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Advanced Structural Health Monitoring and Predictive Maintenance of the Parchi Viaduct Using Distributed Fiber Optic Sensors and Digital Twin Technology

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ABSTRACT: Aging infrastructure poses significant challenges in ensuring safety, reliability, and long-term serviceability. The Parchi Viaduct, a 3-km multi-span structure on Milan's A51 Eastern Ring Road, experienced critical degradation in its Gerber saddles, necessitating temporary closure for safety assessments. In response, Milano Serravalle Milano Tangenziali S.p.A. and CAEmate S.R.L. deployed an advanced Structural Health Monitoring (SHM) system, integrating distributed fiber optic sensing (DOFS) and a physics-informed digital twin (PINN) to enable real-time load-bearing capacity evaluation and predictive maintenance. This paper presents the implementation of the WeStatiX SHM platform, utilizing DOFS to capture strain, temperature, and vibration data while dynamically updating a finite element model (FEM) through inverse analysis and multi-objective optimization. By continuously refining modal parameters such as natural frequencies, mode shapes, and damping ratios, the system enables early detection of structural anomalies and degradation trends.
The validated digital twin successfully predicted real-world structural behavior, confirming residual load-bearing capacity despite saddle deterioration and supporting the safe reopening of the viaduct under real-time monitoring per Italian NTC standards. Load test results and FEM simulations demonstrated excellent agreement, with taller piers exhibiting ~20% greater deflection, emphasizing pier height's impact on load distribution and deformation patterns. These findings enhance predictive maintenance planning, improve stress redistribution modeling, and contribute to prolonging the structural lifespan of aging infrastructure assets.

KEY WORDS: Structural Health Monitoring (SHM); Digital Twin; Distributed Fiber Optic Sensors (DOFS); Finite Element Modeling (FEM); Predictive Maintenance; Artificial Intelligence (AI); Operational Modal Analysis (OMA); Physics-Informed Neural Networks (PINN); Machine learning (ML)

1 INTRODUCTION

The Milano Serravalle Milano Tangenziali S.p.A. manages a motorway network with over 400 bridges and viaducts, requiring regular structural assessment to comply with national safety regulations. Increasing traffic loads, environmental exposure, and material aging necessitated the implementation of an advanced Structural Health Monitoring (SHM) system for real-time diagnostics and predictive maintenance.
Following the Ponti Guidelines, the SHM deployment prioritizes viaducts with high traffic volumes, complex configurations, or significant material degradation. The strategy captures structural responses under traffic-induced loading, providing quantitative safety assessments. The network includes various bridge types, many built in the 1960s and expanded in the 1990s, making SHM essential for early damage detection, optimized maintenance, and long-term serviceability.
This paper presents the Milano Serravalle SHM initiative, detailing sensor deployment, real-time data processing, and AI-driven digital twin modeling for viaduct safety assessment and predictive maintenance.

Figure 1. Sensors installed under the deck of viaducts over piazza Maggi.

2 SYSTEM ARCHITECTURE

2.1 Structural Health Monitoring Framework

The SHM system deployed on the Milano Serravalle motorway network provides real-time structural diagnostics by continuously measuring key mechanical and dynamic parameters. It integrates threshold-based evaluation with a data-driven digital twin, ensuring a comprehensive and adaptive approach to infrastructure monitoring.

2.2 Threshold-Based Evaluation Approach

Conventional SHM relies on predefined safety thresholds derived from design standards, material properties, and historical data to detect deviations from expected behavior. While effective for early anomaly detection, this method is limited by uncertainties in aging structures, undocumented modifications, and hidden defects such as microcracks and corrosion. To address these gaps, advanced sensor-driven modeling techniques complement threshold-based assessments.

2.3 Model-Driven Digital Twin Approach

To overcome static threshold limitations, the SHM system employs a model-driven digital twin that continuously refines structural models using real-time sensor data. A finite element model (FEM) serves as the foundation, integrating as-built documentation, material properties, and initial boundary conditions. However, continuous refinement is essential to align the model with actual structural behavior.
Real-time sensor data from distributed fiber optic sensors (DOFS), MEMS-based accelerometers, and inclinometers is processed in the SHM cloud platform, where inverse modeling techniques, including physics-informed neural networks (PINNs), adjust structural parameters dynamically. This

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feedback loop enhances damage detection, predictive maintenance, and risk assessment.

Modal and frequency analysis further refine the model by tracking changes in natural frequencies, mode shapes, and damping ratios, key indicators of stiffness loss, fatigue, or settlement issues. This enables early intervention and cost-effective maintenance planning.

2.4 Multi-Sensor Data Acquisition System

The SHM system relies on a multi-sensor network to capture the structure’s response under various conditions. Triaxial MEMS accelerometers facilitate Operational Modal Analysis (OMA) for detecting stiffness reductions. Inclinometers and displacement transducers measure rotations and deflections at critical structural interfaces, identifying foundation movements and misalignment.

DOFS technology provides continuous strain, temperature, and stress distribution data, crucial for detecting localized stress

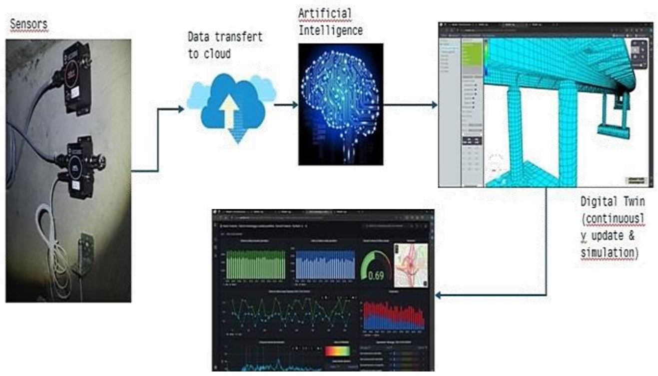

Figure 2. Logical scheme of the system architecture implemented by Milano Serravalle.

concentrations and thermal expansion effects contributing to material fatigue.

