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From Insight to Action: Deploying SHM for a suspension bridge

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ABSTRACT: This paper presents the implementation of a structural health monitoring (SHM) system for a suspension bridge approaching the end of its service life. Constructed in the 1960s with a 220-meter main span, the bridge is the sole vital link to a region hosting key socioeconomic industries. Over time, heavy traffic—with vehicles often exceeding 80 tons—has led to pronounced fatigue issues. Throughout its operational life, extensive repairs—such as the addition of a cantilevered pedestrian lane, modifications to the bearing system, and hanger replacements—have been undertaken. More than a decade of monitoring via over 50 sensors has yielded comprehensive data that both ensures safety and informs maintenance strategies. A sophisticated finite element (FE) model, developed in 2023 and calibrated using real-time data, improved the correlation between simulated and actual performance. Following this, a streamlined near-real-time monitoring framework was established in early 2024 to promptly identify structural anomalies. Designed for adaptability, the SHM system can be implemented on various structures. This study highlights the importance of clear data presentation in enabling informed decisions that optimize infrastructure management and enhance operational safety.

KEY WORDS: SHM, suspension bridge, fatigue, data-informed decision making, safety, reliability, FEM, predictive maintenance, sustainability

1 BACKGROUND AND MOTIVATION

Ensuring the safety and longevity of aging infrastructure is increasingly challenging as many critical bridges worldwide approach or exceed their intended service life. Traditionally, structural integrity is assessed via periodic inspections—typically every three to six years—which may overlook gradual deterioration. Historically, bridge monitoring data has been analyzed on a case-by-case basis, a fragmented approach that hinders a comprehensive understanding of structural behavior over time. A shift toward a structured and standardized methodology is essential to interpret monitoring results more effectively, optimize sensor placement, reduce instrumentation costs, and fully leverage the rich datasets available. Grounded in big data principles, such an approach can transform stored information into actionable insights.

Constructed in the 1960s, the case bridge is the sole transportation route serving a region with vital socioeconomic industries. Unlike modern bridges, it was designed based on historical traffic load models that did not anticipate today's heavier vehicles and increased traffic density. Heavy trucks, often exceeding 80 tons, regularly traverse the structure, introducing forces well beyond the original design assumptions. Although various repairs have been undertaken over the years, concerns regarding progressive material fatigue and overall structural performance persist.

In response to these challenges, an SHM system was implemented to deliver real-time insights into structural behavior—facilitating early anomaly detection, proactive maintenance, and a reduction in the risk of sudden failures. By integrating continuous monitoring with analytical tools, this system represents a significant advancement in managing aging infrastructure.

Figure 1. The case bridge.

2 CHALLENGES IN MAINTAINING AGING BRIDGES

A significant portion of the bridge network was constructed over 50 years ago, using traffic load models that are no longer representative of current conditions. At the time of design, fatigue considerations were not always fully incorporated into design practices, leading to unforeseen long-term issues. Suspension bridges, such as the case bridge, face particularly complex challenges. Increased traffic loads exacerbate non-linear deformations and amplify fatigue effects, contributing to localized failures.

Traditional periodic inspections suffer from significant blind spots. Critical issues such as fatigue cracks and unforeseen deformations can evolve and propagate well between scheduled evaluations, resulting in missed opportunities for early intervention. This limitation underscores the urgent need for continuous, data-driven monitoring to capture dynamic structural behaviors in real time.

While periodic inspections provide valuable assessments, they

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often fail to capture detailed long-term behavioral trends. Undetected fatigue cracks, excessive displacement, or gradual load redistribution may develop between inspections, increasing the risk of structural failure. This growing need for a proactive approach has driven the development of Structural Health Monitoring (SHM) systems. By continuously tracking critical parameters, SHM provides timely insights into bridge performance, allowing for early interventions and more informed maintenance decisions.

3 KEY STRUCTURAL CHALLENGES AND REPAIRS OF THE CASE BRIDGE

One of the problems detected has been the formation of fatigue cracks in the wind bracings, which has altered the bridge's behavior. In some cases, these changes have been noticeable under traffic loads, with visibly increased vibrations and unexpected movement patterns. However, assessing whether the main load-bearing components have also been affected remains a challenge.

