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Next-generation of Monitoring Systems towards Infrastructure Resilience

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ABSTRACT

Resilience has become an increasingly important concept in our society. More precisely, it is a concept that applies to many aspects related to human life quality, from ecology and environment to societal and organizational structures as well as from infrastructure and built environment to economy.

In this context, this work aims to introduce a concept on Structural Health Monitoring to enhance the resilience of infrastructure. Firstly, how monitoring may offer useful information to the pre-event measures (pro-active monitoring) and the post-event measures (reactive monitoring) is introduced. Then, the Performance Indicators (PI) that may significantly benefit from monitoring data, i.e. better quantification, will be identified, including policy indicators, technical-specific indicators, and economic and social indicators. Finally, and towards the desired better quantification, both current monitoring techniques and future trends, by benefiting from Industry 4.0, will be addressed.

Keywords: Resilience, monitoring, infrastructure, Industry 4.0

INTRODUCTION

This paper aims to provide an introduction to the activities of the IABSE - Task Group 1.8. (IABSE-TG1.8) Design Requirements for Infrastructure Resilience (IABSE, 2019), mainly on how Structural Health Monitoring (SHM) and more in general data concerning the state of civil engineering structures and the hazards that may adversely impact their reliability can be used to support a more accurate assessment of Infrastructure Resilience (H. Sousa & Santos, 2021).

Indeed, SHM of Civil Engineering structures has attained some degree of maturity in the last decades, with many practical applications documented in the literature worldwide. Nevertheless, these applications are often limited to single infrastructure assets. Thus, there are still some research needs in the definition of strategies for using SHM data and available information for supporting decision making in the management of interdependent infrastructure assets, and in the quantification of the benefits, they provide in terms of resilience enhancement.

As part of the activities of IABSE-TG1.8, a chapter is devoted to reviewing the role played by SHM in the context of infrastructure resilience, with a focus on interdependent infrastructure systems such as assets belonging to the same type of network or infrastructure system of various natures (e.g., a network of bridges serving as a support to other critical infrastructures such as power, gas, water, communication networks).

Hence, the chapter is organized into five main sections, mainly: (i). Monitoring in the context of infrastructure resilience, (ii) Monitoring levels and interdependencies, (iii) Monitoring-based Performance

Indicators, (iv) Suitable monitoring techniques, and (v) Trends on monitoring of infrastructure resilience by benefiting from Industry 4.0. An overview and objectives of these are presented in this piece of work.

MONITORING IN THE CONTEXT OF INFRASTRUCTURE RESILIENCE

SHM can effectively and significantly contribute to the four dimensions of resilience against any natural and anthropogenic hazard (Bruneau et al., 2003). The main contributions are briefly summarized below:

- enhancing the infrastructure robustness by providing useful information for defining optimal maintenance strategies,
- increasing the network redundancy by identifying alternative paths when a network component is damaged,
- identifying problems, establishing priorities, and mobilizing resources in case of emergency (resourcefulness) and
- helping a speedy recovery after shocks by providing alerts to first responders (rapidity).

Methodology & approach to support the definition of monitoring requirements

Taking into account that monitoring can hold short- or long-term observation periods (Helder Sousa, 2020; Zolghadri, 2017), Figure 1 illustrates the objectives aimed for monitoring in the context of the resilience of infrastructure. For example, during an event an accelerometer-based system including an earthquake early-warning systems could be used – i.e., during the event –, as part of a proactive monitoring system, supported by routine, inspection, and maintenance focusing on ageing monitoring – i.e., pre-event –, which can be then complemented by drones, helicopters survey, as immediate reactive action (short-term observations) envisaging eventual repair, retrofitting, as a planned reactive action (long-term observations) – i.e., post-event.