All sensor data is synchronized via satellite-linked data acquisition units (UCLs) and transmitted through fiber optic networks to the SHM cloud platform, ensuring precise temporal alignment for real-time analysis.

3 DISCRETE SENSORS

The structural health monitoring (SHM) system deployed across the Milano Serravalle motorway network incorporates a comprehensive array of discrete sensors, each carefully selected to measure critical structural and environmental parameters. The placement and configuration of these sensors were strategically determined based on the structural scheme, constraint conditions, and anticipated mechanical behavior of each viaduct. This systematic deployment ensures that all relevant dynamic, thermal, and displacement-related phenomena are captured with high accuracy and precision.

3.1 Sensor Types and Technical Specifications

A range of high-precision sensors was employed to monitor key structural response parameters, including vibrations, rotations, displacements, and temperature variations. The primary sensor types used in the monitoring network include:

- Triaxial MEMS-Based Accelerometers: These sensors are used for capturing dynamic structural response by measuring accelerations in three orthogonal directions. The accelerometers deployed in this system have a measurement range of ±2 g, with a frequency response spanning from 0 Hz to 500 Hz and a spectral noise level of ±22.5 μg/√Hz, ensuring high-resolution vibration monitoring. Their role is particularly critical for Operational Modal Analysis (OMA), which enables real-time identification of stiffness variations and localized damage detection.
- Biaxial MEMS Inclinometers: The inclinometers are installed to measure angular rotations at key structural joints and supports. These sensors feature a measurement range of ±15° with an angular resolution of 0.001°, enabling precise detection of structural tilting, pier settlements, and deformation trends over time.
- Potentiometric Displacement Transducers: To monitor relative displacements between structural components, potentiometric displacement transducers were installed at expansion joints and pier connections. These devices have a measurement range of 0–150 mm, with a precision of 0.05 mm, allowing for accurate tracking of longitudinal and transverse displacement variations.
- High-Sensitivity Thermometers: Thermal effects play a significant role in structural deformation and stress redistribution, particularly in reinforced and prestressed concrete structures. Thermometers were deployed across critical structural sections, enabling the continuous monitoring of temperature variations. This data is essential for compensating thermal expansion effects in stress analysis and predicting long-term material fatigue due to cyclic temperature fluctuations.

3.2 Sensor Placement Strategy

The placement of sensors was carefully optimized to ensure maximum coverage of structural behavior while minimizing redundancy. In general, accelerometers and inclinometers were mounted along the lateral edges of the bridge decks, with installations concentrated at on-axis sections and quarter-span positions. These locations were selected to provide a detailed characterization of modal behavior, resonance effects, and dynamic loading conditions.

To capture pier behavior and bridge support movements, inclinometers and displacement transducers were positioned at the tops of piers and at expansion joints, where rotational deformations and relative displacements are most pronounced. This setup allows for early detection of differential settlements, support degradation, and abnormal structural movements that could indicate potential failure mechanisms.

Thermometers were distributed across key structural regions, including deck intrados, piers, and expansion joints, ensuring comprehensive thermal profiling. This placement allows for accurate correlation of temperature-induced stresses with real-time displacement and strain measurements.

3.3 Data Acquisition and Synchronization

All sensors were hardwired to a high-speed data transmission network, ensuring continuous and reliable data flow to the central processing platform. The monitoring system employs a satellite-synchronized local control unit (UCL), which manages data acquisition, synchronization, and pre-processing before transmitting the information to the SHM cloud platform.

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The optical fiber transmission BUS provides a secure and interference-free data link, enabling real-time sensor readings to be collected, processed, and stored in a structured database. The synchronized nature of this setup ensures that all measurements are precisely time-aligned, allowing for accurate modal and frequency analysis of the structures.
Once collected, the sensor data is integrated with the digital twin platform, where it undergoes automated noise filtering, anomaly detection, and inverse modeling-based calibration. This process allows engineers to rapidly detect deviations from expected structural behavior and implement predictive maintenance strategies.

3.4 Role of Discrete Sensors in the Digital Twin Model

The real-time measurements from discrete sensors serve as the foundation for updating and refining the digital twin model. By continuously integrating modal data from accelerometers, rotational data from inclinometers, and displacement readings from transducers, the FEM-based digital twin can iteratively adjust its parameters to match actual structural behavior.
The long-term tracking of temperature variations and displacement trends further enhances the predictive capabilities of the model, allowing for proactive intervention before critical failure conditions arise. As a result, the combination of discrete sensor data and AI-driven model updating enables a high-fidelity representation of viaduct performance, significantly improving the reliability of maintenance planning and infrastructure resilience.

Figure 3. Discrete sensors used: displacement transducers (top), biaxial inclinometer (bottom left), triaxial accelerometer and biaxial inclinometer (bottom right).

4 THE "VIADOTTO DEI PARCHI" AND THE DISTRIBUTED FIBER OPTIC SENSORS (DOFS)

4.1 Structural Characteristics of the Viadotto dei Parchi

The Viadotto dei Parchi is a critical viaduct on Milan's A51 Eastern Ring Road. Originally designed by engineer Silvano Zorzi in 1970, the structure features a continuous deck plate integrated with the piers, forming spans of 24 meters. Its design includes a zero-moment point positioned 7 meters from the pier axis, materialized through a Gerber-type saddle system that ensures efficient load redistribution and structural continuity.
The viaduct consists of two parallel structures, each supporting a separate motorway carriageway, with a center-to-center distance of approximately 29 to 30 meters. Extending nearly 3,000 meters in total length, it is one of the longest and most strategically significant bridges within the Milan motorway network.

4.2 Structural Expansion and Modification

In 1992, the viaduct underwent a major expansion to accommodate increased traffic demand, adding a third lane to the Eastern Ring Road. The available space between the two existing viaducts allowed for the construction of two additional structures, effectively increasing capacity while maintaining overall structural integrity. However, this intervention introduced engineering challenges, including increased dynamic loads, differential settlements, and stress redistribution between the old and new structures.
Due to the viaduct's scale and the number of spans, an advanced monitoring system was required to assess its real-time structural performance, particularly in response to dynamic traffic loading, thermal variations, and long-term material degradation. This necessity led to the deployment of a Distributed Fiber Optic Sensor (DOFS) network, providing high-resolution continuous monitoring across the entire structure.

