Service-life extension of transport infrastructure through structural health monitoring

Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

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ABSTRACT: Transportation Infrastructure systems are recognized as essential for economic development, territorial cohesion, and social transformation. Unfortunately, some of the key structural components of this massive system, such as bridges, are rapidly ageing, while load conditions are exceeding those for which these systems initially envisaged as they are subjected to different hazards, such as natural events or new man-made phenomena. Given that a substantial portion of the current bridge stock was constructed many decades ago, degradation phenomena and a rise in service conditions greater than those employed in the original design may have contributed to reducing the reliability level, if countermeasures are not adopted. Therefore, the assessment of the current state and the prediction of the future condition of Transportation Infrastructure, and their protection against external hazards, turn out to be essential. This contribution firstly focused on an in-depth study of the role of structural health monitoring in improving the structural resilience of transportation infrastructure and consequently its life-cycle. Subsequently, a practical example is provided to highlight the role of SHM toward structural resilience improvement for an Italian common transport infrastructure.

1 INTRODUCTION

With respect to a variety of causes, including corrosion brought on by severe weather conditions and fatigue damage, steel structures are vulnerable to time-dependent degradation and aging effects. Due to the extensive usage of steel bridges in many nations across the globe, the economic implications of these consequences are especially pertinent. Steel girders that are exposed to sea water and atmospheric corrosion deteriorate over time. In addition to other things, corrosion reduces the original thickness of connections and profiles, such as the web and flanges of steel I-girders. The damage affects the element's and section's structural characteristics owing to thickness decreases brought on by corrosion penetration (e.g. strength and stiffness) (Biondini & Frangopol 2016).

The issue of life-cycle of bridges with respect to degradation phenomena, such as corrosion and fatigue, has been investigated in the literature. The cumulative seismic damage and corrosion effects on bridges' life-cycle is deepened by Kumar et al. (2009) highlighting how the the cumulative seismic damage affects the structural reliability over time more than corrosion. The issue of corrosion deterioration effects on the seismic response of RC bridge piers has been also studied by Bartolozzi et al. (2022). The role played by bonding in the degradation of the seismic capacity has been highlighted.

DOI: 10.1201/9781003323020-509

With specific respect to transport infrastructure management, Kim et al. (2013) proposes a framework for structural inspection and maintenance planning, highlighting how the dependence between the appropriate maintenance and the damage degree. Aspects related to analysis and decision-making for assessing bridge life-cycle performance and cost have been deepened in Frangopol et al. (2017), considering also climate change and structural health monitoring. Life-cycle reliability, risk and resilience-based design of transportation infrastructures have been studied by Akiyama et al. (2020), highlighting the importance of studying both independent and interacting hazards to assess the bridge reliability (e.g. earthquake and tsunami, or landslide).

The relationship between structural health monitoring (SHM) and the life-cycle of bridges has been discussed in the literature, e.g. in the review work by Biondini & Frangopol (2016). Focusing on railway bridges, their reliability assessment and the role played by SHM has been studied by Vagnoli et al. (2018), comparing different types of structural health monitoring methods (e.g. model, non-model).

Despite the improvements in the knowledge provided by the existing literature, the impact of SHM in the life-cycle of transport infrastructures would need a further in-depth study. To this end, this contribution is offered; specifically to investigate how SHM can positively influence the resilience and, consequently, the life-cycle of bridge structures.

The next section brings together some aspects related to SHM toward structural resilience improvement. The following one provides an application example to highlight the relationship between structural health monitoring, resilience, and life-cycle.

2 SHM CONTRIBUTION TO STRUCTURAL RESILIENCE AND LIFE-CYCLE

2.1 *Diagnosis and prognosis*

Damage diagnosis enables decision-makers to be informed about the various forms of deterioration in civil engineering structures and the proper course of action to take in response to dangerous structural circumstances. Damage detection, localisation, quantification, and prognosis are the core stages of structural health monitoring (SHM) for damage diagnosis. The four stages may be described in more depth as follows:

- Phase 1: Determining if the building has been damaged.
- Phase 2: Phase 1 plus determining the geometric location of the damage.
- Phase 3 comprises Phase 2 and a calculation of the damage intensity.
- Phase 3 plus the assessment of the structure's remaining service life is Phase 4.

