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

MS08: Hybrid construction and strengthening with wire arc additive manufacturing

Organizers:

Yvonne Ciupack (TU Darmstadt, Germany)
Leroy Gardner (Imperial College London, UK)
Elyas Ghafoori (LU Hannover, Germany)
Vittoria Laghi (University of Bologna, Italy)
Vlad Silvestru (ETH Zurich, Switzerland)

ABSTRACT

Wire Arc Additive Manufacturing (WAAM) is rapidly emerging as a transformative technology in structural engineering. This Mini Symposium explores the integration of WAAM into the construction sector, focusing on its potential for strengthening existing components, enabling the reuse of deconstructed steel elements, and facilitating digitally enhanced fabrication and monitoring workflows. Contributions will cover pioneering applications in structural retrofitting, the design of first-of-their-kind WAAM-printed bridges, process monitoring and quality assurance, as well as sustainability aspects such as life cycle assessment. Bringing together experts from academia, applied research, and industry, the session aligns with SMAR2026's core themes of smart assessment, monitoring, and rehabilitation. It addresses both the opportunities and challenges of introducing WAAM as a robust and scalable solution in civil infrastructure. The symposium will also highlight interdisciplinary insights from welding engineering and digital fabrication, fostering cross-sector innovation for the future of sustainable and adaptive steel structures.

Integrating WAAM into an adaptive and systematic digital workflow applicable to steel components and their rehabilitation

Benedikt Waldschmitt^a, Philipp Grebner^a, Yvonne Ciupack^a, Jörg Lange^a

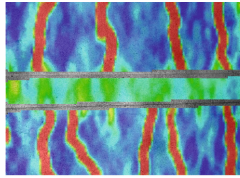
^a *Institute for Steel Construction and Materials Mechanics, Technical University of Darmstadt, Franziska-Braun-Straße 3, 64287 Darmstadt, Germany*

Abstract

Wire Arc Additive Manufacturing (WAAM) offers new opportunities for the rehabilitation and upgrading of civil structures through the on-site manufacturing and repair of customized steel components. Its layer-by-layer deposition process can be adapted to new structures or damaged geometries and integrated into digital monitoring workflows, supporting service-life extension and material-efficient interventions. This article presents a study on the additive manufacturing of free-formed column structures using two printing strategies: a continuous strategy for closed cross-sections and a dot-by-dot strategy for lattice structures, both implemented using the CMT Cycle Step welding process. The manufacturing process follows a digital design-to-manufacturing workflow, resulting in a digital shadow suitable for integration into Building Information Modeling (BIM) processes. Both strategies are described and corresponding digital models are developed to define welding parameters, process settings, and material properties. The manufacturing process is analysed regarding time efficiency, resource consumption, and process stability. Despite a mass reduction of 40 % and a welding time reduction of 53 % for the lattice design, shielding gas savings remain negligible due to higher gas flow rates for printed dots. Both strategies exhibited high process stability, with printing-related errors ranging from 0.28 % to 7.1 %, of which 60 % were only brief process interruptions. Comparison of 3D scans with the original digital models showed that the lattice structure achieved a dimensional accuracy of ± 2.0 mm at the top. The results form the basis for an adaptive digital workflow for WAAM of structural elements, enabling process and geometry data to be stored and retrieved within a digital shadow on both a layer-wise and spatially resolved level.

Keywords: WAAM; CMT cycle step; adaptiv digital workflow; dot-by-dot printing; steel structures

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Strengthening of structural steel elements using additive manufacturing

Leroy Gardner^{a,1}, Jiachi Yang^a, Pinelopi Kyvelou^a

Imperial College London, London SW7 2AZ, UK

Keywords: Rehabilitation; strengthening; additive manufacturing; steel structures

1. Introduction

Recently, wire arc additive manufacturing (WAAM) has been explored as a viable means of strengthening steel structures and as a strategy for hybrid construction (Gardner et al. 2024, Yang et al. 2024, Yang et al. 2025), while also showing the potential of reducing the embodied carbon of steel structures (Shah et al. 2023). Presently, the structural and environmental performance of a series of hybrid hot-rolled-WAAM steel I-section beams is examined. The concept, design and manufacture of the hybrid beams are presented in brief. The structural performance of the hybrid beams/WAAM-strengthened beams is described. The findings presented in this paper underscore the potential of WAAM and the hybrid hot-rolled-WAAM manufacturing strategy to enhance the efficiency and the sustainability of steel construction.

2. Methodology

Conventional prismatic hot-rolled steel I-section beams often experience non-uniform bending moments under real-world loading scenarios, resulting in non-uniform stress distributions along the beam length. This hence leads to relatively low material efficiency where the stress level is low. The hybrid manufacturing strategy aims to enhance the material efficiency of the hot-rolled I-section beams by optimally depositing steel additions onto the I-section through WAAM. A typical hybrid hot-rolled-WAAM steel I-section beam designed for three-point bending condition is presented in Fig. 1, featuring additional steel deposited at the tips of the compression flange and on the outer surface of the tension flange. The steel additions are optimised based on the bending moment diagram caused by the applied load(s), seeking for a moment resistance diagram that closely matches with the bending moment diagram within the deposition regions, as illustrated in Figs. 2(a) and (b) for two typical loading conditions – three- and four-point bending, respectively, and thereby leading to a more uniform stress distribution and higher material efficiency.

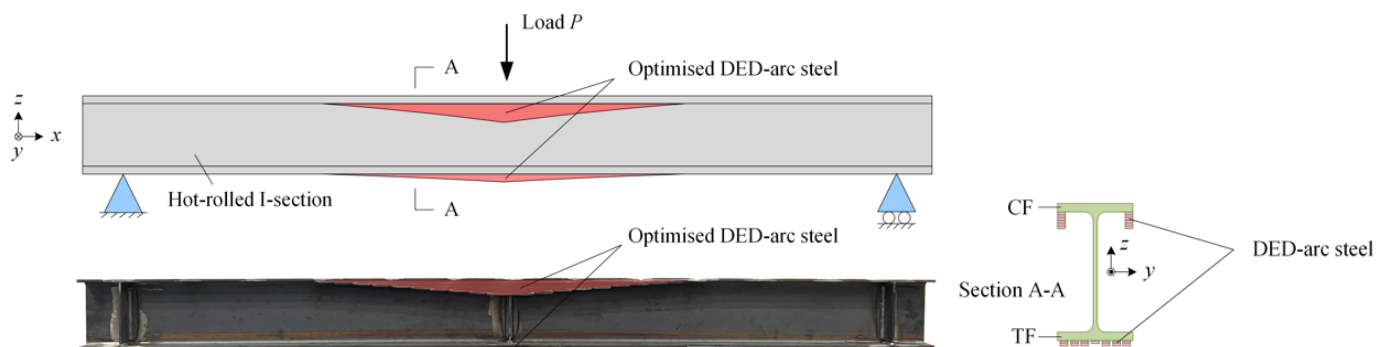


Fig. 1. Typical hot-rolled-WAAM steel I-section beam (CF – compression flange, TF – tension flange).

A series of 1.8 m long hybrid beams comprising hot-rolled bare I-sections in steel grade S355, and WAAM steel additions fabricated using ER70S-2 (normal strength), ER110S-G or ER120S-G (high strength) welding wire, were designed and fabricated.

The information of these hybrid beam specimens is presented in Table 1, where m_i and m_w are the mass of the bare I-section and the mass of the steel additions respectively, and m is the total mass of the beam specimen. Each specimen is named in the convention of “wire grade—loading condition—nominal m_w/m_i ”. These hybrid specimens were manufactured using a 6-axis ABB robotic arm.

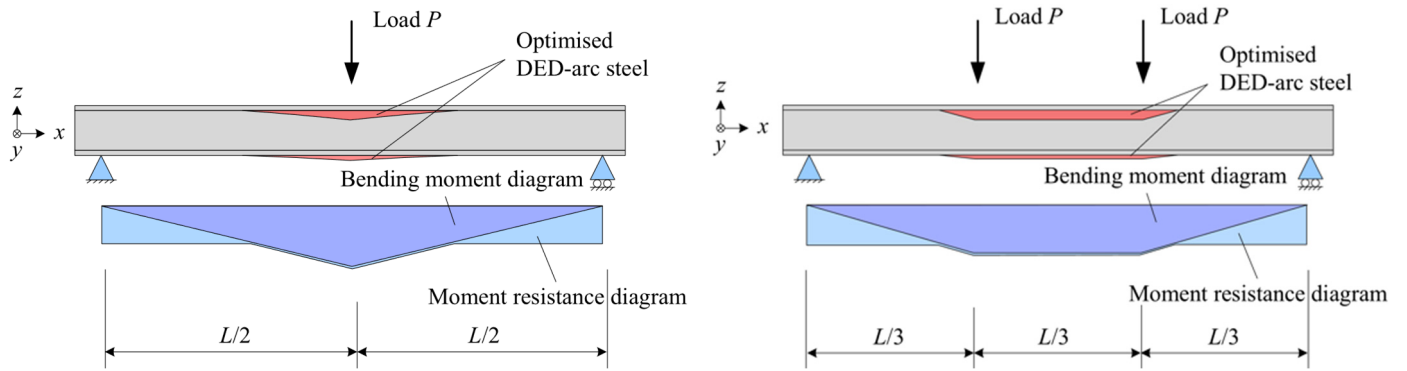


Fig. 2. Illustration of optimal deposition of steel additions under (left) three-point bending and (right) four-point bending conditions (L – beam span).

Table 1. Information of hybrid beam specimens (3PB--three-point bending, 4PB--four-point bending).

Beam ID	I-section profile	m_i in (kg)	m_w in (kg)	m in (kg)	m_w/m_i in (%)
ER70-3PB-10%	UB152×89×16	28.81	3.18	31.99	11.04
ER110-3PB-5%		29.13	1.64	30.77	5.63
ER110-3PB-10%		28.92	3.10	32.02	10.72
ER110-3PB-15%		28.82	4.46	33.28	15.48
ER120-3PB-5%		29.22	1.61	30.83	5.51
ER120-3PB-10%		28.73	2.97	31.70	10.34
ER120-3PB-15%	IPE160	28.92	4.45	33.37	15.39
ER70-4PB-10%		28.89	3.37	32.26	11.66
ER110-4PB-5%		28.73	1.67	30.40	5.81
ER110-4PB-10%		29.10	3.19	32.29	10.96
ER110-4PB-15%		28.70	4.42	33.12	15.40
ER120-4PB-5%		28.66	1.73	30.39	6.04
ER120-4PB-10%	IPE160	28.50	3.34	31.84	11.72
ER120-4PB-15%		28.73	4.34	33.07	15.11

The material properties of the hot-rolled steel in grade S355, and of the WAAM steels were obtained through tensile testing. The major-axis flexural behaviour of the hybrid beam specimens was assessed through physical three- or four-point bending tests, as illustrated in Fig. 2. For comparison purpose, bare I-sections with UB 152×89×16 and IPE160 profiles were also tested as benchmarks.

3. Results

The key results of the bending tests are presented in Table 2, where M_u is the ultimate bending moment resistance of the beam specimens, $M_{u,b}$ is the ultimate bending moment resistance of the corresponding benchmark model. For completeness, the analytically derived plastic bending moment resistance, M_{pl} , of the mid-span cross-section of each beam specimen is also given in Table 2. Similarly, $M_{pl,b}$ denotes the plastic bending moment resistance of the corresponding benchmark specimen. Additionally, the mid-span bending moment versus the mid-span deflection curves of all beam specimens are plotted in Fig. 3.

The results of the physical beam tests showed that dramatic increases of between 30% and 84% in the ultimate bending moment resistance of the strengthened specimens were achieved with just modest increases in mass of between 6% and 15% compared to the benchmarks. A further cradle-to-gate life cycle assessment demonstrates that the hybrid hot-rolled-WAAM manufacturing strategy is capable of reducing the overall mass of the steel beams by 20%-30%, and the overall embodied carbon associated with steel beams by, on average, 11% and 14% for normal and high strength steel additions to S355 steel profiles, and up to approximately 40%, for some typical loading conditions. For S275 steel profiles, which are likely to feature prominently in retrofitting and re-use scenarios, the savings in embodied carbon are even greater, up to 45%.

Table 2. Key testing results for three-point and four-point bending specimens (*--benchmark specimen).

Three-point bending specimens					Four-point bending specimens				
Beam ID	M_u (kNm)	$M_u/M_{u,b}$	M_{pl} (kNm)	$M_{pl}/M_{pl,b}$	Beam ID	M_u (kNm)	$M_u/M_{u,b}$	M_{pl} (kNm)	$M_{pl}/M_{pl,b}$
*UB152×89×16-3PB	67.36	1	49.43	1	*UB152×89×16-4PB	56.70	1	50.02	1
ER70-3PB-10%	84.75	1.26	68.96	1.40	ER70-4PB-10%	75.53	1.33	61.99	1.24
*IPE160-3PB	66.85	1	51.92	1	*IPE160-4PB	54.38	1	51.17	1
ER110-3PB-5%	87.88	1.30	76.13	1.54	ER110-4PB-5%	73.18	1.29	62.17	1.24
ER110-3PB-10%	104.60	1.55	86.52	1.75	ER110-4PB-10%	86.79	1.53	72.18	1.44
ER110-3PB-15%	114.12	1.69	98.49	1.99	ER110-4PB-15%	92.01	1.62	79.22	1.58
ER120-3PB-5%	96.23	1.43	75.35	1.52	ER120-4PB-5%	77.45	1.37	63.56	1.27
ER120-3PB-10%	106.26	1.58	84.33	1.71	ER120-4PB-10%	87.80	1.55	72.39	1.45
ER120-3PB-15%	123.12	1.83	96.80	1.96	ER120-4PB-15%	97.39	1.72	81.36	1.63

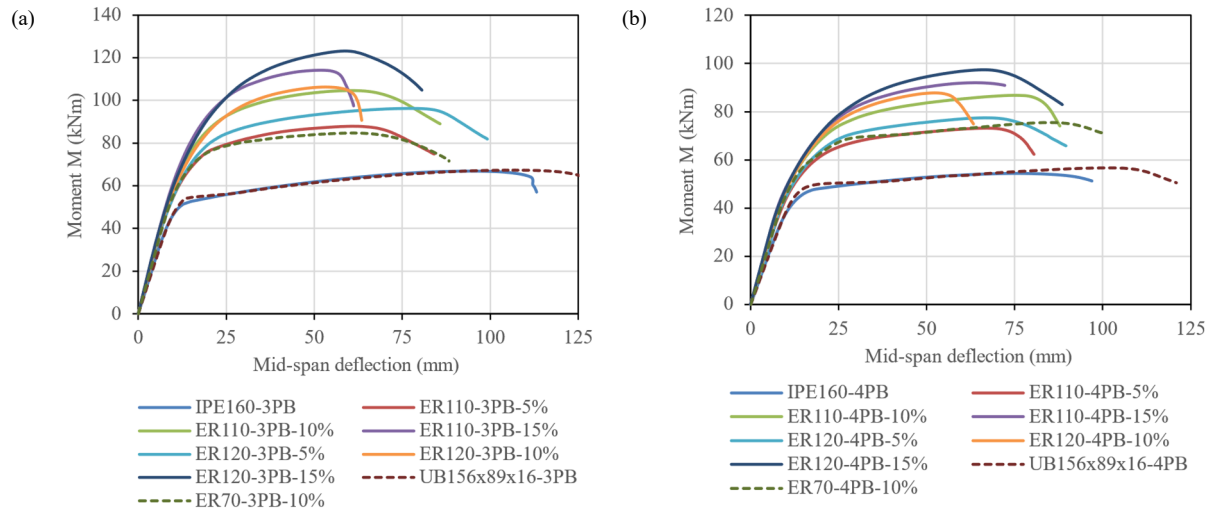
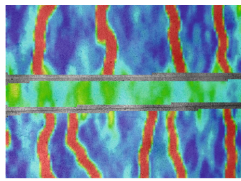


Fig. 3. Mid-span bending moment versus the mid-span deflection curves of (a) three-point bending specimens and (b) four-point bending specimens.

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Feasibility study on the rehabilitation of fatigue-damaged steel plates using wire arc additive manufacturing

L. Gilliar-Schönenberger^a, V.-A. Silvestru^a, H. Dahaghin^b, H. Heydarinouri^{c1}

^aETH Zurich, Swiss Federal Institute of Technology, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland

^bDepartment of Civil and Environmental Engineering, University of Waterloo, 200 University Avenue West, ON, Canada N2L 3G1

^cEmpa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf, Switzerland

Keywords: Fatigue; wire arc additive manufacturing; crack; strengthening

1. Objectives and motivation

Fatigue damage is a governing deterioration mechanism in many aging steel infrastructures such as bridges (Adey and Jamali 2012, Helmerich et al. 2007). As a large portion of the existing infrastructure network approaches or exceeds its design life, the need for efficient strengthening and rehabilitation strategies becomes increasingly important. Replacement of entire structures is often economically and environmentally unfavorable; therefore, targeted repair and strengthening methods capable of extending service life are of considerable interest. In this context, Wire-Arc Additive Manufacturing (WAAM) has recently emerged as a promising technology that enables the deposition of steel alloys directly onto existing steel components (Ghafoori et al. 2023).

WAAM allows the fabrication of geometry-adaptive repairs that can locally modify structural stiffness and stress distribution (Dai et al. 2025). Compared with existing strengthening techniques such as externally bonded fiber-reinforced polymers (Hosseini et al. 2017) or prestressed iron-based shape memory alloys (Fe-SMA) strips (Izadi et al. 2016), WAAM repairs eliminate bonded interfaces and produce a monolithic metallic connection with the base material. Additionally, previous studies have shown that localized WAAM deposition can significantly reduce crack-driving stresses in pre-damaged steel elements (Ghafoori et al. 2023), and similar benefits have been reported for fatigue crack arrest using carbon fiber reinforced polymer (CFRP) reinforcement (Hosseini et al. 2017). However, the influence of WAAM patch geometry and as-built surface characteristics on fatigue behavior remains insufficiently understood (Pichler et al. 2025), particularly when repairs are applied to already cracked steel components and performance is strongly dependent on patch geometry (Dahaghin et al. 2024). This study experimentally investigates the feasibility of using WAAM patches with different geometries for fatigue strengthening of cracked steel plates and extending their remaining fatigue life.

2. Methods and materials

Fig. 1 illustrates the workflow of the experimental investigations conducted in this study. Rectangular S355J2+N steel plates (850 mm × 150 mm × 10 mm), featuring ASTM E647-23a compliant Hole/Slot notches, were first subjected to controlled cyclic loading to generate reproducible fatigue pre-cracks. The pre-cracking procedure followed ASTM E647-23a guidelines and was performed under constant amplitude loading (CAL) with a stress range of 75 MPa and a non-reversed stress ratio of $R = 0.2$. After pre-cracking, three specimens were strengthened using robotic WAAM deposition with different patch geometries, while one specimen was kept as a non-strengthened reference.

Three different WAAM patch configurations were investigated: (i) a single-layer prismatic patch, (ii) a two-layer stepped patch, and (iii) a three-layer prismatic patch, as shown in Fig. 1b. The dimensions of the 1st layer for all patches were 24 mm × 30 mm in depth and width, respectively. Specimens 1 and 3 were prismatic volumes, with a target height of 2 mm and 6 mm, respectively. Specimen 2 was a stepped volume where the 2nd layer was 12 mm × 24 mm in depth and width, respectively. Deposition was

¹ Corresponding author. Tel.: +41 58 765 4192
E-mail address: hossein.heydarinouri@empa.ch

performed using an MX3D robotic system equipped with a gas metal arc welding process (GMAW) and 1.0 mm ER70S-6 filler wire. The patches were printed directly over the pre-crack region on both sides of the plate using a zig-zag toolpath pattern.

The WAAM patches were fabricated using an MX3D M1 Metal AM system consisting of an ABB robotic arm equipped with a Fronius GMAW/CMT welding system. Patch geometry was measured using a caliper, and deviations from the target dimensions of up to 2.2 mm in depth and 0.9 mm in width were observed. Following geometric characterization, all specimens were subjected to cyclic fatigue loading until failure. The CAL fatigue tests were conducted at sequential load levels, i.e., load levels 1 and 2, consisting of alternating effective cycles and beach-marking cycles, allowing the crack propagation history to be observed. Load level 1 was applied with an effective stress range of 75 MPa ($R = 0.2$), while in load level 2, the effective stress range was increased to 90 MPa while maintaining the same stress ratio.

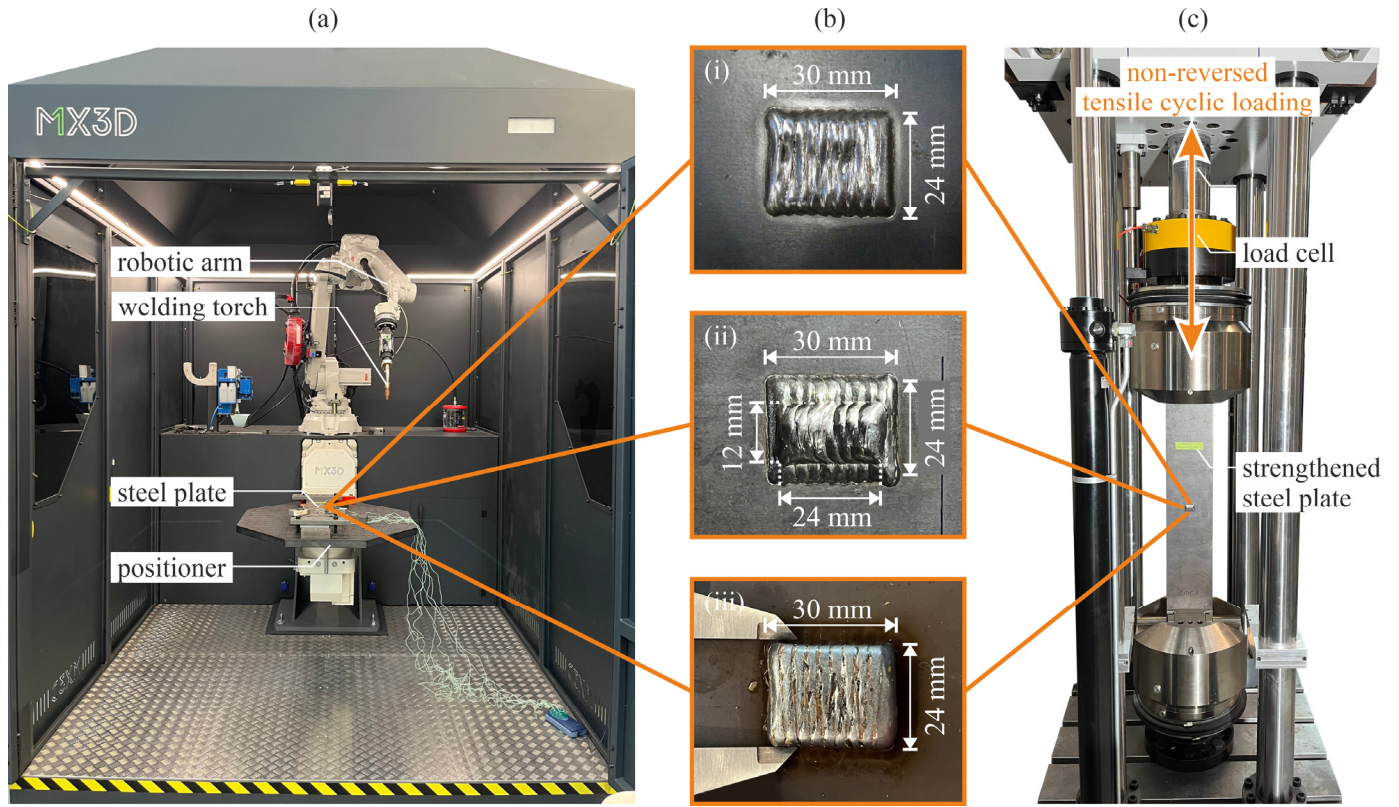


Fig. 1. Workflow of experimental investigations: (a) WAAM system; (b) printed WAAM patches; and (c) fatigue testing setup.

3. Major findings

The fatigue test results showed that all WAAM-strengthened specimens exhibited improved fatigue performance compared with the non-strengthened reference specimen. The reference plate failed (final fracture) at load level 1 after approximately 1.0 million effective cycles due to continued propagation of the initial pre-crack.

The fatigue behavior of the strengthened specimens strongly depended on the geometry of the WAAM patch. All strengthened plates survived load level 1, reaching 2.5 million effective cycles without fracture. The single-layer exhibited crack retardation at load level 2 and ultimately failed through continued pre-crack propagation after less than 0.7 million effective cycles. For the two-layer stepped patch and the three-layer prismatic patch, no propagation of the original fatigue crack was observed; failure occurred instead through initiation of a new crack at the weld toe between the WAAM material and the base plate. The plate with the three-layer prismatic patch ultimately fractured at load level 2 after less than 0.8 million effective cycles. Among all configurations, the stepped two-layer patch achieved the best performance with final fracture after around 1.9 million cycles under load level 2. The WAAM patches after rupture are presented in Figure 2.

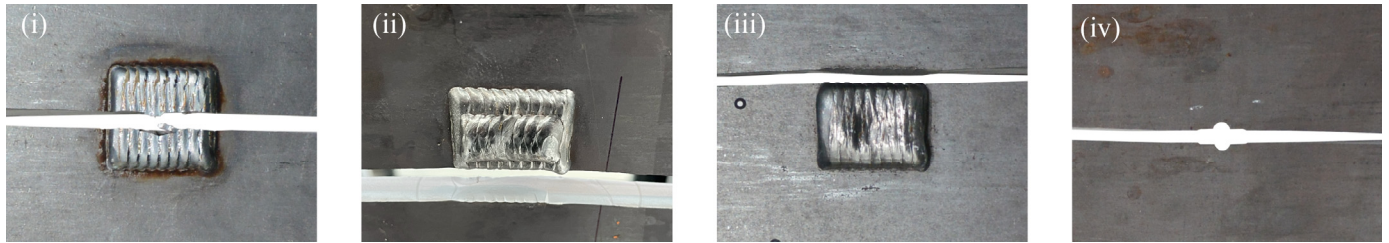


Fig. 2. Fatigue failure modes of specimens: (i) single-layer prismatic; (ii) two-layer stepped; (iii) three-layer prismatic patches; and (iv) reference plate.

Overall, the stepped two-layer configuration extended the fatigue life to approximately three times that of the non-strengthened reference specimen. Although the three-layer prismatic patch contained the largest material volume, its fatigue life extension was lower than the two-layer stepped patch, indicating that geometric distribution and transition govern fatigue performance more than the total deposited material volume.

4. Conclusion

The findings highlight that the effectiveness of WAAM repairs is governed not only by the amount of deposited material but also by the geometric transition between the patch and the base plate, which influences local stress concentrations at the weld toe. Residual stresses arising from the WAAM patch deposition process may affect crack arrest and fatigue life, suggesting a need for future measurement if thermo-mechanical behavior is to be considered alongside geometric effects. The results further indicate that while WAAM patches can retard or arrest existing fatigue cracks, fatigue failure may shift to new crack initiation at the weld toe introduced by the repair geometry. Future work should further investigate the influence of residual stresses, optimized patch geometries, and post-processing strategies to enhance fatigue behavior and enable reliable design guidelines for WAAM-based structural repairs. Overall, the results demonstrate the potential of WAAM as a fully metallic, geometry-adaptive repair strategy for fatigue-critical steel structures, offering an alternative to bonded systems such as CFRP or Fe-SMA.

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DED-arc strengthening of steel beams: design, manufacturing and mechanical performance

Lukas Ledderose^a, Marc Muggenburg^b, Martin Gabriel Altobelli^c, Kevin Hoefer^c, Markus Köhler^c, Nina Kugler^d, Julian Unglaub^b, Christina Radlbeck^d, Jonas Hensel^c, Harald Kloft^a

^a*Institute of Structural Design, TU Braunschweig, Braunschweig 38106, Germany*

^b*Institute of Steel Structures, TU Braunschweig, Braunschweig 38106, Germany*

^c*Institute of Joining and Assembly, Chair of Welding Engineering, Chemnitz University of Technology, Chemnitz 09126, Germany*

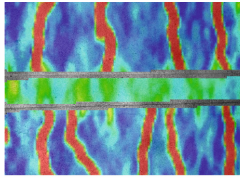
^d*Chair of Metal Structures, TU Munich, Munich 80333, Germany*

Abstract

Wire-Arc directed energy deposition (DED-Arc) enables metal-based additive manufacturing using high deposition rates and robotic flexibility, offering significant potential for the targeted reinforcement of existing steel structures. This paper investigates a hybrid construction method where standard IPE 200 beams are strengthened to achieve the bending stiffness of a larger IPE 220 profile. Within a continuous digital workflow, 44 reinforcement geometries were modeled and evaluated using a material efficiency factor (η). Two optimized DED-Arc variants and one conventionally welded reference were manufactured using a collaborative robotic setup. The production process included real-time monitoring of electrical parameters and subsequent mobile 3D scanning to verify as-built geometries against the digital models. The mechanical properties were determined using quasi-static tensile tests on dog-bones made from walls printed with the same parameters. The results show that, for the same increase in stiffness, a 24% reduction in material usage can be achieved compared to conventional methods. These insights confirm DED-Arc as a viable, automated alternative for the precise rehabilitation of steel components in the built environment.

Keywords: Additive manufacturing; strengthening; hybrid steel components; DED-arc; digital construction

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Strengthening end-of-life steel sections for reuse through wire arc additive manufacturing

V.-A. Silvestru^{a,1}

^aETH Zurich, Institute of Structural Engineering, Stefano-Francini-Platz 5, 8093 Zurich, Switzerland

Keywords: Wire arc additive manufacturing; reuse of steel profiles; strengthening steel profiles; hybrid manufacturing; adapting steel profiles

1. Introduction

Steel, around 70% of which is produced globally from virgin raw materials through highly energy-intensive processes in basic oxygen furnaces according to World Steel Association AISBL (2025), exhibits one of the highest recovery rates among structural materials at the end of its service life. Efforts in facilitating the reuse of reclaimed steel components in construction are reflected by recent publications by Girao et al. (2020), Kanyilmaz et al. (2023), or Bartsch (2025). Nevertheless, the majority of recovered steel, including hot-rolled profiles reclaimed from buildings, is recycled rather than directly reused or repurposed. Two principal challenges that hinder the direct reuse or repurposing of hot-rolled steel profiles are (i) the reliable non-destructive assessment of the recovered material's condition, and (ii) the dimensional and structural suitability of such profiles for integration into new structures. The research project “WAAM for Reuse” aims to address these challenges by developing strategies for strengthening and adapting reclaimed hot-rolled steel profiles using wire arc additive manufacturing (WAAM). While studies on strengthening steel I-profiles by WAAM – e.g., see Yang et al. (2025) – as well as various investigations on hybrid WAAM were conducted previously – see overview in Meng and Gardner (2025) – they have dealt with new steel profiles, not reclaimed ones. The research project primarily focuses on recovered profiles with I-shaped cross-section that have not experienced cyclic loading or significant corrosion during their previous service life. The extended abstract briefly presents the research project and gives insights into first investigations and their preliminary results.

2. Conducted investigations and applied methods

The research project covers different types of investigations related to adapting and strengthening salvaged steel sections. At material level, a first objective is to evaluate different methods for assessing the condition of salvaged steel sections. Among others, highly relevant aspects for strengthening by WAAM are the mechanical properties of the reclaimed steel profiles as well as their surface condition and weldability. A second objective at material level is to analyze the behavior of hybrid WAAM samples and especially of the combined base material and deposited material.

First investigations at material level included uniaxial tensile tests and hardness measurements on material from new and reclaimed I-sections. Hardness measurements were conducted with the Leeb method and the UCI (ultrasonic contact impedance) method on differently treated steel surfaces (see setup in Figure 1a). Web and flange samples from new IPE 240 sections and web samples from salvaged HEA 240 and HEA 280 sections were analyzed. In addition to the as-received surfaces, surfaces treated by milling, sandblasting or grinding with different tools were assessed. The new material had a steel grade S355 while the grade of the salvaged steel was initially unknown. In parallel to the hardness measurements, uniaxial tensile tests were conducted on dog-bone samples cut from the web and the flanges of the same sections. The geometry of the dog-bone samples is given in Figure 1b. The tests were conducted under displacement control with a universal testing machine according to EN ISO 6892-1 (2016). The objective of these investigations was to evaluate what the least invasive and easiest to apply surface treatment is, that allows a sufficiently reliable correlation between nondestructive (or minimally invasive) hardness measurements and strength values (yield

¹ Corresponding author. Tel.: +41 44 633 2134
E-mail address: silvestru@ibk.baug.ethz.ch

strength and ultimate strength) determined in uniaxial tests. The correlation approaches proposed by Fujita and Kuki (2016) and by EN ISO 18265 (2013) were considered.

To assess the material behavior in components consisting of both base material and deposited materials, hybrid samples were fabricated by depositing WAAM walls on the webs of half-I-sections (see setup in Figure 1c). From these walls, dog-bone samples were cut at different angles (0° , 45° and 90° relative to the deposition direction). An example of a 90° dog-bone with the same geometry as in Figure 1b is shown in Figure 1d. In addition, dog-bones consisting of only base material and only deposited material were investigated for reference. The applied methodology for investigating the samples included geometry evaluation by 3D scanning and uniaxial tensile tests according to EN ISO 6892-1 (2016), both on as-printed and machined samples. Digital image correlation was used for evaluating the strain development in the samples. Microstructure analysis and derivation of material models for application in finite element simulations are planned to be conducted in future steps. The base material parts used for these samples were IPE 240 sections cut in half from new profiles of steel grade S355. The deposited material wire was ER70S-6 and had a diameter of 1.0 mm. As shielding gas, CORGON 18, a mixture of 82% argon and 18% CO_2 was used. An MX3D M1 System consisting of an ABB IRB 2600ID robotic arm and a Fronius TPS 500i welder equipped with a GMAW/CMT welding torch was used for manufacturing the walls. The main process parameters used to obtain walls with a target thickness of 6 mm were a travel speed of 4 mm/s, a wire feed rate of 4.5 m/min, a current of 89 A, a voltage of 13.4 V, and an interpass temperature of 180°C . The dog-bones were cut from the walls by waterjet cutting.

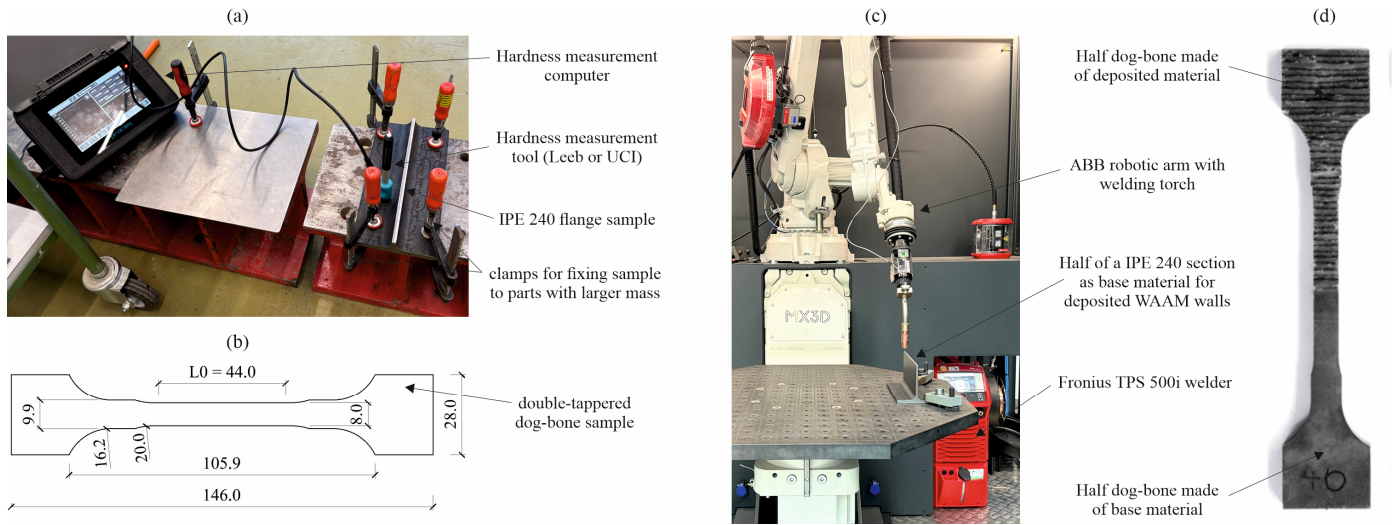


Fig. 1. Experimental investigations: (a) hardness measurements, (b) dog-bone geometry (dimensions in [mm]), (c) WAAM setup used for manufacturing hybrid WAAM samples, (d) hybrid WAAM dog-bone sample after waterjet cutting from a wall.

At structure level, the main objective of the research project is to develop a framework that combines computational design, robotic fabrication, and performance assessment for adapting and strengthening steel sections through WAAM. Currently, the digital design processes for optimized WAAM components are fragmented, applying various software applications for different tasks and including numerous manual steps for interacting between these software applications. The work within the “*WAAM for Reuse*” project focuses on improving the integration of computer aided design, engineering and manufacturing (CAD, CAE, and CAM) for strengthening reclaimed steel profiles by WAAM, by considering optimization of material distribution, structural efficiency and production constraints. A preliminary case study on a steel frame, for which only a limited stock of reclaimed IPE and HEA profiles is available, was conducted. In such a case, beam profiles have to be used, which are not strong enough for the frame corner regions in certain load combinations. Different strengthening scenarios of these regions were evaluated, including one with a conventional haunch consisting from welded steel sheets, and one with a topology-optimized haunch to be fabricated by WAAM. The considered steel frame is illustrated in Figure 2a, and the two investigated haunch solutions are shown in Figure 2b and Figure 2c, respectively. More details on the preliminary study can be found in Ortiz et al. (2026). The main objective of the study was to identify challenges for tasks combining different optimization software applications and exchanging data between them. While for the global optimization task (selection of best-fit profiles for the steel frame from the available stock), a model with 1-dimensional elements was used in Rhinoceros 3D, Grasshopper and Karamba3D, for the local optimization in the frame corner region, a model with solid 3-dimensional elements was applied in Abaqus CAE and Tosca.

3. Preliminary results

The investigations on correlating hardness measurements with strength values revealed several relevant preliminary outcomes. The strength values derived from UCI hardness measurements on the profile surfaces tended to be higher than those determined in uniaxial tensile tests, while strength values derived from Leeb hardness measurements were generally lower. The deviations between derived strength values and measured ones could be reduced in average down to around 25% by milling or grinding the surfaces (for both yield strength and ultimate strength). However, these deviations are still too high for allowing a reliable hardness-

strength correlation. Significantly better correlations were obtained based on hardness measurements conducted in the center of the samples in thickness direction (deviations of around 5-10% in average). This indicated that the mill scale from the hot-rolling process significantly influences the hardness measurements even after milling or grinding the surfaces.

The evaluation of the uniaxial tests on hybrid dog-bones was in progress at the moment of submission of the extended abstract. While quantitative results will be presented at the conference, preliminary qualitative observations from the tests indicated that the base material exhibited slightly higher yield and ultimate strength compared to the deposited WAAM material. For the WAAM samples tested with as-printed surfaces, it was noticed that the more irregular surfaces led to less pronounced yield plateaus. An interesting feature observed in the hybrid WAAM samples was the formation of two distinct yield plateaus, a first one in the WAAM part, and a second one in the base material part.

The case study conducted on strengthening the corner of a frame designed with a limited stock of steel profiles revealed that for a fully automatized and parameterized export/import to generate the model used for the local optimization based on the one available in the software used for global optimization, further script developments are necessary. Moreover, extending the approach to fabrication will require an additional optimization/rationalization step for allowing such optimized haunches to be manufactured by WAAM. This could include, for example, an approximation of the topology-optimized geometry of the haunch shown in Figure 2c by hollow-section elements. The topology-optimized haunch solution from this study required 23% less mass compared to the conventional haunch shown in Figure 2b, while leading to similar stress distributions and deflections.

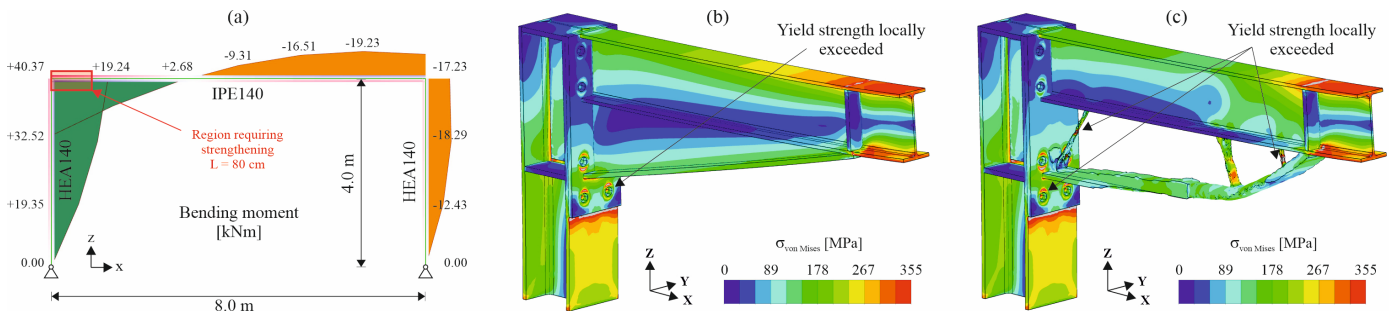


Fig. 2. Preliminary case study for developing a computational framework for adapting and strengthening reclaimed steel profiles by WAAM: (a) considered steel frame with bending moment diagram, (b) von Mises stresses for solution with conventional haunch, and (c) von Mises stresses for solution with topology-optimized haunch.

Acknowledgements

The research project “WAAM for Reuse – Adapting and Strengthening End-of-Life Steel Sections for Reuse through Wire Arc Additive Manufacturing” is supported by the Swiss National Science Foundation (SNSF) through the grant no. 10004487. Fabricio Ortiz (Doctoral student), as well as Antoine Pommerell and Matteo Dozio (Master students) are acknowledged for their work on the presented topics. Moreover, the collaboration with the group of Circular Engineering for Architecture at ETH Zurich and the Structural Engineering Research Laboratory at Empa within this research project are acknowledged.

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Investigation on the load-bearing capacity of thin sheet steel façades reinforced using WAAM

Philipp Grebner^a, Benedikt Waldschmitt^a, Yvonne Ciupack^a, Felicitas Rädels^a, Jörg Lange^a

^a Institute for Steel Construction and Materials Mechanics, Technical University of Darmstadt, Franziska-Braun-Straße 3, 64287 Darmstadt, Germany

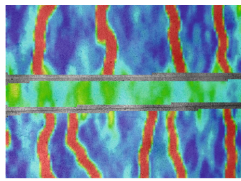
Abstract

In the context of decarbonizing the construction industry, Wire Arc Additive Manufacturing (WAAM) is gaining increasing attention as a promising technology for steel-based lightweight and resource-efficient structures. By depositing material exclusively where structurally required using gas metal arc welding, WAAM enables the layer-by-layer fabrication of steel components, offering potential for material and weight savings. To date, free-form sheet metal façades often rely on complex and solid substructures and large sheet thicknesses, resulting in high dead weights, excessive material consumption, and increased costs. Reinforcing thin steel sheets using WAAM represents an innovative approach to reduce material demand while maintaining structural performance.

This study investigates the structural performance of WAAM-reinforced DC01 steel sheets through a combined experimental and numerical approach. Steel specimens ($2200 \times 400 \times 1$ mm) were reinforced on one side with two welded ribs of 6 or 10 layers with a thickness of 2.0 mm and tested under six-point bending to simulate wind loading. Finite element simulations validated and extended the experiments. The results demonstrate that WAAM reinforcement can significantly enhance the load-bearing capacity of thin steel sheets, suggesting a viable alternative to conventional sheet façade elements. While an increase in the number of WAAM layers improves strength, it also reduces welding-induced deformations, leading to a decrease in arching effects that otherwise contribute to load transfer. These insights contribute to the development of structurally efficient façade systems and highlight the potential of WAAM as an enabler of performance-based material savings in architectural steel applications.

Keywords: WAAM; additive manufacturing, façade, load bearing capacity, sheet metal, steel

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



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Wire arc additive manufacturing to the rescue of historic structures

Nicolas Hadjipantelis^{a,1}, Andreas Georgiou^a, Ioannis Ioannou^a, Odysseas Kontovourkis^b, Marios Mavros^a

^aDepartment of Civil and Environmental Engineering, University of Cyprus, 1 Panepistimiou Avenue, Nicosia, 2109, Cyprus

^bDepartment of Architecture, University of Cyprus, 1 Panepistimiou Avenue, Nicosia, 2109, Cyprus

Keywords: Heritage unreinforced masonry; hybrid construction; retrofitting; stone masonry; strengthening; wire arc additive manufacturing; wire-arc directed energy deposition; 3D-printed steel reinforcement

1. Introduction

Historic unreinforced masonry (URM) structures are invaluable to our cultural and architectural heritage; however, they are highly vulnerable to seismic actions and may therefore suffer severe damage or catastrophic collapse during earthquake events. Historic URM structures are often protected by international and national organisations and/or local authorities, which require conservation works to respect the authenticity of the structure, impose minimum intervention, and be compatible, reversible and durable (ICOMOS, 2004).

Many conventional retrofitting methods fall short of meeting all of the aforementioned criteria while providing the required enhancements in structural performance. Such methods include shotcrete- and ferrocement-based techniques (e.g. Rezaee et al., 2022), externally-bonded steel reinforcement, fiber reinforced polymers (FRP) and textile reinforced mortars (e.g. Valluzzi et al., 2002), the so-called 'CAM system' (Active Confinement of Masonry) (e.g. Rai and Goel, 1996), base isolation, energy dissipation systems, the so-called 'Reticulatus' system (e.g. Borri et al., 2011), Near Surface Mounted (NSM) techniques, and traditional repointing (e.g. Valluzzi et al., 2005).

A ground-breaking concept, whereby unreinforced stone masonry walls are retrofitted using custom-fit 3D-printed steel reinforcing meshes, has recently been proposed by Mavros et al. (2025). The reinforcing meshes are manufactured by utilising 3D laser scanning and wire arc additive manufacturing and they are embedded within the mortar profile of the walls. This retrofitting approach enhances both the load-carrying capacity and the energy dissipation of the stone masonry, while preserving its architectural authenticity.

In the present study, the overall concept of this novel retrofitting approach is described and initial results from a proof-of-concept experimental programme are presented.

2. Retrofitting methodology

In the proposed concept, the reinforcing steel meshes are printed using wire arc additive manufacturing (WAAM), also known as wire-arc directed energy deposition (DED-Arc) according to ISO/ASTM 52900 (2021). WAAM utilises robotic and welding equipment to print steel components in a layer-upon-layer manner. Guidelines for the WAAM of steel structures are described by Hadjipantelis (2025). Owing to the large scale, geometric flexibility and high deposition rates it offers, WAAM is highly suitable for structural engineering applications, as described by Gardner (2023) and Hadjipantelis (2025).

In the proposed concept, WAAM enables the manufacture of meshes that resemble the non-orthogonal and highly irregular geometry of the mortar profiles of stone masonry walls, which would be challenging to achieve using conventional fabrication techniques. In the context of hybrid construction, this research work has been the first study to explore the use of large-scale metal 3D printing techniques for strengthening structures built with traditional construction materials, such as stone. The proposed retrofitting methodology comprises five steps, as detailed by Mavros et al. (2025) and summarised below:

- **Step 1:** The mortar joints are stripped to a depth of approximately 30 mm, as shown in Fig. 1(a). This step is typically performed in traditional repointing, too, in order to remove deteriorated mortar.
- **Step 2:** 3D laser scanning is employed to map the geometry of the mortar profile. Based on the scanned geometry, the centreline of the mortar profile is extracted, as shown in Fig. 1(b), using the methodology described by Mavros et al. (2025).
- **Step 3:** The centreline of the mortar profile is used as the design geometry in the WAAM process. As shown in Fig. 1(c), the WAAM reinforcing steel mesh is printed on a steel base plate setup, from which it is removed using robotic plasma cutting.
- **Step 4:** The WAAM reinforcing mesh, shown in Fig. 1(d), is test-fitted, then a uniform base layer of mortar is applied along the entire profile trench using a mortar gun, and the WAAM mesh is inserted into the mortar profile, as shown in Fig. 1(e).
- **Step 5:** The mortar profile is repointed, as shown in Fig. 1(f), concealing the WAAM mesh within the wall and restoring its original appearance.

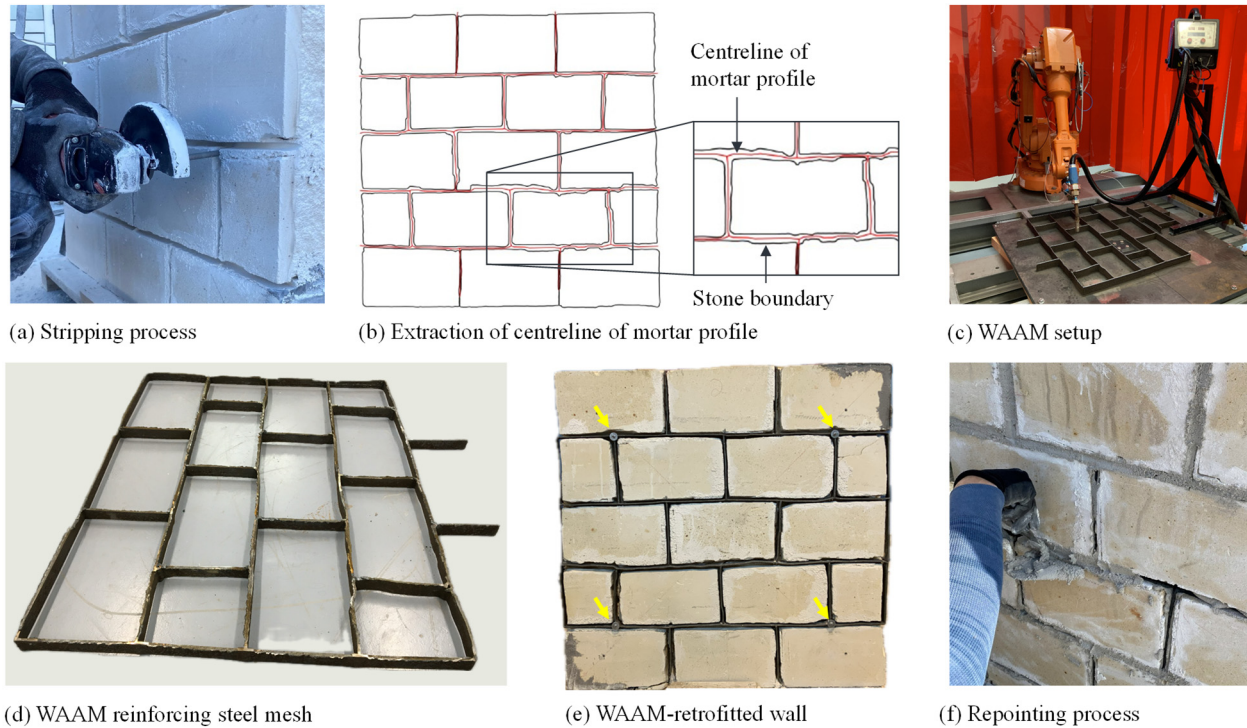


Fig. 1. Key steps in the proposed retrofitting method involving the manufacture of custom-fit WAAM steel meshes that are embedded within the mortar profile of historic stone masonry walls; the yellow arrows in (e) indicate the location of the steel rods that were used to interconnect the two reinforcing meshes.

3. Experimental proof-of-concept

The proposed concept has been demonstrated by Mavros et al. (2025) through an experimental programme that investigated the structural performance of two 0.8×0.8 m walls, before and after retrofitting, when subjected to diagonal compression. The test setup, shown in Fig. 2(a), comprised steel loading shoes, diagonal connection bars connecting two stiff steel beams located at opposite corners of the specimen, and a hydraulic jack that applied the loading. The test setup was in self-equilibrium while introducing the desired diagonal compressive load on the wall. In the proof-of-concept tests, the coursed ashlar masonry specimens were constructed by an experienced stonemason using locally quarried limestone from the Pachna Geological Formation in Cyprus.

Each wall specimen was retrofitted using two WAAM reinforcing meshes (one on each side) that were interconnected using threaded steel rods (4 mm in diameter) through the wall thickness. To accommodate the rods, circular hollow junctions were printed in the four corner regions of the WAAM meshes, as indicated in Fig. 1(e); more details are provided by Mavros et al. (2025). The WAAM meshes had a nominal thickness of 4.0 mm and an average depth of 25 mm. The volumetric reinforcement ratio (WAAM steel relative to stone) was approximately 1%.

The WAAM meshes were printed at the Steel Structures Laboratory of the University of Cyprus using normal-strength carbon steel wire (ER70S-6) and 82%Ar-18%CO₂ shielding gas. Tensile tests were conducted on coupons extracted from WAAM plates manufactured using the same process parameters as those used to print the WAAM meshes. The results revealed that the WAAM steel exhibited mechanical properties comparable to those of conventional steel (Mavros et al., 2025).

The diagonal compression versus diagonal shortening diagrams obtained from the tests on both the original and the WAAM-retrofitted wall specimens are shown in Fig. 2(b). The test results revealed that the WAAM-retrofitted specimens exhibited load-carrying capacities that were 3.0 and 3.7 times the capacities of their original counterparts. Furthermore, defining the ultimate point of the tests as the point corresponding to a 20% reduction from the peak load, the retrofitted specimens exhibited substantial enhancements in ductility, reaching 7.9 and 25.7 times the ultimate displacement of their unretrofitted counterparts.

The structural performance enhancements are attributed to the high strength and ductility of the WAAM steel, which effectively mitigated the opening of the mortar joints, and to the interlocking action between the steel mesh and the stone units, which enhanced the sliding shear resistance of the masonry, thus preventing sliding of the stone units along the mortar joints when the combined adhesion and friction of the mortar were insufficient.

The observed differences in the behaviour of the two repeat wall specimens are primarily attributed to the heterogeneous nature of the stone material (Mavros et al., 2025) and to unavoidable minor variations in the construction details (e.g. stone placement and mortar thickness), although both specimens were constructed by the same stonemason using the same raw materials.

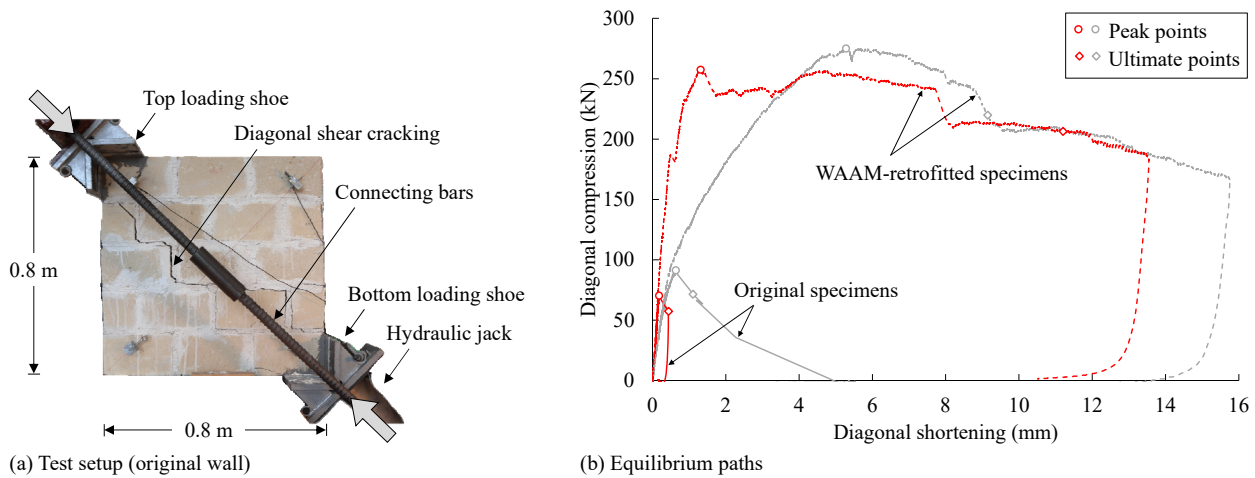


Fig. 2. (a) Test setup used in the proof-of-concept experiments; the original wall at the end of the tests is shown; (b) diagonal load-shortening graphs corresponding to the original (solid lines) and WAAM-retrofitted (dashed lines) specimens.

4. Conclusions

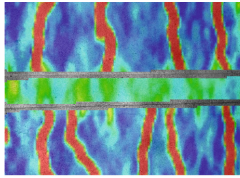
Recognising our common responsibility to safeguard historic structures for future generations, the present concept proposes a novel solution for the retrofitting of historic unreinforced stone masonry structures, enabling significant improvements in their load-bearing capacity, ductility, and energy dissipation while preserving their original architectural aesthetics. The proposed concept is founded on the use of large-scale robotic metal 3D printing, namely wire arc additive manufacturing (WAAM), in conjunction with 3D laser scanning, to manufacture custom-fit steel meshes that are embedded within the mortar profile of stone masonry walls. For the purposes of the experiments presented herein, the WAAM reinforcing steel meshes cover the entire mortar profile of the wall. However, in practice, wall assemblies would be retrofitted only partially, choosing strategic reinforcement layouts, identified by means of, for instance, topology optimisation.

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A digital workflow for optimized repair of corroded steel bridges via cold spray deposition

Georgios Tzortzinis^{a,1}, Kaushik Abhyankar^a, Bruno Christoff^a, Brian Schagen^b, A. John Hart^c, Simos Gerasimidis^b, Maik Gude^a

^aTUD Dresden University of Technology, Holbeinstraße 3, Dresden 01037, Germany

^bUniversity of Massachusetts Amherst, 130 Natural Resources Road, Amherst 01003, USA

^cMassachusetts Institute of Technology, 77 Massachusetts 02139, Cambridge, USA

Keywords: Additive manufacturing; laser scanning; finite element analysis; cold spray

1. Introduction

Corrosion-induced deterioration of steel bridge girders remains one of the most persistent challenges in infrastructure management, primarily due to its highly localized, irregular, and evolving nature. Material loss caused by corrosion does not occur uniformly but is instead governed by environmental exposure, geometric features, and electrochemical processes, leading to complex spatial patterns of degradation. Even relatively small localized losses can significantly alter stiffness, load redistribution, and stability, often governing failure mechanisms (Tzortzinis et al., 2021). Despite this, current engineering practice frequently relies on simplified or idealized representations of corrosion, which fail to capture its spatial variability and consequently introduce uncertainty into structural assessment and repair design.

Conventional repair methods for corroded steel girders include welded plates (Tarasova et al., 2024), bolted reinforcements (Li et al., 2024), fiber-reinforced polymers (Miyashita et al., 2015), and ultra-high-performance concrete encasements (Zmetra et al., 2017). These approaches are typically labor-intensive, require extensive surface preparation, and apply uniform strengthening over relatively large areas. As a result, they are often conservative and material-inefficient, as they do not account for the localized nature of corrosion damage or the actual structural demand. This mismatch between damage morphology and repair strategy motivates the development of more adaptive, data-informed approaches capable of delivering targeted and efficient rehabilitation solutions.