Figure 4. "Viadotto dei Parchi" after the widening in the early 1990s.

4.3 Advantages of Distributed Fiber Optic Sensors Over Discrete Fiber Sensors

The DOFS system implemented on the Viadotto dei Parchi represents a significant advancement over traditional discrete fiber optic sensors, such as Fiber Bragg Gratings (FBG). FBG sensors operate through spectroscopic techniques that measure strain at discrete points along the fiber. While useful in localized assessments, they present several limitations, including restricted spatial resolution, installation complexity, and fragility.
FBG sensors are typically deployed in limited chains, resulting in spatial gaps in the monitoring data and reduced effectiveness in capturing localized stress concentrations or progressive deformation. Their fabrication process modifies the fiber optic core, making them prone to breakage, and installation requires precise alignment with specialized equipment, increasing deployment costs and long-term maintenance efforts.

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DOFS technology overcomes these limitations by using a continuous optical fiber embedded into the structure with mortar or adhesive compounds. This approach enables uninterrupted, high-resolution measurements of strain, temperature, and mechanical deformation along the entire monitored length. The method ensures superior durability, simplified installation, and greater resistance to environmental degradation, making it a more reliable solution for long-term structural health monitoring.

4.4 Measurement Principles and Data Acquisition in DOFS Systems

DOFS measurements rely on light scattering phenomena that occur within the optical fiber when subjected to external loads. The Brillouin Scattering Effect, a nonlinear optical phenomenon, forms the foundation of the measurement system. By analyzing the Brillouin frequency shift, the system determines absolute strain and temperature variations with high precision.
The system achieves a strain resolution in the micro-epsilon range, allowing the detection of extremely subtle structural deformations. The spatial resolution is adjustable, ranging from a few meters to a few centimeters, depending on the interrogation time and system configuration. Temperature effects are automatically compensated through a dual-wavelength technique, ensuring that strain measurements remain unaffected by thermal fluctuations. A secondary optical fiber within the same system provides independent temperature readings, allowing precise differentiation between temperature-induced expansion and load-induced deformation.
In addition to static strain and temperature measurements, DOFS systems capture real-time structural vibrations, enabling the identification of natural frequencies, mode shapes, and transient dynamic events. Unlike traditional accelerometers, which have bandwidth limitations, DOFS technology measures broad-spectrum vibrational activity with unmatched sensitivity, further enhancing the accuracy of structural assessments.

4.5 Deployment of DOFS on the Viadotto dei Parchi

The DOFS network was installed to maximize monitoring effectiveness across critical structural components. Optical fibers were embedded along both the intrados and extrados of the deck, covering longitudinal stress paths to ensure comprehensive strain tracking. Their positioning was optimized based on FEM simulations, allowing accurate assessment of curvature, bending moments, and stress redistribution.
By integrating DOFS with the digital twin model, the monitoring system provides real-time structural assessments. This integration enables the early detection of microcracking and stress concentrations before they evolve into critical failures. Additionally, long-term deformations associated with creep, shrinkage, and fatigue effects can be tracked, ensuring that maintenance strategies are data-driven and proactive. The continuous monitoring and validation of FEM predictions ensure that theoretical models remain aligned with real structural behavior.
The sensors used in this project were developed as a patented technology by a spin-off company of the Polytechnic of Milan, further enhancing the resolution, reliability, and predictive capabilities of SHM methodologies employed on the Viadotto dei Parchi.

4.6 Impact of DOFS-Based Monitoring on Structural Management

The implementation of DOFS-based SHM on the Viadotto dei Parchi has significantly improved structural assessment methodologies. The ability to obtain continuous, high-resolution strain and temperature data across the entire viaduct allows for more effective maintenance planning and risk mitigation.
Real-time monitoring enables early detection of evolving structural anomalies, allowing timely intervention before critical damage occurs. By tracking long-term performance trends, engineers can optimize reinforcement and retrofitting strategies, extending the viaduct's service life while reducing maintenance costs. Furthermore, the integration of DOFS technology with digital twin modeling minimizes reliance on costly manual inspections, enhancing efficiency in infrastructure management while ensuring compliance with safety regulations.

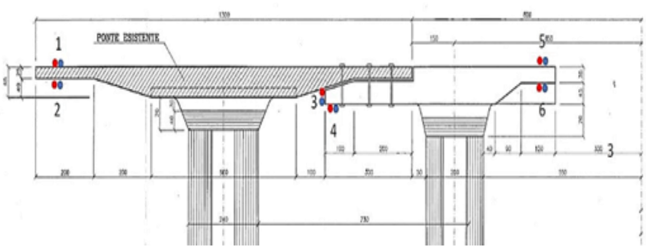

Figure 5. Cross section of DOFS fiber arrangement.

4.7 DOFS Findings

The Viadotto dei Parchi serves as a pioneering case study in the application of distributed fiber optic sensing for SHM. The successful deployment of DOFS technology has demonstrated its superiority over traditional discrete sensor networks, providing unmatched measurement resolution, real-time diagnostics, and enhanced predictive maintenance capabilities. The combination of DOFS with AI-enhanced digital twin modeling establishes a comprehensive framework for long-term structural health assessment. By continuously integrating high-fidelity monitoring data into predictive maintenance strategies, this approach sets a new benchmark for SHM in large-scale civil infrastructure applications. Future implementations of similar systems across other critical viaducts will further refine predictive models and improve infrastructure resilience.

5 FINITE ELEMENT MODELING AND DIGITAL TWIN TECHNOLOGY

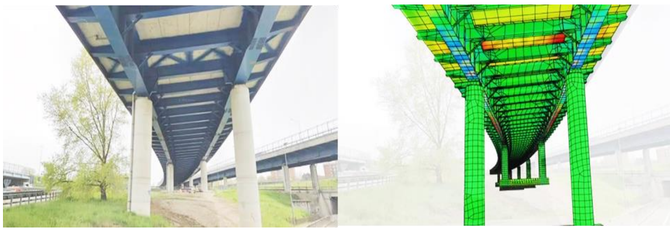

Figure 6. Comparison between real structure and Digital Twin.