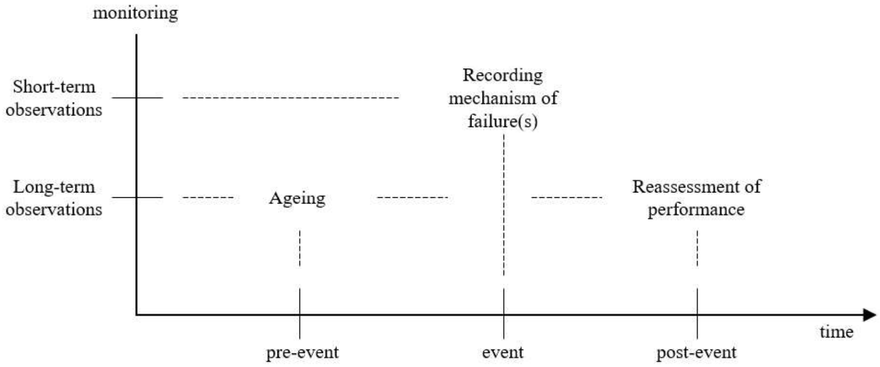

Figure 1. *Monitoring objectives in the context of event type vs. period of observation*

MONITORING LEVELS AND INTERDEPENDENCIES

With such (re)definition of SHM, with the aim to consider the perspective of infrastructure resilience, the following two dimensions are envisaged in order to deepen the main components/variables that should be addressed when designing an SHM system, mainly levels and interdependencies.

In the context of infrastructure resilience, it becomes important to better understand the different levels of analysis associated with, i.e., from local/low level to global/high level. Hence, this becomes also important in the perspective of monitoring, i.e., a systematic collection of data, at the different levels involved, towards better knowledge on the observation of pre-events and post-events. Figure 2 schematically illustrates the different levels considered in this analysis (based on (Ivanković, Strauss, & Sousa, 2020).

While some events make it possible to consider one infrastructure separately from another (e.g. monitoring of cracks by strain gauges on a steel bridge, because of fatigue cracking), other risks have to be considered by grouping several pieces of infrastructures or other elements: for example, when considering scour issues on retaining wall or bridge supports, one may group the assessment by river type and intensity of pluviometry. Indeed, some rivers are known to lead to more scour than others, and interconnecting this information with one of water speed makes it possible to infer conclusions on the vulnerability of the structure to scour. A vision by the river has to be applied, leading to monitoring by river type. Similarly, when considering the resilience of a given region to flooding, one will have to consider the risk of the whole watershed. Moreover, the adaptation or mitigation measures implemented at one place may have an impact on the vulnerability of other elements of the same region. Therefore monitoring may have to begin with a high granularity assessment (ex: on the whole watershed) before refining it for the various elements and their interdependencies (Rasol et al., 2021).

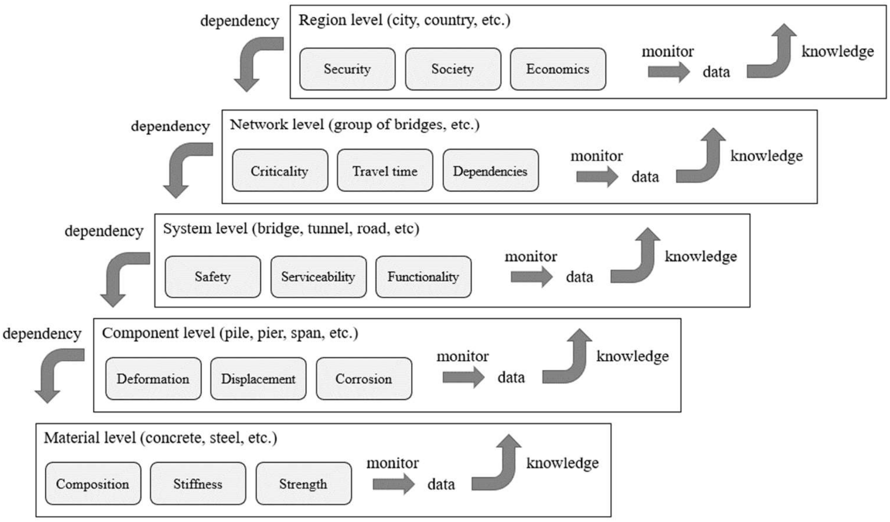

Figure 2. *Levels of analysis and design for monitoring systems (based on (Ivanković et al., 2020)*

As indicated in Figure 2, the decision associated with the different levels may influence each other, i.e., either from the perspective that a decision in a level above depends on the performance of the ones below (rows at the left in Figure 2), as well as the information collected from a level below may be relevant for the levels above (rows at the right in Figure 2).

