On the standardization of procedures for Structural Health Monitoring

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Abstract

The aim of this paper is to outline the different aspects of the Structural Health Monitoring process that should be standardized in order to provide the stakeholders with consensual procedures for their implementation and use on the lifecycle, thereby improving the diffusion of such systems at a large scale on structures and infrastructures.

1. Scope and current situation of SHM standardization

Notwithstanding several successful applications and important scientific efforts, Structural Health Monitoring (SHM) is not yet extensively used for condition assessment of civil structures. Beyond the insufficient knowledge of the process on behalf of the stakeholders (from owners to sensors producers) and the reluctance to invest on these systems, due to the difficulty to estimate their return on investment, a further important cause of this situation is the lack of standards.

Standardization may provide guidelines on which a consensus exists that facilitate the design and implementation of SHM systems. Guidance is needed on several aspect of the SHM process that include the implementation of structure specific SHM, the incorporation of SHM within current maintenance best practices, the treatment of the environmental and operational variability boundary conditions, the basic requirements of SHM technology and not least the harmonization of SHM glossary for an improved understanding between stakeholders.

In the last years, there have been several efforts all over the world to outline guidelines and recommendations for SHM for Civil Structures [2]-[6] but, to date, the only compulsory code on SHM of buildings and bridges, has been published in China by the Ministry of Transportation [6]

There are several challenges connected with the standardization of SHM procedures for Civil Engineering asset: differently from aerospace or mechanical components, each civil structure has its own peculiarities and therefore requires the design of a 'structure specific' monitoring system. Environmental effect due to temperature, humidity, moving loads and wind and to the non-linear behavior of materials such as concrete or masonry must be carefully accounted for, in order to decrease the uncertainty connected with the results of structural identification.

Different monitoring tools used to investigate the same physical phenomenon should provide consistent data and the possibility to compare data collected by different techniques. Minimum requirements of the tools used for the entire process of data collection - from measuring to transmitting and processing – must be specified together with the possible shortcoming in order to guide the choice on behalf of the stakeholders.

Further to this aspect related to the specific monitoring tools, standardization should enable the use of SHM in structural assessment therefore should provide guidance on the type of functionalities that can be investigated with specific tests and on how to obtain indicators relevant for the assessment of the structural condition with respect to a given functionality.
In the following sections, the needs in terms of standardization of SHM are outlined with reference to the choices connected with the implementation of an SHM program and to the guidance that should be provided to enable the design and use of the most effective monitoring system for each specific structure.

1. PRINCIPAL STEPS IN THE DESIGN OF AN SHM SYSTEM

The first step in the definition of a procedure for condition monitoring must be the specification of the objectives of the stakeholders.
For civil structures a key purpose of SHM is to inform decision making related to an efficient (usually from a cost/benefit balance perspective) management of structures throughout their entire life cycle.
However, currently no standardized guidelines exist to enable the stakeholders to:

- develop and implement condition monitoring programs and to integrate them into a condition management program.
- identify the available tools and techniques to assess the structural condition.
- quantify the value of the monitoring systems in terms of benefits produced by the increased management efficiency.

The specific information expected by the monitoring system must be defined based on the stakeholders needs (e.g. information about the development of degrading phenomena) and conversely, in order to decide whether a procedure for condition monitoring is suitable for a specific case, the stakeholders must be able to understand the characteristics of the procedure. This requires a clear definition and descriptions of the characteristics of the monitoring system e.g. its performance in terms of damage identification, the ease of application and installation of the instruments, the frequency of tests needed and so on. Based on this information, the decision makers can evaluate and compare different condition monitoring procedures and make an educated choice of those most suited for their needs. As previously mentioned, in order to provide a return over the investment, the cost of the monitoring system must not exceed the expected benefits it brings in the asset management procedure. The choice of the monitoring system should therefore always include a quantification of its value before its implementation. This topic has been recently the object of a research project [1] that will produce, as one of the outcomes, guidelines on the quantification of the value of Information from SHM.
Further steps in the design of a monitoring system relate to the choice of data needed to provide the information required by the stakeholders. Decision-making procedures supported by SHM usually make use of Indicators to check the structural performance with respect to pre-defined goals. Therefore, once the objectives of the SHM are defined, the corresponding Indicators (usually termed Key Performance Indicators to address the specific indicators of interest for the problem at hand) are chosen and the data needed to compute these indicators are defined.
Further to the choice of the data needed to compute the indicators, the specific procedures to collect, process and store these data must be defined and detailed.