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5.1 The Role of Digital Twins in Structural Health Monitoring

The integration of digital twin technology within the Milano Serravalle motorway network represents a paradigm shift in structural health monitoring (SHM), enabling a continuous, bidirectional exchange of information between the physical structure and its virtual counterpart. These simulation-based digital twins leverage high-fidelity finite element models (FEMs) to replicate the mechanical, thermal, and dynamic behavior of infrastructure assets, allowing engineers to conduct real-time diagnostics, predictive maintenance, and performance optimization.

The development of digital twins follows a phased modeling approach, in which each structural component is incrementally integrated into the model, mirroring the actual construction sequence of the viaduct. This approach ensures that time-dependent effects, such as viscosity (creep), concrete shrinkage, and load redistribution, are accurately accounted for. By incorporating historical construction data, including post-tensioning phases and material aging effects, the digital twin provides a high-fidelity representation of the viaduct's evolving mechanical properties over its operational lifespan.

The thermomechanical behavior of the structure is also explicitly modeled, allowing for the simulation of temperature-induced stresses, expansion effects, and seasonal thermal cycles. This is particularly relevant for large-scale viaducts, where differential thermal expansion between spans can lead to progressive degradation and altered load paths over time.

5.2 Finite Element Model Development for the Parchi Viaduct

A comprehensive FEM was developed for the Parchi Viaduct, following standard structural simulation methodologies used in the design and assessment of large-scale infrastructure assets. The model accurately represents the structural geometry, material properties, and support conditions of the viaduct, ensuring that its simulated response aligns with real-world structural behavior.

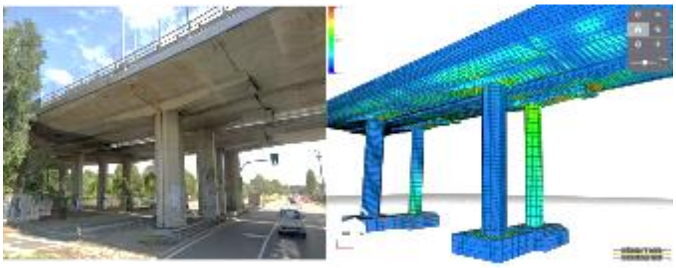

Figure 7. Parchi Viaduct and its Digital Twin (side view).

The deck, piers, and foundations were modeled using 20-node brick finite elements with quadratic shape functions, which provide a high degree of accuracy in stress and strain calculations. The DYWIDAG bars and post-tensioning tendons were modeled as axially loaded structural elements, ensuring a realistic representation of prestress-induced force distributions.

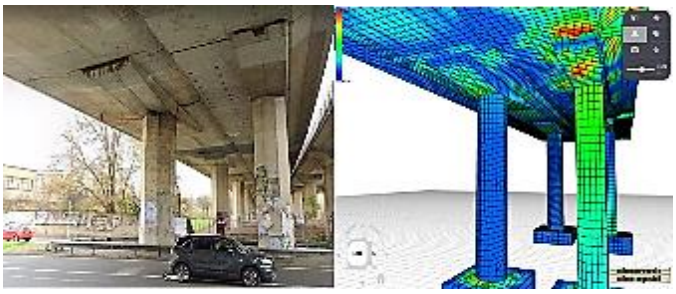

Figure 8. Parchi Viaduct and its Digital Twin (bottom view).

Given the variable pier heights of the viaduct, multiple models were generated to account for differential stiffness effects associated with varying substructure configurations. The selected pier heights of 7.5 m, 12.5 m, and 17.5 m reflect the actual structural conditions encountered during field inspections. These variations were included in the FEM to ensure accurate modeling of load redistribution effects and differential settlements.

5.3 Interaction Between Spans and Load Redistribution Effects

One of the key challenges in modeling the Parchi Viaduct was accurately simulating the interaction between successive spans. The viaduct's Gerber saddle system introduces complex load redistribution mechanisms, requiring nonlinear contact elements to properly model stiffness discontinuities and stress transfer zones.

The interaction between successive spans was simulated using contact elements with linear elastic behavior, which were constrained to react only in compression. This approach captures the realistic load transfer behavior between deck segments, allowing for accurate assessment of bending moments and shear forces (Figure 9).

The original deck structure incorporated a system of longitudinal and transverse post-tensioning bars, while the widened deck sections utilized 12 additional longitudinal cables, each containing 19 strands of 0.6-inch steel tendons. The interaction between these newly introduced elements and the existing structural components was modeled using tensioned beam-type elements, accurately representing the anchoring effects and prestress redistribution mechanisms (Figure 10).

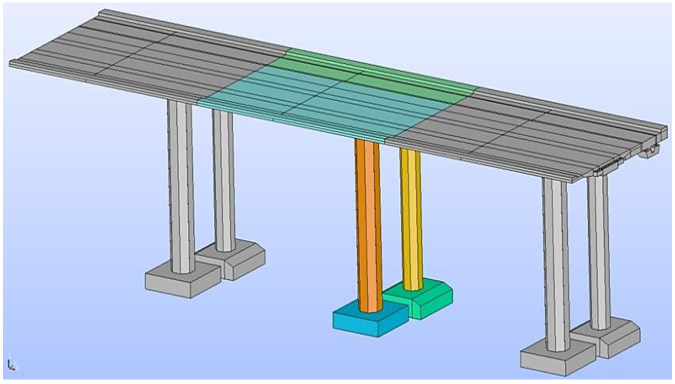

Figure 9. Model of three adjacent spans of the Parchi Viaduct.

