Structural Health Monitoring for cultural heritage constructions: a resilience perspective

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Structural Health Monitoring for cultural heritage constructions: a resilience perspective

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Abstract

Disturbances or disruptive events may induce reductions of functionality of the built environment. For Cultural Heritage (CH) structures, functionalities may range from technical, to economic ones linked to touristic activities, up to intangible functionalities related to the cultural and social value of these constructions. Resilience can be defined as the capability of a system overcome a disturbance with the minimum total loss of functionality over time. Structural Health Monitoring (SHM) may enhance resilience by providing information that can support decision making, aiming to reduce the impact of the disturbances. In this paper, the benefits of SHM systems as means for improving resilience of CH structures are addressed and discussed with specific reference to the three different decision situations; before, during and after events of disturbances. Examples of real applications of SHM for CH structures and its effect on the resilience of the system conclude the paper.

Keywords: Structural Health Monitoring, Cultural Heritage, Resilience, Prevention, Recovery

1. Introduction

CH structures may be particularly prone to natural hazard events due to both their state of degradation and due to the long standing lack of knowledge about structural characteristics arising from inadequate management and human errors. However, the resilience of the CH structures is particularly important for local communities due to the functionalities provided by structure, i.e. cultural and social functions associated with the knowledge, identity and memories of communities that they preserve. This characteristic gives a slightly different perspective to the concept of resilience of CH, intended as the capability to overcome a disturbance with the minimum total loss of functionality in time. First of all, due to their unique and irreplaceable character, maintenance and recovery are much more difficult compared to ordinary constructions. Indeed, decision making with respect to reconstruction and restoration of CH has always been subject to controversy, involving ethical considerations. Furthermore, in the recovery phase, after the first emergency operations aimed to rescue and save lives and to restore quickly the essential functionalities, the prompt recovery of the social and cultural functions of the CH structures may leverage the resilience of the communities by recreating a societal cohesion around the common historical legacy, represented by the buildings themselves. The fast reduction of losses during the disturbance for CH structures are therefore a goal with a higher importance compared to ordinary constructions. The loss of functionality during the disturbance phase generally depends on the state of the system at the occurrence of the disturbance. From this perspective, the phase before the disturbance may play an important role in increasing resilience through the implementation of measures that keep the functionality at its original level or counteract degradation. In this context, SHM systems may support decision making aimed to prepare the structure to the future disturbances, to manage the emergency efficiently and to accelerate the recovery phase. In the following sections, the benefits of SHM for CH structures are outlined with reference to the different phases of a disturbance classified as before, during and after the event, and exemplified using real applications of SHM systems to CH constructions.

2. SHM, resilience and cultural heritage

2.1 Cultural Heritage Structures

CH was defined by UNESCO in 1972 World Convention as monuments, groups of buildings and sites unanimously considered of universal value in the light of history, art and science (1). The Council of Europe described the "European architectural heritage" which includes both important monuments and groups of lesser buildings located in historical towns and villages (2). Exceptionally, the attribution of CH can be extended also to modern constructions (3). In general terms, CH constructions can be thought as systems which involve built environment, society which they belong to, environment and stakeholders namely owner, operator and users of the structure. Moreover, CH structures provide functionalities, namely cultural, social, environmental and economic. The cultural functionalities involve physical and non-physical features: manufactured culture i.e. construction techniques etc.. Images and symbols placed on the construction and visual attractiveness are some of the physical features of cultural functionalities while creativity, identity and traditions of community are non-physical features. The social functionalities of CH provide identity of the community, sense of place, social cohesion, and continuity of social life. The economic functionality of CH is defined as "direct use values", i.e. tourist expenses, income from lease, place of living, and for organizing economic, cultural and leisure activities (4). These economic functionalities are quantifiable in terms of monetary value and the tourism has a significant share in economic functionalities. Finally, the environmental functionality supports sustainable development, reducing unplanned settlements and increasing knowledge on energy efficiency techniques for the new constructions.

2.2 Resilience

Resilience has been defined in literature (5) (6). Referring to one of the functionalities of the system - that is the capability to provide a certain functionality - its evolution in time enables a graphical interpretation of resilience, see Figure 1. Structural functionality is considered 100% until t_0 when, due to a disturbance, a sudden loss of the functionality occurs. After the disturbance, the recovery phase starts and at t_1 the functionality of the structure may return to its previous level, with full recovery.

