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On potentials and challenges of physics-informed structural health monitoring for civil engineering structures

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ABSTRACT: Physics-informed structural health monitoring, which integrates realistic physical models of material behavior, structural response, damage mechanisms, and aging processes, offers a promising approach to improve monitoring capabilities and inform operation and maintenance planning. However, the associated technical challenges and model requirements are context-specific and vary widely across applications. To illustrate the relevance and potential of the topic, two application examples are presented. The first focuses on monitoring the modal characteristics of a prestressed road bridge, where strong sensitivity to temperature variations limits the diagnostic capabilities of conventional vibration-based global monitoring. The discussion highlights how environmental influences can obscure structural changes, and emphasizes that purely data-based approaches are inherently limited to detecting anomalies and do not enable comprehensive condition diagnostics. The second example explores a physics-informed monitoring approach for prestressed concrete bridges affected by hydrogen-induced stress corrosion cracking. By combining acoustic emission data with a calibrated acoustic model of the structure, it is possible to detect and localize wire failures. As an outlook, the integration of mechano-electro-chemical models for stress corrosion cracking is discussed, enabling predictive assessments of the strand condition.

KEY WORDS: Physics-informed SHM; Diagnostics, Prognostics, Structural Assessment, Structural Integrity Management

1 INTRODUCTION

Civil engineering structures are subject to damage, aging and deterioration processes such as fatigue, corrosion, shrinkage, creep, and scour – all of which can affect their safety and serviceability. Additionally, they are exposed to environmental and operational variations. In particular, fluctuating structural temperature distributions caused by changing environmental conditions may alter structural behavior and, in some cases, even impact structural capacity. Moreover, structures may experience rare and extreme events during their service lives – such as storms, floods, fires, explosions, earthquakes, extreme traffic loads or ship impacts – which can also impair safety and serviceability. Some structures may even already exhibit damage, which could progress to a critical state, affecting structural performance.

To effectively manage the structural safety and serviceability of engineering structures, owners and operators require information on loads and their effects, environmental influences, operational conditions, and the structural condition. This information forms the basis for assessing and forecasting structural performance, thereby enabling informed decisions on operation and maintenance.

Structural health monitoring (SHM) – in the sense of monitoring the condition of a structure – is intended to support diagnostics, prognostics, structural assessment, and maintenance planning. Diagnostics involves inferring the current condition or changes in structural characteristics from measurements or observations that are indirectly related to them. In this process, environmental and operational variability must typically be taken into account, as their impact on structural behavior can alter the measured signals, thereby potentially masking the presence of damage.

Ideally, the diagnostic information obtained through SHM is used to predict the future structural condition and to quantitively assess structural safety and serviceability.

Research in SHM for engineering structures has a long history [1]. While significant progress has been made in the field, in practice, SHM is primarily used to measure loads and their effects, collect structural response data as a basis for calibrating structural models, and monitor known damages locally [2]. SHM-informed diagnostics, prognostics, structural assessment, and maintenance planning for engineering structures remain an evolving field.

This contribution discusses the potential and challenges of integrating physical modelling into SHM to enhance these tasks. At its core, physics-informed SHM couples physical models that describe the processes influencing structural condition and capacity with models of the structural performance, and continuously updates them with inspection and monitoring data from the actual system [3]. Within this framework, physical models are also employed to link measurements and observations to the structural condition and damage states, thereby providing an indirect connection to the processes driving deterioration and structural damage.

The paper is organized as follows: Section 2 provides a more detailed discussion on the motivation for adopting a physics-informed approach in SHM, drawing from our group's long-term monitoring experience of a road bridge in Berlin. Section 3 than explores the potential and challenges of applying physics-informed SHM to extend the lifetime of prestressed concrete bridges subject to stress corrosion cracking. Finally, Section 4 provides concluding remarks.