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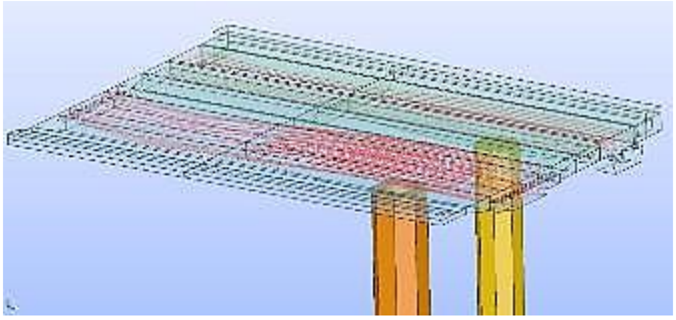

Figure 10. Modelling of the bars and longitudinal tendons within the original and widened deck.

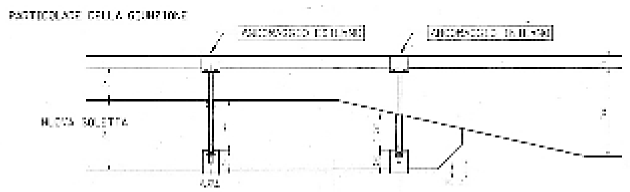

Figure 11. Anchor detail used in the joint area.

5.4 Calibration of the Digital Twin Using SHM Data

To ensure that the finite element model remains an accurate representation of the actual viaduct, the WeStatiX SHM platform employs AI-driven inverse modeling techniques for continuous model updating. The calibration process follows a multi-step approach:

1) Initial FEM Validation
- The FEM is initially validated against historical design calculations and load test results from the viaduct's original construction phase.

2) Integration of Real-Time SHM Data
- Sensor data from DOFS, MEMS accelerometers, and displacement transducers is used to update strain fields, displacement trends, and modal parameters in the model.

3) Iterative Model Refinement via AI Optimization
- A multi-objective optimization framework iteratively refines material properties, boundary conditions, and stiffness coefficients, ensuring alignment with measured structural response data.
- Physics-informed neural networks (PINNs) are employed to enhance the accuracy of model predictions, particularly in identifying early-stage stiffness degradation.

4) Utilization Factor Computation and Structural Safety Assessment
- The stress state of individual structural components is computed through numerical integration of the finite element stress field.
- The exploitation coefficient of materials (concrete, reinforcement bars, prestressing cables) is evaluated to ensure compliance with design safety margins and regulatory requirements (Figure 9).

5.5 Structural Joint Modeling and Connection Reinforcement

The integration of widened structural segments introduced new connection challenges, requiring specialized modeling techniques to assess joint behavior and stress redistribution. In the transition zones between the original deck and the expanded deck, beam-type elements were used to model anchor connections, ensuring that the prestress force transfer was accurately simulated (Figure 12).

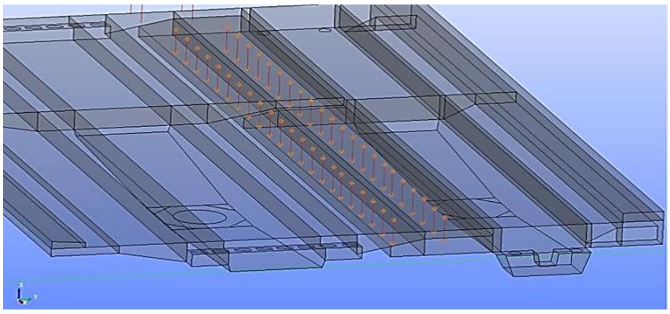

Figure 12. Modelling of the anchors used in the joint area.

Additionally, the joints were analyzed under both static and dynamic loading conditions, allowing for detailed assessment of fatigue-induced stress cycles. By incorporating nonlinear contact constraints, the model was able to replicate realistic load transfer mechanisms, ensuring that joint regions remained within safe stress limits under operational loads.

5.6 Structural Monitoring and Digital Twin Utilization for Predictive Maintenance

The calibrated digital twin model serves as a decision-support tool for predictive maintenance, enabling engineers to:

- Simulate various loading conditions and forecast long-term degradation trends.
- Identify structural weaknesses by detecting deviations in modal properties.
- Optimize maintenance schedules by predicting the remaining fatigue life of critical components.
- Ensure regulatory compliance by continuously monitoring stress utilization factors.

By integrating real-time SHM data with FEM simulations, the digital twin enables a data-driven approach to infrastructure management, reducing reliance on reactive maintenance strategies and minimizing the risk of unexpected structural failures.

6 POST-PROCESSING OF MEASUREMENTS AND DIGITAL TWIN CALIBRATION

6.1 Dynamic Adaptation of the Digital Twin to Measured Data

A fundamental feature of the digital twin framework employed in the Milano Serravalle motorway network is its ability to dynamically update its properties based on the real-time behavior of the structure. Unlike static numerical models, which rely solely on design assumptions and material properties, the digital twin is designed to minimize discrepancies between theoretical simulations and measured structural response data. This ensures that the computed stress states, deformation patterns, and modal properties of the viaducts reflect their actual in-service conditions rather than idealized design scenarios.

The primary objective of the digital twin calibration process is to ensure that the numerical model accurately represents the structure's response across its entire load history. By continuously refining key structural parameters, the system enhances predictive accuracy and enables early detection of damage mechanisms. Through an automated and iterative

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inverse analysis (back-analysis) framework, the digital twin minimizes deviations between sensor-acquired data and finite element simulations, allowing for high-fidelity structural assessments.

6.2 Inverse Analysis and Model Calibration Techniques

The real-time calibration of the digital twin is achieved using advanced inverse modeling techniques, which allow for the automated identification and refinement of uncertain structural parameters. The WeStatiX SHM platform implements an iterative multi-objective optimization framework, leveraging surrogate models trained on thousands of numerical simulations to efficiently estimate unknown properties.
The parameters subject to calibration include both linear and nonlinear material characteristics, whose variation over time may indicate the onset of damage or degradation. Some key parameters continuously updated in the digital twin include:

- Elastic and nonlinear material properties (stiffness variations due to progressive damage).
- Time-dependent effects such as creep, shrinkage, and corrosion-related stiffness reductions.
- Boundary conditions and joint behavior changes caused by foundation settlements or bearing degradation.
- Temperature-dependent stress redistributions due to seasonal thermal cycles.

