ce/papers Proceedings in civil engineering

Ernst & Sohn A Wiley Brand

ORIGINAL ARTICLE

EUROSTRUCT

# Structural Control and Health Monitoring Contributions to Service-life Extension of Bridges

Marco Domaneschi[1] | Luca Martinelli[2] | Raffaele Cucuzza[1] | Mohammad Noori[3] | Giuseppe Carlo Marano[1]

**Correspondence**

Dr. Marco Domaneschi
Department of Structural, Geotechnical and Building Engineering - Politecnico di Torino
Corso Duca degli Abruzzi, 24
10129 Turin (TO) Italy
Email: marco.domaneschi@polito.it

[1] Politecnico di Torino DISEG, Turin, Italy
[2] Politecnico di Milano DICA, Milan, Italy
[3] California Polytechnic State University, San Luis Obispo, USA; Visiting Professor, School of Civil Engineering, University of Leeds, Leeds, UK

## Abstract

Transportation Infrastructure networks are acknowledged as crucial for economic growth, territorial coherence, and social change. Unfortunately, some of this vast system's most important structural elements, like the bridges, are rapidly aging while the load conditions that these systems were designed to withstand are now being exceeded as a result of various threats, including natural disasters and newly discovered man-made phenomena. Considering that a large amount of the existing bridge stock was built many years ago, if countermeasures are not taken, deterioration phenomena and an increase in service conditions larger than those used in the original design may have contributed to diminishing the dependability level. Hence, it becomes crucial to evaluate the existing status of transportation infrastructure, make predictions about its future state, and safeguard it from outside threats. This contribution focuses on an in-depth investigation of the impact of Structural Control and Health Monitoring in increasing the structural resilience of transportation infrastructure and subsequently its life-cycle.

## Keywords

Structural Control and Health Monitoring, Resilience, Bridge and Transportation Infrastructure

## 1 Introduction

Steel and composite steel constructions are susceptible to time-dependent deterioration and aging effects due to a range of factors, such as corrosion brought on by harsh weather conditions and fatigue damage [1]. The economic ramifications of these repercussions are particularly important since steel bridges are widely used in many countries across the world. Steel girders that are exposed to air and salt water corrosion over time. The initial thickness of connections and profiles, such as the web and flanges of steel I-girders, are reduced by corrosion, in addition to other things. Due to thickness reductions brought on by corrosion penetration (e.g., strength and stiffness), the damage affects the element's and section's structural properties [2].

In the literature, the topic of bridge life cycles in relation to deterioration events like corrosion and fatigue has been explored. The impacts of cumulative seismic damage and corrosion on the lifespan of bridges are further explored by Kumar et al. [3], who point out that cumulative seismic damage has a longer-lasting impact on structural dependability than corrosion. The effects of corrosion degradation on the seismic response of RC bridge piers have also been investigated [4,5]. It has been made clear how bonding contributes to the seismic capacity's decline.

A paradigm for structural inspection and maintenance planning is put out by Kim et al. [6] with particular reference to the management of transportation infrastructure, emphasising the relationship between the necessary maintenance and the degree of damage. In Frangopol et al. [7], factors such as climate change and structural health monitoring were taken into account while analyzing and making decisions for evaluating bridge life-cycle performance and cost. According to Akiyama et al. [8], life-cycle reliability, risk, and resilience-based design of transportation infrastructures have been researched. This emphasizes the significance of researching both independent and interdependent risks to gauge bridge dependability (e.g. earthquake and tsunami, or landslide).

In the literature, for instance in the review study of Biondini & Frangopol [9], the link between Structural Control and Health Monitoring (SC&HM) and the life-cycle of bridges has been examined. Vagnoli et al. [10] examined railway bridges with a focus on dependability evaluation and the function SC&HM plays, contrasting various structural health monitoring techniques (e.g. model, non-model).

https://doi.org/10.1002/cepa.2104

The influence of SC&HM on the life-cycle of transportation infrastructures would need more in-depth research notwithstanding the advances in information supplied by the current literature. In order to explore how SC&HM might favourably affect the resilience and, in turn, the life-cycle of bridge structures, this contribution is being made.