MONITORING-BASED PERFORMANCE INDICATORS

Performance indicators

According to (Ivanković et al., 2020), in order to assess the performance goals that may be defined to the different levels (Figure 2), a Performance Indicator (PI) can be defined as a property related to a bridge characteristic that gives information about the condition of a bridge. This can be expressed in the form of either a dimensional parameter or a dimensionless index. The former is a measurable/testable quantitative parameter describing a specific characteristic related to the structure performance (e.g. crack width on a component element), whereas the latter is a qualitative representation (e.g. the importance of bridge in the roadway network). In addition, thresholds and/or criteria need to be set in advance in order to allow interpretation of the value given by a PI and the subsequent decision-making approach. The former is a boundary region for (i) monitoring (e.g. an effect is observed or not), (ii) assessing (e.g. an effect is low or high), and (iii) decision-making (e.g. an effect is critical or not). On the other hand, the latter is a characteristic that is relevant for the choice between processes, such as maintenance actions or others (Cost Action TU1402, 2014; COST Action TU 1406, 2016).

These concepts set the basis to identify and define the monitoring-based PI that can represent and properly quantify the several aspects of interest on infrastructure resilience. More precisely, the objective here is to identify the PI where monitoring can help to better quantify them (i.e., by significantly reducing uncertainty). Nevertheless, the question of which PIs are worthwhile to be monitored remains partially unanswered. Several European experts from both academia and industry have been collaborating and discussing in a joint effort to answer this question by developing a framework for structuring and systematising concepts when bringing SHM and system performance together (Figure 3). This allowed a better understanding of what PIs would benefit from this for achieving optimal lifetime performance and those that are quantifiable in terms of monetary units.

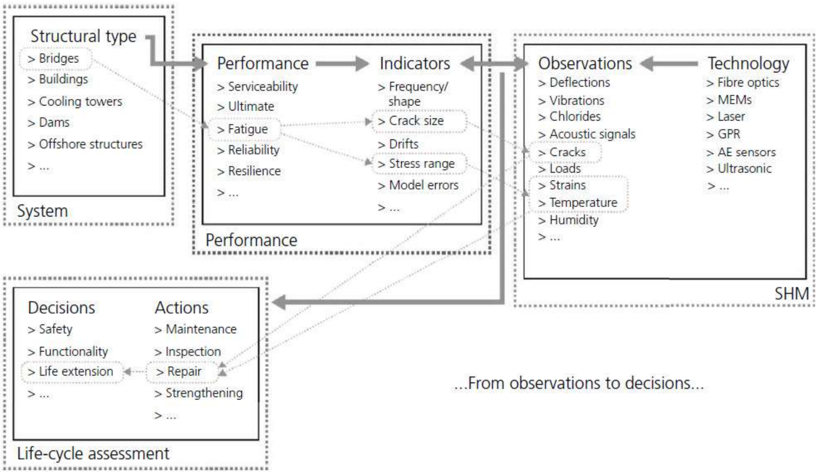

Figure 3. *Framework for structuring and systematising concepts when bringing SHM and system performance together (Cost Action TU1402, 2014).*

Further to this, concepts related to (i) *baseline indicators* (i.e., monitoring on the existing conditions), (ii) *technical-specific indicators* (e.g., reliability, robustness, redundancy, safe-to-fail), (iii) *economic and social indicators* (e.g., experience, leadership, behaviour response, change readiness, monetary losses, society response, and culture), and (iv) *Policy indicators* (e.g., input indicators, output indicators, outcome indicators, and process indicators) are important to be addressed in the context of the resilience of infrastructure.

SUITABLE MONITORING TECHNIQUES

In the context of the life cycle of Civil Engineering structures, two approaches are currently in practice regarding monitoring: (i) *periodic/short-term monitoring* by using high sampling rates (e.g., up to 500 Hz), focusing on the operational conditions of the structure (e.g. on the observation of the in situ traffic loading patterns that each bridge is effectively subjected to), and (ii) *permanent/long-term monitoring* with a modus operandi set to low sampling rates (e.g., up to hourly measurements), focusing on the trends related to climate- and weather-related inputs, changes (e.g., the ground and soil movements of the foundations of a building).

