) surface preparation; (c) TIG welding; (d) installing chemical anchors and applying adhesive; (e) installing Fe-SMA plates; (f) activation.

Table 1. Variable parameters of the specimens.

Specimen no.	λ	T	β	Use of adhesive
B-λ1.0		-	-	-
B-λ1.0-N-β90	1.0	N	90°	Yes
B-λ1.0-T150-β90		150 °C	90°	Yes
B-λ2.0		-	-	-
B-λ2.0-N-β90	2.0	N	90°	Yes
B-λ2.0-T150-β90		150 °C	90°	Yes
B-λ1.5		-	-	-
B-λ1.5-N-β90		N	90°	Yes
B-λ1.5-T150-β90		150 °C	90°	Yes
B-λ1.5-T250-β90		250 °C	90°	Yes
B-λ1.5-N-β90-N	1.5	N	90°	No
B-λ1.5-T150-β90-N		150 °C	90°	No
B-λ1.5-T250-β90-N		250 °C	90°	No
B-λ1.5-N-β45		N	45°	Yes
B-λ1.5-T150-β45		150 °C	45°	Yes

4. Results and discussion

Shear capacity and deformation behavior. The strengthened beams exhibited significantly improved load-bearing capacity and stiffness. Compared with the control beams, the activated Fe-SMA strengthening system increased the shear capacity by up to 43%. The shear-span ratio strongly influenced structural behavior. Beams with smaller shear-span ratios showed higher shear capacities and stiffness, whereas larger ratios resulted in greater deformation capacity. Diagonal Fe-SMA strengthening (β = 45°) provided better strengthening efficiency than vertical strengthening. Aligning the Fe-SMA plates with the principal tensile stress direction resulted in improved load redistribution and higher shear resistance.

Crack development and failure mode. All specimens exhibited typical shear failure characterized by diagonal cracking between the loading point and support. Strengthened specimens showed finer and more distributed crack patterns. Activation of Fe-SMA significantly improved crack control. The maximum diagonal crack width was reduced by more than 60%, while the initial cracking load increased by up to 116%. Bonded strengthening systems exhibited significantly smaller crack widths and more uniform crack distribution than unbonded configurations, indicating more efficient prestress transfer.

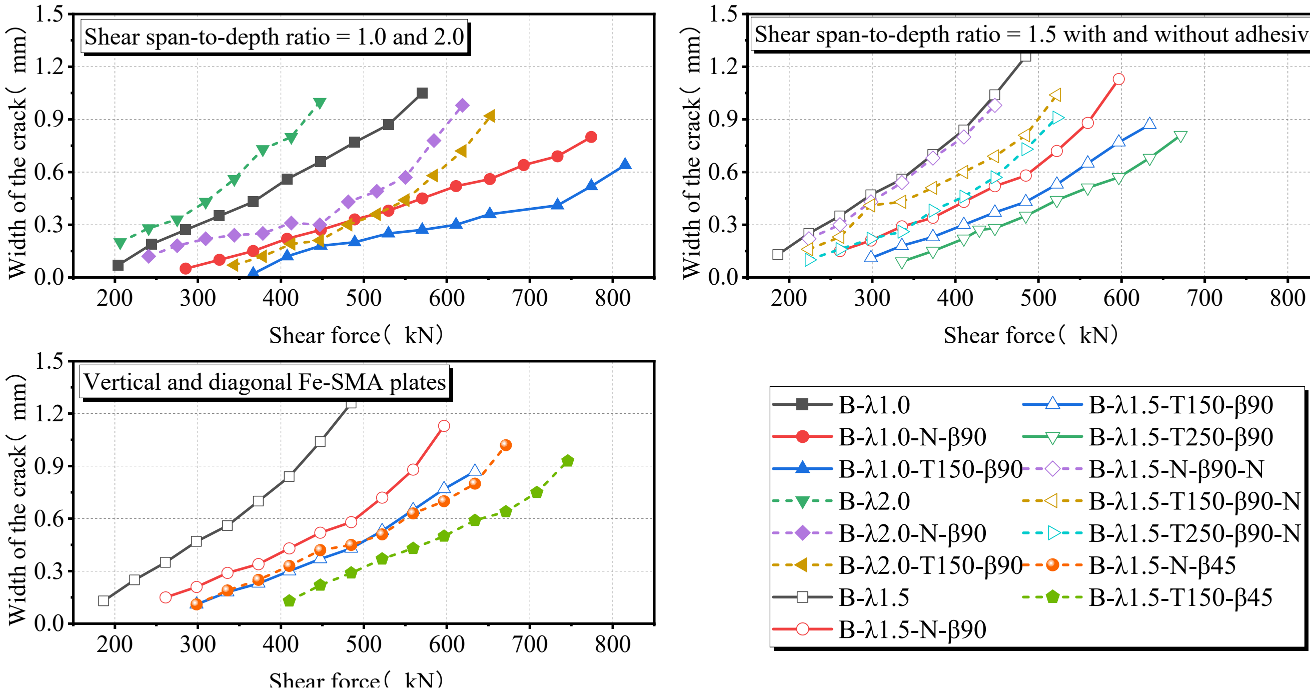

Fig. 3. Critical diagonal crack width vs. shear force.

Contribution of Fe-SMA to shear resistance. The total shear capacity of strengthened beams can be expressed as the sum of the contributions from concrete, stirrups, and Fe-SMA plates. Experimental strain measurements indicate that the contribution of Fe-SMA plates increased significantly after activation. In optimal configurations, the Fe-SMA contribution exceeded that of stirrups by more than two times, confirming the dominant role of self-prestressing in enhancing shear resistance.

Acknowledgements

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Tensile behavior of Fe-SMA bar reinforced UHPFRC

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Abstract

The combination of ultra-high performance fiber-reinforced concrete (UHPFRC) and steel rebars provides higher tensile strength and structural applicability. However, the interaction between steel rebars and UHPFRC can lead to a decrease in the elastic limit caused by the suppression of free shrinkage of UHPFRC, as well as premature strain concentration of steel bars due to the localization of a single macrocrack. To address these limitations, this study investigated a steam-curing activated self-prestressed UHPFRC system reinforced with ribbed iron-based shape memory alloy (Fe-SMA) bars (SMA-UHPFRC). Direct tensile tests were conducted on dumbbell specimens with reinforcement ratios of 0%, 1.96%, and 3.93%, and micro/macrocrack development was recorded using digital image correlation (DIC) system. The results showed that, compared with conventional UHPFRC reinforced with HRB500 bars (HRB500-UHPFRC), the tensile elastic limit strength increased by 44.3% and 81.9%, and the hardening strain increased by 33.2% and 54.6% for SMA-UHPFRC with reinforcement ratio of 1.96% and 3.93%, respectively. The fracture pattern transformed from a single dominant macrocrack in HRB500-UHPFRC to a multi-macrocrack mode in SMA-UHPFRC. These findings indicate that self-prestressing of Fe-SMA can simultaneously improve elastic limit, ductility, and crack dispersion of UHPFRC, providing a practical approach for thin reinforcement layers and connection areas that require strict usability and durability.

Keywords: Fe-SMA bar; reinforced UHPFRC; self-prestressing; tensile behavior; elastic limit; strain-hardening

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Modeling pure shear in Z-shaped mortar specimens reinforced with SMA fibers

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Abstract

This study develops a mesoscale finite element (FE) model to evaluate the pure shear behavior of Z-shaped mortar specimens reinforced with randomly distributed, crimped NiTi shape memory alloy (SMA) fibers. A Python-based algorithm was implemented to automate fiber generation, while thermal activation was modeled to capture active prestressing. Validation against experimental push-off tests across 0%, 1.0%, and 1.25% SMA fiber contents demonstrated that the peak load predictions in the numerical model deviated from the experimental data by approximately 6%. Results indicate that thermal activation is the primary factor in enhancing shear performance, generating recovery stresses and increasing peak strength by 17.2%. While fiber orientation is negligible before cracking, fibers aligned near 90° to the shear plane carry the highest stresses post-crack. The 1.25% fiber fraction yielded the highest strength, while 1.0% ensured more stable post-peak behavior. This validated FE framework provides a reliable tool for optimizing smart reinforcement in cementitious composites.

Keywords: SMA fibers; pure shear behavior; FE analysis; thermal activation; fiber orientation effect.

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

Activation of shape memory Fe-SMA reinforced concrete beams subjected to localized fires

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Abstract

During fire events, drift limits can be surpassed due to stiffness and strength degradation of materials at elevated temperatures. If transient drifts are within acceptable limits, residual drifts can still necessitate significant repair or reconstruction of elements after a fire event, resulting in significant downtime and capital losses. Reinforced concrete (RC) beams will experience material degradation when reinforcing steel reaches temperatures above 200 °C. This temperature range coincides with shape memory effect activation temperature of iron-based Shape Memory Alloys (Fe-SMAs), suggesting an opportunity to improve the structural response to fires. The work presented aims to determine if a localized fire could activate Fe-SMA reinforcing bars in concrete beams and understand what effect Fe-SMA activation may have on the beams' post-fire structural response. Four RC beams were tested under 4-point bending, reinforced with traditional steel or Fe-SMA reinforcing bars. One control beam for each reinforcement type was first tested under bending and subsequently subjected to a 30-minute fire to understand the influence of pre-cracking on activation of the Fe-SMA. The remaining beams were exposed to a 30-minute localized fire prior to the bending test. Activation of Fe-SMA was observed in both beams due to an upward camber beyond what was observed in traditional reinforced beams; the presence of cracks increased the camber. The load-displacement responses of reinforced beams subjected to fire prior to flexural testing illustrated a reduced initial stiffness but similar load resistance to the control beams. The results demonstrate that localized fires can activate Fe-SMAs and, in turn, reduce fire induced displacements with no significant effect on residual load capacity.

Keywords: Fe-SMAs; shape memory effect; reinforced concrete; localized fire; flexure

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

Seismic retrofit strategy based on self-centering rocking frames

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Abstract

Seismic hazards pose a significant risk to reinforced concrete (RC) school structures, which are frequently compromised by insufficient ductility and structural irregularities. To enhance resilience and minimize downtime, this research evaluates an innovative self-centering rocking system (SC-RS) retrofit, specifically designed for rapid re-centering and controlled energy dissipation. The proposed system employs both single and dual rocking steel frame that incorporates prestressed tendons for restoring forces and dumbbell-shaped steel strips–acting as structural fuses–to prevent buckling and localize hysteretic damping. Utilizing a displacement-based design (DBD) procedure, the efficacy of the SC-RS is tested via a comprehensive nonlinear dynamic analysis of a full-scale RC school buildings. The structural performance under multiple seismic scenarios is assessed via nonlinear time history analyses. The findings confirm that this strategy improves the buildings' seismic performance, achieving reliable damage control and complete self-centering, thus establishing the SC-RS as a viable, high-performance retrofit for critical facilities.

Keywords: Steel braced rocking frames; self-centering; seismic retrofit

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

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

MS06: Monitoring, assessment and design of lightweight metal façades

Organizers:
Felicitas Rädel (TU Darmstadt, Germany)
Zbigniew Pozorski (Poznan University of Technology, Poland)
Markus Kuhnhenne (RWTH Aachen, Germany)

ABSTRACT

Lightweight metal façade systems have significantly evolved over recent decades, achieving advancements in material selection, energy efficiency, and sustainability. With increasing demands for multifunctionality, durability, and resource efficiency, integrating photovoltaic modules, adaptive systems, and smart monitoring technologies into building envelopes has become paramount.

This Mini Symposium will explore current developments in the design, monitoring, and assessment of such façade systems. Topics include innovative measurement techniques, lifecycle analyses, and strategies for damage prevention and rehabilitation. The goal is to present and discuss interdisciplinary approaches for future-proof façade solutions.

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The problem of load transfer in multi-layer façades

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Keywords: Sandwich panels; multi-layer façades; load transfer; structural behavior; torsion

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1. Introduction

The continuous increase in requirements related to thermal insulation, energy efficiency, durability, and architectural quality of buildings has led to the widespread use of advanced façade systems, particularly in the modernization of existing industrial, commercial, and public buildings, which was noticed by Dernie and Gaspari (2015), Firoozi et al. (2025) and many others. In many structures erected in the late twentieth and early twenty-first century, the external envelope was made of sandwich panels, which combine relatively thin, stiff facings with a lightweight core providing thermal insulation. Such panels are commonly used because they enable fast construction, provide good thermal performance, and can serve as both enclosure and load-carrying elements within a limited range of loading conditions. However, contemporary expectations concerning the energy efficiency of buildings, as well as the need to improve their visual appearance, often require the addition of a new external façade layer without removing the original cladding. This approach allows the reuse of existing building components, reduces construction waste, shortens renovation time, and fits well within the principles of sustainable development and circular economy in construction.

2. Description of the problem

The introduction of an additional façade layer attached to the existing wall leads to the creation of a multi-layer façade system in which loads must be transferred through several cooperating structural components. Example solutions were presented and discussed by Marrone et al. (2025). Although such solutions are increasingly used in engineering practice, the problem of load transfer in multi-layer façades is still frequently treated in a simplified manner at the design stage. In many practical cases, the additional façade is assumed to transfer loads directly to the main structural frame, while the influence of the existing sandwich panels is either neglected or represented in a highly idealized way. In reality, however, the external façade, the supporting substructure, the sandwich panels, and the primary load-bearing system of the building form a complex spatial arrangement in which stiffness, eccentricity, and connection behavior significantly influence the internal force distribution as it was presented by Pradhan et al. (2025). As a result, simplified design assumptions may lead to incorrect estimation of stresses, excessive deformations, or unsafe loading of the existing cladding elements.