Additive manufacturing (AM) technologies provide a promising pathway toward such solutions by enabling spatially controlled material placement. In particular, cold-spray additive manufacturing is well suited for infrastructure repair due to its solid-state deposition mechanism, in which metallic particles bond through high-velocity impact without melting. This avoids thermal distortion, residual stresses, and metallurgical transformations associated with conventional thermal processes, while preserving the base material's microstructure (Villafrute, 2018). Consequently, cold spray offers the potential to rebuild lost material directly on-site in a controlled and localized manner (Kang et al., 2017). However, the effectiveness of such an approach depends critically on how deposition patterns are designed and executed, necessitating an integrated framework that links inspection data, structural analysis, and fabrication.

This work presents an end-to-end workflow for the optimized repair of corroded steel bridge girders using cold-spray deposition. The proposed framework combines high-resolution laser scanning, computational modeling, and gradient-based optimization to enable performance-informed rehabilitation of steel bridge infrastructure.

¹ Corresponding author. Tel.: +49-351-463-39463
E-mail address: georgios.tzortzinis@tu-dresden.de

2. Methodology

2.1. Point clouds to corrosion mapping

Central to this workflow is the development of an algorithmic framework that converts scan-derived point cloud data into a structured representation of corrosion that is both accurate and computationally efficient. In this approach, a grid-based thickness field is introduced, whereby the corroded region is discretized into a finite number of rectangular blocks, each assigned a representative thickness value. This transformation results in a piecewise-constant representation that preserves the essential characteristics of the corrosion while enabling efficient integration with finite element analysis and optimization procedures. It is important to note that the proposed post-processing framework is independent of the type or technology of the scanning equipment used to acquire the point cloud data.

2.2. Experimental benchmark and numerical validation

To evaluate the suitability of the structured thickness representation for capacity assessment, a nonlinear finite element model is developed to simulate the structural response of a scanned corroded girder. A Python script is implemented to integrate the previously developed thickness representation into a three-dimensional finite element model in Abaqus. The web surface is partitioned, and thickness values are automatically assigned to each segment. Although the methodology described in Section 2.1 enables the representation of the entire web domain, only the lower portion of the web is considered in this study to achieve a balance between accuracy, computational efficiency and ease of data handling.

The scanned girder is subjected to full-scale experimental testing under simply supported boundary conditions. The load is applied upward at the corroded end using two hydraulic jacks positioned beneath a load-spreading beam (Fig. 1a). To restrain upward displacement of the girder, a cross beam anchored to the strong floor is placed on top of the upper flange at a distance of 1.2 m from the tested end. The experimental setup and instrumentation are described in detail in Tzortzinis et al. (2022). The obtained bearing capacity of 478 kN is used as a benchmark for validating the computational model. The structured grid model accurately reproduces the observed load–displacement response, with a minor deviation of 4.4% in the predicted capacity.

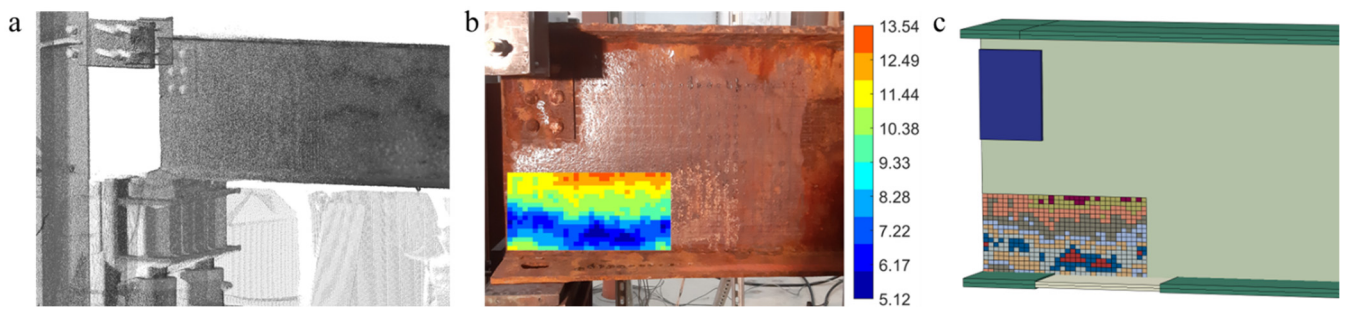


Fig. 1. (a) Point cloud of a decommissioned bridge girder in lab conditions; (b) remaining web thickness, in mm, projected on the actual beam; (c) and the corresponding geometry for analysis with the finite element method.

2.3. Optimization framework for additive repair design

Building on the previously calibrated computational model, the repaired regions are simulated using a symmetric three-layer composite shell formulation that explicitly accounts for the base material, the interface between the substrate and the deposited layer, and the cold-spray additive material. The material properties assigned to each layer are derived from experimental testing conducted in accordance with ASTM E9. The test program includes specimens of the base material (A36 steel), pure cold-spray material, and composite specimens consisting of cold-spray deposits applied to A36 steel.

The core of the proposed methodology is a gradient-based optimization framework that determines the spatial distribution of deposited material required to address the repair design objectives. The design variables correspond to the thickness of the cold-spray deposit applied to each grid block, and the objective is to achieve an optimal balance between structural capacity recovery and material efficiency. Two complementary formulations are introduced. The first is a Pareto-based multi-objective approach that explicitly captures the trade-off between added material volume and recovered load-carrying capacity. This formulation allows exploration of a range of admissible solutions, providing insight into efficiency trends and diminishing returns associated with increased material deposition. The second formulation adopts a penalty-based approach that targets a prescribed capacity level, reflecting practical engineering requirements in which repairs must meet specific load-rating criteria. In this case, the optimization seeks to minimize material usage while ensuring that the desired structural performance is achieved.

The optimization process proceeds iteratively, with sensitivities of structural capacity to local thickness variations (a perturbation introduced to each grid block) computed using finite differences. At each iteration, the thickness field is updated in the direction of the gradient, subject to constraints that ensure manufacturability and physical realism. These constraints include bounds on minimum and maximum deposition thickness, reflecting limitations of the cold-spray process and the need to avoid unrealistic

stiffness gradients. The use of a structured grid representation enables a direct correspondence between design variables and physical deposition regions, facilitating both optimization and subsequent fabrication planning.

3. Results

The optimization framework is applied to the girder shown in Fig. 1. The results of the optimization reveal that spatially varying, non-uniform deposition patterns can achieve substantial improvements in structural capacity with significantly reduced material usage compared to conventional repair strategies. In particular, the Pareto-based analysis identifies distinct reinforcement patterns characterized by localized zones of increased thickness, which play a critical role in restoring load-carrying capacity. These results highlight the importance of aligning material placement with the underlying mechanics of structural response, rather than applying uniform reinforcement. Furthermore, the penalty-based formulation (Fig. 2) successfully generates repair designs that meet prescribed capacity targets while maintaining material efficiency.

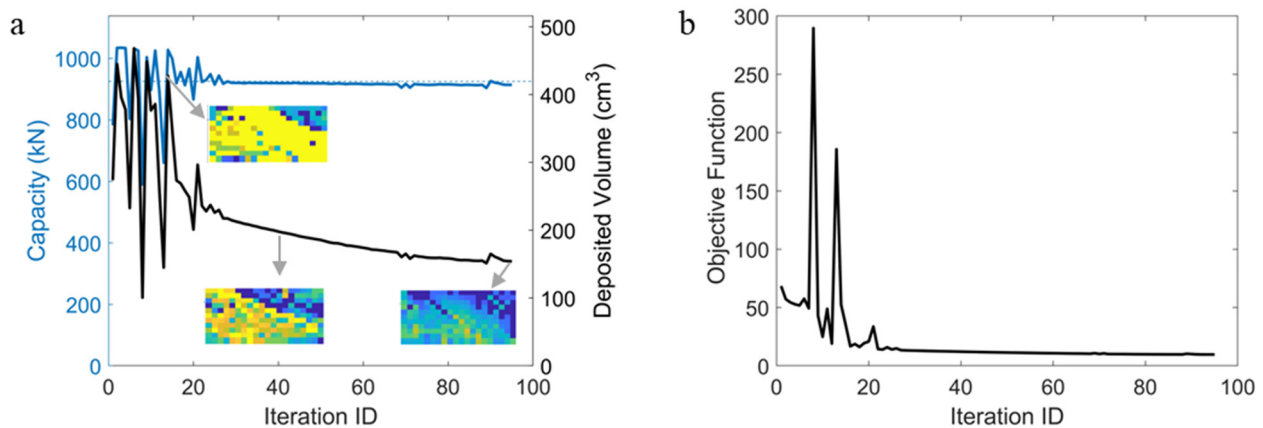


Fig. 2. Penalty-based optimization results for capacity restoration (dotted horizontal line): (a) evolution of material deposition and capacity over iterations; (b) convergence of the objective function.

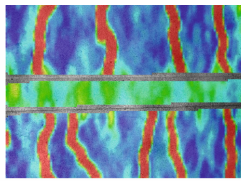
4. Conclusion

The main contributions and conclusions are summarized as follows:

- The proposed grid-based representation of corrosion enhances computational efficiency while maintaining accuracy in predicting structural capacity.
- The developed gradient-based optimization framework enables the exploration of trade-offs between material-efficient reinforcement patterns (Pareto front) and the identification of solutions that satisfy specified target capacities (Penalty method).
- The proposed framework is not limited to steel bridges and can be adapted to other types of corrosion-prone infrastructure.

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Large-scale WAAM setup for hybrid construction and strengthening

Elyas Ghafoori^{a,1}, Hessam Moshayedi^a, Maximilian Löwe^a, Tim Brömer^a

^a*Institute for Steel Construction, Leibniz University Hannover, Germany*

Keywords: WAAM, hybrid construction, structural strengthening, XRD setup, large-scale additive manufacturing, in-situ process monitoring, multi material printing

Extended abstract

Wire and arc additive manufacturing (WAAM) is increasingly recognized as a promising technology for large-scale metallic fabrication in civil and structural engineering. In contrast to powder-based additive manufacturing processes, WAAM enables high deposition rates, large build volumes, and comparatively efficient production of structural-scale components. These characteristics make it particularly attractive not only for the fabrication of new components, but also for hybrid construction, repair, geometric adaptation, and strengthening of existing steel or composite structures. The possibility to deposit material only where it is structurally needed opens new opportunities for resource-efficient construction, fatigue-sensitive reinforcement, and the development of customized structural solutions.

This contribution presents the concept and development plan of a large-scale WAAM research setup intended for hybrid construction and structural strengthening applications at Institute for Steel Construction at Leibniz University Hannover. The planned facility provides the flexibility and process control required for structural engineering research. The setup combines multi-axis robotic motion, high-deposition arc welding processes, and the capability for multi-material deposition, enabling the production or strengthening of complex structural geometries at scales relevant to real construction components. Particular emphasis is placed on the deposition of metallic material onto existing substrates, such as steel members, welded joints, or hybrid assemblies, where geometric complexity, heat input control, and metallurgical compatibility are critical.

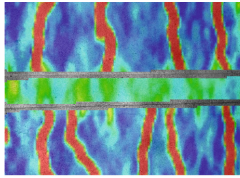
A key objective of the proposed setup is the systematic investigation of WAAM for strengthening and rehabilitation of fatigue-critical and damage-prone structures. Targeted applications include local reinforcement of welded joints, geometry restoration in degraded components, repair of damaged steel details, and the creation of hybrid steel–composite assemblies with tailored reinforcement zones. In such applications, WAAM offers the possibility to locally increase stiffness, reduce stress concentrations, recover lost section geometry, or introduce optimized load paths without the need for complete replacement of the component. This is particularly relevant for aging infrastructure and offshore or industrial structures, where access constraints, high replacement costs, and sustainability considerations motivate advanced repair technologies.

To enable research at this level, the WAAM cell is planned to integrate advanced process monitoring and thermal management strategies. These include in-situ sensing for deposition geometry and process stability, as well as monitoring approaches for thermal history, microstructure evolution, and residual stress development. A distinctive feature of the planned setup is the integration of an in-situ X-ray diffraction (XRD) system for residual stress characterization. This allows direct observation of stress evolution during or after deposition and supports the development of process–structure–property relationships for WAAM-based strengthening solutions. Such knowledge is essential because residual stresses, distortions, and heat-affected zone properties can strongly influence fatigue performance, dimensional accuracy, and structural reliability.

Overall, the proposed large-scale WAAM setup is intended to establish a scalable and versatile research infrastructure for civil engineering applications of additive manufacturing. By combining robotic deposition, multi-material capability, in-situ sensing, XRD-based residual stress monitoring, and digital modelling, it will support the development of new strategies for hybrid

¹ Corresponding author. Tel.: +49 511 762 3781
E-mail address: ghafoori@stahl.uni-hannover.de

construction, strengthening, repair, and structural adaptation. The platform is expected to contribute significantly to the transition of WAAM from a manufacturing concept to a deployable structural technology for resilient and sustainable infrastructure.



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Influences of shielding gas on wire arc additive manufacturing process for structural steel

Dirk Kampffmeyer^{a,1}

Messer SE & Co. KGaA, Kleinewefersstraße 1, 47803 Krefeld, Germany

Keywords: Shielding gas; wire arc additive manufacturing; structural steel, deposition speed

1. 3D-Printing with wire arc additive manufacturing (WAAM) process

The 3D-Printing or Additive manufacturing has been offering an alternative form of production for structural steel components for several years. Various printing processes are used today for 3D printing metallic materials. While the processes in the powder bed are more suitable for complex components with small dimensions, the direct energy deposition (DED) processes are particularly suitable for larger structures. These methods fuse selectively and apply filler material to the component in the form of wire or powder. A robot or an automated multi-axis system provides the necessary tool movements. Suitable energy sources include the laser and the electric arc, whereby the standards also specify the official classification direct energy deposition – laser beam (DED-LB) and direct energy deposition – arc (DED-Arc). Today, the best-known representative of the DED processes is the DED-Arc process which is more known as WAAM.

2. Influences of typical shielding gases components

When using wire arc additive manufacturing, well-known gases from welding technology are very often used, which cause good penetration into the component. When welding structural steel components, three shielding gas components are essentially possible. These are argon, carbon dioxide and oxygen, the influence of which will be examined in more detail below.

Argon is an inert gas that produces an even and stable arc thanks to its good ionisability. In metal active gas (MAG) welding, it is never used in its pure form, but rather as the main component in gas mixtures. Gas mixtures with a very high argon content are associated with low spatter and deep, narrow weld penetration (Kampffmeyer and Wolters, 2015).

Carbon dioxide (CO₂) is an active gas and can be used in MAG welding as a pure gas or as a gas mixture component. Welding with pure carbon dioxide produces an uneven arc that leads to a lot of spatter and an uneven weld surface. A positive feature is the sizeable weld penetration that can be achieved with this gas. Carbon dioxide is often used mixed with argon. In the arc, it dissociates to form carbon monoxide and oxygen. Alloy elements (but also iron) react with the oxygen, resulting in the formation of slag on the surface of the weld. The greater the CO₂ content, the more intensive the penetration and the more spatter and slag is produced on the surface of the weld (Kampffmeyer and Wolters, 2015).

Oxygen (O₂) can only be used in MAG welding as a component in a gas mixture. It produces fine-droplet metal transfer, resulting in low spatter and good weld surface appearance. In addition, it produces a low-viscosity molten pool that becomes more fluid as the oxygen content increases. Gas mixtures with a higher oxygen content can therefore only be used when welding in the flat position (PA position). Oxygen also dissociates in the arc and leads to burn-out losses of the alloy elements (Kampffmeyer and Wolters, 2015).

With 3D printing, however, a small penetration of the melted material is necessary to achieve a good layer structure and low heat input. This must be taken into account when selecting the shielding gas. Experience from welding technology is very helpful here.

¹ Corresponding author. E-mail address: dirk.kampffmeyer@messergroup.com

3. Shielding gases and their applications

The choice of the shielding gas depends on its application. Essentially, four different areas of application can be distinguished. These are described below and recommendations for the selection of the shielding gas are given:

3.1. Application to movable components

Multi-axis systems such as 5-axis or 6-axis machining centers are often used here. The component can always be positioned in such a way that the WAAM process takes place almost exclusively in the flat position (PA position). For the printing process, this means that small penetration is required, and a lot of additional material can be used for layer construction. This enables fast and effective production.

In a research project carried out at TU Ilmenau on behalf of Messer, a sample product was produced with various shielding gases. The walls of the hexagon were printed next to each other with three seams per layer. In principle, the sample product could be produced with all tested shielding gas. It is striking, however, that shielding gases with a low active gas content enable a significant increase in printing speed. On the one hand, the welding time could be reduced and on the other hand, the cooling time between the layers could be reduced, Fig. 1.



Fig. 1. Project with TU Ilmenau: WAAM component that has been printed four times with a different shielding gas; sample dimensions (left), macro cuts (middle), production time separated in welding and cooling time (right).

The best result is a shielding gas with 2.5% CO₂ in Argon (Ar) (Ar 97.5%; CO₂ 2.5%). The recommendation is the following shielding gas: ISO 14175 (2008) - M12-ArC-2,5 - Inoxline C2

3.2. Application to non-movable components

This application area applies particularly to large components. A good example here is the bridge in Darmstadt, Fig. 2. In order to be able to print such structures, the movement must take place through the printing head (the welding torch). The structures, also known as cantilevered structures, can be used also for horizontal printing direction. The main challenge here is to stabilize the melt so that it retains its shape and does not fall off. For successful 3D printing, the right selection of process control variant, welding parameters, cooling and also shielding gas is necessary. The shielding gas influences the energy input into the melt and the penetration (Feucht et al., 2022, Feucht et al., 2021).



Fig. 2. WAAM printed bridge of TU Darmstadt: during production.

In a research project together with the Technical University of Darmstadt, various shielding gases were investigated for the production directions 45° and 90° (horizontal). Forming the weld seam is particularly challenging at a 90° angle (horizontal), Fig. 3. The design and mechanical-technological quality values were used for the evaluation (Feucht et al., 2022, Feucht et al., 2021).

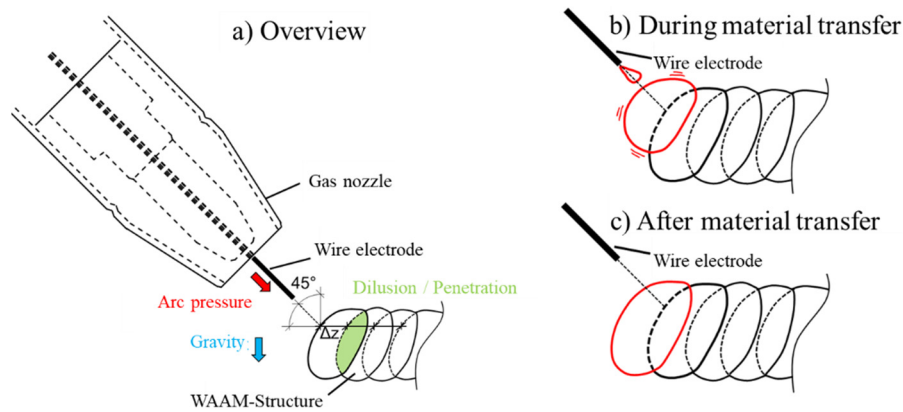


Fig. 3. Schematic representation at the production site for the test specimen with a horizontal production orientation (90°) (Feucht et al., 2021).

To achieve good printing results, it is important that the penetration depth is shallow and that the molten material is liquid enough to form the weld seam. For the evaluation of the best shielding gas the design and mechanical-technological quality values were used. The best and most stable results were achieved by a shielding gas with 6% CO₂ and 1% O₂ in Argon (Ar 93%; CO₂ 6%; O₂ 1%), Table 1 (Feucht et al., 2022, Feucht et al., 2021). The recommendation is the following shielding gas: ISO 14175 (2008) - M24-ArCO-6/1 - Ferroline C6X1.

Table 1. Material characteristics (mean values and standard deviations) (Feucht et al., 2021).

	Tensile strength in N/mm ²		Elongation at break in %		Yield strength R _e in N/mm ²		Modulus of elasticity at 0.2% elongation in N/mm ²	
Production direction	45°	90°	45°	90°	45°	90°	45°	90°
Ferroline C18	537 ± 5	529 ± 4	29 ± 1	29 ± 1	418 ± 8	412 ± 6	144.000 ± 20.000	182.000 ± 18.000
Ferroline C6X1	567 ± 10	534 ± 4	25 ± 1	30 ± 3	471 ± 10	423 ± 3	175.000 ± 16.000	147.000 ± 25.000
Inoxline C2	560 ± 7	534 ± 23	28 ± 2	13 ± 5	459 ± 11	438 ± 22	189.000 ± 6.000	171.000 ± 18.000

3.3. Repair and rehabilitation of civil structures

For repair, support structures can be printed into the steel structure. Here, too, the component is usually not movable, so that the print of the support structures poses special challenges. On the one hand, these are typical challenges with all non-moving components. On the other hand, it is the positioning of the printer. A shielding gas with 6% CO₂ and 1% O₂ in Argon should be used for a good result. The recommendation is the following shielding gas: ISO 14175 (2008) - M24-ArCO-6/1 - Ferroline C6X1

3.4. Repairs to components

Another area of application is repairs to components, most of which have been damaged by frictional wear. These can be repairs to shovels of shovel excavators or loading areas for bulk material. Since there are often no major requirements for the design, typical standard gases from welding technology can be used here.

4. Production of steel structures

The WAAM process can be used in a variety of ways for the production of steel structures. Essentially, a distinction must be made: Is the component movable and the print can always be applied in the PA position, or the component is not movable and the torch position must be changed. This always means challenges to the printed seam and affects the choice of the shielding gas. Shielding gases with reduced active gas components such as Inoxline C2 (Ar 97.5%; CO₂ 2.5%) or Ferroline C6X1 (Ar 93%; CO₂ 6%; O₂ 1%) should be used.

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Hybrid DED-arc of multi-materials: mechanical properties and FE analysis

Aatif Imran^a, Mohsen Amraei^a, Antti Salminen^a

^a*Department of Mechanical & Materials Engineering, University of Turku, Turku 20520, Finland*

Abstract

Directed Energy Deposition using electric arc (DED-Arc) additive manufacturing enables the fabrication of large-scale steel components and the integration of multiple materials within a single structure. This capability creates opportunities for developing hybrid steel members with tailored mechanical properties and improved structural performance. Combining materials with different strength and ductility characteristics can enhance load-bearing capacity while maintaining sufficient deformation capacity, making this approach attractive for performance-based design and structural strengthening. This study investigates the mechanical behavior of multi-material DED-Arc steel specimens composed of SS316L stainless steel and ER70S-6 mild steel arranged in different stacking configurations. A combined experimental–numerical approach was adopted to evaluate the influence of material distribution on structural response. Tensile tests provided force–displacement behavior, stress–strain response, ductility, and fracture characteristics. Finite element models were calibrated using stress–strain curves from single-material specimens and subsequently applied to hybrid configurations to analyze stress redistribution, strain localization, and load transfer across material interfaces. The results show that stacking sequence significantly influences strength and deformation capacity. Balanced material distributions exhibited improved ductility and stable plastic deformation, whereas strength-dominated layouts showed earlier strain localization. Stress concentrations occurred primarily near material transition zones, where stiffness mismatch governed fracture initiation. These findings demonstrate that hybrid DED-Arc steel members can be mechanically tailored through strategic material placement to achieve optimized combinations of strength and ductility.

Keywords: Directed energy deposition; DED-arc; hybrid steel structures; additive manufacturing; multi-material additive manufacturing; interface behavior; structural strengthening

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

Mechanical performance and failure of ultrahigh-strength welded hybrid structures

Shahriar Afkhami^a, Antti Ahola^b, Sakari Penttilä^a, Kalle Lipiäinen^b, Hannu Lund^a, Tuomas Skriko^a

^a*Laboratory of Welding Technology, LUT University, Lappeenranta, Finland*

^b*Laboratory of Steel Structures, LUT University, Lappeenranta, Finland*

Abstract

Hybrid steel structures combining additively manufactured components with traditionally manufactured ones via welding offer new opportunities to achieve high strength-to-weight ratios in civil engineering. However, the mechanical performance of such hybrid structures requires further investigation. This study evaluates the performance and failure behavior of ultrahigh-strength hybrid structures composed of direct-energy-deposited X96 steel welded to thermomechanically processed S960 steel under quasi-static tensile loading. The influence of the direct deposition direction (normal or parallel to the loading axis), welding process (laser or gas metal arc), and surface condition (as-built or machined) were examined. Radiographic inspection, surface roughness measurements, and digital image correlation complemented quasi-static tensile testing. The results show that the alignment of inherent defects, such as lack-of-fusion and interlayer boundaries, relative to the loading direction can govern ductility and fracture energy, whereas strength remains comparatively less sensitive. Specimens with the build direction normal to loading exhibited superior elongation and toughness. The welding method had a minimal effect on overall performance. Machining improved fracture behavior but slightly reduced strength in some cases, possibly due to a subsequent decrease in the effective cross-section (the effective cross-section being smaller than the apparent cross-section due to internal flaws).

Keywords: Hybrid structure; direct-energy deposition; welding; mechanical properties; fracture

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

3D-scan based determination of an equivalent relative rib area f_R for additively manufactured reinforcement using WAAM

Luca Locher^a, Thomas Braml^a

^aUniversity of the Bundeswehr Munich, Werner-Heisenberg-Weg 39, 85579 Neubiberg, Germany

Abstract

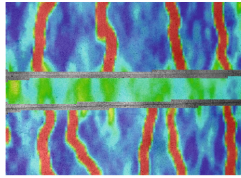
The bond behaviour of reinforcing steel in concrete is strongly influenced by the surface characteristics of the reinforcement bar. For conventional hot rolled reinforcement (B500), this behaviour is commonly described by the relative rib area f_R , which represents a key geometric parameter influencing the bond behaviour of reinforcement in concrete. However, additively manufactured reinforcement bars produced by Wire Arc Additive Manufacturing (WAAM) exhibit continuously structured surfaces without clearly defined ribs and lateral surface area, making the established determination methods for the relative rib area f_R not directly applicable.

This study presents a 3D-scan based methodology to analyse the surface characteristics of additively manufactured reinforcement bars and to determine an equivalent relative rib area f_R . High resolution laser scanning was used to digitize the surface geometry of WAAM manufactured specimens. The resulting scans were processed to evaluate geometric deviations relative to an idealized reference cylinder and to quantify the surface characteristics.

The proposed methodology enables a comparable geometric characterization of additively manufactured reinforcement and provides a basis for evaluating the equivalent relative rib area f_R with respect to conventional reinforcement bars.

Keywords: Bond behaviour; relative rib area; WAAM; reinforcement; 3D-scan

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



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Geometric imperfections and post-fire behavior of WAAM stub columns

Lu Yan^a, Dechuang Liu^a, Senbin Huang^b, Yancheng Cai^b, Martin Mensinger^a

^a Technical University of Munich, Munich 80333, Germany

^b Hong Kong Metropolitan University, Hongkong 999077, China

Keywords: WAAM; geometric imperfection; compressive behavior; post-fire performance

1. Introduction

Wire Arc Additive Manufacturing (WAAM) is an efficient technology for large-scale metal structures. However, the layer-by-layer deposition process introduces geometric imperfections that affect the local buckling resistance of thin-walled components like square hollow section (SHS) stub columns. Post-fire evaluation is critical for safety, yet studies on the degradation of WAAM components are currently limited. This study investigates the post-fire compressive behavior of WAAM SHS stub columns made from ER120S high-strength carbon steel and ER2209 duplex stainless steel. The degradation of material properties due to high-temperature exposure (post-fire) is explained based on microstructural evolution. Finally, this paper analyzes the impact of WAAM geometric imperfections on finite element simulation accuracy.

2. Materials and methods

A total of 16 WAAM SHS stub columns were fabricated with two different materials, utilizing the process parameters listed in Table 1. Dimensions of the stub column specimens can be found in Table 2. Each specimen and its corresponding microstructural sample were then exposed to a specific temperature of 22 °C (room temperature), 300 °C, 500 °C, 700 °C, 850 °C or 1000 °C. They were soaked for 20 minutes, followed by cooling inside the furnace to room temperature (Cai et al., 2025). The remaining two columns of each material were used for replicate experiments for the 22 °C and 850 °C conditions.

Table 1. Materials and nominal dimensions of stub column specimens.

Feedstock wires	Wire diameter (mm)	Welding speed (m/min)	Wirefeed rate (m/min)	Deposition rate (kg/h)	Current (A)	Arc voltage (V)	Shielding gas	Gas flow (L/min)
ER120S	1.2	0.3	2.9	1.555	83	11.8	98%Ar+2%CO ₂	22
ER2209	1.2	0.6	3.8	2.037	102	12.7	98%Ar+2%CO ₂	22

Initial geometric imperfections were captured using a HandySCAN 3D laser scanner for external surfaces and silicone casting for internal profiles (Kyvelou et al., 2021). The acquired surface point clouds were precisely registered using the Iterative Closest Point (ICP) algorithm in CloudCompare.

Table 2. Nominal dimensions of WAAM stub column specimens.

Height (mm)	Width (mm)	Length (mm)	Thickness (mm)	Inner radius (mm)
60	60	180	2.5	5.0

Compression tests were subsequently conducted at room temperature on a 600 kN ZwickRoell machine at a loading rate of 0.18 mm/min (Evans et al., 2024). A dual-camera Digital Image Correlation (DIC) system monitored strain and displacement fields. To minimize load eccentricity, a fixed platen was mounted at the top of the machine and a spherical seat at the bottom, ensuring

full contact with the specimen ends. To prevent local outward bulging (Su et al., 2020), reinforcement frames were positioned 5 mm from both ends of the stub columns, as shown in Fig. 1(a).

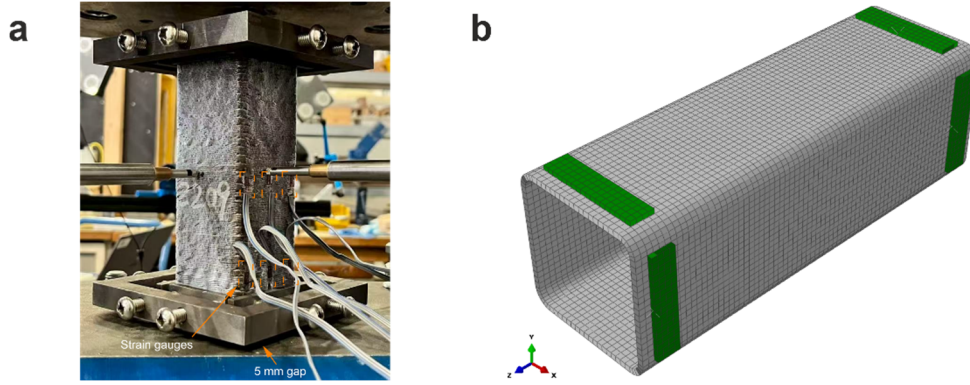


Fig. 1. (a) Test setup of a WAAM stub column, (b) finite element model.

Numerical investigations were performed in ABAQUS, incorporating the initial imperfections by comparing the conventional eigenmode-based method (Huang et al., 2024) with the measured-geometry method (Ban and Mei, 2023). Regarding the measured-geometry method, a nearest-neighbor algorithm was employed to identify the closest point in the 3D scanned point cloud for each node. The nodal coordinates and thickness definitions were then updated to accurately reflect the actual geometry and surface topography. Material stress-strain relationships were derived from coupon tensile tests. For the boundary conditions, both ends of the specimen were fully restrained across all degrees of freedom, except for the axial displacement applied at the loading end (Castanheira et al., 2022). As depicted in Fig. 1(b), to simulate the reinforcement frames, stiff plates were modeled to interact with the specimen via hard contact with tangential friction.

3. Results and discussions

High-temperature exposure significantly affects the material properties and ultimate load-bearing capacity of stub columns. For the duplex stainless steel ER2209, temperatures above 850 °C resulted in material embrittlement and strengthening due to the intermetallic σ -phase precipitation (Tang et al., 2025). Following heat treatment at 1000 °C, the yield strength decreased by 7.9%, dropping from the as-built 521 MPa to 480 MPa, whereas the ultimate tensile strength increased by 4.2%, rising from 693 MPa to 722 MPa. Furthermore, the ultimate compressive capacity of these stub columns at 1000 °C rose by 13.9%, from 260.4 kN to 296.6 kN. This increase is attributed to the combined effects of material property evolution and fluctuations in the as-built cross-sectional dimensions inherent to the WAAM process.

In contrast, the as-built high-strength carbon steel ER120S exhibits yield and ultimate tensile strengths of 927.3 MPa and 980.9 MPa, respectively. After heat treatment at 700 °C, the ultimate tensile strength increased by 7.8% to a peak of 1057.0 MPa, but the yield strength dropped by 14.3% to 795.0 MPa. Furthermore, heat treatment above 850 °C caused significant degradation in mechanical properties. Consequently, the compressive capacity of the ER120S stub columns decreased by 15.3%, from 487.5 kN at room temperature to 412.9 kN at 1000 °C.

To accurately capture these structural behaviors, 3D scanning was conducted, revealing global geometric deviations of less than 0.4 mm and average wall thickness variations of up to 0.38 mm, as demonstrated by the most pronounced case in Fig. 2. These findings highlight the necessity of optimizing process parameters to achieve greater manufacturing consistency and dimensional control.

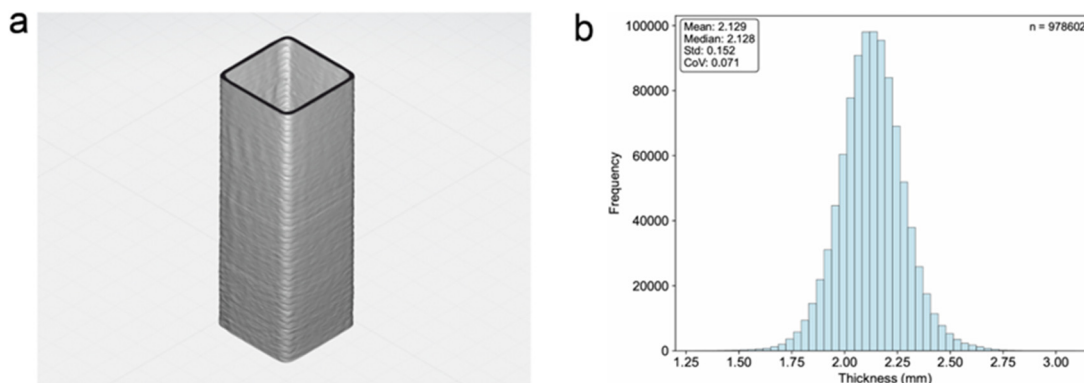


Fig. 2. (a) Laser-scanned data and (b) thickness distribution of representative specimen.

Both modeling approaches accurately predicted the ultimate capacities with a maximum difference of 11%, as depicted in the load-shortening (P - δ) curves in Fig. 3. Notably, the numerical models yielded a much more accurate prediction of the axial shortening at the ultimate capacity for the post-fire specimens than for the as-built ones. Although the eigenmode method (E model) offered high computational efficiency, the measured-geometry model (M-G model) yielded a more accurate simulation of the buckling positions by directly mapping the scanned point clouds.

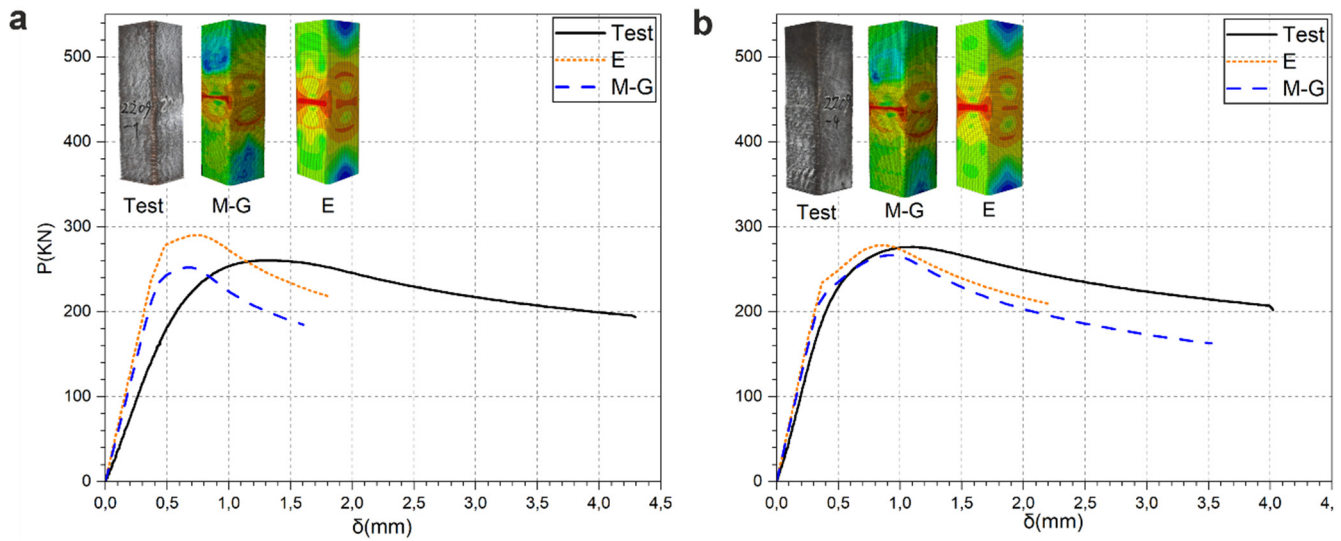


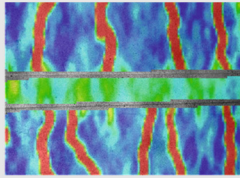
Fig. 3. Representative load-deformation (P - δ) curves of specimens: (a) ER2209 at 22 °C without post-fire condition; (b) ER2209 after exposure to 700 °C.

4. Conclusion

The structural response of WAAM stub columns to heat treatment is highly material dependent. For the duplex stainless steel ER2209, temperatures higher than 850 °C induce embrittlement and ductility reduction. Despite this, its ultimate tensile strength and overall compressive capacity improve after post-fire temperature of 1000 °C. Conversely, heat treatments above 850 °C significantly degrade the ultimate load capacity of high-strength carbon steel ER120S stub columns. In numerical analysis of WAAM columns, the choice of initial imperfections depends on the design objective. Conventional eigenmode-based methods efficiently predict the ultimate capacity. However, integrating 3D-scanned measured geometry is essential for accurately simulating actual local instability and exact buckling mechanisms.

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SMAR 2026



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MS09: Monitoring of structural health, noise and vibration of urban transportation infrastructure, and its assessment planning

Organizer:
Duo Liu (TU Dresden, Germany)

ABSTRACT

In contrast to pure road and rail construction, there is currently no independent rules or concept that deals with the condition assessment of urban transportation infrastructures in municipal areas. As a result, each network operator has developed its own individual approach over time. Only very few network operators maintain digital platforms for data management. Overall, there is currently no structured and systematic assessment of urban transportation infrastructure. In addition, sustainable, long-term monitoring and assessment approaches are required to control noise and vibration emissions in urban areas. Current maintenance practice provides only for a corrective maintenance strategy. For economic and sustainable reasons alone, the discussion about the ways of monitoring of structural health, noise and vibration of urban transportation infrastructure, and its assessment planning to enable predictive maintenance should be the aim of this Mini Symposium.

Monitoring of tramway superstructures using short- and long-term measurements

Jia Liu^a, Kazim Uzar^a

^a*Technical University of Darmstadt, Institute of Transportation Infrastructure Engineering, Otto-Berndt-Str. 2, 64287 Darmstadt, Germany*

Abstract

In many cities, trams form an integral part of the local public transport network. In the tram sector, there are two types of tramway superstructure: open and closed. The open type is only used by trams, while the closed type can also be used by individual vehicles. Different build-up designs are used for each variation. As there are no binding specifications, transport companies rely on their own experience. Experience also shows that identical build-up designs may be damage-free in one case, while causing damage in another. To address this issue systematically, data and facts must be obtained to reflect how a superstructure system with a certain build-up design actually functions. To this end, the Institute for Transport Infrastructure Engineering at the Technical University of Darmstadt conducts various measurements on tram tracks during operation. Important parameters such as the deformation, temperature and velocity of superstructure components are recorded and analyzed. Particular consideration was given to sections of track with tight curves. Here, additional high lateral forces are at work, which are necessary for guiding the tram. These forces in turn influence the deformation behavior and mechanical stress of the track components. To determine the realistic loads on corresponding sections, it is important to consider the service life of the superstructure system. This publication presents various measurement sections (e.g. green track, open ballast superstructure and closed track with asphalt paving). Additionally, it presents a long-term measurement designed to determine track curvature breathing in tight curves.

Keywords: Tramway superstructure, short- and long-term measurement, lateral force, deformation, stress

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

Railway track irregularity estimation based on sleeper acceleration and Kalman filter (KF) method

Xiaodong Han^a, Shaoguang Li^b, Liangliang Cheng^a

^a*Engineering and Technology Institute Groningen, University of Groningen, Nijenborgh 4 9747 AG, Groningen, The Netherlands*

^b*RailTechnology GmbH, Industriestraße 12 31655, Stadthagen, Germany*

Abstract

Traditional geometry inspection methods are often costly, infrequent, or labor-intensive. As sleeper-based sensing becomes increasingly feasible in smart railway infrastructures, an important challenge is how to use such measurements for track geometry estimation. This study proposes a Kalman filter (KF)-based framework to estimate track irregularities from sleeper acceleration measurements. A vehicle-track model is formulated as the observation model within the KF framework. The model represents a single-axle vehicle moving along a flexible track supported by multiple sleepers. Sleeper acceleration measurements are incorporated into the KF as observations, and track irregularities are reconstructed through recursive state estimation. Case studies show that the proposed framework can successfully recover the overall shape and dominant wavelength characteristics of track irregularities under different signal-to-noise-ratio (SNR) conditions, including SNR15, SNR25, SNR35, and SNR45. Under high SNR conditions, the estimated profile matches the true irregularity closely, and the estimation error remains relatively small. As the SNR decreases, the estimation error increases and amplitude reconstruction becomes less accurate. Wavelength-domain analysis further indicates that the short wavelength features are preserved more robustly, whereas noise mainly affects amplitude consistency and long wavelength components. Overall, the results suggest that the proposed framework provides an effective inverse estimation approach for track geometry monitoring when sleeper acceleration measurements are available.

Keywords: Kalman filter; ballasted track; structural health monitoring; smart sleeper; model updating.

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

Inspection of rail roughness with acoustic based vehicle side and way side measurement

Martin Unger^a, Prof. Dr.-Ing. Duo Liu^a

^a*Chair of Railway Track Engineering, TUD Dresden University of Technology, 01062 Dresden, Germany*

Abstract

Rail surface roughness is major source of rolling noise and accelerated wheel-rail deterioration, making regular inspection essential. While direct measurement methods such as the Corrugation Analysis Trolley offer high accuracy, they are unsuitable for continuous, network-wide monitoring. This paper investigates an indirect, acoustic-based approach using on-board microphones near the axle bearings to estimate rail roughness via vehicle-side transfer functions. Based on measurement campaigns conducted in 2025 on the German railway network, transfer functions were derived for two ballasted track sections differing only in rail pad stiffness, revealing level differences up to 20 dB and a clear dependence on superstructure properties. Complementary wayside impact hammer tests, evaluated according to a modified DIN EN 17936 procedure, showed analogous discrepancies in the same frequency ranges, indicating that transposition of vehicle-side transfer functions to unknown track sections via wayside measurements is fundamentally feasible.

Keywords: Rail roughness; indirect measurements; condition monitoring; way-side measurement; rolling noise

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

Experimental validation of a drive-by bridge monitoring algorithm

Suzana Ereiz^{a,b}, Maria Pina Limongelli^a, Abdollah Malekjafarian^c, Ivan Duvnjak^b

^a*Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering, Piazza Leonardo da Vinci, 32, Milano 20133, Italy*

^b*University of Zagreb Faculty of Civil Engineering, Fra Andrije Kačića-Miošića 26, Zagreb, 10000, Croatia*

^c*Structural Dynamics and Assessment Laboratory, School of Civil Engineering, University College Dublin, Newstead, Belfield, Dublin 4, Ireland*

Abstract

This paper presents an experimental validation of a MATLAB-based algorithm for drive-by bridge monitoring, aimed at identifying natural frequencies and mode shapes of bridge structures from vehicle acceleration signals. While the drive-by monitoring concept has been extensively studied analytically and numerically, experimental validation on full-scale bridges under systematically varied conditions remains limited. A four-span continuous reinforced concrete bridge was used as the test structure, and dynamic measurements were obtained using a four-axle truck crossing at constant speeds of 20, 30, 40, and 50 km/h. A three-dimensional finite element model of the bridge was developed as an independent reference for validation, alongside a two-dimensional numerical vehicle-bridge interaction model implemented in MATLAB. The comparison between experimentally identified frequencies, finite element model predictions, and MATLAB algorithm results shows good agreement for the dominant vibration modes, with larger but physically consistent deviations observed for higher modes due to their reduced energy content in the vehicle response. Validation using the Modal Assurance Criterion confirmed that the algorithm reliably identifies not only the dominant bridge frequencies but also the corresponding mode shapes. A parametric study investigated the influence of vehicle mass and travelling speed on identification accuracy, demonstrating that vehicle speed is the dominant factor determining the quality of frequency identification. The results confirm that the drive-by monitoring approach can successfully identify the dominant dynamic properties of bridge structures using only vehicle-mounted sensors, offering a cost-efficient and scalable complement to conventional structural health monitoring systems, particularly for bridge networks where permanent sensor installations are not feasible.

Keywords: Drive by bridge monitoring, structural modal identification, dynamic properties, finite element modelling

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

SmartPontem – overload detection on structures via embedded instrumentation

Brossard Baptiste^a, Mercier Julien^a, Sabir Najeeb^a

^a*Freyssinet, 280 avenue Napoléon Bonaparte, 92506 Rueil-Malmaison, France*

Abstract

SmartPontem is a lightweight structural health monitoring approach designed to detect overload events on small suspension bridges by instrumenting a limited number of suspenders. The method combines strain measurements, vibration monitoring and model-based interpretation to capture quasi-static effects and dynamic signatures generated by traffic. A monitoring campaign was carried out on a representative single-lane suspension bridge in service, subjected to frequent heavy-vehicle crossings, using calibrated convoys to characterize suspender response under controlled conditions. The results show that stress variations in suspenders provide a reliable indicator of vehicle loading, allowing each suspender to operate as an independent load sensor. Modal analysis extracted from strain and acceleration data reveals consistent longitudinal and transverse modes, enabling tension estimation and confirming structural coherence. Comparisons with numerical modelling indicate satisfactory agreement in load effects and dynamic behavior, supporting the robustness of the measurement strategy. Beyond overload detection, the instrumentation provides indicators of structural condition by linking measured load effects, modal signatures and calibrated vehicle characteristics. These indicators can support predictive maintenance and help infrastructure owners assess the risk associated with overweight convoys. SmartPontem thus offers an operational, minimally intrusive framework for overload detection suitable for infrastructure owners needing practical monitoring solutions with limited instrumentation. This approach opens the way to integrating additional connected sensors embedded in bearings, expansion joints or pavement interfaces, creating more comprehensive monitoring systems capable of supporting predictive maintenance and real-time diagnostics.

Keywords: Structural health monitoring; predictive maintenance; digital twin modeling

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

A large-scale experimental setup for cyclically loaded soils beneath road pavements

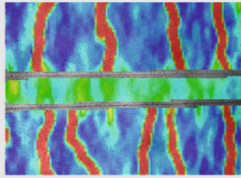
Sebastian Ullmann^a, Markus Uhlig^a, Maximilian Kahnt^a, Ivo Herle^a

^a*TU Dresden, Institute of Geotechnical Engineering, George-Bähr-Str. 1, 01069 Dresden, Germany*

Abstract

Within the framework of the Collaborative Research Centre SFB/TRR 339 “Digital Twin of the Road”, one research objective is the realistic numerical representation of the subgrade soil beneath road pavements. The mechanical behavior of soils strongly depends on its state variables, including the stress state, density, fabric and hydraulic conditions. To investigate the soil behaviour beneath road pavements under controlled conditions, a large-scale laboratory experiment has been constructed. The experimental setup consists of a cylindrical soil column that allows controlled mechanical loading and adjustable groundwater conditions while enabling comprehensive sensor-based monitoring of the soil state. This paper presents the concept, construction, and instrumentation of the experimental setup and reports results from the first preliminary test. The measurements demonstrate the functionality of the monitoring system and provide physically plausible responses to mechanical loading and hydraulic changes.

Keywords: Road pavements, subgrade soil behavior, large-scale testing, soil sensors



SMAR 2026



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

MS10: Advances and applications of vibration-based structural health monitoring

Organizers:

Álvaro Cunha (University of Porto, Portugal)
Carlos Moutinho (University of Porto, Portugal)
Sérgio Pereira (University of Porto, Portugal)

ABSTRACT

This Mini Symposium covers recent developments and applications of vibration-based structural health monitoring to broadly defined structural systems used in the civil, geotechnical, transportation, earthquake, wind, marine, mechanical, and related engineering fields, such as bridges, buildings, dams, towers, wind turbines, offshore and subsea structures, pipelines, foundations, geotechnical structures, railway tracks, etc.

Innovations and practical experiences in monitoring cable forces in cable-stayed bridges

Max Vollmering^a, Simon Bieber^a, Werner Brand^a

^aDYWIDAG-Systems International GmbH, Neuhofweg 5, 85716 Unterschleißheim, Germany

Abstract

This paper presents recent innovations and practical experiences in the monitoring of cable-supported bridges, with a particular focus on vibration-based cable force assessment. Case studies from bridge inspections in the United States and Germany illustrate how structural details—such as cable ties, bending stiffness, and additional concentrated masses—can significantly influence measurable vibration properties and therefore must be properly considered to ensure accurate force estimation. In addition, two examples of long-term cable force monitoring are presented, highlighting temporal trends and correlations with temperature.

Keywords: Structural health monitoring; cable-stayed bridges; cable force; vibration analysis

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

Calculation of normal forces in hangers of tied-arch-bridges based on frequency measurements considering model uncertainty and boundary condition sensitivity

Lukas Schneider^a, Felix Mols^a, Philipp Weidner^a, Thomas Ummenhofer^a

^aKIT Steel and Lightweight Structures, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

Abstract

Tied-arch bridges in railway infrastructure are increasingly exhibiting fatigue damage at the connection details of the vertical hangers. To assess their structural condition, short-term vibration measurements are taken on the hangers to determine their natural frequencies. This allows the normal forces acting on them to be calculated using prestressed modal analysis. Measurements conducted on seven tied-arch railway bridges revealed systematic deviations between the designed and actual normal forces, with discrepancies of up to 45% between hangers of identical length and construction. These deviations are attributed to complex fabrication and assembly processes during construction, including the effects of temperature, welding sequences, and support conditions during erection. As there is no independent validation method for the frequency-based approach, the accuracy of the back-calculated forces critically depends on the modelling assumptions. This paper investigates the sensitivity of normal force identification with respect to two key parameters: (i) the rotational connection stiffnesses at the arch and stiffening girder; and (ii) geometric imperfections in the form of sinusoidal pre-deflections. A parametric study based on Timoshenko beam theory shows that the uncertainty range between pinned and fully clamped boundary conditions remains significant, even for long hangers. An analytical investigation based on the Rayleigh–Ritz method shows that initial imperfections alter the natural frequencies through the coupling of longitudinal and transverse vibration modes. These findings lay the groundwork for the development of simplified, practical back-calculation recommendations.

Keywords: Tied-arch bridge; normal force identification; vibration-based-monitoring; boundary condition sensitivity; imperfections

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

Preliminary dynamic characterization of the Pisa baptistery (Italy) using ambient vibration testing

Caterina Caffarri^a, Giada Bartolini^b, Anna De Falco^a, Filippo Landi^a and Laura Vignali^a

^aDepartment of Civil and Industrial Engineering, University of Pisa, Largo Lucio Lazzarino 1, 56122, Italy

^bDepartment of Civil and Environmental Engineering, University of Strathclyde, 75 Montrose Street, Glasgow, G1 1XJ, Scotland

Abstract

Understanding the structural behaviour of monumental buildings is fundamental for the design of effective conservation and strengthening interventions. In this context, non-destructive techniques based on ambient vibration measurements provide valuable information on the global dynamic response of structures under operational conditions.

This study presents a short-term ambient vibration campaign carried out on the Baptistery of San Giovanni in Pisa, part of the UNESCO World Heritage site of Cathedral Square. The investigation aims to provide an initial characterization of the monument's dynamic behaviour, supporting subsequent monitoring strategies and numerical model calibration. The study demonstrates how short-term ambient vibration campaigns can effectively support the design of targeted monitoring strategies for cultural heritage structures. Measurements were performed using two different acquisition systems: a network of piezoelectric accelerometers arranged in multiple configurations and a portable device equipped with both accelerometers and velocimeters. This setup allows a direct comparison between sensing technologies with different measurement principles, installation requirements, and frequency response ranges. The results provide estimates of the main dynamic properties of the structure and highlight the capabilities and limitations of the adopted measurement systems in the context of rapid, low-intrusive surveys.

Keywords: SHM, cultural heritage, accelerometers, velocimeters, ambient response

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

Modal-based damage assessment of an arch dam

Leonie Rossmann^a, Alexander Stark^a

^aKarlsruhe Institute of Technology, 76131 Karlsruhe, Germany

Abstract

High dams are an essential part of the infrastructure. They are built for irrigation purposes, for drinking water supply and for renewable energy generation, among other things. Failure of such structures can have catastrophic consequences with high damage costs and sometimes even fatalities. Therefore, high dams are under constant observation to ensure safe operation. Conventional monitoring consists mainly of plumb line measurements, seepage observations and visual inspections. None of these measurements can be accessed remotely, and visual inspections are time-consuming and depend on the subjective view of the inspecting engineer. A promising method for damage detection in civil engineering is modal-based Structural Health Monitoring (SHM). The basic principle is the change in the characteristic dynamic behaviour of a structure in case of damage, because the global modal parameters, eigenfrequency, and mode shape, depend directly on the mass and stiffness distribution of the structure. Thus, damage that affects the mass and stiffness distribution of the dam can be detected using acceleration sensors attached to the dam body. Given that the impact of different damage scenarios on the dynamic behaviour of a structure is known, modal-based SHM has the potential to not only detect damage but also locate and quantify it. In order to establish the basics for modal-based SHM on curved dams, this work numerically investigates the influence of different damage scenarios on the dynamic behaviour of the Enguri Arch dam as an example. The double-curved Enguri Arch Dam in the Northwest of Georgia is one of the highest dams in the world and has been exposed to various environmental influences during its 40 years of operation. Damage due to seasonal temperature variations, changes in the rock foundation, and sediment deposition are particularly conceivable. The goal is to find a method that can successfully detect and locate these damage scenarios using modal-based SHM.

Keywords: SHM; dynamic analysis; damage detection; concrete dam; finite element analysis

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

Catching the shift: anomaly detection in concrete dams

Sergio Pereira^a, Chanalisa Salvi^a, Filipe Magalhães^a, Juan Mata^b, Jorge Gomes^b, Álvaro Cunha^a

^a CONSTRUCT – ViBest, Faculty of Engineering of the University of Porto, Rua Dr. Roberto Frias s/n, Porto, Portugal

^b Concrete Dams Department, National Laboratory for Civil Engineering, Avenida do Brasil, 101, Lisboa, Portugal

Abstract

Civil engineering structures require systematic monitoring to assess their integrity and performance, which naturally declines over time due to external actions and loads, as well as to material wear. Therefore, the early identification of structural anomalies is crucial for effective, well-planned management, which allows for timely interventions and ensures long-term structural operation in safe conditions.

For instance, to identify damage or ongoing deterioration through continuous data-based Structural Health Monitoring (SHM), damage-sensitive features should be obtained, which allow models to be built that facilitate the detection of statistical anomalies.

In this context, the present work relies on experimental data obtained from the continuous dynamic monitoring of a concrete dam to study the ability of both control charts and clustering techniques, such as DBSCAN, to detect the occurrence of simulated damages, either suddenly occurring or gradually progressing. It was possible to detect average frequency shifts as low as 0.31 %.

Keywords: Dam monitoring, structural health monitoring (SHM), data normalization, anomaly detection

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

Vibration-based structural health monitoring of an industrial plant: methodology and findings

Georgios Balaskas^a, Benno Hoffmeister^a, Christoph Butenweg^a

^aCenter for Wind and Earthquake Engineering, RWTH Aachen, Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany

Abstract

The reliable operation of critical infrastructure, such as chemical plants, requires rapid post-hazard assessment to support efficient and timely decision-making. Within the research project ROBUST, a user-oriented earthquake early warning and rapid response system was developed integrating: (i) a regional seismic sensors network deployed across the Lower Rhine Region, (ii) vibration-based structural health monitoring (SHM) systems installed on critical infrastructure assets, (iii) an interconnected real-time communication platform and (iv) building information models (BIM) for post-seismic damage visualization. This paper presents the conceptual design and initial operational of a vibration-based SHM system implemented at a chemical facility near Cologne, Germany. The monitoring objectives, sensor layout, and operational methodology are described, and the first two months of monitoring data are evaluated to establish a baseline condition for system identification. The identified modal properties, including natural frequencies, mode shapes, and damping ratios, as well as the influence of environmental conditions, are discussed. These findings provide the basis for robust baseline models and reduced false alarm rates in future damage detection applications. Damage detection methodologies are beyond the scope of this paper.

Keywords: Structural health monitoring; vibration-based system identification; industrial facilities

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

Self-sensing cementitious composites for SHM: insights from the PRIN 2022 SUCCESS project

Florence More Dattu Shanker More^a, Paolino Cassese^b, Francesca Fantasma^a, Vincenzo De Felice^a, Giovanni Fabbrocino^{a,c}, Carlo Rainieri^b

^aUniversity of Molise, Department of Biosciences and Territory (DiBT), Campobasso, Italy

^bNational Research Council (CNR), Institute for Construction Technologies (ITC) – Secondary Branch of Naples, Italy

^cNational Research Council (CNR), Institute for Construction Technologies (ITC) – Secondary Branch of L'Aquila, Italy

Abstract

Self-sensing cement-based composites (SSCCs) have gained popularity in the research field due to their relevant mechanical and electrical properties, which make them promising in the field of structural health monitoring (SHM) of civil works. Due to the presence of conductive particles, SSCCs acquire a significant piezoresistive capacity when subjected to an electric field, which allows them to detect the deformation and, eventually, the damage. This intrinsic self-sensing ability makes them a potential alternative to traditional external off-the-shelf sensors for Reinforced Concrete hosting structures, also because of their seamless integration within the structural elements. This paper presents, first, a literature review on the recent advancements concerning SSCCs. Attention is specifically focused on manufacturing methodologies and challenges, particularly on filler dispersion issues. The results of the literature review have been used within the ongoing PRIN 2022 SUCCESS project to develop smart cementitious composites. Then, the quality of the filler dispersion is addressed through a laboratory activity carried out to determine the microstructural homogeneity of the smart composites by scanning electron microscopy (SEM).