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2 THE MOTIVATION BEHIND PHYSICS-INFORMED SHM: THE WESTEND BRIDGE EXPERIENCE

2.1 Westend Bridge

Our group's research related to SHM began in 1994 with the continuous monitoring of the Westend Bridge. This example is also used because the bridge is currently being demolished. The 30-year measurement project is likely to be one of the longest in the world. The Westend Bridge in Berlin, which has been carrying heavy traffic for several decades, had suffered a number of damages since its construction. Strengthening work was repeatedly required to ensure adequate load-bearing capacity in the long term. Figure 1 shows the normal operating conditions at the start of the monitoring measure. Figure 2 and Figure 3 are recent photos taken shortly before and during disassembly respectively.

Figure 1. Westend Bridge in service.

Figure 2. Westend Bridge in recent years, featuring implemented safety measures.

Figure 3. Demolition of the Westend Bridge, April 2025.

Among other things, it was found that the coupling joints of the bridge deck had opened. Under the influence of external loads and temperature changes, significant changes in joint width were observed during inspection and finally monitored by measurement. It was found that above a certain temperature, the crack width of the joint increased disproportionately under traffic load.

Westend Bridge is or was a prestressed concrete box girder bridge, commissioned in (1965) with full prestressing. It has 7 spans and a total length of 237m. The cross-sections of the bridge proved to be problematic: The flat three-cell box girder has a tendency to high residual stresses due to temperature, but also a significant influence of the asphalt layer on the structural behavior and a significant influence of the nominally non-structural components (rails and caps) was identified. The effect of temperature variations in the structure has not been considered in the design.

The prestressing tendons are coupled at couplers. Shear reinforcement and concrete cover (chloride ingress) have been shown to be inadequate. In addition, the bridge is subject to heavy traffic. As a result, the bridge has been strengthened several times.

The bridge reacts non-linearly due to temperature changes and high traffic loads. The coupling joint has opened due to traffic loads at high temperatures, resulting in increased fatigue demands on the prestressing tendons. Temperature variations affect the stiffness of the asphalt, change the stress/strain state within the section and lead to longitudinal cracking in the webs and base plate.

From a detailed modelling perspective, the degree of fixation between the columns and the box girder is unknown, as is the degree of fixation between the columns and the foundation.

The management of the structural data is similar to that of a normal existing bridge: Data and information about the bridge is recorded and stored in printed documents and drawings. Minimal or no as-built documentation is available. There is no information on actual physical parameters (e.g. material properties). The lack of physical information in the documentation and the lack of digitization of the data are a major obstacle to the introduction of a SHM system.

2.2 SHM Installation and global damage detection

An SHM system has been installed for the purpose of identifying damage or changes in structural characteristics based on data indirectly related to these damage/changes in structural characteristics.

At the beginning, an experimental modal analysis was carried out with a hydraulic shaker from EMPA. The bridge was then equipped with geophones, temperature sensors and local strain gauges in one section for a continuous monitoring.

At the time of initial installation, the aim was to identify structural changes based on a shift in natural frequencies. This initial diagnostic idea quickly proved to be flawed, as the bridge has a strong dependence of its natural vibration behavior on the structural temperatures (Figure 4). Possible approaches to understanding the temperature dependency were subsequently analyzed in a diploma thesis [4]. A major influence for this bridge is attributed to the significant stiffness contribution of the asphalt at low temperatures.

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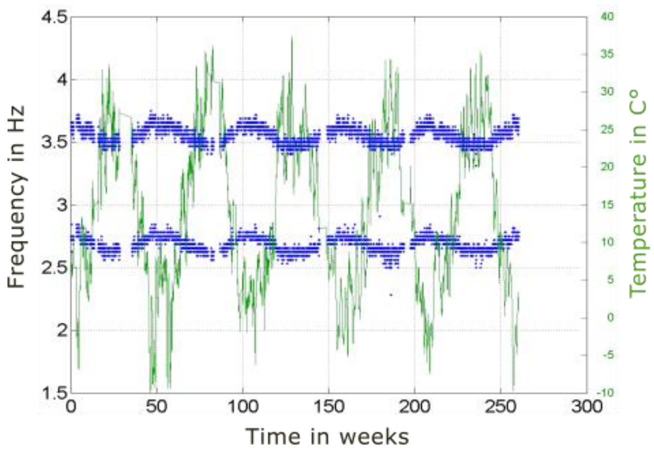


Figure 4. Dependence between natural frequency and temperature (or changes in structural behavior due to temperature effects).