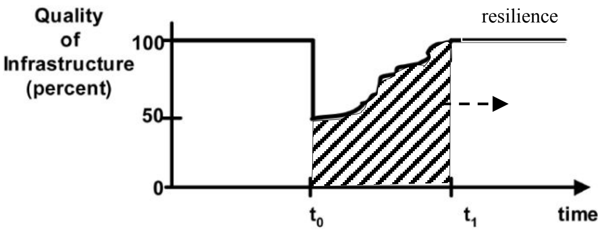

Figure 1 Conceptual definition of resilience (adapted from (5))

Depending on the type of system, the functionality can be technical, economic, cultural, social, etc. Regarding, an infrastructure, technical and economic functionalities might be the most important functionalities that the system is expected to provide. As for a CH structure, also cultural and social functions must be carefully considered, as stated previously. In Figure 1 two main phases are highlighted: the disturbance phase and the recovery phase; the dashed area gives a measure of resilience. The three main factors affecting resilience are the immediate loss of functionality at the time of the disturbance, the length of the recovery phase and the evolution of functionality during the recovery phase. In general, these three factors depend mainly on four characteristics of the system that can be defined as technical, social, organizational and economic *capacities* (6) or *dimensions* (5). The first two describe the capacity of physical systems (*technical* dimension) and vulnerable communities (*social* dimension) to reduce the impact (losses) induced by the disturbance. The other two dimensions describe the ability of the system to make decisions and undertake actions to foster recovery (*organizational*) and the capacity to decrease both direct and indirect *economic* losses resulting from the disturbance. Whereas the technical and social capacities govern the disturbance phase, the latter two characteristics have a stronger influence on the recovery phase. The previous description does not account for the pre-event phase, that influences the state of the system at the occurrence of the shock. For instance, the structural functionality may be reduced by degradation due to aging and increased by repair or strengthening interventions that prepare the system in view of a future event of disturbance. The state of the system at the occurrence of the disturbance may influence the magnitude of the drop of functionality during disturbance. To account for this, a *planning phase* is introduced herein to consider all the activities that can be performed to plan or prepare the system to the possible event of disturbance. This phase is particularly important for CH structures due to their unique character that they may be irreplaceable. In this paper, the chronological sequence of phases centered on the disturbance is described using the following framework:

(i) Before event phase (*planning or preparation*);
(ii) During event phase (*disturbance and emergency*);
(iii) After event Phase (*emergency and recovery*).

Figure 2 shows the variation in time of a generic functionality during these phases:

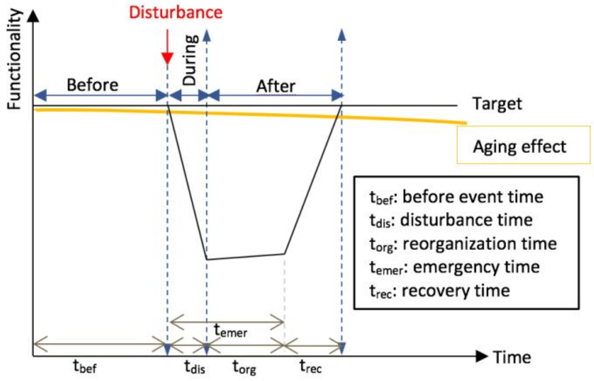

Figure 2 Evolution of functionality in time.

Herein this evolution is described with reference to the technical functionality, but similar considerations hold for the other possible functionalities of the system. Since CH structures are deteriorating over time, a functionality loss is expected to occur over time. If there is not a destructive event (fast decrease of functionality), this loss can be seen in longer period. Measures may be put in place to limit or recover this loss of functionality. The duration of the before event phase can be considered as the time elapsed (t_{bef}) from the last intervention performed to re-establish the functionality. During the event (disturbance phase) the functionality decreases. The length of this phase t_{dis} varies depending on the disturbance: some hazard events, like earthquakes or explosions have sudden impact, others may have longer duration such as floods or storms. In the after event phase, the organization, in a period of length t_{org} and the recovery in a period of lengt6h t_{rec} take place, ending possibly with a return to optimal functionality. The emergency phase starts at the occurrence of the disturbance and includes the reorganization time t_{org}, needed to decision makers and first responders to organize first interventions.