In the following sections, the design of an SHM program will be described with reference to the 6 steps represented in Figure 1, pointing out the needs in terms of standardization:

Step 1. Specification of the objectives and benefit of monitoring
Step 2. Selection of the Indicators and Data
Step 3. Design of the SHM system
Step 4. Collection of data
Step 5. Processing of data
Step 6. Retrieval and storing of the information

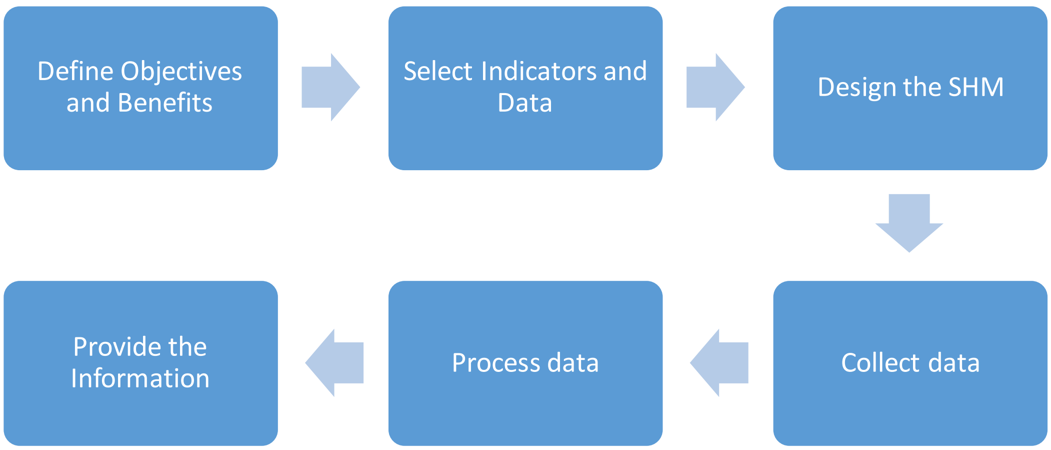

Figure 1. Stepwise representation of the SHM process

Step 1. Specification of the objectives of the stakeholders
Needs and expectations of the stakeholders are the targets driving the monitoring of the structural condition. Main drives are related to
a) to *manage risk*, that is to maximize structure reliability/availability by providing information about possible damages therefore triggering immediate remedial actions;
b) to *reduce the cost of maintenance over life-cycle* optimizing preventive maintenance or enabling condition-based maintenance approaches. At a higher level SHM may support:
c) *codes calibration* toward an optimized design of structures, enabling them to provide the required functionalities at minimum costs;
d) *prototype development*, through the gathering and use of information about the performance of structural prototypes intended for a future series production (e.g. wind turbines), in order to optimize their design.
Different benefit of the information from the monitoring system may be expected in the different cases and must be properly assessed, using standardized procedures, before the implementation of the system.

Step 2. Selection of the Indicators and Data
The information needed from SHM must support decisions related to the targets specified at step1. This requires the assessment of the structural condition that is usually carried out using **Indicators** able to describe the structural 'fitness for purpose' with respect to the different functionalities of the structure, involved in the targets defined at step 1 [9].

When the aim of monitoring is to assess the safety of the structure, the risk of failure can be assumed as indicator whereas indicators related to the structural flexibility or to other damage/degradation phenomena could be more useful to describe the behavior at the relevant serviceability limit states. For each indicator a metric must be defined in order to assess the structural state against predefined goals that are often defined through threshold values or extreme (minimum or maximum) requirements. Once the list of the indicators needed is compiled, the data (legacy and/or measurements taken on the structure) required to compute these indicators can be identified. Data must describe the different aspects affecting the structural performance: structural details, existing damage/degradation processes; actions on the structures; environmental conditions. Their temporal and spatial distribution must be defined based on the accuracy requested in the description of the structural performance and accounting for budget constraints. As previously mentioned, the choice between different strategies of data collection can be effectively supported by a Value of Information analyses.

Step 3. Design the SHM

Once the data needed to compute the indicators are defined, the selection of the most appropriate SHM tools and techniques to collect them can be done accounting for factors that consider the practical implementation of the SHM tools for the specific structure and namely:

a) *the feasibility of the tool for the type of asset* that may depend on the type and size of the asset, on the structural material and on practical limitations related to access restrictions and/or need to keep the structure in service during the tests;
b) *the capability to collect the data* that depends on the type and accuracy of data and on the possibility to integrate the sensing system with efficient hardware/software tools for transmission and post-processing.
c) the *technical capacity of the user and of the tool itself* like the expertise of the operator, the technological sophistication, the availability of on-line technical support for the tool, etc.
d) *the cost/benefit balance* that should be identified and evaluated before the system is put in place in order to have a clear return over the investment [1]. This must account not only for the cost of the monitoring system itself, but considering the full life cycle (depending on the frequency of the tests and on the amount of data to collect) and the human resources (training and work) needed to act the system.