Through inverse analysis, these parameters are iteratively adjusted until the numerical model converges with real-world sensor measurements, ensuring that structural assessments remain highly accurate and reliable (Figure 13)

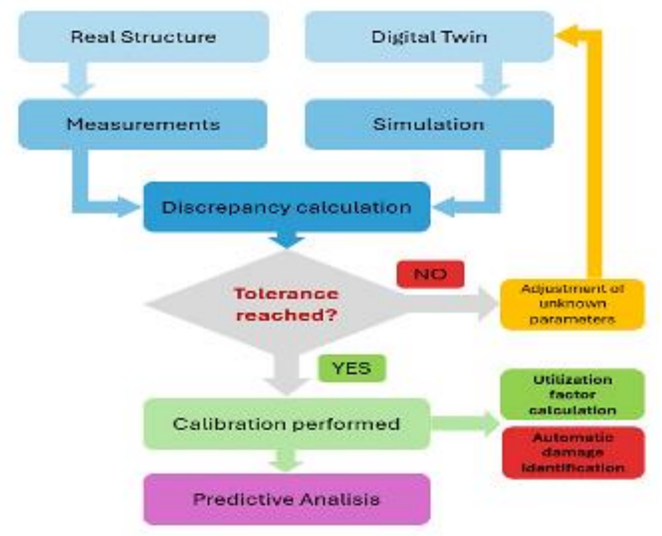

Figure 13. Calibration through inverse analysis.

6.3 Operational Modal Analysis (OMA) for Dynamic Parameter Identification

A key component of digital twin calibration is the identification of the structure's dynamic properties through Operational Modal Analysis (OMA). Unlike traditional modal testing, which requires artificial excitation sources such as shakers or impact hammers, OMA leverages the ambient vibrations naturally present in the structure, such as those induced by wind, traffic loads, and micro-seismic activity.
By processing acceleration data from MEMS-based sensors placed along the viaduct deck and piers, the system is able to accurately determine the structure's modal frequencies, mode shapes, and damping ratios (Figure 14). This enables continuous tracking of structural stiffness variations, which are critical for detecting:

- Local reductions in stiffness caused by fatigue, cracking, or reinforcement deterioration.
- Progressive changes in modal parameters indicative of structural aging.
- Sudden shifts in dynamic response due to damage events such as bearing failures or impact loads.

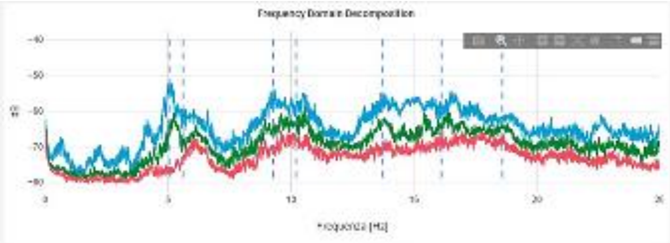

Figure 14. Inverse analysis calibration.

The digital twin is continuously updated to minimize discrepancies between FEM-based modal predictions and OMA-extracted parameters, ensuring real-time identification of structural changes. This approach allows for the detection of subtle stiffness reductions before they become critical, enabling early intervention strategies.

6.4 Distinguishing Thermal, Transient, and Permanent Deformation Components

One of the key challenges in long-term structural monitoring is the ability to differentiate between transient deformations (due to environmental conditions) and permanent structural changes (indicative of damage evolution). The WeStatiX SHM platform employs an automated algorithmic framework to process rotation, displacement, and strain data, allowing it to reconstruct the full deformation state of the viaduct. The system applies multi-stage filtering and correlation techniques to distinguish between:

- Thermal deformations, caused by seasonal and diurnal temperature fluctuations.
- Transient load-induced deformations, resulting from traffic loads and dynamic excitation.
- Permanent deformation trends, which may indicate creep effects, prestress losses, or progressive material fatigue.

Unlike traditional calibration approaches that simply enforce measurement-matching, the WeStatiX SHM methodology does not impose measured data onto the numerical model directly. Instead, it utilizes a cause-and-effect framework, ensuring that the structural behavior is characterized over time, across its entire operational lifespan.
6.5 Multi-Timescale Calibration Strategies
To provide a comprehensive assessment of structural performance, the digital twin employs two interrelated

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calibration procedures, tailored to identify different categories of structural changes:

1) Long-Term Calibration

This process is designed to track slow-evolving structural characteristics, such as material degradation, creep progression, and corrosion effects.

Using longitudinal datasets spanning months to years, the calibration process refines the governing material laws, ensuring that the digital twin reflects the actual deterioration mechanisms influencing the structure (Figure 15).

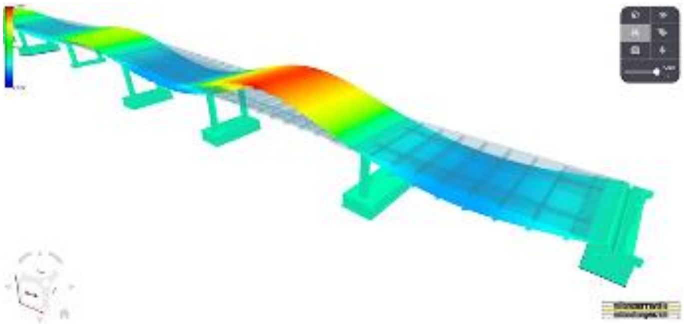

Figure 15. Modal shape identification.

2) Short-Term Calibration

This process is focused on detecting rapid changes in structural behavior, such as those caused by thermal fluctuations, sudden damage events, or traffic-induced loading variations.

It enables precise assessment of thermomechanical material properties, as well as the quantification of elastic and plastic deformations caused by transient loads.

Both calibration processes work in tandem, allowing the system to accurately separate transient anomalies from permanent structural changes while ensuring that the digital twin remains an accurate and reliable decision-support tool.

