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Structural Health Monitoring in the Italian Guidelines for bridges

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EXTENDED ABSTRACT

KEY WORDS: Structural Health Monitoring; Italian Guidelines; Bridge management; Infrastructures.

1 INTRODUCTION

Bridge management plays a critical role in safeguarding transportation safety and functionality against aggressive environmental conditions, increasing load demands, and extreme events, making it an indispensable pillar of modern infrastructure systems. Recognizing the need for standardized practices, the Italian Ministry of Infrastructures and Transport issued the 2020 "*Guidelines for Risk Classification and Management, Safety Evaluation, and Monitoring of Existing Bridges*" [1]. These guidelines categorize bridges into five attention classes (ACs), determined by comprehensive assessments of structural and foundational conditions, as well as seismic, hydraulic, and landslide risks. Each attention class dictates specific analyses and Structural Health Monitoring (SHM) activities to enhance structural understanding and safety. This work provides a brief integrated overview of the 2020 Italian Guidelines in conjunction with the 2015 national "*Guidelines for Structural Health Monitoring*" [2], exploring their synergies and identifying key challenges in their application. The potential of SHM technologies is critically assessed, focusing on their role in evaluating structural performance and reducing uncertainties related to material properties and operational conditions.

2 THE ITALIAN GUIDELINES FOR BRIDGES

The Italian Guidelines for Bridges (IGB) are characterized by an innovative multi-level and multi-risk approach. The six levels of analysis present a progressive increment in complexity and detail, while the number of bridges that require this analysis should decrease. Level 0 consists of the collection of design information, structural and geometric data, road traffic information, and past maintenance interventions. This census and collection process involves the whole bridge portfolio, as well as levels 1 and 2. Level 1 corresponds to the visual inspection of bridges to verify the design geometry and evaluate the presence of defects, which are noted in the defectiveness sheets provided by the IGB for each structural element. The number of defects and their intensity establish the defectiveness level of the bridge. Further, level 2 evaluates the bridge AC, combining four risk types: structure and foundation, seismic, hydraulic, and landslide. For each risk type, a partial AC is defined as a combination of hazard, vulnerability, and exposure. The combination of the partial ACs leads to a total AC for the bridge, which influences the application of the following level 3 and 4 analyses. Five ACs are defined, namely, low, medium-low, medium, medium-high, and high. Level 3 is a preliminary assessment of the bridge condition and is performed for bridges with a medium or medium-high AC to assess whether detailed analyses are needed. Level 4 represents a detailed structural analysis of the bridge according to the current standard, and it is mandatory for bridges in high AC. Structures are classified as: "adequate" if the analysis is satisfied for loads with a return period of 50 years, "operative" if the verification is satisfied for loads with a return period of 30 years, or "transitable" if it is verified for loads with a return period of 5 years. Transitable bridges need a maintenance intervention within 5 years, and during this period, can receive restrictions such as roadway partial closure or load limitations. Finally, level 5 corresponds to a resilience evaluation of roadways considering the consequences due to the loss of functionality of the bridge on the entire transport network. However, this level of analysis is not yet detailed in the current version of the IG.

3 THE ITALIAN GUIDELINES FOR MONITORING

The Italian Guidelines for Structural Health Monitoring (IGSHM) define the objectives and the minimum requirements for a monitoring system to be installed on a bridge. Two main objectives are identified: (i) the check of the structural performance with respect to specific limit states, e.g., collapse and serviceability, and (ii) the identification of a degrading effect in-act. Thus, based on the monitoring data, surveillance and maintenance activities can be planned, the service life of crucial assets can be evaluated (and extended), and innovative constructive methods or structural schemes can be investigated. Monitoring activities are distinguished in:

- occasional, when performed continuously for a limited period of time (from a few days to 1 or 2 years) to augment the knowledge of the structural performance before and after a rehabilitation activity,
- periodic, when performed continuously for a limited period of time (typically a few hours or days) every few years, to investigate specific degradation phenomena that may occur over time,
- continuous, when the monitoring system is permanently installed on the structure. This monitoring activity is

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advised on complex structural systems (e.g., long-span bridges) or for structures that are subjected to rare, accidental, or exceptional actions (earthquakes, collisions, etc.).

While monitoring activities are defined depending on their scopes, the design process of an SHM system usually follows eight steps, herein illustrated in Figure 1.