Detection of damage or changes in structural properties has been further explored using signal processing techniques for dynamic data in [5]; This attempt provides a feature that is sensitive to global and significant structural damage/changes in structural properties. The procedure eliminates the effect of temperature-dependent periodic variations by normalizing the vibration data.

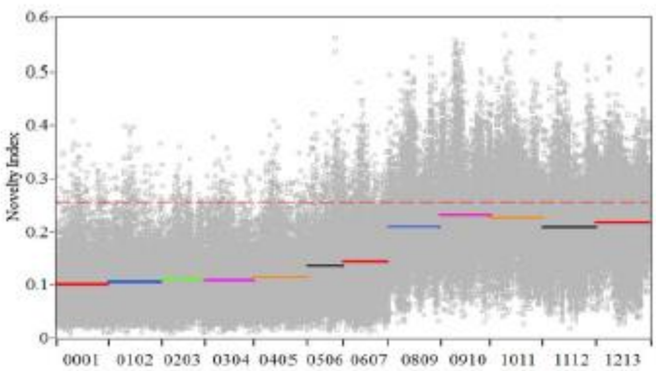


Figure 5. Statistical damage indicator derived with the novelty detection method [5].

In this example, the global damage identification can optimally show that there is a change in the measurement data and possibly in the building response. Such an anomaly would generally be recognizable after a few measurement intervals (e.g. 10-minute intervals), see Figure 5. It would then be possible to start a diagnosis as to whether there is a measurement error or whether a change in the structure is actually the cause of the changes in the measurement signal. As no information about the size and location of the damage can be determined, further damage diagnosis is only possible on site and, depending on the structure, involves considerable effort.

2.3 *Physical modelling*

It is not possible to infer the structural safety and service ability from variations in the natural frequency alone.

The SHM at Westend bridge as previously outlined lacks information on damage location, damage size and damage evolution. One of the most serious problems, however, is that it is not clear whether and to what extent the structural changes represent damage relevant to structural safety.

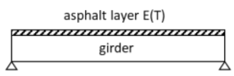
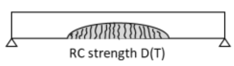
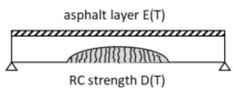
 asphalt layer E(T) girder	**Asphalt Layer:** Strong temperature dependence of asphalt stiffness; contributes to overall structural stiffness, but not to structural load-bearing capacity.
 RC strength D(T)	**Concrete – RC and prestressed:** Stiffness can vary ▪ Stiffness depends on temperature and humidity ▪ Cracks of coupling joints may open with temperature and effect capacity
 asphalt layer E(T) RC strength D(T)	**Combination** How can the individual mechanisms be distinguished?

Figure 6. Influence of temperature on structural components.

As shown in Figure 6, a load-bearing contribution of the asphalt layer is not relevant to safety. However, if cracks open in the reinforced concrete under temperature, a temperature load represents real damage to the load-bearing structure. In reality we see a combination of both mechanism which have to be separated in a structural assessment.

In order to enable a more precise analysis, it is usually necessary to switch from a model-free data analysis to a model-based data analysis. Figure 7 shows a general scheme. Identifying a structural model is a necessary step that must be accompanied by an assignment of physical material and component properties.