This paper presents a detailed analysis of the problem of load transfer in multi-layer façades composed of an additional external façade mounted on an existing wall made of sandwich panels, which are connected to the main structural system of the building. The study focuses on identifying the actual load path from the newly added façade through the original building envelope to the primary structural members such as columns, beams, or frames. Particular attention is given to loads acting in the plane of the wall, because these loads may produce structural effects that are not usually considered in the standard design of sandwich panels, which was noticed by Pradhan and Lange (2024). While such panels are typically designed to resist loads acting perpendicular to their surface, for example wind pressure or suction, the introduction of an external façade layer may generate significant in-plane forces, bending moments, and torsional effects that must be taken into account in order to ensure structural safety.

One of the main sources of additional loading is the self-weight of the external façade together with the weight of its supporting substructure. These loads are transferred to the sandwich panels through rails, or other mounting elements. Because the façade is

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usually installed at a certain distance from the original wall, the load transfer occurs with eccentricity relative to the mid-plane of the panels. This eccentricity causes not only in-plane bending but also torsion of the sandwich panels, leading to a complex stress state in both facings and in the core. The magnitude of these effects depends on the geometry of the façade system, the stiffness of the supporting elements, the spacing of fasteners, and the mechanical properties of the sandwich panel components. In addition, the connections between panels and the main structural frame may be subjected to forces different from those assumed in the original design, which may influence the safety and serviceability of the entire building envelope.

3. Numerical analysis

In order to investigate the problem of load transfer in multi-layer façades, a series of spatial numerical models that simulate the behavior of façade systems under various loading conditions was prepared. The models were developed in Abaqus using three-dimensional finite element representations that include the sandwich panels, the façade substructure, the external cladding layer, and the connections to the main structural frame. The modelling approach allows the consideration of eccentric load application, partial stiffness of fasteners, and the interaction between different layers of the façade. Special attention is paid to loads acting in the plane of the wall, including the self-weight of the façade, horizontal forces resulting from temperature effects or assembly imperfections, and loads caused by differential movements between the façade and the structural frame.

For example, an analysis was carried out of a single-span system with a span of 5 m. The 0.12 m thick sandwich panel is placed horizontally and mounted to the steel structure. Three vertical hat profiles are attached to the panel at 1.25 m spacing. The panel is attached to steel columns using 10 connectors (5 on each side). To model the sandwich panel's connection to the steel substructure, bushing connectors were used, which allow for the definition of relative movement between the two connected points. The possibility of mutual displacement is defined by specifying stiffness in a given direction of displacement or rotation. The connection of the hat profiles to the external steel cladding of the sandwich panel was defined in a similar manner, with all connectors limiting the possibility of detachment of the façade from the sandwich panel, and one pair of connectors per profile also limiting the possibility of movement in the façade plane.

The external façade is mounted on additional profiles, and the total distance between the façade and the external facing of the sandwich panel is 0.10 m. Figure 1 shows the effect of the façade's weight (displacement in the z-direction given in meters), which causes torsion of the sandwich panel. The effect of additional wind pressure on the façade, with the façade's weight constantly acting, is illustrated in Figure 2.

The numerical analysis made it possible to determine the distribution of internal forces, stresses, and displacements in the sandwich panels and in the mounting elements. Particular emphasis is placed on identifying the locations where the highest stresses occur, such as around fasteners, at panel joints, and near the supports connecting the panels to the main structure. The results show that even relatively small eccentricities may lead to significant torsional effects, which in turn increase the stresses in the panel facings and in the fasteners. In some cases, the additional façade may cause loading conditions that were not considered in the original design of the building, which may require strengthening of the existing cladding or modification of the mounting system.

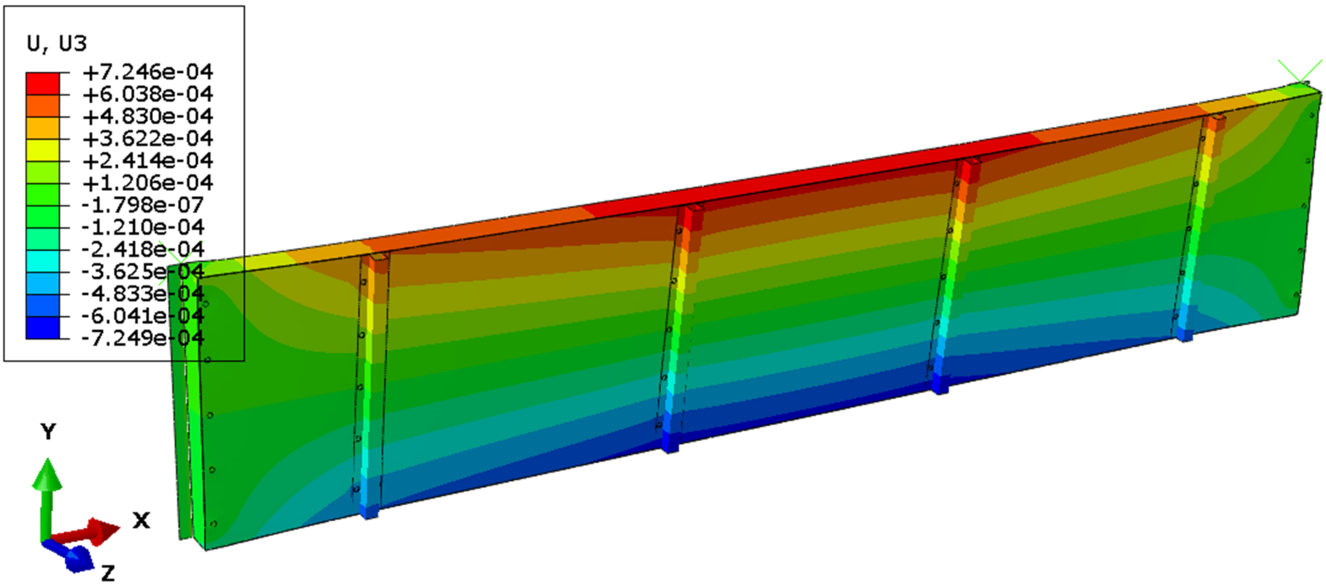

Fig. 1. Displacement of the sandwich panel in the z-axis direction [m], caused by the weight of the attached façade.

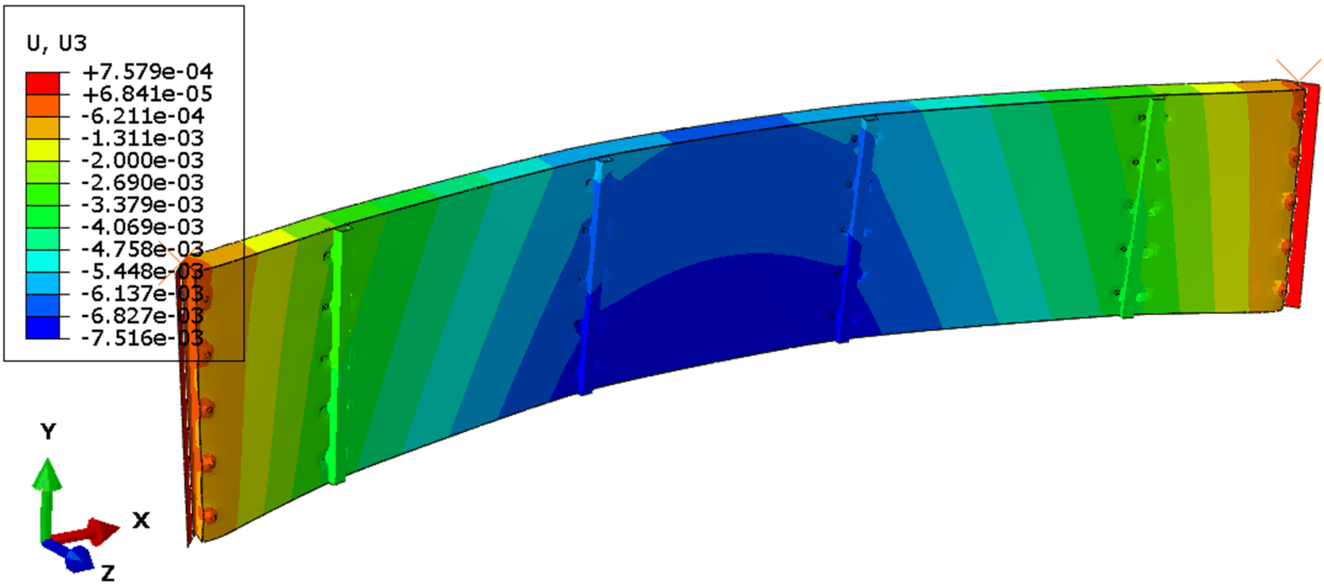

Fig. 2. Displacement of the sandwich panel in the *z*-axis direction [m], caused by the weight of the attached façade and wind pressure.

4. Concluding remarks

The presented research contributes to a better understanding of the structural behavior of multi-layer façade systems and highlights the importance of considering realistic load transfer mechanisms between the individual layers of the building envelope. The results may be useful for designers, engineers, and researchers involved in the modernization of buildings with sandwich panel cladding, as well as for the development of more accurate design recommendations and guidelines for multi-layer façade structures. In particular, the study emphasizes that safe and reliable design requires taking into account not only the strength of individual elements but also the stiffness of connections, the spatial arrangement of components, and the interaction between the façade and the main structural system.

The conclusions drawn from the analysis may support the development of design procedures that better reflect the real behavior of multi-layer façades and help avoid unsafe simplifications at the design stage. This is especially important in the context of the increasing number of renovation projects in which new façade layers are added to existing buildings in order to improve their thermal performance and appearance without removing the original cladding. Proper understanding of load transfer mechanisms in such systems is therefore essential for ensuring both structural safety and long-term durability of the building envelope.

Acknowledgements

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On the use of long, multi-span, thermally loaded sandwich façade panels

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Keywords: Sandwich panels; thermal actions, façades; numerical modelling

1. Introduction

Sandwich façade panels are widely used as elements of building envelopes due to their favorable mechanical performance, low weight, good thermal insulation properties, high level of prefabrication, and relatively fast installation process. They are commonly applied in industrial, commercial, and public buildings, where they serve both structural and cladding functions. Despite the extensive knowledge concerning the mechanics of sandwich panels and the availability of well-established design procedures, the use of long, multi-span panels in façade systems subjected to thermal actions still raises a number of practical and theoretical difficulties as it was indicated by Błaszczuk and Pozorski (2010). These difficulties become particularly significant when the panel length increases beyond the ranges typically assumed in standard design recommendations, and when panels are installed in systems where the boundary conditions are not clearly defined or vary along the façade height. Complex support conditions may result from the use of flexible cold-formed profiles discussed by Ciesielczyk and Studziński (2022).

In engineering practice, manufacturers often introduce limitations on the maximum allowable panel length regardless of the specific support conditions or thermal loading scenario. Such restrictions are usually conservative and are intended to prevent excessive stresses, local instability, or damage to joints and fasteners. However, these limitations may conflict with architectural and economic expectations, as longer panels reduce the number of joints, improve the visual appearance of the façade, and shorten installation time. Therefore, a more accurate understanding of the behavior of long sandwich panels subjected to thermal loads is necessary in order to enable safe but less restrictive design.

2. Description of the problem

In short panels, the dominant thermal effect is usually related to temperature differences between the outer and inner facings, which lead to bending and curvature of the panel. These effects are relatively well described in the literature and are commonly included in design procedures. However, when the panel length becomes large, the overall thermal expansion or contraction of the facings produces additional forces that may significantly influence the internal stress distribution and the global deformation of the panel, what was indicated by Davies (2013).

The problem becomes more complex when panels are supported at several points along their length, forming multi-span or asymmetrical systems, such as those discussed by Studziński et al. (2015) or Pozo-Lora and Maguire (2020). In such cases, thermal elongation of the facings may be partially restrained by the supports, which leads to the development of axial forces and bending moments that are not present in simply supported short panels. The magnitude of these forces strongly depends on the stiffness of the supports and on the ability of the panel to move relative to the substructure. In theoretical analyses, supports are often assumed to be either perfectly rigid or perfectly flexible, which simplifies the calculations but may lead to unrealistic results. In real façade systems, the behavior of the support is semi-rigid and depends on many factors, such as the type of fasteners, the stiffness of the secondary structure, the arrangement of joints, and the position of the panel within the façade.

The present study focuses on the behavior of long, multi-span sandwich façade panels subjected to significant thermal actions, with particular attention paid to the influence of support flexibility and panel length. The main objective is to provide a

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comprehensive analysis of the mechanisms governing the transfer of thermal loads in such systems and to propose calculation methods that can be used in engineering practice without excessive simplifications. The study considers panels composed of thin steel facings and a soft core, which is the most common configuration in façade applications, but the conclusions may also be relevant for other types of sandwich elements.

3. Numerical analysis

To investigate the problem of structural behavior of multi-span, thermally loaded sandwich panels, spatial numerical models of various panels and their supporting systems were developed using Abaqus software. The models include the mechanical properties of the facings and the core, the geometry of the panel, the arrangement of supports, and the characteristics of the fasteners connecting the panel to the substructure. Thermal loads are introduced in the form of uniform temperature changes as well as temperature differences between the facings. Special attention is given to the modelling of semi-rigid supports, which are represented by elastic elements with finite stiffness. This approach allows the analysis to capture the interaction between thermal expansion of the panel and the deformation of the supporting structure.

One of the cases analyzed was a 5-span panel with a total length of 10 m (each span was 2.0 m). The 0.12 m thick panel was attached to rigid supports with two connectors. To model the connection, the definition of a bushing connector was used, which allows for determining the relative displacement of two connected points. The possibility of mutual displacement or rotation is controlled by defining the stiffness in a given direction. In the presented example, points on the external facing are connected to points located on rigid supports. The supports are capable of rotation about the *y*-axis but not displacements. The initial temperature was assumed to be 10°C. The thermal action was defined such that the lower (inner) facing heated to 20°C, and the outer facing heated to 90°C.