The first two steps serve as the primary pillars of the most used vibration-based damage diagnosis approaches (without the use of structural models). Phase 3 damage diagnosis may sometimes be accomplished by integrating vibration-based methods with a structural model. Phase 4 is still a difficult engineering challenge that needs interdisciplinary and predictive modelling skills, but it might provide enormous safety and financial advantages to the management of structures and infrastructure (Faravelli & Casciati 2004; Cheung et al. 2008; Domaneschi et al. 2017; Morgese et al. 2021).

A review of the literature on the many methods for spotting damage and keeping track of a structure's health based on changes in its observed dynamic characteristics is given by Doebling et al. in 1996. They are based on

- modifying modal features,
- altering dynamic flexibility,
- updating structural matrices while undergoing restricted optimization,
- nonlinear approaches,
- and neural network-based techniques.

Many of the techniques rely on a dataset of the undamaged structure as a baseline, while others need access to a comprehensive FEM of the structure to get more understanding and access to higher levels of data (e.g. quantification). The number of sensors in an SHM system has expanded over the last ten years due to significant advancements in growing processing

power and sensing technology, which in turn has led to an increase in the amount of data gathered. Advanced processing techniques are required to be used to handle this massive volume of data to transform the heterogeneous, multi-source data into various sorts of particular indications and enable efficient inspection, maintenance, and management choices. As a result, the scientific community has seen an increase in the usage of automated algorithms for data management, calculation, and structural (such as damage) detection.

Machine learning techniques, particularly deep learning algorithms, have been more useful and extensively used in vibration-based structural damage diagnostics because of their elegant performance and frequent, exacting correctness. The first involves data preparation (human involvement) to extract certain features or qualities, in contrast to the second, which may find a straight mapping from the initial inputs to the final outputs without the need for feature extraction. Deep learning is thus effectively used to handle massive volumes of data (big data) for many purposes (Avci et al. 2021).

In addition to Deep Learning, a combination of Wavelet and other time-frequency analysis and feature extraction techniques have been recently developed and applied for the processing of big data from sensor networks for the health assessment of bridge structures (Silik et al. 2022; Ghiasi et al. 2020).

2.2 *Structural resilience and dimensions*

Robustness, resourcefulness, redundancy, and rapidity are the four main components, or dimensions, of resilience, according to MCEER researchers (Bruneau & Reinhorn 2007). In detail: (1) Robustness refers to a structure's or an element's capacity to tolerate a certain amount of demand (such as damage) while retaining its usual degree of usefulness. Alternatively, one may refer to it as the idea of damage tolerance. (2) Redundancy, for instance, of load-bearing components: the capacity to create alternate load-supporting paths after the deterioration of the primary parts has a place (i.e., original elements that are replaceable); (3) Resourcefulness: The capacity to recognize problems, establish priorities, and gather materials when conditions pose a risk to the stability of the structure or one of its components; (4) Rapidity: The capacity to prioritize interventions and complete them as soon as possible to minimize losses, restore functioning, and stop additional interruptions.

There have been several studies published to help us understand structural resilience in buildings. The Resilience approach proposed by Cimellaro et al. (2010) for a condensed recovery plan is one example. The notion of immediate resilience is proposed in Domaneschi & Martinelli (2016) as being related to the automated function of certain components to make up for local out-of-services. Structural resilience has also been explored in many areas.

2.3 *SHM toward structural resilience*

The relationship between resilience and emerging digital technologies including the structure and infrastructure monitoring is a topic that hof attracted the interest of the scientific community worldwide in recent years (Domaneschi et al. 2021; Wu et al. 2020).

Structural resilience is herein assumed as a Performance Indicator for life-cycle considerations of transport infrastructures accordingly with Biondini & Frangopol (2016). Following the identification of the four distinct SHM levels and the Resilience dimensions, a relationship between them can be drawn to show how the four SHM phases may be used as effective tools and methods for the assessment and enhancement of the Resilience dimensions (Domaneschi & Cucuzza 2023). Figure 1 reports the scheme with the conceptual connection between SHM phases and resilience dimensions.