## 2 SC&HM contribution to Structural Resilience

### 2.1 Diagnosis and prognosis

Damage diagnosis allows decision-makers to know about the different types of deterioration in civil engineering structures and the appropriate course of action to follow in response to hazardous structural conditions. Damage diagnosis is accomplished by structural health monitoring (SHM), which focuses on damage detection, localization, quantification, and prognosis. According to Doebling et al. [11], the four steps may be further explained as follows:

- Finding out whether the structure has been termed as Phase 1.
- Phase 2 includes Phase 1 as well as the site of the damage.
- Phase 2 and a determination of the intensity make up Phase 3.
- Phase 3 plus the evaluation of the structure's remaining useful life constitute Phase 4.

The most common vibration-based damage diagnostic methods include the first two phases as its main foundations (without the use of structural models). By combining vibration-based techniques with a structural model, phase 3 damage diagnosis may sometimes be completed. Phase 4 might provide significant safety and economic benefits to the management of structures and infrastructure, but it is still a challenging engineering task that requires transdisciplinary and predictive modeling abilities [11-16].

Doebling et al. provided a review of the literature in 1996 [17] about the various techniques for identifying damage and monitoring a structure's condition based on changes in its observable dynamic properties. They are based on adjusting dynamic flexibility, modifying modal properties, updating structural matrices while undergoing constrained optimization, nonlinear methods, and neural network-based methodologies.

Although some algorithms need access to a thorough FEM of the structure to get a deeper insight and access to higher levels of data, others depend on a dataset of the undamaged structure as a baseline (e.g. quantification). During the last 10 years, considerable improvements in processing power and sensing technologies have increased the number of sensors in a SHM system, increasing the quantity of data collected in turn. Sophisticated processing methods must be utilized to handle this enormous number of data in order to translate the heterogeneous, multi-source data into different types of specific indications and make effective management, inspection, and maintenance decisions possible. As a consequence, automated algorithms are increasingly being used in science for data management, computation, and structural (like damage) identification.

Because of their elegant performance and frequent, demanding accuracy, machine learning methods, especially deep learning algorithms, have been increasingly beneficial and widely employed in vibration-based structural damage assessments. The second may discover a direct mapping from the original inputs to the final outputs without the requirement for feature extraction, in contrast to the first which requires data preparation (human involvement) to extract certain characteristics or attributes. Deep learning can thus manage enormous amounts of data (big data) successfully and for a variety of reasons [18-21].

Wavelet and other time-frequency analysis and feature extraction approaches have recently been developed and deployed for the processing of large data from sensor networks for the health evaluation of bridge constructions in addition to Deep Learning [22,23].

### 2.2 Resilience dimensions

According to MCEER researchers, the four primary elements, or dimensions, of resilience are robustness, resourcefulness, redundancy, and rapidity [24-26]. In depth: (1) The ability of a structure or element to withstand a particular amount of stress (such as damage) and maintain its regular level of usefulness is referred to as robustness. You may also call it the concept of damage tolerance. (2) Redundancy, for example, of load-bearing components: the ability to develop alternative load-supporting pathways after the deterioration of the primary parts has taken place (i.e., original elements that are replaceable); (3) Resourcefulness: The ability to identify issues, set priorities, and gather materials when circumstances threaten the stability of the structure or one of its components; (4) Rapidity: The ability to prioritize interventions and finish the job quickly.

Many research has been published to aid in our understanding of structural resilience in buildings. One such is the condensed recovery plan suggested by Cimellaro et al. [27] using the resilience method. In Domaneschi & Martinelli [28], the idea of instant resilience is put up as being connected to the automated operation of certain components to make up for local out-of-services. Several fields have also studied structural resilience.

### 2.3 Monitoring toward resilience

In recent years, the scientific community has been more interested in the connection between resilience and developing digital technologies, such as structural and infrastructure monitoring [29,30].