2.3 Structural health monitoring for CH

In very general terms, SHM is defined as “the process of determining and tracking structural integrity and assessing the nature of damage in a structure” (7). SHM belongs to the range of non-destructive techniques for structural characterization and therefore is suitable for architectural heritage according to the principle of minimum intervention (8). According to ICOMOS/ISCARSAH (8), the decision-making process related to conservation activities on heritage structure is based on the four phases of anamnesis, diagnosis, therapy, and control. SHM is providing knowledge to all four phases and is the major support for Anamnesis and Control. Indeed, since each heritage structure is unique and presents a particular behavior, it is not recommended to provide general and standardized types of interventions. Data collected by SHM on a specific structure facilitates appropriate interventions. The starting point of any SHM strategy is the observation of a physical phenomenon, which usually produces an electric signal, by means of sensors. Data acquisition, transmission, analysis and storage follow. In the context of CH structures, the monitored parameters can be dynamic or static. Typically, also environmental sensors are installed to allow for the differentiation between the changes in the structural behavior caused by exogenous effects (e.g. environmental actions) and changes caused by endogenous effects, from alterations due to endogenous agents (i.e. occurrence of damages). Monitored environmental effects are commonly temperature, humidity and wind. Dynamic SHM addresses the global structural behavior and aims at estimating and tracking the dynamic properties of the structure. This is done by recording the vibrational responses of the structure under operational conditions, i.e. under the effect of ambient vibration such as those induced by traffic and wind. The measured physical quantities are accelerations or velocities in several locations. Different Operational Modal Analysis (OMA) techniques are then available to estimate the modal characteristics of the structure, i.e. natural frequencies, mode shapes and damping. The observation of parameters related to the static behavior, complement the analysis. They include: tilt of vertical elements, crack widths, strains, relative displacements.

3 Benefits of SHM for Resilience Performances

The resilience of systems subjected to disturbances can be improved using information gathered by SHM. Here, the possible benefits in terms of resilience related to the adoption of an SHM system will be described with reference to three different decision situations – before, during, after - defined in the previous section.

The general benefit related to the use of SHM systems is due to the information they provide. This in turn allows for reducing the uncertainties related to the structural condition and behavior and for improving the estimation of structural safety. In the following, benefits of SHM in terms of resilience will be described specifically with reference to CH structures.

3.1 Before Event Phase (BEF)

This phase corresponds to the normal functionality of the system before the disturbance. The information provided by SHM may foster a reduction of the degradation of technical capacity if it is used to manage the maintenance of the system. Moreover, increased knowledge about the actual structural conditions support a more efficient allocation of resources for strengthening interventions, thus increasing organizational resilience. Also, in some cases the installation of a monitoring system may indirectly produce a reduction of the hazard or of the exposition with a corresponding reduction of risk therefore the losses during the disturbance phase. Specifically, information from a SHM system allows to:

1. monitor continuously the actual structural conditions without invasive interventions. This allows to perform repair/maintenance interventions with an impact on technical capacity. A continuous SHM enables also to study the effect of environmental sources that may hinder the identification of damage thus hampering the implementations of prompt recovery measures. Increased knowledge about their effect fosters a higher efficiency of interventions therefore increase of organizational capacity;
2. enhance the knowledge on actual structural conditions allowing to account for the effective state, i.e. degradation due to ageing) of the structure. This enables more accurate safety level assessment fostering the rational implementation of mitigating measures with an impact on both technical and economic capacities;
3. perform condition-based instead of planned maintenance, allowing to target the interventions to the actual structural condition. This reduces unnecessary interventions and downtime, the latter impacting both the functionalities and the income (e.g. from tourists). This improves the efficiency in the use of available economic resources for integrity management and thereby enhances economic capacity;
4. act as a deterrent for malevolent act therefore reducing the associated hazard (e.g. vandalism). These are particularly important for CH structures that are often iconic or landmark structures. Despite the small fingerprint of this type of hazards, their social impact may be huge due to the long-lasting security measures that are usually put in place following such events. The use of cameras for

vision-based SHM has been largely investigated in the last years by several researchers (9). The use of video cameras as multitasking devices, able to record images of the structure but also of people thus denouncing their presence, may act as deterrent for malicious acts therefore reducing the hazard;

5. provide early warning about a possible hazard event therefore enabling the adoption of emergency measures (e.g. evacuation, traffic reduction, shutting off critical facilities) that decrease exposition to the hazard event therefore reducing risk.

