# A Preliminary Qualification Approach for Structural Health Monitoring Systems

Paolino Cassese[1(✉)], Giuseppina De Luca[2], Antonio Bonati[2], Carlo Rainieri[1], and Antonio Occhiuzzi[1,3]

[1] Construction Technologies Institute of the Italian National Research Council (ITC-CNR), Naples, Italy
paolino.cassese@itc.cnr.it
[2] Construction Technologies Institute of the Italian National Research Council (ITC-CNR), San Giuliano Milanese, Milan, Italy
[3] Department of Engineering, University of Naples "Parthenope", Naples, Italy

**Abstract.** Structural Health Monitoring (SHM) is gaining increasing attention in Italy and worldwide due to structural obsolescence and sudden collapses occurring from time to time due to insufficient maintenance or extreme events. On the other hand, the technological progress in the SHM field is making it particularly attractive as a complement to visual inspections and in-situ surveys aimed at assessing the structural safety. Accordingly, several guidelines have been developed with the aim to provide useful recommendations to technician for the design of SHM systems. Nevertheless, because of very case-specific design, so far, a general qualification procedure aimed at assessing the performance of a SHM system is still missing. On the contrary, construction products already share a thorough and well-established harmonized standardization framework since many years, and this resulted in a reliable control of performance. In this study, a preliminary qualification approach for SHM systems is proposed. The qualification scheme is scenario dependent and allows to check the effectiveness of a given SHM system defined in terms of hardware as well as software components. In order to validate the approach, different SHM systems are hypothesized and checked for possible qualification with respect to different scenarios, obtaining encouraging results. The proposed approach, therefore, represents a promising attempt towards a more exhaustive and comprehensive qualification framework for civil SHM applications.

**Keywords:** Qualification · Guidelines · Standard · Civil SHM systems

## 1 Introduction

Structural performance of civil structures and infrastructures experiences a reduction throughout their service life because of several factors (aging, defects, external actions, and so on). Maintaining safe and reliable structures to be used every day represents a paramount social issue and, in addition, from an economic point of view, it allows countries saving costs of downtime and significant interventions [1]. In this context, structural health monitoring (SHM) systems are gaining increased attention due to the


P. Rizzo and A. Milazzo (Eds.): EWSHM 2022, LNCE 270, pp. 635–644, 2023.
https://doi.org/10.1007/978-3-031-07322-9_64

opportunities they offer for remote damage detection and for lifespan extension of existing structures [2].

Civil SHM has received increasing attention also in Italy after an unfortunate series of collapses occurred to several structures due to their obsolescence or insufficient maintenance [3–5]. Thus, an effort has been done to extend the fairly limited national legislation framework concerning the SHM sector, which consisted of a single standard focused on vibration analysis of bridges [6] until April 2016, when the Italian guidelines for structural health monitoring were issued [7]. They suggest a structured approach for the design of SHM systems depending on the considered structural typology, with detailed discussion about data interpretation methods. In addition, in 2020 the Italian Ministry of Infrastructures and Transportations issued guidelines for risk classification and management, safety assessment and surveillance of existing bridges [8], providing additional instructions for the application of SHM technologies to existing bridges.

Technical documents concerning SHM commonly recognize that the design of a SHM system is not univocal, but it is highly dependent on a series of aspects, such as general scopes, structural typology, measuring strategy, and so on, as well as various involved stakeholders [9]. Although frequently invoked, the development of a qualification process for SHM systems is therefore very challenging, and an existing regulatory framework, such as the CE marking framework laid down by the Construction Product Regulation (CPR) [10], can be hardly applied in this case.

The CE marking procedure allows to evaluate the essential characteristics of construction products according to standardized assessment methodologies. A similar qualification approach concerning SHM systems is still missing, even though it is highly desirable because of the potential impact it might have in the rational assessment and control of SHM system performance, and in the comparative assessment of different technological solutions [11].

This study aims at contributing to the investigation efforts towards the development of a qualification approach appropriate for civil SHM systems. Starting from the analysis of the CE marking certification procedure for construction products, a qualification approach is herein proposed, and a preliminary application to a simple case-study is described and discussed.