According to Biondini & Frangopol [9], structural resilience is considered here as a Performance Indicator for life-cycle considerations of transportation infrastructures. The four unique SHM levels and the Resilience dimensions may be linked together after their identification in order to demonstrate how the four SHM phases can be utilized as efficient instruments and procedures for the evaluation and improvement of the Resilience dimensions [31]. The conceptual relationship between SHM phases and resilience dimensions is shown in Figure 1. The information provided is the presence or absence of structural damage if Damage Detection is considered the first level of the SHM. It is not feasible to provide any details on the location or scope of the damage. In this case, the identical structure's redundancy dimension and structural damage are correlated directly. Regardless of the kind of damage, a redundant structure consistently appears to be more safe than one that is statically defined. The Polcevera's Viaduct tragedy in Italy shows that the problem of corrosion of the steel strands within the concrete remains reasonably reflected the principal cause of the disaster due to the structure's intrinsic lack of redundancy [32,33]. For this reason, 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 in order to implement the appropriate countermeasures, such as emergency measures (e.g., evacuation, traffic reduction, shutting down of critical facilities).

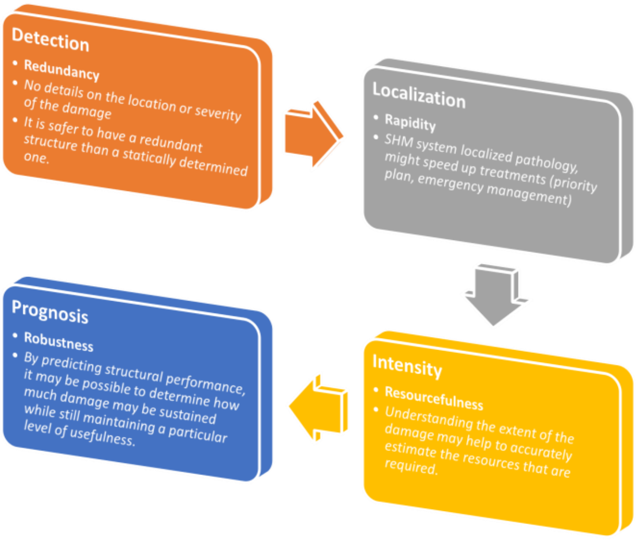

**Figure 1** Resilence & SHM phases.

The second level of SHM, Damage Localization, is connected to resilience's Rapidity dimension. If the pathology has been recognized and any localized or diffuse damage has been localized, the intervention and recovery steps must move quickly. In this case, the SHM system may be used to facilitate decision-making to efficiently handle the emergency while expediting actions that adhere to a prioritized plan.

Moreover, a relationship between the Resourcefulness dimension and the third degree of Damage Intensity may be seen. Knowing the degree of the damage after interruptions helps to properly assist the organizing and recovery stages by allowing for an accurate evaluation of the resources needed.

The fourth level of SHM, Prognosis, is linked to resilience's Robustness quality. The estimate of the structure's remaining life is the important topic, given an assessment of its current condition. This SHM level provides an oblique measurement of structural resilience by attempting to forecast the structural performance to tolerate a certain degree of damage while retaining its typical level of functioning.

The relevance of installing monitoring systems on buildings and infrastructure to increase their resilience and safety, hence prolonging their life cycle, is thus made clear in light of this description and the links emphasized.

## 2.4 Effects of Structural Control on structural Resilience

The assessment of the system performance while taking into account aging and degradation is a crucial component of a life-cycle assessment. The Functionality function Q(t) at the base of Resilience (R) [24-26], considered here as a performance indicator for life-cycle considerations of transportation infrastructures, accordingly to Biondini & Frangopol [9], allows to give a thorough description of the time evolution of the structural resources. This description includes deterioration as well as the potential occurrence of local and global failures. The ability of a system, group, or community to adapt and endure by modifying non-essential characteristics and reconstructing itself is known as resilience [34]. It is connected to the system's capacity to survive the consequences of extraordinary events and quickly restore its previous functionality and performance [24-26].