Another significant concern was the corrosion of the hangers, particularly the shorter ones. Due to their positioning, these hangers experienced greater angular movements as the main cable deformed under traffic loads. This fluctuation in stress accelerated wear, leading to localized material deterioration. In 2020, a heavily corroded hanger was removed and subjected to laboratory testing, which provided crucial insights into the remaining safety margins of the hangers. The results confirmed that the less-corroded hangers were still within operational limits.

Figure 2. Corroded hanger

Figure 3. Installation of temporary hanger bars.

Additionally, the ongoing construction of a new cable-stayed bridge to the west of the case bridge has introduced further challenges. The transportation of construction materials over the existing bridge has led to increased loads, while related activities—such as the drilling of large-diameter steel piles and controlled blasting—have induced minor disturbances. The continuous monitoring system has furnished real-time insights into the bridge's condition, thereby ensuring its safe operation throughout these construction activities.

These challenges illustrate the limitations of relying solely on periodic inspections. Although past repairs addressed specific damage, they did not provide a comprehensive picture of the bridge's evolving condition. This underscores the critical need for continuous monitoring to detect subtle structural changes before they escalate into major failures.

4 DESIGN AND IMPLEMENTATION OF SHM SYSTEM

The case bridge is equipped with over 50 sensors, including strain gauges, displacement sensors, accelerometers, as well as temperature and wind sensors. These instruments provide a comprehensive dataset for assessing the bridge's structural behavior under varying conditions. Over its lifespan, additional sensors were installed to monitor specific concerns, such as localized fatigue-prone areas; however, until recently, data analysis was performed sporadically and primarily in response to observed anomalies.

In 2023, the construction of a new bridge adjacent to the case bridge prompted a shift toward a more structured and systematic data analysis framework. The client required assurance that the existing bridge could safely serve its final years of operation while construction was ongoing. Consequently, a daily evaluation system was introduced to track changes in load distribution, deformations, and stress concentrations over time.

This transition from sporadic analysis to continuous monitoring has provided deeper insights into the bridge's behavior, significantly enhancing the ability to detect subtle structural changes before they escalate into critical issues. By integrating real-time sensor data with analytical tools, the monitoring framework has evolved from a reactive assessment method into a proactive instrument for infrastructure management.

5 FINITE ELEMENT MODEL CALIBRATION

Before beginning the more detailed structured data analysis phase, a state-of-the-art nonlinear finite element (FE) model of the case bridge was developed. This model was designed to replicate the bridge's actual behavior under modern traffic loads, using sensor data for validation. However, early comparisons between the model and real-world measurements revealed significant discrepancies, indicating that the first iteration did not fully capture the actual structural response.

This phase was crucial in enhancing the understanding of the bridge's performance. Iterative refinements identified previously overlooked structural traits, leading to a more accurate representation of the bridge's behavior. To ensure reliable comparisons, known heavy vehicles with documented

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axle weights were used as test loads during operation, allowing for direct validation of the model against real-world conditions.

Figure 4. 3D visualization of the FE model.

For example, calibration provided insights into the behavior of the elastomeric bearings between the deck structure (a concrete slab with longitudinal steel girders) and the main steel truss. The bridge deck was observed to move unpredictably in both longitudinal directions, raising concerns until the behavior was computationally verified and found to be harmless, given the bridge's remaining service life.

Figure 5 deck structure supported by the steel cross truss by elastomeric bearings.

This movement had not been anticipated; the elastomeric bearings had deteriorated to such an extent that their response was no longer elastic and, therefore, not linear. Instead of behaving elastically, the bearings acted as fixed supports until the friction between the rubber and steel was overcome, causing them to slide. This resulted in residual movement, which initially caused confusion until it was successfully captured in the FE model and understood. A comparison of monitoring results and the FE model (depicting the movement of the concrete slab relative to the cross beam) is shown in Figures 6 and 7.

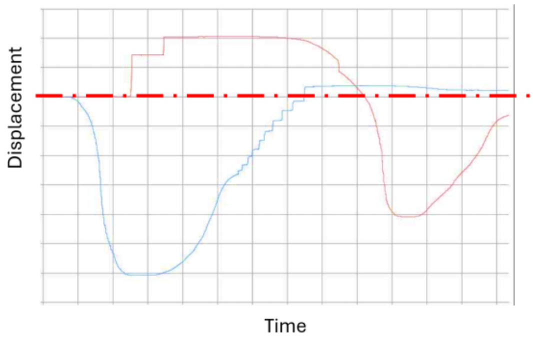

Figure 6. relative displacements while a vehicle crossing the bridge (monitored results). Staggered displacements showed the friction exceeded on the bearing leading to residual displacement at the end.