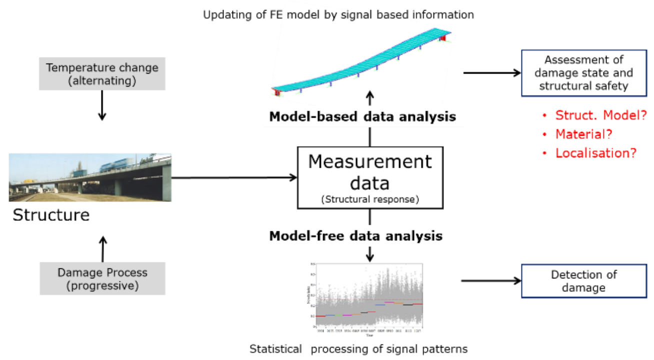


Figure 7. Updating scheme for SHM that accounts for temperature fluctuations, which may mask structural damages.

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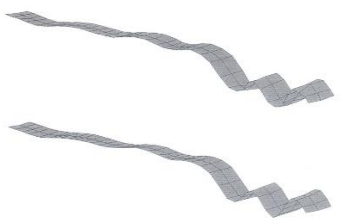

Frequency measured in Hz	Frequency calculated in Hz	MAC
1.845	1.92	0.89
2.26	2.40	0.79
2.63	2.62	0.96
3.53	3.47	0.97
4.02	4.13	0.89
4.56	4.46	0.83
6.47	6.47	0.85

Figure 8. left: Vibration mode identified from measurements (top) vs vibration mode determined via finite element modelling (bottom). right: Identified and numerical natural frequencies

Various detailed FE models were created for the Westend Bridge and adapted to reality by means of experimental modal analyses. The models make a significant contribution to understanding the structural behaviour. The updated model is good, see Figure 8, but unfortunately not very sensitive to severe damage when compared to environmentally induced changes. The general lack of a link between the modal parameters and the (local) strength properties continues to prevent a substantial structural assessment.

2.4 What can be learned from Westend bridge

The key findings from the Westend Bridge monitoring can be summarised as follows:

- Data management: Construction documents are available in paper form. These are primarily planning data (not as built, no material parameters). The data storage is not linked to ongoing digital data management.
- A global damage detection has been successfully implemented. However, the detection of a specific damage or of changes in structural characteristics was not possible. Global damage detection provides incomplete diagnostic information, no information on type, location and size of damage.
- To obtain complete diagnostic information based on SHM data it is necessary couple data with physical models. A physical model should consist of a structural model and its physical parameters describing local strength and deterioration characteristics.
- The Westend Bridge has many weak structural points, but specific hot spots are difficult to identify. What becomes apparent is that a scenario-free monitoring is extremely difficult. A monitoring task becomes easier the more clearly the potential damage scenarios can be described. This is particularly the case when disturbances such as temperature fluctuations mask changes in the structure’s condition.
  → Chapter 3 presents a scenario-orientated approach for a physics-based SHM procedure.

3 PHYSICS-INFORMED SHM OF BRIDGES SUBJECT TO STRESS CORROSION CRACKING

Numerous incidents in Germany have shown that concrete bridges containing prestressing steel susceptible to hydrogen-induced stress corrosion cracking experience a characteristic deterioration process [6-8]. Damage typically initiates during the construction phase due to a mechanical-electrochemical mechanism triggered by aggressive ambient conditions. As the bridge enters its operational phase, and the prestressing ducts are grouted, damage continues to develop due to fatigue crack growth caused by dynamic traffic loads and temperature fluctuations. Over time, this can result in the failure of individual prestressing wires, each of which emits acoustic signals upon breaking. If a critical number of wires fail, the structural integrity of the bridge can be severely compromised, potentially leading to substantial damage or even collapse. In this context, the following section discusses the challenges and potentials of physics-informed SHM to extend the lifetime of bridges identified as vulnerable to this specific deterioration process.

A fundamental prerequisite for SHM-informed, model-based integrity management of bridges is the implementation of a consistent digital data management. Such a system must provide storage and access to all relevant physical information across the design, construction, and operational phases of a bridge’s lifetime. It must be able to handle heterogeneous data objects, including design reports, quality control protocols, inspection records, sensor data, and assessment results. Furthermore, the system should support automated workflows that integrate this diverse data with model-based methods to enable accurate diagnosis and prediction of structural condition, as well as assessment of structural safety.