Keywords: Structural health monitoring; self-sensing cementitious composites; multi-walled carbon nanotubes; vibration-based SHM; scanning electron microscopy (SEM)

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

Data-driven structural health monitoring under static and dynamic loading

Alexandros Arailopoulos^a Andreas Kardoulas^a, Panagiotis Seventekidis^b

^aDepartment of Mechanical Engineering, University of Western Macedonia, GR-50100 Kozani, Greece

^bDepartment of Mechanical Engineering, Aristotle University of Thessaloniki, GR-54124 Thessaloniki, Greece

Abstract

Structural Health Monitoring (SHM) is essential for maintaining the integrity and safety of critical infrastructure. While traditional SHM techniques have long relied on physics-based models such as finite element analysis (FEA), the integration of data-driven approaches, particularly Machine Learning (ML), has opened new avenues for improved damage detection and condition assessment. This study explores the use of neural networks (NNs) for damage classification in a truss bridge model, providing datasets generated from detailed FEA simulations under both static loads and dynamic excitations. The objective is to evaluate how the source and type of training data influence the predictive capabilities of neural networks in identifying structural damage. The investigation begins with a binary classification task, where the networks are trained to distinguish between healthy and damaged structural states. To enrich the analysis, two subcategories are introduced based on varying levels of damage severity. The study then extends to a multi-class classification problem, involving three distinct damage classes of equal severity. Comparative results reveal that while all trained networks achieved acceptable training performance, prediction accuracy varied significantly, with success rates ranging from 55% to 90% depending on the classification task, loading type, and model parameters. Notably, networks trained on dynamic response data often demonstrated improved generalization. The findings highlight the critical influence of training data characteristics and damage magnitude on the overall reliability of ML-based SHM systems. Moreover, the study underscores the potential of combining simulation-driven datasets with neural networks to support early damage identification in structures where physical measurements are limited or infeasible.

Keywords: Structural health monitoring (SHM); binary and multi-class classification; machine learning

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

How financial methods can help to evaluate sensor data

Carina Beering^a

^aHelmut Schmidt University Hamburg, Holstenhofweg 85, 22043 Hamburg, Germany

Abstract

Sensor data forms a time series, where each point is influenced by its past to some extent. However, said influence is not always the same for every point in time. Yet, many models to describe the time series rely on fixed coefficients. The so-called Random Coefficient Autoregressive (RCA) Model by Nicholls and Quinn (1982) solves this issue by enabling variation of the past's effect through the addition of randomness to the regression coefficient itself. Borrowing methods from financial mathematics, we fit an RCA(1) model to the engineering analogue of log-returns of the development of a crack found on a concrete bridge in Bochum, Germany, via a quasi-maximum-likelihood estimator proposed by Aue et al. (2006). Moreover, we use risk measures known, again, from finance, such as the value at risk, to determine whether the crack is likely to broaden to a problematic width based on simulations using the previously established model parameters.

Keywords: Random coefficient autoregressive model; bridge data; risk measures; structural health monitoring

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

Assessing displacement estimation from velocity vs. acceleration: effectiveness and limitations for SHM applications

Hamid Imani Moghaddam^a, Salvatore Russo^a, Raimondo Betti^b, Alberto Stella^a, Anna Saetta^a

^aIuav University of Venice, Dorsoduro 2206, 30123 Venice, Italy

^bColumbia University of New York, 500 West 120th Street, SW Mudd 610 · New York, NY 10025, United States of America

Abstract

Accurate displacement measurements are critical for the health monitoring of civil structures. Displacement time series can be retrieved in many ways, such as via time integration of acceleration or velocity series. These integration processes, however, are known to be susceptible to significant inaccuracies, since time integration amplifies noise and baseline drift, leading to cumulative errors. Various procedures and data processing algorithms can be used to mitigate such errors. In this context, a research project was initiated with the aim of analysing some of the aforementioned approaches, using experimental data retrieved from tests performed on full-scale structural components, to show potential and criticalities of different data processing techniques. Specifically, tests were performed on reinforced concrete beams instrumented with co-located accelerometers, velocity seismometers, and displacement transducers, and subjected to different loading protocols. During tests, sensors recorded the complete transient response, which served to assess the methodologies used to obtain displacement from time integration of acceleration or velocity. This work presents preliminary results of the aforementioned investigation. Discussions are provided on the comparison between displacement values measured by displacement transducers and those obtained by time integrations, considering effectiveness as well as limits of the adopted sensors and data processing approaches. Preliminary findings provide a basis and may offer some guidance on improvements required for achieving reliable displacement-based monitoring procedures.

Keywords: SHM; displacements; time integration; noise removal; filtering; experimental validation

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

Covariate-dependent functional principal component analysis for SHM

Philipp Wittenberg^a, Lizzie Neumann^a, Kristof Maes^b, Jan Gertheiss^a

^a*Helmut Schmidt University, Holstenhofweg 85, 22043 Hamburg, Germany*

^b*KU Leuven, Kasteelpark Arenberg 40, 3001 Leuven, Belgium*

Abstract

In Structural Health Monitoring (SHM), sensor measurements and derived features such as eigenfrequencies often exhibit systematic daily patterns and can therefore be naturally represented as functional data. Furthermore, these patterns are typically influenced by environmental factors, particularly temperature, which can substantially affect the observed system response. While most existing methods for removing environmental effects assume that confounding influences affect only the mean response, it has been shown that environmental and operational factors may also alter the covariance structure of the residual process. To address this limitation in a functional data monitoring framework, we incorporate so-called covariate-dependent functional principal component analysis (CD-FPCA), which allows eigenfunctions and eigenvalues of the residual process to vary smoothly with covariates such as temperature. The proposed methodology is illustrated using an extended version of the KW51 railway bridge eigenfrequency dataset. This case study suggests that accounting for covariate effects beyond the functional mean can improve the robustness of the monitoring procedure, in particular by reducing environmentally induced (false) alarms under challenging low-temperature conditions.

Keywords: Environmental variability; functional data analysis; natural frequencies; structural health monitoring; statistical learning

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

A simulated data-driven SHM framework for bridge infrastructures

Vera Rillo^a, Alessandra De Angelis^a, Giuseppe Maddaloni^a

^a*Department of Engineering, Piazza Roma, Benevento, 82100, Italy*

Abstract

The bridge infrastructure throughout the world is aging rapidly. Therefore, maintenance and inspection of the bridges are very important today and Structural Health Monitoring (SHM) techniques are very attractive to have real-time and objective data about the condition of the bridges. Vibration-based methods are widely applied since they are based on the readily available vibration data and provides an opportunity for damage detection at global level without prior knowledge about potential damage location. In particular, these methods are based on detecting the changes in one or more dynamic features of the structural system between the known undamaged state of the structure and the unknown damage situation. Variation in stiffness directly influence the bridge's modal properties, including natural frequencies, mode shapes, and the overall vibration response under ambient excitation.

This study presents a structural health monitoring (SHM) procedure applied to a prestressed concrete bridge located in Montefalcione, Italy. A numerical model of a 19.20m span was developed using Midas Gen and calibrated against experimental data from in situ dynamic testing. The research focuses on a damage detection method based on autoregressive (AR) modeling and Mahalanobis Squared Distance (MSD), using acceleration signals under ambient excitation. Several damage scenarios were simulated by reducing the elastic modulus of the beams and the slab at different severity levels (5% to 80%). The results demonstrate that the proposed method is highly effective in tracking progressive stiffness degradation. Specifically, the damage index shows a monotonic correlation with damage severity, with higher sensitivity to localized beam damage, particularly at mid-span, compared to widespread slab degradation. These findings confirm the robustness of the AR-MSD approach in providing reliable qualitative insights into both the extent and location of structural damage in concrete bridges.

Keywords: Bridge, SHM, damage detection, FE model, updating

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

Investigating the dynamic characteristics of a viaduct with steel orthotropic deck

Angelo Savio Calabrese^a, Carmelo Gentile^a, Riccardo Pagot^b

^a*Department of Architecture, Built Environment and Construction Engineering (ABCE), Politecnico di Milano, Italy*

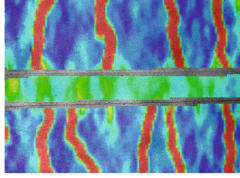
^b*Autostrade Alto Adriatico S.p.A., Italy*

Abstract

Selected results collected in the dynamic characterization of a multi-span bridge with steel orthotropic deck are reported in the paper. The investigated viaduct consists of 9 spans and belongs to the motorways serving the Veneto region (Northern Italy) that are managed by Concessioni Autostradali Venete S.p.A. (CAV S.p.A.). The bridge exhibits a span composition of $(24.0 + 7 \times 30.0 + 24.0)$ m, where the steel deck plate – 13.3 m wide – is stiffened in both the longitudinal and transverse directions and is supported by two main longitudinal girders; the distance between the main girders is about 7.50 m, with the girders' height being of 1.40 m whereas the transverse cross-beams connecting the girders are only 0.675 m high. It is worth noting that the deck exhibits a slight curve and a transverse slope of the cross-section of about 3.5° . Within the systematic monitoring activity recently promoted by the Italian Government, a dynamic monitoring system has been installed on the bridge; hence, to verify the accuracy and reliability of the monitoring devices, 3 spans of the bridge were instrumented using high quality accelerometers. Furthermore, a detailed numerical finite element model of the viaduct was developed and validated against the experimental modal parameters, allowing for a sound interpretation of the dynamic behavior. After a concise description of the bridge and the monitoring system, details are given on the structural modelling and the identified dynamic characteristics of the infrastructure, exhibiting very peculiar and distinctive mode shapes that are conceivably determined by the aspect ratio of the deck cross-section.

Keywords: Aspect ratio; multi-span bridge; mode shapes; operational modal analysis; steel orthotropic deck

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



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Effect of damage versus environmental variations on the background-resonant-inertial components

Margaux Geuzaine^{a,b,1}

^aUniversity of Liège, Allée de la Découverte 9, 4000 Liège, Belgium,

^bBelgian Fund for Scientific Research (FRS-FNRS), Rue d'Egmont 5, 1000 Brussels, Belgium

Keywords: Spectral decomposition; interpretative diagnostic; damage detectability

1. Introduction

Recent structural health monitoring research for large-scale civil structures has mainly relied on output-only vibration-based approaches, in which damage is inferred from changes of identified modal parameters (Yan et al., 2019). For systems exposed to strong environmental and operational variability, however, such indicators are often difficult to interpret unambiguously, which explains the sustained interest in compensation, normalization and classification strategies (Zhu et al., 2025).

In this context, the present work positions itself as a physics-informed complement to purely data-driven methods, which are the most common. It relies on a new set of features, a.k.a. the background, resonant and inertial components of the response, whose semi-analytical expressions are provided by the Multiple Timescale Spectral Analysis framework (Denoël, 2015). Being physically meaningful, these indicators offer the possibility to further interpret observed changes over spectral regimes.

Originally rooted in Davenport's wind load compatible decomposition (Davenport, 1961) and later formalized within the scope of the perturbation theory (Hinch, 1995), MTSA's range of applicability has recently been extended to wave-loaded floating structures (Geuzaine, 2022). This extension was necessary to account for the inertial loading contributions (Geuzaine, Fenerci, et al., 2023) as well as fluid–structure interaction effects (Geuzaine, Heremans, et al., 2023; Heremans et al., 2023).

Building on these developments, the present contribution shifts the use of MTSA from a forward decomposition of response statistics toward a sensitivity-oriented interpretation of monitoring features. The background, resonant and inertial components are treated as physically meaningful indicators whose closed-form expressions make it possible to examine how structural and environmental parameters enter the response separately.

A parametric analysis is first conducted on a linear oscillator and used as a controlled setting to identify the role of the frequency ratio, damping ratio and loading spectral shape. The novelty then lies in using the analytical structure of the extended MTSA formulas to assess the diagnostic content of these components. This provides the basis for the subsequent sensitivity analysis and for the planned extension to floating-tunnel models.

2. Direct analysis

For the sake of the understanding, the methodology is introduced on a linear oscillator of mass m and stiffness k . It is subjected to a stationary excitation of power spectral density $S_F(\omega)$, whose peak circular frequency is denoted α . Multiplication by the structural kernel then provides

$$S_X(\omega) = |H_X(\omega)|^2 S_F(\omega) \quad (1)$$

for the response spectrum, with

¹ Corresponding author. Tel.: +32 4 366 99 35
E-mail address: mgeuzaine@uliege.be

$$H_X(\omega) = 1/(k - m\omega^2 + 2i\xi\omega) \quad (2)$$

corresponding to the frequency response function and ξ to the damping ratio of the mechanical system. The variance of the response is subsequently obtained by integration of $S_X(\omega)$. As shown in Figure 1 for typical wind and wave loaded systems, the integrand wind exhibits resonant peaks induced by the structural kernel around $\omega = \bar{\omega}$, with $\bar{\omega} = \sqrt{k/m}$ denoting the natural frequency, and loading peaks inherited from $S_F(\omega)$ around $\omega = \alpha$. They are interpreted as background if $\alpha \ll \bar{\omega}$ and inertial if $\bar{\omega} \ll \alpha$.

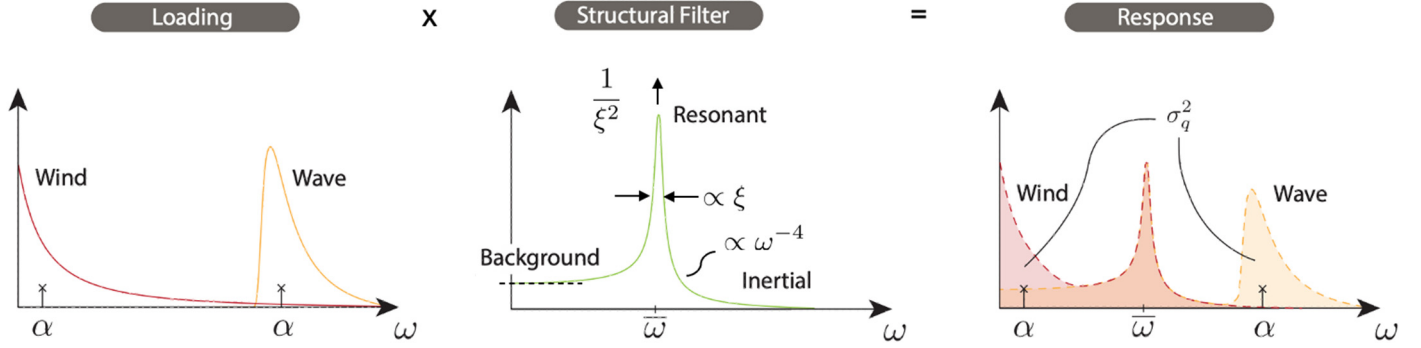


Fig. 1. Power spectral density of wind and wave loads, structural kernel function, and resulting power spectral density of response.

The central idea of MTSA is to exploit this separation of scales and approximate the integral by the sum of the contributions associated with the resonant and loading peaks, respectively, rather than by a full numerical treatment of the entire spectrum. In this context, the resonant component reads

$$\sigma_R^2 = \frac{\pi\omega_0}{2\xi} \frac{S_F(\omega_0)}{k^2} \quad (3)$$

which clearly reflects how much excitation energy is available in the vicinity of resonance, and how it is amplified by the sharpness of the structural filter, due to the smallness of the damping ratio. By contrast, the loading contribution is attached to the neighborhood of the loading peak, and to how the structural filter behaves in this zone. Depending on whether the background or inertial regime is activated, this function either stays as a constant value, either decays as a rational function of degree minus four. The unified loading component hence reads

$$\sigma_L^2 = \left(1 - \frac{S_F(\bar{\omega})}{S_F(\alpha)}\right) \int_{-\infty}^{\infty} \frac{S_F(\omega)}{1 + C_G(\omega)} d\omega \quad \text{with} \quad C_G(\omega) = \left(\frac{\omega}{\alpha}\right)^i (|H_X(\alpha)|^{-2} - 1) \quad (4)$$

and $i = 1$ if $\alpha \ll \bar{\omega}$ or 4 if $\bar{\omega} \ll \alpha$, respectively.

The practical implications of this decomposition are illustrated by the parametric analysis reported in Figure 2 with λ_u denoting the relative length of waves, see (Geuzaine, 2022). The resonant and loading contributions coexist and their relative weights evolve with the damping and the frequency ratio ($\alpha_v = \alpha/\bar{\omega}$). This observation is essential for the present study because it shows that the MTSA decomposition is not a purely formal split of the variance, but a compact way of describing how the structure and the excitation jointly shape the response statistics.

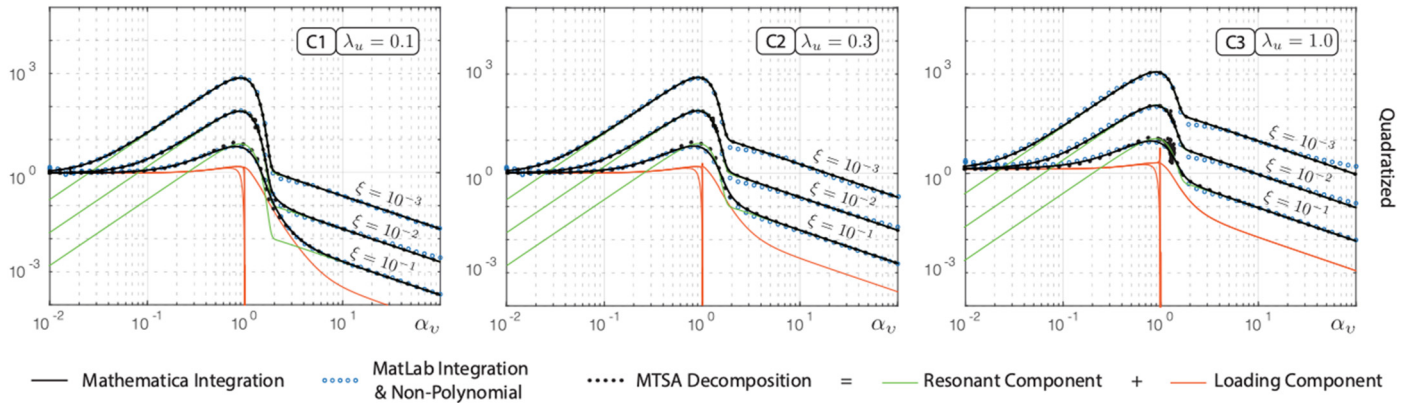


Fig. 2. Parametric analysis performed using a quadratic loading process, characterized by a Pierson-Moskovitz wave spectrum.

3. Inverse analysis

The inverse interpretation relies on the fact that each MTSA-derived feature is primarily associated with a different physical mechanism. The resonant component is governed by the amount of excitation energy available at the natural frequency and by the sharpness of the structural amplification; it is therefore especially sensitive to damping and to any stiffness or mass modification that shifts the natural frequency along the loading spectrum. The loading-controlled component, by contrast, is governed by the neighborhood of the loading peak and is thus more directly affected by changes in the environmental spectrum, including a shift of the wave peak frequency or a reshaping of the loading induced by the sea state. The ratio between the resonant and loading-controlled components is expected to be particularly useful for identification, because it reduces the first-order influence of a uniform increase in loading amplitude while preserving the effect of a redistribution of energy between the two mechanisms.

Consequently, the strongest diagnostic signature is not expected to come from the absolute response level alone, but from the joint evolution of the two components and their ratio: damping changes mainly alter the resonant amplification, stiffness loss or added mass mainly act through the frequency ratio, and environmental variations mainly modify either the global excitation level or the spectral position of the loading peak.

4. Planned extensions

Transferred to the floating-tunnel application, the work introduced in here will therefore consist in computing the response spectra of the numerical model under selected environmental states, then in extracting from them the MTSA-based component statistics in the modal responses of interest. This will require explanation on multi-degree-of-freedom extensions. At this stage, the objective will not be to identify damage, but to understand how the dynamic response is distributed between loading-controlled and resonance-controlled mechanisms over the modes of the structure. In that sense, the results shown in Section 2 serves as a reading grid: it clarifies which part of the monitored variance is mainly inherited from the excitation spectrum and which part is mainly governed by structural amplification. This direct interpretation step is intended to provide the physical basis on which more advanced diagnostic analyses will later be built.

5. Expected conclusions

Overall, this work investigates a more structured and interpretative approach to explain deviations in monitored spectra. Rather than relying on a single global quantity, the proposed framework provides indicators to better understand which mechanism is changing: a slow loading envelope, a structural resonance, or a fast-varying excitation.

The main limitations are already known from the derivations reported in previous work. MTSA is most reliable when the loading spectra vary smoothly around the resonant peaks and when the characteristic frequencies of the loading and the structure remain sufficiently separated. The transition regime is more delicate, but the unified loading expression shall help to mitigate the associated error by progressively reducing the loading-controlled contribution when the two peaks come closer.

Despite these limitations, the gain is expected to be substantial. The framework should offer a fast and physically interpretable screening tool for marine structures, to identify which sensors are the most informative for each perturbation family, and may support the definition of component-specific warning thresholds.

More broadly, it also opens the way to monitoring strategies in which environmental compensation and damage diagnosis are performed within the same spectral language, which is especially appealing for innovative marine infrastructures.

Acknowledgements

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Smartphone-assisted dynamic identification of infrastructures using scaled vehicles

Chiara Masnata^a, Antonina Pirrotta^a

^a*Dipartimento di Ingegneria, Università degli Studi di Palermo, Viale delle Scienze, 90128, Palermo, Italy*

Abstract

This study presents the preliminary outcomes of an experimental campaign aimed at evaluating the applicability and reliability of smartphone-based techniques for structural monitoring of civil infrastructures in the city of Palermo (Italy). The research explores a vehicle–structure interaction approach, employing a small-scale vehicle equipped with both traditional accelerometers and a smartphone device to acquire acceleration data during crossings. The primary goal is to assess the feasibility of using smartphone sensors and related mobile applications as low-cost, easily deployable tools for vibration-based monitoring. Several tests are conducted by driving the instrumented vehicle over the structure, allowing the collection of dynamic response data from both the vehicle and the underlying system. Specific attention is devoted to comparing the performance of smartphone micro-electro-mechanical systems (Mems) accelerometers with that of conventional piezoelectric sensors, in terms of sensitivity, noise levels, and accuracy in identifying modal characteristics. The results contribute to the broader goal of developing cost-effective and user-friendly methodologies for continuous vibration-based assessment of transportation infrastructures in urban environments.

Keywords: Structural health monitoring; smartphone sensors; scaled vehicle tests; vibration-based monitoring

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Ambient vibration tests before, during and after rehabilitation – a case study

Alexandru Aldea^a, Ruxandra Enache^a, Etienne Bertrand^b, George Nica^a, Georgiana Ionică^a

^a*Technical University of Civil Engineering Bucharest, Romania*

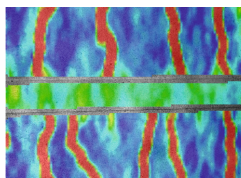
^b*Gustave Eiffel University, France*

Abstract

The paper presents the case study of the main building of the Technical University of Civil Engineering Bucharest (Romania), constructed in 1964 and subsequently subjected to seismic and functional rehabilitation (completed in 2025). The building comprises four independent sections separated by seismic joints. Ambient vibration tests were performed on the main and larger section of the building, aiming the assessment of its dynamic characteristics. The paper focuses on the ambient vibrations' tests carried out prior to retrofitting (in 2003) and after completion of the works (in 2026). Some monitoring data were also obtained during the retrofitting works in 2016 and 2018. Before retrofitting, this building section consisted of a semi-basement, a ground floor and three stories. The building is rectangular, with a central longitudinal corridor dividing functional spaces located on both sides. The initial building had a reinforced concrete frame structure. The retrofitting solution consisted in the addition of several reinforced concrete shear walls. Following the retrofitting, a steel attic was added. The final measurements confirmed the expected increase in stiffness through its influence on the building's dynamic characteristics. The study highlights ambient vibration testing as a non-destructive and cost-effective method for identifying the dynamic characteristics of buildings and for assessing the effects of seismic retrofitting.

Keywords: Ambient vibrations; modal frequencies; retrofitting

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Updating the numerical model of the cable-stayed footbridge over the Wisłok River in Rzeszów

Dominika Ziaja^{a,1}, Ewa Błazik-Borowa^b

^a*Department of Structural Mechanics, Rzeszow University of Technology, al. Powstańców Warszawy 12, 35-029 Rzeszów, Poland*

^b*Faculty of Civil Engineering and Architecture, Lublin University of Technology, ul. Nadbystrzycka 38D, 20-618 Lublin, Poland*

Keywords: Dynamics, cable-stayed footbridge, system identification, structural health monitoring (SHM)

1. Introduction

The footbridge modeling, due to the necessity of its dynamic properties' consideration, is not a trivial task, as mentioned in many research papers. Each numerical model should describe the real behavior of the object, taking into account actual boundary conditions, imperfections, or material properties. Simplifications adopted at the design stage of the facility should be validated based on experimental data from static and dynamic tests (Lourens et al., 2012; Nunes et al., 2023; Nicolettiet al., 2023). This process, called model updating (Yuen, 2012), can be made thanks to the implementation of various tools, e.g., Genetic Algorithms (GA) like in Chisari et al. (2015), Bayesian inference like in Pepi et al. (2019).

The paper concerns the numerical modeling of cables of a cable-stayed footbridge (Fig. 1) over the Wisłok River in Rzeszów (Poland) that has undergone significant degradation. An analyzed footbridge is a nearly 30-year-old structure, highly dynamically susceptible to pedestrian traffic. Additionally, the footbridge design documentation has been lost, and consequently, the method and order of assembly of individual components remain unknown. During its operation, the facility was subject to modifications and renovations, but the last historical data on the structure's vibrations (Janas and Basiaga, 2010) come from before the footbridge deck was replaced, and considered only the span's vibration, not cables. It increases the number of possible variable parameters of the system.



Fig. 1. Cable-stayed footbridge over the Wisłok River in Rzeszów.

¹ Corresponding author. Tel.: +48 17 865 16 22
E-mail address: dziaja@prz.edu.pl

Based on the first dynamic test of cables, an uneven distribution of pre-tension in cables was detected. The difference between the first free frequencies of two inner cables on the north side was as high as 16%. This unevenness, as a potentially dangerous situation, was the reason for more advanced studies of the structure presented in this paper.

2. Materials and methods

2.1. Proposed procedure and crucial parameters of the model

The approach for model updating applied in the presented research is inspired by Miller and Ziemiański (2025) and shown in Fig. 2. The detailed description of its every step is shown in the following subsections.

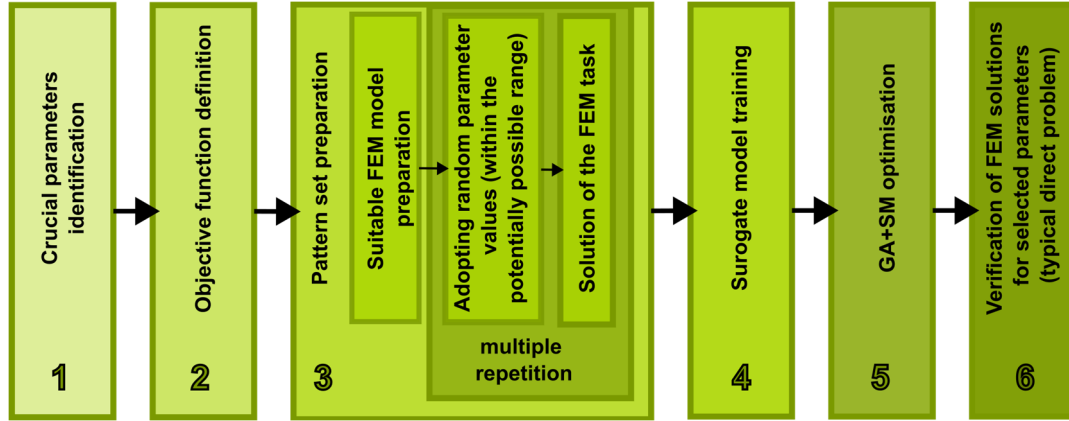


Fig. 2. The procedure applied in model updating.

Preliminary numerical simulations of the footbridge presented in Ziaja and Błazik-Borowa (2025) assumed the even and equal values of the pre-tension for all eight cables, which, based on the dynamic test, turned out to be an oversimplification. In the new models, the cable pre-tensions are determined individually for each two part of eight cables (external and internal), based on the dynamic parameters obtained from measurements. The influence of possible initial executive elevation of the deck, as well as changes in the material properties of the cables (described in simplification by one parameter – Young’s modulus) due to the rheology was also considered.

2.2. Objective function definition

Using the data from the previous examination, collected in Table 1, the objective function (Of) is set in the following form:

$$Of(T_1, T_2, \dots, T_i, \dots, T_{16}, E_c, w_{ini}) = \frac{1}{17} \cdot \left(\sum_{i=1}^{16} \left(1 - \frac{f_{1,i}^n}{f_{1,i}^e} \right)^2 + \left(1 - \frac{w_n}{w_e} \right)^2 \right) \quad (1)$$

where: T_i – initial temperature loading the i -th cable to model pre-tension, E_c – Young’s Modulus of cables (on this stage identical for all cables), w_{ini} – the rise of the parabolic arch used to model the geometry of a footbridge truss girders, $f_{1,i}^e$, $f_{1,i}^n$ – first natural frequency for i -th cable obtained from dynamic measurement and numerical model respectively, w_e – the middle point of the historical grade line, w_n – the vertical coordinate of the midpoint of the footbridge deck obtained from numerical calculation.

Table 1. First natural frequencies of cable vibration obtained via dynamic measurement based on Ziaja, D., Błazik-Borowa (2025).

$f_{1,1}$ [Hz]	$f_{1,2}$ [Hz]	$f_{1,3}$ [Hz]	$f_{1,4}$ [Hz]	$f_{1,5}$ [Hz]	$f_{1,6}$ [Hz]	$f_{1,7}$ [Hz]	$f_{1,8}$ [Hz]	$f_{1,9}$ [Hz]	$f_{1,10}$ [Hz]	$f_{1,11}$ [Hz]	$f_{1,12}$ [Hz]	$f_{1,13}$ [Hz]	$f_{1,14}$ [Hz]	$f_{1,15}$ [Hz]	$f_{1,16}$ [Hz]	w_e [m]
1.97	1.97	1.83	1.91	2.46	2.18	2.23	2.22	2.12	1.99	2.11	2.16	1.83	1.92	1.94	2.00	0.179

2.3. Pattern set preparation

Solving the inverse problem requires a vast number of training patterns. To address this, the process is automated using Ansys Mechanical APDL (MAPDL, 2024 R2) as the core FEA solver. The FEM model contains linear frame elements (‘BEAM188’ - six degrees of freedom in each node; 7182 elements) for bars, uniaxial quadratic elements in 3D space (‘CABLE280’ - three degrees of freedom in each node, tensile stress to provide adequate transverse stiffness is required for cables; 160 elements), and shell elements (‘SHELL181’, 3D 4-node quadrilateral shell elements, five degrees of freedom in each node, without drilling DOF; 7909 elements) for the bridge deck. The large displacement analysis is applied.

In the aim of a single pattern preparation, the set of eighteen parameters is randomly (within the range considered possible) adopted. Considering the assumed rise of the parabolic arch, the location of deck nodes is recalculated, and they are moved in the model. After changing the geometry, the increase in temperature for each cable is added in ten steps. After that, the dead load of the footbridge deck is added. The static analysis is made, and the location of the midpoint of the object is saved. The model with the deformed shape (as a result of pre-tension and the weight of elements) is used for modal analysis, and the first modal frequencies for cables are gathered. In this way, one single pattern is collected with 18 inputs and 17 outputs. The procedure is repeated multiple times.

2.4. Surogate model (SM) training

The collected pattern set is divided into two subsets - for learning and testing. Deep neural networks with eighteen input neurons and seventeen output neurons, and with varying numbers of hidden layers and neurons in them, are used. The application of ADAM optimizer together with varying activation and loss functions is studied.

2.5. Genetic algorithms (GA) optimization

The GA optimization involves searching the input parameter space to find the minimum of the objective function (here specified in eq.1). In the typical way, all patterns for each population of potential solutions are generated by FE task solving. A multitude of parameters results in a very computationally demanding and highly time-consuming. To simplify the searching in parameter space, the best-trained surrogate model is applied. However, taking into account the adopted simplification, each set of parameters selected as optimal in the GA solution has to be checked in a direct calculation in the FE solver (step no. 6 in the procedure shown in Fig. 2).

3. Discussion and conclusions

Proper numerical model preparation is a difficult task and requires validation considering the real object behavior, and in many cases, model updating. Identifying the system's actual properties, such as internal forces or material properties, especially in old, degraded structures like the examined footbridge, is a difficult inverse problem. In the case of multiple variables, the direct checking of their whole space is impossible due to the multitude of their combinations and the time consumption of calculation. In such a case, using simplified, fast-working surrogate models and artificial intelligence algorithms enables a much faster solution to the problem.

Acknowledgements

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Integrated SHM of prestressed concrete bridges: a full-scale experimental campaign

Francesco Mariani^a, Laura Ierimonti^b, Matteo Castellani^a, Enrique García-Macías^c, Leonardo Casali^d, Manuel Boccolini^d, Filippo Ubertini^a, Ilaria Venanzi^a

^a Department of Civil and Environmental Engineering, University of Perugia, Via Goffredo Duranti, Perugia, 06125, Italy

^b Department of Economics, Engineering, Society and Business Organization, University of Tuscia, Largo dell'Università, Viterbo, 01100, Italy

^c Department of Structural Mechanics and Hydraulic Engineering, University of Granada, Granada, Spain

^d Manini Prefabbricati s.p.a., Santa Maria degli Angeli, Assisi, Italy

Abstract

The integration of digital technologies is transforming Structural Health Monitoring (SHM) practices for civil engineering infrastructures. Prestressed concrete bridges, although valued for their high strength and durability, remain particularly challenging to monitor, as prestress losses and local stiffness degradations often induce only subtle changes in their response under service conditions. This study presents a full-scale experimental campaign designed to establish a comprehensive benchmark for the SHM of prestressed concrete bridge decks. The test structure, a 20 m-long bridge consisting of three precast pre- and post-tensioned girders and a cast-in-place concrete slab, was subjected to controlled loading sequences and varying prestress levels. A dense, heterogeneous sensor network, including accelerometers, strain gauges, load cells, inclinometers, and environmental sensors, was deployed to continuously capture both static and dynamic responses. Complementarily, drone-based photogrammetry provided high-resolution, full-field deflection maps, enabling non-contact validation of displacement patterns and cross-verification with traditional measurements. The experimental results highlight the influence of post-tensioning on global and local behaviors, offering an in-depth assessment of prestress-induced effects. Comparison between measured responses and refined finite element simulations demonstrated the accuracy, sensitivity, and robustness of the integrated monitoring framework. Overall, this work delivers a unique full-scale reference case for validating SHM methodologies and demonstrates the potential of combining heterogeneous sensing and digital technologies for the reliable monitoring of prestressed concrete bridges.

Keywords: Structural health monitoring; prestress loss detection; traffic load monitoring; finite element validation; experimental benchmark

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

Dynamic monitoring of two similar bridges and preliminary results on knowledge transfer

Ana Avramova^a, Carmelo Gentile^a

^a Department of Architecture, Built environment and Construction engineering (ABCE), Politecnico di Milano, Milan, Italy

Abstract

The paper refers to the continuous dynamic monitoring of two similar steel-concrete composite bridges. The investigated bridges, consisting of 4 spans and crossing the Olona River, belong to a motorway serving several provinces of the Lombardy region. Although some structural differences (in terms of span length and cross-sections) induce a clear shift of natural frequencies between the two bridges, an excellent correspondence is found in terms of mode shapes of the lower 12 modes for the two monitored infrastructures. The almost linear dependence on ambient temperature that is exhibited by the identified natural frequencies of both bridges as well as one long interruption in data acquisition that occurred on one of the two infrastructures, suggested to use the knowledge available on the natural frequencies of one bridge to predict the unobserved frequencies of the other bridge. After an appropriate training period, the comparison between predicted and observed frequencies during periods of continuous operation of the monitoring on both bridges confirmed the prediction capability and indicated that the simple adopted procedure turns out to be adequate for accurately providing the unobserved dynamic behavior.

Keywords: Environmental and operational effects; knowledge transfer; natural frequencies; operational modal analysis; steel-concrete composite bridge

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

A data-driven framework for vibration-based damage detection: application to the openLAB bridge benchmark

Charikleia Stoura^{a,b}, Xudong Jian^a, Vasilis Dertimanis^a, Giulia Aguzzi^c, Giacomo Imposa^c, Eleni Chatzi^a

^a*Department of Civil, Environmental and Geomatic Engineering, ETH Zürich, Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland*

^b*Department of Mechanical Engineering, Politecnico di Milano, Via La Masa 1, 20156 Milan, Italy*

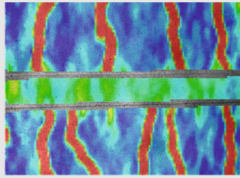
^c*Kistler Instrumente AG, Eulachstrasse 22, 8408 Winterthur, Switzerland*

Abstract

This study presents a vibration-based structural health monitoring (SHM) framework developed in partnership with Kistler Instrumente AG and applied to the openLAB Bridge experimental campaign to highlight the capability of high-quality acceleration measurements in bridge damage detection. The openLAB Bridge, a three-span prestressed concrete structure in Bautzen (Germany), was instrumented with high-quality MEMS accelerometers and subjected to controlled loading and progressive damage. Within this framework, a suite of vibration-based damage indicators, ranging from modal analysis metrics to purely data-driven features, was explored. Initially, statistical features were analyzed to identify deviations from a healthy baseline. These were complemented by unsupervised learning methods that capture subtle, nonlinear response variations indicative of stiffness loss. Subsequently, output-only modal identification techniques were employed to estimate modal parameters, thereby enabling modal tracking over time. Modal indicators provide physically interpretable trends when seeking a monotonic linkage to damage, whereas learning-based features exhibit high sensitivity to early, nonlinear response changes. These complementary indicators were used to derive hybrid damage metrics that combine the robustness of physics-based modal parameters with the adaptability of data-driven features. The presented approach demonstrates that vibration-based monitoring can reliably detect damage in real bridges, providing a practical step toward integrating autonomous SHM frameworks into commercial bridge monitoring.

Keywords: Structural health monitoring, damage detection, vibration-based monitoring, operational modal analysis, bridge infrastructure

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MS11: Monitoring of corrosion relevant parameters

Organizers:

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Sylvia Keßler (Helmut-Schmidt-Universität – Universität der Bundeswehr Hamburg, Germany)

Jörg Harnisch (FH Münster, Germany)

ABSTRACT

Corrosion of steel reinforcement is the main damage mechanism that poses a threat to the stability of infrastructure structures made of steel or reinforced concrete. Monitoring corrosion-related parameters can therefore make an important contribution to the safer operation of these structures, either during the initial phase or to monitor the success of repair measures. This mini-symposium will present findings from current research projects and interesting practical examples, as well as providing an overview of the latest technology for damage diagnosis and monitoring. The contributions may focus on both electrochemical corrosion as well as stress corrosion cracking and also on the measurement of material parameters affecting the corrosion initiation or propagation.

Novel monitoring solution of all corrosion-relevant parameters for predictive maintenance

Yurena Seguí Femenias^a, Meeke van Ede^a, Géorgia Honegger^a

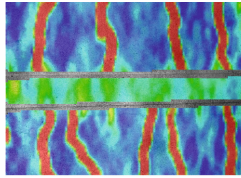
^a*DuraMon AG, Lerzenstrasse 15, Dietikon, Switzerland*

Abstract

This paper presents a novel multi-parameter monitoring system, capable of simultaneously measuring all relevant parameters for corrosion assessment in reinforced concrete, enabling predictive maintenance and depth- and time-resolved evaluation of corrosion processes. Field data from two real structures are presented: (i) a bridge exposed to deicing salts and carbonation, where the system demonstrates the early detection of corrosion initiation, and (ii) a chloride-contaminated parking garage repaired with a surface treatment, where the system evaluates the effectiveness of this repair measure. The results demonstrate that combining key corrosion drivers (pH and chloride content) with electrochemical indicators (corrosion current) and moisture-related parameters (concrete electrical resistance) enables improved interpretation of corrosion risk and early detection of unfavorable conditions. The study highlights the added value of continuous multi-parameter monitoring for reliable condition assessment, showing that critical conditions depend on the specific combination of parameters.

Keywords: Corrosion monitoring; multi-parameter corrosion assesment; field monitoring; reinforced concrete durability; predictive maintenance

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Influence of cathodic polarization on the chloride threshold for carbon steel in concrete

Konstantin Fache^{a,1}, Sylvia Keßler^b, Jörg Harnisch^a

^aFH Münster University of Applied Sciences, Corrensstraße 25, 48149 Münster, Germany

^bHelmut-Schmidt-University/University of the Federal Armed Forces Hamburg, Holstenhofweg 85, 22043 Hamburg, Germany

Keywords: Concrete; reinforcement corrosion; cathodic polarization; chloride threshold

1. Introduction

Chloride-induced reinforcement corrosion remains a major durability challenge in concrete structures. Service life models for reinforced concrete structures exposed to chlorides typically distinguish between two phases: (1) the initiation phase, during which the steel remains passive while chlorides accumulate in the concrete until the chloride threshold C_T is reached at the reinforcement level, causing local steel depassivation; and (2) the propagation phase, characterized by active corrosion (Tuutti, 1982). A key challenge lies in the spatial variability of chloride-induced damages (e.g., Pfändler et al., 2022), which arises from inherent systematic and probabilistic variations in both exposure and resistance properties, including C_T (Bentz, 2003). Current modeling approaches typically neglect this spatial variability.

Polarization effects associated with local steel depassivations contribute to variability in C_T . Once a macrocell has been established, active steel areas undergo anodic polarization while they are electrochemically coupled with surrounding passive steel areas being cathodically polarized depending on the driving voltage. This cathodic polarization locally increases C_T , which may delay further corrosion initiation and alter damage progression (Sagüés et al., 2014). Although fully probabilistic modeling approaches exist (e.g., fib, 2006), they typically neglect this phenomenon and therefore limit the models' ability to reliably predict further corrosion initiations after a first macrocell formation.

Only few studies systematically investigated the influence of cathodic polarization on C_T (Alonso et al, 2002; Sánchez, 2014). This study examines the influence of cathodic polarization on C_T for reinforcement steel in concrete and supports the development of corrosion models that account for both spatial and temporal variability in C_T .

2. Experimental methods

2.1. Potentiostatic and open circuit tests

Concrete specimens ($l \times b \times h = 26 \text{ cm} \times 13 \text{ cm} \times 8 \text{ cm}$) were made with Portland limestone cement (CEM II/A-LL) and contained a three-electrode setup consisting of a ribbed rebar as the working electrode (WE), strips of mixed metal oxide (MMO)-coated titanium mesh as the counter electrode (CE), and a MnO_2 reference electrode, which was placed 10 mm below the WE rear face. The specimens were exposed to a cyclic wetting-drying regime with NaCl solution. Detailed information on the specimen design and preparation is provided in (Fache et al., 2026).

During chloride exposure, the WE was polarized cathodically by applying a negative overvoltage η relative to its open circuit potential (E_{OC}), resulting in a polarization potential E_{pol} . Overvoltages of -50, -100, -200 and -300 mV vs. E_{OC} were used, with four replicate specimens per series. One additional specimen was tested at $\eta = -150 \text{ mV}$, and four specimens remained unpolarized in open circuit condition (OCP specimens). Instant-off measurements after the potentiostatic tests corrected E_{pol} for the IR -drop. The current I between WE and CE was converted to current density i relative to the entire WE surface area. A polarized specimen was

¹ Corresponding author. Tel.: +49 251 8365249
E-mail address: k.fache@fh-muenster.de

considered active once i exceeded $0.1 \mu\text{Acm}^{-2}$. For OCP specimens, corrosion initiation was defined by a drop in E_{OC} of at least 150 mV within 24 hours.

2.2. Chloride threshold determination

After detection of corrosion initiation, the specimens were split longitudinally along the WE axis. For both specimen halves, a 4 mm-thick and approximately 10 mm-deep cut was sawn along the crown line of the rebar imprint closest to the chloride-exposed surface. The cut was centered on the crown line to remove concrete within ± 2 mm of the upper edge of the rebar imprint. Concrete powder was collected along the chloride-exposed surface from both specimen halves and dried at 50 °C until $\Delta m \leq 0.1$ wt.-% within 24 hours. Then, the acid-soluble chloride content was determined by potentiometric titration. The reported C_T represents the mean total chloride content of both halves, related to the cement weight.

3. Results and discussion

3.1. Chloride threshold

Visual inspection after specimen splitting confirmed corrosion initiation of all specimens declared as active. Figure 1 shows C_T in dependence of the steel potential E . For cathodically polarized specimens, E refers to the IR -compensated E_{pol} , whereas for OCP specimens, E represents the final E_{OC} reading prior to depassivation. Increasing cathodic polarization generally increased the time to corrosion initiation and the corresponding C_T . However, for $\eta = -200$ and -300 mV, all specimens remained passive until the tests ended, despite exposure times over 450 days and chloride contents of up to 3.75 %/cem wt. at the WE level. These chloride contents therefore represent possible lower bounds for the actual C_T , indicated as an arrow in Figure 1. The OCP specimens yielded a mean C_T of 1.39 %/cem wt. The results reveal a clear increase in C_T at more cathodic potentials, while C_T appears largely independent of E for potentials more anodic than approximately $-150 \text{ mV}_{\text{SCE}}$. These observations indicate two distinct regions governing the influence of E on C_T .

3.2. Intrinsic and extrinsic mechanisms

Two complementary mechanisms may explain the potential dependence of C_T . The intrinsic mechanism involves beneficial changes in the composition of the passive layer formed on the steel surface in alkaline environments. Under external polarization and at a given pH, the impressed potential determines the oxide composition and structure of the passive layer (Alonso et al. 2002). Different polarization levels therefore generate distinct oxide microstructures with varying resistance to chloride ions, resulting in a potential-dependent C_T . The experimentally observed transition between an apparently potential-independent and a potential-dependent region of C_T around $-150 \text{ mV}_{\text{SCE}}$ agrees with findings of (Alonso et al., 2002), who observed a separation at $-200 \pm 50 \text{ mV}_{\text{SCE}}$, and with the limit of $-100 \text{ mV}_{\text{SCE}}$ reported by (Sagüés et al., 2014). This threshold likely corresponds to potential-dependent phase transformations within the passive layer. At potentials more anodic than approximately -200 to $-300 \text{ mV}_{\text{SCE}}$, oxidation of magnetite leads to a more ferric rich passive layer. At more cathodic potentials, other ferrous oxides are more stable, and magnetite formation dominates the phase transformation in the outer part (Andrade et al., 1995; Alonso et al., 1998).

The extrinsic mechanism attributes the C_T increase to changes in the local steel environment induced by the polarization current. Chloride ions may migrate away from the steel surface, reducing the local chloride concentration. Simultaneously, oxygen reduction at the cathodic sites generates hydroxide ions that raise the local pH (Glass and Chadwick, 1994). A higher pH affects competitive adsorption of chloride and hydroxide ions onto the steel surface (Leckie and Uhlig, 1966), enhancing the resistance to depassivation.

3.3. Relationship between steel potential and chloride threshold

In (Macdonald et al., 2021), a theoretical framework for calculating C_T is proposed, implying a linear relationship between $\log(C_T)$ and E . This relationship agrees with the well-established dependence between passivity breakdown potential and chloride concentration observed for steel probes in aqueous solutions (Galvele, 1976). Considering both this theoretical formulation and the experimentally observed potential-independent and potential-dependent regions of C_T , the relationship between E and C_T can be described by Eq. (1) and (2), using the approach of (Sagüés et al., 2014):

$$C_T = C_{T0} = 1.30 \text{ \%/cem wt.} \quad \text{for } E \geq E_{T0} = -160 \text{ mV}_{\text{SCE}} \quad (1)$$

$$C_T = C_{T0} \cdot 10^{\frac{E_{T0} - E}{\beta_{CT}}} = 1.30 \cdot 10^{\frac{-160 - E}{520}} \text{ \%/cem wt.} \quad \text{for } E < E_{T0} = -160 \text{ mV}_{\text{SCE}} \quad (2)$$

where C_{T0} is the baseline chloride threshold (%/cem wt.), E_{T0} is the threshold potential (mV_{SCE}), and β_{CT} is the cathodic prevention slope (mV/dec). The value of C_{T0} corresponds to the mean C_T obtained for the OCP specimens, as no potential dependence was observed under open circuit conditions. All seven polarized specimens that exhibited corrosion initiation were used to determine β_{CT} . The intersection of C_{T0} and the linear relationship between $\log(C_T)$ and E defines E_{T0} . Please note that for practical applicability and slightly more conservative estimates, the parameters in Eq. (1) and (2) represent rounded values of the experimentally fitted

parameters. Detailed information is provided in (Fache et al., 2026). It is emphasized that the key outcome is not an absolute baseline C_T for field application but its relative increase due to cathodic polarization. Figure 1 illustrates Eq. (1) and (2) together with the experimental results. Since all specimens polarized below $-300 \text{ mV}_{\text{SCE}}$ remained passive, the estimated β_{CT} may be considered conservative. The value of 520 mV/dec matches closely the 550 mV/dec reported by (Sánchez, 2014). The proposed relationship provides a framework for incorporating potential-dependent C_T behavior into corrosion prediction models. However, practical applicability requires knowledge of the steel potential distribution and remains constrained by additional factors that strongly influence C_T , such as moisture conditions at the steel-concrete interface.

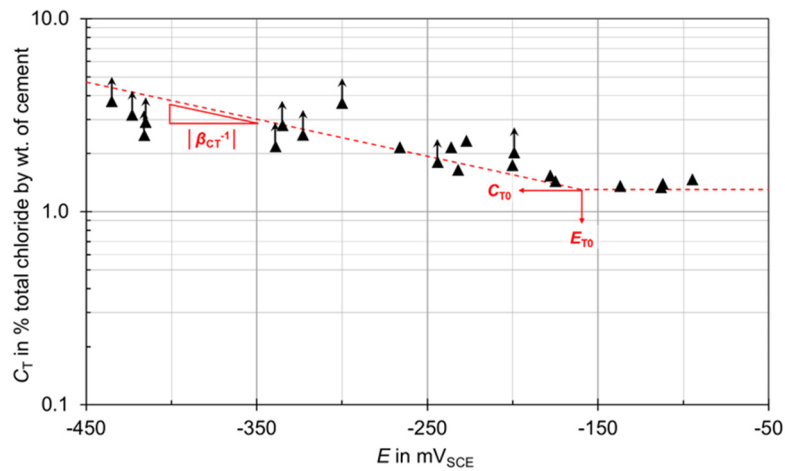


Fig. 1. Experimental results (triangles; arrows indicate lower bounds for C_T) and derived relationship between E and C_T according to Eq. (1) and (2) with rounded parameters (dashed line) from Fache et al. (2026); C_{T0} is the baseline chloride threshold, E_{T0} is the threshold potential, and β_{CT} is the cathodic prevention slope.

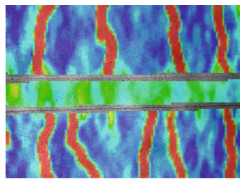
4. Summary

The experimental results indicate that the chloride threshold C_T remains potential-independent for steel potentials more anodic than approximately $-160 \text{ mV}_{\text{SCE}}$ and increases at more cathodic potentials with a slope of 520 mV/dec .

The derived relationship provides a framework for incorporating a potential-dependent C_T into corrosion prediction models. Models that account for a potential-dependent C_T can improve predictions of further corrosion initiation after a first macrocell formation, supporting reliability-based assessment and more efficient maintenance planning. Further research should focus on integrating potential-dependent C_T behavior into corrosion prediction models and exploring the implications for service life predictions.

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Electrochemical characteristics of reinforcement steel in contact with novel binder types

Rebecca Achenbach^{a,1}

^aRWTH Aachen University, Institute of Building Materials Research (ibac), Aachen, Germany

Keywords: Corrosion of steel in concrete; passivation; alternative binder types; electrochemical measurements

1. Introduction

With the aim of reducing CO₂ emissions from cement production, viable alternatives to Portland cement (OPC) are entering the market. Some of them are already in use to build reinforced concrete structures. Many different approaches are followed, for example, the reduction of the clinker amount by novel supplementary cementitious materials (SCMs), the production of Calcium-sulfoaluminate (CSA-) cements, the use of C-S-H phases from an autoclave, or the alkaline activation of different precursor materials. These changes in the raw materials and production techniques affect the binder chemistry and, therefore, the electrochemical behavior of embedded steel reinforcement. To monitor corrosion initiation or progress, the measurement of the open circuit potential or corrosion current density is often used as a parameter. The resistivity of the concrete is also used as an indicator for the material's durability. To assess new binder types with those methods, a deep understanding of the binder characteristics and their influence on the measured parameters is necessary.

2. Approaches to reduce CO₂ in cement production

To reduce CO₂ emissions from cement production, various approaches are being pursued in the materials development sector. Figure 1 provides a systematic overview of the approaches currently being pursued for use in reinforced concrete structures.

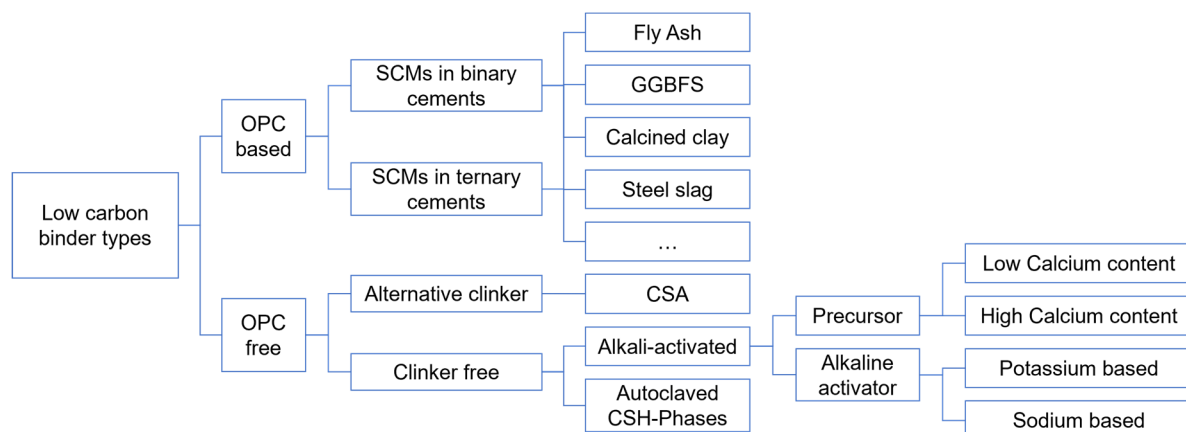


Fig. 1. Material developments for low carbon binder types.

¹ Corresponding author.

E-mail address: achenbach@ibac.rwth-aachen.de

In some cases, raw materials other than Portland cement are used. In other cases, similar materials are used, but they are produced using different manufacturing processes. The concrete and mortar produced using these low-carbon binder types have different effects on electrochemical measurements taken on the embedded reinforcing steel.

3. Influences on electrical resistivity

The electrical resistivity is a parameter for characterizing different binders. At a young age, the hardening progress and the formation of the pore structure can be observed on the basis of the resistivity. In connection with the electrical conductivity of the pore solution, statements about the pore structure and the resistance to the penetration of corrosion-promoting substances e.g. chlorides are possible. Finally, the resistivity is an influencing factor on the corrosion process after depassivation of the steel reinforcement. When planning electrochemical measurements that require polarization of the working electrode, resistivity affects the appropriate electrode configurations, spacing, and measurement parameters, as IR can have a significant impact.

Among the low-carbon binders shown above, OPC-based materials with a high proportion of calcined clay are characterized by high electrical resistivity. This is due to a refinement of the pore structure. CSA cements exhibit high resistivity, which is attributed to a less conductive pore solution. In contrast, alkaline-activated materials based on precursors with low calcium content (fly ash or calcined clay) exhibit comparatively low resistivity.

4. Influences on open circuit potential

The open circuit potential (OCP) versus a reference electrode is an electrochemical parameter that is widely used to assess the corrosion state of the working electrode in a laboratory experiment. This parameter is rather easy to measure and does not require the polarization of the working electrode and therefore does not affect the redox system at the steel surface in contact with the mortar or concrete. The simplest interpretation of these measurements is that a more negative OCP is associated with a higher likelihood of corrosion. Of course, fundamental electrochemical principles also apply to low-carbon binder types. However, there are different mechanisms by which negative potential readings can occur in various types of binders.

4.1. Corrosion promoting substances

A common reason for negative potential readings is the presence of corrosion-promoting substances associated with corrosion processes on the steel surface. These could be caused by unknown compositions of the binders, for example, when industrial byproducts containing corrosion-promoting substances are processed as SCM or alkaline-activated. High sulfate content, such as that possible in CSA cements, can also promote corrosion and cause negative potential readings.

4.2. Reducing pore solutions

Another possibility is the presence of reducing pore solutions. These occur, for example, when large proportions of granulated blast furnace slag (GGBFS) are used, which leads to a high sulfide content in the pore solution. This can occur either when GGBFS is used as SCM or after the alkaline activation of GGBFS. The sulfides in the pore solution react with the dissolved oxygen, which is then no longer available for the cathodic reaction of the corrosion process.

4.3. pH value

Different pH values also affect the measured OCP. In the group of OPC-based binders, a higher substitution rate typically results in lower pH values. CSA cements also have lower pH values, which are slightly below those of OPC-based cements. In the case of alkaline-activated materials, the pH value can be very high - even exceeding 14 - especially when the mortar or concrete is fresh, due to the highly alkaline activator solutions. This can also lead to very low OCP readings.

5. Conclusions

The resistivity of a mortar or concrete based on low carbon binder types should be taken into account when planning corrosion tests in the laboratory with electrochemical measurements as the resistivity can deviate much from the values known in OPC mortars and concretes.

The open circuit potential can be influenced by the substances in the pore solution that either affect the corrosion process or the availability of oxygen or by the pH value. Combined effects of more than one influencing are also conceivable in low carbon binder types, e.g., when GGBFS is activated with a very alkaline solution.

Geometric effects in Wenner resistivity measurements: methods to determine form factors for concrete specimens

Kenji Reichling^a, Jörg Harnisch^b, Konstantin Fache^b

^aKiel University of Applied Sciences, 24149 Kiel, Germany

^bFH Münster – University of Applied Sciences, 48149 Münster, Germany

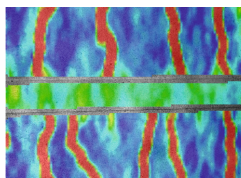
Abstract

The electrical resistivity of concrete represents a valuable complement to conventional testing methods in both structural diagnostics and quality assurance in concrete production. Using a Wenner probe, the apparent resistivity can be determined with relatively little effort, for instance on standard concrete specimens or core samples extracted from existing structures. In practice the resistivity is often determined without explicitly accounting for compact specimen dimensions. However, as specimen size decreases, the propagation of the electric field becomes increasingly constrained, which may lead to systematic misinterpretations. To mitigate this effect, form factors are introduced in DIN EN 12390-19, although these are specified only for a limited set of specimen geometries.