The normalized region below a system's functionality function Q(t) is known as resilience R (Figure 2), where the functionality function Q(t) is measured as a dimensionless function of time t, $t_{r0}$ is the time at which recovery starts after a damaging event and $T_{LC}$ is a time set by stakeholders to recover the functionality of the infrastructure. To a value of Q(t) = 1 it corresponds no loss-of-function for the system, while to a suitable small value (not necessarily zero if only a Serviceability Limit State has been exceeded) it corresponds to the out-of-service of the system or the structure.

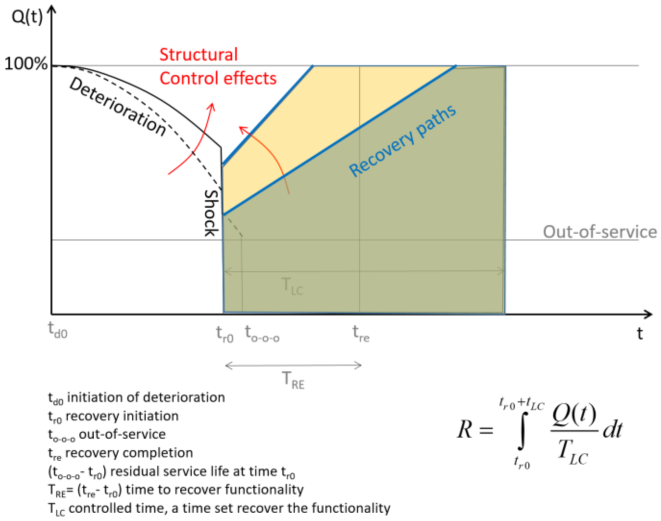

**Figure 2** Structural Control contribution to structural resilience.

It can be observed with initially the degradation can affect the functionality of the structure by gradually reducing it. This is the case, for example, with the effects of fatigue over the long term. However, it has been shown in the literature how appropriate control devices can mitigate the effects of, for example, wind on metal elements [35].

Upon the intervention of a shock such as a strong earthquake on the structure, the control system can effectively mitigate its effects by significantly reducing the internal actions of structural members and the response as a whole. So the structure thus controlled prevents an essentially larger state of damage in advance as if such a control system were not implemented (uncontrolled structure) [36].

## 3 Conclusions

The paper explores the relationship between structural monitoring and control with respect to resilience and lifecycle, with particular reference to transportation infrastructure. The conceptual approach proposed in this paper has made it possible to highlight the benefits that an efficient monitoring system can bring to structural resilience, as well as a structural control system. It becomes evident how such systems when implemented on a bridge for example can improve resilience and safety, allowing it to extend its life cycle.

It becomes clear that improving the resilience of structures and infrastructure depends critically on the ability of the monitoring system to identify with greater depth than simple periodic inspections the factors related to damage and their evolution, thus solving knowledge problems of increasing complexity.

The implemented monitoring system can enable the structure both to limit the rate of natural degradation, for example with respect to fatigue phenomena of metallic elements, and to reduce the effects of a sudden shock, such as an earthquake, by reducing the peak of the response and thus limiting possible damage compared with the case where the structure considered was without the monitoring system.

## Acknowledgements

The research leading to these results has received funding from the European Research 501 Council under the Grant agreement ID: 101007595 of the project ADDOPTML, MSCA RISE 502 2020 Marie Skodowska Curie Research and Innovation Staff Exchange (RISE).

## References

[1] Victor, R. (2013) *Report Card for America’s Infrastructure*. In: American Society of Civil Engineers.

[2] Biondini, F.; Frangopol, D. (2016) *Life-cycle performance of deteriorating structural systems under uncertainty*. Journal of Structural Engineering, 142.9: F4016001.

[3] Kumar, R; Gardoni, P.; Sanchez-Silva, M. (2009) *Effect of cumulative seismic damage and corrosion on the life-cycle cost of reinforced concrete bridges*. Earthquake Engineering & Structural Dynamics, 38.7: 887-905.