## 2 The European Framework for Qualification of Construction Products

The construction industry currently represents about 9% of the GDP in the European Union (EU) [12]. Such an enormous economic significance is nourished by the pursuit of one of the most important principles of the EU itself, which is the prohibition of quantitative restrictions between member states to ensure free trade of goods [13]. Indeed, in 1988 the European Commission (EC) issued the Directive 89/106/EEC [14], generally identified as Construction Products Directive (CPD) with the aim to overcome the impediments due to not common certification systems among Member States

(MS); this was a first attempt for a harmonization of procedures concerning performance of construction products, which are defined as elements permanently incorporated in construction works and whose performance affects the performance of the resulting construction. Harmonized technical specifications, defining performance assessment methodologies and control operations, were introduced, along with approval and notified bodies involved in assessment and control, respectively. According to CPD, two different technical specifications were defined: (*i*) harmonized European standard (hEN), developed by the European Committee on Standardization (CEN) under CE mandate and valid for conventional construction products; (*ii*) Guidelines for European Technical Approval (ETAG), issued by an approval body in concert with the European Organization for Technical Approvals (EOTA) and with the final consent of the EC, concerning non-standardized innovative construction products. Six generic Essential Requirements (ERs) were established, directly referred to construction works, with respect to which specific performances of the products were to be identified. Specifically, the ERs were: (*i*) mechanical resistance and stability (ER 1); (*ii*) safety in case of fire (ER 2); (*iii*) hygiene, health, and the environment (ER 3); (*iv*) safety in use (ER 4); (*v*) protection against noise (ER 5); (*vi*) energy economy and heat retention (ER 6). For standardized construction products, the approval was confirmed by means of testing reports, according to hEN dispositions. Conversely, for innovative construction products, a specific document was issued, called European Technical Approval (ETA). After checking the manufacturing process, an attestation of conformity (AoC) was obtained and the Declaration of Conformity (DoC) was drawn up along with CE Marking on products of interest, proving their conformity with respect to the requirements of the corresponding harmonized specification.

Despite the ambitious objective, the certification approach established by the CPD was not effective, mainly due to the difficulty in national transposition (requiring complex and long-term operations) and to confusion with competencies of MS in approval for use. Therefore, a CPD revision was developed which led to the EU Regulation N. 305/2011 [9], commonly known as Construction Product Regulation (CPR) valid since July 1st, 2013, and replacing the CPD. The replacement of a directive with a regulation allowed the direct application of the latter within national legislation. The CPR inherited a certification approach similar to CPD's one, but with a substantial change of paradigm from the approval (or attestation of conformity) to the Declaration of the Performance (DoP), in order to avoid overlapping with MS' rules regarding fitness for use. Within the DoP, the manufacturer reports information about performances, intended use, manufacturer details, and system of assessment and verification of constancy of performance (AVCP) and he takes the responsibility to declare the conformity of the construction product with such declared performances. The DoP is referred to the product type, defined as a set of representative performance levels or classes of a construction product, in relation to its essential characteristics, produced using a given combination of raw materials or other elements in a specific production process. The product-type is univocally related to a-unique identification code; thus, the DoP represents a crucial part of the product information chain from production to commercialization. With the CPR, the ERs evolved into Basic Works Requirements

(BWRs), and greater attention was given to environment and use of resources. Indeed, a new BWR specifically addressing the sustainable use of natural resources was introduced (BWR 7), related to reuse and durability of construction works. In addition, the ETAG and the ETA (Approval) were replaced by the European Assessment Document (EAD) and the European Technical Assessment (ETA), respectively. The EAD is a harmonized technical specification for performance assessment of non-standardized construction products. The ETA reports the performances of a specific product assessed according to the relevant EAD. The ETA may be requested by the manufacturer to a Technical Assessment Body (TAB) when the product does not fall within the scope of an existing technical specification. The ETA process is therefore generally industry-driven and associated with the need for innovation.

## 3 A Proposal for Qualification of Civil SHM Systems

A SHM system usually consists of the following basic components: (*i*) sensors; (*ii*) data acquisition and transmission system; (*iii*) data management and processing system; (*iv*) structural diagnosis and prognosis system [7, 9]. The sensing system can be made of a variety of sensors differing for typology, fabrication, and sensing principle. Sensors are used to measure mechanical, physical, and environmental variables relevant to the assessment of the structural global and local responses. Sensors are a critical component of SHM systems because the quality of the collected data directly affects the reliability and accuracy of monitoring results. The data acquisition system performs basic operations such as signal conditioning, digitization, pre-processing, and storage. Depending on the SHM strategy, the collected data may be temporary stored in local or central units. Data transmission exploits either wired or wireless architectures, or different combinations of the two. The collected monitoring data are finally processed to automatically extract relevant features for damage detection. After diagnosis, additional evaluation and analyses can be carried out for prognosis purposes (estimation of residual life).