Figure 1 shows the resulting displacement values, although it is worth noting that the displacement component in the direction perpendicular to the panel, i.e., the *z*-direction, is dominant. Figures 2 and 3 show the normal stresses in the outer and inner facings, respectively, occurring along the *x*-axis. The complex nature of the stresses, the high stress levels, and the wrinkling effects visible on both facings are noteworthy. It is also worth noting that the displacements vary along both the *x*- and *y*-axes.

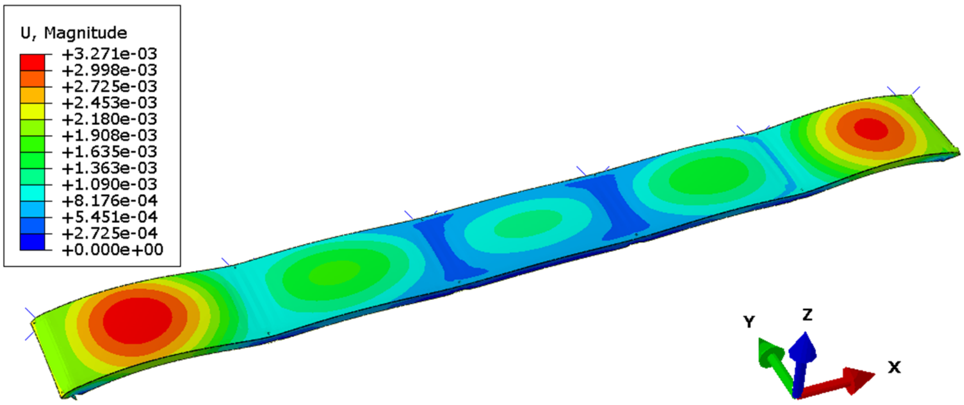

Fig. 1. Resultant displacement values [m] of a multi-span sandwich panel subjected to thermal loading.

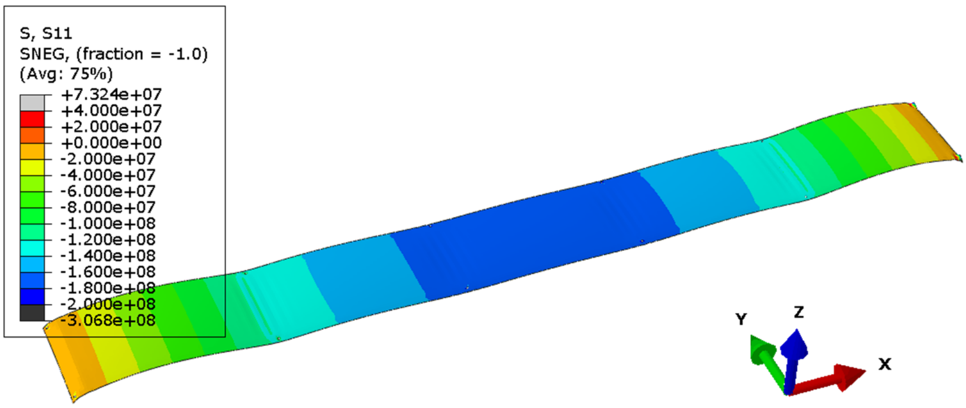

Fig. 2. Normal stresses along the *x*-axis [Pa], occurring in the upper (outer) facing.

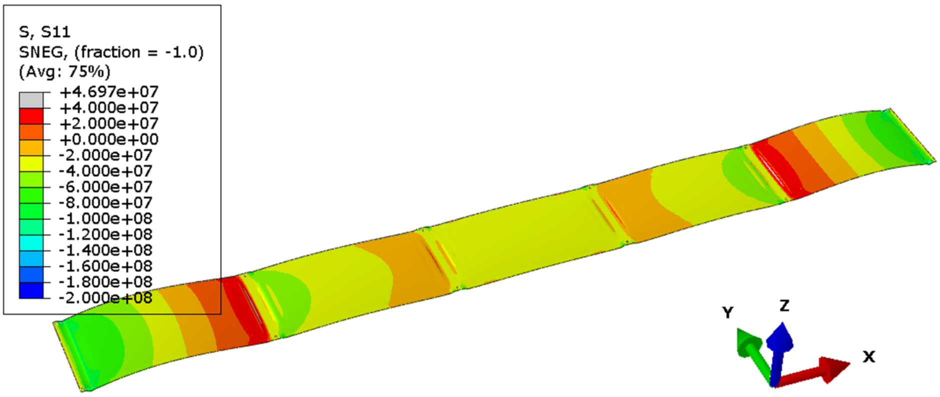

Fig. 3. Normal stresses along the x-axis [Pa], occurring in the lower (inner) facing.

The numerical simulations show that the influence of thermal elongation becomes dominant when the panel length increases and when the movement of the panel is restrained at several points. In such cases, significant axial forces may develop in the facings, which in turn increase the risk of local instability, especially in the compressed facing. The results also indicate that even small differences in support stiffness may lead to noticeable changes in the internal force distribution. Therefore, the assumption of identical boundary conditions for all panels in the façade may lead to inaccurate predictions of stresses and deflections.

Another important observation is that the behavior of long panels cannot be correctly described by models based only on bending theory. The coupling between axial deformation, bending, and shear deformation in the core must be taken into account, particularly when thermal loads are combined with mechanical loads such as wind pressure or self-weight. In multi-span systems, the interaction between adjacent spans also plays a significant role, because the restraint at one support influences the deformation of the entire panel.

4. Concluding remarks

Based on the results of the numerical analyses, new approaches for the evaluation of thermal effects in long sandwich façade panels are proposed. These approaches aim to bridge the gap between overly simplified analytical models and complex numerical simulations that are not always practical in everyday design. The proposed methods take into account the finite stiffness of supports, the possibility of partial restraint of thermal expansion, and the influence of panel length on the internal force distribution. Recommendations are also formulated regarding the modelling of façade systems in which the support conditions vary along the height of the building.

In conclusion, the use of long sandwich panels in façade applications is feasible, but it requires careful consideration of thermal loads, support flexibility, and the interaction between the panel and the supporting structure. Spatial numerical modelling provides valuable insight into these phenomena and makes it possible to develop improved design methods. The results of this work contribute to a better understanding of the mechanical behavior of thermally loaded sandwich panels and may help to extend their application range while maintaining the required level of safety and reliability.

Acknowledgements

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Determination of the shear properties of sandwich core materials

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Abstract

Due to their excellent weight-to-load ratio, good thermal insulation, high load-bearing capacity, and cost-efficient manufacturing and installation processes, sandwich panels are widely used for building envelopes.
A comparison of the core materials of sandwich panels has revealed inconsistent relationships between their stiffness moduli for varying core thicknesses. Therefore, two test methods for determining the shear properties of the core material in sandwich panels were assessed theoretically and experimentally. The results show that a correct determination of the shear modulus requires a more precise specification of the load distribution plates in the shear beam test according to EN 14509, while the usual neglection of the indentation at the support is justified only for panels of small and medium thickness. The investigations of the square shear test show the significant influence of the eccentricity between the joint plane and the top edge of the specimen and led to the development of a new test setup. The findings provide a basis for more realistic modelling of the load-bearing behavior of sandwich panels. Moreover, the new test setup enables the investigation of shear properties in any desired direction.

Keywords: Lightweight steel structures; composite steel structures; sandwich panels; shear test

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

Mechanical characterization of mineral core layer materials using digital image correlation

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Abstract

Mineral foams are a promising alternative to petroleum-based insulation materials with regard to both technical and ecological performance. For their application as core materials in multilayer reinforced concrete elements, comprehensive quality assurance is required. However, standardized methods for determining mechanical properties are lacking, while experimental testing is often complex and time-consuming. This study presents an approach for deriving tensile strength from uniaxial compression tests using digital image correlation (DIC). By linking deformation and stress states and combining continuum- and fracture-mechanical concepts, the methodology enables a reliable analysis of mechanical relationships with reduced testing effort. Experimental investigations demonstrate its applicability, and comparison with results from uniaxial tensile tests confirms the validity of the approach. The proposed method contributes to the efficient and standards-compliant evaluation of mineral foams.

Keywords: Mineral foam; digital image correlation (DIC); standardization and quality assurance; composite structures

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

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Optimization of metal cladding perforation and bending load capacity of sandwich panels

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Keywords: Perforated steel sheet; composite panel; optimization; bending load capacity; FEM numerical simulations

1. Introduction

For many years sandwich panels have been used in building construction as roofing, exterior and interior walls and ceilings components. Their claddings are primarily made of solid steel sheets. However, sandwich panels with a single perforated cladding are also appearing on the construction market. The applicable standard EN 14509:2013 does not cover, and in fact excludes from its scope, this type of construction product. Consequently, there are formally no test methods available to evaluate it in terms of, among other things, acoustic parameters as well as strength properties. It seems obvious that the inclusion of openings in the interior cladding, in combination with a mineral wool core (a highly sound-absorbing material), contributes to improving the acoustic performance of the partition and thus reducing the noise level inside the room. On the other hand, increasing the perforation rate reduces the bending load capacity and stiffness of the sandwich panel. By weighing these two factors against each other, it is possible to determine the optimal point at which further increases in the perforation rate will no longer result in improved acoustic performance.

Taking into account the above, determining the maximum perforation degree requires conducting acoustic tests to measure the sound insulation index R_w and the sound absorption coefficient α_w. To determine the critical stresses in the compressed cladding, bending load capacity tests has to be conducted, taking into account various hole diameters and spacings.

Given the large number of possible combinations, numerical simulations using the Finite Element Method (FEM) can be used as a tool to aid in the analysis. However, in order to correctly model a sandwich panel and achieve satisfactory agreement between the calculation results and test data in specialized software, it is necessary to conduct a series of material verification tests to determine the core's compressive strength, shear strength, tensile strength, and apparent density. The final outcome of this work will be the development of empirical formulas / correction factors / charts that enable the calculation of critical stresses in compressed sandwich panel claddings as a function of the varying perforation area of the cladding per square meter.

2. Methodology

There are numerous publications discussing the impact of perforations in external cladding on the sound-absorbing properties of the entire element. Similarly, the effect of holes in a given material on the internal stresses within it - and thus its bending load capacity - is well known. However, it is difficult to find studies that consider these aspects simultaneously in composite materials, a good example of which is a sandwich panel with a perforated cladding. While improving acoustic properties, there is a corresponding reduction in bending load capacity. The conducted research as part of this publication aims to determine the perforation degree in the inner cladding that is common to both of these issues, serving as a basis for further considerations regarding the strength and optimal design of sandwich panels.

Acoustic tests were conducted on samples consisting of sandwich panels with the mineral wool core with a total thickness of 80 or 150 mm (and corresponding lengths of 5.2 m or 6.2 m, respectively), with an inner cladding, flat, perforated in a 60° cylindrical arrangement (Rv 3-7.4 – 15.0% or Rv 3-5 – 32.8%) (see Figure 1), with a thickness of 0.5 mm and an outer, solid, lightly profiled, with a thickness of 0.5 mm as well as with inner and outer cladding, solid, lightly profiled, each with a thickness of 0.5 mm.

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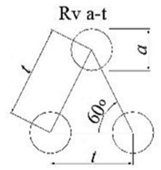

Designation:
a - diameter of the hole
t - spacing between holes
relative clearance (%):
$P = 0.91\ a^2/t^2/100$

Fig. 1. Perforation pattern in a 60° cylindrical arrangement.

Tests of the specific sound insulation index R_w were conducted in accordance with the standard EN ISO 10140-2:2021. Each test specimen consisted of three sandwich panels, each 4200 mm long. Its total width was 2730 ± 20 mm (two panels with a modular width of 1150 mm and one cut to size). The samples were mounted horizontally on the test stand with existing gaps at the edges sealed using mineral wool and cement-lime plaster.

The exact same samples as above were used to test the sound absorption coefficient α_w of sandwich panels (with the exception of sandwich panels with solid claddings). They were placed directly on the floor (using installation type A in accordance with the standard EN ISO 354:2003 [3]). The side surfaces of the samples were covered with foil to prevent air (and sound waves) from reaching the sound-absorbing material from the sides of the samples.

Strength tests were conducted on sandwich panels with the mineral wool core with a total thickness of 150 mm (and a corresponding length of 6.2 m), with an inner cladding, flat, perforated in a 60° cylindrical pattern (Rv 3-7.4 – 15.0 %, Rv 3-5 – 32.8% or Rv 6-10 – 32.8%), with a thickness of 0.5 or 0.6 mm and an outer, solid, lightly profiled, with a thickness of 0.5 mm as well as with inner cladding, solid, lightly profiled, with a thickness of 0.5 or 0.6 mm and outer, solid, lightly profiled, with a thickness of 0.5 mm.

Strength tests for bending moment capacity of a simply supported sandwich panel were conducted in accordance with the standard EN 14509:2013, Annex A.5 [1]. It was assumed that the specified test method is representative for sandwich panels where one of the claddings is perforated. The test was conducted in a vacuum chamber by applying air pressure to a simply supported sandwich panel in a single-span configuration, with the load acting in a one direction, simulating wind suction.

The load was measured using force transducers with a range of 10 kN, mounted on the supports. Steel load-distributing plates, 60 mm wide and 8 mm thick, were placed on the load cells. Displacement sensors with a measuring range of 100 and 200 mm were used to record the deflection of the sandwich panel.

Continuous measurements were taken of the loads on the supports and the displacements at two extreme points, 50 mm from the edge at the center of the sandwich panel's span. During the tests, attention was paid to the nature of the damage, which was consistent each time, i.e., the compressed inner cladding first wrinkled and then delaminated from the core.