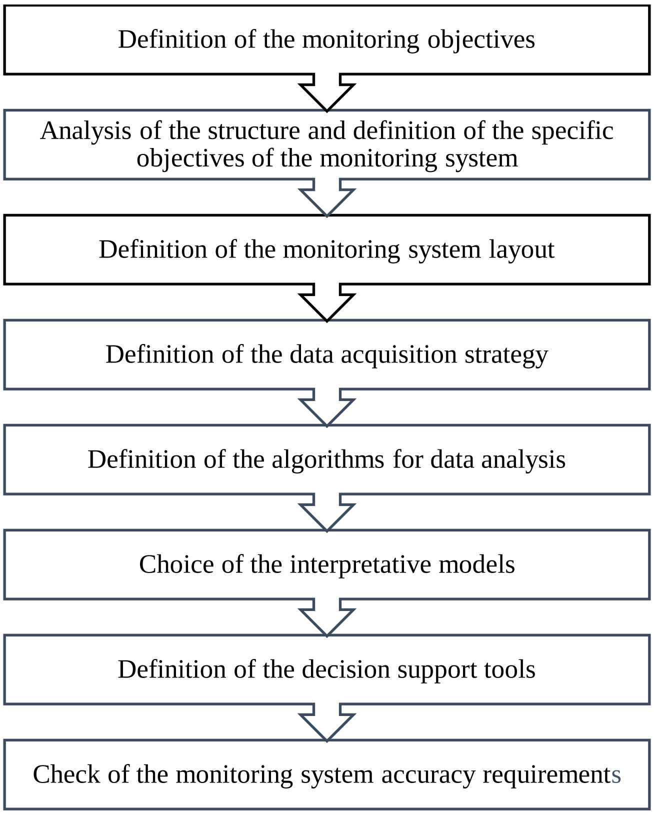

Figure 1: Steps in the design of a monitoring system according to [2].

The monitoring objectives, such as the knowledge of structural performance and the identification of in-act degrading phenomena, can be expressed in terms of an index (of damage, performance, or residual life) or through low-to-high classification (on damage or performance evolution). The estimation of such indices is based on the mechanical (both referring to the structural response and the actions that are applied to the structure), thermodynamic, chemical, or electromagnetic characteristics that are measured on the structure. The layout of the sensors is defined according to the structure types and static scheme, and the model that is used to interpret the collected data. In the case of a vibration-based monitoring system, the layout of the sensors should be conceived to effectively capture the mode shapes and natural frequencies. In doing so, the redundancy of the monitoring system is crucial to limiting the effects of malfunctions.

Therefore, the collected data are processed and interpreted. In some cases, the data already indicate the presence of damage (e.g., the scour depth or a crack size), while in some other cases, such as for a vibration-based monitoring system, data must be processed to estimate the natural frequencies and the mode shapes. Damage can be detected by investigating the variation of such modal parameters.

Further, decision support tools can be developed based on the collected data by the definition of thresholds on the measured characteristics and associating them with warning alarms and/or interventions.

4 THE ROLE OF SHM IN THE ITALIAN GUIDELINES FOR BRIDGES

Within the IGB, SHM is defined as an essential tool in the optimization of the management of critical infrastructure. Its role extends beyond data acquisition, as it augments structural understanding, reduces epistemic uncertainties, and enhances targeted maintenance scheduling. SHM systems are presented as complementary to inspections, destructive, and non-destructive testing methods, offering continuous information in bridge condition assessment. The real-time monitoring of stress responses, crack propagation, and displacements under operational and extreme load conditions, see Paragraph 6.2 of the IGB, can effectively support structural performance assessment and maintenance scheduling. Further, SHM data can allow for early warning by detecting anomalies and deterioration trends whenever periodic visual inspections are not performed. Emergency response planning can be supported by SHM, as for the cases of landslide (see Paragraph 4.4.2) or hydraulic (see Paragraph 4.5.1) hazards.