6.6 Digital Twin Utilization for Predictive Maintenance and Decision Support

The continuously calibrated digital twin provides a quantitative basis for structural decision-making, allowing engineers to:

- Predict the remaining service life of critical components based on degradation trends.
- Assess real-time stress utilization factors to ensure that safety margins are maintained.
- Optimize maintenance schedules based on accurate forecasts of fatigue life and prestress losses.
- Trigger automated damage alerts, allowing for targeted inspections and cost-effective interventions.
- Through automated calibration, inverse modeling, and real-time FEM updating, the digital twin enables a fully predictive maintenance approach, shifting away from traditional schedule-based inspections toward data-driven infrastructure management.

The post-processing and calibration methodologies implemented in the WeStatiX SHM platform represent a state-of-the-art approach to real-time structural assessment. By leveraging inverse analysis, OMA-based modal tracking, and AI-driven optimization techniques, the system ensures that the digital twin remains dynamically synchronized with real-world structural behavior.

This multi-layered calibration framework provides a powerful tool for early damage detection, predictive maintenance, and infrastructure resilience assessment, setting a new benchmark for SHM in large-scale civil infrastructure applications.

7 VALIDATION RESULTS AND PREDICTIVE ANALYSIS

7.1 Load Testing and Digital Twin Validation

To ensure the accuracy and reliability of the digital twin model, validation was conducted by simulating controlled load tests, comparing the numerical results with real-world structural behavior observed during field testing. For the Parchi Viaduct, these load tests took place in May 2021, during which multiple spans of the viaduct were subjected to static loading using a maximum of six fully loaded trucks, each weighing approximately 30–32 tons. The arrangement of the vehicles on the deck, as illustrated in Figure 16, was designed to produce representative loading conditions for evaluating the structural response.

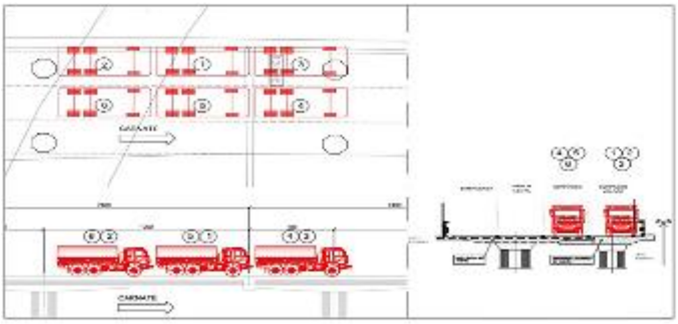

Figure 16. Truck loading configuration.

During the tests, topographic survey methods were used to measure deck displacements and assess deformation trends under loading conditions. The digital twin model, previously described, was utilized to numerically simulate the load tests, integrating precise vehicle positions, tire contact pressures, and asphalt-layer load distribution effects in accordance with regulatory standards. These elements were accurately modeled to ensure a realistic representation of stress propagation through the bridge deck and substructure (Figures 17, 18, 19).

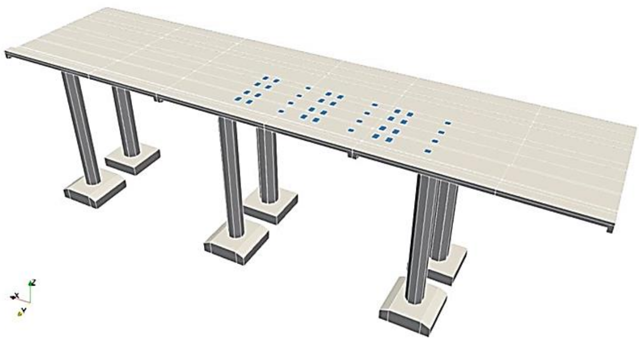

Figure 17. Parchi Digital Twin load configuration (side view).

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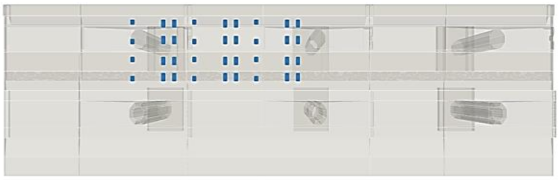

Figure 18. Parchi Digital Twin load configuration (top view).

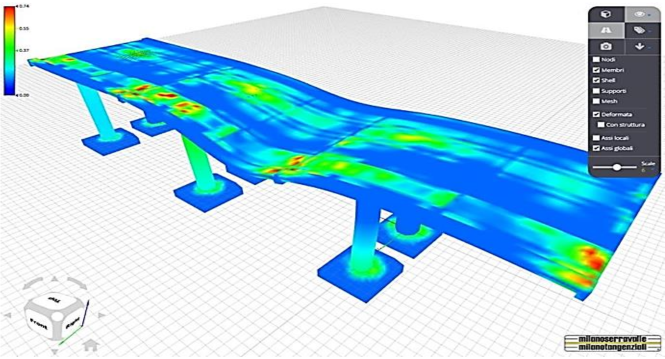

Figure 19. Utilization factor visualization of Parchi Twin.

7.2 Pier Height Influence on Structural Response

The simulation model was further refined by incorporating variations in pier heights, introducing additional pier elevations of 15 m and 9 m, corresponding to different spans of the viaduct. The results demonstrated a significant correlation between pier height and deflection response, with taller piers exhibiting approximately 20% greater maximum deflection under the same applied loads (Figure 20). This effect highlights the importance of accounting for pier stiffness variations in structural assessment and maintenance planning, as local stiffness differences can influence global load redistribution patterns.

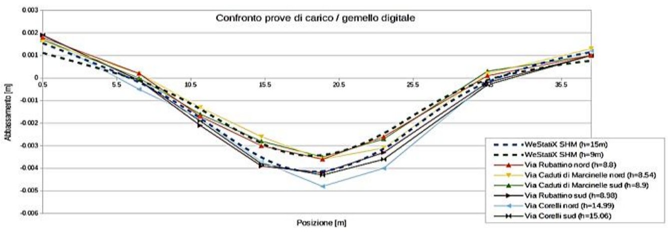

Figure 20. Pier height load test correlation of Parchi Twin.