3. Results and discussion

The evaluation of the obtained results for the specific sound insulation index R_w was conducted in accordance with the EN ISO 717-1:2020 standard. The values of the weighted sound absorption coefficient α_w were determined in accordance with the standard EN ISO 354:2003, while the acoustic class was determined in accordance with the standard EN ISO 11654:1997. The test results are summarized in Table 1.

Table 1. Summary of the specific sound insulation index R_w and sound absorption coefficient α_w for the tested samples.

Designation of internal cladding	Core thickness (m)	Specific sound insulation index R_W (C; C_{tr}) (dB)	Sound absorption coefficient α_W (-)	Acoustic class
Rv 3-7.4 (15%)	0.08 / 0.15	34 (-2; -4) / 34 (-3; -4)	0.95 / 1.00	A / A
Rv 3-5 (32.8%)	0.08 / 0.15	34 (-2; -5) / 35 (-3; -4)	1.00 / 1.00	A / A
Solid cladding	0.08 / 0.15	31 (-2; -3) / 30 (-2; -3)	- / -	- / -

Due to the claddings are lightweight and the core is rigid, the system's resonance frequency occurs in the mid- and high-frequency range. As the thickness of the sandwich panel's core increases, the system's resonance frequency shifts toward lower frequencies. As a result, in certain frequency ranges, sandwich panels with greater thickness have a lower specific sound insulation index (R_w). This phenomenon is particularly evident in sandwich panels with solid claddings. Perforating one of the claddings reduces the specific sound insulation index R_w at the resonance frequency, however, this trend remains consistent. This relationship is only partially reflected in the measured values. Despite changes in the thickness of sandwich panels, the change in the specific sound insulation index R_w does not typically exceed ± 3 dB. However, it is important to note that sandwich panels with perforated claddings (R_w of 34 dB) offer higher specific sound insulation than sandwich panels with solid claddings (R_w equal to 31 dB).

As the thickness of the sandwich panel core increased, no significant change in the sound absorption coefficient α_w was observed regardless of the perforation type. The differences between the results for individual samples increase with sound frequency.

The critical stresses σ_w in the compressed cladding were determined based on the formulas contained in the standard EN 14509:2013, assuming, for the cross-sectional area of the compressed cladding of the sandwich panel A_{F1}, the most unfavorable case - a cross-section passing through the centerline of the perforation. The obtained values of the maximum bending moment M_u

and critical stresses σ_w, taking into account the self-weight of the sandwich panel, are summarized in Table 2. Each row of this table presents the results of series of tests consisting of one or two identical samples. The results are consistent with expectations.

Increasing the perforation rate of the inner cladding, regardless of the size and spacing of the holes, results in a decrease in bending strength compared to sandwich panels with solid claddings on both sides. Using inner cladding perforation Rv 3-5 (32.8%) and Rv 6-10 (32.8%) gives similar results.

It is worth noting, however, that the use of perforated inner cladding in sandwich panels results in greater variability in load and deflection test results compared to sandwich panels with solid claddings on both sides.

Table 2. Summary of the maximum bending moment M_u and critical stresses σ_w values– direction of the load: wind suction.

Designation of internal cladding	Designation of the sample	Internal cladding thickness (m)	Thickness (m)	Maximum bending moment M_u (kNm/m)	Critical stress in a compressed cladding σ_w (MPa)
Rv 3-7.4 (15%)	I – 3a	$0.5\cdot10^{-3}$		3.91	100.53
Rv 3-7.4 (15%)	I – 3c / 4c	$0.6\cdot10^{-}$		4.59 / 5.06	118.23 / 108.64
Rv 3-5 (32.8%)	II – 3a	$0.5\cdot10^{-}$		2.19	46.94
Rv 3-5 (32.8%)	II – 4c	$0.6\cdot10^{-}$	0.08	4.25	138.35
Rv 6-10 (32.8%)	IV – 3a	$0.5\cdot10^{-}$		2.75	89.52
Rv 6-10 (32.8%)	IV – 3c	$0.6\cdot10^{-}$		2.59	70.41
Solid	III – 3c	$0.6\cdot10^{-}$		6.91	187.47
Rv 3-7.4 (15%)	I – 3e / 4e	$0.5\cdot10^{-}$		7.52 / 7.38	102.85 / 101.00
Rv 3-7.4 (15%)	I – 3g / 4g	$0.6\cdot10^{-}$		9.86 / 3.15	112.43 / 35.94
Rv 3-5 (32.8%)	II – 3e / 4e	$0.5\cdot10^{-}$		5.72 / 2.39	98.93 / 41.29
Rv 3-5 (32.8%)	II – 3g / 4g	$0.6\cdot10^{-}$	0.15	7.70 / 2.97	111.04 / 42.86
Rv 6-10 (32.8%)	IV – 3e	$0.5\cdot10^{-}$		2.21	38.17
Rv 6-10 (32.8%)	IV – 3g	$0.6\cdot10^{-}$		6.62	114.51
Solid	III – 2e	$0.5\cdot10^{-}$		7.92	114.29
Solid	III – 2g	$0.6\cdot10^{-}$		11.03	159.10

4. Conclusions

The results of acoustic tests indicate that the sound absorption coefficient α_w for sandwich panels with a core thickness of 80 mm increases as the perforation rate of their inner cladding rises to approximately 30%. For sandwich panels with a core thickness of 150 mm, the effect of increasing the cladding perforation rate above 15% becomes negligible. Therefore, as a basis for further comparative analysis regarding the decrease in bending load capacity and stiffness of sandwich panels as a function of the increasing perforation rate, the maximum perforation degree in the inner cladding on the level 30% has been adopted.

Discrepancies in the results observed in strength tests, caused in part by the wide tolerance in the apparent density of the core, can be eliminated by using strain gauges to measure the deformation of the claddings. Conducting a series of verification material tests will also help determine the impact of the heterogeneous mineral wool core on the test results.

As part of further research, in addition to performing numerical simulations using the Finite Element Method (FEM) on selected test specimens, it is planned to conduct bending load capacity tests on sandwich panels with perforated claddings in a multi-span configuration, while simultaneously observing the deformations of the core in the longitudinal direction of the sandwich panel. The results of the preliminary research analysis confirmed the feasibility of using sandwich panels with one, internal, perforated cladding in a multi-span configuration. This solution has not been yet implemented in practice.

Acknowledgements

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EN ISO 354:2003 Acoustics - Measurement of sound absorption in a reverberation room.
EN ISO 717-1:2020 Acoustics - Rating of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation.
EN ISO 11654:1997 Acoustics - Sound absorbers for use in buildings - Rating of sound absorption.
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Analysis of heat transfer through imperfect sandwich panel joints

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Keywords: Sandwich panels; joint imperfection; numerical modelling; thermal performance

1. Introduction

Sandwich panels are widely used in building envelopes due to their excellent thermal insulation properties and structural efficiency. Their layered configuration, typically consisting of thin steel facings bonded to a lightweight insulating core, enables high stiffness while maintaining low thermal conductivity. Consequently, sandwich panels have become a common solution in industrial, commercial, and cold-storage buildings.

Despite their generally good thermal performance, the introduction of connectors and joints in sandwich panel systems may create thermal bridges, which can significantly increase heat transfer and reduce overall insulation effectiveness. Recent research has highlighted how connector type and geometry influence local heat flux through a thermal bridge in insulated panel systems. For example, Zhang Y. et al. (2026) showed that different connector configurations can produce substantial variations in thermal bridge effects and overall heat loss in high-performance sandwich insulation wall panels.

In practical applications, imperfections in panel joints often arise from manufacturing defects, assembly inaccuracies, or localized material degradation during transport or construction. These imperfections may lead to localized heat losses and reduce the overall thermal performance of building envelopes. The present study therefore focuses on the numerical investigation of thermal effects caused by joint imperfections in sandwich panels.

2. Problem formulation

This study focuses on the numerical analysis of thermal effects caused by joint imperfections in sandwich panels using the Finite Element Method (FEM), in accordance with EN 14509:2013. The analysis is based on a real-case defect observed in an improperly manufactured wall sandwich panel with a polyurethane foam core of 100 mm thickness. The imperfection consists of a local convexity of the core on the male joint side, accompanied by slight misalignments of the outer and inner facings, resulting in the formation of air gaps within the joint region.

FEM simulations were performed for different geometric configurations of defects, including air gaps and partial discontinuities of the insulating core. The influence of panel thickness on the thermal response of imperfect joints is also considered.

In the numerical model, the defects are represented as air cavities of varying geometry and size, enabling the analysis of different levels of severity. The considered scenarios correspond to typical imperfections observed in engineering practice.

3. Numerical analysis

3.1. Theoretical background

In engineering problems aimed at determining the thermal insulation performance of building envelopes, the analyzed heat transfer processes are typically considered steady – state. This means that the changes occurring within the analyzed systems take

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place over sufficiently long time intervals so that stationary thermal condition can be assumed. Consequently, the heat flow is independent of time and the temperature field is assumed to remain constant.

Analyses base on the definition of the thermal transmittance coefficient U, expressed in W/(m²K), defines the amount of heat energy that flows through a building partition with a unit surface area of 1 m² within 1 second when the temperature difference between its surfaces is equal to $\Delta\theta = 1$ K. Sandwich panels are structural elements in which one dimension (their length) is significantly larger than the other two. Each panel therefore possesses a cross-section that remains constant along its length. For this reason, it is possible to consider a representative fragment of the panel with a length of 1.0 m and analyse it using a two-dimensional model of the panel cross-section.

In this case, the heat flow rate represents the amount of heat transferred within 1 second through a 1 m long segment of the panel. By introducing a boundary condition in which the temperatures of the external panel surfaces differ by 1 K, the heat flow rate can be denoted as $\tilde{Q}$ [W/m], while the thermal transmittance coefficient can be expressed as:

$$U = \tilde{Q}_{(\Delta\theta=1\,K)} \left[\frac{W}{m^2K}\right]. \tag{1}$$

In steady-state heat transfer problems where materials are assumed to be isotropic with linear properties (i.e., a constant thermal conductivity coefficient independent of temperature), the quality of the numerical results depends mainly on the accuracy with which the geometry of the system is represented. Therefore, the computational models of the sandwich panel cross-sections analysed in this study were discretized into triangular finite elements whose size was determined by the requirements of accurate geometric representation.

To calculate the thermal transmittance coefficient according to its physical interpretation, a temperature difference of $\Delta\theta = 1$ K was imposed between the lower and upper surfaces of the sandwich panel. In order to achieve this condition, a first-type boundary condition (Dirichlet boundary condition) was applied. The temperature values imposed at the nodes representing the upper and lower surfaces of the panel correspond to those shown in Fig. 1

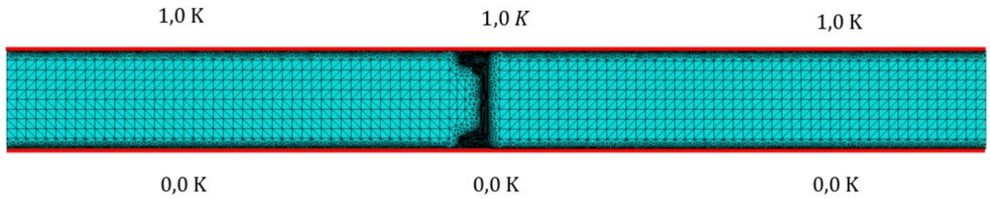

Fig. 1. Finite element discretization and applied boundary conditions.

For each of the finite elements shown in Fig. 1, element conductivity matrices are constructed and subsequently assembled into the global conductivity matrix of the entire system. This procedure is possible because neighboring elements share common nodes within the finite element mesh.

3.2. Numerical example

In this study, the influence of defect geometry in the form of air voids and material configuration on heat transfer and temperature distribution in the joint region was investigated. The assumed joint geometry together with the location of the air cavities is presented in Fig. 2a. The thermal conductivity of the air filling the cavities in the joint was calculated according to the methodology specified in EN ISO 10077-2:2017 [2]. This standard is commonly applied in the calculation of thermal transmittance of windows and doors, however, it was adopted here due to the similarity of the modeled heat transfer process. The temperature field obtained for the analyzed sandwich panel is presented in Fig. 2b.

Based on the obtained heat flow data, it is possible to construct a diagram illustrating the relationship between the heat flow intensity and the coordinate x, where x represents the coordinate across the width of the sandwich panel. The distribution of heat flow intensity along this coordinate is shown in Fig. 3.

The average value of the thermal transmittance coefficient U_m is calculated using the following expression:

$$U_m = \frac{1}{|x_2 - x_1|} \int_{x_1}^{x_2} Q_\perp(x)\,dx \tag{2}$$

where x_1 and x_2 denote the coordinates of the computational model across the width of the panel, and $Q_\perp(x)$ represents the component of the heat flux perpendicular to the panel surface.

The integration shown in Eq. (2) was performed during the post-processing stage, outside the FEM software. The integral was evaluated using the trapezoidal rule by linearly interpolating the heat flux values between known nodal values. In further stages of the study, additional FEM simulations will be performed to investigate various types of joint defects, including gaps and partial discontinuities of the insulating core, and to assess the influence of defect geometry, panel thickness, as well as material configuration on heat transfer and temperature distribution in the joint region.