The first step in developing a physics-informed strategy for monitoring and managing the structural integrity of concrete bridges susceptible to stress corrosion cracking is to thoroughly analyze the potential failure modes resulting from the loss of a significant number of prestressing wires. It is crucial to ensure that the bridge possesses sufficient structural redundancy so that the failure of prestressing strands does not lead to sudden, catastrophic collapse. This redundancy is typically provided through reinforcement, which allows for large deformations after strand failure – acting as warning signs before failure and preventing brittle, unannounced collapse. Furthermore, it must be demonstrated that observable indicators accompany significant damage to prestressing strands. Examples of such indicators include horizontal longitudinal cracks in the webs of box girders or beams [6]. The appearance of these signs suggests advanced damage and necessitates immediate action, including bridge closure for detailed assessment, reinforcement measures, or potential decommissioning.

If the previously discussed conditions are fulfilled—in addition to the requirements that the bridge is intact, shows no signs of significant damage to the prestressing tendons, and retains sufficient load-bearing capacity (potentially confirmed through a proof load test)—then a dedicated monitoring strategy can be implemented. In this case, the evolution of stress corrosion cracking, specifically the failure of individual prestressing wires, can be monitored using acoustic emission techniques. Following the detection of a tendon failure event, a detailed visual inspection of the bridge has to be carried out to check for any newly developed visible indicators of advanced damage.

The primary aim of acoustic emission monitoring is to detect failures of prestressing wires in time and space [9, 10]. This identification problem is currently approached by utilizing pure data-based signal processing methods. However, by adopting a

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physics-informed strategy—combining physical modeling of the acoustic wave propagation from wire failures with measured data—the accuracy of rupture identification can be significantly improved. In this approach, data and modeling of wire failures are brought together by identifying the model prediction that best explains the measured acoustic signal, either through optimization or Bayesian updating. Research has been initiated at BAM to develop and validate this combined methodology [11].

The first step in a physics-informed approach to diagnosing wire failures from acoustic emission signals is the development of an acoustic reference model that accurately captures the acoustic properties of the structure. This model can be established and refined using data collected during in situ reference tests. A valuable source of such data comes from the sampling of prestressing wires, which emit acoustic signals when cut. These samples, typically taken to check for defect initiation and perform material testing, provide relevant emission characteristics that support model development.

Within a physics-informed approach to SHM, the reference model is a central component of a reference certificate or birth certificate, if created at the beginning of the structure's lifetime, as outlined in the upcoming revision of DIN 1076 [12]. The reference certificate contains all information required to develop and describe the reference model, including the underlying assumptions, the data used for its calibration and validation, as well as calibration and validation results. It is incorporated into the structure's data management system to ensure traceability and long-term use.

The first major application of the calibrated reference model is the optimization of sensor placement for the acoustic emission monitoring system. Sensor locations are selected to maximize the system's ability to perform the intended diagnostic tasks. This can be achieved, for example, through model-based value of information (VoI) analysis [13].

As an outlook, a physical model of the deterioration process can provide a basis for predicting the condition of prestressing tendons. The initiation of stress corrosion cracking during the construction phase may be described using mechano-electro-chemical principles [14], while crack propagation during the operational phase can be modeled through fracture mechanics [15]. Material properties and data on the initiation and evolution of the deterioration process from laboratory tests can be used to calibrate the model. Fatigue demands resulting from traffic loads and temperature variations are incorporated via models of the respective actions and a structural model to simulate the evolution of damage over time. Capturing the stochastic nature of the deterioration process is essential to ensure realistic predictions. By coupling the deterioration model with diagnostic information from acoustic emission monitoring and visual inspection, predictions can be continuously updated. Furthermore, integrating the deterioration model with a structural model allows for assessments of safety and serviceability throughout the structure's extended lifetime [16].