SHM is seen to contribute to both diagnosis and prognosis, aiding characterizing the current condition of the bridge and predicting its future behavior. As pointed out in Paragraph 6.3.3.5, SHM enables the calibration and update of bridge numerical models, reducing epistemic uncertainties related to material properties, loading conditions, and model assumptions. Also, as highlighted in Paragraph 7.6, SHM can optimize inspection scheduling by identifying zones of concern and providing long-term trends. The adaptive use of real-time data also supports the dynamic update of threshold values for alerts and interventions (see Paragraph 7.7), facilitating the transition from time-based to condition-based maintenance strategies. Furthermore, the integration of SHM data with Bridge Management Systems (BMS) can aid prioritizing interventions across a network of assets, enhancing long-term planning capabilities and aligning structural management with resilience and sustainability goals.

5 MONITORABLE PARAMETERS IN THE ITALIAN GUIDELINES FOR BRIDGES

SHM can aid at Level 1, Level 2, and Level 4 of the IGB by automatically collecting data about the structural condition and refining the risk classification and the detailed analyses.

At Level 1, the automatic collection of data can both aid (i) detecting damage on bridge components that are not easy to inspect and (ii) investigating the evolution of defects in time.

Within Level 2, numerous parameters are considered in the definition of the attention class, which can be low, medium-low, medium, medium-high, and high. Defects that were detected during the inspections of Level 1, and other parameters proper to the four hazards (structural-foundational, seismic, hydraulic, and landslide) are examined, and an attention class is assigned to each bridge. SHM implementation is advised for medium-high and high attention classes.

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A reclassification of the bridge attention class would consider the collected data from a monitoring system, therefore possibly repositioning the bridge in another attention class. Reclassifications are advised periodically or in the case interventions are implemented on the structure. Among the monitorable parameters that drive the risk-based classification, there are:

- Level of Defects, including all the possible defects that can be observed on bridge components,
- Average Daily Traffic, indicating the average number of vehicles that cross the bridge in a day,
- Frequency of commercial transit, indicating the average number of heavy loads, such as lorries, that cross the bridge in a day,
- Scour depth, indicating the erosion of soil or sediment by flowing water, particularly around bridge piers and abutments.

The level of defects is a primary parameter for the evaluation of the vulnerability within the structural-foundational risk, and it is characterized by gravity, intensity, and extension. As demonstrated in [3], the level of defects drives the attention classification – when the level of defects is high, the attention class is high regardless of the other parameters. Thus, the presence of defects with high or medium-high severity (and high intensity and extension) is defined as a critical condition for the attention classification [4]. Several monitoring techniques can be implemented to monitor the evolution of defects, such as extensimeters, tiltmeters, strain gauges, and accelerometers. Novel techniques include Interferometric Synthetic Aperture Radar (InSAR), video-based, and crowd-sensing [5].

The frequency of commercial transit is a parameter that characterizes the structural-foundational hazard within the attention class determination. Heavy loads, such as lorries, represent a criticality for bridge integrity management, as they may exceed the traffic load for which the bridge has been designed.

Further, the average daily traffic characterizes both the structural-foundational hazard and exposure. While together with the frequency of commercial transit is indicative of the traffic demand over the bridge, it is essential in estimating its exposure, i.e., the consequences in case of a collapse. Weight-in-motion systems can be implemented to investigate the load demand on bridges and eventually set limitations [6].

The scour depth is a crucial parameter in the hydraulic risk assessment, specifically for the evaluation of the hazard for the local scour. The scour depth can be monitored by, for example, a vibration-based monitoring system. A decrease in the natural frequency or a variation in the mode shapes may refer to a loss of stiffness in the support of a bridge pier caused by scour.

Noticeably, also the evaluation of the landslide hazard may be supported by SHM data, and its evolution may be monitored through several techniques, such as InSAR.

Within Level 4 of the IGB, SHM may be used to calibrate and update the numerical model that is built for the detailed analysis. Bridge components may be modelled accounting for the defect severity, extension, and intensity, as a local decrease of the component stiffness. Further, the traffic demand on the bridge can be evaluated and modelled to verify the bridge condition and impose traffic limitations. Digital twins (of physical structures) can be created and continuously updated by SHM data.

6 CONCLUSIONS

This work provides a brief integrated overview of the Italian 2020 "Guidelines for Risk Classification and Management, Safety Evaluation, and Monitoring of Existing Bridges" (IGB) and the national 2015 "Guidelines for Structural Health Monitoring" (IGSHM). The role of Structural Health Monitoring (SHM) in the IGB is investigated. Monitorable parameters that can affect the attention classification of Level 2 and the detailed analysis of Level 4 are stated, and possible monitoring techniques are suggested.

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