The common CE marking process, summarized in Sect. 2, cannot be directly applied to a SHM system as previously defined because the latter is not coherent with definitions and scopes of CPR [10]. SHM systems are usually tailored technical solution resulting from a specific design procedure; as such, SHM systems as a whole are strongly dependent on the effective scenario, which is characterized by several parameters related to structure category, actions, and monitoring objectives. Nevertheless, the qualification approach reported in the CPR may represent a reference for developing a new procedure aiming at qualifying SHM systems by assessing their performance and then their effectiveness with respect to specific targets associated to a given scenario. A conceptual representation of such a "scenario-based qualification" procedure is shown in Fig. 1.

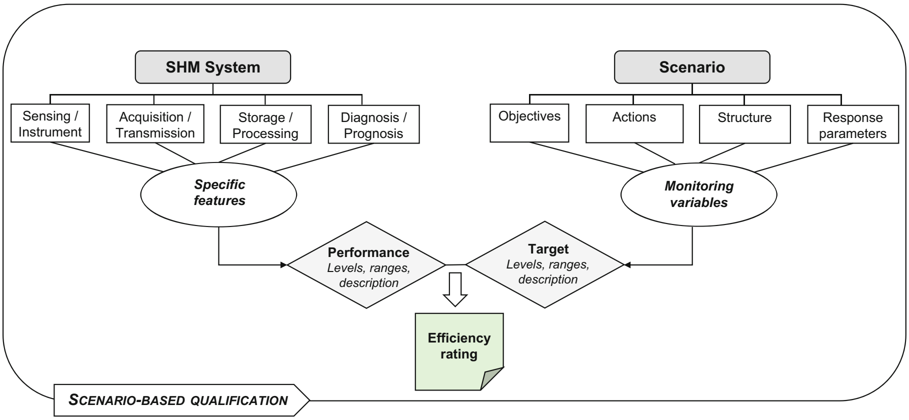


**Fig. 1.** Scheme of the scenario-based qualification of civil SHM systems.

Comparing construction products (with specific reference to the case of the kits, defined as products obtained by putting together at least two separate components before being incorporated in the construction works) and SHM systems, they show some similarities; indeed, both consist of different components and are characterized by specific features (essential characteristics for construction products according to CPR). The performances associated to those features directly affect the global performance of construction work and SHM, respectively for construction products and SHM system. Specific features and corresponding performances of the individual component of a SHM system can be identified according to the relevant standards, if available. By similarity with the construction products, generic performance of SHM system may be expressed as level (i.e., single numeric value), range (i.e., interval of levels characterized by a minimum and a maximum value), or description. For sensors, measurement equipment and data transmission devices, the performance values are commonly declared in their technical datasheet.

A large variety of sensors are available on market, different for measurand (strain, displacement, velocity, acceleration, force, pressure, corrosion, temperature, wind velocity, rotation, among others) and sensing technology. A detailed description of sensor categories is out-of-scope of the present study and can be found elsewhere [15]. However, several specific features common to different sensor typologies may be identified.

The data acquisition system usually consists of hardware and software components. The hardware components can be distinguished into: (*i*) electronic devices aimed at collecting, conditioning, converting, and transmitting signals (e.g., signal conditioners, analogic-to-digital converters, power supply, communications devices, among others), (*ii*) cables, connectors, and any other physical connection. The software controls the measurement hardware and data storage.

Different typologies of data transmission systems are available for SHM, depending on the architecture of the system: wired network, wireless network, and a combination of the two. Different network layouts can be also identified: (*i*) the centralized layout, characterized by a large number of sensors and a centralized storage/control unit; (*ii*) the distributed layout. In addition, the following configurations are generally adopted: (*i*) bus, with all connections along a main cable connecting two terminals; (*ii*) star, with a central hub and all devices connected to it; (*iii*) tree, with gradual hierarchical connections; (*iv*) ring, with devices connected each other; (v) mesh, characterized by multiple connection paths.

Data storage largely depends on the adopted architecture and on the objective of the monitoring strategy (e.g., frequency of data interrogation, data retention, type of elaboration). The collected raw data are further processed for damage identification purposes and evaluation of the structural condition. Damage detection can be carried-out at various levels, from the simple determination of the presence of damage to its localization, type, and magnitude, up to prognosis [9].

Relevant specific features of sensors, data acquisition systems (specifically related to the hardware part), and data transmission systems (and their architectures as well) are summarized in Table 1. A similar summary for data processing requires an extensive evaluation of damage identification procedures and their peculiarities that cannot be completed at this stage of development of the qualification procedure.