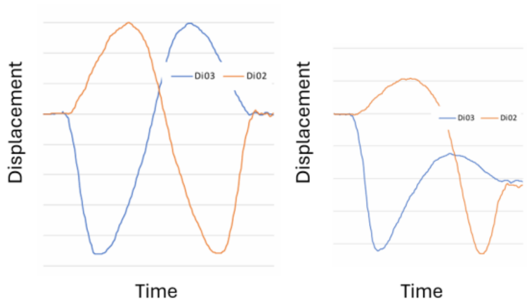

Figure 7. Analysis results of the differential displacement between the deck and the cross truss. Elastic bearings (left) vs nonlinear (sliding) bearings.

Another complex aspect addressed was the behavior of the replaced hanger. The original corroded hanger, consisting of a pair of spiral cables arranged perpendicular to the bridge axis, was replaced with two steel bars. Unlike the cables, the new steel bars run along the bridge axis, allowing for their installation before dismantling the existing hangers. However, this configuration complicates load distribution predictions. Additionally, the longitudinal steel bars are susceptible to bending, particularly when the superstructure sways in the bridge's longitudinal direction. A refined analysis helped define the expected range of stress variations and identify conditions requiring closer monitoring—such as instances when a hanger comes into contact with the edge of its recess.

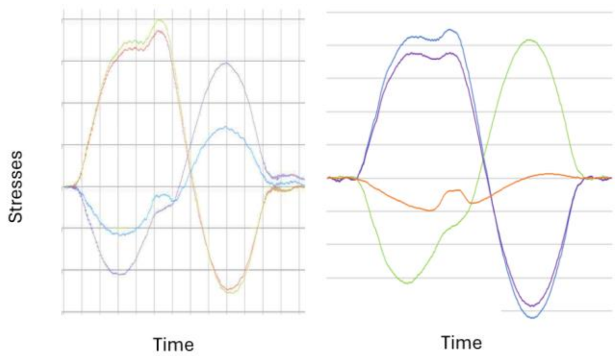

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Figure 8 compares the monitoring readings in 4 strain gauges to the FE model under service loads.

Figure 9. Hanger arrangement resulting in bending stresses due the superstructure longitudinal movement,

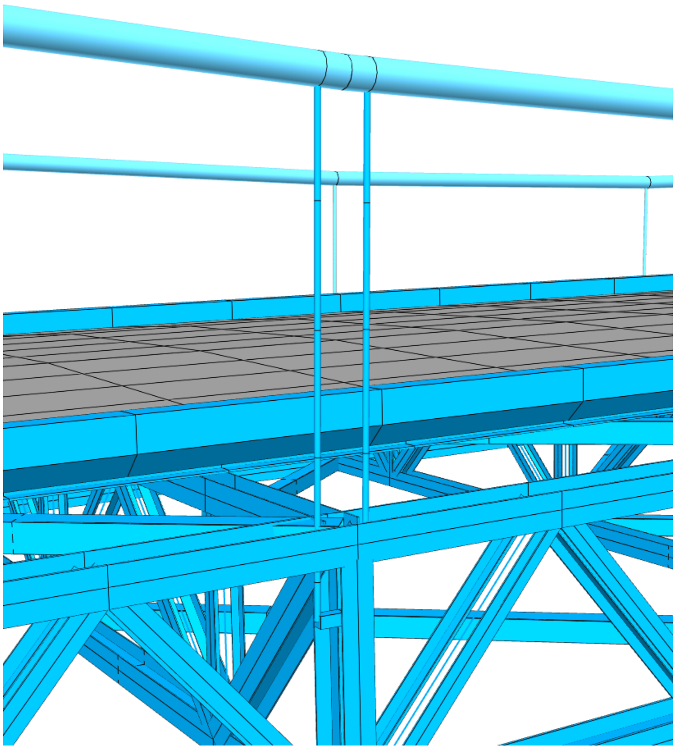

Figure 10. Hanger arrangements in the FE model.