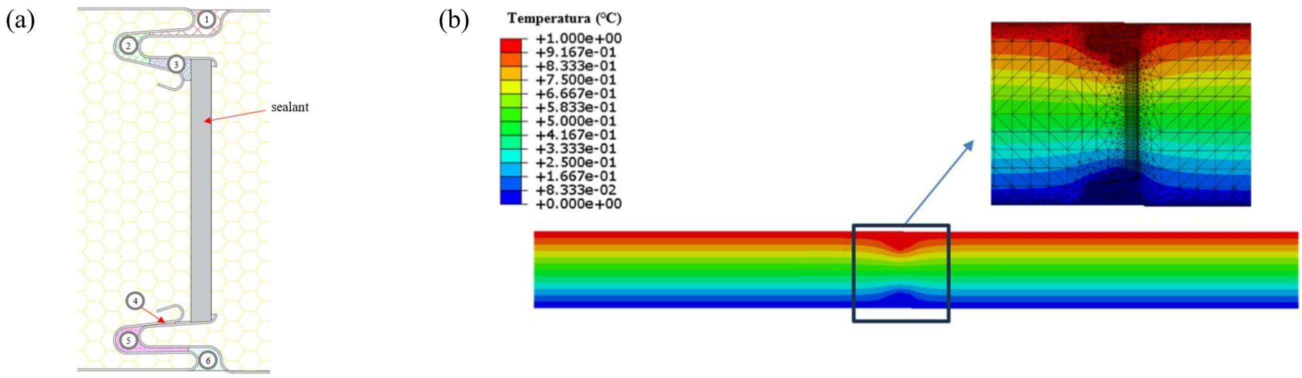

Fig. 2. (a) Numbering of air cavities in the joint; (b) temperature field of the analyzed sandwich panel.

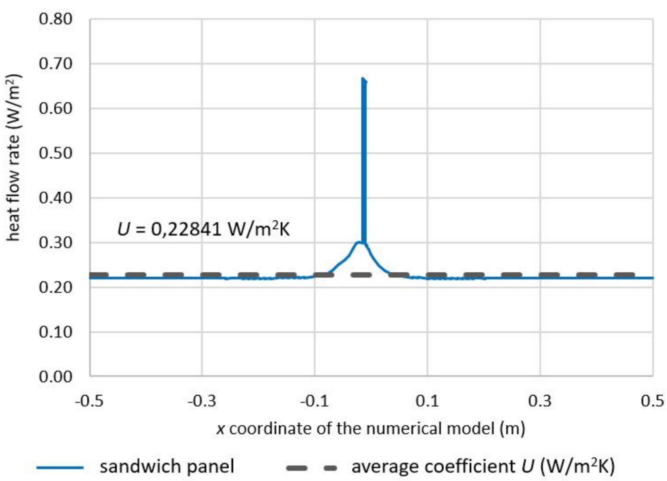

Fig. 3. Heat flow intensity through the panel as a function of the coordinate x in the numerical model; the diagram includes averaged values of the thermal transmittance coefficient U.

4. Conclusions

This study highlights the influence of joint imperfections on the thermal performance of sandwich panels. Even minor discontinuities in the joint region lead to localized heat transfer intensification and the formation of thermal bridges, emphasizing the importance of precise assembly and proper joint detailing.

The results indicate that the thermal response of the joint depends on the geometry and severity of imperfections, as well as on panel thickness. The numerical example presented provides a framework for assessing the thermal effects of such defects and demonstrates the utility of FEM simulations in the analysis and design of panel connections.

Future work will focus on experimental validation of the models and on extending the analysis toward systematic parametric studies, enabling a more comprehensive evaluation of the impact of joint imperfections on the overall thermal performance of sandwich panel systems.

Acknowledgements

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Monitoring-based hygrothermal evaluation of a hybrid timber-sandwich façade

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Abstract

This article examines the structural performance of a solid timber building combined with a sandwich façade. The analysis is based on continuous measurement data on temperature and relative humidity within the exterior wall construction. This data is evaluated and analyzed graphically in conjunction with local weather data, in order to assess the influence of weather and usage on hygrothermal behavior. Additionally, transient simulations were performed using WUFI® Pro software to evaluate condensation and moisture-related risks. Two different interior climate models were applied, based on DIN 4108-3 and EN ISO 13788, to assess their consistency with the measured data. The results show that the temperature profiles within the exterior wall are significantly impacted by weather-related outdoor temperatures, whereas relative humidity is more strongly influenced by usage-related and structural factors. The simulations confirm that no interstitial condensation is expected under the investigated conditions. Furthermore, the indoor climate approach according to DIN 4108-3 shows significantly better agreement with the measured data than the model defined in EN ISO 13788 and that the exterior wall provides high thermal insulation and moisture-proof performance. Overall, the investigated hybrid construction demonstrates high thermal insulation performance and favorable hygrothermal behavior under real operation conditions.

Keywords: Sandwich panels; hybrid timber construction; monitoring and data analysis; building physics

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In-situ analysis of airtightness and hygrothermal properties for metal building envelopes

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Abstract

Lightweight metal constructions used in building envelopes are well established in industrial and commercial construction. Besides the high prefabrication potential and structural efficiency, aspects of building physics are becoming increasingly challenging. To meet the increasing requirements of the last decades, existing solutions have been continuously optimized and refined. Despite the improvements, a growing number of failures related to moisture content, corrosion, thermal bridging and air leakage can be observed. Direct assessment methods of building physics properties offer potential both for development of lightweight metal construction and the successful prevention in existing systems. Experimental approaches including blower door testing, thermographic analysis, moisture content measurement and hygrothermal monitoring constitute a toolkit for scientific investigation. Based on previous research results, experimental concepts can be developed and subsequently validated with existing data and corresponding numerical simulations. Due to the limited understanding of the underlying damage mechanisms resulting from influencing factors and given boundary conditions, insights on both impact and resistance side can be gained. A transfer from element to construction scale is necessary to capture more complex process interactions and system correlations. Information from this concept can be effectively applied in the development of new technical rules for production and assembly level. In addition, a precise and target-oriented use of monitoring procedures is supported.

Keywords: Metal building envelopes; airtightness; hygrothermics; monitoring

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Air-coupled ultrasound driven inline quality control of lightweight metal façades

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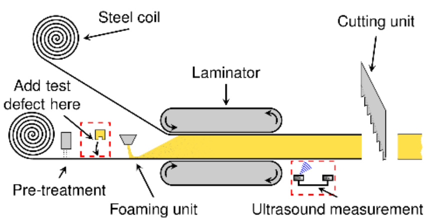
Keywords: Sandwich panels; non-destructive testing (NDT); air-coupled ultrasound; inline monitoring; Lamb waves

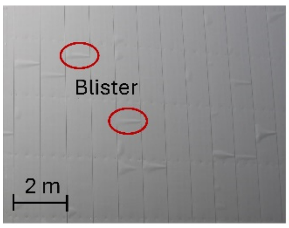
1. Introduction

Lightweight sandwich panels with steel faces and a rigid polyisocyanurate (PIR) foam core combine low weight, good insulation performance, and rapid installation (Jelčić Rukavina et al., 2022; Khan et al., 2020). A recurring problem is the formation of large blisters on the outer face after installation. These blisters can expand over time and may reduce load-bearing capacity (Kühn et al., 2024), so affected panels often require costly replacement. One plausible mechanism is that blister growth initiates from small near-interface degradations that already exist after manufacturing, such as air voids, locally altered foam structure, or weak bonding between the steel face and the foam (Fig. 1a,b) (Burman et al., 2019).

Because naturally occurring defects are typically detected only with off-line methods, there is strong motivation for an inline non-destructive inspection method that can screen panels directly in the production line. Air-coupled ultrasound is a promising approach for production environments because it avoids couplant layers, works on all materials and simplifies integration into a moving production line (Essig et al., 2021; Siegmund et al., 2010). Prior work has shown that ultrasound can detect air voids the size of a few centimeters in the foam of sandwich panels (Haugwitz et al., 2024; Yang et al., 2023). Translating such methods from laboratory conditions to a production line (Fig. 1c) requires robustness against noise, temperature, and material variability and introduces temporal and spatial constraints.



(a)



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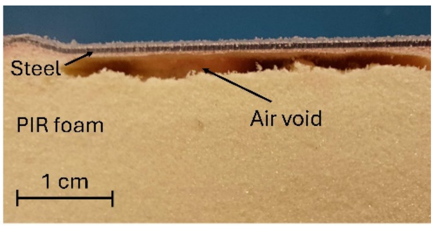

(c)

Fig. 1. Motivation and inline inspection concept. Blister formation in sandwich panels after installation should be avoided (a). A near-interface void or interface degradation might be a possible starting point for blister formation (b). An ultrasonic measurement in the sandwich panel production line can detect defects early (c). In this case the ultrasonic measurement unit is placed downstream of the laminator to inspect the hardened panel inline. It is placed from below since the lower steel face of the production line will be the outer face in its constructed state, which is subject to higher stress. (Images from (Haugwitz et al., 2026)).

In earlier work (Haugwitz et al., 2026), we developed and deployed an industrial prototype operating at 216 kHz to excite guided waves in the steel face sheet and to evaluate amplitude variations along the production direction (Fig. 1c). The system was validated

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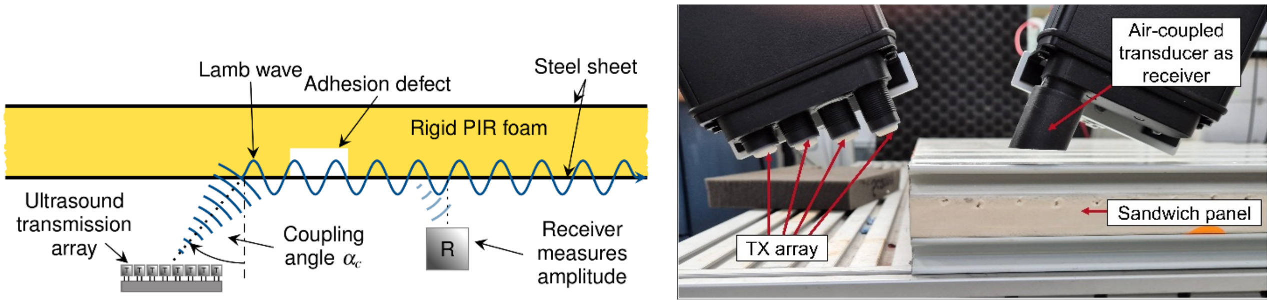
on the production line using reproducible artificial near-interface air voids introduced via inserted foam blocks. Using a conservative fixed threshold corresponding to four standard deviations of the noise, the prototype achieved a detection rate of 63% for air-void defects while showing no false detections during the reported measurement interval. Lowering the threshold increased detection at the expense of false alarms. These results establish that the setup can operate under real production constraints. However, to date, only air-void defects have been evaluated, whereas real-world defects are more diverse and may also be detectable using ultrasound. These interface-related defects can also be one cause for blister formation (Kühn et al., 2024).

This work tests whether the same non-contact system can also detect interface-related degradation induced by reduced primer application. For this purpose, a sandwich panel with a pronounced adhesion problem between the PIR foam and one steel face near a panel edge is produced and evaluated using the established 216 kHz industrial prototype (Haugwitz et al., 2026).

2. Experimental setup

The inspected component is a typical sandwich panel with thin (0.63 mm) steel faces and a thick rigid PIR foam core, manufactured on a continuous production line. The lower steel sheet in the production line, which is the outer sheet in the constructed state, is pretreated using a primer to increase adhesion between the face and the core. This is followed by application of the foam precursor and curing in the laminator, after which the continuous structure is cut into individual panels (Fig. 1(c). For this work, the pretreatment, i.e., the primer, is omitted along the left outer groove, to induce a lower-adhesion zone there (Fig. 3(b).

In this work, the air-coupled ultrasonic system is used on the cut sandwich panels in a lab (Fig. 2). The ultrasonic unit operates at 216 kHz and uses air-coupled ultrasonic transducers for both transmission and reception. The transmission unit consists of a four-by-one array of air-coupled transducers (AIR SCAN 200) driven at 200 Vpp to excite a Lamb wave in the outer steel face sheet. The receiving transducer is mounted at an inclination angle close to the coupling angle to maximize sensitivity to the leaky Lamb wave radiated from the steel face sheet into air (Fig. 2).



(a) (b)

Fig. 2. Measurement principle and prototype. An air-coupled Lamb wave is excited in the steel sheet and then received (a). Any anomaly, such as an interface condition change can alter the measured amplitude. The 216 kHz setup used with transmitter and receiver aligned with the coupling geometry is mounted on a 2D mechanical scanning unit (b). The sandwich panel is flipped upside down, such that the lower steel sheet in the production line is measured.

On the receiving side, analog-to-digital converters (LTC2325-16) are used at a sampling rate of 5 MHz. The received signal is preamplified and prefiltered using an analog low-pass filter with a 400 kHz cutoff frequency and then transmitted via UDP to a measurement PC for processing.

To cover the full panel width of 1 m with higher spatial resolution than the production-line prototype, a 2D mechanical scanning procedure is used, where the panel is scanned by mounting the ultrasonic setup on a 2D stage. The scan step in this experiment is 1 mm. The acoustic path is oriented along the production direction because the profiled grooves strongly attenuate propagation in the transverse direction.

For each measurement, a five-cycle burst at 216 kHz is transmitted and the received waveform is recorded. This sequence is repeated every 5 ms. Signal processing consists of bandpass filtering around the center frequency and extraction of the maximum envelope amplitude. The amplitude is then mapped to spatial position to form a scan image.

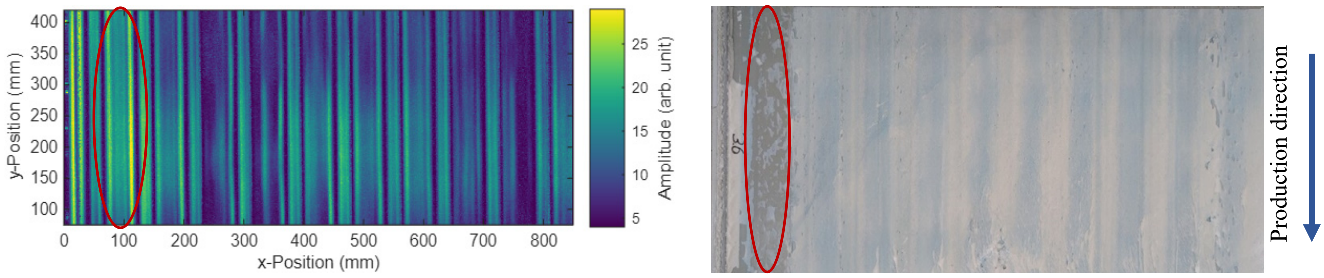
3. Results and discussion

A scan of the produced defective panel shows higher amplitude on the left side of the sandwich panel (Fig. 3a). The measured amplitude is higher in the low-adhesion zone (left) than in the adjacent region with normal pretreatment. The vertical stripe pattern in the scan is attributed to the grooves in the profiled steel face of the sandwich panel.