[4] Domaneschi, M.; De Gaetano, A.; Casas, J.R.; Cimellaro, G.P. (2020) *Deteriorated seismic capacity assessment of reinforced concrete bridge piers in corrosive environment*. Structural Concrete, 21.5: 1823-1838.

[5] Bartolozzi, M; Casas, J.R.; Domaneschi, M. (2022) *Bond deterioration effects on corroded RC bridge pier in seismic zone*. Structural Concrete, 23.1: 51-66.

[6] Kim, S.; Frangopol, D.; Soliman, M. (2013) Generalized probabilistic framework for optimum inspection and maintenance planning. Journal of Structural Engineering, 139.3: 435-447.

[7] Frangopol, D.; Dong, Y.; Sabatino, S. (2017) Bridge life-cycle performance and cost: analysis, prediction, optimisation and decision-making. Structure and Infrastructure Engineering, 13.10: 1239-1257.

[8] Akiyama, M.; Frangopol, D.; Ishibashi, H. (2020) *Toward life-cycle reliability-, risk-and resilience-based design and assessment of bridges and bridge networks under independent and interacting hazards: emphasis on earthquake, tsunami and corrosion*. Structure and Infrastructure Engineering, 16.1: 26-50.

[9] Biondini, F.; Frangopol, D. (2016) *Life-cycle performance of deteriorating structural systems under uncertainty*. Journal of Structural Engineering, 142.9: F4016001.

[10] Vagnoli, M.; Remenyte-Prescott, R.; Andrews, J. (2018) *Railway bridge structural health monitoring and fault detection: State-of-the-art methods and future challenges*. Structural Health Monitoring, 17.4: 971-1007.

[11] Doebling, S.W.; Farrar, C.R.; Prime, M.B. (1998) *A summary review of vibration-based damage identification methods*. Shock and vibration digest, 30.2: 91-105.

[12] Faravelli, L.; Casciati, S. (2004) *Structural damage detection and localization by response change diagnosis*. Progress in Structural Engineering and Materials, 6.2: 104-115.

[13] Cheung, A.; Cabrera, C.; Sarabandi, P.; Nair, K.K.; Kiremidjian, A.; Wenzel, H. (2008) *The application of statistical pattern recognition methods for damage detection to field data*. Smart materials and structures, 17.6: 065023.

[14] Domaneschi, M.; Limongelli, M.P.; Martinelli, L. (2013) *Vibration based damage localization using MEMS on a suspension bridge model*. Smart Structures and Systems, 12.6: 679-694.

[15] Domaneschi, M.; Sigurdardottir, D.; Glisic, B. (2017) *Damage detection on output-only monitoring of dynamic curvature in composite decks*. Structural Monitoring and Maintenance, 4.1: 1-15.

[16] Morgese, M.; Domaneschi, M.; Ansari, F.; Cimellaro, G.P.; Inaudi, D. (2021) *Improving Distributed Fiber-Optic Sensor Measures by Digital Image Correlation: Two-Stage Structural Health Monitoring*. ACI Structural Journal, 118.6.

[17] Doebling, S.W.; Farrar, C.R.; Prime, M.B.; Shevitz, D.W. (1996) Damage identification and health monitoring of structural and mechanical systems from changes in their vibration char-

acteristics: a literature review. www.osti.gov/biblio/249299

[18] Ye, X.W.; Jin, T.; Yun, C.B. (2019) *A review on deep learning-based structural health monitoring of civil infrastructures*. Smart Struct Syst, 24.5: 567-585.

[19] Azimi, M.; Eslamlou, A.D.; Pekcan, G. (2020) *Data-driven structural health monitoring and damage detection through deep learning: State-of-the-art review*. Sensors, 20.10: 2778.

[20] Sun, L.; Shang, Z.; Xia, Y.; Bhowmick, S (2020) *Review of bridge structural health monitoring aided by big data and artificial intelligence: From condition assessment to damage detection*. Journal of Structural Engineering, 146.5: 04020073.

[21] Avci, O.; Abdeljaber, O.; Kiranyaz, S.; Hussein, M.; Gabbouj, M.; Inman, D.J. (2021) *A review of vibration-based damage detection in civil structures: From traditional methods to Machine Learning and Deep Learning applications*. Mechanical systems and signal processing, 147: 107077.