If Damage Detection is taken into account as the initial level of the SHM, the information presented is the existence or absence of structural damage. It is impossible to provide any information about the location or severity of the damage. In this condition, the redundancy dimension of the same structure is directly related to the damaged state of the structure.

A redundant structure proves to be safer than a statically determined one, regardless of the sort of damage. Due to the structure's inherent lack of redundancy, the experience of the

Polcevera's Viaduct in Italy demonstrates that the issue of corrosion of the steel strands inside the concrete stays reasonably reflected the primary cause of the disaster (Domaneschi et al. 2021). For this reason, to implement the appropriate countermeasures, such as emergency measures (e.g. evacuation, traffic reduction, shutting of critical facilities), the simplest information on the presence of diseases in the structures through SHM techniques must be associated with the grade of redundancy of the structure.

Damage Localization, the second level of SHM, is related to the Rapidity dimension of resilience. The speed of the intervention and recovery stages is critical after the pathology has been identified and any localized or diffuse damage has been localized. In this situation, the SHM system may aid in decision-making to manage the emergency effectively while accelerating interventions that follow a prioritized plan.

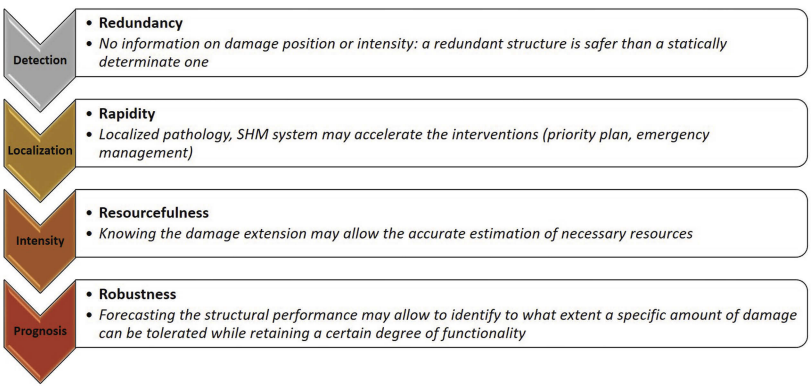

Figure 1. SHM toward structural resilience.

It is also possible to identify a connection between the Resourcefulness dimension and the third degree of Damage Intensity. The organizing and recovery phases are successfully supported by knowledge of the extent of the damage after disruptions, enabling the precise assessment of the resources that will be required.

The Prognosis level of SHM, the fourth level, is connected to the Robustness attribute of resilience. Given an evaluation of the structure's present state, the estimation of the structure's remaining life is the key subject. This SHM level attempts to predict the structural performance to withstand a given level of damage while maintaining its normal level of functionality, offering an indirect measure of structural robustness.

Thus, in light of this description and the relationships highlighted, the significance of implementing monitoring systems on structures and infrastructure to improve their resilience and safety, thereby extending their life cycle, becomes evident.

2.4 *SHM toward resilience, quantitative aspects: Functionality and indices*

The effect of degradation on the infrastructure is to affect and reduce its functionality. This is in association with loading conditions acting on the infrastructure, be they service actions or shocks such as severe weather conditions or medium to high intensity earthquakes. The reduction in functionality is the benchmark for calculating the infrastructure resilience (Vishwanath & Banerjee 2019).

Being able to take timely countermeasures to maintain the infrastructure before degradation significantly reduces functionality and thus becomes a critically important issue. SHM actions are intended in this direction, as they enable the restoration of functionality and thus improve infrastructure resilience. Depending on the level of SHM that can be developed on the infrastructure (from damage detection to prognosis), it will be possible to affect and improve resilience at different levels.

The detection of damage (SHM Phase 1) has a different weight on the further location information about the maintenance and functionality restoration of the infrastructure (Figure 2). And therefore, resilience *R* will also be positively affected by a more comprehensive SHM process that includes not only simple information about the presence of damage but also its location and quantification, to improve the speed of intervention and prepare resources for restoration as quickly as possible. A linear restoration curve has been shown in the figure for simplicity.

Moreover, Figure 2 highlights also the information related to the residual service life of the infrastructure, provided by the last and more complex SHM Phase related to predictive scenarios.