The monitoring scenario is outlined in terms of: (*i*) monitoring objectives and principles (e.g., proactive maintenance, emergency management, troubleshooting), (*ii*) types of action on the structure (e.g., service, extreme hazard, environmental), (*iii*) structural category and details (e.g., existing or newly built, building or infrastructure), (*iv*) relevant response parameters or damage sensitive features (e.g., drift, modal parameters, deflection). Once the characteristics of the scenario are defined, the monitoring variables, such as acceleration or displacement or humidity/temperature values, are conveniently identified. Thus, a full characterization of the requested target performance is carried-out in terms of level, range, or description of each monitoring variable. Target specifications address the minimum performance requirements of the hardware and software components of a SHM system for the given scenario.

After the definition of the monitoring targets for the scenario and the performance for the SHM system, the final step of the scenario-based qualification procedure (Fig. 1) is the evaluation of the efficiency rating. Different approaches may be established to quantitatively compute it. As a matter of principle, the efficiency rating represents the respondence of the performance values of SHM system components to the monitoring targets characterizing the given scenario.

## 4 Case Study and Discussion

The qualification procedure described in the Sect. 3 has been preliminary applied to a simplified case study. The main aspects and results of such an application are herein presented and discussed.

Two different scenarios have been considered (named “A” and “B”, respectively); the same structural typology (simply supported bridge) has been assumed for the sake of simplicity, whereas all remaining scenario features were different.

**Table 1.** Summary of relevant specific features of sensor, data acquisition system, and data transmission system.

| Specific features | | | |
|---|---|---|---|
| Type | Sensor | Data acquisition | Data transmission |
| Technical parameters | Sensitivity | Resolution | Transmission distance |
| | Resolution | Synchronization | Transmission velocity |
| | Operating range | Acquisition mode (continuous, programmed, manual, triggered) | Transmission capacity (Throughput) |
| | Linearity | Possibility of on-line data filtering | Scalability |
| | Accuracy | | Robustness Redundancy |
| | Response time | | |
| | Sensor self-noise | | |
| Environmental and durability parameters | Sensor size | Size | Type of installation |
| | Temperature range | Energy consumption | Maintainability/ Replaceability |
| | Thermal effects | Power type | Electro-magnetic interference |
| | Humidity range | | Energy consumption |
| | Electro-magnetic interference | | Power type |
| | Energy consumption | | |
| | Power type | | |
| | Type of installation | | |
| | Maintainability/ Replaceability | | |
| | Protection rating (IP) | | |
| | Working life | | |

In case A, the action of interest was earthquake loading, the monitoring objective was emergency management, and the response parameters were drift values measured on top of the piers. On the contrary, the following features characterized the case B scenario: condition-based maintenance (objective), traffic load combined with varying environmental conditions (actions), modal parameters (response). Once all the features of the scenario were completely defined, monitoring targets have been detailed, as reported in Table 2. Notice that, for the sake of convenience, monitoring targets have been provided only for some of the most relevant technical features of the generic SHM system components.

Known the monitoring targets, the efficiency rating of the SHM system is basically obtained according to a "checklist" approach, namely as sum of the fulfilled targets. However, many further formulations may be assumed for evaluating the efficiency ratio, including, for instance, by introducing importance factors (weight) variable as function of the relevance of the targets within the monitoring objectives.

**Table 2.** Monitoring targets for cases A and B.*

| SHM component | Technical parameter | Case A | Case B |
|---|---|---|---|
| Sensors | Sensitivity [V/g] | $\geq 10$ | $\geq 1$ |
| | Resolution [g] | 10–5 | $10^{-3}$ |
| | Operating range [g] | $\leq \pm 0.5$ | $\leq \pm 0.5$ |
| | Linearity [%] | <1 | < 1 |
| | Response time* [s] | NC | C |
| | Sensor self-noise [μg/√Hz] | <1 | >1 |
| DAQ | Resolution [dB] | $\geq 24$ | $\geq 16$ |
| | Acquisition mode** [-] | Cont | Trig |
| Transmission | Transmission distance* [m] | NC | NC |
| | Throughput* [bps] | NC | C |
| Processing | Automated OMA procedure [yes/no] | yes | no |
| | Removal of EOV effects [yes/no] | yes | no |
| | Double integration of acceleration [yes/no] | no | yes |

* *C stands for "Critical", NC for "Not Critical".*
** *Acquisition mode: continuous (cont), programmed (prog), manual (man), triggered (trig).*