Currently, BAM is developing a physics-informed SHM procedure within the research project ReSKoMB, aimed at enabling the safe extension of the service life of prestressed road bridges suspected to be affected by stress corrosion cracking. The procedure is being developed using the Baumgarten Bridge near Potsdam as a reference structure (Figure 9).

Figure 9. Baumgarten Bridge near Potsdam.

A key element of the procedure is the collection of prestressing wire samples taken directly from the bridge, providing essential information about the current condition of the wires (Figure 10).

Figure 10. Sampling of prestressing wires from an existing road bridge for material testing (source: LS Brandenburg).

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These material samples are subject to various tests, including non-destructive testing to detect defect initiation. Additionally, laboratory experiments are conducted to study the onset of damage through stress corrosion cracking and the subsequent growth of fatigue cracks under cyclic loading (Figure 11).

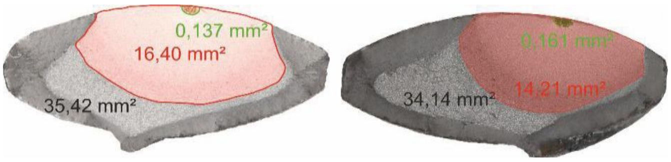

Figure 11. Fracture surfaces of two prestressing wires after a fatigue test. Green: pre-existing defects, red: crack propagation during the fatigue test, light gray: residual fracture surface [6].

A physical model of the damage processes is then developed based on these tests, allowing for predictions of the time to wire failure. To enhance these predictions, object-specific traffic load models are developed for the bridge. As part of this modeling, traffic loads are classified based on vibration measurements, enabling a more accurate representation of the actual loading conditions (Figure 12). This work builds on a project funded by the German Research Foundation within the Priority Programme "Hundred Plus" [17]

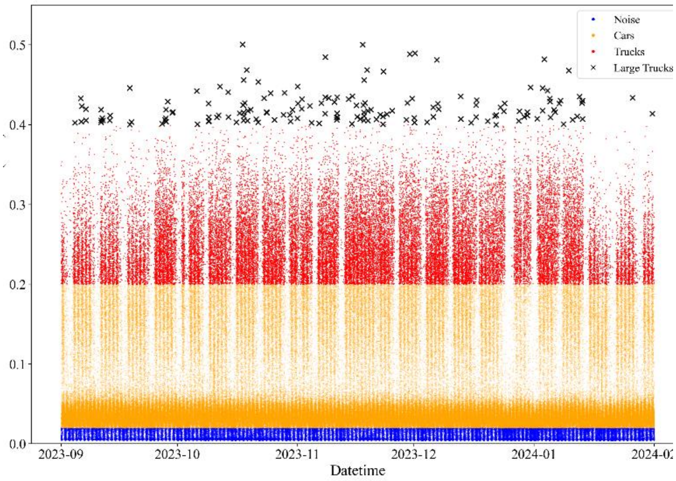

Figure 12. Classification of vehicles crossing a road bridge using machine learning techniques. The classification is based on acceleration signals [17].

Further, diagnostic information from acoustic emission monitoring, enhanced with physical modeling of acoustic wave propagation from wire failures, is used to update the predictions (Figure 13). This work is being performed as part of a parallel project at BAM called SimAS, which focuses on acoustic modeling techniques to improve the diagnosis of wire failures based on acoustic emission data [11].

As an alternative to acoustic emission methods, the project is also exploring the potential to detect wire failures using acceleration signals recorded with MEMS sensors, a method which has been successfully used in a previous project with progressive severing of prestressing wires (Figure 14).

Additional information on visible indicators of critical damage, such as horizontal longitudinal cracks in the bridge webs, is obtained through automated UAS-based inspections [18], which is triggered by continuous monitoring of prestressing wire failures.