Most of the main elements were easier to model; as an example, Figure 11 shows the typical behavior of main truss stresses and Figure 12 shows the typical behavior of the stresses in cross beam diagonals.

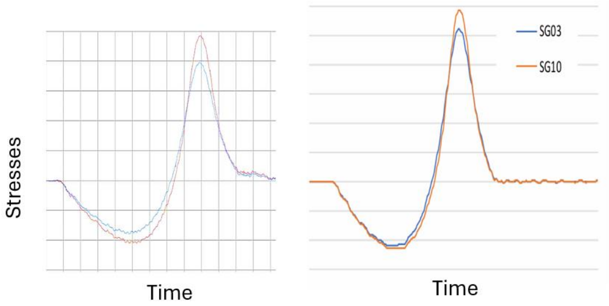

Figure 11. Main truss stresses (measured/modelled).

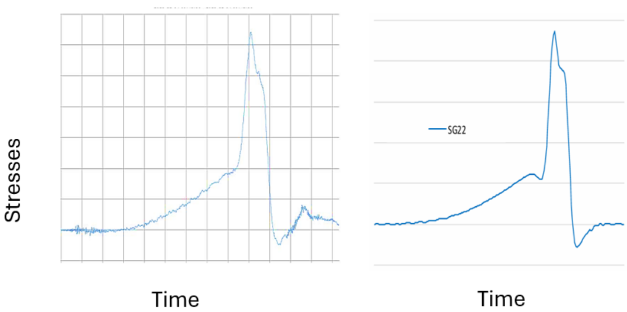

Figure 12. Cross beam diagonal stresses (measured/modelled).

The calibration of the FE model against monitoring results provided assurance that the behavior of the bridge is well understood, enhancing the potential for data-driven decisions.

6 REAL-TIME MONITORING FRAMEWORK

To manage the vast amounts of sensor data efficiently, an automated preselection of loading events was introduced. This system relies on a designated "trigger sensor"—in the case bridge, the maximum deflection of the main span. Each day, the ten most severe loading events are identified, ensuring that comparisons are made based on similar traffic conditions.

Once trigger events are selected, a full one-minute dataset is retrieved for all sensors, ensuring that both immediate effects and short-term recovery behaviors are captured. To establish a reference point for long-term monitoring, the first 30 days of operation were designated as the baseline, against which all subsequent readings are compared.

For comparative analysis, stress and displacement fluctuations under traffic loads were selected. These results provide insights into structural response variations and were also utilized for fatigue analysis of critical details.

The real-time monitoring system is accompanied by a standardized dashboard, which presents weekly summaries of key indicators. This allowed the Client to easily track trends

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without needing to analyze raw data manually. While the current monitoring system does not yet fully utilize advanced AI tools, its structured approach has already demonstrated reliability, providing trustworthy insights that inform safety decisions.

The work done in the calibration of the FE model offered such detailed insights into the bridge's behavior that it significantly enhanced our interpretation of the monitoring results, enabling us to differentiate between normal operating patterns and potential anomalies.

Figures 13 to 15 illustrate the primary views of the dashboard, which facilitates the detection of both long-term trends and short-term changes in the bridge's behavior. The dashboard is engineered to emulate the analytical interpretations of an experienced structural engineer, significantly reducing the time required for data interpretation while still necessitating periodic expert review—an achievement made possible by advances in AI. Notably, the fatigue view has spurred a spin-off project aimed at developing comprehensive fatigue assessment software applicable to any structure monitored by the system, including preliminary studies on HFMI-treatment in line with the forthcoming second-generation Eurocodes.

Figure 13. Summary view of the dashboard.

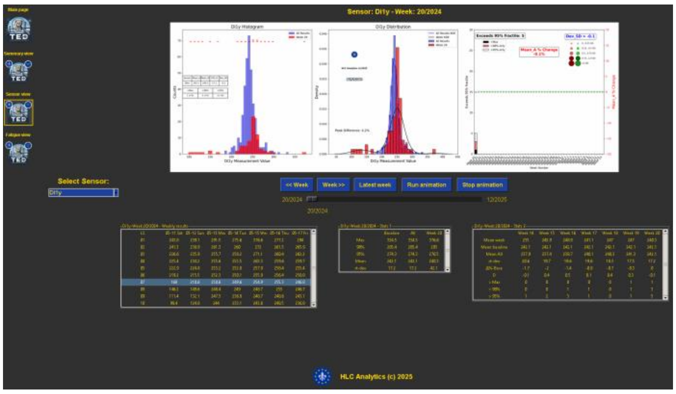

Figure 14. Detailed sensor-view of the dashboard.