Periodic/short-term monitoring

In the context of bridges, the implementation of weigh-in-motion (WIM) is one of the most common applications of SHM with the objective of better characterisation of traffic loading into multilevel bridge assessment. The main information collected is indeed related to the vehicle loads but is not limited to this. Marginal information can also be derived from this, such as travel direction and vehicle speed. The utilisation of these data can result in a higher value of the bridge reliability index and, consequently, in unrestricted use of the bridge in a much longer remaining service life (Mandić Ivanković, Skokandić, Žnidarič, & Kreslin, 2017; Skokandić, Ivanković, Žnidarič, & Kreslin, 2017). To enhance the calculation of structural safety and/or reliability, this last research recognised measured influence lines, girder distribution factors and dynamic amplification factors as the crucial bridge WIM-based PIs at the system level before decisions are to be made at the network level.

Nowadays, WIM is a reality across several countries, such as Poland (Gajda, 2008), Lithuania (Andriejauskas, Vaitkus, & Tumavičė, 2013), France, Slovenia (Žnidarič, Kreslin, Lavrič, & Kalin, 2012), Hungary, and the Netherlands (Jacob & Loo, 2008). Table 1 summarises the main established and available monitoring systems devoted to observing short-term events. It is also worth mentioning that, apart from the case of bridge WIM, the remaining ones are installed outside the bridge length. This means that these are particularly interesting from the perspective of the network level since, if well designed, these allow characterising traffic load patterns for a set of bridges within a roadway network.

Table 1. *Typical monitoring solutions for periodical/short-term monitoring (H. Sousa & Santos, 2016).*

Monitoring system	**Advantages**	**Disadvantages**
Bridge WIM	Exceptionally durable, Invisible to the drivers, Installation/replacement without requiring traffic disruption, Redundancy of recordings, Allows bridge assessments, Extreme loads can be accurately quantified.	High costs of installation, Dependent on bridge location, Requires calibration (each bridge is unique), Requires expert technicians, Dependent on vehicle position, length of the structure and the traffic density.
Load cells	Highly accurate, Direct measurement of loads, Fully automated weighing system, Can weigh all vehicle types regardless of speed or axle configuration.	High equipment, installation, and maintenance costs, Require civil engineering work and can cause damage to the pavement, Require a concrete foundation.
Bending plates	Good accuracy, Fully automated weighing system, Can weigh all vehicle types regardless of speed or axle configuration, Obtain full tyre imprints.	High installation costs, Require a large amount of civil engineering work and can cause damage to the pavement, Require a concrete foundation, Sensitive to temperature effects.
Strip sensors	Cheaper solution, mainly regarding the installation costs, Requires less civil engineering work for installation.	Do not measure directly the wheel/axle load, High equipment/maintenance costs, Sensitive to temperature effects and pavement characteristics.
Multiple sensors	Improved accuracy when compared with one-sensor-based systems.	Accuracy depends on the number/spacing of sensors.
Accelerometers	Highly sensitive to any type of disturbance in the structure (e.g., traffic loads, wind effects, ship collision).	Highly affected by temperature and need correction for a correct interpretation of the results.

Permanent/long-term observations

Continuing with the example of bridges, and in complement, the observation of the long-term behaviour is based on the measurement of a set of parameters with the aim of getting a good understanding either of the structural performance of the structure (i.e. how it deflects over time, mainly deflections of mid-span sections, horizontal displacements at bearings/joints, rotations of supporting sections and strains in critical spots) or of the structural condition (i.e. durability of concrete, steel corrosion). For that purpose, the parameters usually monitored can be clustered into three main categories: (i) structural measurements; (ii) specimen measurements – that is, strain and temperature measurements collected over time from small concrete samples made of the same concrete as the structure (mainly critical for prestressed concrete bridges); and (iii) environmental measurements. Table 2 summarises the parameters usually monitored in the context of the long-term performance of bridges and the respective SHM technologies that support those observations. Even though most of the cases reported in the literature on bridge collapse are often related to local damage – that is, this type of damage normally does not modify stiffness, unless the failure is imminent – the observation of the long-term patterns of deformations might contribute to early detection of abnormal behaviours that might, in turn, lead to other phenomena implying collapse.