This study demonstrates how form factors can be determined both numerically and experimentally. Additionally, a novel mathematical approach is presented to estimate form factors for cubic and cylindrical concrete test specimens. By extending this methodology, form factors can be readily derived for a broad spectrum of specimen geometries commonly encountered in practical applications.

Keywords: Resistivity; concrete; form factor; structural assessment; quality assurance

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Corrosion monitoring to verify the applicability of the W-CL repair principle

Gino Ebell^{a,1}, Andreas Burkert^a

^a*Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, Berlin 12205, Germany*

Keywords: corrosion sensors; W-CL; corrosion monitoring; pitting corrosion

1. Introduction

As part of a WIPANO research project funded by the German Federal Ministry for Economic Affairs and Energy, the BAM investigated how moisture affects ongoing corrosion processes caused by chlorides. The objective of WIPANO projects is to enhance the transfer of knowledge to industry and ensure the successful commercialization and standardization of research outcomes. In this project, various corrosion sensors were employed. These include sensors that can be installed directly in new buildings and sensors that can be incorporated into existing structures. Therefore, specimens were produced to simulate typical concrete conditions found in car park ceilings. The aim of the project was to ensure the effectiveness of the so-called W/Cl concrete repair system. By applying surface sealing systems, this system is designed to dry out the concrete and thereby reduce further corrosion.

1.1. Specimen design and sensors

The specimen design is shown in Fig. 1. In general, we used a different specimen to simulate each implementation condition: one for new structures and another for existing ones. The red concrete layer contains 4.0 M% chloride by weight of cement. Two series were produced using different types of cement: one with CEM I 42.5 N and one with CEM III/A 32.5 N-LH. The dimensions of the test specimens are $L/W/H = 300/300/150$ mm. To ensure that moisture exchange occurs at the upper and lower surfaces of the specimens rather than at the side surfaces, the specimens are wrapped in aluminum-backed butyl tape. In summary, three specimens were produced for each condition.

Anode ladders and multi-ring electrodes were chosen for implementing sensors in new structures. Existing structures were fitted with CorroRisk sensors and spread-ring anodes, along with multi-ring electrodes embedded in mortar. To measure the potential of all the embedded sensors, an ERE20 Mn/MnO reference electrode was also implemented. In this extended abstract, we demonstrate the influence of relative humidity on the corrosion current. Therefore, the current was measured using the anode ladder in comparison with the CorroRisk sensor.

2. Results

The results of the corrosion current measurements taken from the anode ladder and the CorroRisk sensor (nails) during the humidification period are summarized in Fig. 2 a). In the results without scatterplots, the deviation of the measured values from the mean was so small that it fell below the symbol size. A significant increase in current density can be used to detect the rise in moisture within the test specimen and the associated risk of corrosion, both via the anode ladder and the CorroRisk sensors. With the CorroRisk sensor, corrosion currents are measured at all depths during CEM I; for the anode ladder, however, this only applies to segments 1 and 2. For CEM III test specimens, however, clear indications of corrosion are only detected on the CorroRisk sensor up to and including sensor element 2 and on the anode ladder at segment 1.

¹ Corresponding author. E-mail address: gino.ebell@bam.de

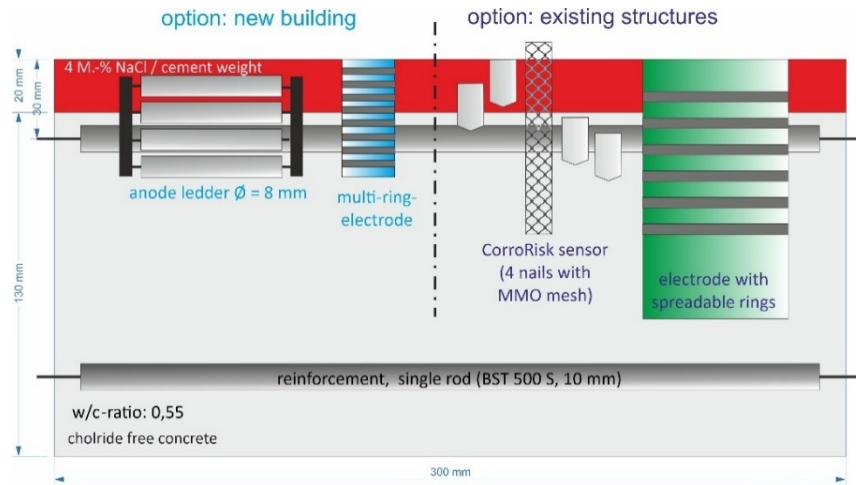


Fig. 1. Draft of the specimen design with embedded sensors and red colored chloride containing concrete on top (MMO = mixed metal oxide mesh).

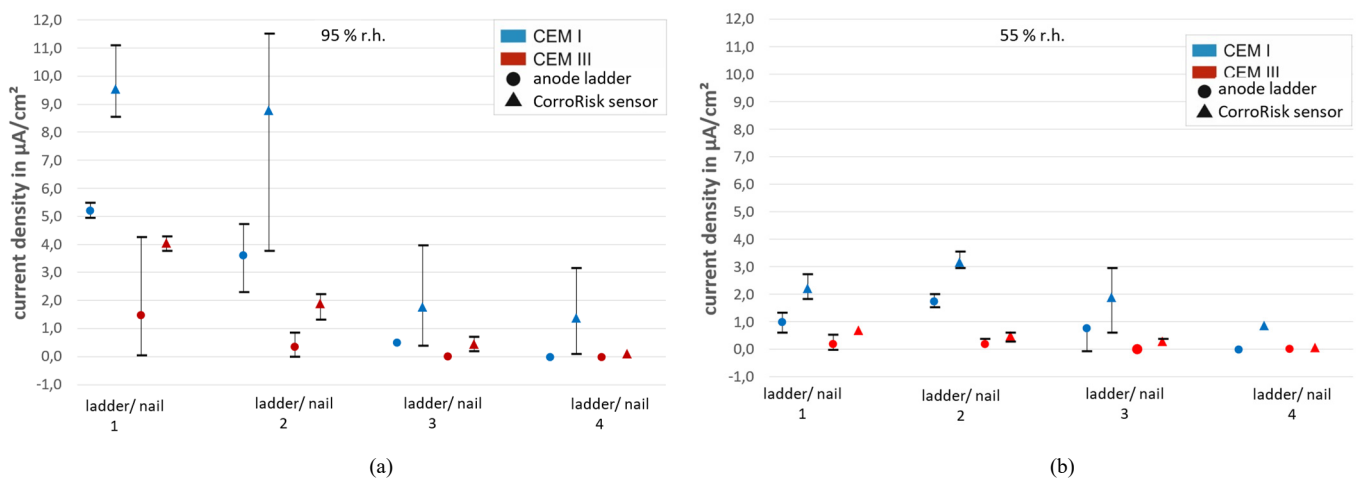


Fig. 2. (a) Mean values and standard deviation for current densities during galvanic cell formation in corrosion sensors during the wet phase at 95% relative humidity, for all three test specimens, 512 days after concreting. Current density $<1.0 \mu\text{A}/\text{cm}^2$ indicates no technically significant corrosion current; (b) mean values and standard deviation for current densities during galvanic cell formation in the corrosion sensors following the second drying phase at 55% relative humidity, for all three test specimens, 40 days after the dry cycle started; current density $<1.0 \mu\text{A}/\text{cm}^2 \triangleq$ no significant technical corrosion current.

Reducing the moisture content of the specimens by drying them significantly reduces the measured corrosion current density.

As can be seen from the measurement results in Fig. 2, signs of corrosion should be evident on ladders 1 and 2, and possibly 3, of the CEM I test specimen. Fig. 3 a) shows the first ladder of test specimen 1 in its dismantled and pickled state. Fig. 3 b) shows the upper nail of test specimen 4, which is also heavily corroded by chloride-induced pitting corrosion.

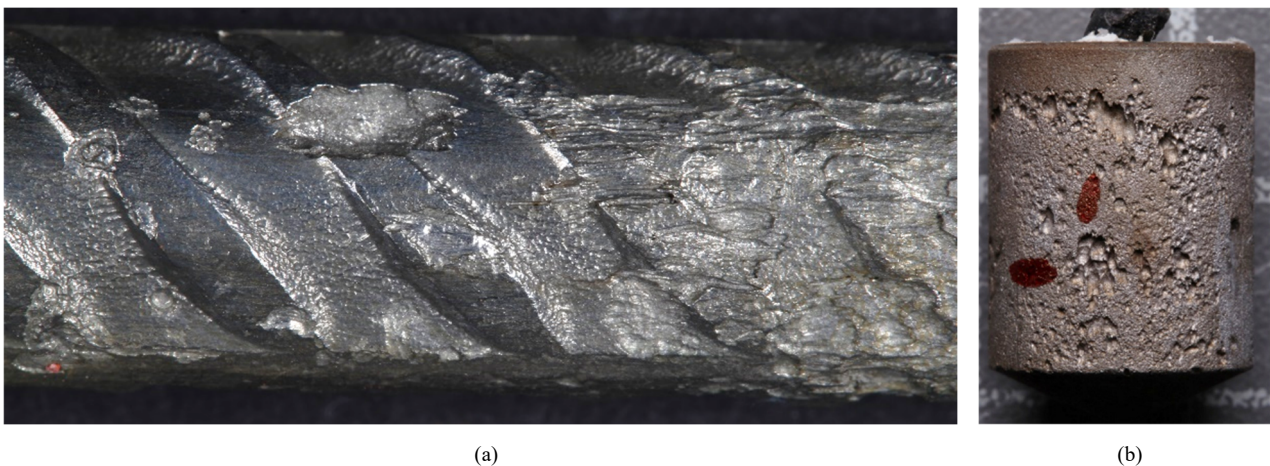


Fig. 3. (a) pickled anode ladder part 1 of specimen 1 (CEM I) and (b) CorroRisk nail 1 in a pickled state of specimen 4 (CEM III).

3. Conclusions

3.1. Sensors for the new-built option (direct installation prior to concreting)

The anode ladders should be installed directly on the reinforcement or formwork and positioned so that the area within the concrete cover and at the level of the reinforcement can be accessed. The potential of the individual bars can be measured using a high-impedance multimeter. During the wetting process, an immediate potential drop occurred at all four bars, accompanied by an increase in current at bars one and two. After approximately 500 days, a slight galvanic current formed at the third bar due to diffusion-induced chloride redistribution during the wetting phase, which explains the corrosion signs observed there. As bar 3 is located at the level of the upper reinforcement layer, or immediately below bars showing clear signs of corrosion, the anode ladder reliably indicates a risk to the reinforcement. During the drying phase, a significant potential rise was recorded at ladder 1 at PK 1, accompanied by a reduction in corrosion current density. No significant increase in potential was recorded for bars 2 and 3. After a drying phase of approximately 40 days, the potential levels and corrosion current density were comparable for bars 1, 2 and 3.

3.2. Sensors for existing structures

The CorroRisk nails are driven into drill holes at various depths, up to the level of the upper reinforcement, and are then filled with silicone. Figure 3 shows that the individual nails are more sensitive to corrosion-inducing conditions than the anode ladder. Higher current densities can subsequently be attributed to the more pronounced anodic sub-areas. This suggests that using the total electrode area to determine the corrosion current density results in a smaller margin of error. Nails 3 and 4 also exhibit slight currents during wetting. Additional laser-induced breakdown spectroscopy (LIBS) investigations (see Fig. 4) show that chloride redistribution occurred in the test specimen with CEM I down to a depth of 4 cm, which explains the corrosion phenomena observed on nails 3 and 4.

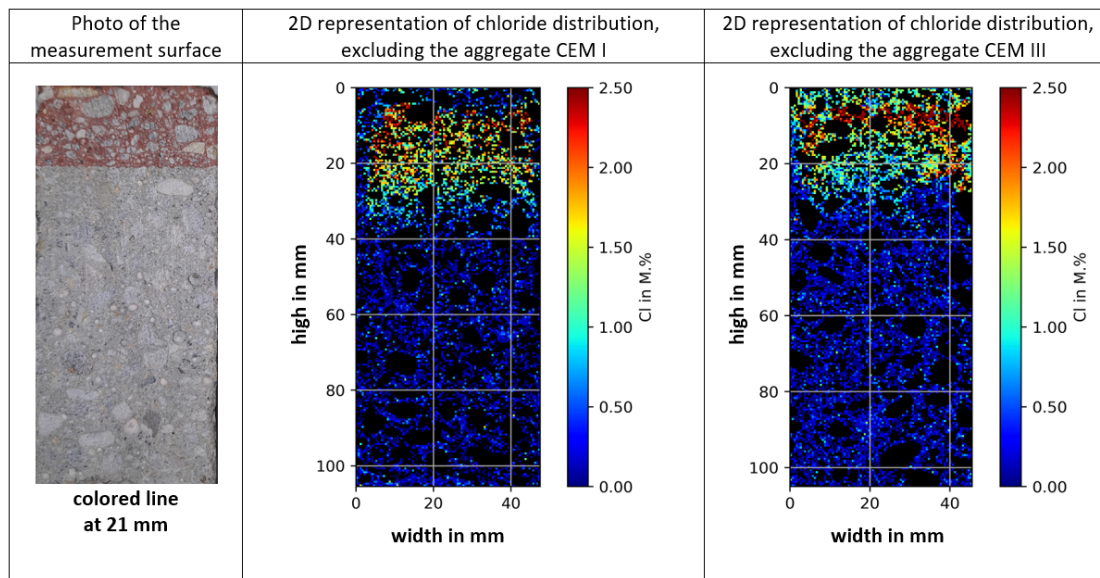


Fig. 4. determination of the chloride distribution by LIBS measurements for example at specimen 1 CEM I and specimen 4 CEM III.

The CorroRisk sensor reliably indicates risk to the reinforcement. However, installing the sensors can introduce chlorides into deeper layers, shifting the corrosion risk to greater depths. These sensors can also be used to record the drying phase of the samples and the resulting reduction in corrosion activity. PK 4 shows a clear increase in potential for all nails, with active corrosion evident in nail 4. All corrosion current densities decrease significantly during the drying phase. The sensor system detects the onset of corrosion when moisture is absorbed and a reduction in corrosion activity when moisture levels in the concrete decrease.

Chloride ion ingress monitoring via self-sensing CNT-coated fiber-reinforced concretes

Ali Bashiri Rezaie^a, Marco Liebscher^{a,b}, Mahsa Mohammadi^a, Mahmoud Shaikh Ahmad^a, Viktor Mechtcherine^{a,b}

^a*Institute of Construction Materials, Faculty of Civil Engineering, Dresden University of Technology, 01062 Dresden, Germany*

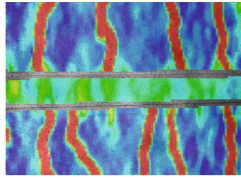
^b*Cluster of Excellence CARE, TU Dresden and RWTH Aachen, Germany*

Abstract

Chloride ion ingress reduces durability and service life of reinforced concrete by initiating and accelerating steel corrosion. In marine or de-icing environments, chloride ion penetration destroys the steel's passive layer, triggering corrosion and rust expansion that cause cracking and spalling. Early and continuous monitoring of chloride ingress is therefore essential. Self-sensing concrete composites can be here an innovative solution, enabling real-time chloride detection while maintaining load-bearing capacity. Herein, chloride ion ingress in cementitious composites was monitored using carbon nanotube (CNT)-coated polymer fibers. These self-sensing reinforcements were fabricated by using two single, continuous CNT-coated polyethylene (PE) fibers embedded in a normal-strength cementitious matrix. To enhance hydrophilicity, chloride reactivity, and fiber adhesion, CNTs were functionalized with tannic acid (TA) and ethanolamine before being coated onto TA-modified PE fibers, forming electrically conductive fibers. Sensory responses to chloride ions were evaluated at both the single-fiber and composite levels by immersing samples in a 2 g/100 mL NaCl solution while measuring electrical resistance in situ. The CNT coating was confirmed by optical microscopy, and both the smart fibers and composites showed strong sensing performance, with relative electrical resistance (RER) changes of $72.8 \pm 7.3\%$ and $8.1 \pm 3.7\%$ under chloride exposure, and $43.8 \pm 5.9\%$ and $36.1 \pm 8.6\%$ under distilled water, respectively. Distinct RER–time patterns differentiated chloride and water ingress, highlighting the potential of these smart composites for early detection of chloride penetration and corrosion risk in concrete structures.

Keywords: Chloride; self-sensing concrete; corrosion detection; structural health monitoring

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NDT for the in-situ assessment of external tendons

Kilian Heldt^a, Karla Hornbostel^{b,c}, Magdalena Osmolska^b, Fabian Dethof^a, Ahmad Takriti^a,
Christopher Alexander^d, Alberto Sagüés^d, Sylvia Keßler^{a,1}

^{a)} Helmut Schmidt University/ UniBw Hamburg, Germany

^{b)} Norwegian Public Roads Administration, Operations and Maintenance, Norway

^{c)} Norwegian University of Science and Technology, Norway

^{d)} University of South Florida, USA

Keywords: External post-tensioned tendons; NDT; tendon imaging unit; defect detection

1. Introduction

1.1. Motivation

Prestressed concrete plays a decisive role in the development of durable and efficient bridges and large-scale infrastructure. Post-tensioned systems are widely applied due to their high load-carrying capacity, serviceability, economic efficiency, and their capability to strengthen existing structures. However, the long-term performance of such systems strongly depends on the integrity of prestressing tendons (Lau et al. 2013; Carsana et al. 2016; Osmolska et al. 2020; Hartt & Theryo 2024).

As in all steel-containing structural systems exposed to environmental influences, corrosion represents a major durability concern. Although prestressing strands are typically protected within cementitious grout inside ducts, providing an alkaline environment and physical barrier against aggressive agents, this configuration simultaneously prevents direct visual inspection. Consequently, deterioration may progress unnoticed until advanced damage or sudden tendon failure occurs, posing significant risks for infrastructure owners and managers.

The corrosion protection of post-tensioned tendons depends strongly on grout quality and construction practice. Ideally, grout fully encapsulates the strands, prevents ingress of moisture and chlorides, and maintains passivating alkalinity (Kamalakannan et al. 2018; Osmolska et al. 2020). In practice, however, factors such as incomplete filling, segregation, or bleed-water accumulation frequently lead to voids or porous regions that promote corrosion.

Field investigations have repeatedly linked tendon failures to grouting deficiencies. A notable case study on failed external tendons from a Florida bridge revealed highly porous segregated grout with elevated sulfate concentrations and high water content (Lau et al. 2013). Despite alkaline pore solution conditions, localized corrosion developed due to moisture, aggressive ions, and macrocell coupling between anodic and cathodic regions. These findings demonstrate that grout segregation can create highly corrosive environments and highlight the need for reliable inspection methods.

External tendons offer improved accessibility compared to internal systems, yet their assessment remains challenging. Direct inspections are invasive and localized, whereas indirect non-destructive testing (NDT) methods require careful interpretation. A comprehensive evaluation therefore relies on combining complementary techniques.

1.2. Objective

The combined application of non-destructive testing (NDT) methods enables cross-validation of results and thereby improves the reliability of condition assessments for external post-tensioning systems. In this study, the joint use of impact-echo (IE) testing and the Tendon Imaging Unit (TIU) is investigated under real field conditions. While the impact-echo method is well suited for detecting voids, it does not allow differentiation between air- and water-filled cavities. The TIU complements this limitation by

¹ Corresponding author. Tel.: +49 - 40 - 6541 35 56
E-mail address: sylvia.kessler@hsu-hh.de

identifying grouting irregularities and providing indications regarding the type of void, while simultaneously determining the position and geometry of the strand bundle within the duct. This information is essential for the correct interpretation of IE measurements, as the relative position of the tendon significantly influences wave propagation and signal response.

The study therefore aims to evaluate the applicability and limitations of both methods when applied to external tendons in practice, to examine their complementary capabilities, and to develop recommendations for their combined use within inspection strategies. Ultimately, the objective is to support risk-based evaluation and maintenance planning for prestressed concrete structures through a more reliable assessment of the tendon condition.

2. Case study – Hafrsfjord Bridge

2.1. Structure

The Hafrsfjord Bridge, constructed in 1967 in southwestern Norway, is a prestressed concrete beam bridge forming part of national road Rv. 509 between Stavanger and Sola. The structure consists of ten spans with a total length of 207 m and is exposed to a harsh marine environment characterized by salt spray, strong winds, and fluctuating weather conditions. Chloride-induced corrosion has been the dominant deterioration mechanism. Major rehabilitation works between 1999 and 2000 included installation of an external post-tensioning system consisting of seven-strand tendons housed in polyethylene ducts and grouted with cementitious mortar.

After 25 years of service, a comprehensive special inspection was initiated to evaluate the condition of the strengthening system and to support planning for an additional 25-year service life.

2.2. Inspection

The externally mounted tendons allowed access from all sides, enabling the application of extensive non-destructive testing while avoiding invasive interventions that could compromise system integrity. Owing to limited inspection time, measurements were concentrated at locations with an increased likelihood of defects. These included anchorage zones, tendon deviation points, and extended horizontal sections where void formation or grout segregation is most likely to occur. The selection of measurement points was supported by a preliminary sounding test, which provided a rapid qualitative indication of possible grouting irregularities. In total, forty tendon locations distributed along the bridge length were investigated. Prior to testing, the duct surfaces were cleaned to ensure proper sensor contact, and a visual inspection was carried out. No visible surface damage or signs of grout leakage were detected.

The Tendon Imaging Unit (TIU) was used to obtain cross-sectional information about the internal condition of the tendons at selected locations (Freij et al. 2020, Freij et al. 2021). The system generates an image showing the duct boundary, the geometry of the strand bundle, and a color-coded representation of the grout condition between strands and duct wall. The device consists of a cylindrical clamshell that is mounted around the tendon and connected to a laptop for data acquisition and visualization. During measurement, the unit is manually rotated once around the tendon while sensors continuously record magnetic attraction forces and electrical impedance values. Variations in magnetic attraction are used to reconstruct the position and shape of the strand bundle based on calibrated relationships between force and distance. The assessment of grout condition is derived from impedance measurements between a sensing plate on the duct surface and the grounded strand bundle. Sound grout produces relatively constant impedance values, whereas air-filled voids lead to increased impedance and water-filled regions to reduced impedance. Because the measured impedance depends on void geometry and electrical pathways, the evaluation provides probabilistic indications rather than definitive classifications.

In addition, impact-echo (IE) testing was applied as a complementary method. IE is a well-established non-destructive testing technique that analyzes elastic wave resonances generated by short mechanical impacts on the structure's surface (Sansalone and Carino 1988, Gibson and Popovics 2005, Schubert and Köhler 2008). Lamb wave interactions with internal interfaces produce characteristic frequency responses that are sensitive to changes in material continuity. While the method is commonly used to determine structural thickness in concrete elements, interpretation differs for tendon ducts. Measurements performed directly on cylindrical ducts result in complex responses, making absolute thickness evaluation impractical. Therefore, the assessment was carried out using comparative analysis between measurement locations. Grouting defects or voids generally reduce the effective wave velocity and shift resonance frequencies, and they may also influence signal damping or energy content (Terzioglu, et al. 2019). However, IE measurements alone do not allow differentiation between air- and water-filled voids, highlighting the benefit of combining the method with TIU measurements.

2.3. Results

The initial TIU measurements were used to establish a calibration reference, resulting in an average impedance value of approximately 10 k Ω derived from the first measurement series. The method successfully provided cross-sectional visualizations of the investigated tendons and allowed an assessment of grout distribution along the inspected sections. In most locations, the measurements indicated uniform grout conditions, which was consistent with the absence of visible external damage observed during the visual inspection. Nevertheless, localized deviations were detected at several measurement points, suggesting the

possible presence of voids or zones with increased moisture content. These indications were spatially limited and did not reveal systematic deficiencies along the tendons.

IE measurements were carried out at 20 selected locations and evaluated in both the time and frequency domains using B-scan representations. A dominant frequency range between approximately 2.5 and 3.5 kHz was observed in most measurements and was interpreted as representative of homogeneous and well-grouted tendon conditions. Localized anomalies were identified at a small number of locations and were characterized by reduced resonance frequencies, decreased signal damping, or locally broadened frequency responses. Based on the observed signal characteristics, the measurements were classified into four categories reflecting their condition assessment. Most locations were categorized as intact, while only a few measurements showed minor or critical indications. A portion of the data could not be evaluated due to measurement artifacts or incomplete recordings. No systematic relationship between detected anomalies and tendon inclination or geometric configuration was observed.

The field investigations demonstrate that the combined application of IE and TIU testing provides complementary information for the assessment of external post-tensioned tendons. IE proved effective as a rapid screening tool capable of identifying anomalous regions through changes in wave propagation behavior over relatively large areas. The TIU measurements, in contrast, offered localized cross-sectional insight and supported interpretation by providing indications of grout condition and tendon geometry. While IE alone cannot distinguish between different void contents, TIU results enable differentiation between probable air-filled and water-filled defects. Conversely, impact-echo measurements can assist in prioritizing locations for detailed TIU investigations.

Despite the promising results, several limitations remain. Measurement outcomes were influenced by field conditions and surface accessibility, and uncertainties persist in the interpretation of impedance-based indicators. In addition, data quality issues encountered during field measurements highlight the need for careful planning and robust data acquisition procedures in practical applications.

3. Conclusions

This study demonstrates the feasibility and practical applicability of combining IE and TIU for the condition assessment of external post-tensioned tendons under real bridge conditions. The results indicate that the majority of the inspected tendons exhibited intact and largely homogeneous grouting conditions even after approximately 25 years of service in a harsh marine environment. Impact-echo measurements proved to be an efficient method for the comparative identification of anomalous regions and enabled rapid screening along extended tendon lengths. The Tendon Imaging Unit complemented these findings by providing cross-sectional information and indications regarding grout condition and potential void characteristics, thereby supporting a more reliable interpretation of detected anomalies.

The combined application of both methods significantly increased the robustness of the assessment compared with single-method investigations, as each technique compensated for the limitations of the other. Consequently, the proposed approach provides a valuable basis for risk-based maintenance planning and supports informed decision-making for the management of aging prestressed concrete infrastructure. Future research should focus on improved calibration procedures, quantitative characterization of detected defects, and the integration of non-destructive testing results into digital inspection and asset management workflows to further enhance long-term infrastructure monitoring.

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Condition monitoring and sensor concepts for assessing the technical service life of structural components in interim storage facilities for high-level radioactive waste

Thorsten Leusmann^a, Stephan von Wehren^a, Thomas Matschei^a, Silvio Sperbeck^b, Julius Oeff^c, Ernst Niederleithinger^c

^a*TU Braunschweig, Institute of Building Materials, Concrete Construction and Fire Safety (iBMB), Beethovenstraße 52, 38106 Braunschweig, Germany*

^b*Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Security Department, Kurfürstendamm 200, 10719 Berlin, Germany*

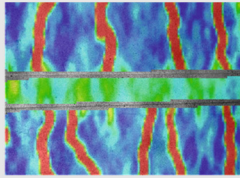
^c*Bundesanstalt für Materialforschung und -prüfung (BAM), NDT methods for civil engineering, Unter den Eichen 87, 12205 Berlin, Germany*

Abstract

The operating licenses of Germany's interim storage facilities for high-level radioactive waste are currently limited to 40 years from first container placement. Given the substantial uncertainties surrounding the timeline for a permanent repository, these facilities may need to remain in service far beyond their originally planned design life of 50 years. This necessitates robust, evidence-based methods for determining residual service life. The joint research project ZuMoBau-ZL addresses this challenge by developing an integrated condition monitoring and sensor framework tailored to the structural particularities of interim storage facilities. This paper presents the conceptual design of the monitoring system, covering the identification of dominant degradation mechanisms, the selection and evaluation of sensing technologies for both global and local parameters, and the approach toward an adaptive service life prognosis. Key sensor technologies under investigation include embedded ultrasonic transducers, NFC-based moisture and temperature sensors and corrosion wire sensors. Results from a full-scale test structure are used to validate sensor performance. The monitoring concept is designed to interface with Building Information Modelling (BIM) environments and a digital twin framework, enabling continuous, data-driven updates to structural condition assessments.

Keywords: Structural health monitoring, interim storage, radioactive waste, reinforced concrete, service life prognosis, sensor technology

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SMAR 2026



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

MS12: Advanced fatigue assessment and life design of steel structures

Organizers:

Chongjie Kang (TU Dresden, Germany)

Steffen Marx (TU Dresden, Germany)

ABSTRACT

Fatigue governs the durability and structural integrity of many steel components that are exposed to cyclic loads. This Mini Symposium invites contributions on innovative methods for fatigue assessment and life-oriented design of steel structures. Relevant topics include experimental investigations, the fatigue behavior of welded and unwelded components, the influence of defects and manufacturing processes, fracture mechanics approaches, and probabilistic or data-based life cycle predictions. The MS promotes detail-specific strategies that go beyond conventional design curves, including structural-scale testing and system-level modelling. In addition, fatigue-related challenges in the retrofitting and reuse of steel components – such as estimating remaining fatigue life and suitability for secondary uses – are welcome. The session aims to encourage exchange between researchers and practitioners involved in both fundamental mechanisms and application-oriented solutions for extending the service life of fatigue-sensitive structures such as bridges, towers and offshore installations.

Rethinking renewal: sufficiency strategies for historic steel railway bridges in the German railway network of Deutsche Bahn

Clara J. Schulte^a

^a BTU Cottbus-Senftenberg, SPP Kulturerbe Konstruktion, Konrad-Wachsmann-Allee 8, 03046 Cottbus, Germany

Abstract

Across the Deutsche Bahn network, approximately 5,000 steel bridges remain in service. Nearly half of them were built around 1900 and are of potential heritage significance. Although their preservation is technically feasible, institutional conditions often impede such efforts. As a result, preservation options are rarely examined or are dismissed prematurely, despite their substantial cultural, economic, and ecological potential. The conservation of steel railway bridges is particularly relevant considering the embodied (or “gray”) energy they contain and the significant CO₂ emissions associated with replacement structures. A modular planning approach that allows the targeted replacement or strengthening of critical components while preserving elements in good condition offers new perspectives for resource conservation and maintaining the cultural value of historic bridges. This approach follows a sufficiency-oriented strategy that does not reject new construction per se but critically questions replacement as the default option. The proposed paper builds on the dissertation “Steel Railway Bridges as a Legacy of High Modernism – Fundamentals for a Holistic Decision-Making Process Between Repair and Renewal”, which introduced a parameterized assessment methodology that considers technical, economic, cultural, and ecological criteria equally and is intended for application already during the conceptual or preliminary design phase. Based on four case studies it can be shown that continuation-oriented, modular rebuilding approaches are at least equivalent to replacement projects while offering greater contributions to sustainable bridge practice.

Keywords: Historic steel bridges; bridge preservation; sufficiency strategies; heritage value; replacement vs. renovation

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

Fatigue strength of circular hollow section tube-to-gusset plate detail with extended welds

Kalle Lipiäinen^a, Kiia Grönlund^a, Antti Ahola^a

^aSteel Structures, Lappeenranta-Lahti University of Technology LUT, P.O. Box 20, FI-53851 Lappeenranta, Finland

Abstract

Local structural and notch stress concentrations at the gusset ends have a major influence on the fatigue strength of welded circular hollow section (CHS) joints, and improving the weld geometry at this critical detail can thus be regarded as essential. Different welding techniques have a high potential for enhancing fatigue performance, and they could be implemented at a minimal cost as a part of the manufacturing process without any additional work steps or tools. In this study, the fatigue performance of a CHS tube-to-gusset plate detail was investigated in a large-scale configuration with the CHS specimen manufactured by using multipass welding. In addition, the multipass welds had incrementally located stop positions to locally decrease the stress concentration at the gusset ends. A finite element (FE) model was created based on a 3D laser-scanned model to evaluate the fatigue strength. Furthermore, FE analyses were used to evaluate the fatigue performance of the welded CHS detail, accounting for the findings on the small-scale coupon specimens. Finally, a manufactured CHS-to-plate detail was fatigue-tested to experimentally validate the fatigue strength and the related numerical analyses. The fatigue strength of the tested component significantly exceeded that of typical slotted joints described in design codes. A mean fatigue strength of $\Delta\sigma_{c,50\%} = 113$ MPa, based on nominal strain gauges at the gusset ends, was determined based on the test results, including the first crack and the data after the repair.

Keywords: Component-scale fatigue tests; fatigue design; manufacturing quality

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Fatigue strength properties of a connection subjected to far-field compressive stresses

John Leander^a, Oskar Skoglund^a

^aKTH Royal Institute of Technology, 100 44 Stockholm, Sweden

Abstract

In the fatigue assessment of existing structures, the choice of strength properties can be decisive for ensuring adequate safety, directly informing decisions on maintenance or replacement. Selecting an appropriate reference strength requires that the detail under assessment has been tested and is covered by the governing standards. This is not always the case for older structures, which may differ in geometry and execution from the standardised details developed for new construction. This paper reports results from fatigue testing of a connection detail in an existing bridge. This detail occurs frequently in older structures yet is not adequately represented in the detail categories of, e.g., Eurocode 3. Fatigue endurance data obtained under alternating compression and tension loading are presented, alongside results from crack growth testing. The findings demonstrate a significant increase in fatigue strength relative to the conservative assumptions imposed by the standards, enabling more accurate safety assessments of similar connection details.

Keywords: Fatigue; steel bridges; stress ratio; detail category; crack propagation

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Effect of weld imperfections on the fatigue strength of single-sided butt-welded connections

Kevin Mouradian^{a,b}, André Beyer^a, Maël Couchaux^b

^aCentre Technique Industriel de la Construction Métallique, 91190 Saint-Aubin, France

^bInstitut National des Sciences Appliquées de Rennes, 35700 Rennes, France

Abstract

This paper investigates the fatigue resistance of single-sided butt welds containing imperfections. In prEN 1993-1-9 (Eurocode 3 Part 1-9), the design fatigue resistance is associated with ISO 5817 quality level B; however, this assumption lacks systematic experimental validation. To address this, a database of 347 fatigue test results was compiled from the background document of prEN 1993-1-9 and additional results reported from the literature, including specimens with quantified weld imperfections. In addition, new experimental tests were conducted on butt welds exhibiting undercuts, excess weld metal, and porosity. Results show that external weld imperfections have a more pronounced impact on the fatigue resistance than internal imperfections. Undercuts within quality levels D and lower exhibited a characteristic fatigue strength of 62 MPa, while excess weld metal at quality level C yielded 70 MPa. Lack of penetration up to 10% of plate thickness (quality level below D) achieved a characteristic fatigue strength of 49 MPa, and larger values (10–20%) further decreased it to 35 MPa. In contrast, internal imperfections showed a limited effect: porosity at quality level below D resulted in a characteristic fatigue strength of 69 MPa, while slag inclusions at quality level below D yielded 74 MPa. These results highlight the distinct effects of various weld imperfections and suggest that, depending on the selected acceptance limit, a weld containing a given imperfection may satisfy or fail to satisfy the corresponding Eurocode 3 detail category.

Keywords: Fatigue resistance; weld imperfections; butt-welded connections; Eurocode 3

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Fatigue strength of cold-formed high-strength steel hollow sections – a fracture mechanical assessment on the imperfection effects

Antti Ahola^a, Kalle Lipiäinen^a, Tuomas Skriko^b, Juha Tulonen^c, Anssi Hyvärinen^c, Juha Ikkala^c

^a*Steel Structures, LUT University, Yliopistonkatu 34, FI-53850 Lappeenranta, Finland*

^b*Welding Technology, LUT University, Yliopistonkatu 34, FI-53850 Lappeenranta, Finland*

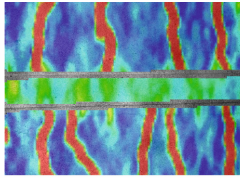
^c*SSAB Europe Oy, Harvialantie 420, FI-13300 Hämeenlinna Finland*

Abstract

Next generation high-strength low-alloy steels offers fine-grained bainitic-ferritic microstructures, resulting in high toughness and formability, enabling high-quality cold-formed hollow sections. High degree of cold-forming, however, might cause reduced ductility or local manufacturing imperfections. The aim of the current work is to experimentally and numerically study the fatigue performance of cold-formed structural hollow sections, focusing on the influence of local imperfections on fatigue behavior through fracture mechanical assessments. Scanning electron microscopy was applied to examine imperfection characteristics and fatigue damage mechanisms in fatigue-tested cold-formed hollow sections with yield strength of 500 MPa. Fracture mechanical fatigue assessments were conducted using Paris' law models. The computational results were then compared with experimental data. High fatigue strength was obtained – up to a characteristic fatigue strength of 257 MPa (slope parameter of $m = 5$) – under worst-case transversal loading. The two-stage Paris' law model accurately predicted the fatigue performance of the cold-formed areas.

Keywords: Fatigue; cold forming; high-strength steel; linear elastic fracture mechanics

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Crack propagation in welded specimens with biaxial non-correlated loading

Simon Steinhoff^{1,a}, Stefanie Roescher^b, Rebekka Winkler^a, Markus Knobloch^b

^a Chair of Steel, Lightweight and Composite Structures, Ruhr-University Bochum, Universitätsstrasse 150, 44801 Bochum, Germany

^b Institute of Structural Design, University of Stuttgart, Pfaffenwaldring 7, 70569 Stuttgart, Germany

Keywords: Fatigue; XFEM; crack propagation; multiaxial loadings, welded joint

1. Introduction

Many components of structural engineering are subjected to cyclic multiaxial loading. In steel bridge construction, a noteworthy example is the main girder – crossbeam connection, where flange joints are subjected to biaxial stress states, typically characterized by nominal stress ranges ΔS_x and ΔS_y . Since the individual load histories generally differ, the stress components do not interact proportionally ($S_x / S_y \neq \text{const.}$), resulting in non-correlated stress states.

While rare experimental investigations on multiaxial fatigue of welded joints primarily focus on combined tension–torsion loading, e.g. Winther (2026), the influence of a second, non-correlated stress component on the fatigue behaviour of welded joints under biaxial stress states remains insufficiently understood and only rarely investigated experimentally. To the authors' knowledge, the work of Takahashi (1999) represents one of the few comparable studies. Moreover, predicting the crack path is challenging due to the varying local weld geometry and the interaction between the stress components ΔS_x and ΔS_y . To address these research needs, cyclic fatigue tests were conducted on welded cruciform joints. The tests aimed to investigate two key aspects: (i) the orientation of the crack path and (ii) the crack-propagation life N_p under different biaxial loading conditions. The corresponding results are discussed in the results section. Additionally, a numerical simulation of crack growth was performed and compared with experimental observations to further improve the understanding of fatigue behaviour under biaxial loading conditions.

2. Experimental investigations

2.1. Test setup

Fatigue tests were conducted using a custom-designed strong-floor rig at the Materials Testing Institute (MPA) in Stuttgart. The test setup included two hydraulic actuators to apply independent, non-correlated loads in the x and y directions. Pinned connections were employed for load introduction points and supports to minimize constraints and ensure uniform load distribution. The specimens were installed upright, with the continuous plate forming the vertical x -axis and the welded attachments defining the horizontal y -axis.

The specimen geometry is shown in Figure 1a. The investigated transverse butt weld at intersecting flanges represents a typical detail found in steel bridge construction. The specimens were fabricated from 15 mm thick S355J2+N steel plates with a width of 150 mm. To prevent premature failure at the load introduction points, the plate ends were locally widened. The attached plates were joined using fully penetrated double-bevel butt welds, with weld preparation provided at the attachment plates. Due to the multiaxial stress state, crack initiation was expected to occur at the inner weld toes.

A total of six specimens were tested under two different biaxial non-correlated stress states ($R_x \neq R_y$). The applied nominal stress histories for both directions are illustrated in Figure 1b. The nominal stress history in the x -direction was equal for all six specimens and resulted in a stress range of $\Delta S_x = 110$ MPa. In the y -direction, two stress ranges were investigated: specimens P7 to P9 were subjected to a stress range of $\Delta S_y = 165$ MPa, while specimens P10 to P12 were loaded with a stress range of $\Delta S_y = 146$ MPa. All

¹ Corresponding author. Tel.: +49 234 3222565
E-mail address: simon.steinhoff@rub.de

fatigue tests were performed under force control at loading frequencies up to 1.5 Hz, with maximum nominal stresses of $S_{x,\max} = S_{y,\max} = 183$ MPa. Testing was terminated when the actuator displacement deviated by 5 mm from a stabilized reference value, corresponding to crack lengths up to approximately 90 mm.

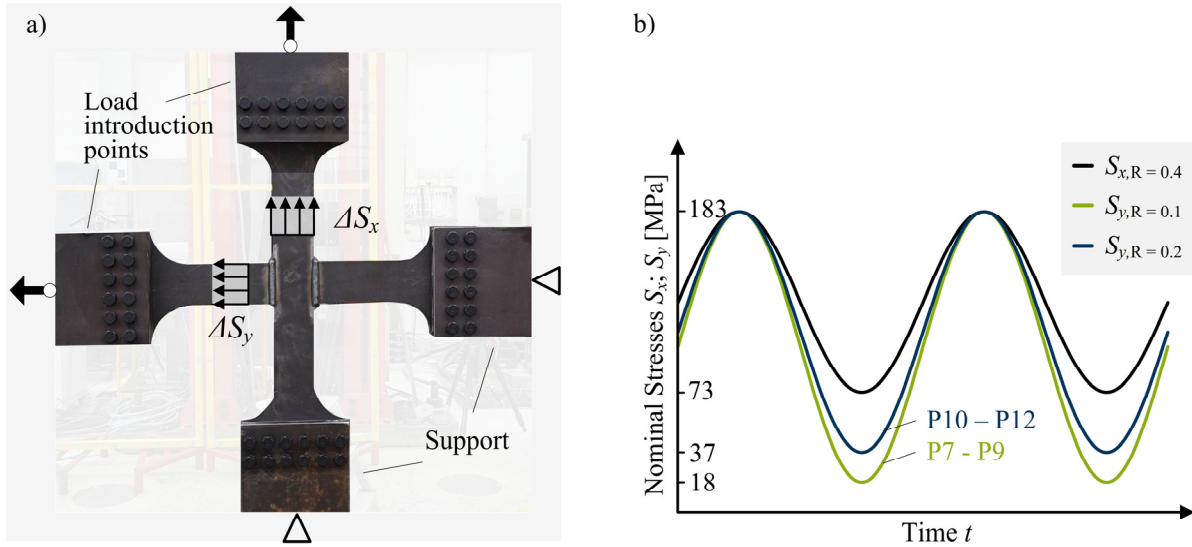


Fig. 1. (a) Test specimen; (b) nominal stress histories.

2.2. Test results

The primary focus of the presented work is the investigation of the crack growth with biaxial loading situations. To analyse the fatigue lives associated with this process, they were phenomenologically divided into two stages: (i) the initiation life N_i , encompassing crack nucleation and micro-crack growth, and (ii) the propagation life N_p , comprising macro-crack growth. The end of the crack initiation stage was defined by a 5% change in the strain range, measured by a strain gauge located 5 mm from the weld toe. This established criterion, also used by Takahashi (1999) for a comparable application, results in a very small crack size, barely visible to the naked eye. The resulting crack propagation lives N_p are shown in Figure 2a. For the specimens subjected to higher horizontal stress range (P7 to P9) the mean propagation life is $N_{p,\text{mean}} = 64910$. The lower horizontal stress ranges for specimens P10 to P12 intuitively resulted in slightly higher propagation lives, with a mean value of $N_{p,\text{mean}} = 70500$.

The corresponding crack paths are shown in Figure 2b and a photograph of the tested specimen P9 is shown in Figure 2c. In all cases, cracks propagated diagonally towards the centre of the specimen and can be attributed to a dominant mode I crack opening mechanism. Notably, the crack paths were independent of the applied stress range ΔS_y , as both configurations produced nearly identical crack path. This observation indicates that the crack path orientation is primarily governed by the maximum applied stress state rather than by differences in stress ranges. However, the crack propagation life was found to depend on the applied stress ranges.

Although the experimental programme was completed successfully, further numerical investigations are required to comprehensively describe fatigue life under biaxial stress states. Nevertheless, experimental testing remains essential for the verification and validation of advanced crack propagation models

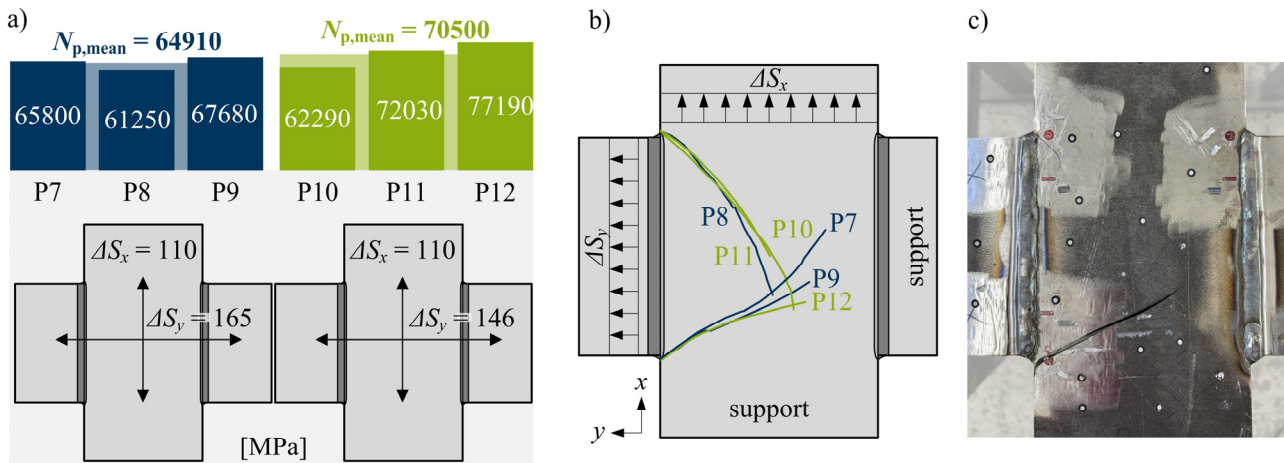


Fig. 2. (a) Crack propagation lives N_p of all specimens; (b) crack paths of all specimens; (c) failed specimen P9.

3. Simulation

The assessment of the crack propagation was performed using the extended finite element method (XFEM) within Abaqus and a cyclic crack growth calculation based on the VCCT, using principles of linear elastic fracture mechanics, as described by Röscher (2019). This approach allows the simulation of arbitrary, non-predefined crack growth under various loading situations, by using the maximum energy release rate to compute the crack orientation. The initial crack was introduced as an edge crack with a depth of $a = 0.5$ mm and a corresponding surface length of $c = 1.0$ mm, consistent with the phenomenological differentiation. Starting from this initial flaw, crack growth was simulated using the Paris law. The material parameters C and m were taken from Pedrosa (2022), who reported values of $C = 1.63 \times 10^{-8} \text{ MPa} \cdot \text{m}^{0.5}$ and $m = 2.62$ for the same steel grade S355J2+N and similar load ratios.

Figure 3b shows the numerical crack growth for specimen P8. Figure 3a compares the experimentally observed crack paths (solid lines) with the numerically computed paths (dotted lines). For cracks initiating at the lower left corner, the numerical simulation reproduces the paths with very good agreement. However, for cracks starting at the upper left corner, the simulation accurately predicts the initial path but deviates from the actual crack path as growth progresses. This discrepancy may be attributed to the test setup, which combines two actuators with two supports, resulting in an asymmetric loading arrangement for multiaxial fatigue investigations. This asymmetry was not accounted for in the numerical simulations.

The prognosed crack propagation lives for both loading situations are close, and can be denoted to $N_{p, \text{XFEM}, \text{P7-P9}} = 100000$ and $N_{p, \text{XFEM}, \text{P10-P12}} = 110000$. The comparison with the mean values of the obtained experimental propagation lives $N_{p, \text{mean}}$ shows that the simulations reproduce the correct relative ranking of propagation lives, but overestimate the actual values. The deviations between the assessed and the experimentally observed crack propagation lives can be attributed to the estimated material properties.

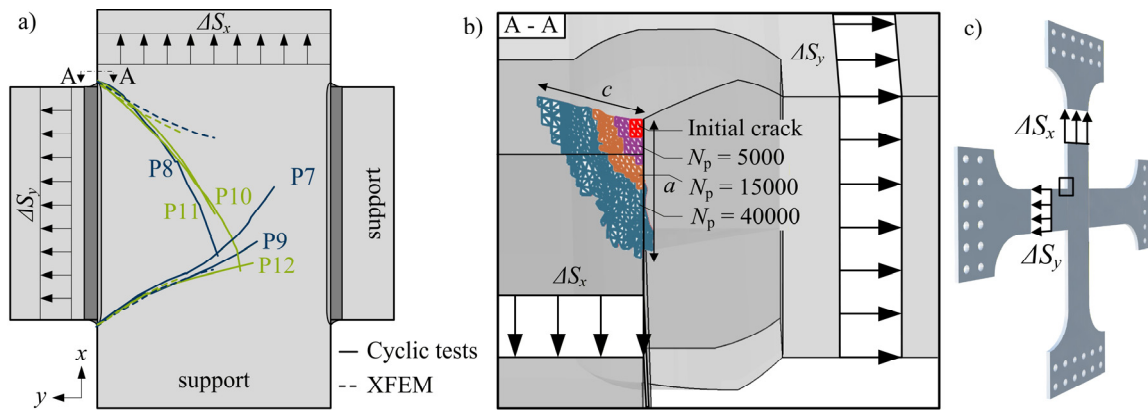


Fig. 3. (a) Simulated crack path of all specimens; (b) simulated crack growth in specimen P8; (c) location of initial crack within the specimen.

4. Conclusion

The experimentally advanced cyclic tests presented in this study demonstrated the complex nature of fatigue assessment under biaxial loading. The main findings can be summarized as follows:

- The experimentally observed crack paths were largely independent of the applied stress range in y-direction and showed similar propagation directions for all investigated loading conditions.
- In contrast, the crack propagation life was strongly influenced by the magnitude of the stress range in y-direction, indicating a decoupling between crack path orientation and fatigue life.
- XFEM simulations reproduced the experimentally observed crack paths with good agreement and furthermore captured the general trend of crack propagation life.

Overall, this study provides a unique experimental basis for the validation and further development of advanced crack propagation models for welded joints subjected to biaxial loading.

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Fatigue limit estimation of WAAM specimens using temperature-based load increase tests

H. Heydarinouri^a, S. Canclini^b, L. Gilliar-Schönenberger^b, M. Mohri^a, V.-A. Silvestru^b, C. Affolter^a, C. Leinenbach^{a,c}

^a*Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf, Switzerland*

^b*ETH Zurich, Swiss Federal Institute of Technology Zurich, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland*

^c*EPFL, Swiss Federal Institute of Technology Lausanne, CH-1015 Lausanne, Switzerland*

Abstract

Wire-arc additive manufacturing (WAAM) is increasingly used for producing large structural steel components; however, reliable and efficient fatigue assessment methods are required for their reliable application. This study investigates the applicability of the load-increase test (LIT) approach combined with thermal evolution for rapid estimation of the fatigue limit of WAAM carbon steel specimens. Dog-bone specimens were fabricated from ER70S-6 steel using a robotic WAAM system and subsequently machined for fatigue testing. Two LIT experiments were conducted under a stress ratio of $R = 0.05$. The fatigue limit, defined as the stress amplitude σ_a corresponding to a given stress ratio R , was estimated using the temperature evolution measured during cyclic loading. The results indicated fatigue limits of $\sigma_{a-LIT} = 154.5$ MPa and $\sigma_{a-LIT} = 161.9$ MPa ($R = 0.05$) for the two tests. The estimated fatigue limits were further evaluated using a constant-life diagram (CLD) considering mean stress effects and compared with Goodman and Gerber fatigue criteria. The LIT-based results were found to align closely with the Gerber prediction, demonstrating consistency with established fatigue assessment methods. The study demonstrates that the LIT method can provide a rapid and reliable approach for estimating fatigue limits of WAAM steel components, significantly reducing experimental effort compared to conventional constant-amplitude fatigue testing.

Keywords: Wire-arc additive manufacturing; fatigue; load increase test; constant life diagram

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

Consideration of residual stresses in fatigue verification of 60 E2 rails

Elias Will^a, Marc Wenner^b, Steffen Marx^a, Chongjie Kang^a

^a*Institute of Concrete Structures, Technische Universität Dresden, Georg-Bähr-Straße 1, Dresden 01069, Germany*

^b*MKP GmbH, Zum Hospitalgraben 2, 99425 Weimar, Germany*

Abstract

Bridge deformations can induce additional load actions in the rails compared to those occurring on open track, resulting in either tensile or compressive stresses. If the additional compressive stresses exceed the permissible limit, rail buckling may occur. Excessive tensile stresses, in turn, have been shown to lead to fatigue failure of the rail. To prevent rail fracture, it is therefore necessary to ensure that the additional stresses remain below the allowable threshold. Residual stresses represent a key factor in this verification. They are particularly pronounced at the center of the rail foot, where they coincide with the maximum tensile stresses induced by traffic loading. In current fatigue verification practice according to EN 1991-2 and UIC 774-3, residual stresses are considered using a standard deviation of 80 N/mm². However, the reference basis for this standard deviation can no longer be clearly identified. The present study investigates the influence of residual stresses on the permissible additional rail stresses. For this purpose, 45 residual stress tests on profile 60 E2, steel grade R260, obtained from manufacturers' quality control, were evaluated. Based on the measured residual stress values, the following sections describe a consistent approach for incorporating residual stresses into the verification procedure and assess the resulting effect on the permissible additional rail stresses.

Keywords: Rail, residual stresses, fatigue, track-bridge-interaction, railway infrastructure

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Dealing with fatigue cracks in steel components

Peter Knoedel^a, Stefanos Gkatzogiannis^b, Christoph Hörenbaum^c

^a*Dr Knoedel Engineering Consultants, 76530 Baden-Baden, Germany*

^b*Institute of Steel Structures, NTUA, Zografou Campus, 15772, Athens, Greece*

^c*IPU Ingenieurgesellschaft Karlsruhe mbH, 76185 Karlsruhe, Germany*

Abstract

In this paper, practical methods are compiled. These are used to assess steel components with fatigue cracks along the lifetime of the structure. Focus is given on providing a useful and practice-oriented overview rather than presenting new scientific results.

Structures under cyclic loading exhibit two phases during their lifetime: In Phase 1 the crack develops from the micro structural level up to a technical crack. In Phase 2 the crack grows up to a fracture of the residual cross section.

However, from a designer's point of view, Phase 1 can be further subdivided. In Phase 1a, which reflects the designed lifetime, stochastic considerations dictate that no crack is expected, as the design rules are calibrated to 95 % survival probability. Thus, Phase 1a (the design lifetime without a technical crack developing) transitions into Phase 1b during which the first crack is expected, but has not occurred so far. In Phases 1b and 2 the structure needs to be monitored, in order to catch the crack's length while it is still sub-critical. Typically, this is done by an LEFM (linear elastic fracture mechanics) approach, where crack propagation rate and critical crack length are estimated. With this information inspection intervals are determined.

In this paper, the above mentioned methods are discussed along with their backgrounds, analytical methods as well as advanced methods based on FEA. Practical rules are given for dealing with the crack after detection. As an example, a 50-year-old, 180 m long crane runway in a

Keywords: Fatigue; crack initiation; crack growth; fracture mechanics; inspection interval;

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

Increasing residual lifetime of steel structures through use of nanometallic multilayer treatment

Marcus Rutner^{a,b}

^a*Hamburg University of Technology, Institute for Metal and Composite Structures, Am Schwarzenberg-Campus 3, 21073 Hamburg, Germany*

^b*United Nations University Hub on Engineering to Face Climate Change at the Hamburg University of Technology, United Nations University Institute for Water, Environment and Health (UNU-INWEH), Hamburg, Germany*

Abstract

Steel bridges are experiencing premature aging due to fatigue with structural connections particularly affected. According to the International Institute of Welding (IIW), welded connections deteriorate because of inherent geometric notches as well as material changes that occur during the welding and cooling process. Researchers at Hamburg University of Technology have developed a novel post-weld treatment known as nanometallic multilayer (NMM) treatment. This method applies a nanolaminate coating using electrodeposition, covering the entire connection area. Upon solidification, the NMM induces compressive residual stresses in the steel substrate adjacent to the surface, further, acting as a high-strength and ductile layer on the welded area, effectively delaying crack initiation. Recent findings demonstrate a significant increase in fatigue strength of the butt-welded double-V weld from FAT class 80 to FAT class 225, which corresponds to a more than tenfold extension in service life. This study for the first time investigates the potential of NMM technology as maintenance method for existing steel structures. Local fatigue-critical welded joints, which limit the service life of the overall structure, are treated with NMM and significantly increase the residual lifetime of the overall structure. This study presents a quantitative assessment of this residual lifetime increase and underlines the potential in regard to sustainability goals, economic viability and readiness of steel infrastructure.

Keywords: Residual lifetime; fatigue; steel structures; infrastructure; sustainable design; SDG

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

Optimization of composite bridge design using high-frequency mechanical impact: a case study

Hassan Al-Karawi^a, Mohammad Al-Emrani^b, Saffa Dagduk^c, Cecelia Englund^d, Mattias Öst^a

^a*COWI, Vikningsgatan 3, 41104, Göteborg, Sweden*

^b*Chalmers University of Technology, Vikningsgatan Chalmersplatsen 1, 41296, Göteborg, Sweden*

^c*DEKRA, Lagergaten 5, 41511, Göteborg, Sweden*

^d*AFRY, Grafiska vägen 2, 41283, Göteborg, Sweden*

Abstract

Bridges are usually subjected to cyclic loading that can lead to irreversible fatigue damage, especially in welded joints, which are therefore critical to structural integrity. High-Frequency Mechanical Impact (HFMI) treatment is a promising post-weld treatment method that significantly enhances fatigue resistance by improving the local geometry and inducing beneficial residual stresses. The method has proven potential for fatigue strength improvement of both new and existing structures. However, the application of this method to bridge structures, while accounting for design considerations specific to HFMI treatment, has been only sparsely addressed in the existing literature. This study investigates the possibility of optimizing a case study steel bridge design with HFMI treatment in addition to higher-strength steel. The results show that using HFMI treatment improves overall fatigue performance and significantly reduces utilization ratios for fatigue limit state. For the bridge studied, steel grade S460 is found to be the most cost-effective option. In the end, the study shows that using higher-strength steel with HFMI treatment in new bridge design can result in significant advantages, such as material and cost savings.