Once to appropriate tools are selected, the time schedule of the tests must be decided in order to:
a) get information about environmental and operational conditions that are representative of the real *in-service* situation;
b) provide all the data needed to assess the structural condition.
To this aim protocols of the tests should provide for each type of test, guidance on the planning of the tests (set the frequency and the schedule); on data requirement (e.g. need of legacy data), collection (locations of sensors/tests, specific protocols of the tests), transmission (wired/wireless) and processing; on the structural components to test (bearings, expansion joints,…) and on the practical implementation of the test (power and network requirement, traffic restrictions, etc).
In reference [6] a quite comprehensive list of all the aspects of the tests that need to be organized according to a specific protocol is suggested. The interested reader can refer to reference [6], freely available on the web, for a more detailed list.

Step 4. Collect data

Protocols must ensure that tests provide data of constant quality regardless of when, where, or by whom the data are collected [6].

To this aim criteria to assess both the *quantity* the *quality* of data should be given by the protocols. The *quality* of data should be assessed according to specified confidence criteria, which can include some or all of the following aspects of data quality [7]:

– Accuracy – Are the data reliable?
– Completeness – What is the data coverage; are there any gaps?
– Currency – Are the data sufficiently up to date?
– Consistency – Is there any contradictory data or information?
– Compatibility – Are the data produced on the same basis as other similar information?
– Credibility – Does the data align with local knowledge or typical ranges of values?

Quantity of data is also important since collection and storing of data are costly, therefore it is important to collect only sufficient structural performance data to provide the information required by the stakeholders.

Step 5. Processing data

As mentioned before, data are processed to compute the so-called *Indicators*, whose values are correlated to the structural health condition. Permanent monitoring systems can generate huge amount of data and current technology to measure, store and transmit data does not always provide the ideal conditions for an effective processing of the measured data. Further insight and investigations are also needed to bring the methodologies for the computation of the indicators at the operational level. Many of these indicators are still at the research level and issues exist for their routinely implementation for condition monitoring The computation of indicators must always include a careful processing of data, aimed to reduce the influence of uncertainties introduced during the phases of data collection, transmission and processing [9].

Step 6. Retrieval and storing of the information

Once the indicator is extracted, basing on its value, a decision must be made about the (health) state of the structure in order to discriminate between the undamaged and the damaged states.
To this aim can be used statistical models derived from machine learning techniques falling into two main categories of: [9].

- *supervised learning* algorithms when data are available from both the undamaged and damaged structure. Group classification and regression analysis are examples of such algorithms
- *unsupervised learning* algorithms when only data from the undamaged structure are available for training. Outlier or novelty detection methods are examples of this category.

The application of these techniques of Artificial Intelligence and other based on big data analytics – allowing also the processing of data from different sources, as legacy data for example – is becoming more and more effective to treat the large amount of data made available by the new sensing technologies. Standardization can facilitate and foster a wide diffusion in the employment of such technique and technologies.
Another aspect related to the large amount of data and information provided by surveys and monitoring is the need to *store* them. Data or information collected by the SHM process must be documented using for example collection forms, and then stored in a database for future use. This database should collect all the possible information over the lifecycle of the structure that are necessary to assess structural deterioration. Protocols should be defined regarding the required format of data and the procedures to readily access and interrogate the database and for data unloading and uploading. As an example, in reference [6] a detailed protocol is proposed for data collected during visual inspections and NDTs.

2. CONCLUSIONS

In this paper the design and implementation of an SHM system is described emphasizing the standardization needs of the different phases connected with the monitoring process. In a large part of the world, visual inspections are the primary tool for condition monitoring if civil structures and infrastructures. The implementation of advanced performance-monitoring systems is still at a very early stage. Possible reasons for this situation are on one side the lack of harmonized procedures for their design, implementation and use and, on the other, the difficulties connected with the quantification, before their implementation, of the benefit they bring into the asset management best practices.

Guidelines and standards on both aspects would facilitate and foster the utilization of such systems enabling a more objective information about the structural condition and thereby an increased efficiency and benefits connected to their use for civil asset management.

3. REFERENCES

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