[22] Silik, A.; Noori, M.; Altabey, W.A.; Dang, J.; Ghiasi, R.; Wu, Z. (2022) *Optimum wavelet selection for nonparametric analysis toward structural health monitoring for processing big data from sensor network: A comparative study*. Structural Health Monitoring, 21.3: 803-825.

[23] Ghiasi, R.; Ghasemi, M.R.; Noori, M.; Altabey, W.A. (2020) *A non-parametric approach toward structural health monitoring for processing big data collected from the sensor network*. In: Experimental Vibration Analysis for Civil Structures. CRC Press, p. 419-426.

[24] Bruneau, M.; Chang, S.E.; Eguchi, R.T.; Lee, G.C.; O'Rourke, T.D.; Reinhorn, A.M.; Shinozuka, M.; Tierney, K; Wallace, W.A.; von Winterfeldt, D. (2003) *A framework to quantitatively assess and enhance the seismic resilience of communities*. Earthquake spectra, 19.4: 733-752.

[25] Bruneau, M.; Reinhorn, A. (2006) *Overview of the resilience concept*. In: Proceedings of the 8th US national conference on earthquake engineering. 2006. p. 18-22.

[26] Bruneau, M.; Reinhorn, A. (2007) *Exploring the concept of seismic resilience for acute care facilities*. Earthquake spectra, 23.1: 41-62.

[27] Cimellaro, G.P.; Reinhorn, A.; Bruneau, M. (2010) *Framework for analytical quantification of disaster resilience*. Engineering structures, 32.11: 3639-3649.

[28] Domaneschi, M.; Martinelli, L. (2016) *Earthquake-resilience-based control solutions for the extended benchmark cable-stayed bridge*. Journal of Structural Engineering, 142.8: C4015009.

[29] Domaneschi, M.; Cimellaro, G.P.; Xie, L.; Bruneau, M.; Wu, Z.; Didier, M.; Noori, M.; Mufti, A.; Lu, X.; Lu, X.; Ou, J.; Sheikh, S.; Zhou, Y.; Yoda, T.; Taciroglu, E.; Häring, I.; Sextos A. (2021). *Present and future resilience research driven by science and technology*. International Journal of Sustainable Materials and Structural Systems, 5.1-2: 50-89.

[30] Wu, Z.; Lu, X.; Noori, M. (2020) *Resilience of Critical Infrastructure Systems: Emerging Developments and Future Challenges*. CRC Press.

[31] Domaneschi, M.; Martinelli, L. (2023) *Structural Resilience through SHM: a critical review*. In M. Noori, C. Rainieri, M. Domaneschi, V. Sarhosis, "Data Driven Methods for Civil Structural Health Monitoring and Resilience: Latest Developments and Applications", CRC Press. In Press.

[32] Morgese, M.; Ansari, F.; Domaneschi, M.; Cimellaro, G.P. (2020). *Post-collapse analysis of Morandi's Polcevera viaduct in Genoa Italy*. Journal of Civil Structural Health Monitoring, 10: 69-85.

[33] Domaneschi, M.; Pellecchia, C.; De Iuliis, E.; Cimellaro, G.P.; Morgese, M.; Khalil, A.A.; Ansari, F. (2020) *Collapse analysis of the Polcevera viaduct by the applied element method*. Engineering Structures, 214: 110659.

[34] Manyena, S.B. (2006) *The concept of resilience revisited*. Disasters, 30.4: 434-450.

[35] Martinelli, L.; Domaneschi, M. (2017) *Effect of structural control on wind fatigue mitigation in suspension bridges.* International Journal of Structural Engineering, 8.4: 289-307.

[36] Domaneschi, M.; Martinelli, L.; Perotti, F. (2016) *Wind and earthquake protection of cable-supported bridges*. In: Proceedings of the Institution of Civil Engineers-Bridge Engineering. Thomas Telford Ltd. p. 157-171.