With the aim of illustrating the application of the qualification procedure, two SHM systems are considered, namely "System 1" and "System 2". The first employs wireless accelerometers with on-board processing (operating range equal to ±1 g, sensor self-noise of 12 μg/√Hz) installed on top of piers, able to carry out double integration of acceleration and triggered acquisition/transmission beyond a certain acceleration threshold. The second system consists of high-sensitivity wired accelerometers with ±0.25 g operating range and mounted on the bridge deck together with temperature and humidity sensors; continuous data acquisition/transmission and processing for automated output-only modal parameter estimation and compensation of environmental/operational factors are implemented. Comparing the performance of these SHM systems with the targets of Table 2 shows that System 1 obtains a high efficiency rating if applied to the case A, while its monitoring performance in case B are poor because of the absence of adequate sensors and processing tools, among others. On the contrary, System 2 cannot be considered efficient for case A, due to, for instance, limited operating range and inappropriate processing.

## 5 Conclusions and Future Developments

A preliminary attempt to define a qualification approach suitable for SHM systems has been presented. Due to the highly tailored nature of SHM applications, standardization of SHM systems is hard to achieve; therefore, the CE marking approach commonly adopted for non-structural construction products, cannot be directly applied to SHM systems. However, the latter approach, robust and well-established, has been analyzed in detail with the aim to find useful analogies to adopt for SHM system qualification.

The proposed qualification procedure is scenario-based: the primary features of the monitoring application are outlined, and the corresponding target are defined, on one hand, while the relevant features and the associated performance of the SHM system are collected, on the other hand. Comparing the performances of the SHM system with the monitoring targets, an efficiency rating is obtained, in the current formulation, by applying a checklist-based approach. Sample case studies have been considered for the practical application of the proposed approach, and to demonstrate its potentialities. Despite the very preliminary development stage of the procedure, the proposed scenario-based qualification framework appears promising and useful to support decision-making aimed, for instance, at selecting the most efficient SHM system in a group. However, further investigations are needed to refine it and provide a complete overview of SHM technologies and their performance and limitations. Finally, a further line of exploration associated to the CE marking approach used for structural construction products is currently under study.

**Acknowledgments.** The present study has been carried out in the framework of the PON RICERCA E INNOVAZIONE 2020 E FSC "INSIST" code ARS01_00913, whose financial support is gratefully acknowledged.

## References

1. Chang, P.C., Flatau, A., Liu, S.C.: Health monitoring of civil infrastructure. Struct. Health Monit. **2**(3), 257–267 (2003)
2. Fan, W., Qiao, P.: Vibration-based damage identification methods: a review and comparative study. Struct. Health Monit. **10**(1), 83–111 (2011)
3. Calvi, G.M., et al.: Once upon a time in Italy: the tale of the morandi bridge. Struct. Eng. Int. **29**(2), 198–217 (2019)
4. Pinto, P.E., Lupoi, A., Franchin, P.: Valutazione e consolidamento sismico dei ponti esistenti. Iuss Press (2009)
5. Gatti, M.: Structural health monitoring of an operational bridge: a case study. Eng. Struct. **195**, 200–209 (2019)
6. UNI (Ente nazionale italiano di unificazione). Vibrations on bridges and viaducts – guidelines for the execution of dynamic tests and surveys. UNI 10985:2002 (2002). In Italian

7. UNI (Ente nazionale italiano di unificazione). Guidelines for structural health monitoring. UNI/TR 11634:2016 (2016). In Italian
8. Ministero delle Infrastrutture, Consiglio Superiore dei Lavori Pubblici, Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti. Rome, Italy (2020). In Italian
9. Farrar, C.R., Worden, K.: Structural Health Monitoring: A Machine Learning Perspective. John Wiley and Sons Ltd., Chichester (2012)
10. Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 Laying Down Harmonised Conditions for the Marketing of Construction Products and Repealing Council Directive 89/106/EEC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32011R0305. Accessed 15 Feb 2022
11. Kabban, C. M., Derriso, M. M. Certification in structural health monitoring systems. Reprot, Air Force Institute of Technology, Ohio, United States (2011)
12. Construction Sector. https://ec.europa.eu/growth/sectors/construction_en. Accessed 22 Feb 2022
13. Official Journal of the European Union, Consolidated version of treaty on the functioning of the European Union, C 326/47. 26 Oct 2012
14. Council Directive 89/106/EEC of 21 December 1988 on the Approximation of Laws, Regulations and Administrative Provisions of the Member States Relating to Construction Products. https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:31989L0106. Accessed 23 Feb 2022
15. Webb, G.T., Vardanega, P.J., Middleton, C.R.: Categories of SHM deployments: technologies and capabilities. J. Bridg. Eng. **20**(11), 04014118 (2015)