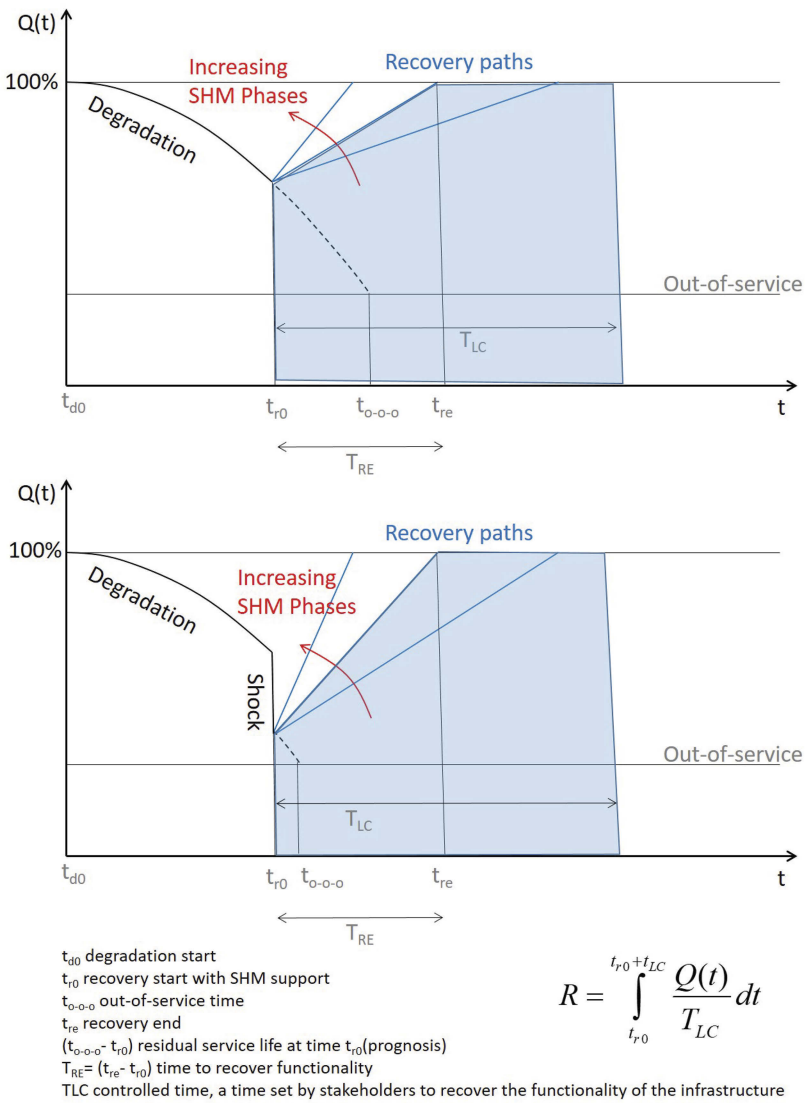

Figure 2. Resilience function: degradation only (top), and degradation with shock (bottom).

3 APPLICATION

This section provides an application example on resilience assessment of comparison between one condition without and another with a monitoring system for a reinforced concrete (RC) and prestressed concrete (PC) girder viaduct in Italy that is made up of 10 spans that are each 40 meters long. On Italian territory, this is a very frequent case study. It is a highway viaduct with three transit lanes that has been deteriorating for 20 years, starting from the time it was put into service, due to phenomena like, for instance, corrosion. A shock has been also considered, such as a significant earthquake that happened in the 20th year of the bridge's operation life.

Specialists and administrators with decades of experience in Italy's road infrastructure were consulted to quantify some useful parameters for the resilience evaluations presented in this section.

It is worth underlining that the present study is not focused on assessing the origin or the evolution of degradation; moreover, it is assumed that the monitoring system is able to detect, locate, and reasonably quantify the intensity of the damage. Figure 3 presents the functionality curves, representative of the two case studies under investigation, adopted for the present case study.

During the first 20 years after the viaduct is put into service, a reasonable reduction (roughly from 100% to 92%) in functionality due to various degradation phenomena in the structural components or, for example, even in the asphalt surface of the road, can be observed. In the 20th year an additional localized disturbance is superimposed, represented for example by an earthquake event that punctually and drastically reduces the functionality to 30% (i.e., a smaller transit lane in order to control and limit loads on the damaged infrastructure - one reduced transit lane open over three in total).