A total of n=8 of these defective panels is examined, and the average amplitude increase from the left groove with adhesion defect to its neighboring groove without adhesion defect is 49% with a standard deviation of 10%.

After ultrasonic measurement, the steel face sheet is torn off from the foam core to test adhesion quality (Fig. 3(b). On the far left side of the investigated face, the steel sheet shows almost no foam residue, which indicates poor adhesion due to the omitted primer layer, whereas other areas show normal remaining foam on the steel surface.

A plausible physical explanation for the increased received amplitude is that locally weakened bonding changes the effective boundary condition at the steel-foam interface. Reduced interfacial contact or reduced viscoelastic loading can decrease guided-wave attenuation, thereby increasing the received amplitude, which is consistent with the observed sign of the change. However, amplitude changes are not uniquely attributable to adhesion. Another explanation is that reduced primer application alters the interface mass loading and/or damping, also potentially decreasing attenuation and increasing amplitude. With this measurement setup, the experiment cannot discriminate between a primer-layer effect and an adhesion-strength effect.



(a) (b)

Fig. 3 The ultrasonic scan of the panel prior to the tear-off (a) shows an amplitude increase of about 50% over the low-adhesion region (a, red oval). The vertical stripe pattern is due to the profiled grooves of the steel sheet. After tearing off the steel face sheet (b), it shows almost no foam residue on the left side, indicating poor adhesion in the same region as the ultrasonic anomaly.

Overall, this case demonstrates that the ultrasound unit from the industrial prototype previously developed for near-interface air-void detection can measure a pronounced amplitude change co-located with the region of omitted primer and a corresponding poor adhesion. The measurement is therefore sensitive to the induced sandwich panel interface modification.

4. Conclusion

This work evaluates an existing 216 kHz air-coupled ultrasonic prototype, previously validated for near-interface air-void detection, for its sensitivity to interface-related degradation produced by omitted primer application near a panel side. The measurement showed a localized amplitude increase of on average 49% in the region corresponding to omitted primer. Post-test tear-off inspection confirms the poor adhesion with little foam residue on the steel face in this region on the left side.

The main finding is that the non-contact guided-wave measurement is sensitive to the reduced primer and its reduced adhesion, producing a significant amplitude contrast relative to adjacent nominal regions. A limitation is that the observed amplitude increase may result from reduced adhesion, from changes in primer-related mass loading, or from a combination of both. Therefore, although the anomaly was detected, it cannot be concluded that ultrasound can measure adhesion strength in sandwich panels. Additionally, generalization is limited due to only eight measurement panels without direct reference.

Future work can include a larger set of panels to assess variability and repeatability, incorporate quantitative adhesion measurements, and develop a controlled method to reduce adhesion strength independently of primer layer reduction, enabling separation of primer-layer effects from adhesion-related changes in the ultrasonic response.

Acknowledgements

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Aging processes and lifecycle monitoring of polyurethane sandwich panels

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Abstract

Sandwich panels with polyurethane rigid-foam cores are widely used as roof and façade elements in industrial construction due to their favorable thermal performance, low weight and high degree of prefabrication. However, increasing numbers of damage cases indicate that the long-term behavior of currently used polyurethane core systems is not yet sufficiently understood. Existing approval procedures and design concepts are largely based on historical material systems, whereas currently installed panels contain significantly modified polyisocyanurate (PIR) foam cores. Recent investigations demonstrated that temperature exposure, aging processes and production-related parameters influence the mechanical and physical behavior of sandwich panels. Experimental investigations included temperature measurements under realistic service conditions, investigations of cell-gas composition, density distributions and temperature-dependent material properties. Nevertheless, the interaction between production parameters, environmental exposure and long-term degradation remains insufficiently described. This paper summarizes the current understanding of aging processes in polyurethane sandwich panels and derives a mechanism-based lifecycle monitoring framework. Based on recent experimental findings, degradation mechanisms and monitoring-relevant parameters are identified and integrated into a conceptual digital twin approach. The proposed framework aims to support future durability assessment, early damage detection and resource-efficient lifecycle management of sandwich structures.

Keywords: Sandwich panels; polyurethane foam; aging process; lifecycle monitoring; digital twin

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Assessment of existing sandwich panel façades for reuse and retrofit

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Abstract

Sandwich panels with polyurethane (PU) cores have been widely used as building envelopes in industrial construction. In Germany alone, approximately 500 million m² have been installed since the 1990s. In the context of climate change mitigation and the circular economy, both their reuse after deconstruction and the retrofitting of existing buildings are gaining increasing importance. In addition to residual load-bearing capacity, the suitability of these panels for additional functions, such as photovoltaics, curtain wall façades, or greenery, is particularly relevant. However, no standardized assessment procedures currently exist, highlighting the need for systematic research. This study investigates the reuse potential and retrofitting capacity of deconstructed sandwich panels with an age of approximately 30 years. The research methodology combines a review of literature and standards, evaluation of historical approval documents and experimental testing of dismantled as well as comparable new components. The tests range from visual inspections to material characterization. The results are compared with both the original approval values and current normative requirements. Based on these findings, an initial methodology is outlined for assessing residual load-bearing capacity and adaptability for functional retrofits. The results indicate that even decades-old sandwich panels may retain sufficient mechanical performance to allow further structural use. The work therefore represents a starting point towards resource efficiency by extending the service life of building materials.

Keywords: Sandwich panels, reuse, retrofit, residual capacity, dismantled panels, sustainable construction

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Parametrized life cycle assessment of modular construction systems

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Keywords: Carbon-reinforced concrete, modular construction, life cycle assessment, sustainability, design

1. Introduction

The construction sector is under increasing pressure to reduce its environmental impact while maintaining structural performance. According to the Global Status Report for Buildings and Construction 2024/2025, it accounts for 34% of the global energy demand, and CO_2 emissions have continuously risen since 2015 (UNEP 2025). Embodied carbon from materials such as steel and cement is a major source of emissions, contributing to 18% of the global building-related CO_2 emissions in 2024. Since monolithic designs made of steel- reinforced concrete continue to be the most commonly used construction approaches worldwide (Flatt et al. 2012; Bischof et al. 2022), there is a need for environmentally less burdensome construction approaches. As the structural weight of buildings is one of the driving factors of embodied emissions (Machado et al. 2025), a replacement with lighter, thin-walled components guided by new design strategies has the potential to pave the way for more environmentally sustainable construction. One potential solution for that is carbon-reinforced concrete (CRC). Using carbon reinforcement not only leads to a substantial reduction in material usage (Backes et al. 2023) but also opens up opportunities for new design possibilities. Modular designs in particular have been found promising by the scientific community in increasing disassembly and reuse rates (Minunno et al. 2020), and decreasing the potential environmental impact of the building sector (Andersen et al. 2022; Kamali et al. 2025). However, Lamberti Tornaghi et al. (2018) point out that, to incorporate sustainability considerations into decision-making within the construction sector, they must be integrated early on in the design stage alongside structural assessments. So far, environmental life cycle assessments (LCAs) have mostly been applied to finalised building designs, where adjustments are no longer possible. Existing literature on parametrized approaches in the built environment often does not conduct a simultaneous assessment of both environmental and structural aspects, and focuses on only limited impact categories such as Global Warming Potential (GWP).

2. Research objective

This study introduces a dynamic evaluation strategy for the potential environmental impact of a modular ceiling element based on variable geometric design parameters, while fulfilling structural integrity. The objective is to create a method that can support decision makers in the early design stage of building construction, considering not only structural requirements, but also environmental performance according to the concept of ecodesign for sustainable products regulation (Moch et al. 2026). The method is presented on the example of a modular ceiling system based on a waterbomb origami design made of CRC. The present study therefore assesses the potential of design innovation and material substitution to mitigate potential environmental impacts while maintaining structural performance.

3. Method

To guide decision makers in the construction sector, who are not necessarily LCA experts, this study developed a methodology combining structural strength assessment and LCA. It is divided into four main steps: *1) Definition of the product system*, *2)*

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Structural strength assessment, *3) Environmental sustainability assessment*, and *4) Combined interpretation*. In the first step, the product system is properly defined, including geometric parameters and material specifications. In this step, it is additionally specified which parameters will be fixed and which variable for the structural and environmental assessment. Secondly, the structural strength is assessed, in dependence on the variable parameters. This results in setting a boundary of the variable parameter, which needs to be kept as a requirement to ensure structural integrity, and thus the fulfilment of the building components' function for all other parameter variations. Only then can the parametrized cradle-to-gate LCA, in accordance with ISO 14040/44, be conducted to quantify potential environmental impacts (ISO 2006a; ISO 2006b). The same functionality of the design variations is ensured by the boundary defined in the second step. On the example of a modular ceiling system of a ceiling system made of reinforced concrete modules, the calculations in step 3 are done as follows (equation 1): The potential environmental impact of the ceiling structure is made of the potential environmental impact of the necessary materials for one module, multiplied by the number of modules ($\mathrm{No}_{\mathrm{modules}}$) and the potential environmental impact arising from the assembly ($\mathrm{EIP}_{\mathrm{assembly}}$). The potential environmental impact of the necessary materials is the sum of the potential environmental impact of the concrete ($\mathrm{EIP}_{\mathrm{c}}$) per m³ multiplied by the necessary Volume V_c, and the potential environmental impact of the reinforcement (EIP_r) per kg multiplied by the necessary mass m_r. Compared to conventional LCA approaches, the reference flow varies according to the chosen parameters. This makes it easy to assess the potential environmental impact of multiple design variations.

$$EIP_{ceiling} = (EIP_c \cdot V_c + EIP_r \cdot m_r) \cdot No_{modules} + EIP_{assembly} \tag{1}$$

One of the main advantages of the proposed approach is that, besides the scenario analysis of different parameter variations, it also allows analysis of multiple impact categories beyond climate change. Following that, in the final step, the results of the structural strength assessment and the LCA are interpreted in a combined evaluation. Here, the influence of the variable parameters on environmental and structural performance can be shown simultaneously, and trade-offs can be easily identified.

4. Results and discussion

Step 1) Definition of the product system: The applicability of the proposed approach is demonstrated using an origami-inspired folded carbon-reinforced concrete module (Gomes et al., 2025). This module is designed for modular structural systems like slabs and walls. Its folded geometry enables efficient load transfer and high material utilization, supporting the development of lightweight, high-performance, and environmentally responsible construction systems. At this initial stage, a single waterbomb module is selected to quantify both its flexural load-capacity and environmental performance, thereby illustrating the potential of this design approach. The module geometry is parametrized by the length design ($a, b, c,$ e), the folding angle (γ), thickness (t) (Chudoba et al. 2021). Reinforcement is provided by carbon-textile grids characterized by grid spacing (s_x, s_y), textile linear density (T_{warp}, T_{weft}), density of the impregnated textile (ρ_r), and the number of reinforcement layers (N). This parametrization enables a systematic exploration of the design space to assess how geometric and reinforcement variables influence the cross-sectional load-bearing capacity and the associated environmental impacts.

Step 2) Cross-sectional flexural load-capacity of waterbomb modules: To evaluate the flexural capacity of the waterbomb module, a representative cross-section is extracted by introducing a cut at mid-span. The flexural load capacity is then determined through an iterative cross-section capacity (Spartali et al. 2021). The module with t = 15 mm and N = 2, which reaches a flexural capacity of 5 kNm, is used as the baseline reference $t_{base,min}$ (Gomes et al. 2025). Because the flexural capacity scales linearly with the amount of reinforcement, doubling the number of reinforcement layers results in a proportional increase in load-carrying capacity.

Step 3) Environmental sustainability assessment: The potential environmental impacts are calculated following the four-phase approach of a cradle-to-gate LCA according to ISO 14040/44. The functional unit is specified as one waterbomb module as defined in *step 1)*, which meets the flexural load-capacity baseline. Accordingly, the reference flows are equations dependant on the variable parameters t and N, within the bounds of $t_{base,min}$, as specified in s*tep 2)*. The potential environmental impact is calculated for the 16 impact categories of the Environmental Footprint (EF 3.1) methodology, using the software GaBi ts.

Step 4) Combined interpretation: Analysing the potential environmental impact of the product system for various impact categories together with the results of the flexural capacity, we state that the cross-section thickness should accommodate the maximum reinforcement possible, as it scaled linearly, and the failure of the module is given by the rupture of the textile reinforcement. Increasing the module thickness without adding reinforcement yields only a marginal structural benefit - about a 10% increase in flexural capacity - whereas doubling the reinforcement layers produces a proportional and far more substantial gain in flexural load-capacity. This difference is enabled by the origami-inspired geometry, which uses very little concrete in combination with the flexibility of the textile reinforcement to be shaped directly to the folded form. As a result, the reinforcement governs the structural behavior, and additional concrete volume contributes far less to overall performance. This clearly shows that structural efficiency in the waterbomb module is driven primarily by reinforcement content rather than by increasing thickness alone. Meanwhile, the potential environmental impact increases linearly with the thickness of the material, with jumps occurring when a reinforcement layer is added. With our proposed approach, interrelationships between the structural and environmental properties of the product system can be identified. The combined evaluation clearly shows that there is a trade-off between increased structural strength and lower environmental impact, when varying the module's thickness t and number of reinforcement layers N. The minimal threshold value $t_{base,min}$ for compliance with the structural requirements is defined as the lower limit of the evaluated variations of t. A possible extension of the model could include an additional upper limit $t_{base,max}$, which is defined by a condition of maximum environmental impact.