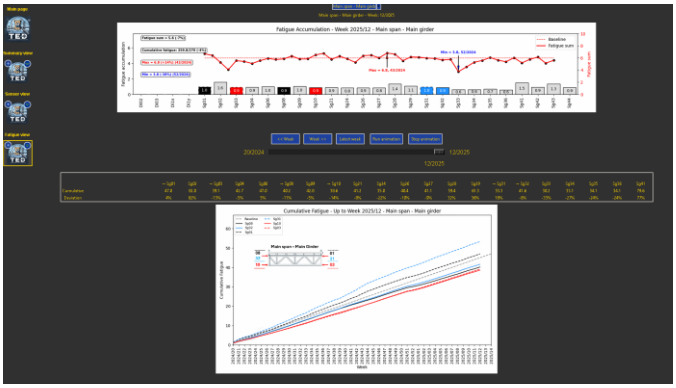

Figure 15. Fatigue-view of the dashboard.

The dashboard will provide clear alarms when anomalies are detected, offering users the ability to explore the data further. Each meaningful event can be visualized as needed, enabling a deeper understanding of the bridge's condition and facilitating informed decision-making.

In addition to these dashboard views, a largely automated weekly report and other analytical insights are provided. The implementation of this system reduces the active expert time required from hundreds of hours to single-digit hours per report. Naturally, any detected changes in behavior can trigger more in-depth studies.

7 EXAMPLES OF ABNORMALITIES DETECTED WITH THE INSTALLED SHM-SYSTEM

The new hangers have occasionally exhibited higher stress values, indicating that relative motion is occurring between the hangers and the deck. This behavior is likely driven by temperature-induced movements of the main cables, although displacements from heavy traffic loads are also contributing—especially if the deck does not fully return to its original position after loading. As a result, this relative motion may cause the hanger bars to contact adjacent structural components, leading to elevated strain gauge readings. Since the hanger bars are designed with considerable built-in safety factors, these modest increases (occasionally up to 50%) in sensor readings do not presently signify an immediate structural risk; however, if not adequately addressed through maintenance, they could eventually evolve into more critical issues.

The changes in the behavior are well seen when the fatigue accumulation for the hanger bars is plotted for each week (see Figure 16), from week 47/2024 the Fatigue accumulation increases strongly.

Following the removal of a cover plate (see Figure 17), stress levels temporarily decreased, only for similar patterns to re-emerge a few weeks later. Although the current stress levels are not critically hazardous, the repeated contact between the hanger bars and adjacent structural elements could eventually lead to fretting fatigue cracks. As a precaution, immediate repairs to widen the openings around the bars were

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recommended. These stress increases were quickly detected by the dashboard, which employs AI algorithms with accuracy comparable to that of a human expert, ensuring that such anomalies are reliably flagged.

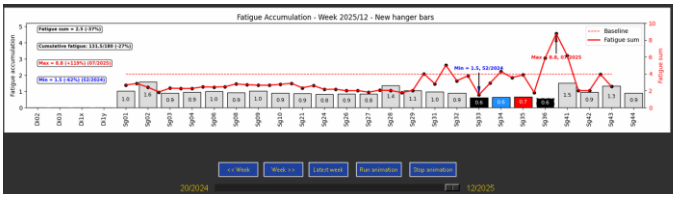

Figure 16. Sudden increase in fatigue accumulation of new hanger bars

Figure 17. Contact of the hanger bar and cover plate

Additionally, significant deflections and stress variations were detected sporadically, often coinciding with instances when heavy vehicles failed to comply with the new restrictions. Camera footage confirmed that two—or sometimes even three—heavy vehicles crossed the bridge simultaneously (see Figure 18). Although the occurrence of multiple heavy vehicles clearly violates the established restrictions, these restrictions remain essential, as frequent violations could have a much more detrimental impact than isolated incidents.