Comparisons between measured displacements from the load tests and simulated results from the digital twin showed excellent agreement, with negligible discrepancies in both maximum deflection values and the overall deformation trends (Figure 20). These results confirm the high fidelity of the digital twin model and its ability to accurately capture real-world structural behavior under operational conditions.

7.3 Distributed Fiber Optic Sensor Data Analysis

In addition to traditional displacement monitoring, the distributed fiber optic sensing (DOFS) system installed on the Parchi Viaduct provided continuous real-time strain measurements, enabling both dynamic characterization and modal parameter identification for each individual span.

The DOFS system measures strain rate values, defined as the derivative of strain over time.

This data is automatically processed by the SHM platform to extract modal characteristics, including natural frequencies and damping ratios (Figure 21).

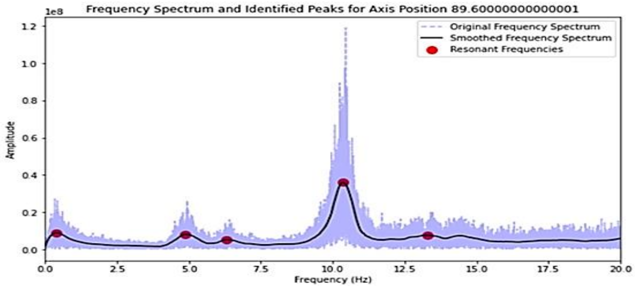

Figure 21. Natural frequency identification.

Continuous strain measurements allow for full-field reconstruction of structural deformation.

Any anomalous strain distributions or unexpected deformation patterns are automatically flagged, triggering maintenance alerts before failure conditions develop.

For other viaducts within the highway network, similar modal parameter identification and deformation reconstructions were performed using accelerometer and inclinometer data, combined with temperature compensation models. An example of this modal analysis workflow is shown in Figure 22, where deformation trends were reconstructed based on correlated inclinometrics and temperature data.

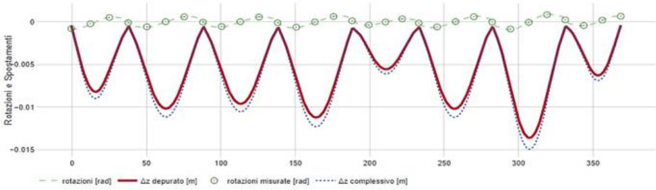

Figure 22. Deformation reconstruction using inclinometric data.

7.4 Interactive Visualization and Digital Twin Integration

One of the key features of the WeStatiX SHM platform is the integration of digital twins within an interactive geospatial interface, providing real-time access to structural health data for all monitored viaducts in the motorway network. Through an interactive map interface, engineers can:

- Select specific viaducts and bridge structures to access real-time monitoring data.
- Perform virtual inspections through 3D visualization of the digital twin model.
- Review sensor data trends, including modal parameters, stress distributions, and temperature variations (Figure 23).

This user-friendly visualization system ensures that structural assessment personnel can efficiently analyze infrastructure health indicators, facilitating rapid response to emerging issues while streamlining the decision-making process for maintenance planning.

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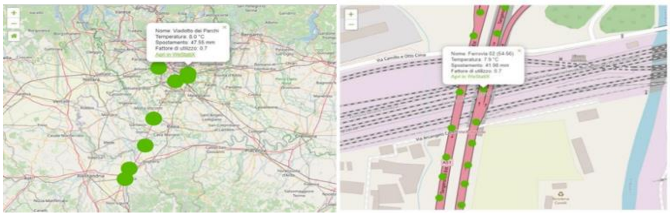

Figure 23. Interactive map.

7.5 AI-Based Predictive Maintenance and Self-Learning Algorithms

A distinguishing feature of the WeStatiX SHM platform is its advanced predictive analysis capabilities, which leverage physics-informed artificial intelligence to anticipate future structural behavior based on:

- Historical SHM data trends
- Machine learning-trained degradation models
- Structural simulations under progressive load scenarios

By continuously assimilating real-world monitoring data, the digital twin functions as a self-learning system, progressively improving its predictive accuracy (Figure 24). This automated learning process enhances the platform’s ability to:

- Predict structural degradation trends and forecast the remaining service life of individual bridge components.
- Simulate long-term performance under variable load conditions, identifying potential failure scenarios before they occur.
- Optimize maintenance scheduling, ensuring that interventions are proactively planned based on data-driven insights rather than reactive repairs.

Figure 24. Monitoring and prediction dashboard.

The WeStatiX SHM system integrates a suite of real-time dashboards, enabling infrastructure managers to analyze monitoring data and numerical simulation outputs simultaneously. These dashboards display key structural health indicators, including:

- Current stress states and utilization factors
- Real-time displacement and deformation trends
- Predicted deterioration pathways based on historical load conditions

By integrating AI-driven forecasting with SHM diagnostics, the platform provides unprecedented decision-making capabilities, supporting a predictive maintenance strategy that optimizes resource allocation, minimizes intervention costs, and ensures long-term infrastructure resilience.

8 CONCLUSIONS

The AI-enhanced digital twin framework implemented for the Parchi Viaduct has demonstrated the effectiveness of real-time SHM in large-scale infrastructure monitoring. By integrating DOFS, OMA, and PINN-based inverse modeling, the WeStatiX SHM platform accurately captures structural behavior, detects damage progression, and optimizes predictive maintenance.

Load test comparisons validated the high accuracy of the digital twin, with minimal discrepancies in displacement predictions. The observed 20% increase in deflection for taller piers underscores the need to incorporate pier height variations in FEM-based assessments. Real-time monitoring has provided crucial insights into stress redistribution, long-term deformation, and material degradation, enabling early anomaly detection.

Beyond reactive damage identification, self-learning AI algorithms support long-term deterioration forecasting and data-driven maintenance planning. Interactive visualization tools further enhance usability, enabling real-time virtual inspections and safety assessments.

This study establishes a scalable SHM methodology for infrastructure asset management, lifecycle extension, and cost-effective maintenance. Future work will refine AI-driven anomaly detection, expand digital twin applications, and integrate multi-hazard risk assessments, advancing proactive structural assessment and predictive maintenance strategies.

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