Keywords: HFMI treatment, fatigue strength, steel bridges, welded details

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A monitoring concept for grouted connections: state of the art and application to the FINO3 research platform

Tilman Sievers^{a,b}, Kenji Reichling^b, Peter Rozsar^b, Stephan Goertz^b

^a*F&E GmbH, 24149 Kiel, Germany*

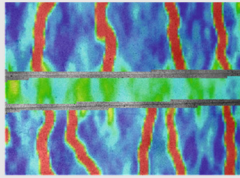
^b*Kiel University of Applied Sciences, 24149 Kiel, Germany*

Abstract

This paper presents a monitoring concept for grouted connections in offshore monopile structures, using the FINO 3 research platform as a reference case. Grouted connections remain a critical component in offshore wind and research support structures, where cyclic loading, interface degradation, and potential washout can reduce stiffness and alter load transfer mechanisms over time. To define measurable indicators for such global stiffness changes, the study first combines a concise state of the art review with a preliminary numerical assessment of the expected structural response. A structural health indicating factor is introduced to relate applied forces to measured relative movement, allowing continuous tracking of stiffness changes and the identification of onset of slippage. For this purpose, a simplified finite element spring model of the FINO3 grouted connection is developed to approximate load sharing between outer contact regions and shear keys and to quantify relative movements between Transition piece and Monopile under bending. Based on the insights from the literature review and the model results, a sensor concept is proposed. Strain gauges at a level where the transition piece behaves close to an idealized tubular member enable bending moment estimation, while circumferential eddy current displacement sensors capture relative tilt and displacement across the grout connection.

Keywords: Grouted connection, structural health monitoring, offshore wind energy

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SMAR 2026



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

MS13: Intelligent digital methods for extending the service life of structures beyond 100 years

Organizers:

Chongjie Kang (TU Dresden, Germany)

Steffen Marx (TU Dresden, Germany)

ABSTRACT

The condition of a structure is increasingly characterized by accelerated degradation as it ages. Preventive measures against aging are more effective the earlier they are implemented. In order to extend the service life of complex structures, significantly more information is required at a much earlier stage than is currently common practice. To drastically reduce this deficit and enable predictive maintenance, innovative intelligent digital methods for acquiring, linking, and evaluating all relevant data on geometry, material, loading, and aging are of essential importance.

This Mini Symposium presents cutting-edge digital approaches—including digital twin modelling, finite element methods (FEM), structural health monitoring (SHM), and data-driven analytics—that address these practical challenges in construction engineering. It offers a platform for sharing research and applications aimed at enabling smarter, more resilient infrastructure.

Information-guided Bayesian modelling for structural health monitoring

T. Bakeer^a, M. Herbers^b, S. Marx^c

^aIndependent Researcher, 01067 Dresden, Germany

^bMarx Krontal Partner, 30163, Hannover, Germany

^cTechnische Universität Dresden, Institute of Concrete Structures, 01062 Dresden, Germany

Abstract

Structural health monitoring (SHM) increasingly relies on probabilistic inference to convert noisy measurements into defensible assessments. This contribution presents an information-guided Bayesian framework that generalises classical deterministic regularisation approaches within a probabilistic formulation. Inverse problems in SHM are modelled through a Gaussian likelihood with correlated measurement errors and a spatially structured prior represented by Gaussian Markov random fields. The Bayesian perspective embeds regularisation as a prior, quantifies parameter uncertainty through posterior distributions, and enables its propagation to derived engineering quantities. Sensor informativeness is assessed using the Fisher information matrix and posterior variance, providing spatially resolved diagnostics that relate sensor placement and load trajectories to the identifiability of structural parameters and the practical limits of inference. The framework is demonstrated on a full-scale bridge under repeatable quasi-static traversing loads. Measured responses are used to identify distributed mechanical parameters and to evaluate the uncertainty associated with their estimation. The analysis highlights regions where the data are weakly informative, shows how sensor configurations influence achievable resolution, and delineates the predictive limits imposed by experimental design. By embedding deterministic regularisation within a Bayesian formulation, the approach unifies inverse parameter identification with uncertainty quantification and provides information-based guidance for sensor placement, load testing, and digital-twin calibration in SHM.

Keywords: Bayesian inference; structural health monitoring; uncertainty quantification; Fisher information; sensor placement

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

Temperature-informed autoencoder for structural health monitoring of bridges

Benjamin Baasch^a, Sebastian Degener^a, Ralf Herrmann^a, Matthias Baeßler^a

^aBundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, 12205 Berlin, Germany

Abstract

Bridges are subject to environmental (e.g., structural temperature fluctuations between day and night or across seasons) and operational (e.g., traffic load) conditions. These factors affect the bridge's vibrational response to external forces, which is reflected in its frequency response. The goal of this study is to separate the effects of temperature and traffic load on structural behavior to better understand their respective impacts on bridge health. Moreover, accounting for such variability is crucial in structural health monitoring, as their impact on structural behavior and hence on the measured signals can potentially mask possible damage. To address this challenge, we developed a deep autoencoder that encodes and reconstructs the bridge's frequency responses derived from vibration monitoring data. The decoder of the autoencoder incorporates temperature information, enabling the latent space representation to be invariant to temperature changes. This temperature-independent encoding serves as an indicator of traffic-induced variations in vibrational behavior. The results demonstrate that this traffic-related indicator effectively captures variations in traffic volume between day and night, as well as between weekdays and weekends. Additionally, the autoencoder's reconstruction error provides a measure of uncertainty, potentially indicating data anomalies or model drift. The model was trained and evaluated using two years of vibration data gathered via geophones installed near the expansion joint of the Nibelungen bridge in Worms – Germany's first large cantilever prestressed concrete bridge.

Keywords: Structural Health Monitoring, Autoencoder, Nibelungen Bridge, Frequency Response Analysis, Anomaly Detection

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

Applied structural health monitoring utilizing state projection estimation error (SP2E)

Max Moeller^a, Armin Lenzen^a

^a*IAS, University of applied sciences Leipzig, Karl-Liebknecht-Str. 132, 04277 Leipzig, Germany*

Abstract

The damage detection and localization method State Projection Estimation Error (SP2E), which has been theoretically developed and validated in the laboratory in recent years, is applied to large-scale structures while accounting for Environmental and Operational Conditions (EOC) in the localization process. SP2E is based on multiple output-only identified state-space models over time, which are normalized to an input pattern process using an H_2/H_∞ -optimization approach. SP2E outputs a damage localization indicator computed as the mean difference process. EOC effects are compensated using a pairing algorithm. This contribution presents the application of SP2E to two large-scale structures – the seven-span Floßgraben Bridge and the openBridgeLab demonstrator. The approximately 350 m long Floßgraben Bridge, which is in operation, is subjected to a reversible damage-equivalent induced by mass alterations using cargo trucks, serving as proof of concept under real operating conditions. The openBridgeLab Bridge is used to investigate the performance of SP2E in detecting actual damage.

Keywords: Damage localization; large-scale experiment; system identification

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GA-based FE model updating for damage detection: application to the openBridgeLAB

Bjarne Sprenger^a, Martina Schnellenbach-Held^a

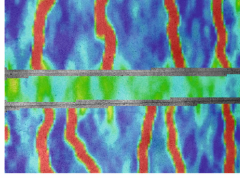
^a*Institute of Structural Concrete, University of Duisburg-Essen, Universitätsstr. 15, 45141 Essen, Germany*

Abstract

Structural Health Monitoring (SHM) involves the systematic acquisition and analysis of sensor data to detect damage and ensure long-term reliability of the structure. Within SHM, finite element model updating (FEMU) is applied to adapt a numerical model to the investigated structure by iteratively modifying uncertain system parameters of the model until the simulated responses correspond with the measured data of the physical structure. The updated model provides valuable insights into the system behavior and potential damage scenarios. The monitoring concept proposed by the authors employs nonlinear FE model updating combined with an artificial intelligence-based algorithm for system identification. The approach comprises genetic algorithms (GA) and Kriging surrogates to iteratively update uncertain model parameters based on measured data and k-means clustering to increase the robustness of the parameter identification. The model adaptation relies on the observation of static structural responses. To demonstrate the proposed methodology, the model updating approach is applied to the openBridgeLAB. The initial finite element (FE) model of the bridge is validated and then coupled with the proposed GA-based updating approach, enabling iterative updating of integrated damage functions based on measurement data. This work aims to demonstrate the applicability of the approach including nonlinear FE simulations for a SHM of real structures. Further, this paper illustrates how a model updating approach can be applied to realistic experimental setups, using the openBridgeLAB as a practical example.

Keywords: Finite element model updating; nonlinear finite element analyses; genetic algorithms; static load tests; openBridgeLAB

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



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Physics-informed neural networks for inverse modeling of non-uniform bending stiffness in beams

Amelie Hendricks^{a,1}, Nils Radin^a, Sven Klinkel^a

^aChair of Structural Analysis and Dynamics, RWTH Aachen University, Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany

Keywords: Structural health monitoring, physics-informed neural networks, inverse problem, parameter identification, damage detection

1. Introduction

Material parameters determine the behavior of structural systems. One important parameter in structural health monitoring is the bending stiffness, as it controls the load-bearing capacity and bending behavior of beams. Local reductions in bending stiffness may indicate damage and can therefore be used for its detection and localization. Since bending stiffness cannot be measured directly, it needs to be reconstructed from structural responses such as displacements (Al-Adly and Kripakaran, 2025). This leads to an inverse problem. In this context, Physics-Informed Neural Networks (PINNs) introduced by Raissi et al. (2019) have emerged as a promising approach for solving inverse problems. By embedding the governing equation directly into the loss function, the networks prediction of the solution is regulated. In addition, inverse problems require measurements, which are additionally incorporated into the loss function. Within a single training process, the proposed PINN framework simultaneously approximates the displacement and the non-uniform bending stiffness, enabling inverse identification of localized structural degradation.

2. Method

Most bridges can be modeled as slender beam-like structures, since their structural response is primarily governed by bending behavior. For slender and shear-rigid beams, the mechanical behavior can be described using the Euler–Bernoulli beam equation,

$$EI(x)w''''(x) + 2EI'(x)w'''(x) + EI''(x)w''(x) = q(x), \quad (1)$$

where $EI(x)$ denotes the bending stiffness varying along the beam length, $w(x)$ the beam deformation and $q(x)$ the external load (Spura, 2019).

To identify localized degradations in the bending stiffness distribution, PINNs are introduced. They use artificial neural networks to approximate the solution of partial differential equations. In this framework, two separate neural networks are used: one network approximates the displacement field, while the second network approximates the bending stiffness. The neural network is trained by optimizing its network parameters such that the predicted solution satisfies the differential equation, boundary conditions and measurements. This is achieved by minimizing a loss function. The loss function consists of a physics-based loss, a boundary condition loss and a data loss term,

$$\begin{aligned} L_{pde} &= |EI(x)w''''(x) + 2EI'(x)w'''(x) + EI''(x)w''(x) - q|_{\Omega}, \\ L_{bc} &= |w(x) - B_N|_{\Gamma_N} + |EI(x)w''(x) - B_D|_{\Gamma_D}, \\ L_{data} &= |w(x) - w_*(x)| + |w''(x) - w_*''(x)|, \end{aligned} \quad (2)$$

¹ Corresponding author. Tel.: +492418025089,
E-Mail address: hendricks@lbb.rwth-aachen.de

where B_N and B_D represent the Neumann and Dirichlet boundary conditions applied to the boundary domains Γ_N and Γ_D , respectively. Since damage is primarily visible in the curvature prediction, curvature information derived from strain measurements greatly improves the reliable bending stiffness identification. Here, $w_*(x)$ corresponds to the displacement measurements and $w'_*(x)$ to the curvature information. The total loss function is obtained as a weighted sum of the individual loss terms,

$$L_{total} = \tau_{pde} L_{pde} + \tau_{bc} L_{bc} + \tau_{data} L_{data}, \quad (3)$$

where τ_i are the weighting factors associated with the corresponding loss terms. An appropriate balance between these weights is essential to ensure stable training and accurate convergence (Radin et al., 2023).

3. Example

The proposed PINN approach is applied to a simply supported beam subjected to a uniformly distributed load, as illustrated in Figure 1. The figure includes the problem setup as well as the corresponding boundary conditions.

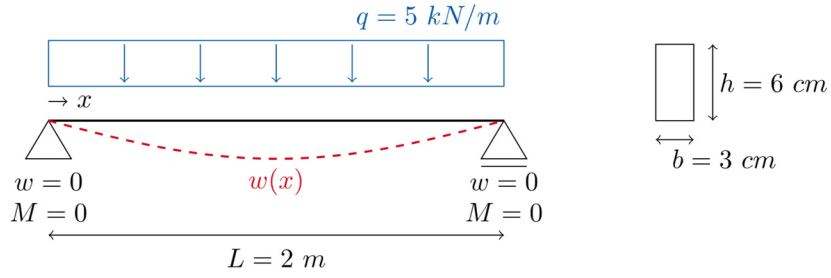


Fig. 1. Simply supported beam subjected to a distributed load q .

The spatial coordinate x , defined along the beam length, is used as input to the neural network, while the beam deformation $w(x)$ and the non-uniform bending stiffness $EI(x)$ are predicted as outputs using separate neural networks trained simultaneously within a single training process. To represent different structural conditions of a beam, two cases are considered: an undamaged beam with constant bending stiffness and a damaged beam with locally reduced stiffness representing structural degradation. Both cases are evaluated using PINNs, as shown in Figure 2.

To solve this inverse problem, training data is required to predict the displacement based on measurements and subsequently identify the bending stiffness. The training data consists of synthetic displacement and curvature measurements obtained from a finite element (FE) reference solution. To account for uncertainties and evaluate the robustness of the proposed method, 10% Gaussian noise is added to the FE-generated measurements. The displacement measurements are distributed regularly along the beam to capture the global structural behavior, while the curvature data are distributed more sparsely. Consequently, in Figure 2, the PINN predictions are compared against the FE reference solution and against the corresponding noisy FE-derived measurement data used for training.

The results show that the PINN framework can accurately predict the displacement, curvature and bending stiffness for both cases, with the predicted solution matching the reference solution. The constant bending stiffness of $\bar{EI} = 5.94 \text{ kNm}^2$ is approximated with a relative L^2 -error of 0.0040. For the damaged case, the bending stiffness is reduced by 50% at the center of the beam, resulting in larger deformations and an increased L^2 -error of 0.019. The increased error in the damaged case indicates the complexity of inverse identification for non-uniform material parameters. In particular, the accurate prediction of displacements and their derivatives is important, as these derivatives are required in the Euler–Bernoulli beam equation to model non-uniform bending stiffness.

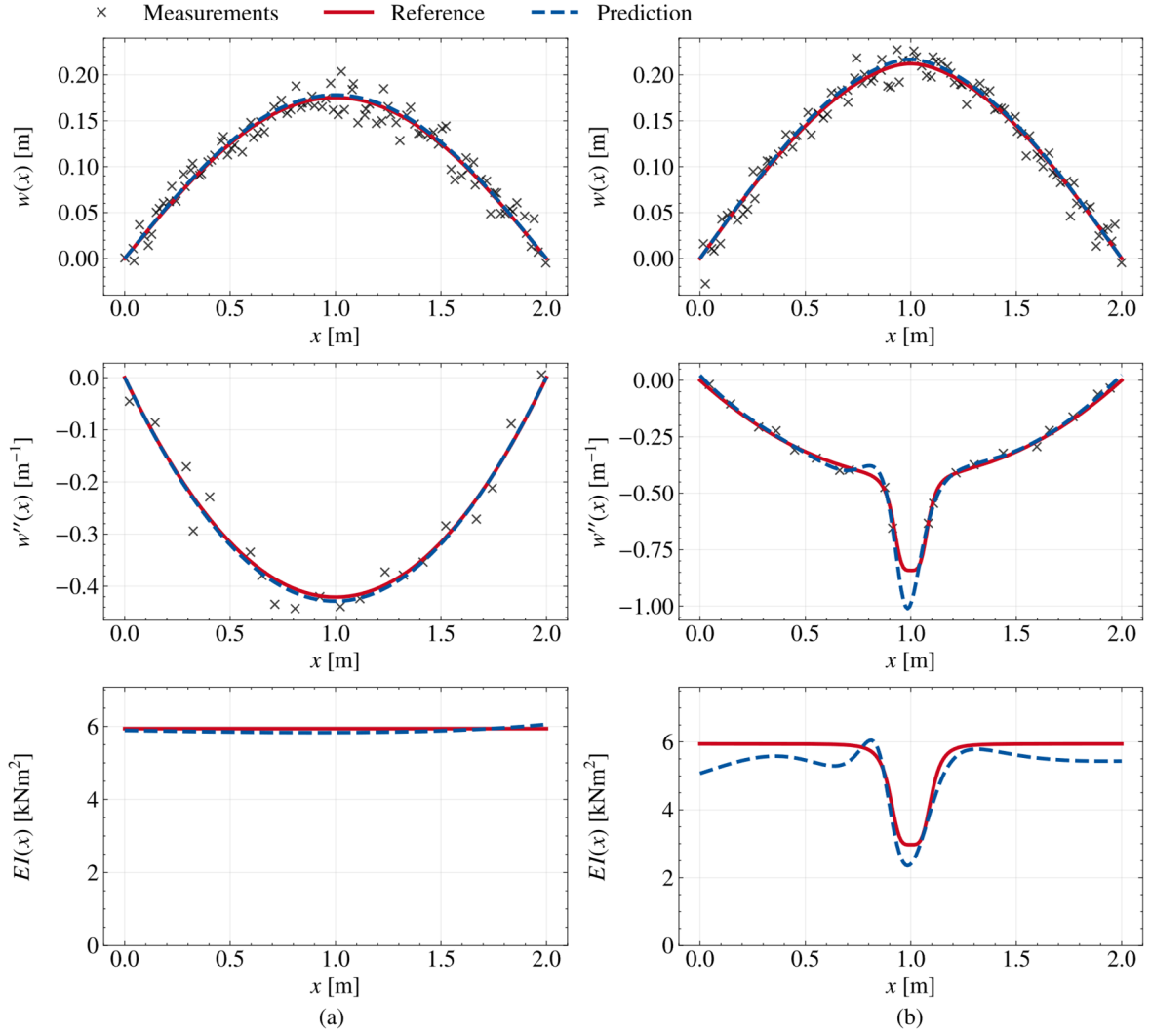


Fig. 2. Prediction of the displacement $w(x)$, curvature $w''(x)$ and non-uniform bending stiffness $EI(x)$, while (a) represents the undamaged and (b) the damaged case.

4. Outlook

Overall, the PINN approach demonstrates its capability to approximate displacement fields and identify spatial variations in bending stiffness without prior knowledge of the damage location. However, several limitations remain. An appropriate balancing of the loss terms represents a challenge for stable training and convergence. In addition, the practical availability and reliability of curvature information derived from strain measurements should be critically assessed. Despite these challenges, the method shows promising potential for real-world applications in structural health monitoring of bridges.

Acknowledgment

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Transfer learning for traffic identification in SHM based on visual and vibration data

Ralf Herrmann^a, Sebastian Degener^a, Benjamin Baasch^a, Matthias Baeßler^a

^a*Fachbereich 7.2 Ingenieurbau, Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, 12205 Berlin, Germany*

Abstract

The increasing use of digital tools to assess and inspect engineering structures makes data from various sources accessible. For road bridges in Germany, the typical visual inspection according to DIN 1076 will be expanded to include more visual models and monitoring results. Detecting damage based on the data is challenging and often requires information from various sources to be fused. Information about environmental and operational conditions (EOC) can be modelled or measured continuously to provide an accurate record of the loads experienced by the individual structure. AI image recognition models can be used to identify traffic on a bridge. Vibration-based traffic detection often requires additional manual training and adjustment. Combining visual image recognition with vibration-based identification and applying transfer learning techniques can increase prediction performance without manual annotation. This study will investigate how model size affects performance, as this has a strong effect on computational effort. Using larger models requires more computational resources for training and for interference in the Structural Health Monitoring (SHM) application on the structure. The results will be validated on the Baumgarten Bridge, Werder, Germany equipped with a combination of traffic camera and vibration sensors at the expansion joints.

Keywords: Structural health monitoring; AI; traffic identification; transfer learning

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

Validation of a cloud-based digital twin for long-term structural health monitoring of the Terfener Inn Bridge

Nils Weissenbach^a, Massimo Penasa^b

^a*CAEmate s.r.l., via Alessandria 15, Bolzano, 39100, Italy*

Abstract

Physics-informed digital twins are a key step toward understanding the real behavior of bridge structures over their full lifecycle. This paper presents the field validation of a high-fidelity digital twin for a prestressed concrete highway bridge commissioned by ASFINAG Austria, in continuous operation for over four years from construction to long-term service. The system integrates distributed fiber-optic sensing, nonlinear finite element analysis, and inverse parameter identification within a unified, self-calibrating framework. More than 7 km of fiber-optic cables embedded in deck, webs, piers, and foundations provide distributed strain and temperature data, processed via the cloud-based WeStatiX SHM platform using physics-informed neural networks (PINNs) and operational modal analysis (OMA). Results show that the digital twin remains consistent with governing physics while adapting to evolving conditions. Long-term monitoring reveals significant deviations between measured and design-predicted behavior, especially due to creep, shrinkage, and thermal gradients, which dominate deformation and stress redistribution. Daily nonlinear simulations confirm these effects as key drivers of long-term structural response. Validation through live load testing shows agreement between measured and simulated strains within 1%, demonstrating the robustness of the self-calibrating approach. Overall, this represents one of the first long-term validations of an autonomous, physics-informed bridge digital twin, shifting structural health monitoring from data collection toward predictive, knowledge-based asset management and enabling more reliable condition assessment and maintenance planning.

Keywords: PINNs; OMA; fiber-optic sensing; nonlinear finite element analysis; inverse parameter identification

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

Multi-sensor equipped load testing on the openBridgeLAB

Maria Walker^a, Bertram Richter^a, Kerstin Speck^a, Anett Kielreiter^b, Steffen Marx^a

^a*Institute of Concrete Structures, TUD Dresden University of Technology, George-Bähr-Str. 1, 01069 Dresden, Germany*

^b*Hentschke Bau GmbH, Department of Research and Development, Zeppelinstr. 15, 02625 Bautzen, Germany*

Abstract

Many bridges on Germany's federal highways were constructed in the 1960s and 1970s. Structural monitoring data enables more accurate assessment of real loads and structural resistance of these existing structures. However, monitoring methods applied in practice are heterogeneous, with no guidelines for the design of measurement systems, data evaluation, or data integration in the condition assessment. In September 2025, static load tests were carried out at the openBridgeLAB – a 45-meter-long prestressed concrete bridge located in Bautzen, Germany – to test and compare monitoring concepts under real-world conditions using various sensors. This paper presents crack monitoring approaches utilizing conventional sensors, including consideration of sensor placement influence and data evaluation methods. The focus lies on identifying the decompression load, as well as crack propagation over the cross-section and crack width under varying loads in the coupling joint cross-section. The study evaluates existing monitoring methods and highlights potential improvements.

Keywords: openBridgeLAB; existing structures; decompression; coupling joint; prestressed concrete; crack monitoring

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

Ontology-based integration of spatial sensor information in digital twins

Fabian Rolke^a, Henrik Becks^b, Anne Göbels^a, Oliver Schulz^a, Jakob Beetz^a

^a*Design Computation, RWTH Aachen University, 52072 Aachen, Germany*

^b*Chair and Institute of Structural Concrete, RWTH Aachen University, 52072 Aachen, Germany*

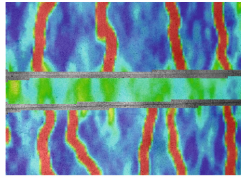
Abstract

Structural Health Monitoring (SHM) systems generate measurement data whose interpretation depends on the precise spatial contextualization of sensors relative to the monitored structure, allowing engineers to relate measurements to specific structural components, load paths, or environmental influences. In practice, sensor positions are often documented across distributed heterogeneous resources such as technical drawings, photographs, and textual descriptions, limiting accessibility, interoperability, and machine-readability. As these formats are limited to 2D space, relating them and their implicit spatial sensor and observation information to the physical infrastructure asset typically requires cross-referencing multiple resources.

This paper presents a method for transforming spatially implicit sensor documentation into a Resource Description Framework (RDF) dataset, utilizing the Space Types Ontology (SPOT) and the Relative Location Ontology (RELOC) for expressing spatial relations, and the Sensor, Observation, Sample, and Actuator Ontology (SOSA) for sensor semantics. The resulting graph enables qualitative and quantitative queries on topological and directional relations between sensors, their observations, and the resources documenting them. The approach contributes to the broader goal of

Keywords: Spatial linking; structural health monitoring; digital twins; sensor localization

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Automatic semantic enrichment for BIM-based SHM

Iryna Rudenko^{a,1}, Philipp Kähler^b, Frank Rackwitz^a, Yuri Petryna^{b,*}

^a*Technische Universität Berlin, Chair of Soil Mechanics and Geotechnical Engineering, Gustav-Meyer-Allee 25
13355 Berlin, Germany*

^b*Technische Universität Berlin, Chair of Structural Mechanics, Gustav-Meyer-Allee 25, 13355 Berlin, Germany*

Keywords: Building Information Modeling; structural health monitoring; Industry Foundation Classes; finite element model

1. Introduction

The application of Building Information Modeling (BIM) aims at optimizing project workflows at every stage of a structural life cycle. Since BIM models contain geometric and semantic information, they can also serve as a basis for structural health monitoring (SHM). BIM-based SHM inherently requires specific semantic information to be stored within the BIM model, while SHM includes various components and workflows depending on the structure and the purpose of monitoring.

The use of BIM in the field of SHM is versatile. Some studies focus on enriching the BIM model with monitoring data and detected anomaly information. For instance, Kwon et al. (2021) developed an Industry Foundation Classes (IFC) BIM-based framework for anomaly detection under complex loading conditions. An artificial neural network (ANN) was designed based on structural analysis theory and used to predict the behavior from the loading conditions. Furthermore, the resulting anomaly information was propagated to the IFC-BIM model. Machete et al. (2023), investigated the possibility of real-time structural monitoring with the help of IoT (Internet of Things) sensors and aimed at storing sensor data within the BIM model. Qin et al. (2025) focused on designing a BIM-based SHM system for an asymmetric butterfly arch bridge. In this study, the BIM model was linked to the structured query language (SQL) database allowing automatic access and reading of the monitoring data of physical sensors stored in the database. The real-time maximum strain value was compared to the predefined threshold and updated within the BIM model. In contrast, there are also studies, which investigate BIM-based design and setup of SHM systems, such as Gragnaniello et al. (2024). The information on sensors was added to the BIM model in the preliminary phase after the preliminary design team of the SHM system defined their type and placement. Moreover, the BIM model was utilized at the construction site to visualize the sensor locations and system specifications. After the sensors were installed, the documentation related to the installation, testing and maintenance was linked to the As-built BIM model of the SHM system.

It is evident that the semantic enrichment of the BIM models with various SHM-relevant information is a part of many studies. The research gap that is addressed by the present contribution is the automatic semantic enrichment of the BIM model with finite element method (FEM)-relevant information and some of the SHM-relevant information, namely sensors, to support the consecutive automatic finite element (FE) model generation. Rudenko and Petryna (2025) proposed an approach to automatic BIM-based generation of FE models of different complexity and FE dimensionality. The approach requires a property set with FEM-relevant information to be assigned to every IFC object within the BIM model. Certainly, automatic semantic enrichment would ease the pre-processing of the BIM model for the user and speed up the FE model generation. Therefore, an approach to automatic semantic BIM model enrichment with FEM- and SHM-relevant information is presented at this point.

2. Methodology

The workflow for automatic semantic enrichment of the BIM model with FEM- and SHM-relevant information as well as the subsequent FE model generation based on BIM is shown in Fig. 1. The starting point is an initial BIM model, which is an IFC file

¹ Corresponding author. Tel.: +49-30-314-72319

E-mail address: i.rudenko@tu-berlin.de

* We deeply regret to announce that the author passed away before this extended abstract could be published.

containing geometry, materials and structural supports. The IFC objects have two representations: SweptSolid or AdvancedSweptSolid with parameterized profile definition and Tessellation. The SweptSolid or AdvancedSweptSolid representation describes a 3D solid through sweeping a 2D cross-section along a path. The parameterized profile definition and accordingly the knowledge of a profile shape are beneficial for the generation of FE models with beam, shell, and solid finite elements. In case of Tessellation representation, the surface of the object is represented by triangles and polygons. In this approach, the SweptSolid representation is used to describe a slightly simplified geometry of the structure, for example, neglecting voids irrelevant to structural analysis or bolts. On the other hand, the Tessellation representation is considered to express detailed and realistic geometry. It is worth noting that the user may work with one BIM model containing both representations or with two BIM models containing different representations if the objects in both IFC files have the same Globally Unique Identifiers (GUIDs).

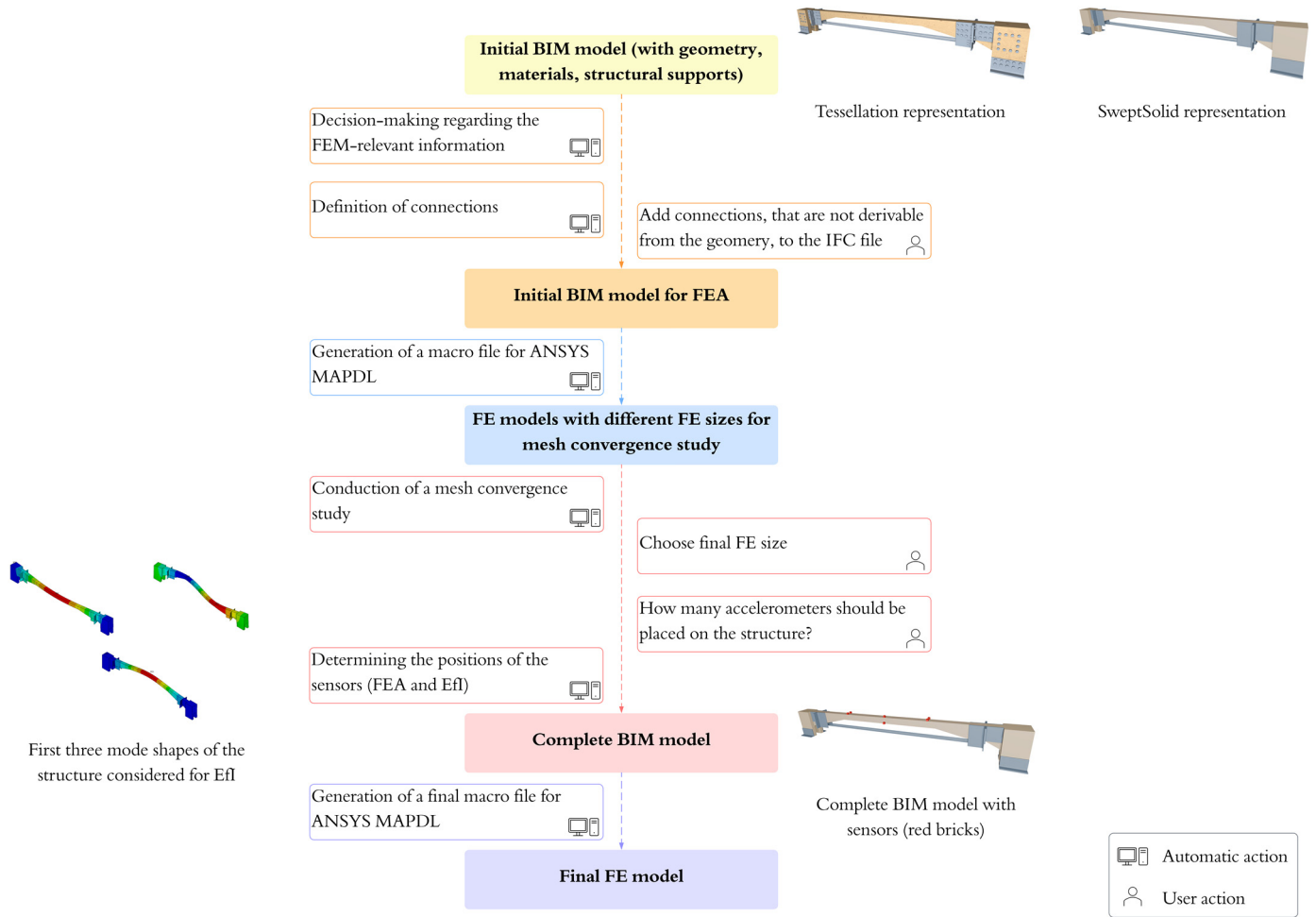


Fig. 1. Workflow for automatic semantic BIM model enrichment with FEM- and SHM-relevant information as well as BIM-based FE model generation.

Based on the initial BIM model, automatic decision-making regarding what IFC objects should be used for FE analysis of an entire structure, their FE dimensionality, type and initial FE size is performed. These properties are assigned to corresponding IFC objects as a property set with FEM-relevant information *Custom_Pset_FE_ANSYS*. The property is named this way, since a macro file for the FE software ANSYS Mechanical APDL (MAPDL) is generated and some entries of the property set, such as FE type, are software-specific. In addition, the connections between IFC elements are identified and written to the IFC file. Here, Tessellation representation of the objects is used to detect clearance clashes. The connections are specified with the help of the relationship *IfcRelConnectsElements* and considered fixed within FE model. Another important aspect for proper establishment of connections is an automatic definition of section offset, for instance, when both objects should be meshed with shell finite elements. In this case, the relationship *IfcRelConnectsElements* is not necessary, since the objects are connected through the section offset. Furthermore, IFC objects that should be used for mesh convergence study are specified in this step. Subsequently, the user should add connections that are not derivable from the geometry of the structure to the IFC file. After these actions, the enriched BIM model should be checked for errors or inconsistencies, since it serves as initial BIM model for performing finite element analysis (FEA). In the next step, it is used to generate a macro file for ANSYS MAPDL with varying FE size factors. Afterwards, modal analysis is performed, and the values of natural frequencies are examined as part of a mesh convergence study. The user may specify the desired number of natural frequencies to consider. Otherwise, the first five natural frequencies are taken into account. Thereafter, final FE size factor is determined by the user with the help of the results of the mesh convergence study.

The FE model with final FE size is then used for optimal sensor placement. The user should input the desired number of accelerometers to be placed on the structure. It is also possible to specify the number of mode shapes to be considered. In a standard case, the first three mode shapes are utilized. The effective independence (Efi) method proposed by Kammer (1991) is employed to determine optimal positions of the sensors and degrees of freedom that are relevant for measurement. Afterwards, the final FE sizes of all structural objects and the information on the sensors are propagated into the BIM model. The objects of the class *IfcSensor* are automatically established within the BIM model with property sets *Pset_SensorTypeCommon* and *Custom_Pset_Sensors*. The custom property set contains information on the relevant degree of freedom, minimum sampling rate and provisional path to data. The sensors are also connected to the corresponding structural objects by using the relationship *IfcRelConnectsElements*. If the structural object is meshed with beam elements, a node is created at the position of the sensor during the generation of the FE model. Otherwise, the nearest node is found later.

At this point, the BIM model is complete, and the user should perform a consistency check. Thereafter, a final macro file for ANSYS MAPDL is written. The newly generated FE model incorporates the final FE sizes from the mesh convergence study and has nodes at or near the locations of the sensors to allow the simulation of sensor data within the FE software. Finally, the FE model should be checked for errors.

3. Results

The proposed approach was applied to a laboratory test structure and subsequently validated. The structure is a timber bridge with a total length of 4 m. Two BIM models of this bridge were created, as depicted at the top of Fig. 1. The first one is a detailed BIM model with Tessellation representation, and the second one is a simplified BIM model with SweptSolid or AdvancedSweptSolid representation. All steps of the presented workflow were tested with the help of these BIM models. FEM- and SHM-relevant information was successfully added to the BIM model with SweptSolid representation. As an example, the first three mode shapes of the structure without tendons that were considered for optimal sensor placement and the final BIM model with six accelerometers represented as red bricks are shown in Fig. 1.

4. Conclusion and outlook

This contribution presented an approach to automatic semantic BIM model enrichment with FEM- and SHM-relevant information. The automatic pre-processing of the BIM model prior to FE model generation was considerably faster and less error-prone than the manual one, proving the proposed method to be efficient and practical. The automatic decision-making regarding FEM-relevant information as well as the definition of connections and section offsets showed robust results and required only minor modifications by the user. Moreover, the optimal positions of the sensors and the DOF to be measured were successfully identified with the help of the Efi method. In addition, this approach also contributes to enhancing the interoperability and accessibility of digital data by focusing on vendor-neutral data transfer format IFC. One of the limitations of the presented method could be that a cross-section must be defined as parametrized profile within the BIM model. However, the IFC standard supports parameterized profile definitions for the majority of common profiles.

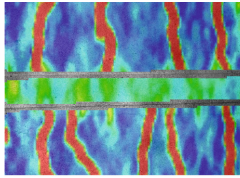
Future studies may extend this work by including automatic calculation and definition of additional mass within the BIM model since it may have a significant effect on the results of the FE analysis.

Acknowledgements

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Scan2SAM – a concept for the derivation of structural analytic models of bridges from point clouds

Hristo Vassilev^{a,b,1}, Jörg Blankenbach^{a,b}

^a*RWTH, Mies-van-der-Rohe Straße 1, Aachen 52064, Germany*

^b*Cluster of Excellence CARE, TU Dresden and RWTH Aachen, Germany*

Keywords: Point clouds; structural analytical models; structural graphs; scan-to-FEM; digital twins; topology extraction

1. Introduction

This contribution proposes a concept for automating the process of deriving simplified geometric models from point clouds that enable downstream finite element models (FEM). By preserving the underlying connectivity topology of the structural members, the focus of this work is to define a data model that jointly describes point cloud semantics and structural analytical models (SAM). This will guide the creation of training datasets for future implementations of deep learning models for deriving the structural graph. Notably, the focus of the method is not to guess all boundary conditions needed for simulation, as often there is insufficient evidence in point clouds to support a confident decision – rather, our methodology abstracts geometry as object placeholder nodes for engineers to enter kinematic behavior information into e.g. after either observing construction drawings or site visits. We further show that annotating point clouds with instance and topology information is sufficient to facilitate gradient-based fitting of parametric loft profiles. Existing Scan-to-FEM research has demonstrated the feasibility of deriving structural analysis models from laser scanning data through geometric reconstruction and parametric abstraction (Castellazzi et al., 2015; Funari et al., 2021). More recently, topology-aware approaches have shown that member centerlines and structural connectivity can be recovered directly from point clouds to generate beam-and-joint representations suitable for simulation (Smith and Sarlo, 2022; Selman et al., 2022). Nevertheless, these methods typically rely on predefined or predominantly prismatic member representations and focus primarily on the generation of simulation-ready analytical geometry. Comparatively little attention has been paid to jointly representing structural topology and semantic point cloud associations within a unified data model. This work therefore proposes a representation (Section 2.1) that explicitly models structural graphs while associating graph entities with semantic point cloud instances and parameterized profile descriptions, providing a basis for future Scan-to-SAM workflows and the creation of training datasets for learning-based structural graph reconstruction. Additionally, an algorithm is discussed that can leverage this representation to accurately approximate the point cloud geometry of tapered parametric members (Section 2.2).

2. Method

2.1. Data model

To facilitate learning-based topology extraction from raw point clouds our data model combines descriptions of point clouds with analytical models represented as spatial graphs (see Fig. 1). The point cloud is represented by a $N \times 3$ array of points in Euclidian space. Additional optional per-point properties are described by fields that share a predefined ontology, which is crucial for training machine learning models. Targets for segmentation models, for example are placed in semantic and instance segmentation fields, where object class and instance identity are stored correspondingly. The analytical model is a separate layer, that sits on top and references the captured point cloud. It is represented by a graph, consisting of vertices and edges. The vertices represent beam end

¹ Corresponding author. Tel.: +49 241 80-95293

E-mail address: hristo.vassilev@gia.rwth-aachen.de

points and consist of a position and model role semantics, i.e. to differentiate ‘joint’ vs ‘support’ vertices. Further description of the kinematic behavior of each vertex is omitted at this level, as this is often not deducible by point cloud geometry alone. Edges combine two vertices to form a rough centerline for each beam with topologically connected beams sharing vertex instances. Notably, their attributes include a reference to the ID of a specific building part described by an instance segmentation field in the point cloud, which establishes the link between the two layers. Edges are additionally designed to hold information about the parametric template that describes their geometry, which after optimization can also include the individual parameters and cross-section locations along the beam’s length.

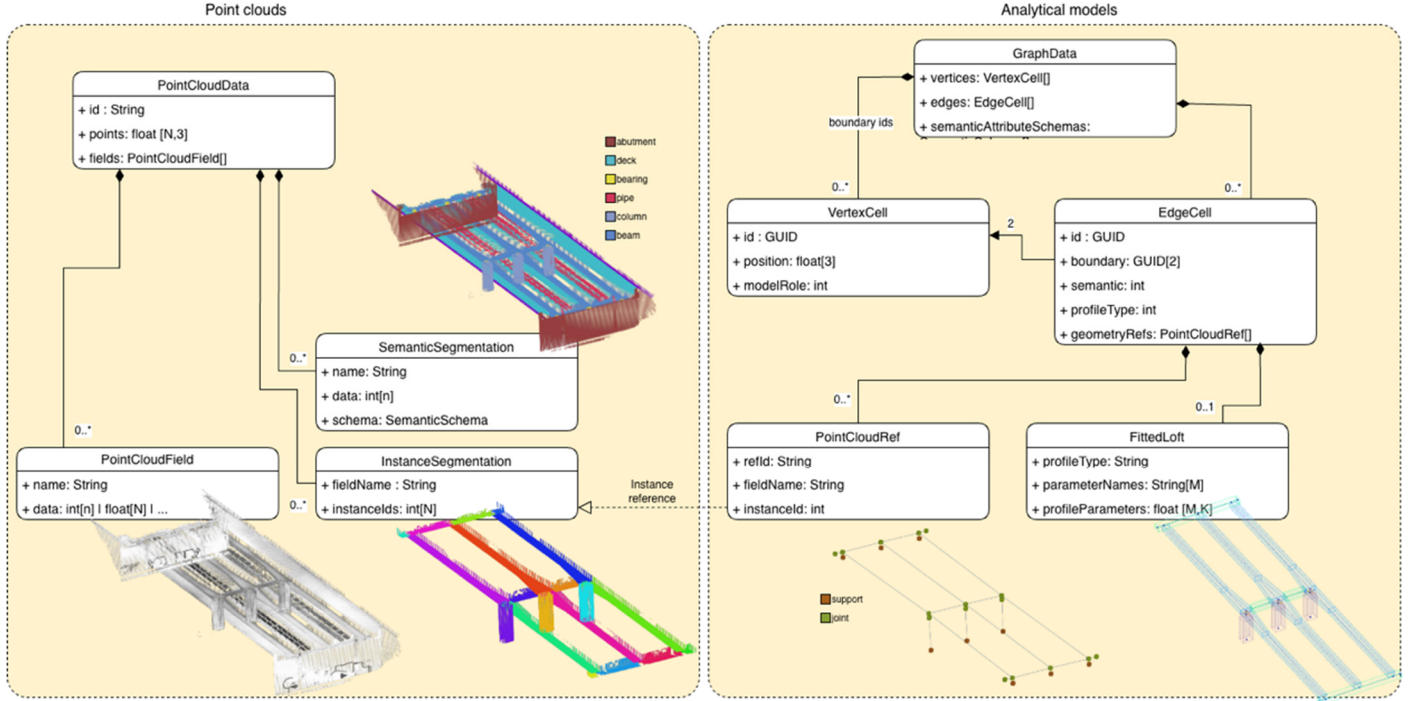


Fig. 1. The proposed joint data model.

2.2. Profile fitting

We represent the scanned member as a lofted surface generated by a sequence of parametric cross-sections placed along its longitudinal axis. Each cross-section is described by a small set of geometric parameters (see Fig 2), and the 3D shape between two neighboring sections is obtained by piecewise-linear interpolation of these parameters. Therefore, the center position, size, and orientation vary continuously from one profile to the next. This gives a compact and differentiable geometric model that is flexible enough to capture gradual shape changes while remaining simple to optimize. The fitting objective compares the observed point cloud to the visible faces of the lofted surface and includes regularization terms that discourage implausible profile changes and stabilize the solution in the presence of noise, missing data, and partial occlusion. Because the model is differentiable, gradient-based optimization is a natural choice: it efficiently exploits the low-dimensional parameterization, scales well to large point sets, and allows all geometric parameters to be refined jointly.

The optimization is performed in two stages. In the first stage, we fit candidate loft segments between fixed axial grid locations and use their fitting costs to determine a suitable segmentation of the object, i.e., how many profiles are needed and where they should be placed approximately. In the second stage, we perform a global refinement in which the selected profiles are optimized jointly, and the interior profile locations can also be adjusted continuously. This two-step strategy is important because the full problem is both combinatorial and highly non-convex: solving profile placement and geometric fitting simultaneously from scratch is unstable and sensitive to initialization. The first stage provides a robust discrete initialization, while the second stage removes grid bias and improves geometric consistency over the entire lofted model.

2.3. Preliminary results

The fitting algorithm was tested on 8-point clouds with promising initial results. Tapered building members were successfully modelled (See Fig 3.) with mean mesh-to-cloud distance of 1.88 mm. The algorithm furthermore successfully determines the optimal number of required profiles and their locations to describe changes in the cross-section parameters.

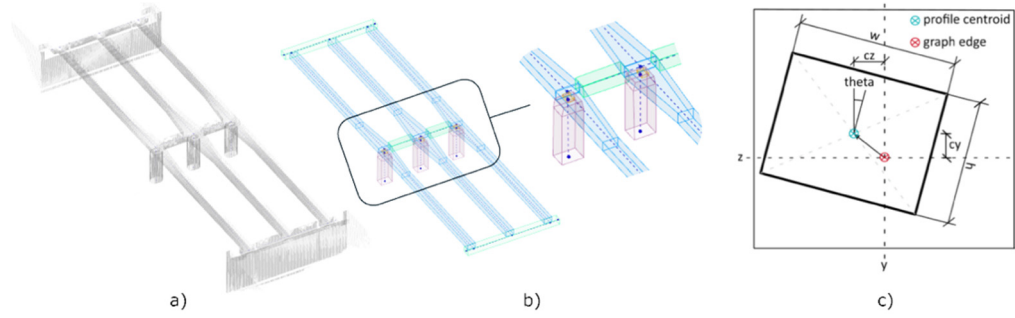


Fig. 2. (a) Pre-segmented point cloud of structural bridge members; (b) reconstructed model; (c) parametrization of a rectangle profile.

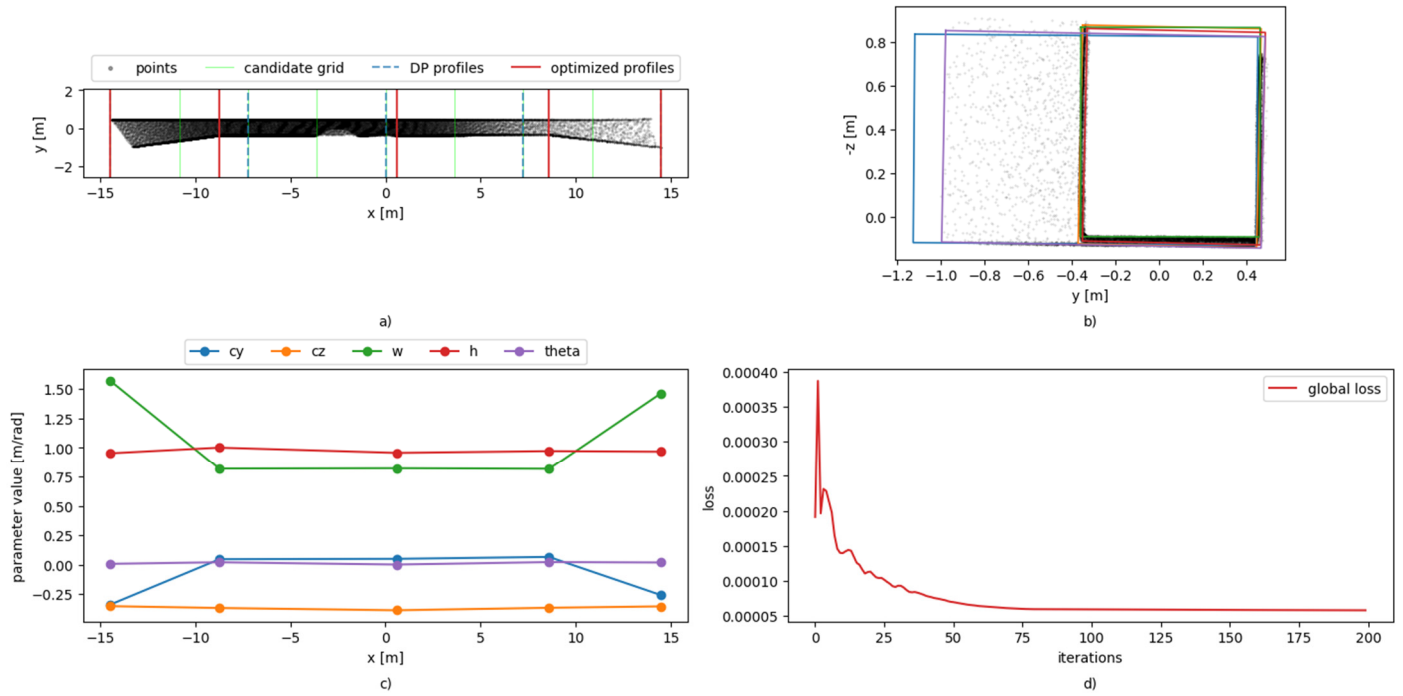


Fig. 3. Example input to the proposed algorithm; (a) Top view – showing the candidate grid in stage 1 and the finalized profiles of stage 2; (b) cross-section view of the same results; (c) optimized parameters; (d) global optimization objective.

3. Conclusion and future work

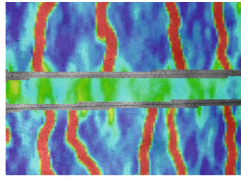
This extended abstract showed initial efforts into formalizing the problem of jointly describing point cloud and structural graph machine learning datasets. The utility of the resulting representation was also demonstrated with a proposed piece-wise linear profile fitting algorithm. Future work will focus on automatically deriving the joint representation from raw point clouds, which has a strong potential to automate time-intensive manual efforts.

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Towards reliable digital twins for bridges: quantifying model form uncertainty

Daniel Andrés Arcones^{a,b,1}, Martin Weiser^c, Phaedon-Stelios Koutsourelakis^b, Jörg F. Unger^a

^aBundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, Berlin 12205, Germany

^bTechnical University of Munich (TUM), Boltzmannstraße 15, Garching bei München 85748, Germany

^cZuse Institute Berlin (ZIB), Takustraße 7, Berlin 14195, Germany

Keywords: Digital twins; uncertainty quantification; bridge monitoring; model updating

1. Introduction

The widespread deployment of sensor networks in recent years has enabled the development of digital twins for critical infrastructure such as bridges. In many cases, their primary objective is to extend the service life of these assets, particularly in countries such as Germany, where a large portion of the infrastructure is approaching or has already exceeded its original design life. Achieving this goal requires reliable data-driven assessment, performance prediction, and proactive maintenance planning. While considerable attention has been devoted to the treatment of measurement noise and parameter uncertainty in digital twin models, model form uncertainty (MFU) arising from simplifications in the underlying physical representation is often neglected or treated only implicitly, despite its potentially significant influence on predictive reliability.

Purely data-driven digital twins are inherently limited by the spatial and temporal coverage of their sensor networks, which restricts their ability to perform full-field assessments and reliable forecasts. Simulation-based digital twins address this limitation by incorporating physics-based models capable of extrapolating information beyond the measured quantities. However, such models must be carefully calibrated to ensure that their predictions faithfully represent the structural behavior. This requires the identification of model parameters based on available measurements. In particular, reliable diagnostics demand that the model be continuously updated to reflect the evolving state of the bridge. Nevertheless, any model formulation necessarily involves simplifications and assumptions of an inherently complex reality. These simplifications introduce MFU, which systematically leads to discrepancies between model predictions and observations.

The interaction between monitoring data, model identification, and predictive simulations can therefore be understood as a sequential modeling workflow, in which information is progressively transferred from sensor observations to increasingly detailed predictive models. This workflow is illustrated schematically in Fig. 1. Starting from the monitoring system and structural health monitoring (SHM) concept, sensor data are used to identify parameters of a simplified thermal model of the bridge cross-section. The inferred parameters are subsequently used to construct a three-dimensional thermal representation of the structure, which in turn serves as the basis for a thermo-mechanical model capable of predicting thermal deformations. Throughout this process, different sources of uncertainty are introduced and propagated along the modeling chain. Measurement noise affects the initial sensor observations, while MFU emerges from the simplified physical representations employed at different modeling stages. Additional discrepancies may arise when transferring information between models of different dimensionality, such as when parameters inferred from a two-dimensional representation are applied to three-dimensional simulations.

¹ Corresponding author.

E-mail address: daniel.andres-arcones@bam.de

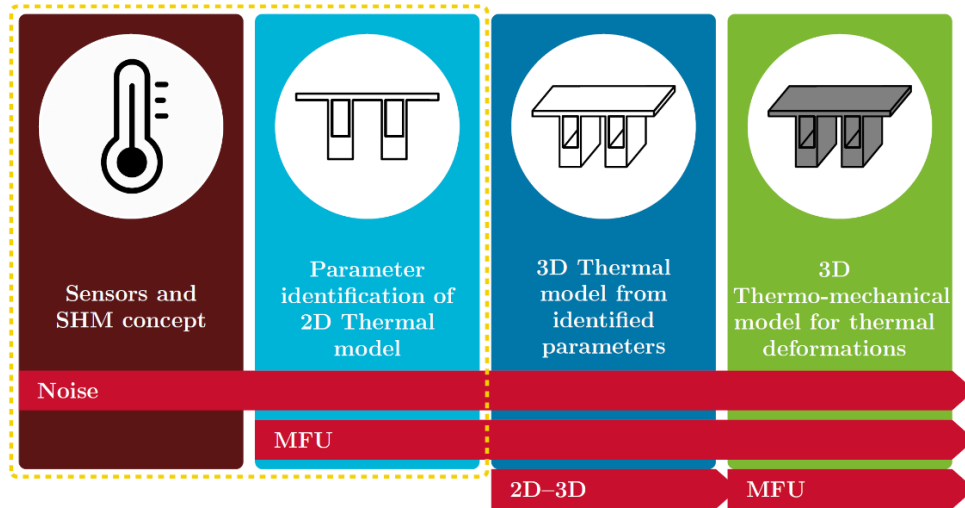


Fig. 1. Diagram of the proposed framework for the thermal deformation compensation in the digital twin with the main uncertainties introduced in each phase and how they propagate throughout the stages.

Thermal loading represents a particularly relevant case for such modeling challenges in bridge digital twins. Temperature variations constitute one of the dominant environmental actions affecting bridges, producing significant stress states and long-term structural responses. At the same time, the spatial distribution of temperature within bridge components is difficult to observe directly, as monitoring systems typically provide measurements only at discrete sensor locations. As a result, thermal digital twins must rely heavily on physics-based simulations to reconstruct and predict temperature fields across the structure. These simulations are typically based on simplified geometric representations and boundary conditions, which introduce additional sources of modeling discrepancy and uncertainty.

This contribution focuses explicitly on the quantification and propagation of MFU within the context of simulation-based digital twins. Quantifying this uncertainty would provide engineers and asset managers with additional information to support more informed decision-making processes. In contrast to sensor noise or other aleatoric uncertainties arising from stochastic loads or environmental conditions, MFU originates exclusively from the model formulation itself.

To enable a consistent propagation of MFU through the digital twin, the embedded uncertainty approach proposed by Sargsyan et al. (2019) and recently extended in Andrés Arcones et al. (2026) presents several advantages. In this framework, MFU is quantified through a stochastic extension of selected model parameters, preventing their posterior distributions from collapsing to deterministic values during the inference process. Consequently, the objective of parameter identification shifts from a simple fitting of observations to the generation of uncertainty bounds that consistently cover the sensor measurements, even in the presence of systematic discrepancies in the mean predictions. Because the MFU is embedded directly in the model parameters, any subsequent prediction or propagation to quantities of interest (QoIs) naturally inherits a probabilistic structure that captures the associated uncertainty. This ensures a consistent propagation of uncertainty to all relevant outputs of the digital twin, including condition indicators and prognostic metrics.

The present contribution proposes the application of this embedded MFU quantification framework to the inference of parameters in a transient thermal digital twin of a monitored bridge. The approach is demonstrated using the Nibelungenbrücke in Worms, Germany, within the framework of the initiative *SPP100+: Extending the Service Life of Complex Building Structures through Smart Digitalization*. Using monitoring data from the bridge instrumentation system described in Kang et al. (2024), a simplified model of the bridge cross-section is employed to infer the thermal model parameters governing the temperature evolution within the structure. Geometric and physical simplifications introduced in the model require the identification of corrective terms in the boundary conditions that control the heat input to the system. These corrective parameters account for discrepancies between the simplified representation of environmental heat exchange and the actual thermal behavior of the bridge.

MFU is embedded in these parameters in order to quantify the discrepancy generated by the simplified representation of the heat intake mechanisms, which is expected to influence the resulting thermal predictions. Since these parameters are used in any thermal simulation that relies on the same model formulation, their inferred probability distributions can be propagated to new predictions and future simulations along the modeling chain illustrated in Fig. 1. In this way, the proposed framework enables uncertainty-aware forecasting within the thermal digital twin. By explicitly accounting for MFU and consistently propagating it through the different stages of the digital twin, a more reliable basis is provided for structural assessment, condition monitoring, and long-term infrastructure management decisions.

2. Methodology

Within the digital twin framework, the parameters governing the thermal model must be identified from sensor observations while accounting for the different sources of uncertainty affecting the measurements and the model formulation. In particular, the simplified representation of the bridge cross-section and the environmental heat exchange introduces model form uncertainties that

cannot be fully eliminated through parameter updating. The objective of the parameter identification procedure is therefore not only to determine parameter values that reproduce the measured temperatures, but also to quantify the uncertainty associated with the simplified model representation so that it can be propagated to subsequent simulations within the digital twin. Directly estimating all uncertain quantities simultaneously would lead to strong correlations between geometric uncertainties, model parameters, and measurement noise. Such couplings can make the inference unstable and may obscure the physical interpretation of the resulting parameter estimates. For this reason, the identification is performed using a sequential calibration strategy, in which different groups of parameters are inferred in successive stages while previously estimated quantities are kept fixed. The resulting procedure, illustrated in the central panel of Fig. 2 (a), separates the inference problem into three phases. First, the effective sensor positions within the simplified cross-sectional model are identified in order to ensure geometric consistency between the monitoring system and the numerical model. Second, the thermal model parameters are inferred while accounting for the MFU associated with the simplified representation of the heat exchange mechanisms. Finally, the measurement noise is characterized individually for each sensor to capture differences in measurement variability across the monitoring system. This staged approach allows the different sources of uncertainty to be isolated and quantified in a controlled manner. An example for the posterior predictive for a virtual sensor situated at the southern side of the bridge is represented in Fig. 2 (b).