Figure 18. Two heavy vehicles at main span

8 BROADER APPLICATIONS OF THE SHM SYSTEM

The development of the SHM dashboard was carried out in close collaboration with the Client responsible for the bridge's safety. Their involvement ensured that the system presented clear, actionable information, making it easier to interpret monitoring data without requiring specialized expertise. As a result, the dashboard became a practical tool for real-time decision-making, rather than just a data visualization platform.

Bridging the gap between large-scale monitoring efforts and local stakeholders is crucial. Often, local communities must place their trust in decisions made at a national or corporate level. By bringing monitoring tools closer to end clients and asset owners—through transparent, standardized, and analytically robust dashboards—we empower them with the insights needed for informed decision-making. This approach not only enhances transparency but also fosters a culture of shared responsibility and improved safety at the local level.

Due to its successful implementation, the system was designed with scalability in mind, allowing it to be applied to other projects with minimal modifications. The fundamental approach—selecting relevant loading events, establishing a baseline, and tracking deviations—can be adapted to any bridge or infrastructure type. In fact, this methodology extends beyond bridge SHM and can be used in any time-series data analysis application where there is a need to detect long-term trends or sudden changes in any monitored metric.

Furthermore, a deep understanding of the bridge's structural behavior enables the optimization of sensor placement. This refined design not only enhances data quality but also reduces the number of sensors required, thereby lowering the overall costs of individual monitoring projects.

Recognizing this potential, developers began shifting focus toward building a next-generation standardized SHM analysis

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dashboard. The next iterations will incorporate AI-assisted automated damage detection and advanced pattern recognition, allowing engineers to identify anomalies without needing to manually go through raw data. Importantly, all collected data has been stored in a structured format, ensuring that future enhancements—such as machine learning-based predictive maintenance—can be integrated without requiring a complete system overhaul.

Even in its current form, without full AI-driven analysis, the SHM system has proven reliable and trustworthy, providing the data necessary for the Client to make informed maintenance decisions. As computational power increases, real-time monitoring will continue evolving, allowing asset owners to shift from reactive to fully predictive maintenance strategies, ultimately reducing costs and improving safety across critical infrastructure networks.

9 CONCLUSIONS AND FUTURE PERSPECTIVES

Effective infrastructure management relies not just on data collection but on extracting meaningful insights from vast amounts of sensor information. To make data-informed decisions, monitoring systems must filter out irrelevant readings while capturing every critical structural event. In this project, a trigger-based system was implemented to identify the most relevant high-load situations per day, ensuring that engineers could track changes in bridge behavior over time without being overwhelmed by excessive data.

The high-flying promise of adopting a structured and analytical approach in SHM lies in transforming 'known unknowns' into 'known knowns.' By systematically standardizing data analysis, we can significantly enhance the reliability of our decision-making processes. This increased understanding naturally leads to improved safety, cost reductions, and substantial socioeconomic benefits. Ultimately, a more data-informed framework will pave the way for more predictive and preventative maintenance strategies.

Future iterations of the system will incorporate more trigger-sensors, improving detection accuracy and allowing for a more detailed understanding of how different parts of a structure respond to varying loads. Additionally, with advancements in automated data processing and machine learning, monitoring systems will not just detect anomalies but ultimately also predict future deterioration trends, enabling truly proactive maintenance strategies.

For long-term viability, monitoring frameworks must remain scalable and adaptable, allowing new technologies to be integrated without major system overhauls. Greater emphasis should also be placed on load testing and FE-model calibration, ensuring that monitoring data is interpreted within a robust engineering framework.

As SHM systems become more mainstream and data handling becomes more systematic, there is a significant opportunity for transfer learning. By systematically analyzing results from a diverse range of structural configurations, it will be possible to enhance the understanding of different structural behaviors. This transfer learning process has the potential to greatly amplify the benefits of SHM in the future, enabling more accurate predictions and more efficient maintenance strategies for a wide variety of infrastructure types.

We are confident that soon, extremely cost-efficient real-time SHM systems will become a standard part of infrastructure management, allowing asset owners to make fully data-driven maintenance decisions. This shift will significantly reduce long-term costs while improving the safety and reliability of critical infrastructure worldwide.

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