Table 2. *Typical monitoring solutions for permanent/long-term monitoring (H. Sousa & Santos, 2016).*

Category	**Parameter**	**Sensor type (monitoring)**
Structure	Vertical displacement,	Linear variable differential transformers (LVDTs), laser Doppler vibrometer, global navigation satellite system (GNSS), hydrostatic levelling system
	Bearing/joint displacement,	LVDTs, joint meters
	Tower top displacement,	GNSS
	Rotation,	Inclinometers
	Strain,	Electric strain gauges, vibrating wire strain gauges, fibre Bragg grating (FBG) strain gauges
	Support reaction,	Load cells
	Prestressing,	Load cells, accelerometers (cable vibration)
	Corrosion.	Multidepth or ladder-type probe sensors, sense electrodes
Specimens	Creep,	Strain gauges,
	Shrinkage,	Strain gauges,
	Corrosion.	Multidepth or ladder-type probe sensors, sense electrodes.
Environment	Temperature,	Thermistors, thermocouples, resistance temperature detectors, FBG,
	Relative humidity,	Hygrometers,
	Scour	Sonar devices.

Further to these, and in the context of the resilience of Civil Engineering infrastructures other monitoring techniques are considered as: (i) Asset sensor-based systems (e.g. bridges, tunnels, dams, pavement, slopes), (ii) Airborne systems (e.g. unmanned aerial vehicles (UAVs), Synthetic Aperture Radar (SAR) (iii) Terrestrial systems (e.g. Terrestrial Laser Scanning, GNSS), among others.

TRENDS ON MONITORING OF INFRASTRUCTURE RESILIENCE BY BENEFITING FROM INDUSTRY 4.0

Further to this, and according to (Ivanković et al., 2020), the technology evolution since the beginning of this century, allied with the *Industry 4.0* era, the question of how PIs will evolve in the near future arises naturally and with high interest from stakeholders with direct responsibilities in asset management – that is, owners, operators and/or concessionaires of Civil Engineering infrastructure. For this, it is important to understand how the linkage between these different types of PIs will be materialised in the near future and what is the impact of this, in light of the 2030 Agenda for Sustainable Development promoted by the United Nations (United Nations, 2015).

Indeed, and from the decision-making perspective, the main benefit from this will be more rational and better support in the ranking process by means of better information – that is, more accurate data. Table 1 and Table 2 clearly show evidence that technology evolution will play a central role in performance assessment procedures and their indicators, as these methods provide a more accurate approach to quantifying many of the aforementioned PIs. In this context, (Goulet & Smith, 2013) discussed model falsification for the performance assessment of large-scale infrastructure systems, the problem of redundancy and over the instrumentation of monitoring systems and their effects on performance assessment. Therefore, SHM systems should be adaptable and flexible in order to assist site inspection decisions better throughout the bridge's lifetime. This means that both SHM and visual inspections should work together towards a rational risk-based decision framework.

Nevertheless, the question of which PIs are worthwhile to be monitored remains partially unanswered. Several European experts from both academia and industry have been collaborating and discussing in a joint effort to answer this question by developing a framework for structuring and systematizing concepts when bringing SHM and system performance together (Figure 3). This allowed a better understanding of what PIs would benefit from this for achieving optimal lifetime performance and those that are quantifiable in terms of monetary units at the bridge management level.

The role of devices/technologies such as (i) Internet of Things platforms, (ii) Location detection technologies, (iii) smart sensors, (iv) Big Data analytics & advanced algorithms, and (v) Real-time data visualization are going to play a central role in the evolution of SHM and how, in turn, this will support more efficiently the assessment of the resilience of Civil Engineering structures.

CONCLUSIONS

This piece of work offers an overview of the current work done so far under the scope of the activities of the IABSE - Task Group 1.8. (IABSE-TG1.8) Design Requirements for Infrastructure Resilience. The concept and framework are properly introduced, where SHM is presented in the context of the resilience of Civil Engineering infrastructure, and supported on previous work done by the authors and other relevant references in the field of monitoring of Civil Engineering structures.

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