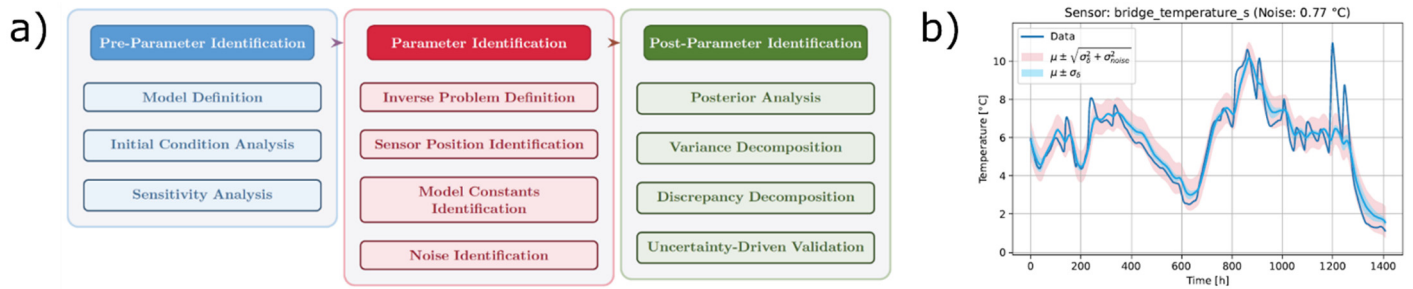


Fig. 2. (a) Diagram of the proposed parameter identification workflow; (b) example of posterior predictive confidence interval for the southern sensor.

The proposed framework adds new requirements to the parameter-updating process during the pre-parameter identification phase (Fig. 2 (a)). Specifically, it requires a careful analysis of the initial conditions and of how model parameters influence the system response over the period of interest. In return, the extended and updated model enables a substantially richer set of analyses in the post-parameter identification phase. In this stage, decomposing the sources of variance and discrepancy allows for a robust statistical validation of the model predictions.

3. Conclusion

Overall, the presented approach provides a systematic methodology for integrating model parameter updating and uncertainty quantification within a digital twin framework. By explicitly addressing the MFU and ensuring its consistent analysis and decomposition, the proposed methodology contributes to improving the credibility of simulation-based digital twins for infrastructure monitoring and decision support.

Acknowledgements

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The authors made use of ChatGPT to assist with the drafting of this abstract for the improvement of text clarity and grammar. All scientific content, ideas and interpretations originate from the authors.

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A surrogate model for approximating the load-bearing behavior of prestressed concrete bridges

Marie Otto^a, Bjarne Sprenger^a, Martina Schnellenbach-Held^a

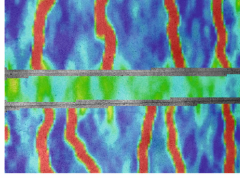
^a*Institut of Structural Concrete, University of Duisburg-Essen, Universitätsstraße 15, 45141 Essen, Germany*

Abstract

Due to continuously increasing loads especially from heavy goods vehicles damage to bridge structures is becoming increasingly apparent. The monitoring and maintenance of these structures poses a significant challenge in the field of civil engineering. Modern technologies such as Structural Health Monitoring (SHM) are used for continuous monitoring and early detection of damage. Finite element (FE) models can be integrated into the SHM, but adapting them can be computationally intensive. To reduce the computing time required to adapt the FE model to the real structure and thus increase efficiency, precise surrogate models based on classical mathematical approaches are used as an innovative solution. The validation structure is the Nibelungen Bridge in Worms, as part of the priority program 2388 “Hundred plus – Extending the Lifetime of Complex Engineering Structures through Intelligent Digitalization”, in which the mathematical approaches of artificial neural networks, Kriging metamodeling, and polynomial chaos expansion are validated.

Keywords: FE model updating; Kriging model; polynomial chaos expansion; surrogate model

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Quantitative damage progression analysis using globally aligned time-series 3D digital models

Hyunjin Bae^a, Yun-kyu An^{a,1}

^a*Department of Architectural Engineering, Sejong University, Seoul, 05006, South Korea*

Keywords: Time-series 3D digital models; quantitative damage progression; global coordinate system alignment; deep learning; digital twin

1. Introduction

The transition of Structural Health Monitoring (SHM) from condition assessment to predictive maintenance requires time-series "4D" digital twins (DTs) capable of modeling the continuous deterioration of aging infrastructure. Crack propagation, spalling expansion, and corrosion growth unfold over years, and the timing and rate of these changes have a decisive impact on maintenance planning. To continuously track these gradual phenomena, vision-based inspection utilizing unmanned aerial vehicles (UAVs) paired with deep learning has rapidly matured, delivering pixel-level damage maps with high accuracy (Azimi et al., 2020; Di Mucci et al., 2024; Plevris and Papazafeiropoulos, 2024). However, a critical obstacle impedes the creation of reliable 4D DTs: the spatial inconsistency across multi-temporal inspections. Due to wind gusts, GPS drift, and slight path deviations, no two UAV flights capture images from identical viewpoints, breaking the spatial consistency required for reliable trend analysis. Consequently, developing robust 4D DTs entails resolving two primary challenges: (1) accurately mapping high-precision 2D damage evaluation results onto 3D model surfaces, and (2) achieving robust alignment among 3D models obtained at different time points. Regarding the first challenge, several studies have attempted to project detection masks onto pre-built 3D mesh models (Liu et al., 2020; Pantoja-Rosero et al., 2023). However, the resulting damage maps inevitably inherit projection errors, as detection output merely overwrites RGB texture. Alternatively, some approaches have quantified damage on single-epoch point clouds through semantic segmentation (Xu et al., 2020; Zhang et al., 2019), yet these lack any mechanism for multi-temporal registration. In addressing the second challenge, Kong and Hucks (2023) compared photogrammetry-based 3D models at two epochs to track the deterioration of a historic bridge, while Lee et al. (2025) constructed fusion-based 3D models across three epochs by establishing GNSS and total-station reference points inside a tunnel. Nevertheless, neither approach maintains a consistent global coordinate frame without relying on ground control points (GCPs). Kong and Hucks (2023) is limited to a simple before-and-after comparison, and Lee et al. (2025) relies on repeatedly surveying the exact same physical reference points. Placing such control points at identical locations over discontinuous inspections spanning several years is practically infeasible for large-scale bridge infrastructure.

To address this technical challenge, this study proposes a GCP-free, camera-pose-based 4D digital twin modeling framework designed for the long-term quantitative tracking of structural damage. Four tightly coupled stages compose the pipeline: (1) multi-resolution deep-learning damage detection on raw UAV imagery; (2) 3D model reconstruction driven by camera poses estimated from the raw images, embedding damage information at the point-cloud generation step; (3) GCP-free alignment of every subsequent model directly to the initial baseline, eliminating sequential cumulative registration error from sequential pairwise alignments; and (4) spatiotemporal quantification of damage metrics within the unified coordinate system. Validation spans a 4.5-year campaign on an in-service concrete bridge pier in South Korea, with three acquisition epochs and a LiDAR-based ground-truth model.

¹ Corresponding author. Tel.: +82-2-3409-2426
E-mail address: yunkyu@sejong.ac.kr

2. Proposed framework

Fig. 1 outlines the end-to-end workflow. The raw vision images acquired by the UAV are initially processed through two parallel tracks. In the first track, a modified DeepLab v3+ network performs pixel-level segmentation of various damage types including cracks, spalling, rebar exposure, efflorescence, and corrosion. This is executed across two resolution scales, with the results fused and fine-tuned specifically for the target structure (Bae et al., 2025). Concurrently, the second track utilizes Structure-from-Motion (SfM) on the identical raw images to estimate the camera's intrinsic and extrinsic parameters, generating a sparse 3D point cloud.

To seamlessly fuse these two tracks, the finalized camera poses derived from the SfM process are preserved, while the raw RGB images are substituted with the 2D segmented damage maps as the input for Multi-View Stereo (MVS) densification. This critical substitution produces a dense 3D point cloud where the color attributes intrinsically encode the semantic damage labels. Subsequently, Poisson surface reconstruction converts this colorized cloud into a watertight mesh, which is finalized by projection-based texture mapping. By embedding the damage information directly during the point-generation phase, the geometric fidelity of the damage boundaries significantly surpasses that of conventional post-hoc texture reprojection methods.

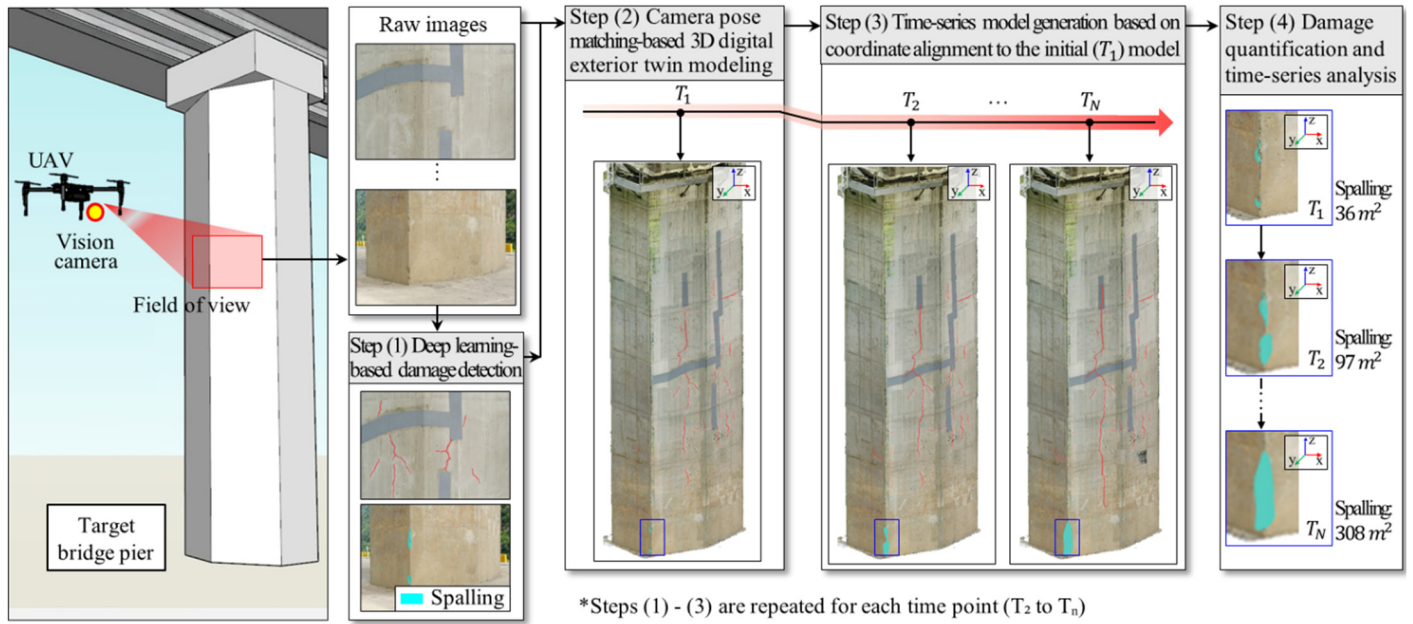


Fig. 1. Overview of the camera pose matching-based 3D digital exterior twin modeling technique for time-series damage analysis.

For time-series registration, the initial-epoch model serves as the reference frame. Each subsequent model is rigidly aligned to this baseline via an Iterative Closest Point (ICP) procedure seeded with corresponding point pairs on structurally invariant surfaces—bearing pads, column-cap interfaces, or construction joints that do not deform appreciably over the service life. No artificial GCPs are required. By strictly aligning each subsequent epoch back to the initial baseline model, sequential cumulative registration errors are structurally bypassed, ensuring that the spatiotemporal damage metrics extracted at each epoch are directly and quantitatively comparable.

3. Experimental validation

The proposed framework was validated through two sets of experiments. First, a lab-scale test using 3D-printed miniature pier models established baseline accuracy against known ground-truth geometry derived from CAD design files. Three model variants—T1, T2, and T3—were fabricated with progressively expanding damage patterns so that time-series progression could be evaluated under controlled conditions. Second, an in-situ field test on an actual bridge pier confirmed the practical applicability of the pipeline over a 4.5-year monitoring period with three acquisition epochs.

3.1. Lab-scale test

A 1/50-scale hexagonal pier model (0.26 m height, polypropylene, 2 mm wall) was 3D-printed in three variants—T1, T2, and T3—each carrying progressively larger spalling and crack patterns whose ground-truth (GT) dimensions are known from CAD design files. An iPhone 12 Pro captured images along a circular scanning path at 250–600 mm working distance (FOV 738×544 mm, 4032×3024 pixels). Table 1 compares the proposed framework against GT for spalling in Region 2. Volumetric underestimation stays within 9 % at T2 and improves to about 6 % at T3, while maximum-depth error ranges between 10 and 14 %. The table also reveals the time-series progression: spalling volume surges roughly 60-fold from T2 to T3, and the framework captures this dramatic growth quantitatively.

Table 1. Time-series spalling quantification of the lab-scale test (Region 2). Columns grouped under T2 and T3.

Metric	GT	Ours	Diff.(%)	GT	Ours	Diff.(%)
Volume (mm ³)	9,957.6	9,081.2	−8.80	605,379.9	570,115.0	−5.83
Max. depth (mm)	12.60	10.81	−14.21	14.02	12.67	−9.63

3.2. Field test

A 13-m hexagonal bridge pier of the Deung-Seon Bridge in Chuncheon, South Korea, was inspected three times: July 2019 (T1), December 2022 (T2), and January 2024 (T3). A DJI Matrice 300 UAV with Zenmuse H20T camera flew a vertical scanning path at 3–7 m standoff (7952×4472 pixels). A Leica BLK 360 LiDAR scanner captured a reference point cloud from twelve stations. The multi-resolution detection network achieved an average F1-score of 92.9 % across scaling, crack, and rebar-exposure classes, confirming robust transferability to in-situ conditions.

After coordinate alignment, the spalling volume estimated by the pipeline differed from LiDAR GT by only −2.89 %. In repaired regions, the measured surface depth dropped from 3–4 mm to less than 1 mm between T1 and T2, validating both detection and alignment accuracy. In an unrepaired crack zone, endpoint coordinates indicated steady growth of 4–11 mm over 4.5 years, with notable acceleration between T2 and T3. These results demonstrate that the framework reliably quantifies both damage restoration and progressive deterioration within a single unified coordinate system.

4. Conclusion

This paper presented a camera-pose-based 3D digital exterior twin modeling framework that enables GCP-free quantitative comparison with minimized registration error through global coordinate unification of structural surface damage across multiple inspection epochs. The key contributions are: (1) a precise 2D-to-3D semantic mapping workflow that embeds damage information at the point-cloud generation step; (2) a robust GCP-free registration framework aligning all models to a single baseline; (3) transformation from one-time snapshots to continuous quantitative damage evaluation; (4) a fully automated and scalable pipeline from raw UAV imagery to spatiotemporal metrics; and (5) a rare, multi-year 3D dataset for real-world validation spanning 4.5 years. Lab-scale experiments confirmed volumetric accuracy within 6–14 % and captured a 60-fold spalling growth. Field validation demonstrated volume estimation within 3 % of LiDAR GT and tracked millimeter-level crack growth with acceleration patterns invisible to 2D analysis. It should be noted that the GCP-free alignment relies on the assumption that the reference surfaces such as pier bases and cap beams undergo negligible displacement during the monitoring period, which generally holds for ordinary service conditions but may not apply to structures subjected to seismic events or significant foundation settlement. Future work will extend the pipeline to other infrastructures such as tunnels, dams, and road pavements, while pursuing higher-resolution reconstruction techniques for precise crack width quantification.

Acknowledgements

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Fatigue life prediction for steel bridges using digital twins and structural health monitoring

Christoph Brenner^a, Marc Müggenburg^a, Stefan Vogts^a, Klaus Thiele^a, Julian Unglaub^a

^a Technische Universität Braunschweig, Institute of Steel Structures, Beethovenstraße 51, 38106 Braunschweig, Germany

Abstract

Aging transportation infrastructure requires reliable predictive maintenance to preserve safety and serviceability. Particularly, steel bridges with orthotropic steel decks present distinct challenges. Their complex welded geometries create numerous potential crack initiation sites, which are difficult to monitor using point sensors or periodic visual inspection. This study evaluates how structural health monitoring (SHM) can address these challenges by integrating distributed fiber optic sensors (DFOS) together with data-driven methods and a simulation-based digital twin (DT). The objective is to detect, monitor, and evaluate fatigue cracks in representative welded notch details, and to predict the remaining service life to support the timely planning and execution of maintenance and rehabilitation measures. Therefore, a welded T-joint specimen is fabricated and subjected to controlled uniaxial cyclic tensile loading to initiate and propagate fatigue damage. DFOS provide spatially distributed strain profiles along the specimens, while a finite element-based DT assimilates the measured data to update the structural state and assess the damage extent. The remaining service life is estimated based on linear elastic fracture mechanics (LEFM). Results indicate that DFOS can localize damage and provide consistent inputs for the DT. The DT framework yields remaining life estimates that are consistent with the observed performance of the physical asset under cyclic loading. Integrating DFOS with data-driven and physics-based models shows promise for fatigue assessment in complex welded steel details and supports condition-based maintenance of orthotropic steel decks. Ongoing work focuses on scaling the DT framework to larger components and validating the performance on full-scale bridges under operational conditions.

Keywords: Steel bridges; digital twin; fatigue life prediction; distributed fiber optic sensing; finite element modeling

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Service life prediction of reinforced concrete structures using 2D-FOS

Till Wellmann^a, Henrik Becks^a, Martin Classen^a

^aInstitute of Structural Concrete, RWTH Aachen University, Im Süsterfeld 9, 52072 Aachen, Germany

Abstract

Reliable service life prediction of reinforced concrete (RC) structures requires a thorough understanding of damage evolution under repetitive subcritical loading. Although numerical models have become increasingly capable of simulating structural behavior, full-scale analyses remain computationally demanding. In addition, uncertainties in loading history and material properties often obscure the actual strain and stress distributions within these models. Consequently, assessing remaining service life usually relies on time-consuming visual inspections of concrete surfaces. To overcome these limitations, continuously acquired strain data from autonomous measurements must be integrated into physical service life prediction models. Incorporating such real-time information significantly enhances the accuracy and reliability of structural condition assessments. Building on this premise, the authors have developed a monitoring strategy employing two-dimensional distributed fiber optic sensors (2D-FOS) applied to the concrete surface for precise, strain measurements. Based on these measurements, automated algorithms for strain visualization, crack detection, crack width calculation, and two-dimensional crack mapping have already been successfully implemented. The next step toward automated service life prediction involves integrating physical models that capture the relationship between tensile fatigue behavior of concrete and strain evolution. This paper presents preliminary experimental results investigating this relationship and proposes a strain based concrete service life prediction method until crack initiation using 2D-FOS.

Keywords: Reinforced concrete (RC); fatigue damage assessment; distributed fiber optic sensing (FOS); service life prediction; structural health monitoring (SHM)

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

Monitoring of chloride-induced corrosion in reinforced concrete beams under sustained load using embedded corrosion sensors and distributed fiber optic sensing

M. Macier^a, T. Leusmann^a, D. Lowke^b

^a *Institute of Building Materials, Concrete Construction and Fire Safety (iBMB), Technische Universität Braunschweig, Germany*

^b *Chair of Materials and Methods in Digital Construction, Technical University of Munich, Germany*

Abstract

The existing bridge infrastructure in Germany and across Europe faces significant challenges due to increasing traffic loads and ageing. Advanced monitoring approaches are increasingly employed to integrate time-dependent condition data into service life prediction models, enabling optimized maintenance planning. The present study experimentally investigates chloride ingress into reinforced concrete beams under sustained loading. Corrosion sensors, including anode ladders and wire sensors, together with Distributed Fiber Optic Sensing (DFOS) technology, provided data on both chloride ingress depth and strain conditions. The objective was to examine how sustained mechanical loading combined with chloride exposure influences corrosion initiation in reinforced concrete. The investigation revealed that microcracks below 100 μm significantly reduce the time to corrosion initiation, with values decreasing from several hundred hours in uncracked concrete to less than 4 h for crack widths of 33 μm . Apparent chloride penetration coefficients derived from the measurements exceeded the effective diffusion coefficients of uncracked concrete by up to two orders of magnitude. Furthermore, a nonlinear relationship between crack width and transport acceleration was identified, expressed by a crack influence coefficient following a power-law with an exponent greater than 2.

Keywords: Monitoring, chloride-induced corrosion, microcracks, chloride ingress, service life prediction

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Analysis of German bridge inventory data for systematic recognition of damage patterns

Cedric Eisermann^a, Jakob Vogt^a, Maria Walker^a, Steffen Marx^a, Chongjie Kang^a

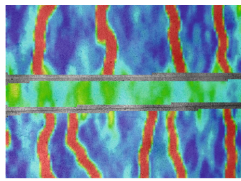
^a *TUD University of Technology Dresden, George-Bähr-Straße 1, 01069 Dresden, Germany*

Abstract

Most German prestressed concrete (PC) bridges were constructed between 1960 and 1980. Since PC construction was still in its infancy at the time, several deficiencies in bridges from this era have become apparent based on current knowledge. A particular concern pertains to the fatigue of prestressing steel at coupling joints, often referred to as “coupling joint problem” (CJP). The issue primarily stems from the design characteristics of coupling joints during that period. Although considerable knowledge about CJP exists today, the exact number of affected structures remains unknown. This study utilized data from the German bridge management system to implement a supervised learning approach using eXtreme Gradient Boosting (XGBoost) to identify PC bridges with CJP based on general bridge features (e.g., age, span length). The developed model achieved an accuracy of 85.2% in training and 83.2% in testing for the classification of the coupling joint status. In testing, 47 out of 65 PC bridges with CPJ were correctly identified. Additionally, the influence of specific bridge features was analyzed by Shapley Additive Explanation (SHAP) values. The average daily traffic volume, bridge age, and construction height were identified as the most influential features. The results highlight the potential of machine learning in maintenance management and risk assessment for PC bridges. However, they also demonstrate that general bridge features alone are insufficient for reliably predicting CJP.

Keywords: Pre-stressed concrete bridges; inventory data; coupling joints; feature selection; XGBoost

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Assessing the value of monitoring for waterways infrastructure

Francesca Marsili^{a,1}, Leandro Iannacone^b, Pietro Croce^c, Sylvia Keßler^a

^aHelmut-Schmidt University / University of the Federal Armed Forces Hamburg, Holstenhofweg 85, 22043 Hamburg, Germany

^bLund University, Box 117, 221 00 Lund, Sweden

^cUniversity of Pisa, Largo Lucio Lazzarino 2, 56126 Pisa, Italy

Keywords: Value of information, Bayesian updating, waterways infrastructure, structural health monitoring

1. Introduction

A new construction typology for navigation locks is currently being investigated, which involves the use of precast elements (Fig. 1) (Lühr et al. 2023). This approach enables a higher degree of standardization, improved execution quality, and reduced uncertainty during construction. However, uncertainties related to the lifecycle behavior of the structure remain, particularly during the operational phase, when the lock chamber walls are subjected to cyclic loading. Consequently, one of the most critical damage mechanisms is the fatigue of reinforcing steel bars. Stress amplitudes are typically evaluated using finite element analysis and compared with the maximum allowable stress amplitude for a given number of load cycles.

Precast elements can be equipped with Structural Health Monitoring (SHM) systems to monitor structural performance during operation. Relevant monitoring parameters are strains, which provide information about the stress state of the structure. Among the available sensing technologies, fiber optic sensors are of particular interest. However, their implementation is associated with significant costs. These costs arise not only from the sensors themselves but also from the interrogator units required to acquire and process the measurements. In addition, the measurements are subject to uncertainty, including measurement errors.

An important preliminary step before installing costly SHM systems is assessing their economic benefit. Their main advantage lies in supporting improved lifecycle decision-making, such as extending or shortening the service life of a structure in response to fatigue in the reinforcement steel. The benefit of SHM systems can be quantified using the Value of Information (VoI) concept.

(VoI) (Ang & Tang 2006).

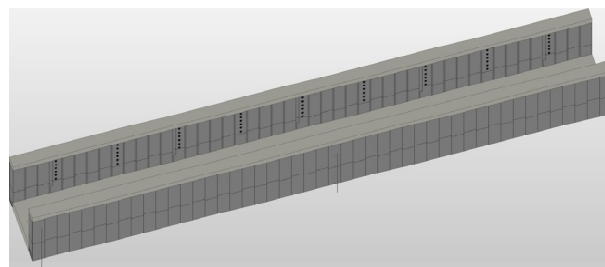


Fig. 1. REVIT® model of the navigation lock in precast elements.

2. Research idea

This work presents an approach to assess the VoI for a navigation lock constructed with precast elements and equipped with a SHM system, namely fiber optic sensors. The scope of the SHM system is to collect data about the stress amplitude in the steel

¹ Corresponding author. Tel.: +49 (0)40 6541 2961
E-mail address: marsilif@hsu-hh.de

reinforcements of the lock chamber walls, which are subject to cyclic loads. The influence of uncertainties affecting the input parameters on the VoI is explicitly considered through a sensitivity analysis.

3. Methods

Decision-event tree. The decision-event tree is a graphical tool which supports the modelling and structuring of decisions problems in which decisions alternatives have random outcomes. It is characterized by nodes and branches. Nodes can be related to decision (indicated with a square) or random events (indicated by a circle). Outgoing branches represent the number of decision alternatives or random outcomes, respectively. While decision alternatives are usually in a finite number, random outcomes might be infinite (as in the case of continuous random variables). Branches representing random outcomes are associated with probabilities (Ang & Tang 2006). Each sequence of branches resulting from decision and random event represents a path within the decision-event tree and it is associated with some consequences. These consequences can be different unit measures; however, they can be often expressed in monetary terms, i.e. they are monetary utilities or costs.

Bayesian updating. The Bayes Theorem allows updating probabilities when data is collected. It requires the following steps: 1) to define the prior probability; 2) to define the likelihood of the data; 3) to compute the evidence, which expresses the marginal likelihood. By multiplying the prior probability $p(x)$ for the likelihood $p(d|x)$ and dividing for the evidence $p(d)$, which is essentially a scaling factor, the posterior probability $p(x|d)$ is obtained (Ang & Tang 2006)

$$p(x|d) = \frac{p(d|x)p(x)}{p(d)} \quad (1)$$

The evidence $p(d)$ requires the computation of a sum if probabilities are discrete or an integral if they are continuous:

$$p(d) = \begin{cases} \int p(d|x)p(x)dx & \text{if } x \text{ is continuous} \\ \sum p(d|x)p(x) & \text{if } x \text{ is discrete} \end{cases} \quad (2)$$

The computation of the integral is usually not straightforward. An exception is represented by the case in which the prior distribution and the likelihood function belong to certain distribution families. In such circumstances, namely in the case of prior distribution which are conjugate to the posterior through the likelihood, the evidence, and thus also the posterior distribution can be computed in closed form.

An analysis based on prior probabilities is usually called prior analysis, while one based on a test result or data collected leading to posterior probabilities is called posterior. It is also possible to perform a pre-posterior analysis: this analysis is based on all the possible test results and their probability, as well as the posterior probability resulting from each data.

Expected monetary value. Regardless of whether the probabilities are prior or posterior, they allow us to compute the expected monetary value (EMV) of a decision alternative a_i , which is defined as follows (Ang & Tang 2006)

$$EMV(a_i) = \sum_j p_{ij}c_{ij} \quad (3)$$

where c_{ij} is the consequence j linked to the decision alternative i and p_{ij} is the probability of the consequence j linked to the decision alternative i . The optimal alternative a_{opt} is the one which maximizes the EMV

$$a_{opt} = \max_i EMV(a_i). \quad (4)$$

Value of Information. The VoI is defined by considering the EMV of the best alternatives linked to the possible test results, and by subtracting from it the EMV of the optimal alternative before a test is performed or data is acquired (Ang & Tang 2006)

$$VoI = EMV(T) - EMV(a_{opt}). \quad (5)$$

In general, the assessment of the VoI requires to perform a preposterior analysis, that is, to consider all possible test results with their associated probabilities, and the related optimal decisions.

4. Application

The VoI is used to assess the value of monitoring the stress amplitude in reinforcing steel bars in lock chamber walls subjected to cyclic loading, using fibre optic sensors. The decision-event tree is shown in Fig. 2. It begins with a decision node with two options: to monitor or not to monitor the structure. The decision node is followed by another decision node, characterized by three possible decision options, which are: 1) to extend, 2) to shorten or 3) to leave unchanged the service life of the structure. Each

decision options is associated to a different number of cycles at failure. The state of the structure is represented by the stress amplitude in the steel reinforcements caused by the cyclic loads. The stress amplitude is affected by uncertainties and modelled as a continuous random variable. Therefore, the state of the structure is represented as a chance node. This node is followed by another chance node, which represents the failure event. A failure event takes place when the stress amplitude in the steel reinforcements exceeds the stress amplitude corresponding to the number of cycles at failure. This last stress amplitude is determined by using the Wöhler curve, also considering the uncertainties in the regression parameters, resulting into a random variable. In case of monitoring, artificial measurements are simulated by considering the distribution of the stress amplitude and the measurement error which characterize fibre optic sensors. The prior distribution assumed for the stress amplitude is updated according to the simulated measurements.

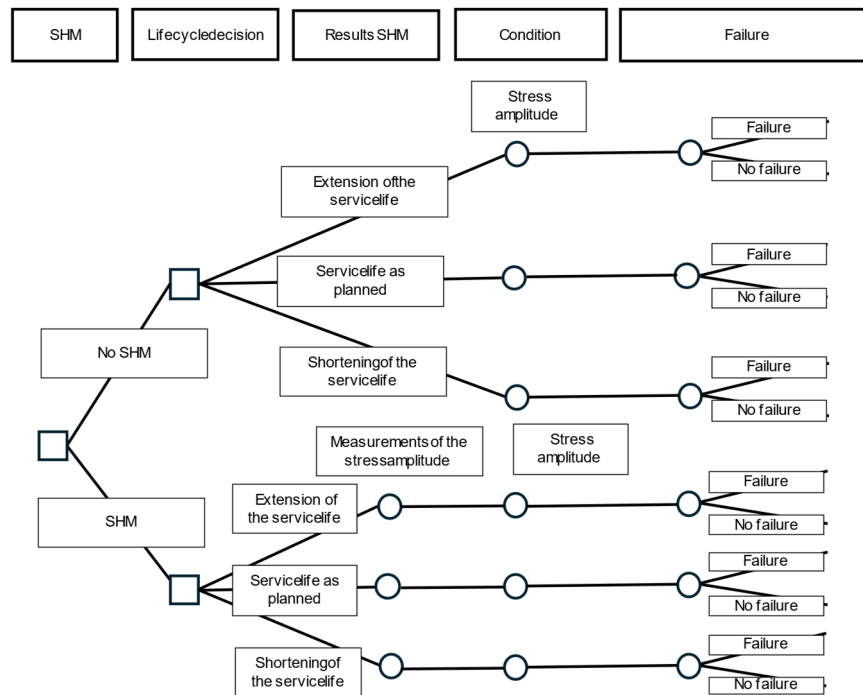


Fig. 2. Decision-event tree to assess the VoI for the lock chamber in precast element equipped with fiber optic sensors.

The consequences of the actions are reflected in different levels of depreciation of the lock construction cost. The consequences of failure include both structural failure impacts and operational interruption losses. Uncertainties affecting these costs, as well as different service life extension or shortening options, are considered by performing a sensitivity analysis. The VoI is computed for each possible combination of parameter values.

5. Conclusion and outlook

In this work, the VoI analysis for the monitoring of a new construction typology, a navigation lock in precast elements, is performed. The analysis supports the planning of the SHM system for the structure, in particular the application of fibre optic sensors to monitor the stress amplitude due to cyclic loads. Since the input parameters for the VoI analysis (namely the cost of the lock construction as well as direct and indirect costs of lock structural failure) are affected by uncertainty, a sensitivity analysis is performed. An additional research path can be the quantification of the uncertainty affecting the stress amplitude by performing a probabilistic Finite Elements (FE) analysis.

Acknowledgements

The authors gratefully acknowledge the financial support provided by Bundesanstalt für Wasserbau (BAW) within the framework of the research project „Automatisierte Datenerfassung zur ganzheitlichen Bauprozess- und Lebenszyklusmanagement-optimierung unter Einsatz von Fertigteilen beim Bau massiver Verkehrsbauwerke mit Kopplung an die BIM-Methodik – Beispiel am theoretischen Projekt einer massiven Schleuse im Binnenbereich“.

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Strain distribution in stacked specimens under static and cyclic mechanical loading

Hanna Schiewe^a, Martin Markert^a, Veit Birtel^a, Mohamed Abubakar Ali^b, Michael Haist^{a,b}

^a*Materials Testing Institute, University of Stuttgart, Pfaffenwaldring 4d, 70569 Stuttgart, Germany*

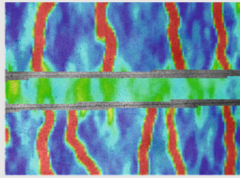
^b*Institute of Construction Materials, University of Stuttgart, Pfaffenwaldring 4, 70569 Stuttgart, Germany*

Abstract

The time-dependent deformation behavior of concrete, in particular creep, has a significant influence on the serviceability and durability of creep-sensitive structures such as prestressed concrete bridges. A realistic description of creep behavior however requires considerable experimental time and resources. To reduce this effort, creep setups were developed in the past, allowing multiple specimens - typically three - to be stacked and loaded under identical loading conditions. This approach, however, is afflicted with various drawbacks, as influences from eccentricities, which may significantly influence the creep behavior. Even more so, for dynamic tests conducted at cyclic-mechanical loadings, the mechanical behavior of the dry joints between the individual specimens is unknown. It is therefore essential, that all samples are subjected to identical mechanical loading as well as a uniform stress distribution over the specimen's cross section. An optical measurement method is being used in addition to standard strain gauge measurements to experimentally investigate this subject. Comprehensive, high-resolution measurement allows stress and strain distributions to be analyzed precisely during cyclic mechanical creep testing. The objective is to experimentally verify the uniformity of load distribution and thus evaluate the reliability of stacked specimens in a testing machine. The results provide a foundation for the further development of efficient creep testing methods under cyclic mechanical and hygric loading and contribute to an improved assessment of the long-term behavior of concrete.

Keywords: Cyclic-mechanical loading; stacked specimen; eccentricity; fiber optic

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MS14: Post-disaster bridge assessment – an integrated approach from monitoring to number crunching

Organizers:

Michael Polter (TU Dresden, Germany)

Karsten Menzel (TU Dresden, Germany)

Tobias Mansperger (Leonhardt, Andrä und Partner Beratende Ingenieure VBI AG, Germany)

ABSTRACT

The immediate and accurate assessment of bridge integrity following a disaster is critical for public safety and rapid response. This Mini Symposium explores an integrated workflow, from initial rapid damage detection to detailed structural analysis. Featuring the latest research and practical insights, the session brings together experts from software development, advanced geospatial surveying, and engineering. Presentations will cover cutting-edge technologies, including rapid UAV-based reconnaissance, innovative sensor applications, and powerful numerical modelling software. Discover how the seamless integration of data acquisition and computational “number crunching” is revolutionizing post-disaster engineering, enabling faster, more reliable decisions for emergency managers and engineers to enhance community resilience.

UAV-based data acquisition for structural digital twins

Emilie Lüdicke^a, Maximilian Alt^a, Frank Pöhlmann^a, Michael Polter^b

^a*Cloud-Vermessung + Planung GmbH, 91438 Bad Windsheim, Germany*

^b*Technische Universität Dresden, 01062 Dresden, Germany*

Abstract

The rapid and accurate geometric capture of structures remains a key challenge in structural assessment, with conventional methods often providing incomplete data that cannot be seamlessly integrated into structural analysis. This paper presents a practical workflow for UAV-based structural assessment, focusing on the generation of a geometric foundation for subsequent structural analysis and the spatial integration of detailed inspection imagery for digital structural models. Initial reconnaissance flights were carried out to gather preliminary data, which informed the manual planning of detailed survey missions using established flight-planning software. Different UAV platforms and sensor configurations were evaluated regarding data quality and processing performance to identify suitable approaches for geometric modeling. In addition, detailed close-range photographs were captured for selected components to document potentially relevant surface damages such as cracks or spalling. The localization accuracy of these images and their integration into a building information model were evaluated. Demonstrated on a motorway bridge, the methods contributed essential UAV-based data and practical insights for establishing a foundation for structural digital twins.

Keywords: UAV-based structural assessment; UAV photogrammetry; point cloud processing; damage documentation; digital structural twin

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An IFC 4.3 ontology hidden damages framework and Python ingestion pipeline for hidden bridge damage representation

Mukta Nisal^a, Karsten Menzel^a

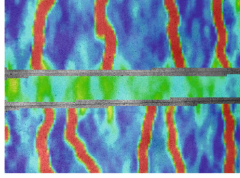
^a*Institute of Construction Informatics (Bauinformatik), Technische Universität Dresden, 01062 Dresden, Germany*

Abstract

Hidden deterioration mechanisms in bridge structures such as reinforcement corrosion, internal delamination, chloride-induced degradation, fatigue micro-cracking, and moisture-driven distress represent a major source of structural uncertainty in aging infrastructure systems. While modern bridge management increasingly relies on digital twins and Building Information Modeling (BIM), existing IFC-based bridge models remain predominantly geometry-centric and lack formal representation of subsurface or probabilistic deterioration phenomena. As a result, inspection data, nondestructive testing (NDT) results, and sensor measurements are typically stored in disconnected systems without semantic interoperability. This paper presents a comprehensive ontology-based extension aligned with IFC 4.3 (ISO 16739-1:2024) to enable structured, machine-interpretable representation of hidden bridge damages. The proposed framework introduces a semantic damage layer linked to IFC elements via persistent GlobalIds and structured around a causal reasoning chain: DamageObservation, Symptom, Damage Process, StructuralConsequence. SHACL-based validation and SPARQL-driven inference mechanisms ensure logical consistency and traceable damage-to-capacity relationships. The resulting hybrid architecture forms a damage-aware digital twin capable of lifecycle deterioration tracking, rule-based reasoning, and interoperable exchange without modifying the IFC schema.

Keywords: Bridge asset management; digital twins; IFC 4.3; semantic interoperability; ontology-based modeling; hidden deterioration mechanisms

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Damage detection with statFEM-VFM

Andrea Morini^{a,1}, Jorge-Humberto Urrea-Quintero^a, Henning Wessels^a

^a*Division Data-Driven Modeling of Mechanical Systems, Institute of Applied Mechanics, TU Braunschweig, Germany*

Keywords: Damage detection; virtual fields method; statistical finite elements

1. Introduction

Structural health monitoring (SHM) systems generate large volumes of datasets which are commonly analyzed using data-analytics. While such approaches have proven effective in identifying the current (“as-is”) structural condition, they often lack robust prognostic capabilities. In particular, purely data-driven methods struggle to extrapolate beyond observed conditions or to provide physically interpretable predictions of future structural performance. The problem of providing accurate predictions of structural health can often be formulated as the identification of structural damage and, in a physics-based modeling framework, this task can be interpreted as a parameter identification problem.

In this setting, damage identification is naturally formulated as an inverse problem. A well-established approach for this purpose is the virtual fields method (VFM) by Pierron and Grédiac (2012), which allows unknown parameters to be identified directly from the virtual work equation based on measured displacement fields. For dense and low-noise data, VFM is particularly attractive because it is both direct and computationally efficient. However, these requirements are often difficult to meet in real SHM applications, where sensor data are typically sparse and affected by measurement noise. In this sense, the Bayesian-based statistical framework for data assimilation (statFEM) by Girolami et al. (2021) and Narouie et al. (2023) is a prominent framework for handling imperfect data. This framework reconstructs the full displacement field from sparse observations by combining the data with a prior mechanical model.

In the present work, statFEM is coupled with the virtual fields method (VFM) to perform damage identification from sparse and noisy displacement measurements in a notched specimen under uniaxial tension. More specifically, statFEM is first applied to reconstruct the full displacement field from limited sensor observations, while VFM is subsequently employed to identify the unknown damage parameter governing the degradation of the material stiffness. In this way, the proposed framework combines the robustness of Bayesian data assimilation with the computational efficiency of the inverse identification step. Instead of applying VFM directly to noisy and incomplete measurements, the statFEM step provides an assimilated displacement field that significantly improves the reliability and accuracy of the subsequent parameter identification. This relaxes the need for dense and low-noise measurements, while avoiding the repeated parameter sampling typically required in fully Bayesian identification methods.

2. Methodology

Let us consider a boundary value problem:

$$\nabla \cdot \boldsymbol{\sigma} = \mathbf{0} \quad \text{in } \Omega; \quad (1a)$$

$$\mathbf{u} = \mathbf{0} \quad \text{on } \Gamma_D; \quad (1b)$$

$$\boldsymbol{\sigma} \cdot \mathbf{n} - \bar{\mathbf{t}} = \mathbf{0} \quad \text{on } \Gamma_N; \quad (1c)$$

¹ Corresponding author. Tel.: +49 531/391 - 94357
E-mail address: andrea.morini@tu-braunschweig.de

Ω denotes the body domain, with boundary $\partial\Omega = \Gamma_D \cup \Gamma_N$ and $\Gamma_D \cap \Gamma_N = \emptyset$. $\mathbf{u}$ represents the displacement of the body; σ the stress; and $\bar{\mathbf{t}}$ the applied traction force, and $\mathbf{n}$ the outward unit normal vector to the Neumann boundary Γ_N .

Eqs. (1b) and (1c) represent the Dirichlet and the Neumann boundary conditions, respectively. The material behavior is governed by the elastic strain energy density function:

$$\Psi(\varepsilon) = \frac{K_d}{2} (\text{tr } \varepsilon)^2 + G_d \varepsilon^{dev} : \varepsilon^{dev} \quad (2)$$

$$\text{with } \varepsilon^{dev} = \varepsilon - \frac{1}{3} (\text{tr } \varepsilon) \mathbf{I}$$

where ε is the infinitesimal strain tensor and ε^{dev} denotes its deviatoric part. Here, $\mathbf{I}$ is the second order identity tensor.

The quantities K_d and G_d denote the damage-dependent bulk and shear moduli, respectively, with their dependence on the damage variable $d \in [0, 1]$ prescribed by the chosen degradation law. The stress is obtained from the strain energy density as:

$$\sigma = \frac{\partial \Psi(\varepsilon)}{\partial \varepsilon} \quad (3)$$

Before proceeding, we emphasize that the material parameters in Eq. (2) are treated as unknown. The deterministic system in Eq. (1) is therefore augmented to account for uncertainty, which is introduced through the boundary conditions by modeling the applied traction as a Gaussian random variable:

$$\bar{\mathbf{t}}_a \sim \mathcal{N}(\bar{\mathbf{t}}, \Sigma_t) \quad (4)$$

Here, $\bar{\mathbf{t}}_a$ denotes the random applied traction, $\bar{\mathbf{t}}$ its mean value, and Σ_t its covariance matrix. The resulting uncertainty is propagated through the finite element model using a non-intrusive polynomial chaos expansion (PCE), which provides a computationally efficient surrogate representation of the stochastic displacement response. This enables the estimation of the predictive mean and variance of the displacement field which are used to compute the updated value of the displacement given the observations data from the sensors.

We employ then the coupled statFEM-VFM framework introduced before by Narouie et al. (2026) to infer the value of the damage parameter d from sparse displacement measurements, following the pipeline here defined:

1. Sample traction forces from a distribution that reflects the uncertainties in the reaction forces.
2. Query the FEM black box and propagate the uncertain traction to the forecasted displacements using a non-intrusive PCE.
3. Check whether the root mean square error (RMSE) between the measurement and the forecasted displacement is sufficiently small:
 - (a) If yes, the algorithm has converged and the current material model represents the best fit.
 - (b) If not, proceed to Step 4.
4. Perform Bayesian updating of the forecasted displacements using the observations to obtain the full-field assimilated displacements.
5. Using the mean of the assimilated displacement field, identify the damage variable d using the VFM.
6. Return to Step 1 and repeat the procedure until the convergence condition (RMSE) in Step 3(a) is satisfied.

As test case, we will consider a notched specimen subject to uniaxial tension. Sensors providing sparse displacement data are located along the axis shown by Fig. 1.

3. Discussion

Synthetic fiber optic sensor (FOS) data are generated through finite element simulations using healthy and damaged material parameters. Gaussian white noise with standard deviation $\sigma_e = 2.5 \times 10^{-4}$ is added to reproduce realistic experimental conditions.

The material is assumed to be weakened within an unknown region Ω_{dm} . The healthy state is recovered in the absence of damage, i.e., $\Omega_{dm} = \emptyset$, for which the material parameters are identified as the healthy moduli G_h and K_h .

Since the exact location of Ω_{dm} is unknown, we introduce a hypothesis regarding a specific subregion of the domain, referred to as the vulnerable region Ω_{vl} , such that $\Omega_{dm} \subseteq \Omega_{vl}$.

Within this region the shear and bulk modulus are both scaled by a damaged parameter d :

$$G_d(\mathbf{x}) = d(\mathbf{x}) \cdot G_h$$

$$K_d(\mathbf{x}) = d(\mathbf{x}) \cdot K_h$$

$$\forall \mathbf{x} \in \Omega_{vl}$$

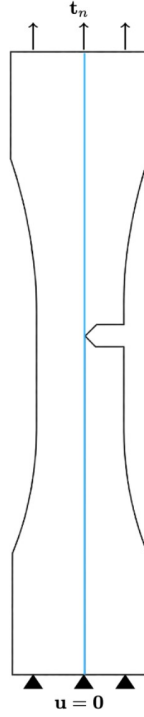


Fig. 1. Sensor placement of an uniaxial tension test of single-notched specimen.

With this formulation, the damage detection problem can be interpreted as a calibration task, where the only unknown is the damage parameter d .

The statFEM-VFM framework is initialized with $d = 1$ in Ω_v and is expected to iteratively converge to a value lying in between the healthy state ($d = 1$) and the damage level used to generate the synthetic data in Ω_{dm} . The results to be presented at the conference, confirm these assumptions.

4. Outlook

The present work demonstrates the capability of the Bayesian-based statFEM-VFM framework to efficiently calibrate unknown parameters in a damage detection setting, considering sparse and noisy measurements data. The obtained results are promising, showing that the framework is able to identify spatial variations of the damage parameter d within the physical domain and to predict to quantify the stiffness degradation caused by damage within the domain.

This opens new perspectives for damage identification and localization using the coupled statFEM-VFM approach, which can lead to further extension towards damage localization, including inhomogeneous damage factors or more complex material behavior.

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Continuous coda wave based monitoring of the Nibelungenbrücke Worms

Niklas Epple^{a,b}, Julia Hau^{a,b}, Daniel Fontoura Barroso^{a,b}, Sven Focht^{a,b}

^a*Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87 12205 Berlin, Germany*

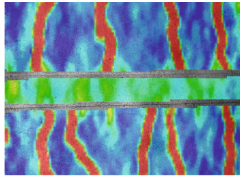
^b*Spree Monitoring GmbH, Germany, Unter den Eichen 87 12205 Berlin, Germany*

Abstract

Active ultrasonic monitoring techniques such as coda-wave interferometry (CWI) have proven highly sensitive and robust for structural health monitoring (SHM) in laboratory studies and real structures. To pave the way for commercial adoption, verification against established, commercially applied monitoring approaches on full-scale installations is required, using long-term data under operational conditions. We report on an installation on the cantilever of the Nibelungenbrücke (Worms, Germany), where we embedded 30 ultrasonic transducers and ten temperature sensors in the sidewall and floor of a prestressed box girder, alongside other commercial and research monitoring systems. A custom-made measurement device has collected ultrasonic waveform data since the sensor installation in October 2025. We present first results showing a clear temperature sensitivity of 0.03–0.04%/°C with a defined temperature influence corridor, a detectable velocity drop of 0.05–0.1% following a controlled tendon cut, and a stress-strain distribution under load consistent with static calculations. The results demonstrate the potential of CWI for permanent bridge monitoring and identify the need for improved spatial analysis using inversion methods and shorter measurement intervals to detect spontaneous damage. Long-term cross-validation with co-installed monitoring systems will be a key next step towards integration of CWI into applied SHM strategies.

Keywords: Coda-wave interferometry (CWI); structural health monitoring (SHM); ultrasonic monitoring; bridge monitoring

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Physics-informed transformer for real-time bridge deflection estimation using sensor fusion

Youn Sang Cho^a, Yun-Kyu An^{a,1}

^a*Department of Architectural Engineering, Sejong University, Gwangjin-gu, Seoul, 05006, South Korea*

Keywords: Bridge deflection; inclinometer-accelerometer fusion; transformer; physics-informed model; real-time bridge monitoring

1. Introduction

Continuous and precise monitoring of bridge deflection is a fundamental requirement for assessing the structural integrity and load-carrying capacity of aging infrastructure. Structural deflection has traditionally been measured directly using sensors such as linear variable differential transformers (LVDTs) or laser Doppler vibrometers. However, installing fixed reference points poses significant logistical challenges for bridges that cross rivers, valleys, or highways. Consequently, field measurements are frequently limited to temporary or periodic inspections, which fall short of the requirements for real-time structural health monitoring.

To overcome the limitations associated with fixed-reference deflection measurements, indirect estimation methods that utilize single sensor types, such as accelerometers or inclinometers, have been extensively investigated. Accelerometers are highly responsive to high-frequency dynamic behavior. However, deriving displacement through double integration of acceleration induces significantly low-frequency drift errors owing to inherent measurement noise. Alternatively, inclinometers can capture quasi-static deformations and low-frequency responses with high stability; however, they suffer from relatively low sampling rates and are inadequate for capturing transient dynamic effects.

Recognizing these technical barriers, recent studies have focused on sensor fusion techniques to combine the complementary frequency characteristics of acceleration and inclination data. Conventional algorithms, such as the Kalman filter and multi-rate state observers, have been widely adopted as standard solutions. However, these analytical methods are heavily dependent on predefined linear mathematical models and often struggle to handle complex nonlinear spatiotemporal noise, resulting in undesirable phase lags or residual drifts under various operating conditions.

To address these limitations, this study proposes a novel deep learning-based sensor fusion framework that utilizes a physics-informed frequency-enhanced decomposed transformer (FEDformer). By embedding kinematic relationships into the frequency-enhanced mechanisms of the model, the proposed framework effectively fused heterogeneous data from accelerometers and inclinometers. This study presents a comprehensive experimental validation conducted on a laboratory-scale beam, with a comparative analysis with a Kalman filter to evaluate the effectiveness of the proposed approach.

2. Methodology

2.1. Sensor fusion framework

The proposed strategy exploits the accurate low-frequency data of inclinometers and the reliable high-frequency components of accelerometers to overcome integration drift and low sampling rates. Full-bandwidth deflection can be reconstructed by synchronizing these heterogeneous data streams. Once the training is complete, the FEDformer can independently estimate the displacements across multiple spatial nodes without the need for fixed reference points during the actual monitoring phase.

¹ Corresponding author. E-mail address: yunkyu@sejong.ac.kr

2.2. Physics-informed FEDformer

The FEDformer architecture, which incorporates a frequency-enhanced attention mechanism, was employed to effectively process these heterogeneous multi-rate signals. This makes it exceptionally well suited for our fusion task, as it can explicitly separate and learn the low-frequency trend components from inclinometers and high-frequency seasonal components from accelerometers before fusing them into a single vector.

Although purely data-driven deep learning models are prone to producing physically inconsistent predictions, our approach introduces a physics-informed regularization grounded in structural dynamics. In structural engineering, the dynamic response of a structure is significantly influenced by its modal frequencies, and accurately estimating the peak dynamic deflection is critical for evaluating the health of the structure. To enforce these physical characteristics, a custom physics-informed loss function is formulated during the training phase

The total loss function, L_{total} , is defined to minimize both the amplitude-weighted temporal error and the frequency-domain discrepancy:

$$L_{total} = L_{time} + \lambda_{freq} L_{freq} \quad (1)$$

where L_{time} introduces an amplitude-dependent loss to heavily penalize errors at peak deflections, ensuring the model prioritizes extreme structural events. The term L_{freq} aligns the frequency spectra of the predicted and ground-truth displacements via Fourier Transform, guiding the model to respect the bridge's inherent modal frequencies. The hyperparameter λ_{freq} balances the temporal and physical frequency regularization terms.

3. Experimental validation

3.1. Experimental setup

To validate the performance of the proposed physics-informed FEDformer model, a laboratory-scale dynamic experiment was designed and performed. A simply supported beam model was constructed to simulate the realistic bridge behavior. As detailed in Table 1, a heterogeneous sensor network was deployed along the beam span to capture spatially distributed responses.

Table 1. Experimental sensor configuration and specifications.

Sensor type	Quantity	Measurement target	Frequency characteristics
Inclinometer	5	Rotational angle	Low-frequency
Accelerometer	3	Vertical acceleration	High-frequency
LVDT (reference)	3	Displacement	Full bandwidth (low-frequency)

Five precision inclinometers and three accelerometers were strategically distributed to capture the dynamic beam behavior. Three LVDTs were installed at the quarter-span, mid-span, and three-quarter-span locations to provide the displacement as the ground truth for training and evaluating the estimation accuracy. The sampling rate of dynamic responses was 100 Hz. Two primary loading scenarios were applied to construct a comprehensive time-history dataset comprising 78,400 data points: (1) static loading coupled with free vibration at varying depths and (2) random dynamic loading. Under these scenarios, the structural responses exhibited a wide range of deflection amplitudes. To evaluate the generalization capability of the model, the continuous dataset was temporally divided into alternating training and validation blocks, ensuring that the model was validated against the test dataset.

3.2. Results and discussion

The time-history data collected from the distributed sensors were synchronized and fed into the FEDformer model. The model was trained using a physics-informed loss function to ensure that the predicted localized deflections at the target reference points aligned seamlessly with the discrete slope measurements. Fig. 1 shows the experimental setup and Fig. 2 the estimation results.

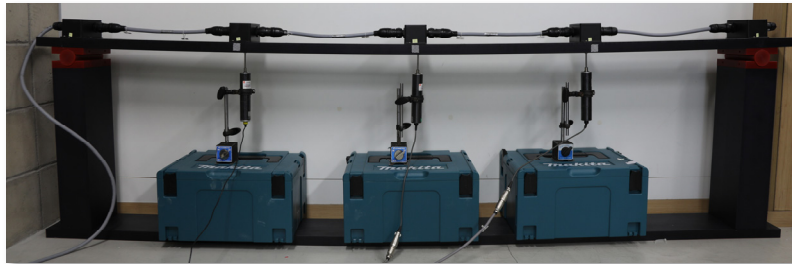


Fig. 1. Experimental validation: laboratory-scale beam experimental setup.

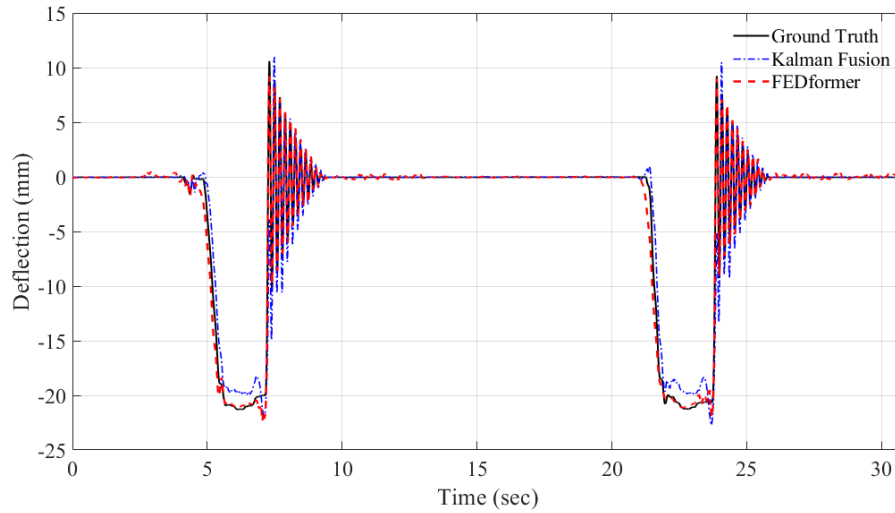


Fig. 2. Experimental validation: comparison of the estimated midspan deflection using the proposed model and LVDT measurements under dynamic loading.

The experimental results demonstrated that the proposed physics-informed FEDformer successfully reconstructed real-time dynamic deflection responses. To comprehensively evaluate the model performance, the estimation was conducted simultaneously at all target measurement locations (LVDT 1, 2, and 3). Across the entire continuous test dataset, which encompassed various static and dynamic scenarios, the proposed method achieved an average RMSD-based estimation accuracy of 98.92% for all target measurement locations compared directly with the LVDT measurements.

To rigorously benchmark the proposed framework, a comparative analysis was conducted using a conventional Kalman filter (KF)-based fusion approach. The KF baseline, which was manually optimized for this specific experimental setup, yielded a respectable accuracy of 94.91% and demonstrated general-tracking capabilities. In stark contrast, the physics-informed FEDformer effectively overcame these limitations, yielding superior accuracy without introducing any phase delay. It robustly suppressed residual drift and accurately captured the peak dynamic displacements. Furthermore, the framework leverages spatially distributed heterogeneous sensors to capture the globally coupled dynamic behavior of the structure. Because the vibration at any specific node is governed by the global modal characteristics of the bridge, integrating multi-node acceleration and inclination data allows the network to physically cross-validate the localized target deflection. By mathematically enforcing these kinematic interdependencies, the FEDformer ensures highly robust estimations and eliminates the instability issues observed in conventional analytical-filtering methods.

4. Conclusion

This study developed a real-time bridge deflection estimation framework using a physics-informed FEDformer that optimally fuses spatially distributed accelerometer and inclinometer in the frequency domain, addressing the limitations of traditional fixed-reference monitoring. A key advantage of this framework is that it effectively captures the globally coupled dynamic behavior of structures using multiple-node sensors. This enables an independent and robust estimation of localized target deflections without the need for fixed reference points during actual operation. The experimental validation demonstrated an average estimation accuracy of 98.92%. Notably, a rigorous comparative analysis revealed that the proposed method outperformed the conventional Kalman filter approach. It substantially reduces the low-frequency integration drift and phase delay while preserving the high-frequency dynamic peaks, which traditional analytical filters struggle to achieve concurrently. The explicit incorporation of structural kinematic laws into the loss function contributes to more robust and reliable estimations. Future research will focus on scaling this framework to full-scale operational bridges under complex environmental and operational conditions such as temperature variations and traffic loads.

Acknowledgements

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Post blast behavior of damaged reinforced concrete slabs strengthened/retroffited with NSM bars

Juwairia Asad^a, Asad-ur-Rehman Khan^a, Shamsoun Fareed^a

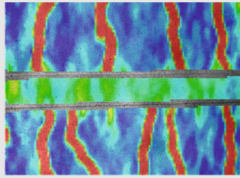
^a*Department of Civil Engineering, NED University of Engineering & Technology, Karachi, Pakistan*

Abstract

In recent past, the use of portable natural gas or LNG (Liquified Natural Gas) cylinder has seen a sharp increase in the domestic usage worldwide, which on one end helps in coping energy crisis, whereas, on the other end, poses a threat on its safe operation as number of fatal accidents have been reported in recent past. It is pertinent to mention that although blast loading produced due to the leakage of gas may not result in the complete collapse of the structure, however, the damage caused to the individual structural element may require strengthening for smooth and safe operation. The behavior of the strengthened reinforced concrete (RC) slabs damaged as a result of domestic internal gas cylinder blast was investigated numerically in this study. Three step methodology was adopted in this study. In the first step, the RC slab was numerically analyzed for the static loading. The second step dealt with the RC slab after it had undergone a blast for finding the residual capacity of the slab. In the third step, damaged RC slab was strengthened with the carbon fiber reinforced polymer (CFRP) near-surface mounted (NSM) bars and analyzed for its load-carrying capacity. It can be concluded on the basis of numerical investigation conducted in the study that the damaged RC slabs strengthened with the NSM bars exhibited improved performance when compared with the slabs without any damage.