5. Conclusion

Within the scope of this study, a parametrized approach to integrate sustainability considerations along with structural assessments in the early design stage of modular building components has been developed. The applicability of the approach was shown on the example of a modular ceiling system made of a CRC waterbomb design. The study demonstrates the potential of coupling advanced structural design with material-efficient CRC technologies to drive sustainable construction. It contributes to redefining criteria for sustainable building components and supports the transition towards resource-efficient practices by integrating structural and environmental performance into design decision-making. It is an important step towards equal integration of structural and environmental considerations in the early design stages of building components. Furthermore, it allows for future adjustments, for example, to integrate an optimization model or environmental boundary conditions. Limitations of our work and research gaps that should be addressed in future research include the application of the introduced approach to a ceiling system made of multiple modules, a comparative application with a state-of-the-art ceiling system, performing an optimization model, inclusion of environmental benchmark values, and further addressing the social and economic dimensions of sustainability, which have been neglected thus far. Nevertheless, this introduced approach of environmentally and structurally assessing modular building components opens the possibility for improved decision-making in the early design stages. It allows decision-makers to equally consider structural and environmental requirements and drive sustainable development in the construction sector.

Acknowledgements

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SMAR 2026

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

MS07: Distributed fiber optic strain sensing for bridge structural health monitoring

Organizers:
Bertram Richter (TU Dresden, Germany)
Steffen Marx (TU Dresden, Germany)

ABSTRACT

The field of civil infrastructure monitoring has seen significant advancements with the adoption of distributed fiber optic strain sensing (DFOSS) technologies, which enables to monitor both global on local structural behavior at the same time. Hence, DFOSS provides a revolutionary monitoring approach, offering unprecedented resolution and comprehensive coverage of complex structures with a single optical fiber.
This Mini Symposium brings together leading experts to share recent experiences and explore new applications of DFOSS-based structural health monitoring (SHM). Topics will include the deployment of DFOSS systems in various bridge types, integrating DFOSS data with existing SHM frameworks, and case studies highlighting successful applications and lessons learned. The symposium will also address the potential of combining DFOSS with emerging technologies, such as machine learning and digital twins, to enhance bridge monitoring capabilities. The insights gained will contribute to developing standardized guidelines and best practices for the use of DFOSS in bridge SHM.

Distributed fibre optic sensors for bridge health measurements: from small to large scale

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Abstract

Distributed fibre optic sensing (DFOS) is increasingly being adopted for bridge health monitoring, providing a powerful alternative to traditional point-based measurement systems. Its capability to deliver continuous strain, vibration and temperature profiles along the entire length of an optical fibre enables engineers to capture localised effects such as cracks or stress concentrations. Moreover, it is also possible to analyse, based on the registered strain profiles, other phisical quantities like curvatures, bending moments and displacements. Although the full potential of this technology becomes most evident in large-scale bridges, where sensing routes may extend for several kilometres, practical experience demonstrates that valuable insights can also be gained from short-span structures and even small-scale components. For example, DFOS applications on short spans or embedded elements, such as steel anchors, have revealed detailed structural behaviour that would otherwise remain inaccessible. This article highlights both large- and small-scale applications of DFOS in bridge engineering. Practical aspects of sensor embedding and installation are discussed, together with examples of monitoring results obtained from real structures. These case studies illustrate the diagnostic and interpretative possibilities offered by DFOS for bridge applications.

Keywords: Distributed sensors; bridge; measurements; strains; cracks

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Structural health monitoring of bridges using distributed fiber optic sensing

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Abstract

Structural health monitoring (SHM) of bridge infrastructure is essential for evaluating performance and ensuring safe operation throughout its service life. Distributed Fiber Optic Sensing (DFOS) has gained increasing attention for bridge monitoring due to its ability to provide high-resolution, spatially continuous strain measurements under both static and dynamic loading. This study presents DFOS-based monitoring of a concrete–steel highway bridge located along Interstate 94 in Wisconsin, USA. Rayleigh-based Optical Frequency Domain Reflectometry (Rayleigh-OFDR) was used to measure static strain distributions during controlled load testing, showing good agreement with finite element analysis results in the midspan region. Distributed Acoustic Sensing (DAS) was employed to capture dynamic strain responses from passing traffic and to detect individual vehicle events. The influence of fiber–structure coupling conditions on DAS measurement quality was also investigated. Results indicate that directly coupled fibers record stronger signal amplitudes, particularly for light vehicle loads, while uncoupled fibers still capture detectable vibration responses. These findings highlight the potential for using both bonded and existing dark fiber infrastructure for scalable bridge monitoring applications.

Keywords: Bridge monitoring; DFOS, Rayleigh-OFDR; DAS; strain sensing

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

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Long-term baseline stability assessment of a BOTDA-based fiber optic sensing textile for bridge monitoring

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Keywords: BOTDA; distributed optical fiber sensing; structural health monitoring; sensing textile, long-term durability

Distributed fiber-optic sensing (DFOS) based on Brillouin optical time-domain analysis (BOTDA) has been widely investigated for bridge structural health monitoring because of its long sensing range, dense spatial sampling, and ability to provide distributed strain measurements under field conditions (Bado and Casas, 2021, Barrias et al., 2026). However, for long-term bridge monitoring, the key challenge is not only acquiring strain profiles but also ensuring that measurements collected over years remain comparable. Apparent changes in baseline strain profiles may arise from temperature variation, connection conditions, loop-back regions, packaging effects, and other non-structural influences, which can obscure or exaggerate actual structural behavior. Therefore, establishing practical and quantitative criteria for long-term baseline stability is essential before BOTDA data can be reliably interpreted for asset management (Bao et al., 2021, Minardo et al., 2012, Chen et al., 2023).

This study presents a six-year baseline stability assessment for a composite bridge girder instrumented with a fiber-optic sensing textile in a loop-back configuration. The dataset consists of six field measurement campaigns conducted from 2020 to 2025 under an unchanged sensing workflow. The sensing chain included two bonded structural sensing sections and several non-structural regions, including connection fibers, a free-fiber section, and a turn-around region. To distinguish structural behavior from measurement-chain effects, a segment-aware framework was developed. The sensing chain was divided into five segments: Sensing fiber (A), sensing section 1 (B), free fiber (C), sensing section 2 (D), and Return fiber (E), as shown in Fig. 1. This segmentation allowed stability metrics to be evaluated separately for structural and non-structural regions (Biondi et al., 2023, Abedin et al., 2023, Wang et al., 2026).

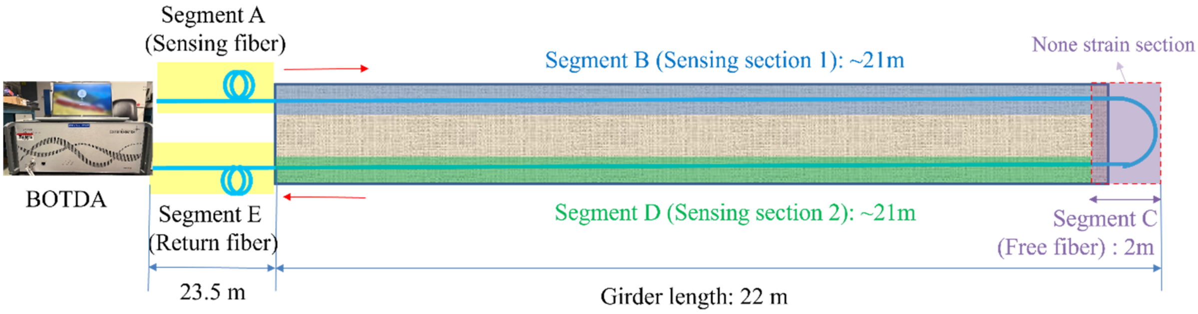

Fig. 1. Schematic of the fiber-optic sensing textile layout and loop-back sensing chain, including the bonded structural sections and non-structural routing regions.

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The sensing fiber was integrated into a smart textile carrier using programmable embroidery, which enabled controlled fiber routing, simplified handling and installation, and improved protection against abrasion and mechanical damage (Wu et al., 2023). The textile carrier also helped maintain consistent anchoring and bonding conditions along the structural sensing sections. The non-structural fiber portions (Segments A, C, and E) were retained for optical launch, return, and loop-back routing and were not intended to serve as structural sensing regions. These portions were routed with strain relief/protection where possible, but they were not mechanically bonded to the girder in the same manner as Segments B and D. Therefore, they were treated as end-effect or free-fiber zones and analyzed independently from the bonded sensing sections. BOTDA interrogation was performed in a loop sensor configuration with a nominal sensing length of 100 m, 1.0 m spatial resolution, 2.5 ns sampling interval, and frequency sweeping over approximately 10.65–10.95 GHz. Figure 2 shows the six-year baseline strain profiles, with the approximate segment boundaries explicitly marked.

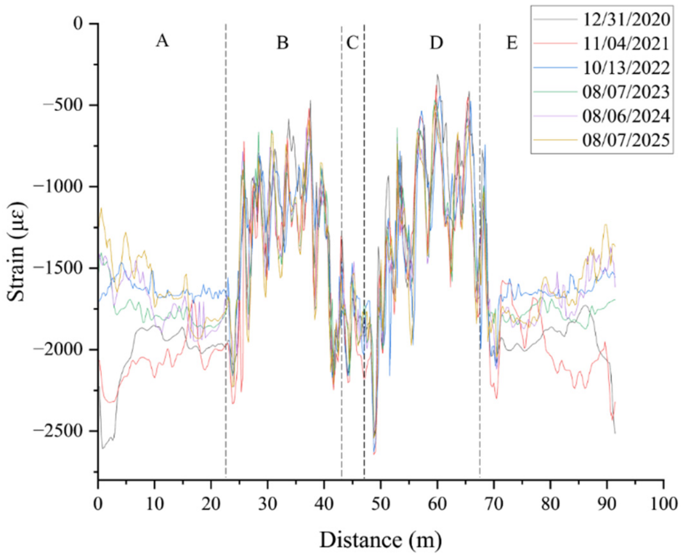

Fig. 2. Six-year baseline strain profiles with approximate segment boundaries (A-E).

Six field tests were conducted on December 31, 2020 (-0.1 °C), November 4, 2021 (3.0 °C), October 13, 2022 (12.6 °C), August 7, 2023 (24.7 °C), August 6, 2024 (26.7 °C), and August 7, 2025 (26.0 °C). Temperature compensation was applied at the Brillouin-frequency level. For each campaign, the temperature-induced component was removed using ΔvB,T = CT(Ti – Tref), where Tref is the 2020 baseline temperature and CT is the BOTDA temperature coefficient from the instrument manual, following the standard BOTDA strain-temperature relation (Ba et al., 2021). The corrected frequency shift was then converted to strain. This accounts for the direct thermal sensitivity of the sensing fiber, while temperature-related structural expansion/contraction was treated as a field-condition effect and evaluated through segment-wise baseline comparisons rather than interpreted directly as damage.

Table 1. Test dates and recorded temperatures.

Date	Temperature (°C)
12/31/2020	−0.1
11/04/2021	3.0
10/13/2022	12.6
08/07/2023	24.7
08/06/2024	26.7
08/07/2025	26.0

The 2020 campaign was selected as the unique reference baseline, and all later campaigns were compared against it. To quantify long-term baseline evolution, segment-wise root-mean-square deviation (RMSD) referenced to the initial baseline was adopted. In addition, because both Brillouin frequency shift (BFS) and strain profiles were available, an internal BFS-strain consistency check was used as a quality-control step to verify cross-campaign comparability. Table 2 summarizes the segment-wise RMSD values and the post-baseline RMSD fluctuation range across the six field campaigns.

Table 2. Segment-wise RMSD values relative to the 2020 baseline for the six field campaigns. The last column shows the post-baseline fluctuation range, ΔRMSD, calculated from 2021 to 2025.

Segment	12/31/2020	11/04/2021	10/13/2022	08/07/2023	08/06/2024	08/07/2025	RMSD range Δ (με)
A	0.0	166.6	471.0	492.1	613.2	550.0	446.6
B	0.0	260.7	266.8	261.2	290.3	291.2	30.5
C	0.0	193.5	112.7	118.7	133.5	128.9	80.8
D	0.0	242.8	271.4	253.0	265.7	293.6	50.8
E	0.0	173.8	234.3	286.8	320.4	363.1	189.3

The results show that apparent long-term variations are strongly segment dependent. Across the full sensing chain, the largest deviations repeatedly occurred in the connection- and return-fiber regions, whereas the two bonded structural sensing sections remained comparatively stable over the six-year monitoring period. By the 2025 campaign, Segment A exhibited the highest RMSD value of 550.0 με, followed by Segment E with 363.1 με. Segment C also showed non-negligible fluctuation (ΔRMSD = 80.8 με), which is consistent with its free-fiber/turn-around condition and lack of mechanical fixation. In contrast, the structural sensing sections (Segments B and D) showed lower long-term variation, with RMSD values remaining within 242.8-293.6 με from 2021 to 2025 and ΔRMSD values of only 30.5 με and 50.8 με, respectively. These results indicate better repeatability and baseline stability in the bonded structural sensing regions. For future warning-system design, thresholds should therefore be derived from persistent changes within the bonded structural sections rather than from whole-chain deviations that include connection, return, or free-fiber effects.

Although the structural sensing sections were significantly more stable overall, several localized points within Segments B and D showed elevated drift relative to their surroundings. Persistent hotspot candidates were identified near approximately 25-27 m, 38.6 m, and 50-53 m along the BOTDA distance axis. These hotspots may be associated with localized strain-transfer differences, anchoring or packaging variation, geometric discontinuities, or local structural behavior. Importantly, the proposed framework does not interpret every hotspot as evidence of damage. Instead, it provides a quantitative screening tool for identifying locations that merit follow-up inspection, repeated measurement, or controlled loading tests.