3.2 During Event Phase (DUR)

During the emergency, a SHM system installed on the structure enables the acquisition of information about:

6. the actual state of the CH structures or of its elements (e.g. frescoes on the walls) during the event. This information enables prompt and targeted interventions thus increasing the efficiency in the allocation of resources (organizational capacity) and also the technical capacity related to the cultural function of the content of the structure;
7. the structural behavior under extreme events. This enables to improve the understanding of the actual structural behavior under extreme events, for example the non-linear behavior of masonry of unknown characteristics and level of degradation. Inter-hazard cascading effects may also be recorded as for example the effect of a sequence of foreshocks, main shock and aftershocks in case of earthquakes. Also, multi-hazard effects due e.g. to the occurrence of a flood on a bridge previously damaged by a seismic event can be better investigated if data recorded during the sequence of events are available. All this information is strategic to improve regulatory systems (e.g. building codes) and to reduce the uncertainty related to future risk assessment of the same or similar structures therefore fostering the increase of technical capacity for future events;
8. a more efficient emergency management (e.g. evacuation of buildings, traffic restrictions, prioritization of interventions). This can be particularly important to reduce exposure on CH structures with an important touristic flow or to reduce downtime for constructions that host strategic functionalities requiring business continuity (e.g. hospitals or government institutions).

3.3 After event Phase (AFT)

The phase after the disturbance includes the organizational and recovery phases. The information provided by SHM enables:

9. to retrieve information about serving lifeline/utility networks connected to the CH structure and that may originate adverse synergetic effects (e.g. between CH structure and the serving lifeline-utility networks), which may increase the impact of extreme events;
10. knowledge about the actual structural condition after the disturbance that constitutes a support for decision making related to different interventions (if any), to optimize plans for recovery. This enables an increase of both the organizational and economic capacities;
11. the possibility to check the effectiveness of the past interventions in real time and to give an updated estimation of the system functionality;
12. information about the performance of innovative repairing or strengthening techniques implemented to regain the full functionality. This is particularly important in the case of heritage structures for which laboratory tests are not a feasible option. This allows an improvement of technical capacity through increase of knowledge;
13. knowledge about the structural state to decide if there is need for any intervention, even if there is no visible damage.

4. SHM for resilience of cultural heritage constructions: applications

This section presents several examples of SHM applications for CH structures. In the presentation, the outlined framework described in the previous section is followed to highlight the contribution of SHM to resilience. In the before event phase, the benefit from monitoring data is mainly related to the possibility of supporting decision about intervention to strengthen the construction in view of future disturbances. On the Peristyle of Diocletian`s Palace in Split a monitoring system has been installed (10) in order to allow an early detection of damage related to excessive structural deformations, enabling interventions that may prevent further degradation of the structure (BEF, point 1). Another example of the same type is the permanent monitoring system that was installed on the Paderno bridge over the Adda river to detect structural performance anomalies and changes in the dynamic characteristics of the bridge, conceivably related to the progress of the damage due to corrosion (BEF, point 1). A further example of utilization of monitoring before the disturbance relates to the possibility to get information about the structural behavior under changing environmental conditions. Variations of temperature, humidity or other environmental parameters may induce changes in the performance parameters that should not be confused with changes caused by structural anomalies In (11) is described the monitoring system deployed also with this scope on the Monastery of Jerónimos in Lisbon (BEF, point 1). An example of an SHM system installed to monitor the structural behavior before a possibly disturbance is the one that was installed on the 31 m tall medieval Aquila Tower, a part of Buonconsiglio Castle located in the city of Trento (12). In view of possible future tunneling work, the monitoring was motivated by the need to protect the valuable artworks hosted in the tower by keeping under control structural deformation and vibration (BEF, point 2). One of the few examples of implementation of a monitoring system to perform condition-based maintenance (BEF, point 3) is the one installed on the Arena of Verona. This is a very precious structure which, during several centuries, experienced natural and anthropogenic hazards (stealing of stones). A SHM system was installed to support a maintenance policy based on the actual system behavior as retrieved from the monitoring system (13). In cases of *programmed disturbances* - as it happens for example when the equipment needed to perform maintenance, interventions may induce damages to the structure - SHM may provide an alert fostering prompt interventions (DUR, point 6). During the works for the restoration of the spire of the Duomo of Milan, a heavy scaffolding was built on top of the dome. Its interactions with the spire induced by wind or any other environmental condition had to be avoided, therefore a real-time monitoring system was designed and realized, to early detect any possible damage and to send alerts about any anomalous situation for the structure and its occupants (14).