Keywords: Reinforced concrete slabs; blast loading; strengthening; near-surface mounted (NSM); CFRP; finite element analysis

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MS15: Data-driven monitoring, modelling and assessment strategies for resilient infrastructure

Organizers:

Mohammad Shamim Miah (Graz University of Technology, Austria)

Md Jihad Miah (University of Brighton, UK)

Subhra Majhi (Curtin University, Australia)

Humera Mughal (Prince Sultan University, Saudi Arabia)

ABSTRACT

Data-driven monitoring of civil infrastructure is increasingly recognized as a vital approach to improving safety, resilience, service life, and long-term sustainability while ensuring cost-effectiveness. Modern structural and architectural systems utilize a variety of systems that include sensors that capture real-time changes, enabling engineers to create targeted retrofitting strategies when necessary. For historical structures and infrastructure, where replacement is neither feasible nor desirable, non-destructive monitoring and assessment methods are essential for maintaining functionality while preserving both architectural and structural integrity. The post-processing data and occupancy evaluation are a crucial part of this process. Advanced system identification techniques further enhance these assessments by creating data-driven models that can be integrated with optimization tools, algorithmic design, and filtering methods. This integrated approach enhances accuracy, reliability, and cost-effectiveness, while supporting sustainable rehabilitation and informed long-term decision-making for structures and infrastructure.

Parameter effects in stochastic subspace identification: a quality assurance framework

Kapil Nichani^a, Steffen Uhlig^a, Bertrand Colson^a, Karina Hettwer^a, Carina Beering^b, Sven Knoth^b

^a QuoData GmbH, Dresden, Germany

^b Department of Mathematics & Statistics, School of Economic and Social Sciences, Helmut Schmidt University Hamburg, Germany

Abstract

Operational Modal Analysis (OMA) is essential for structural health monitoring (SHM) of civil infrastructure, with eigenfrequencies, damping ratios, and mode shapes serving as indicators of structural integrity. In practice, Stochastic Subspace Identification (SSI) shows variation in identified parameters depending on algorithmic configuration and preprocessing, manifesting as temporal discontinuities, spurious modes, and inconsistent estimates that undermine monitoring reliability and motivate quality assurance for OMA-based SHM. This study systematically investigates the sources of this variation using a factorial design of experiments on bridge monitoring datasets, evaluating algorithm, preprocessing, and modeling choices for their effect on reproducibility and stability. Across a replicated Resolution V fractional factorial design, block-row depth emerged as the dominant tuning variable, with frequency error increasing roughly 50-fold from conservative to excessive settings, while variance decomposition revealed that about 83% of frequency-error variability is excitation-driven rather than parameter-driven, in contrast to mode detection rate, which is approximately 90% controlled by parameter choice. The resulting framework provides quality-assurance tools for OMA-based sensing, establishing quantitative performance baselines for modal identification reliability under realistic operating conditions.

Keywords: Operational modal analysis; stochastic subspace identification; frequency domain decomposition; factorial experiment; variance decomposition; structural health monitoring

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

Time-series models performance comparison: feed-forward neural network and autoregressive

Mohammad Shamim Miah^a, Werner Lienhart^a

^aInstitute of Engineering Geodesy and Measurement Systems, Graz University of Technology, 8010 Graz, Austria

Abstract

Measured output-only time-series data are often utilized for structural health monitoring due to many underlying benefits, such as it does not require any information about the input signals. There are many models available to model time-series data, among them, autoregressive (AR) type models are quite popular due to their performances and simple structure. On the contrary, the artificial neural network (ANN) type models are gaining attention due to their suitability and usability. In this study, both of the aforementioned models are utilized to develop models, and later their performances are compared. The overall process involved the data collection, cleaning and preparation, selection of a sample model based on their order, and finally, performance comparison. To do this end, two scenarios are considered (i) where all data of the signal are available, and in the second case (ii) where part of the data is missing. It is observed that both of the studied models type works nicely for the complex time-series data modelling. The performance of the models is excellent in terms of capturing the original dynamics of the signals. However, it is difficult to suggest any model just based on the performance because both ANN and AR type models may require careful assessment before selecting one over the other. Because both of those models' performance can be affected by many underlying factors such as the model orders, network layers, computing power, and data volume.

Keywords: Structural health monitoring; data-driven modelling; artificial neural network; machine learning; autoregressive

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

A framework for load estimation for offshore wind turbines based on Kalman filtering and finite-element models

Anders M. D. Jensen^a, Mathias V. Thing^a, Guiseppe Abbiati^a

^a*Dept. of Civil and Architectural Engineering, Aarhus University, Denmark*

Abstract

Many of the existing offshore wind parks are now approaching their nominal end-of-life according to their original design specifications. Nevertheless, it is widely recognized within the wind energy community that many of these installations continue to exhibit satisfactory structural and operational health and could potentially remain in service for several additional years if their actual condition could be assessed with sufficient confidence. In view of performing an accurate Remaining Useful Life (RUL) analysis, the present contribution presents a framework for virtual sensing to reconstruct both aerodynamic and hydrodynamic loading acting on bottom-fixed Offshore Wind Turbines (OWT). The framework employs an Augmented Unscented Kalman (AUKF) to infer such loads from structural response data measured at few locations and a nonlinear Finite-Element (FE) model of the OWT. The framework is validated numerically using synthetically generated data. The accuracy of reconstructed hydrodynamic and aerodynamic loading is accurate if displacement measurements are used.

Keywords: Structural health monitoring; virtual sensing; remaining useful life; offshore wind turbines

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

Predicting crest displacement at Ridracoli dam using non-co-located temperature data

Asad Ullah^a, Sérgio Pereira^b, Nicola Cavalagli^a, Diana Salciarini^a, Piergiorgio Manciola^a, Giulia Buffi^c, Filippo Ubertini^a

^a*Department of Civil and Environmental Engineering, University of Perugia. Via G. Duranti 93, 06125 Perugia, Italy*

^b*CONSTRUCT - Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*

^c*Romagna Acque Società delle Fonti S.p.A., Piazza del Lavoro 47122 Forlì, Italy*

Abstract

Within the framework of preventive structural monitoring of dams, ensuring the required levels of safety and resilience is closely linked to the accurate prediction of crest displacement among the various measurable parameters. This study explored innovative ways to predict displacement in a dam block, where a direct pendulum was used but no temperature sensor was available at the target location. To this end, three prediction models were investigated, considering not only the effect of the reservoir, but also different approaches for temperature modeling: (i) seasonal temperature variations, (ii) air temperature measurements near the downstream face, and (iii) concrete temperatures from adjacent blocks. The most effective model combined adjacent concrete temperatures with water level data, augmented by a time-dependent component. Including time as a predictor significantly reduced the downward trend in the residuals, stabilizing long-term displacement predictions. This model achieved the best performance, reducing root-mean-square-error (RMSE) by 40% relative to the classical hydrostatic-seasonal-time (HST) model (from 0.750 to 0.451 mm). These findings demonstrate that non-co-located concrete temperature data offer a practical and robust alternative for dam displacement monitoring when direct thermal instrumentation is unavailable.

Keywords: Dam monitoring; crest displacement; concrete temperature; data-driven modeling; time effect

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

Ontology-based modeling of crack width evolution in concrete components

Xiaoli Song^a, Mengyan Peng^a, Steffen Marx^{a,b}, Chongjie Kang^{a,b}

^a*TUD Dresden University of Technology, George-Bähr-Straße 1, 01069 Dresden, Germany*

^b*Cluster of Excellence CARE, TU Dresden and RWTH Aachen, Germany*

Abstract

Ontologies are increasingly used to organize engineering information into meaningful concepts and relationships, enabling consistent interpretation and sharing of knowledge. In this work, a lightweight ontology is developed to model the temporal crack evolution, which is one of the key indicators for assessing the condition and durability of concrete structures. As the behavior of crack width can vary over time, the representation of temporal crack information is important for supporting structural performance assessment. The ontology formalizes crack states across multiple observation points into a machine-interpretable knowledge model and links each observation to its supporting resources, such as sensor data files and crack images. By connecting semantic descriptions with raw monitoring evidence, the approach improves traceability and retrieval of crack-related information, supports transparent interpretation of crack development processes, and facilitates comprehensive digital management of crack records. The ontology-based framework is expected to serve as a semantic structure for interpreting monitoring data and enabling future semantic extensions. Although this work is at an early stage, it highlights the potential of semantic technologies to enhance structural health monitoring (SHM) data utilization and contribute to more resilient infrastructure knowledge management.

Keywords: Ontology; crack monitoring; structural health monitoring; knowledge representation; data traceability

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

Assessing ballast load distribution effects on axle detection in railway B-WIM

László Barbély^a, Attila László Joó^a

^a*Budapest University of Technology and Economics, Műegyetem rkp. 3, Budapest 1111, Hungary*

Abstract

Reliable axle detection is a key requirement for Bridge Weigh-in-Motion (B-WIM) systems, since axle positions are essential input parameters for axle-load estimation. In ballasted railway bridges, wheel loads are transmitted through the rail–sleeper–ballast system before reaching the deck, which smooths the structural response and reduces the prominence of axle-related strain features. This effect limits the applicability of conventional axle-detection methods and has led previous railway B-WIM implementations to use additional rail-mounted sensors, which conflict with the Nothing-on-the-Road (NOR) concept. This study investigates whether axles can be detected using strain responses measured solely on the bridge structure. A finite element model of a steel railway bridge currently under construction in Budapest was developed, and influence lines were generated for different structural sensor locations. Synthetic strain signals were produced for representative train passages using both a simplified load-spreading model and a more detailed rail–sleeper–ballast model. A wavelet-transform-based axle detector was then evaluated on the generated signal sets. The results show that ballast load distribution significantly reduces axle detectability. Longitudinal stiffeners of the orthotropic deck retained the most informative axle signatures. For the detailed ballast model, the detector identified the correct number of axles in 45 out of 60 train passages for this sensor configuration, with a mean axle-position error of 98 mm in the successful cases. These findings indicate that NOR-compatible axle detection on ballasted railway bridges may be feasible, but further improvement of the detection algorithm is required for robust field application.

Keywords: B-WIM; railway; ballast; axle detection; NOR

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Enhanced ultrasonic imaging of curved concrete structures using cascading filters

Subhra Majhi^a, Juan Acevedo Osma^a, Maryam Saberpour^a, Abhijit Mukherjee^a

^a School of Civil and Mechanical Engineering, Curtin University, Kent St, Bentley, WA: 6102, Australia

Abstract

Globally, concrete structures are at various stages of deterioration, predominantly due to their age and proximity to the marine environment. Visual inspections are primarily used to monitor these structures, which can be subjective. Novel inspection techniques that can probe in the sub-surface are warranted to alleviate subjectivity in inspections. Ultrasonic imaging can reveal embedded rebars, pipes and emanating sub-surface cracks. Predominantly flat concrete structures are assessed using ultrasonic imaging. Imaging curved concrete structures can be challenging due to the challenging geometry of the structure.

In this study, piezo-electric sensors generate ultrasonic waves that are used to develop images of curved concrete structures. A series of sensor positions is explored for understanding the optimal positioning of sensors for imaging. Subsequently, the ultrasonic signals are parsed through an imaging algorithm developed in curvilinear coordinates to generate a representative image of the structure's cross-section. A series of three cascading filters has been used to enhance this representative image. In the first filter, the zone of the image is focused, and the second filter enhances the image contrast. In the third filter, improvement in localization of embedded objects achieved is through the averaging of relevant image pixels. As a result, improvements in the overall image quality and the location of the embedded features are achieved. This improvement is demonstrated through imaging model curved concrete specimens.

Keywords: Ultrasonic imaging; image enhancement; concrete structures; curved structures; cascading filters

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

Functionalized carbon fiber textile reinforcements with fiber-based strain sensing

Hung Le Xuan^{a,b}, Anna Happel^a, Paul Penzel^{a,b}, Chokri Cherif^{a,b}

^aInstitute of Textile Machinery and High Performance Material, TUD Dresden University of Technology, Hohe Str. 6, 01069 Dresden, Germany

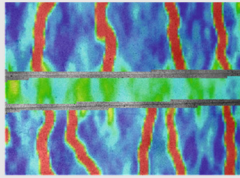
^bCluster of Excellence CARE, TU Dresden and RWTH Aachen, Germany

Abstract

Textile reinforced concrete (TRC) enables lightweight and corrosion-resistant structural components with high mechanical performance. However, conventional carbon fiber non-crimp fabrics (CF-NCF) exhibit limitations in pull-out behavior, as load transfer is mainly governed by the warp-knitting yarn rather than the reinforcing rovings. To address this, CF-NCF were modified by integrating carbon fiber tetrahedral-shaped rods (CF-TSR), while carbon fiber-based textile strain sensors were embedded for in-situ monitoring of strain development and crack formation. Quasi-static tensile tests were performed on TRC specimens to investigate the influence of CF-TSR on mechanical performance. The mechanical response and crack formation were analyzed using digital image correlation (DIC), while the integrated textile strain sensors recorded electrical resistance changes during loading. The results show that CF-TSR modification can slightly improve ductility and energy absorption, although the effect remains limited in the manually manufactured specimens. The elongation at peak stress and at break increased to 1.37 % and 1.49 %, compared to reference values of 1.31 % and 1.38 %, respectively, while approximately 7 % higher absorbed energy was achieved with comparable tensile strength. The combined evaluation of DIC and textile sensor signals enabled analysis of crack initiation and strain redistribution, demonstrating the potential of functionalized textile reinforcements for cost-efficient and reliable structural health monitoring in TRC structures.

Keywords: Smart concrete; textile-reinforced concrete; carbon fiber non-crimp fabric; textile-based strain sensors; structural health monitoring

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MS16: Carbon-negative compression dominant structures for decarbonized and deconstructable concrete buildings

Organizers:

Saim Raza (Empa, Switzerland)

Moslem Shahverdi (Empa, Switzerland)

Stijn Matthys (Ghent University, Belgium)

ABSTRACT

CARBCOMN is a four-year EU EIC Pathfinder project (2024-2028) that tackles the environmental footprint of concrete by coupling CO₂-sequestering, cement-free printable mixes from secondary raw materials with material-efficient, compression-dominant structural systems for 3D concrete printing. The 11-partner European consortium aims to deliver a design-to-fabrication route that measurably reduces embodied carbon and enables deconstruction and reuse by design. This Mini Symposium will present progress from the first two years through papers and extended abstracts spanning material-scale studies, such as CO₂ sequestration in non-activated slag-based printable concretes, to structural advances, including form-finding and shape optimization of compression-dominant slabs assembled from discrete printed blocks with reversible joints.

CARBCOMN: advancing low carbon compression dominant structures

Stijn Matthys^a, Kim Van Titteboom^a, Moslem Shahverdi^b, Alessandro Dell'Endice^c, Catherine (Corina) Papanicolaou^d, Neven Ukrainczyk^e, Helen Hamaekers^f, Johannes Megens^g, Enzo Martinelli^h, Vishu Bhooshanⁱ, Lori Zillante^j, Julien Michels^k

^aGhent University, Department of Structural Engineering and Building Materials, 9052, Ghent, Belgium

^bEmpa, Ueberlandstrasse 129, 8600 Dübendorf, Switzerland

^cETH Zürich, Institute of Technology in Architecture, Stefano-Franscini-Platz 1, 8093 Zürich, Switzerland

^dUniversity of Patras, Department of Civil Engineering, 26504 Rio, Greece

^eTU Darmstadt, Franziska-Braun-Straße 3, 64287 Darmstadt, Germany

^fOrbix, Henry Fordlaan 84, 3600 Genk, Belgium

^gIncremental3d, Erzherzog-Eugen-Str.5, 6020 Innsbruck, Austria

^hTESIS, Piazza Vittorio Emanuele 10, 84084 Penta di Fisciano, Italy

ⁱZaha Hadid Architects, 101 Goswell Road, London EC1V 7EZ, UK

^jMario Cucinella Architects, Via Francesco Flora 6, 40129 Italy

^kre-fer, Riedmattli 9, 6423 Seewen, Switzerland

Abstract

The CARBCOMN project (HORIZON-EIC-101161535), titled “Carbon-negative compression dominant structures for decarbonized and deconstructable concrete buildings”, is funded under the EIC Pathfinder Challenge AEC digitalisation for a new triad of design, fabrication, and materials. The project aims to revolutionize the construction sector by developing carbon-negative, compression-dominant concrete structures. The CARBCOMN construction system focuses on compression dominant stress states, so to utilize the concrete at its strongest stress resisting state, making it intrinsically more durable by being no longer susceptible to reinforcement corrosion (which is the main cause of deterioration of concrete structures), and to be more compatible with extrusion-based 3D printing (that cannot easily integrate embedded tensile reinforcement) of a carbon-curing concrete mix. In the following, the project is introduced, the concepts of the CARBCOMN construction system are elaborated and tentative results are highlighted.

Keywords: Carbon-curing concrete; compression dominant; 3D concrete printing; CARBCOMN

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

Carbonatable binders from waste: pathways toward sustainable construction materials

Panagiotis Gkournelos^a, Kyriakos Karlos^a, Catherine (Corina) Papanicolaou^a, Thanasis Triantafyllou^a

^aStructural Materials Lab, Civil Engineering Department, University of Patras, Greece

Abstract

This paper investigates the feasibility of producing carbonatable mortar systems from waste-derived binder components, with emphasis on two underexplored streams: (i) expired and partially solidified CEM IV 32.5R cement, mechanically reclaimed through sieving and crushing, and (ii) ground eggshell powder used as a biogenic calcium-rich partial cement substitute. Three mortar mixes were prepared at 0%, 10%, and 50% eggshell substitution levels and subjected to four curing regimes combining conventional wet curing (3 and 7 days) and accelerated carbonation (20% CO₂, 95% RH). Compressive and flexural strengths were measured for all combinations. Results confirm that carbonation curing significantly enhances mechanical performance across all mixes, with relative compressive strength increases ranging from +73% to +253% compared to wet-cured counterparts. Even at 50% eggshell substitution, the binder system responds strongly to CO₂ exposure, indicating active participation of biogenic carbonate in strength-forming reactions. These findings support the viability of circular, waste-based carbonatable binder technologies for low-carbon construction applications.

Keywords: Carbonatable binders; waste valorization; sustainable construction; circular economy; accelerated carbonation; eggshell powder; reclaimed cement

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

Carbon-negative mortar mixtures produced with fine recycled aggregates: the experience of CARBCOMN project

Rosario Lombardi^{a,d}, Zohaib Hassan^{b,c}, Saim Raza^b, Marco Pepe^{a,d}, Moslem Shahverdi^b, Enzo Martinelli^{a,d}

^a TESIS srl, Italy

^b Swiss Federal Laboratories for Materials Science and Technology, Switzerland

^c Institute for Building Materials (IfB), ETH Zürich, CH-8093 Zürich, Switzerland

^d Department of Civil Engineering, University of Salerno, Italy

Abstract

The present paper summarizes the results of a preliminary experimental campaign aimed at unveiling the possible influence of fine recycled aggregates (derived from construction and demolition waste, CDW) on the resulting fresh and hardened properties of carbon-negative 3D printable mixtures produced with alternative binders and aggregates. The binder used in this study was a fine powder derived from steel slag (Carbinox), a by-product of the stainless steel industry, and the fine aggregates considered were steel slag (Stinox) as the reference material and CDW as the material under investigation. Three mixtures were produced by considering a 50% and 100% replacement ratio of fine recycled aggregates and measuring the flowability in the fresh state as well as the flexural and compressive strength after controlled drying and CO₂ curing (30% CO₂ and 70% N at 2 bar) in a sealed chamber, resulting in fully carbonated samples. The activities proposed herein are being executed within the context of the CARBCOMN (Carbon-negative compression dominant structures for decarbonized and deconstructable concrete buildings) project, an EU-funded initiative (n. 101161535) which addresses a disruptive innovation in sustainable concrete load-bearing structures by setting forth a new digital AEC (Architecture, Engineering & Construction) design paradigm that is fully compatible with concrete that uses CO₂ as raw material and is carbon-negative. The results highlight the role of alternative aggregates on the resulting mixture performance as a feasible solution for producing optimized elements for 3D printed structures.

Keywords: Carbon-negative concrete; steel slag; recycled aggregates; CO₂ curing; mechanical properties

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

Mechanical behaviour of 3D-printed slag-based formulations with methyl hydroxyethyl cellulose

Thinh Nguyen^a, Danis A Lorika^b, Helen Hamaekers^a, Dirk Van Mechelen^a, Yi Zhang^b, Kim Van Tittelboom^b, Stijn Matthys^b

^aOrbix Productions, Henry Fordlaan 84, 3600 Genk, Belgium

^b Magnel-Vandepitte Laboratory, Department of Structural Engineering and Building Materials, Technologiepark-Zwijnaarde 60, 9052 Ghent, Belgium

Abstract

3D printing with carbonatable stainless-steel slag binders (Carbinox™) differs fundamentally from 3D printing with traditional hydraulic systems. While hydraulic binders harden through hydration, carbonatable binders gain strength exclusively via carbonation. Due to the low hydraulic reactivity of the binder, the mixing water largely remains physically bound for an extended period. Consequently, severe bleeding may occur during printing, leading to inconsistent workability. Addition of a viscosity-modifying agent (VMA) offers a promising solution, yet the interaction between VMA and carbonatable slag-based systems remains limitedly understood. Considering the novelty of both carbonatable binders and their use in 3D printing, addressing this knowledge gap is essential.

This study investigates the effect of methyl hydroxyethyl cellulose (MHEC) – a commercial VMA – on the carbonation behavior of the Carbinox™-based printable mixtures. Preliminary results indicate that high dosages of MHEC adversely affect strength development following carbonation, despite the lack of a clear correlation with the quantity of CaCO₃ formed. Conversely, MHEC enhances the homogeneity of the strength profile, likely by improving homogeneity and inter-layer cohesion. These findings underscore the need for further research into the microstructural and chemical interactions between MHEC and carbonatable binder matrices.

Keywords: Carbonation; slag; VMA; strength; 3D-printing

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

CO₂ transport in 3D-printed carbonatable slag-based mortars from micro-CT pore networks

Neven Ukrainczyk^a, Zohaib Hassan^{b,c}, Annapaola Parrilli^b, Saim Raza^b, Moslem Shahverdi^b, Denis A. Lorika^d, Yi Zhang^d, Eduardus Koenders^a

^a Institute of Construction and Building Materials, TU Darmstadt, Franziska-Braun-Str. 3, 64287 Darmstadt, Germany

^b Swiss Federal Laboratories for Materials Science and Technology, Switzerland Institute for Building Materials (IfB),

^c ETH Zürich, CH-8093 Zürich, Switzerland

^d Magnel-Vandepitte Laboratory of Structural Engineering and Building Materials, Ghent University, Belgium

Abstract

Understanding CO₂ transport in porous construction materials is essential for improving their sustainability and role in carbon capture, utilization, and storage. This study examines gas transport in 3D-printed slag-based (cement-free) carbonatable binders using a micro-CT-derived pore network modeling approach. High-resolution X-ray micro-computed tomography was used to reconstruct the complex 3D pore architecture, followed by segmentation and network analysis to characterize connectivity, size distribution, and transport pathways. The tomography was performed on specimens subjected to different concentrations of CO₂ exposure (3% and 20%) for different durations (1, 2, and 7 days). Results show that porosity has a limited fraction that contributes to long-range diffusion, with pore connectivity being strongly affected by pore size threshold and printing orientation. The integrated imaging-modeling framework provides a robust, efficient route to predict effective CO₂ diffusivity of early age hardening printed mortars, directly from realistic microstructures, offering new insights for optimizing carbonatable binder design.

Keywords: 3D-printing; slag-based carbonatable mortars; pore network modeling; micro-CT; transport properties.

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

3D-printed ultra-high-performance concrete with polymer fibres: feasibility study

Ivan Markovic^a, Thomas Reichlin^a, Nassim Khodari^a

^aOST University of Applied Sciences of Eastern Switzerland, CH-8640 Rapperswil, Switzerland

Abstract

Although 3D-printing with concrete is a very current research topic, there is still a large gap between developments in the lab and application of this technique in engineering practice. The most important reason for this gap is the limitation to reinforce the 3D-printed concrete structures properly with traditional steel bar reinforcement and to ensure enough ductility in this way. The application of steel and polymer fibres in printable concrete mixtures with conventional compressive strength is possible, but in such cases, a serious lack in both tensile strength and ductility can often be observed.

Motivated by the above presented situation, the main goal of present study is to produce printable concrete mixtures containing fibres, so that they possess significantly improved flexural strength and ductility compared with conventional fibre concretes. The solution can be a printable ultra-high performance concrete with polymer fibres (UHPC-P). This choice was made based on flexibility of polymer fibres in 3D-printing process, competitive mechanical properties such as flexural strength and ductility and relatively low costs and good durability of polymer fibres. In the concrete mixtures, both the amount of non-fibrous ingredients of concrete and the polymer fibre amount were varied and the effects of those variations on printability, flexural strength and ductility were measured and compared to the same conventionally molded ultra-high-performance fibre concretes. The water-cement ratio of 0.30 was applied. The fibre volume content was varied from 0.8 vol.-% to 3.0 vol.-%, with the main goal to maintain optimum printability in the fresh state and to measure the influence of fibre dosage and production process (3D-printed vs. conventionally molded) on the flexural behaviour in the hardened state, using displacement-controlled flexural tests.

Keywords: 3D-printing; ultra-high performance concrete UHPC; polymer fibres; flexural strength; ductility; additive manufacturing

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

Shape stability investigation for 3D printed carbon-curing concrete objects using visual inspection methods

Adeleh Farahani^{a,†}, Karol Misiarz^{b,†}, Ticho Ooms^a, Kim Van Tittelboom^a, Jan Aelterman^b, Stijn Matthys^a

^aGhent University, Department of Structural Engineering and Building Materials, Technologiepark-Zwijnaarde 60, 9052 Gent, Belgium

^bGhent University, IPI: Image Processing and Interpretation, Building 3, UFO campus site, 9000 Gent, Belgium

Abstract

In extrusion-based 3D concrete printing, each newly deposited layer imposes a compressive load on the underlying layers, potentially inducing plastic deformation in both vertical and horizontal direction. In this situation, the bottom layer is expected to experience the largest deformation compared to upper layers. The slenderness of 3D-printed elements may further contribute to local instabilities. Ghent University, as a partner in the EIC Pathfinder project CARBCOMN, has developed a mix design tailored for 3D printing of carbon-curing concrete, aimed at producing unreinforced building blocks for compression-dominant modular structures. In such systems, which consist of discrete elements, the geometric accuracy of the printed blocks relative to their initial design is critical. This study evaluates the shape stability of 3D-printed elements during printing. Deformation of the bottom layer was captured during printing using two GoPro cameras and a Time-of-Flight (ToF) camera from multiple angles, including side and bottom of the object. The results show that both camera systems can successfully measure lateral deformations during printing; however, using a GoPro camera with the side view can be the easiest method to reach to sub-millimetre accuracy.

Keywords: 3D concrete printing; carbon curing; visual inspection; shape stability

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

An integrated geometry slicing & 3D scanning framework for 3D concrete printing

Vishu Bhooshan^a, Wo Lin^a, Justin Hanlon^a, Shajay Bhooshan^a, Johannes Megens^b, Sandro Sanin^b, Alessandro Dell'Endice^c, Tom Van Mele^c, Philippe Block^c

^a Computation & Design Group (CODE), Zaha Hadid Architects, United Kingdom

^b Incremental3D, Innsbruck, Austria

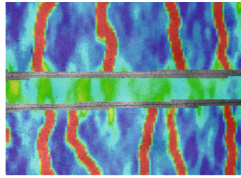
^c Block Research Group (BRG), ETH Zurich, Switzerland

Abstract

This paper presents the implementation of an advanced geometry slicing framework for 3D Concrete Printing (3DCP), refining and extending the methods introduced by Bhooshan et al., (2023) to incorporate non-planar slicing. The paper details the core slicing and print-path procedures based on Signed Distance Fields (SDF), which support adaptive layer generation, variable print heights, and user-defined bracing patterns. These methods handle planar, multi-planar and non-planar slicing of block geometries in compression-dominant masonry systems, improving both geometric fidelity and fabrication adaptability. Motivated by the rapid expansion of large-scale 3DCP, this paper presents the current development of the open-source framework, enabling seamless interoperability across design and fabrication workflows. It also addresses the current lack of standardized file formats by adopting Universal Scene Description (USD) as a unified format for storing mesh geometry, synthesized print paths, and embedded metadata such as layer parameters, print length, and fabrication constraints. Furthermore, a scanning-based feedback loop is implemented to capture and compare as-built geometries with digital models, embedding deviation data into the computational pipeline for iterative calibration. Together, these developments establish an open-source, cross-platform design-to-fabrication toolkit that advances data-driven, geometry-adaptive workflows for 3D concrete printing.

Keywords: 3D concrete printing; geometry slicing; computational toolkits; 3D scanning; digital fabrication; universal scene description (USD)

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A design optimization framework for discrete compression-dominant structures

Mahsa Sakha^{a,1}, Saim Raza^a, Christoph Czaderski^a, Moslem Shahverdi^{a,b}

^a Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf 8600, Switzerland

^b School of Civil Engineering, University of Tehran, Tehran 4563-11155, Iran

Keywords: Compression-dominant system; optimization workflow; discrete structures; topology optimization

1. Introduction

3D concrete printing (3DCP) has received considerable attention in the construction sector in recent years due to its advantages in terms of feasibility in design and fabrication, as well as potential economic and ecological benefits. While this technology appears to be on track toward replacing conventional methods in housing sector, several barriers still limit large-scale industrial investments (see Adaloudis and Bonnin Roca (2021)). To overcome these barriers, the research studies must expand the domain of applicability of 3D-printed structures and demonstrate their impact on key industry-relevant aspects. From a structural perspective, the drawback of 3D-printed elements in flexural applications remain a major challenge. To address this issue, several studies have explored practically simple design solutions. In this regard, some approaches focus on structural configurations that promote compressive-dominant force flows, while others employ externally applied post-tensioning to enhance flexural capacity without interfering with the printing process (see Guan et al. (2025), Raza et al. (2025), and Sakha et al. (2026)). From sustainability perspective, 3D concrete printing typically relies on mortars with high cement content, which raises environmental concerns. While some studies attempt to address this drawback through material optimization, leading to geometries specifically tailored for 3D printing, research on cement-free binders directly tackle the root of the problem and thus offers fundamentally robust solutions. From an economic standpoint, the fabrication of large-scale prefabricated 3D-printed modules often introduces logistical complications related to transportation and handling, which cannot always be easily mitigated through on-site printing. In this context, modular 3D-printed elements are a favorable alternative, particularly when they can be assembled and later disassembled while maintaining structural stability. Considering these aspects collectively represents an important step toward expanding the applicability of 3D concrete printing in the construction industry. In this work, we therefore develop an optimization framework for the design of discrete, deconstructable, compression-dominant 3D-printed structures. Although the binder used in the system is designed to be carbon-negative, this paper only focuses on the structural aspects of the proposed design.

2. Optimization methodology

Fig. 1 outlines the optimization workflow for the full design of a block-wise compression-dominant vaulted structure. This workflow arranges three interrelated and mutually dependent design modules of (i) arch layout, (ii) block optimization, (iii) and joint layout. The methodology adopts a sequential, dependency-driven framework, where each downstream module is conditioned on the full definition of its upstream counterpart. This hierarchical structure is essential, as the geometric and mechanical admissibility of each stage is inherited from the preceding one.

As illustrated in the figure, the arch layout module consists of two main steps: (i) **form-finding**, in which *Thrust network analysis* is used to find the form of a reference mesh whose compressive-only force flow is in equilibrium with the applied external loads; and (ii) **arch shape variations**, where the overall configuration of the extrados and intrados along vault span is defined.

¹ Corresponding author. E-mail address: mahsa.sakha@empa.ch

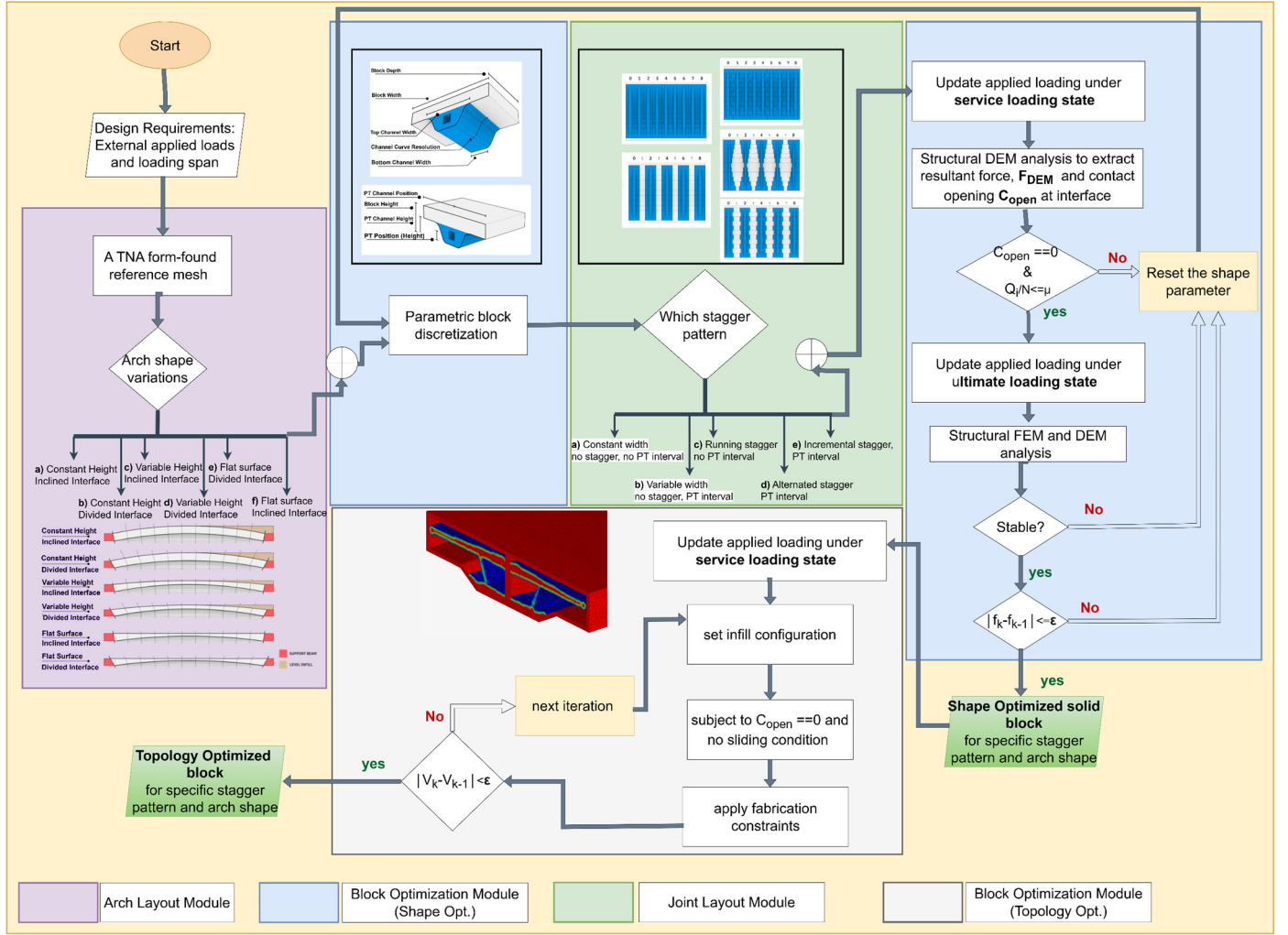


Fig. 1. Design workflow outlining the optimization process of a discrete compression-dominant structure. In this figure, f_k and v_k represent the strain energy and mass fraction at iteration k , respectively.

Following this module, the first stage of block optimization, referred to as **parametric block discretization**, is implemented to materialize and define the shape of solid blocks. A set of candidate blocks is therefore generated by varying the shape parameters that define the outer boundaries of the blocks. This stage is strictly conditioned by the arch layout, as the admissible block geometries are bounded by the previously defined reference mesh and the extrados–intrados configuration. These candidates are subsequently arranged into five different connection patterns, as follows:

1. Constant width – no stagger – no PT interval
2. Variable width – no stagger – PT interval
3. Running stagger – no PT interval
4. Alternated stagger – PT interval
5. Incremental stagger – PT interval

Our design up to this stage is implemented using the Python-based, open-source computational platform COMPAS (Van Mele et al. 2017). Upon full definition of the system, the discretized structure is evaluated in terms of its stability under the applied loading conditions. In this context, the loading conditions include the end-to-end ties together with transverse loads acting under either service or ultimate limit states. Stability under each loading state is assessed differently. Under service loading state, neither opening nor sliding is permitted at the interfaces between blocks. This condition is evaluated through two specific quantities. The first is the contact opening at the interface, C_{open} , which must remain zero at all interfaces. The second is the ratio of shear force to compressive force at each interface, defined as Q_i/N_i , which must not exceed the friction coefficient in order to ensure a no-sliding condition (see Kimura et al. (2020)). Under the ultimate loading state, however, interface opening is permitted provided that the overall structural stability of the system is not compromised. Accordingly, the optimization panel identifies an optimal shape of solid blocks for a given stagger pattern and arch shape by iteratively investigating each shape parameter until a termination condition is reached. The termination occurs when either the maximum number of iterations is exceeded or the minimum strain energy of the system is achieved.

Once the optimal solid geometry is obtained, the workflow proceeds to the next phase, known as infill topology optimization, to generate the final hollow block configuration, in which the outer geometry is fixed as a non-design domain. In this stage, the infill domain of the optimal solid block is refined to minimize mass fraction while ensuring that all design conditions under the service loading state remain satisfied. Compared to the solid counterpart, a hollow configuration may lead to stress concentrations and highly compressive stresses that could exceed the material strength and must therefore be avoided. Within this module, the distribution of infill material is constrained by fabrication requirements associated with the 3D printing technique in this particular case. The optimization must therefore satisfy: (i) minimum and maximum allowable widths of 3D-printed layers, and (ii) extrusion constraints, where the buildability of the block along the printing direction is verified to ensure that it can be fabricated without intermediate support. The topology optimization is conducted using OptiStruct, integrated in Altair HyperMesh, under the academic licensing program of Altair Engineering.

Acknowledgements

This project has received funding from the European Innovation Council (Horizon EIC 2023, grant no. 101161535) and Swiss State Secretariat for Education, Research and Innovation. Special thanks to our academic and industrial partners, ETH Zürich, Universiteit Gent, Technische Universität Darmstadt, TESIS SRL, ORBIX Productions, PANEPISIMIO PATRON, incremental3d.GmbH, re-fer AG, mario cucinella architects and ZAHA HADID LIMITED for providing the materials and technical support for this project. The academic license provided by Altair Engineering is also gratefully acknowledged.

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Sensor-integrated masonry systems for predictive monitoring and circular construction

Daniele Florenzano^a, Alessandro Dell'Endice^a, Tom Van Mele^a, Philippe Block^a

^a*Block Research Group, Institute of Technologies for Architecture, D-ARCH, ETH, Stefano-Franscini-Platz 1, HIB E47, Zürich 8093, Switzerland*

Abstract

The transition toward sustainable and long-lasting construction requires not only innovative structural systems but also new strategies for monitoring and managing structural data throughout the building life cycle. This contribution presents a monitoring and data collection framework for compression-dominant masonry systems, focused on the early detection of structural failures and the integration of performance data to enable predictive maintenance. Developed within the EU-funded CARBCOMN project, this work builds upon the experience of the Block Research Group (BRG) with the Striatum and Phoenix 3D-printed concrete bridges, which showcased the potential of compression-only systems. Extending these foundations, the framework introduces sensor-based monitoring and data-driven assessment of displacements, crack formation, and material response in early prototypes. By embedding sensors within the load bearing block geometries, each element becomes a data source, generating a digital record (or element passport) that traces its mechanical performance and environmental exposure over time. The collected data feed into a comprehensive digital infrastructure, supporting the creation of interoperable digital twins for long-term analysis and reuse. Embedding intelligence at the material-unit scale transforms compression-dominant masonry into a digitally traceable, adaptive, and circular structural system.

Keywords: Compression-dominant masonry; 3D concrete printing; structural monitoring; predictive maintenance; single source of truth

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

Parametric design and life cycle assessment of slab bridges for Swiss road infrastructure with reduced CO₂ emissions

Yunus Emre Harmanci^a, Lukas Kramer^a, Amirhossein Mohammadi^b, Martina Serra^c, Roland Hirschier^c, Mateusz Wyrzykowski^a, Moslem Shahverdi^a, René Steiger^a

^a*Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, 8600, Switzerland*

^b*University of Minho, ISEC Department of Civil Engineering, Guimarães, 4800-058, Portugal*

^c*Empa, Swiss Federal Laboratories for Materials Science and Technology, St. Gallen, 9014, Switzerland*

Abstract

The construction sector accounts today for about 37% of global, as well as over 20% of Switzerland's global warming impacts mainly due to its reliance on CO₂-intensive materials, hence representing a primary target for achieving the necessary CO₂ reduction towards Net-Zero in 2050. This work, conducted within the SCENE (Swiss Center of Excellence on Net-Zero Emissions) project, proposes solutions for reducing the CO₂ footprint of road bridges by investigating alternative designs for straight two-lane bridges with one to two spans and total lengths of 10–100 m in Switzerland. In this paper, the focus is on slab bridges as one of the most prevalent bridge types in Switzerland. Key geometric parameters (i.e. span length and cross-sectional thickness) and required amounts of materials were systematically parametrized within a commercial finite element software, incorporating conventional market materials as well as low-emission alternatives with high technical readiness level. Latin Hypercube Sampling (LHS) was employed to generate a set of bridge configurations that satisfy design and serviceability requirements. The material-related carbon footprint of the required amounts of materials was evaluated utilizing the life cycle assessment (LCA) methodology with background data from the ecoinvent database. The analysis demonstrates that substantial reductions in emissions in view of the applied materials are achievable for both single- and double-span slab bridges. These findings allow identifying preferred materials and their combinations that minimize environmental impacts while meeting structural safety and serviceability criteria imposed by current design standards.

Keywords: Net-zero materials, parametric design, life cycle assessment, embodied carbon, optimized road bridge design, RC slab bridge

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

LCA of bridge and tunnel components – basis for sustainable infrastructure

Angelika Schiessl-Pecka^a, Paul Steinmetz^a, Anne Rausch^a, Marc Zintel^b

^a*Ingenieurbüro Schiessl Gehlen Sodeikat GmbH, Germany*

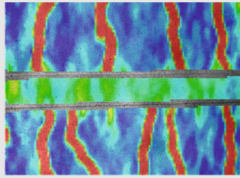
^b*Steeltec AG, Switzerland*

Abstract

Infrastructure components exposed to de-icing salts frequently suffer from chloride-induced reinforcement corrosion, leading to premature repair or replacement. While corrosion-resistant reinforcement steels typically exhibit a higher global warming potential (GWP) during production, their enhanced durability may reduce life cycle emissions by avoiding maintenance interventions and associated traffic disruptions. This paper presents a comparative life-cycle assessment (LCA) of reinforced concrete infrastructure components using conventional carbon steel reinforcement (B500B) and a ferritic stainless reinforcement (Top12). Four representative components are investigated: bridge edge beams, bridge pillars, tunnel emergency walkways, and tunnel interior walls. The analysis combines component-specific service-life modelling, life-cycle carbon accounting according to DIN EN 15804:2022-03 and sensitivity analysis addressing traffic-related emissions during the maintenance measure. Results show that for components requiring durability-related replacement during service life, the use of corrosion-resistant reinforcement can substantially reduce cumulative GWP despite higher initial emissions. For heavily reinforced components, the benefit strongly depends on whether emissions due to traffic disruptions are considered. The findings underline the importance of integrating durability and traffic effects into sustainability assessments of infrastructure systems

Keywords: Life-cycle assessment; reinforced concrete; durability; corrosion-resistant reinforcement; infrastructure; traffic emissions

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SMAR 2026



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

MS17: Distributed fiber optical sensing (DFOS) in structural engineering research

Organizers:

Yasmin Lemcherreq (Empa, Switzerland)

Christoph Czaderski (Empa, Switzerland)

ABSTRACT

Distributed fiber optical sensing (DFOS) based on Rayleigh backscatter is increasingly used in structural engineering research. By providing continuous, high-resolution strain measurement along the sensor, DFOS enables crack detection, deformation monitoring, and the back-calculation of stresses and forces, thereby delivering unprecedented insights into structural behavior.

This Mini Symposium gathers researchers who utilize DFOS in diverse experimental configurations—whether surface-mounted or embedded in the host material—to capture strain distributions or derive secondary quantities. The objective is to exchange experiences and pave the way toward future guidelines addressing instrumentation, data acquisition, processing and ensuring repeatability of measurements.

Key topics include current limitations and challenges of the technique, such as temperature effects, signal noise, treatment of outliers, and measurement uncertainties. In addition, the session will address emerging approaches, such as machine-learning algorithms for automated post-processing, which aim to reduce user bias and enhance the reliability of data interpretation.

Benefits and challenges of DFOS in reinforced, prestressed and 3D-printed concrete research

Tomasz Howiacki^a, Kamil Badura^b, Rafał Sieńko^a, Łukasz Bednarski^c

^a*Faculty of Civil Engineering, Cracow University of Technology, Warszawska 24, 31-155 Kraków, Poland*

^b*SHM System | Nerve-Sensors, Libertów, Jana Pawła II 82A, 30-444 Kraków, Poland*

^c*Faculty of Mechanical Engineering and Robotics, AGH University of Kraków, Mickiewicza 30, 30-059 Kraków, Poland*

Abstract

Concrete structures present some diagnostic challenges due to the inherent heterogeneity of the material. Random distribution of stiff aggregate particles, spatial variations in mechanical properties like elastic modulus, and the presence of local imperfections and discontinuities such as cracks, make it difficult to characterize their behavior using conventional spot gauges. In this context, distributed fiber optic sensing (DFOS) offers significant benefits, as it enables continuous strain monitoring along an embedded optical sensor, providing information that is otherwise inaccessible. Lessons learned has shown that the most effective approach is to embed sensors directly within the concrete matrix and start measurements immediately after casting. This strategy allows for the monitoring of all stages in the structural life cycle: from early-age thermal and shrinkage strains during curing, through prestressing and the activation of self-weight, to the application of mechanical loads. This article emphasizes practical aspects of sensor installation in reinforced concrete, prestressed concrete, and 3D-printed concrete (3DPC) components made in laboratory scale for research purposes. Case studies and experimental results highlight both the benefits and the challenges of DFOS implementation in these different contexts. Ultimately, DFOS emerges as a versatile tool that significantly enhances the accuracy and depth of structural diagnostics in concrete research.

Keywords: DFOS; concrete; measurements; strains; cracks

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

Fiber-optic monitoring of shrinkage eigenstrains and gravity behavior in concrete

Soheil Esfandiari^a, Seyedmorteza Raeisi Oskouei^a, Alexander Scholzen^a, Rostislav Chudoba^a

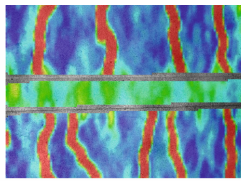
^a*Center for Structural Concrete Physics (CSCP) RWTHAachen University, Im Susterfeld 9, 52072 Aachen, Germany*

Abstract

This study presents an innovative experimental methodology for evaluating shrinkage eigenstrains and the corresponding mechanical properties of hardened concrete using embedded fiber-optic sensing technology. Fiber sensors were embedded vertically in a hollowed-core cylinder (205mm outer diameter and 58mm inner diameter), enabling high-resolution spatial mapping of eigenstrains evolution and gravity-induced consolidation effects. Temperature and humidity compensation was achieved through unbonded reference fibers and calibration measurements reported in the literature. The experimental program covered shrinkage monitoring for up to 88 hours after concreting. Strain field histories are decomposed into thermal and eigenstrain components. The resulting data set serves for calibration and validation of high-fidelity multi-physics models of concrete that predict hygro-thermo-mechanical interactions during the early age of concrete. In the long run, a combined experimental–numerical work-chain will provide deeper insight into the temporal and spatial distribution of temperature, strain, and gravity-effect fields from the earliest age of concrete, with the aim of elucidating the correspondence between the microstructural hydration process and long-term mechanical performance.

Keywords: Distributed fiber-optic sensing (DFOS); shrinkage eigenstrain; early-age concrete; structural health monitoring

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



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Experimental study of concrete tension members reinforced with BFRP-bars with integrated DFOS

Yasmin Lemcherreq^{a,1}, Christoph Czaderski^a

^a*Empa, Swiss Federal Laboratories for Materials Science and Technology, Ueberlandstrasse 129, 8600 Dübendorf, Switzerland*

Keywords: Distributed fiber optic sensing; BFRP reinforcement; strain measurement; bond behavior; integrated sensors

1. Introduction

Corrosion of steel reinforcement is one of the most common causes of damage in reinforced concrete structures worldwide. Particularly exposed structures—such as bridges, retaining walls, or parking decks—are subject to harsh environmental conditions that can lead to significant maintenance costs and reduced service life (Yilmaz & Angst, 2020). In this context, the use of non-metallic reinforcement has gained increasing relevance. Non-metallic reinforcement made of Fiber-Reinforced Polymers (FRP) is considered a potentially durable and sustainable alternative to steel reinforcement due to its corrosion resistance and favorable fatigue performance. Basalt fiber-reinforced polymer (BFRP) is especially promising, as it is cost-effective and environmentally friendly to produce compared to carbon FRP, while still providing high strength and good chemical resistance (Reichenbach et al., 2021).

Despite their promising properties, the widespread adoption of BFRP bars in structural engineering practice requires a thorough understanding of their interaction with the surrounding concrete. Their mechanical properties—characterized by a linear-elastic response until failure and a lower modulus of elasticity compared to steel—present challenges in terms of serviceability and lack of warning before failure. The bond between the FRP reinforcement and the concrete is a fundamental aspect governing the structural performance of FRP-reinforced members, influencing load transfer, crack width and spacing, and overall deformation response. Unlike steel bars, which rely on well-established ribbed surface geometries, the surface geometry of FRP is more variable and depends on the manufacturer. Examples include bars with sand-coating, helical winding, or profiled surfaces. Bond performance is further influenced by fiber type and resin matrix.

Conventional experimental approaches to studying bond behavior, such as pull-out tests, provide useful but limited insight. The pull-out setup imposes boundary conditions that do not accurately reflect the stress state in a real structural member, and provides only global measurements of force and displacement, which are subsequently transformed into a bond shear stress-slip relationship. These can be useful to compare the bond strength of different reinforcement-concrete configurations but neglect local effects. There is therefore a recognized need for more advanced measurement techniques capable of capturing the full strain field along the reinforcement with high spatial resolution under realistic boundary conditions.

Distributed fiber optical sensing (DFOS) based on Rayleigh backscatter has emerged as a powerful strain measurement tool, enabling continuous, high-resolution strain profiles to be measured directly at the reinforcement-concrete interface. The strain profiles enable the direct determination of the local bond stress from the strain, and consequently the stress gradients. DFOS not only overcomes the limitations of discrete strain gauges—which provide only point measurements and may disturb local bond conditions—but also enables the monitoring of shrinkage strains, crack initiation and propagation, and the overall response of the reinforced concrete element. A widely adopted approach for instrumenting the conventional steel reinforcing bars with DFOS is to place the fiber within grooves machined along the bar. This configuration provides a smooth surface for bonding the fiber and ensures good protection from mechanical impact. The drawback of slightly affecting the bar's integrity is accepted in view of the benefits associated with this approach (Lemcherreq et al., 2022). In some cases, the fiber is applied directly to the bar surface, for example along an existing longitudinal ridge. Grooves can similarly be machined along FRP bars to integrate the sensing fiber

¹ Corresponding author.

E-mail address: yasmin.lemcherreq@empa.ch

(Zhou et al., 2023). The physical properties of FRP also allow the sensing fiber to be integrated into the cross-section. Kalamkarov et al. (1998) incorporated fiber Bragg grating sensors into the FRP using a pultrusion process. Ott et al. (2025) incorporated the fiber into CFRP rods manufactured using a lay-up process, enabling them to derive a local bond stress-slip relationship in a pull-out test setup.

This study presents an approach for integrating the single-mode fibers into the pultrusion process of BFRP bars, including the recovery of fiber leads in order to perform the strain measurements. The integration process was designed to preserve the bars' surface quality and mechanical integrity, ensuring reliable continuous strain measurements along the full reinforcement length without compromising structural performance. The presented specimens are part of a larger experimental campaign investigating the bond behavior and structural performance of BFRP-reinforced concrete members. The scope of this extended abstract is limited to the implementation of the sensing fiber in the pultrusion production process and preliminary results obtained from the tension member tests.

2. Methodology and preliminary results

The embedded fiber optic sensor consisted of a single-mode, polyimide-coated fiber with an overall diameter of 125 μm . Given its small diameter, it can be assumed that the fiber will have no influence on the bars' mechanical properties.

The pultrusion was carried out on an industrial pultrusion line. The produced bars had a nominal core diameter of 16 mm and a helically profiled surface. The production was conducted with basalt rovings with a linear density of 2400 tex that were fed into the pultrusion machine. The rovings passed through an epoxy bath where they were impregnated and then through a forming ring to be compacted to a circular cross-section. The impregnated roving then passed through an oven where the resin was cured. After exiting the oven, the continuous rod was cut to the desired length using an automatic saw. The process operated continuously at a controlled pulling speed.

To integrate the optical fiber into the pultruded bar, a carbon rod was glued to the leading end of the glass fiber to guide the fiber through the pultrusion line. The fiber was manually inserted through a feed port ahead of the resin bath and pulled along with the basalt rovings at the production speed. At each end of the fiber, a steel protective tube of 0.8 mm diameter was fitted over a length of 30 cm to facilitate later extraction of the fiber leads. The surrounding rovings held the fiber in an approximately centered position within the bar cross-section, with the glass fiber running unsheathed between the two steel tubes, bonded directly by the epoxy resin matrix of the BFRP. After pultrusion, the bars were cut at the locations of the steel tubes, leaving protected fiber leads at both ends.

After post-curing, trapezoidal ribs were machined into the bars to enhance interlocking with the concrete. To connect a pigtail to one lead of the optical fiber and prepare a free end for water immersion at the other, the fiber ends had to be extracted from the bars. The bar ends were placed in an oven at approximately 500°C to decompose the matrix. The remaining basalt filaments were then trimmed to expose the steel tube. The steel tube was removed, and the pigtail was spliced to the fiber. A laser was used to verify whether the sensors had survived the manufacturing process (Fig. 1). All 21 bars from which fiber leads could be successfully extracted and spliced were functioning, demonstrating the high survivability of the unsheathed fiber within the BFRP matrix. The produced smart bars had a final length of between 1.6 m and 4.0 m and were used as reinforcement in various test specimens.



Fig. 1. Integrating optical fiber into pultruded BFRP bars (a) extracting the fiber from the bar; (b) connected pig tails (c) operational check.

The 1.6 m-long BFRP bars were cast centrally in three prismatic concrete blocks with a cross-section of 150 $\times$ 150 mm and a length of 1000 mm. To allow a direct comparison of the bond and deformation behavior, reference specimens of identical geometry were cast using B500B steel reinforcement of the same nominal diameter (16 mm). The steel bars were also instrumented with optical fibers placed within two grooves machined along the bar in a 180° configuration, following the recommendations by Galkovski et al. (2021). Normal-strength concrete with an expected compressive strength of 30 MPa was used for all specimens.

Figure 2 shows the strain profile measured along an embedded steel bar (a) and along an embedded BFRP (b) bar 27 days after casting, which represents the shrinkage-induced strains accumulated during this period. The optical fiber integrated into the BFRP bar during pultrusion delivered a notably more homogeneous distribution compared to the reference steel bar, where the strain profile shows a considerable fluctuation along the bar length. This difference is likely attributable to the position of the sensor on the bars. The smooth and consistent strain profile obtained from the BFRP bar confirms that the sensing fiber was successfully integrated during the pultrusion process, delivering reliable measurements.

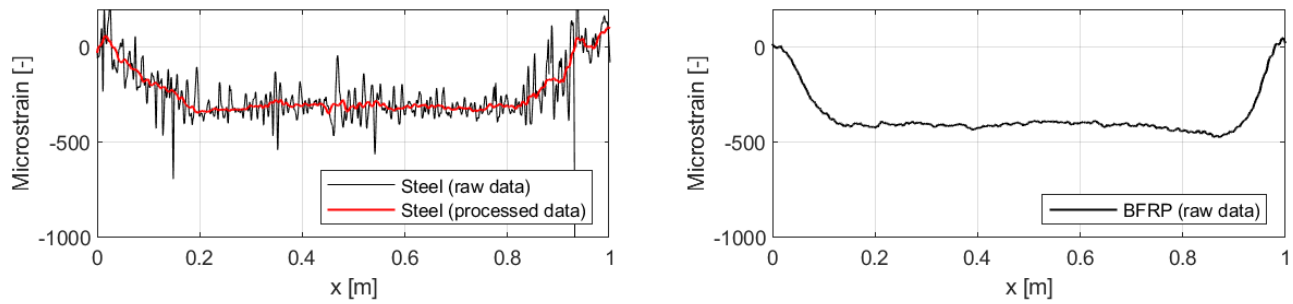


Fig. 2. Shrinkage strains profile 27 days after casting (a) along the embedded steel reinforcing bar; (b) along the embedded BFRP bar.

3. Conclusions

This study demonstrated the feasibility of embedding single-mode fiber optic sensors into BFRP bars during the pultrusion manufacturing process. The integration approach preserved the bars' surface quality and mechanical integrity, and preliminary measurements confirm that the sensing fiber delivers reliable, high-resolution strain profiles along the full reinforcement length. The distributed fiber optic sensing approach represents a powerful tool for performance assessment and structural health monitoring of FRP-reinforced concrete structures. Full results from the ongoing experimental campaign, including a detailed investigation of reinforcement-concrete interaction, crack development, and local bond shear stress-slip relationships, will be presented at SMAR 2026 in Dresden.