From this point, two different paths are highlighted: one represented by the infrastructure without a monitoring and damage detection system and the other where there is a monitoring system that can also locate and assess the intensity of damage with reasonable accuracy.

Both paths highlight common functionality recovery steps that can be represented by the following restoration actions: (i) opening of an alternative route outside the highway on district roads (37% functionality), (ii) widening of the already active highway lane to all vehicles (50% functionality), (iii) opening of a second highway lane (70% functionality), (iv) full opening of the infrastructure's lanes to the vehicle (95% functionality).

However, the presence of the monitoring system makes it possible to reduce the development time for some of the characteristic steps in the process of restoring functionality. In particular, it is reasonably possible to reduce the time for inspection and damage assessment from 2 months to 1 month.

The designer's choice (1 month) doesn't change, while the technical and economic feasibility design benefits from the more detailed and timely information provided by the implemented SHM system (estimated from 2 months to 1 month).

The administrative phase of publication of the call for bids did not change (1 month), while the final and executive design reasonably reduces the timelines from 2 to 1 month, again based on the quality of the information provided by the SHM system.

Finally, the intervention phase on the supports and structural components has also been speeded up from an estimated 10 months with the intervention of two teams working independently and simultaneously on the infrastructure to 6 months total.

The last phase of testing, estimated at 2 months, is assumed unchanged.

As a result of the considerations above, the resilience of the infrastructure for the case under consideration increases from the value of 0.57, without a monitoring system, to 0.71.

4 CONCLUSIONS

The research conducted in this paper delved into the relationship between structural health monitoring (SHM) and resilience, with a focus on how an efficient monitoring system can contribute to the improvement of structural resilience. Through the present exploration, it has

become apparent that monitoring activities have the potential to enhance the safety and resilience of structures and infrastructure, thereby prolonging their life cycle.

The development of a viaduct application has allowed to showcase the practical demonstration of the concepts discussed in this paper. By showing how monitoring activities can provide early warning signs of potential damage and enable rapid response to mitigate risks, it has been highlighted how an efficient monitoring system can be an essential tool in promoting the resilience of structures and infrastructure.

The analysis has also revealed that the effectiveness of a monitoring system in improving the resilience of structures and infrastructure is directly related to its ability to analyze damage-related factors and their evolution with increasing complexity. This requires not only the acquisition of data but also the capacity to interpret it and to identify the potential causes of damage, enabling preventative measures to be implemented before severe damage occurs.

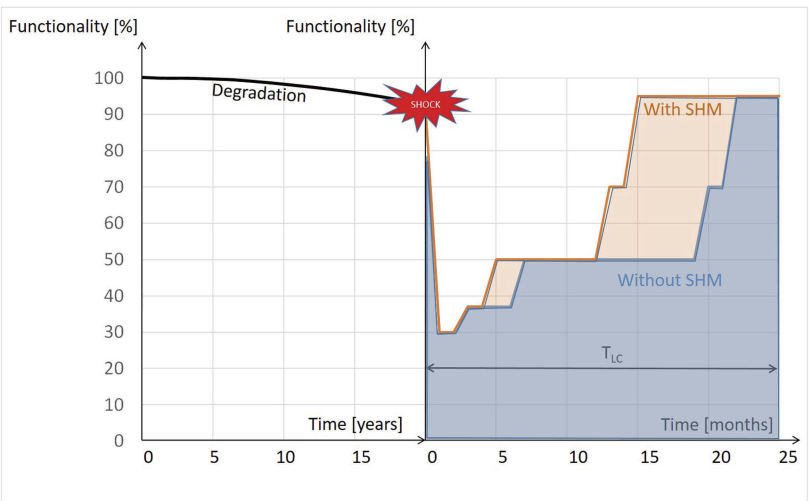

Figure 3. Viaduct application, resilience assessment: w/o and with SHM.

In conclusion, this research has highlighted the crucial role that monitoring activities can play in improving the resilience and safety of structures and infrastructure. By enhancing the capacity of monitoring systems to analyze damage-related factors with increasing depth and complexity, a more comprehensive understanding of structural health and enable the development of targeted interventions to mitigate risks and promote resilience can be provided.

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