Another application, particularly meaningful for CH structures, is the installation of sensors on the structure to monitor the effect of degradation of its content (DUR, point 6). For example, in the Conegliano Cathedral in Italy the frescoes of the Battuti Hall have been monitored to control the evolutions of serious cracks likely due to differential settlements of the façade of the cathedral and of surrounding structures, namely the massive bell-tower (15). In many cases, SHM systems are installed only after disturbances to monitor the structural condition and follow the possible evolution of damage. Monitoring data are then used both as emergency support devices to promptly detect possible worsening of the structural condition (AFT, point 8) and/or to make informed decision about the need of strengthening interventions (AFT, point 10). After the interventions, the SHM also allows to control their effectiveness (AFT point, 11) and/or to retrieve information about innovative repairing techniques (AFT, point 12). Several examples of this type of applications can be found in Italy and most of them are relevant to SHM systems installed after strong seismic events such as the l'Aquila earthquake of 2009. After this earthquake, temporary monitoring systems were installed on critical structures to support emergency management (AFT, point 13) (16). On the Church Santa Maria del Suffragio (known as Anime Sante) in L'Aquila (17) SHM was required by the local board of monuments immediately after the earthquake and implemented before the first safety measures were installed. It had the primary aim of giving prompt information about the behavior of the building thereafter, particularly in terms of decrease in stiffness through time. Later the system was also used to validate the quality of the interventions for structural rehabilitation (AFT point 12). Also on the Basilica of S. Maria di Collemaggio (18) in L'Aquila Immediately after the earthquake of 2009 that caused the partial collapse in the transept area, a monitoring system was deployed to monitor the performance of the scaffolding structures and other temporary reinforcements (tendons between the walls and composite tape wrapped around the columns for confinement). After the implementation of retrofitting intervention, the monitoring system was used to examine its effectiveness. A further example is the Church of St Anna in L'Aquila were the monitoring system was installed to promptly detect possible worsening of the structural condition, to understand the structural behavior and evaluate the effectiveness of the temporary and final strengthening AFT-earthquake interventions (19). In some cases, the SHM system is used as a support for the design of innovative strengthening interventions (AFT, point 12) as is the case of the Margherita Palace and the Civic Tower in L'Aquila that suffered heavy damage during the earthquake. The SHM data were utilized to investigate the dynamic behavior of the structure and to support the design of a base isolation system, aimed to reduce the impact of future events (13). After the 2012 Emilia earthquake monitoring systems were installed on a number of structures to follow the evolution of damage and provide prompt alert about the need of strengthening interventions. One example is the Gabbia Tower, a heritage icon of city of Mantua. Due to the fall of some masonry pieces, surveying and monitoring actions in the tower were initiated immediately after the earthquake (AFT, point 10) (20). The long-term vibration based SHM system has being used since 2014 in San Pietro monumental bell tower of Perugia, Italy (21). The data gathered until 2016 had been processed to calibrate numerical models and to study the influence of environmental agents on dynamic properties of the structure (BEF, point 2). The analysis of data recorded during the Accumoli earthquake in August 2016 denounced a reduction of the modal frequencies due to permanent damages that visual inspections had not been able to capture (AFT, point 10). A similar example is reported in reference (22), about the Basilica of St. Nicola of Tolentino (MC) where a permanent monitoring system with 20 uniaxial capacitive accelerometers was installed on the structure to survey the evolution of the damages occurred during the 2016 earthquake (AFT, point 13). In Saint Torcato church, Portugal, the first simple monitoring system was installed in 1998 to investigate the condition of the structure that presented several old cracks (BEF, point 1). In 2014, after the implementation of strengthening measures, a continuous dynamic monitoring was installed to evaluate the efficacy of the interventions. SHM related to static features was also performed during six years to monitor the damage evolution with time and to investigate the damage mechanism during and after the strengthening interventions (AFT, point 12) (23). A further example of the same type is given by the monitoring system installed on the Duomo of Orvieto after the Umbria earthquake (1997). Several cracks were detected after the seismic shocks therefore dynamic tests were performed to assess the structural health (AFT, point 13) (13).

The last example is the medieval bell tower of S.Giorgio in Trignano which was hit by the 1996 Reggio Emilia Earthquake. A SHM system was installed to follow possible development of the significant cracked pattern induced by the earthquake (AFT, point 13) (13).

5. Conclusions

In this paper the benefits that SHM system may bring to cultural heritage systems in terms of increased resilience are described in a framework for different decision situations, namely before (planning and preparation), during (disturbance and emergency) and after (emergency and recovery) an event of disturbance. Several case studies have been reported to exemplify the contribution of SHM due to the increased knowledge it provides, allowing to make informed decision about mitigation measures.

Usually, resilience is dealt with in terms of loss and recovery of functionality after a disturbance. Herein, also the phase preceding the event is considered. This allows to account for possible changes of functionality induced by events preceding the disturbing one (e.g. aging) and/or by remedial actions fostered by the knowledge acquired by the SHM system.

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