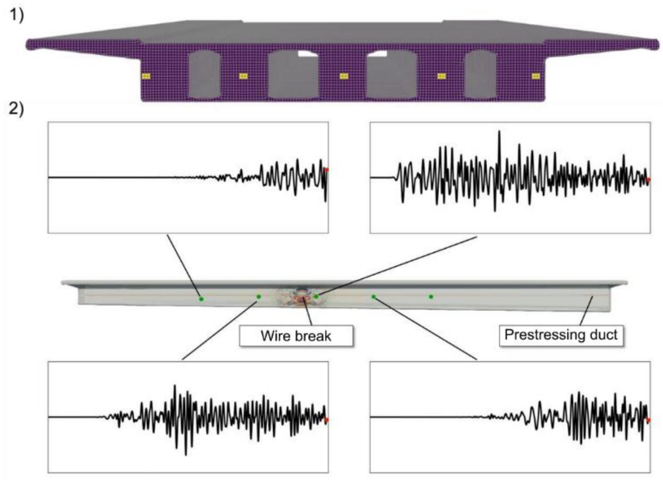

Figure 13. Simulation of acoustic wave propagation from a prestressing wire fracture in a box girder bridge. 1) Numerical mesh. Different material properties for concrete and wires (e.g., sound speed, density, damping) can be assigned to the elements. 2) Side view of the bridge with a simulated wire failure and several point evaluations of the simulated sound emission. [11].

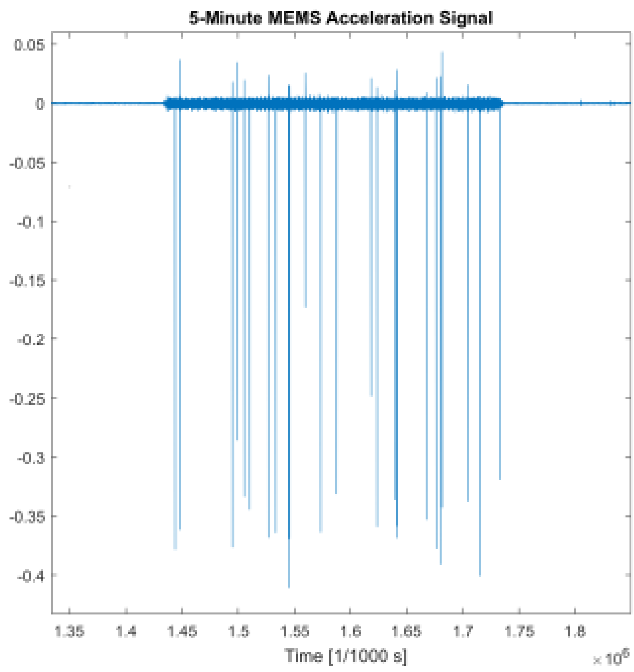

Figure 14. Accelerations measured with MEMS sensors on a bridge during progressive severing of prestressing wires [6].

4 CONCLUDING REMARKS

As outlined in this contribution, physics-informed SHM holds significant potential to enhance diagnostics, prognostics, structural assessment, lifetime evaluation, and planning of operation and maintenance activities. By incorporating physical models into the SHM process, this approach offers a promising way to account for operational and environmental

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variations that typically challenge conventional diagnostic methods.

However, the effectiveness of physics-informed SHM ultimately depends on the inherent sensitivity of the monitoring system to damage. These methods cannot compensate for a lack of sensitivity in the underlying measurement technique – rather, they can only leverage and enhance existing capabilities. Thus, careful consideration must be given to the selection and design of monitoring systems.

Implementing physics-informed SHM approaches requires proper digital data management to enable automated and scalable workflows. It is also associated with substantial modeling effort, making it essential to assess the return on investment for each application context.

These challenges and opportunities will be discussed further with the community at the upcoming CSHM-10 workshop in 2026, to be held in Berlin. As a dedicated forum for experts in SHM and non-destructive evaluation (NDE), CSHM-10 will provide an ideal platform to explore how physics-based models and monitoring data can be effectively combined to improve the safety, resilience, and efficiency of civil infrastructure systems.

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