Acknowledgements

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Experimental investigation of FRP-concrete bond behavior by global and DFOS-based local analysis

Maximilian Kaiser^a, Tobias Wendler^a, Szymon Grzesiak^a, Christoph de Sousa^a, Matthias Pahn^a

^a*Department of Civil Engineering, RPTU University Kaiserslautern-Landau, Paul-Ehrlich-Straße 14, 67663 Kaiserslautern, Germany*

Abstract

Bond behavior between reinforcement and concrete enables force transfer, serviceability, and anchorage performance in concrete members reinforced with fiber-reinforced polymer (FRP) bars. Conventional pull-out test evaluation provides a global bond stress-slip response from pull-out force and unloaded-end slip. However, this evaluation does not resolve the spatial distribution of bond stress and slip along the bond length. This limitation can be addressed using distributed fiber optic sensing (DFOS), which is used to measure strain distributions along the reinforcement with high spatial resolution during loading. In this study, pull-out tests are conducted on concrete specimens reinforced with glass-fiber-reinforced polymer (GFRP) bars using two different surface configurations. The measurements are provided using DFOS sensors to derive local slip distributions, local bond stress distributions and position-dependent local bond stress-slip relationships. The results reveal clear differences between the two bar types in both global and local bond behavior. The sand-coated bar reaches a higher average bond strength and exhibits a stiffer global bond stress-slip response, but it also shows a more localized load transfer along the bond length. In contrast, the helically profiled bar exhibits a more distributed load transfer. Comparison of the local DFOS-based bond stress-slip relationships with the globally determined average relationship shows that the global response lies within the range of the local relationships, but does not represent their arithmetic mean. This distinction results from the use of position-dependent local slip values in the DFOS-based evaluation, whereas the global relationship is based on the measured unloaded-end slip. However, the global response does not fully capture the spatial variability of the local bond mechanisms. The findings demonstrate the value of DFOS for investigating FRP-concrete bond and provide a methodological basis for assessing local bond mechanisms in FRP reinforcement.

Keywords: Bond behavior; fiber-reinforced polymer (FRP) reinforcement; distributed fiber optic sensing (DFOS); bond stress-slip relationship

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

Information gain of distributed fiber optic sensors for concrete bridge monitoring

Numa Bertola^a, Francesco Fabbriatore^a

^a*University of Luxembourg, 2 Place de l'Université, L-4365 Esch-Sur-Alzette, Luxembourg*

Abstract

Distributed fiber optic sensors (DFOS) enable strain monitoring with millimeter-level spatial resolution. This new sensing technology offers unprecedented strain information gain, enabling the simultaneous monitoring of local (crack detection) and global (strain profile) of bridge behavior throughout unidimensional optical fibers up to 50-100 meters. Nonetheless, this sensing technology is still associated with high equipment costs and difficult sensor installation on existing bridges. This paper critically reviews the value of information from DFOS sensors for concrete bridge monitoring, in comparison with other conventional monitoring technologies. A 35-m prestressed concrete bridge in Switzerland is used as a case study. This prestressed-girder bridge from 1958 has been monitored since 2023 with DFOS and alternative technologies such as LVDT sensors, strain gauges, distributed acoustic sensing, and accelerometers. Results demonstrate the promising potential of DFOS as a new sensing technology for bridge monitoring, providing a unique panel of different information on the structural behavior.

Keywords: Distributed fiber optic sensors; bridge monitoring; structural health monitoring; bridge load testing; value of information

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

TRM strengthening of masonry panels with integrated optical fiber monitoring: a preliminary study

Marco Carlo Rampini^a, Eduardo Sellitto^a, Francesco Chiadini^b, Matteo Ferro^c, Marco Pepe^a, Paolo Sommella^b, Enzo Martinelli^a

^a*Department of Civil Engineering, Università degli Studi di Salerno, Italy*

^b*Department of Industrial Engineering, Università degli Studi di Salerno, Italy*

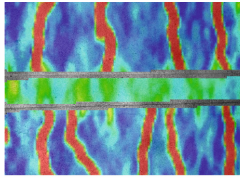
^c*Metering Research srl, Italy*

Abstract

In recent years, textile reinforced mortar (TRM) systems have become a well-established and effective solution for the retrofitting and strengthening of masonry, offering good compatibility with historical materials and improved mechanical performance. In parallel, structural health monitoring (SHM) systems based on optical fiber sensing are being increasingly explored as reliable tools for continuous assessment of structural behavior and early damage detection. This study investigates the shear performance of TRM-strengthened masonry panels using low-cost optical fiber sensors within the reinforcement meshes. Diagonal compression tests served to evaluate the mechanical effectiveness of the TRM strengthening and to assess the capability of the embedded optical fibers to detect crack formation and propagation. The monitoring system relies on optical time domain reflectometry (OTDR) technology, which enables distributed strain measurements along the fiber through a simple and cost-effective setup, including commercial interrogators and standard single-mode optical fibers. Preliminary results have shown the efficiency of the TRM strengthening system in enhancing the shear capacity and the potential of the integrated OTDR-based sensing to identify critical phenomena. Current limitations of the technique are discussed, while future improvements are outlined.

Keywords: Textile reinforced mortars; TRM; masonry structures; diagonal compression test; DFOS; retrofitting; monitoring; OTDR

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Bond stresses in RC tension chords with multiple rebars – influence of concrete cover

Jesper Harrild Sørensen^{a,1}, Linh Cao Hoang^a

^aDTU Construct, Koppels Allé Building 404, 2800 Kgs. Lyngby, Denmark

Keywords: Distributed fiber optical sensing; digital image correlation; bond stress; reinforced concrete

1. Introduction

In recent years, tremendous advancements have been made in the use of distributed fiber optical sensing for determination of bond stresses between rebar and concrete in reinforced concrete structures. The detailed information on the shear transfer that can be extracted allows for development of more precise calculation models, e.g. for implementation in upcoming design codes. This contribution presents experimental results of the shear transfer between rebar and concrete in tension chords with multiple rebars symmetrically placed around the center line of the specimen. A variation of the concrete cover with maintained reinforcement degree reveals that the resulting crack profiles change depending on the location of the rebars – i.e. increasing or decreasing the concrete cover. The results confirm the well-established relations in the literature that are also adopted in code provisions such as Eurocode 2, CEN (2004). A main highlight of this contribution is the experiences gained from attaching the fiber directly to the surface of the embedded rebar (by gluing) and the results should be viewed as trials for achieving a more practical and less time-consuming method than otherwise found as state-of-the-art, see e.g. Cantone et al. (2021) and Galkovski et al. (2022).

2. Experimental investigation

2.1. Specimen design and instrumentation

The experimental campaign comprised 6 tension chords, tested in uniaxial tension and monitored with high resolution 2D DIC for detection of surface cracks and Distributed Fiber Optical Sensing, inspired by Galkovski et al. (2021), for mapping of strain in the embedded rebars. All specimens had a cross section of 200 mm x 200 mm and were reinforced with 4 $\varnothing$ 12 mm rebars placed symmetrically in the cross section. Three variations of concrete cover were investigated, and all rebars were instrumented with a single sensor (green circle), see Fig. 1. The locations of the sensors were random depending on the location of the rebar seam.

2.2. Experimental setup

The experimental setup was prepared in the basement of DTU Structural Lab, where a hydraulic jack placed above the strong floor applied tension to a hinged centrally placed high strength threaded bar that via steel transitions pieces were connected to rebars couplers mounted on the reinforcement, see Fig. 2. For the purpose of 2D DIC, a high-resolution Nikon Z9 camera was used and an ODiSI 7100 system was used for the optical fiber sensors collecting data with a gage pitch of 0.65 mm. The tests were performed in displacement control with a rate of 1 mm/min, and the compressive strength of the concrete was around 50 MPa.

¹ Corresponding author. Tel.: +45 45251841
E-mail address: jhaso@dtu.dk

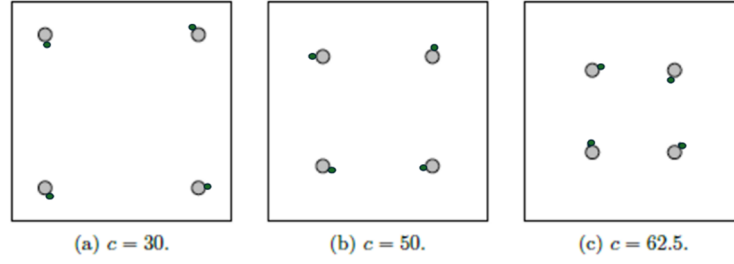


Fig. 1. Variations in reinforcement placement, concrete cover (in mm) and optical fiber placement.

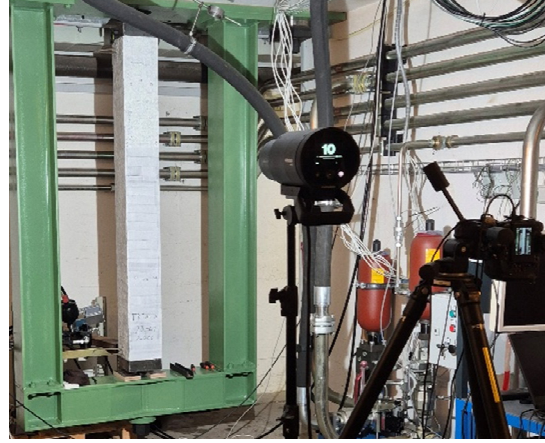


Fig. 2. Experimental setup, including artificial light source and high-resolution digital camera.

3. Experimental results

In the following, selected results of two specimens are presented for comparison. In Fig. 3, the results of a specimen with a concrete cover of 50 mm are shown at the point in time where the fully developed crack pattern was reached (Fig. 3a). The results of the DIC analysis along with the measured rebar strains confirm that at the location of the cracks, the rebar stress corresponds to a level where the rebars alone carries the full tension force (black dashed line, where red dashed line represents yielding). Where the crack spacing is large (e.g. at $x \sim 1.4$ m), the strain in the rebars is relieved, indicating that the concrete and the rebars carried the tension force as one transformed cross section (indicated with the lower black dashed line). In the lower graph in Fig. 3b, the calculated bond stresses are presented (based on the methods presented e.g. in Lemcherreq (2023)). For the purpose of evaluating the installation method of the fibers (by direct gluing onto the rebar), the strains have not been post-processed, and the shear stresses (bond stresses between rebar and concrete) have been averaged as a moving average over 5 data point. This demonstrates that the strains may look uniform and with little spatial variation, however, the derived shear stresses demonstrate a higher level of noise. Nevertheless, the shape of the shear stresses for a segment between two cracks can be generalized in shape and magnitude (horizontal dashed line corresponds to $2f_t$) for comparison with existing bond models, e.g. the fib Model Code 2010.

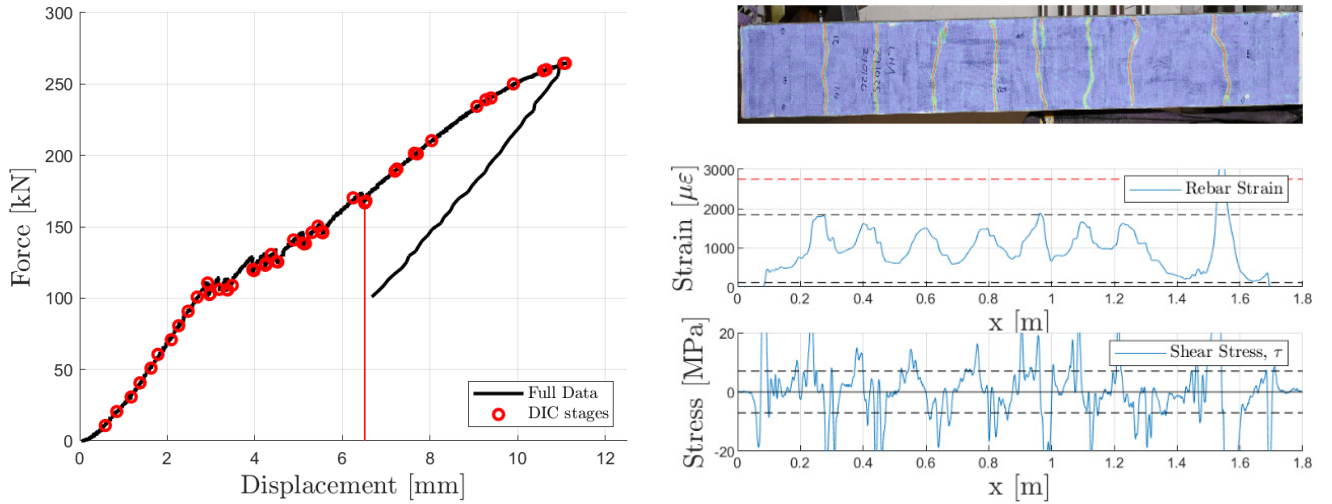


Fig. 3. Specimen with 50 mm cover.

Fig. 4 contains results of a specimens with concrete cover of 30 mm, at a similar stage (all cracks have developed). A preliminary comparison of the results in Fig. 3 and Fig. 4 show that the fully developed crack pattern occurs at a lower load level for the specimens with the smaller concrete cover and the total number of cracks are higher. In addition, longitudinal splitting cracks can be identified for the smaller cover (30 mm), which is not the case for the larger concrete cover (50 mm). The shear stresses show a similar trend in shape, however, deviating to a small extent in the maximum values and appears with fewer spikes (which may refer to the quality of the fiber sensor itself). This is in accordance with existing literature and current design guidelines, however, the additional information that can be extracted from the comparison is that the drop in rebar strain between two cracks (for all crack spacings) is significantly smaller for the smallest concrete cover. This confirms the expected behavior (in relation to effective concrete area per rebar) and demonstrates that there is a potential for extracting detailed information from the use of distributed fiber optical sensing, despite a non-ideal placement and installation procedure of the glass fiber sensors.

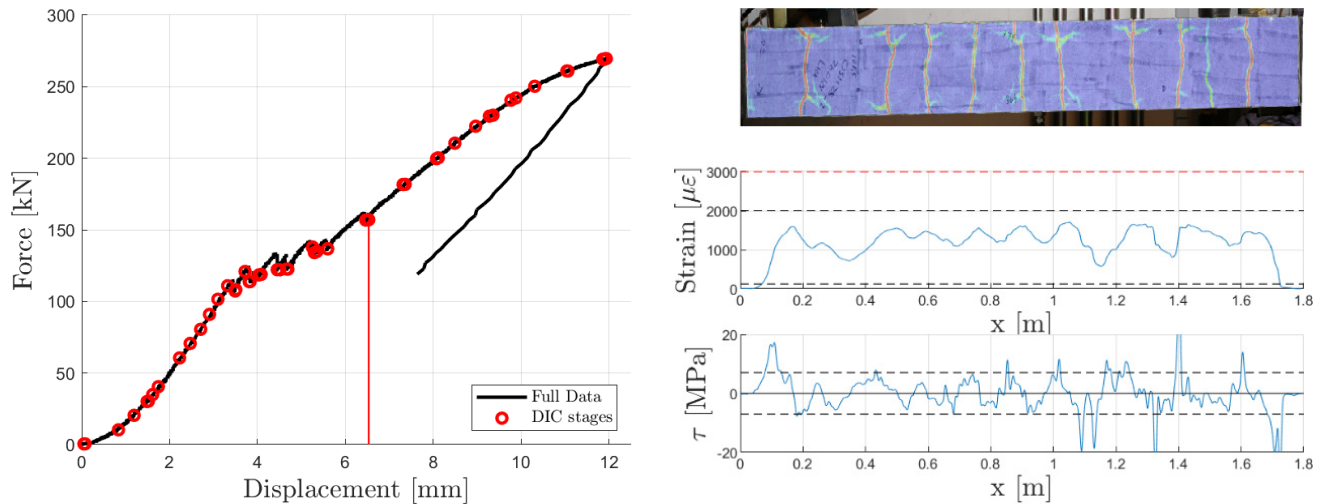


Fig. 4. Specimen with 30 mm cover.

4. Conclusions

The following preliminary conclusions can be drawn from the experimental uniaxial tests on tension chords with identical reinforcement degrees and varying concrete cover - mainly confirming existing knowledge, yet also contributing to the experiences towards a practical use of fiber optical sensors:

- A smaller concrete cover results in smaller crack spacing, e.g. demonstrated by development of a higher absolute number of cracks in the 1.8 m long tension chord, and longitudinal splitting cracks are more likely to develop.
- A larger concrete cover requires a higher load level to reach the final developed crack pattern.
- Fiber optical sensors (tight buffer) can be glued directly to the rebar without compromising the outcome of the measurements.
- When the crack spacing is smaller, the variations in rebar strains are smaller compared to a similar specimen with larger concrete cover.

Acknowledgements

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Preliminary study on crack monitoring in FRCM strengthening equipped with DFOS

Marco Carlo Rampini^a, Mohamed Saidi^b, Gabriele Cazzulani^c, Aron Gabor^d

^a *Department of Civil and Environmental Engineering, Politecnico di Milano, Italy*

^b *LOCIE, Université Savoie Mont Blanc, France*

^c *Department of Mechanical Engineering, Politecnico di Milano, Italy*

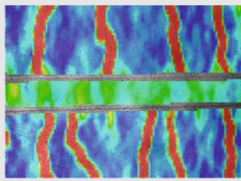
^d *LMC2, Université Claude Bernard Lyon 1, France*

Abstract

Fabric-Reinforced Cementitious Matrix (FRCM) systems are increasingly used for the strengthening and retrofitting of existing structures, offering advantages in terms of mechanical performance, durability, and compatibility with irregular substrates. In parallel, the growing need for innovative monitoring solutions has prompted research into embedding monitoring capabilities directly within strengthening materials. In this context, the present study aims to equip FRCM composites with monitoring capabilities by integrating Distributed Fiber Optic Sensors (DFOS) within the reinforcement to monitor the initiation and propagation of cracks. An experimental program was conducted at the material scale on AR-glass FRCM specimens instrumented with optical fibers. The strain profiles obtained from the DFOS along the reinforcement were analyzed to identify the transfer length and to estimate crack openings during direct tensile tests. These results of this procedure were compared with those measured by traditional instruments and Digital Image Correlation (DIC). The developed procedure was then preliminarily applied to a mesoscale reinforced concrete (RC) element strengthened with FRCM and equipped with DFOS, demonstrating the feasibility of the approach for monitoring crack evolution in composite-reinforced RC members. The outcomes highlight the potential of integrating DFOS into FRCM systems as a step toward smart strengthening materials combining mechanical performance and real-time monitoring.

Keyword: Fabric-reinforced cementitious matrix; FRCM; distributed optical fiber sensing; DFOS; strengthening; crack monitoring

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MS18/19: Advances in monitoring, assessment and rehabilitation of timber structures

Organizers (part 1):

Robert Jockwer (TU Dresden, Germany)

Pedro Palma (Empa, Switzerland)

Organizers (part 2):

Mike Sieder (TU Braunschweig, Germany)

Elena Perria (TU Braunschweig, Germany)

Maria Loebjinski (TU Braunschweig, Germany)

ABSTRACT

There is a strong trend to build timber buildings of greater height and higher consequence class. Given the novelty of taller timber buildings and timber's susceptibility to, e.g., moisture, creep, and brittle failures, these buildings can greatly benefit from monitoring throughout their service life. Simultaneously, as these buildings are exposed to normal use and accidental conditions, there is a need to develop maintenance and rehabilitation techniques.

The activities and techniques related to monitoring, assessment and rehabilitation of timber structures have traditionally focused on historic structures with cultural value. Modern timber buildings, however, require more early, effective, and economic intervention techniques. Research and developing is ongoing, both in academia and industry, and guidance is being implemented in standards and handbooks. All these advances and possibilities for monitoring, assessment and rehabilitation of timber structures will be discussed in this Mini Symposium.

Timber as a construction material is central to climate-friendly, resource-efficient and energy-efficient buildings. To achieve these goals, structures and construction techniques must be continuously improved. This mini-symposium focuses on recent research in the field of monitoring and assessment of new and existing timber structures, as well as on the rehabilitation of existing buildings. Monitoring is essential to detect damages at an early stage and to prevent structural failure. We will present findings on the influence of wood moisture during the construction process and on monitoring systems.

Assessment of timber becomes particularly important when knowledge of material properties in existing structures is limited. In this context, we will present research on material grading and the evaluation of existing structures.

Rehabilitation of structures is required to increase the load-bearing capacity or to preserve historic structures. We will share new insights into materials and structural systems, along with practical case studies

Development of the new Eurocode 5 part on assessment of existing timber structures

Robert Jockwer^a, Maria Loebjinski^b, Mike Sieder^b, Wolfgang Rug^c

^aChair for Timber Engineering, TUD Dresden University of Technology, Germany

^bInstitute for Building Construction and Timber Structures, TU Braunschweig, Germany

^cLaboratory for timber construction and ecological building technology, Eberswalde, Germany

Abstract

With the creation of the new Eurocode part EN 1990-2, there is also a need for the respective material specific Eurocodes dealing with the assessment and rehabilitation of existing structures. That is why the new Working Group (WG) 12 “Assessment and retrofitting of existing timber structures” was established within CEN TC250/SC5. WG12 aims to draft the new Eurocode 5 part with all the specific information and guidance for existing timber structures. This includes information on the assessment methods and procedures for existing timber structures and the determination of material properties as well as the identification and quantification of possible deterioration. Also, guidance is needed on the structural analysis and the subsequent verification methods, with the related possibilities for advanced probabilistic modelling, use of information in the updating of resistance values and partial factors. Furthermore, intervention and rehabilitation techniques should be given, that satisfy the specific and individual demands. The assessment and rehabilitation of existing timber structures require and allows for certain advanced methods and techniques compared to the design of new structures, such as different levels of verification without or with updating of partial factors or by means of probabilistic methods. This allows for the optimization of the intervention measure with regard to safety, economic values, societal demands, and sustainability targets. In the contribution, an overview of the background, objectives, preliminary content and development needs for the new Eurocode 5 part on assessment of existing timber structures will be given.

Keywords: Timber, assessment, rehabilitation, code development

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Preliminary visual assessment of historic timber structures in Georgia

Erkan Kambek^a, Nutsa Papiashvili^b, Gvantsa Potskhishvili^b

^aİstinye University, Ayazağa Mah. Azerbaijan Cad. (Vadi İstanbul 4A) Blok No: 3H Sarıyer/İstanbul, 34396, Türkiye

^bHeritage Conservation Laboratory, 8 Mtskheta Street, 0179, Tbilisi, Georgia

Abstract

This paper presents the initial findings from a collaborative research project focused on the condition assessment of historic structures in Georgia. The study addresses the vulnerability of this built heritage, specifically targeting a representative sample of twelve buildings. The surveyed structures comprise nine timber frame buildings and three timber-masonry hybrid constructions, providing a valuable cross-section of local building techniques.

The methodology centered on a systematic visual assessment campaign conducted in situ. This phase was critical for documenting construction typologies, identifying material degradation patterns, and cataloging significant pathologies specific to each structural system. The condition of primary timber elements (posts, beams, frames) and, in the hybrid structures, the critical interaction between timber and masonry components, was thoroughly evaluated.

Preliminary results reveal distinct degradation mechanisms. The timber frames commonly exhibited issues such as moisture-induced decay at foundations and deterioration of traditional joinery. In contrast, the hybrid structures displayed additional complexities, including potential differential settlement and failures at the timber-masonry interfaces. This data has been synthesized into a preliminary risk matrix, which will directly inform the planning of a subsequent non-destructive testing (NDT) campaign. The outcomes establish a foundational framework for the long-term monitoring and rehabilitation of these vulnerable structures, underscoring the necessity of tailored approaches for different historical construction systems.

Keywords: Historic timber structures; visual assessment; structural condition; Georgian mosques; cultural heritage

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Prediction of mechanical timber properties – experimental investigation and updating

Luca Gehling^a, Maria Loebjinski^{a,b}, Jan Grobe^a, Elena Perria^a, Mike Sieder^a

^a*TU Braunschweig, Institute for Building Construction and Timber Structures, Germany*

^b*WKC Hamburg GmbH, Germany*

Abstract

The determination of mechanical properties of timber components in existing structures by instrument-assisted visual strength grading has great potential. The Sylvatest 4 measures the ultrasonic pulse transit time, which is directly influenced by the wood's characteristics, to infer the modulus of elasticity (MOE) and the modulus of rupture (MOR). The aim of this study was to examine the potential of the Sylvatest 4 and to compare the parameters from destructive testing in accordance with DIN EN 408 (2012) with those from visual strength grading in accordance with DIN 4074-1 (2012). The collected data was then used in a statistical analysis in order to update the target properties. The investigations were conducted on 20 spruce beams without finger joints, produced from solid structural timber of strength class C24 (12×12×240 cm) in direct and indirect configurations. The comparison of the MOE showed that both measurement methods, indirect and direct, exhibited a mean relative deviation of approximately 49% compared to the test results (DIN EN 408). The linear regressions showed a parallel offset relative to the test results. For the MOR, substantial over- and underestimations were identified; however, the absolute mean relative deviation was approximately 7.6%. The data were then used for further statistical analysis. A Stochastic Grading Model was applied to establish a linear regression considering a measurement error. Since in situ sample sizes are often limited, an exemplary dataset was used to update the strength properties by Bayesian updating, combining measured data and prior information.

Keywords: Strength grading, NDT, destructive testing, material updating

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Combination of NDT for assessment of timber beam stiffness in view of reusability

Eline Vandecruys^a, Xander Detremmerie^b, Geert Lombaert^a, Robby Caspeele^b, Els Verstrynge^a

^a*KU Leuven, Department of Civil Engineering, Kasteelpark Arenberg 40, Leuven, Belgium*

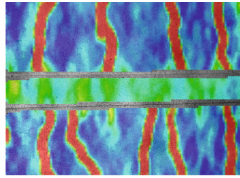
^b*Ghent University, Department of Structural Engineering and Building Materials, Technologiepark-Zwijnaarde 60, Ghent, Belgium*

Abstract

The reuse of construction materials is increasingly recognized as a key research topic to improve the circularity of the construction sector. In this context, investigating the reusability of timber elements is particularly challenging due to the material's intrinsic heterogeneity and the degradation accumulated over its lifetime. This study investigates the static stiffness of reclaimed timber beams within a probabilistic framework through the application of non-destructive test (NDT) methods combined with Bayesian updating. An experimental program was performed on 24 reclaimed timber beams, employing NDTs such as visual analysis and density measurements, ultrasonic pulse velocity (UPV) testing, and dynamic testing (DT), to establish a comprehensive dataset. Linear regression models were developed using a reference subset of beams to relate NDT outputs to static stiffness. Afterwards, Bayesian updating was applied to a remaining independent set of beams to quantify how combining multiple NDTs improves assessment reliability. Prior estimates based on simple indicators (annual ring width or density) were updated using UPV and DT results to obtain posterior distributions of the beams' stiffness. Finally, the posterior predictions were validated against four-point bending tests, demonstrating that Bayesian updating with complementary NDT techniques enhances the accuracy and robustness of stiffness estimation for reclaimed timber elements.

Keywords: Timber reuse; non-destructive testing; Bayesian updating; static stiffness

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Non-destructive assessment of hybrid CLT

Vittoria Borghese^{a,1}, Niels Vonk^a, Jan Niederwestberg^a

^aNetherlands Organisation for Applied Scientific Research (TNO), Molengraaffsingel 8, Delft, 2629 JD, The Netherlands

Keywords: Cross-laminated timber (CLT); finite element analysis (FEA); layer properties; modal analysis; non-destructive testing (NDT)

1. Introduction

Cross-laminated timber (CLT) has become a prominent engineered-wood solution in mass-timber construction because it combines structural efficiency with the environmental advantages typically associated with timber-based systems, as discussed by Pajchrowski et al. (2014). As outlined by Swedish Wood (2019), CLT consists of orthogonally arranged timber layers that enable plate-like structural behaviour in both principal directions. More recently, research on hybrid CLT has explored the combination of different timber resources, including reclaimed wood, in order to enhance material efficiency and broaden the structural application of multilayer timber panels, as shown by Wang et al. (2017) and Llana et al. (2022). However, the increased heterogeneity of these systems makes the prediction of global mechanical properties more complex, particularly when simplified design approaches are based on mean layer stiffness values. In this context, non-destructive techniques and vibration-based methods have proven to be effective tools for estimating stiffness-related properties of CLT panels, as demonstrated by Gulzow (2008) and Giaccu et al. (2019). Against this background, the present study investigates the out-of-plane mechanical behaviour of five-layer hybrid CLT panels composed of Dutch-grown Ash and Douglas-Fir, with reclaimed Spruce adopted in the cross layers, by integrating lamella-level non-destructive characterization, full-scale modal testing, and parametric finite-element modelling.

2. Materials and experimental program

The experimental investigation was carried out on five-layer hybrid CLT panels manufactured from three different timber resources: Dutch-grown Ash (*Fraxinus excelsior*), reclaimed Spruce (likely *Picea abies*), and Dutch Douglas-Fir (*Pseudotsuga menziesii*). Prior to panel fabrication, the individual lamellae were finger-jointed, planed to the target cross-sections, and non-destructively graded in terms of longitudinal modulus of elasticity. In particular, the longitudinal stiffness of each lamella was determined through vibration-based machine grading, in accordance with EN 14081-2 (CEN, 2019), by combining eigenfrequency measurements with density and moisture-content data. Based on these results, a hybrid layout (Tab. 1) was selected in order to maximize bending efficiency, with Ash adopted in the outer longitudinal layers, reclaimed Spruce in the cross layers, and Douglas-Fir in the core layer.

Table 1. Hybrid CLT layout and mean longitudinal stiffness of the layers.

Layer	Material	Thickness [mm]	Mean E_x [MPa]
1	Ash	39	13312
2	Reclaimed spruce	16	10646
3	Douglas-fir	21	10623

Ten panels with overall dimensions of $2980 \times 1200 \times 138$ mm were produced (Fig. 1); because of the limited availability of reclaimed material, the two cross layers had different thicknesses, resulting in a slightly asymmetrical configuration. The lamellae were placed randomly within each layer, while their exact positions were recorded during assembly for subsequent comparison

¹ Corresponding author. Vittoria Borghese
E-mail address: vittoria.borghese@tno.nl

with the numerical models. Out of the ten manufactured panels, eight were assessed through non-destructive modal testing, whereas two were reserved for destructive mechanical tests. The modal campaign was performed under free-free boundary conditions using a grid of accelerometers and an impulse-hammer excitation system, following an approach consistent with vibration-based identification methods previously adopted for CLT panels by Gulzow (2008) and Giaccu et al. (2019). This setup enabled the identification of the natural frequencies and mode shapes required to estimate the out-of-plane bending stiffness in the major and minor directions, as well as the in-plane shear response of the hybrid panels.

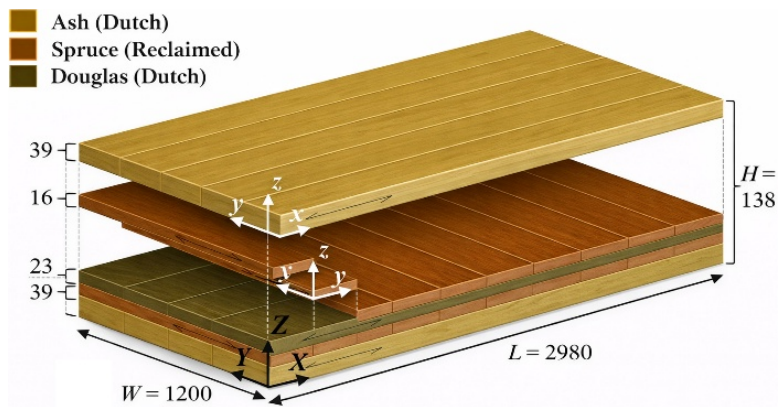


Fig. 1. Schematic layout of the five-layer hybrid CLT panel and experimental setup adopted for modal testing.

3. Numerical modelling

A fully parametric three-dimensional finite-element framework was developed to reproduce the dynamic response of the hybrid CLT panels and to assess the influence of different stiffness-assignment strategies on the predicted modal behaviour (Fig. 2). The numerical model was implemented in DIANA FEA through Python-based routines for input generation, model assembly, and output processing, allowing an explicit representation of the panel geometry and of the orthotropic orientation of each lamella. In contrast with simplified plate-based formulations, the adopted three-dimensional approach was intended to capture through-thickness bending, shear, and torsional effects more accurately, in line with the observations of Reddy (2004). Each lamella was modelled as an eight-node hexahedral solid element and connected to adjacent lamellae through rigid tie constraints reproducing the glued interfaces, while layer-dependent local axes were assigned according to the actual fibre orientation. The elastic behaviour of each lamella was assumed linear-elastic orthotropic, with the full set of material constants derived from the measured longitudinal modulus and from fixed orthotropic ratios based on Senalik and Farber (2021). Within this framework, three alternative modulus-assignment strategies were examined: direct use of the measured modulus of each lamella in its recorded position, use of an average modulus for each layer, and random assignment of moduli sampled from the corresponding layer datasets. Modal analysis was then carried out to extract eigenfrequencies, displacements, and mode shapes, enabling a direct comparison with the experimental campaign and an evaluation of the sensitivity of the numerical predictions to the adopted material idealization. Huang et al. (2020) are also referenced in the paper as an example of alternative, lower-dimensional modelling approaches for CLT systems.

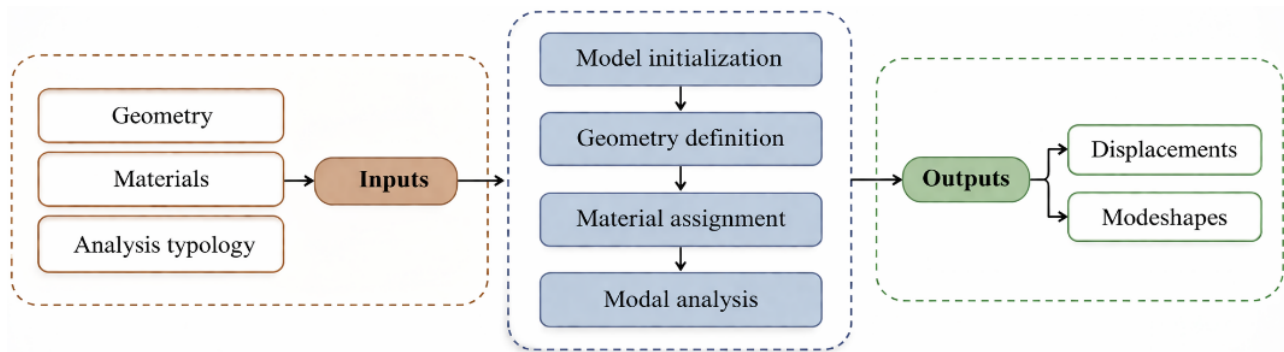


Fig. 2. Flowchart of the structural framework analysing the inputs, the model creation on DIANA FEA environment and the outputs.

4. Main results and discussion

The comparison between numerical predictions, non-destructive experimental estimates, and destructive test results highlights the main mechanical features of the investigated hybrid CLT panels. Overall, the three modulus-assignment strategies produced closely comparable stiffness predictions, indicating that the numerical response is relatively robust with respect to the adopted level of detail in material-property allocation (Fig. 3). This trend is particularly evident for the longitudinal modulus E_x , for which all

modelling approaches yielded values within the range of experimental variability, supporting the use of simplified average layer properties for practical stiffness estimation. A systematic offset, however, was observed between the finite-element predictions and the NDT-based values, suggesting that part of the discrepancy is not random but related to modelling assumptions, including the adopted orthotropic property ratios. In the major direction, the FE model showed very good agreement with destructive testing, with a relative error of only 1.58%, while the NDT estimate differed by 2.5%; the difference between numerical and non-destructive results was 4.1%. This strong agreement can be explained by the dominant role of the outer Ash layers, which are both the thickest and the stiffest and therefore govern the global longitudinal bending response. By contrast, the transverse modulus E_Y and the shear modulus G_{XY} exhibited larger deviations between numerical and non-destructive estimates, equal to 15.6% and 17.3%, respectively. These differences indicate a greater sensitivity of the minor-direction and shear response to orthotropic assumptions and to the material heterogeneity of the thinner reclaimed Spruce cross layers. Overall, the results confirm that the proposed FE framework is highly effective for predicting the dominant longitudinal stiffness of hybrid CLT panels, whereas more refined material characterization and shear modelling are still required to improve the prediction of transverse and torsional-related properties.

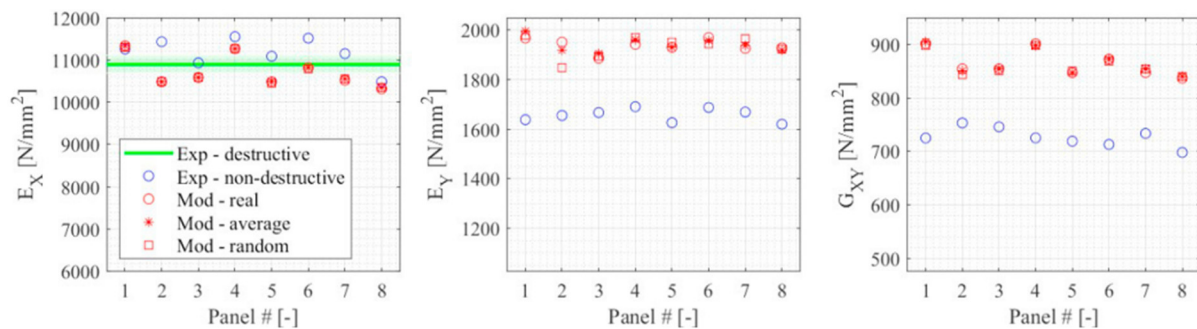


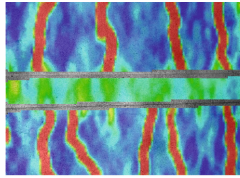
Fig. 3. Comparison between experimental and numerical stiffness values of the hybrid CLT panels in terms of longitudinal modulus (E_X), transverse modulus (E_Y), and shear modulus (G_{XY}).

5. Conclusions and engineering implications

The present study confirms that the combined use of non-destructive testing and parametric finite-element modelling provides an effective framework for evaluating the out-of-plane mechanical behaviour of hybrid CLT panels made from heterogeneous timber resources. The results demonstrate that the numerical approach is able to predict the dominant longitudinal stiffness with high accuracy, showing very limited deviation from destructive reference testing. From an engineering perspective, this suggests that simplified modelling strategies based on average layer properties may be considered sufficiently reliable for estimating the global stiffness in the principal bending direction of similar hybrid panels. At the same time, the larger discrepancies observed for the transverse and shear-related properties indicate that these response components remain more sensitive to orthotropic assumptions, layer heterogeneity, and modelling simplifications. Therefore, while the proposed framework supports the practical structural assessment of hybrid CLT systems and strengthens the case for the inclusion of reclaimed timber in engineered wood products, further refinement is still required for a more accurate prediction of minor-direction and shear behaviour. Overall, the study highlights the potential of hybrid CLT as a structurally viable and resource-efficient solution, while also underlining the importance of calibrated modelling strategies when heterogeneous material configurations are involved.

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Enhancing CT accuracy of historic timber via LTI-SIRT with velocity compensation

Vittoria Borghese^{a,1}, Ling Xuewei^b, Cristoforo Demartino^c, Chen Dongdong^b

^aNetherlands Organisation for Applied Scientific Research (TNO), Molengraaffsingel 8, Delft, 2629 JD, The Netherlands

^bCollege of Civil Engineering, Nanjing Forestry University, Nanjing, Jiangsu, 210037, P.R. China

^cDepartment of Architecture, Roma Tre University, Largo Giovanni Battista Marzi 10, Rome, 00153, Italy

Keywords: Ultrasonic computed tomography; timber diagnostics; wood anisotropy; chord-angle compensation; internal defect detection; historical timber structures

1. Introduction

The condition assessment of ancient timber members requires diagnostic techniques capable of identifying internal voids, cracks, and decay without damaging the original material. Among the available non-destructive methods, ultrasonic testing is particularly attractive because it is safe, portable, and suitable for in-situ inspection, while ultrasonic computed tomography (USCT) can reconstruct the internal velocity distribution of a timber cross-section and therefore support defect localization. However, the reliability of USCT in wood is strongly affected by material anisotropy, since wave propagation varies with grain direction and growth-ring orientation. Previous studies have shown that accounting for orthotropic behaviour significantly improves tomographic reconstruction and defect detection in wood (Perlin et al., 2019; Espinosa et al., 2020; Zielińska and Rucka, 2023). In this context, the present study develops a chord-angle-based wave velocity compensation model and integrates it into the LTI-SIRT reconstruction framework in order to reduce direction-dependent errors in time-of-flight data and improve the imaging of internal defects in ancient timber members.

2. Methodology

The study combined a numerical benchmark with laboratory ultrasonic tomography on timber columns in order to evaluate the proposed chord-angle compensation framework under controlled and realistic conditions (Fig. 1).

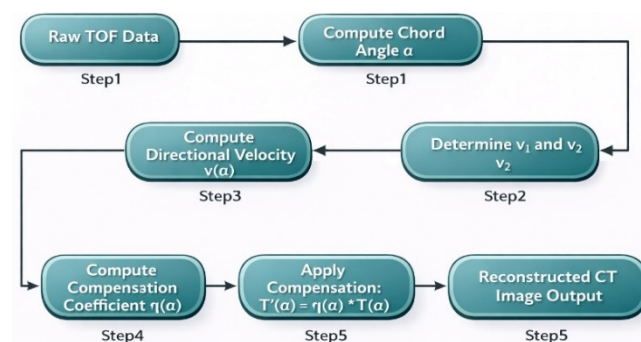


Fig. 1. Workflow of the proposed chord-angle-based wave-velocity compensation method and its integration into the CT reconstruction framework.

¹ Corresponding author. Vittoria Borghese
E-mail address: vittoria.borghese@tno.nl

At the methodological level, the standard LTI-SIRT reconstruction scheme was extended through two alternative compensation strategies. In the first, denoted E-LTI-SIRT, the correction coefficients were derived from wave velocities measured in an intact reference layer. In the second, denoted T-LTI-SIRT, the same coefficients were obtained from an analytical chord-angle-dependent velocity model based on the tangential and radial components of ultrasonic propagation. In both cases, the corrected time-of-flight data were then used as input for tomographic reconstruction.

For validation, two balsam fir columns were tested: a small-hole timber (SHT) specimen and a big-hole timber (BHT) specimen (fig. 2), both 20 cm high and 30 cm in diameter. The SHT contained a cylindrical void 4 cm in diameter and 9 cm deep, whereas the BHT included a larger defect 13.5 cm in diameter and 12 cm deep. Each specimen was instrumented with 20 circumferential measurement points and investigated over five horizontal layers spaced at 3.5 cm.



Fig. 2. Small hole timber (left); Big hole timber (right).

Ultrasonic measurements were acquired with a Proceq Pundit PL-200 system by sequentially activating one point as transmitter and the remaining points as receivers, which yielded 380 signal pairs per layer. In parallel, a two-dimensional finite-element model with matching geometry, sensor layout, and defect configuration was developed to provide a benchmark for the reconstruction procedure and to isolate algorithmic effects from geometric complexity (Fig. 3).

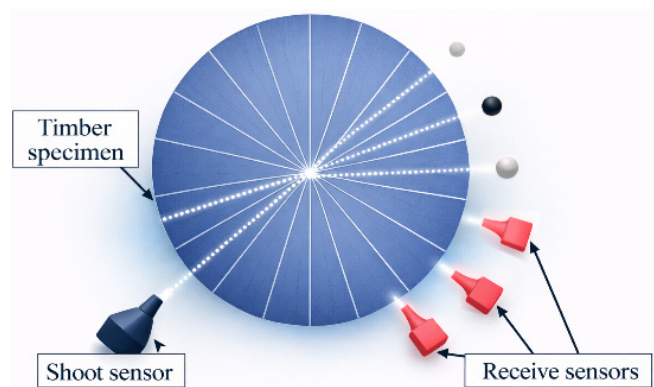


Fig.3. Schematic diagram of timber test.

3. Results and discussion

The results demonstrate that chord-angle-based velocity compensation substantially improves ultrasonic tomographic reconstruction in comparison with the conventional LTI-SIRT approach (Fig. 4). For the small-hole timber (SHT) specimen, the uncompensated algorithm markedly overestimated the defect area, yielding a reconstructed defective area ratio of 6.74% against a true value of 2.17%. By contrast, the compensated schemes provided a much closer agreement with the actual defect geometry, reducing the reconstructed area to 2.44% for E-LTI-SIRT and 2.86% for T-LTI-SIRT. A similar improvement was observed in defect localization: the standard LTI-SIRT method failed to identify the void reliably, whereas the compensated approaches reduced the average displacement error to 9.50 mm and 11.40 mm, respectively (Fig. 5). These results indicate that velocity correction is essential when small defects must be resolved in anisotropic timber sections. A consistent trend was also obtained for the big-hole timber (BHT) specimen. In this case, the real defective area ratio was 18.90%, while the conventional LTI-SIRT reconstruction overestimated it as 28.17%. Both compensation procedures significantly improved the reconstruction accuracy, leading to defect area ratios of 19.86% for E-LTI-SIRT and 19.91% for T-LTI-SIRT. The positional accuracy followed the same pattern: the mean displacement error decreased from 24.17 mm for the uncompensated method to 13.11 mm for E-LTI-SIRT and 16.32 mm for T-

LTI-SIRT. Although the experimentally calibrated strategy achieved the best overall accuracy, the theoretically compensated method still provided a substantial improvement and showed good robustness for larger defects.

From an application perspective, the comparison between the two compensation strategies highlights a trade-off between accuracy and practicality. E-LTI-SIRT performs slightly better because the correction coefficients are derived from measured wave velocities in healthy timber regions. However, this requirement limits its applicability in field conditions, where intact reference layers may not be identifiable. T-LTI-SIRT is therefore particularly relevant for in-situ assessment, since it estimates the compensation coefficients directly from a theoretical velocity model and avoids extensive preliminary calibration. Overall, the results confirm that chord-angle compensation effectively reduces anisotropy-induced imaging errors and significantly enhances defect detection in ancient timber members.

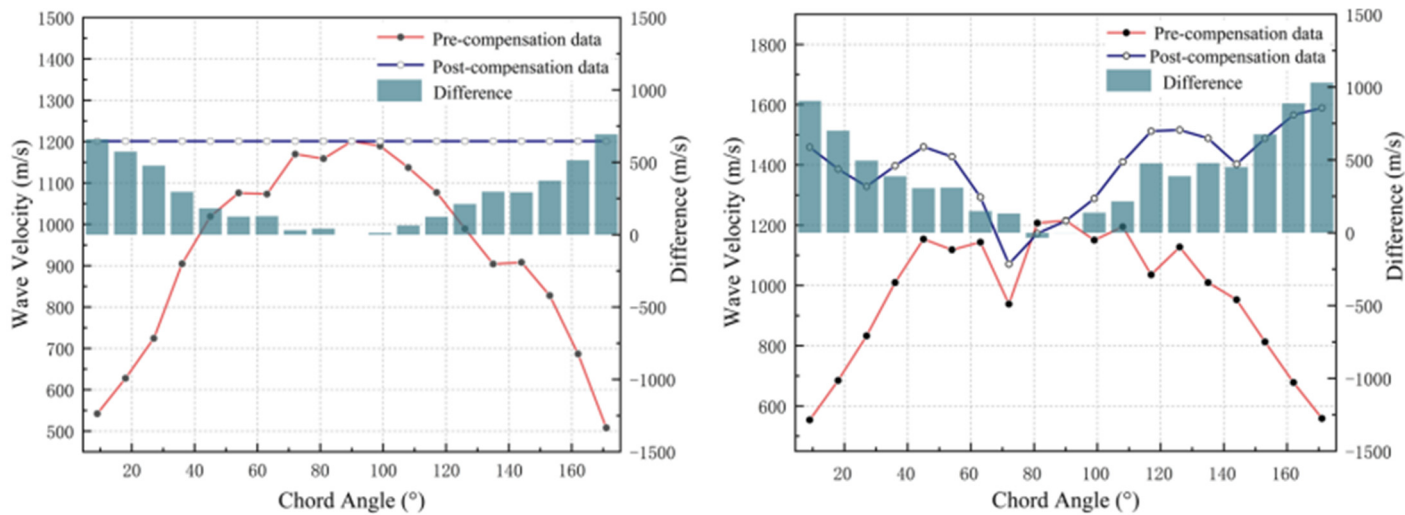


Fig. 4. Wave velocity before and after chord angle compensation for (left) the healthy layer of SHT; and (right) the defective layer of SHT.

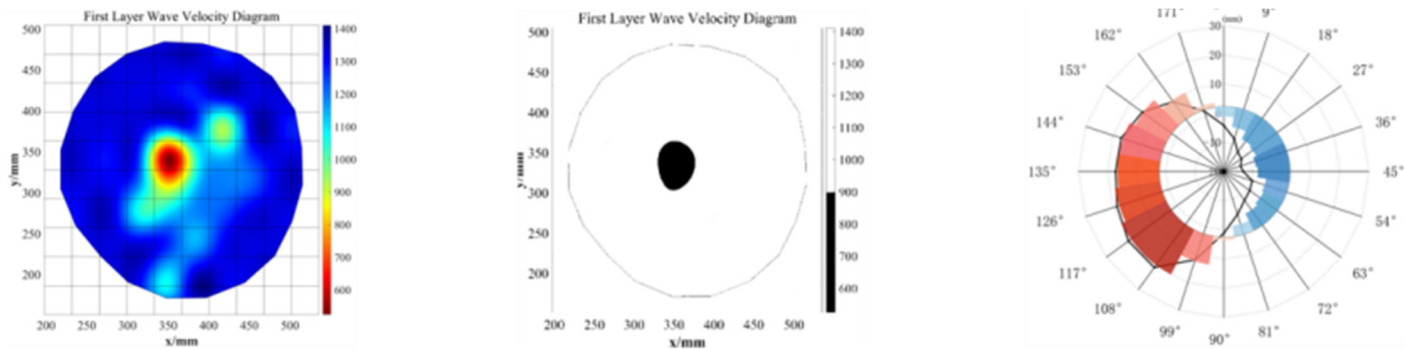


Fig. 5. Chord angle compensation of SHT in first layer using T-LTI-SIRT (left) wave velocity diagram; (center) binary diagram; and (right) error rose diagram.

4. Conclusions

This study shows that incorporating chord-angle-dependent wave velocity compensation into the LTI-SIRT framework significantly improves ultrasonic tomographic imaging of anisotropic timber members. Compared with the conventional uncompensated reconstruction, both E-LTI-SIRT and T-LTI-SIRT provided more accurate estimates of defect size and location in specimens containing either small or large internal voids. The experimentally calibrated strategy achieved the highest accuracy, whereas the theoretical formulation offered a more practical solution for on-site applications because it avoids the need for preliminary measurements in healthy layers. Overall, the proposed compensation approach reduces anisotropy-induced errors in time-of-flight data and enhances the reliability of USCT for the diagnosis of ancient timber structures, making it a promising tool for non-destructive inspection in cultural heritage and structural assessment.

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Hygro-mechanical response of a timber canopy: integrating SHM data and FEM simulations

Sadra Shahsavara, Ine Knoopsa, Dan Dragan^a, Jose Henriques^a, Bram Vandoren^a, Eline Vereecken^a

^a Construction Engineering Research Group, UHasselt, Agoralaan, 3590 Diepenbeek, Belgium

Abstract

Timber structures are sensitive to environmental conditions that affect their moisture content, which in turn influences their mechanical and physical properties over time. structural health monitoring (SHM) plays a crucial role in structural assessment by enabling early damage detection and providing continuous insight into in-service behavior. At the ACB² lab of Hasselt University, an outdoor wooden canopy with a mechanically jointed cross-laminated roof, supported by four timber columns, has been constructed and instrumented as a long-term field demonstrator. The multisensor layout continuously records roof and column moisture content, ambient and surface temperatures, relative humidity, wind speed, and both vertical and horizontal deformations. This paper presents sensor readings and the insights derived from them, highlighting location-dependent differences in moisture content and canopy deformation. In addition, it explores how a finite element model can complement the monitoring data to better interpret the canopy's hygro-mechanical response. The combined analysis provides an improved understanding of the environmental effects on the structural behavior.

Keywords: Timber structures; structural health monitoring (SHM); moisture content; finite element modeling; hygro-mechanical response

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

Can pre-war vernacular houses in the Ore Mountains offer a good indoor microclimate?

Dominika Výšková^a, Daniela Bošová^a

^aCzech Technical University in Prague – Faculty of Architecture, Thákurova 9, 166 34 Prague 6, Czech Republic

Abstract

This paper presents the results of indoor microclimate monitoring conducted in preserved pre-war vernacular family houses located in the Kraslice region in the Ore Mountains.

Although the vernacular dwellings of this region are not legally protected, they possess valuable architectural qualities that are worth preserving. Their design was influenced by the German folkloric style known as “Heimatstil”. Most of the settlements date from the late 19th and early 20th centuries, with some examples originating even earlier. The dating of individual buildings was determined through archival research of original building plans. Most of the studied houses feature log or half-timbered structures, while later buildings incorporate brickwork. The most interesting examples are exposed brickwork with decorative use of yellow bricks, contrasting with red masonry.

To examine whether these preserved pre-war vernacular houses can still provide suitable living conditions for contemporary use, three buildings were selected as case studies. Indoor microclimate monitoring was conducted over one week in different seasons. The autumn period represented average weather conditions, while the summer and winter measurements captured more extreme climatic situations. Data were collected on indoor and outdoor air temperature, relative humidity, and carbon dioxide concentration.

The results indicate that it is possible to achieve a healthy indoor microclimate even in houses that remain largely in their original structural state. However, maintaining comfortable conditions during winter requires considerable effort from the occupants. Houses made of brickwork tend to keep higher relative humidity during the whole year than buildings with log construction.

Keywords: Log construction; half-timbered construction; brickwork; indoor microclimate; vernacular architecture

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

Comprehensive assessment and static analysis enabling rehabilitation through compensatory measures alone: a case study

Perria Elena^a, Mike Sieder^a

^a*Institute of Building Construction and Timber Structures, Schleinitzstrasse 21A, 38106 Braunschweig, Germany*

Abstract

As part of a joint project between the Technische Universität Braunschweig and the Rittergut Lucklum (Lucklum Manor, Lower Saxony, Germany), an object-related investigation was carried out on the historic timber beam construction that forms the floor of the Rittersaal (Knight's Hall). The Rittersaal is located on the first floor of the main building of the manor and is used for public events such as concerts, readings and ceremonies. Directly below the Rittersaal on the ground floor is the living room of a private apartment belonging to the former owners of the manor. Due to the Rittersaal's usage, the floor slab is subjected not only to dead loads, but also to live loads from gatherings of people. As more, partly undocumented changes in the construction and renovation measures have been carried out over the lifetime of the building; therefore, there is little reliable information available about the load-bearing structure itself and the actual load-bearing capacity of the timber ceiling construction. In addition, the timber beams showed clear signs of insect decay. For these reasons, the Institute of Building Construction and Timber Structures was commissioned to carry out a survey of the timber ceiling, identify the existing load-bearing system, map the damage and conduct material tests and a static analysis. Based on the results of these investigations, carried out with the support of student work, it became possible to continue using the hall for events and the exposed timber beam ceiling in the living room without disruptive reinforcement measures, but thanks to compensatory measures.

Keywords: Assessment, timber ceiling, drilling resistance, static analysis, rehabilitation

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

Museum of Local History Sternberg: a holistic rehabilitation of the historic building substance

Andreas Meisel^a, Björn Schlichting^a, Christian Mägde^a, Maria Loebjinski^{a,b}

^a*WKC Hamburg GmbH, Germany*

^b*Technische Universität Braunschweig, Germany*

Abstract

The substance-careful rehabilitation of historic structures aims to combine the preservation of our cultural heritage with modern demands of intended use and safety requirements. The Museum Sternberg, situated in one of the oldest community centers of the town, represents an impressive example for this task. The building is part of an ancient Augustinian monastery that has been erected in the early 16th century. The museum itself was built in 1747 as secular building and served different functions over time before it finally became a museum of local history. During an investigation in 2018 fundamental damages of the substance of the building were documented. The characteristic half-timbered house, built from oak and pine timber, suffered from its exposure to high moisture due to damaged claddings, a diffusion-tight façade coating as well as insufficient height of plinths. Over the decades, these shortages caused local decay of the timber elements, massive deformations and bending failures. The present contribution shows exemplary practical solutions for substance-careful rehabilitation. Using modern technical tools such as 3D-scanning, drilling resistance measurements and interdisciplinary work of engineers, architects, preservationists and carpenters, sustainable rehabilitation solutions have been developed.

Keywords: Historic timber structures; investigation; structural analysis; rehabilitation

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

Re-use of timber piles with the application of CFRP

Jendrik Heithorn^a, Nabil A. Fouad^a

^a*Leibniz Universität Hannover, Institut für Bauphysik, Hannover 30167, Germany*

Abstract

The publication deals with the implementation of rigidly butted wooden piles with CFRP. Wooden piles are used in coastal protection as groynes (German Baltic Sea coast) and in harbour construction as dolphins, for example. However, climate change is causing the spread of *Teredo Navalis*, which is increasingly replacing native woods in hydraulic engineering. The potential for the rigid connection of piles could result in cost savings in terms of boring mussel-resistant wood and the reuse of waste wood. In order to achieve this objective, the CFRP connection was subjected to full-scale bending tests. Subsequently, the load case of pile driving was tested on a 1:1 scale at the Test Centre for Supporting Structures in Hanover. Subsequent to the proof of concept, a series of one-sided tensile shear tests were conducted to investigate the composite properties between CFRP and wood.

Keywords: Wwooden piles; *Teredo Navalis*; pile driving test; shear test; connection; timber

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

Investigation of recoverability of prestressed self-centering rocking timber columns

X. Chen^a, R. Zhang^a, Y.B. Leng^a, F.W. Zhang^a, M.Q. Wang^a, L.Z. Chen^a, Q.F. Xu^a

^a*Shanghai Key Laboratory of Engineering Structure Safety, Shanghai Research Institute of Building Sciences Co. Ltd, Shanghai 200032, China*

Abstract

Previous studies have demonstrated that prestressed glulam columns exhibit excellent self-centering capability, energy dissipation capacity, and ductility under low-cycle reversed loading, and their hysteretic behavior differs significantly from that of conventional reinforced concrete or steel structures. However, reasonable control of prestress level, evaluation of prestress loss, and post-earthquake recoverability remain key issues for promoting their practical application. To address these issues, seven seismic performance tests on prestressed glulam columns were conducted in this study to investigate the effects of different initial prestress levels on mechanical behavior and post-earthquake recovery performance. The test results indicate that the prestressed glulam columns exhibited satisfactory seismic performance and did not suffer severe damage when the story drift ratio reached 1/20. Due to the symmetrical arrangement of prestressing threaded steel bars, as the lateral load increased, the tensile force in one bar increased while that in the opposite bar decreased, and the maximum prestress loss reached approximately 60%. After re-tensioning the prestress following the tests, the load-carrying capacity of the columns was fully restored, and the initial stiffness recovered to more than 90% of that of the original specimens. In addition, stiffness degradation, energy dissipation behavior, and hysteretic characteristics were comparable to those of the original specimens, while prestress loss and residual deformation were reduced. These results demonstrate the favorable post-earthquake recovery capability of prestressed glulam columns and provide experimental evidence for their seismic design and engineering applications.

Keywords: Prestressed glulam column, seismic performance, re-tensioning, post-earthquake recoverability, self-centering behavior

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