In summary, this work demonstrates that long-term baseline variations in BOTDA-monitored bridge girders are dominated by connection, free-fiber, and turn-around effects rather than by the bonded structural sensing sections. A segment-aware assessment framework using temperature normalization, RMSD, and fluctuation-range metrics was shown to provide practical guidance for robust baseline tracking, data-quality screening, and future alarm-threshold design. For long-term bridge monitoring, baseline stability should therefore be quantified on clearly defined structural sensing sections, while connection, return, and loop-back/free-fiber regions should be isolated as non-structural zones. This approach improves the reliability and interpretability of long-term BOTDA measurements and provides a practical pathway for future DFOS-based infrastructure monitoring.

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Realtime DFOS based SHM of a highway bridge

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Abstract

The bridges built during the years of rapid expansion of the European transport infrastructure in the 1960s to 1980s are currently reaching the end of their service life. Decades of increasing traffic loads as well as corrosion reduce the structural capacity. In many cases, replacement of the bridges has already been planned, but planning and construction take time. This is where Structural Health Monitoring (SHM) comes into play, enabling structures to remain in operation even when in critical condition.
The focus of the system introduced here is the reliable detection of tension wire breaks, crack detection and the early assessment of the consequences for operational safety. The measurement technology includes high-resolution distributed fiber optic strain sensors (DFOS) along all bridge girders as well as acoustic emission sensors (AE) and acceleration sensors (ACC). While the latter two systems can be regarded as standard or established, DFOS is relatively new in the field of bridge monitoring. Its unmatched suitability for crack detection has been proven in many laboratory applications and scientific studies in recent years. Individual structural installations have been implemented, but usually as discontinuous measurements taken on specific dates.
In this project, DFOS is used as a permanent system that automatically analyzes crack activity and feeds information into an alarm system in real time, as well as visually processing it in a specially developed dashboard and linking data to a digital twin.

Keywords: Bridge monitoring, distributed fiber optic sensing, integrated monitoring system, 24/7 operation, digital twin, crack monitoring

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

Distributed fiber optic sensors as part of a hybrid structural health monitoring system of an extradosed bridge

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Abstract

This paper presents the implementation and first-year results of a hybrid structural health monitoring (SHM) system installed on an extradosed viaduct. After approximately eight years of service, localized structural damage was identified near the support cross-beams at the abutments. Following repair works, a monitoring program was introduced to verify structural performance and ensure long-term operational safety. The monitoring strategy combines continuous automated monitoring with periodic inspection-based measurements. The automated subsystem records the structural response to static and dynamic loads using vibrating-wire strain gauges, accelerometers, rotation sensors, displacement sensors, and temperature sensors. Additionally, a video system enables approximate identification of traffic loading events. Periodic monitoring includes distributed fiber-optic strain measurements along the girders and geodetic displacement measurements. The results obtained during the first year of operation indicate that temperature effects dominate the measured strain variations, whereas the influence of traffic loads remains relatively small. The study demonstrates that hybrid monitoring significantly improves the reliability of structural assessment by integrating continuous sensor data with inspection measurements.

Keywords: Structural health monitoring; extradosed bridge; hybrid monitoring system; distributed fiber optic sensing

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

Correction of temperature-induced effects in distributed fiber optic strain measurements

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Abstract

Strain measurements obtained through distributed fiber optic sensing (DFOS) are influenced by both mechanical strain and temperature variations of the host material in which the fibers are embedded or attached. When the temperature of the monitored structure changes significantly during measurement, temperature compensation becomes necessary to account for thermal effects. This poses a challenge, as no universal or standardized procedures for temperature compensation in DFOS currently exist. Common approaches include the use of strain-free reference fibers placed parallel to the sensing fiber, known as point-to-point compensation, and the determination of temperature compensation parameters through laboratory calibration. In this work, the derivation of correction coefficients for strain data from fiber optic sensors exposed to a controlled temperature environment in a climate chamber is presented. It is essential to consider not only the cable itself but also the temperature behavior of the entire interconnected system in the real environment (structure material, bonding, coating, and fiber). The derived correction factors are subsequently applied in field applications for different material configurations. Three case studies are presented: i) DFOS integrated during the casting of concrete elements, ii) a combined configuration on a steel-concrete composite railway bridge, and iii) embedded sensors in a highway viaduct. The presented examples demonstrate that appropriate temperature compensation is essential for accurate strain interpretation and long-term structural assessment of infrastructure monitored using DFOS.

Keywords: Distributed fiber optic sensing; temperature compensation; embedded fibers; glued fibers; structural health monitoring

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

Quality indicators for monitoring data: adaptation for distributed fiber optic strain sensing

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Abstract

Structural Health Monitoring of infrastructure became increasingly relevant over the past decades. Quality indicators facilitate an objective assessment of monitoring outcomes. While quality indicators should ideally be applicable independently of the specific monitoring task and measurement technique, certain indicators may only be relevant for particular applications. Additionally, they have to be tailored to the specific monitoring systems, sensor types, and data types involved. Distributed strain sensing (DSS) using distributed fiber optic sensors (DFOS) differs from conventional measurement techniques by generating two-dimensional datasets that encompass both spatial and temporal dimensions. Consequently, quality indicators must be adapted to this two-dimensional characteristic of DSS. The paper provides possible solutions for quality assessment for DSS measurements.

Keywords: Quality indicators; distributed strain sensing; distributed fiber optic sensing

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

Prestressing wire damage detection with surface distributed fiber optic strain sensing

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Abstract

Stress corrosion cracking (SCC) is a brittle failure mechanism in prestressing steel that occurs without visible indications on the concrete surface and may lead to sudden structural collapse. Numerous existing bridge structures in Germany are at risk due to SCC-susceptible steel, particularly those constructed before 1990. The collapse of the Carola Bridge in Dresden in September 2024, which occurred without prior visible signs of damage, highlights the need for reliable monitoring methods for early detection of such failures. Manual visual inspections are inadequate, as SCC is not detectable under direct observation of the concrete surface. Distributed fiber optic sensors (DFOS) enable high-resolution, quasi-continuous strain measurements over extended structural lengths and can detect even small strain variations caused by the breakage of individual prestressing wires. To evaluate the potential of this approach, prestressing wires were cut on a post-tensioned concrete girder during a four-point bending test. The results show that even single wire breaks induce characteristic strain redistributions detectable by DFOS, providing the basis for a strut-and-tie model describing load redistribution.

Keywords: Distributed fiber optic sensing; structural health monitoring; strut-and-tie modeling; prestressing wire break; damage detection

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Automated crack detection and strain mapping of reinforced concrete structures using 2D-FOS

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Abstract

Early detection and quantitative characterization of cracks are essential for assessing the structural integrity and durability of reinforced concrete structures. Conventional inspection methods, however, are limited by low spatial resolution, subjectivity, and discontinuous data acquisition, particularly in regions with complex crack patterns such as shear-critical areas.

To address these limitations, a novel two-dimensional distributed fiber optic sensing approach (2D-FOS) is presented, enabling continuous, high-resolution strain monitoring over extended surface areas. The concept combines a multidirectional fiber layout with an automated evaluation framework that reconstructs two-dimensional strain fields from one-dimensional measurements. Based on these strain fields, crack initiation, propagation, and crack widths can be detected and quantified automatically.

Experimental investigations demonstrate that the proposed approach enables precise localization of strain maxima and crack patterns within a two-dimensional measurement domain. Notably, cracks can be detected prior to visual observability, highlighting the potential of the method for early damage detection. The presented 2D-FOS approach, therefore, provides a robust and automated tool for quantitative crack monitoring and offers significant potential for condition-based maintenance of reinforced concrete structures.

Keywords: Reinforced concrete (RC); fiber optic sensing (FOS); crack localization; crack width; structural health monitoring (SHM)

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Characterization of FRP bar bond behavior on an RC tie using DIC and DFOS

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Abstract

Fiber-reinforced polymer (FRP) reinforcement is a promising alternative to steel reinforcement due to its corrosion resistance. However, the bond behavior between FRP bars and concrete strongly influences crack formation, stiffness and durability, and its transfer from conventional pull-out tests to cracked tension members is still not fully understood. In this study, digital image correlation (DIC) and distributed fiber optic sensing (DFOS) are combined to measure concrete surface displacements and bar strain distributions with high spatial resolution. The aim is to demonstrate a methodology for deriving local bond-stress states in a concrete tie reinforced with a GFRP bar from combined DIC and DFOS measurements, and to investigate their relationship with crack width, bar strain, local slip and pull-out-based bond stress-slip relationships. Based on the measurements, crack positions, crack widths, local slip and bond stress distributions are derived for different load levels. The results show the characteristic deformation behavior of a tension member and indicate that, already at service-level bar stresses, local slip states of the same order of magnitude as those known from pull-out tests can be reached.

Keywords: Fiber-reinforced polymer (FRP) reinforcement; bond behavior; tension member; digital image correlation (DIC); distributed fiber optic sensing (DFOS)

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Smart_tendon – monitoring the post-tensioning process with distributed fiber optic sensors

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Abstract

This study presents the successful application of smart_tendons with integrated distributed fiber optic sensors (DFOS) in post-tensioned concrete girder. Positioned in the inter-wire space, the DFOS enables continuous, high-resolution strain monitoring along the entire tendon, capturing friction losses, seating effects, and elongation with unprecedented detail. The smart_tendon enabled the spatially resolved observation of the tensioning process within the strands. Results of this experiment align well with theoretical calculations according to the standards and the European Technical Assessment (ETA). The measurements enabled the estimation of friction losses and the evaluation of losses due to wedge seating. In this experiment, friction losses were slightly higher than those predicted by the ETA, while losses due to wedge seating were slightly lower than the corresponding ETA predictions. The smart_tendon enables quality control and validation of the tensioning process and generating detailed prestressing records. By capturing structural performance from the earliest construction stage, the integration of DFOS into prestressing strands advances the capabilities of structural health monitoring (SHM) and facilitates improved safety, reliability, and long-term asset management.

Keywords: Distributed fiber optic strain sensing; structural health monitoring; post-tensioning process; quality assurance; early age monitoring

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Fresh-in-fresh fiber optic sensor embedding for monitoring yarn behavior in carbon-fiber-reinforced concrete: a feasibility study

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Abstract

Carbon-Fiber-Reinforced Polymers (CFRPs) are increasingly used in concrete structures due to their high strength-to-weight ratio and durability. To fully exploit CFRPs potentials, a detailed understanding of load-transfer mechanisms and strain development within the structural system is required for an efficient structural design. Integrating sensing capabilities directly into CFRP reinforcement provides a promising approach to capture these internal processes; however, reliable embedding of Fiber Optic Sensors (FOS) remains challenging, particularly during resin impregnation. In this study, a fresh-in-fresh embedding strategy is proposed, in which FOS are integrated directly into carbon fiber rovings during the impregnation and curing process. The feasibility of this approach is investigated experimentally using CFRP-reinforced concrete beams with dry interlocking joints subjected to four-point bending. Distributed strain measurements obtained from the embedded sensors are evaluated and interpreted with respect to crack development and the structural response of a representative specimen. The results demonstrate that the proposed embedding technique enables stable and continuous strain measurements within the CFRP reinforcement. The measured strain profiles reveal localized strain development and provide insight into reinforcement activation and load redistribution within the joint. Peak strains occur predominantly in the post-peak stage, reflecting the progressive reduction of contact between the interlocking faces and the transfer of tensile forces to the reinforcement. Minor local deviations were observed, likely related to reinforcement geometry and embedding conditions, while the overall strain development remained consistent. The study confirms the feasibility of the fresh-in-fresh embedding approach and highlights its potential as a tool for investigating internal load-transfer mechanisms and stress localization in CFRP-reinforced concrete structures.

Keywords: Carbon fiber-reinforced polymers (CFRPs); fiber optic sensors (FOS); Ffresh-in-fresh application; bending test; structural health monitoring (SHM); modular constructions; dry joints

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φ-OTDR for vehicle detection and traffic monitoring

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Abstract

We report the use of a Distributed Acoustic Sensing (DAS) system based on Optical Fiber Sensing (OFS) technology for vehicle detection on a highway bridge in the Netherlands. The sensing system, which is based on the phase-sensitive Optical Time Domain reflectometry (φ-OTDR) was connected to a sensing cable below one of the lanes, measuring four different segments of length up to 20 m each for the demonstration. We test how the system behaves under different sensing conditions (i.e.: probe pulse width) and show that, under optimal conditions, the passage of a vehicle can be visibly detected. In addition, we show how we can use this data to identify multiple features of the passing vehicles, including number of axles and speed.

Keywords: Distributed fiber sensing, OTDR, structural health monitoring, Rayleigh scattering, vehicle detection

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Fiber optic shape sensing in the presence of core breakage

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Abstract

This study focuses on how fiber optic shape sensing accuracy changes when one of the sensing cores of a fiber bundle no longer provides sensing information. Using a case study of a 5-core (1 central, 4 peripheral) fiber bundle, Monte Carlo simulations are performed to simulate the measurement process in the presence of noise in the case when all the cores are intact and the case where the strain from one of the cores is no longer available. It is shown that in this latter case, the accuracy of the measurement is no longer symmetrical. In particular, the accuracy for the estimation of curvature and bending angle depend on the position of the curvature vector with respect to the broken core and they cannot be maximized at the same time. The way this loss of symmetry affects 3D shape reconstruction is also evaluated, using an example of two perfect circles with a different orientation, indicating that for 3D reconstruction uncertainty on curvature might have a greater impact than uncertainty on the bending angle.

Keywords: Fiber optic sensors, shape sensing, fiber damage, strain sensing

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