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STRUCTURAL HEALTH MONITORING OF HISTORICAL BUILDINGS: PREVENTIVE AND POST-EARTHQUAKE CONTROLS

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ABSTRACT: Structural health monitoring (SHM) has been recently more and more utilized in the study of Cultural Heritage (CH) buildings, as a key activity to increase the knowledge on their structural behavior and to have a deeper insight into their conditions. This knowledge allows engineers to carry out with more confidence and only if necessary a strengthening intervention, and it helps to prevent the execution of intrusive repair works, if not justified by an experimentally demonstrated worsening of the structural conditions.

The use of monitoring systems applied under ordinary conditions and installed on CH structures may allow to: (i) validate the functioning of the adopted structural models; (ii) identify the ongoing damaging processes; (iii) validate the effectiveness of the strengthening interventions.

In case of a seismic event, SHM can furthermore prove its usefulness in order to: (i) evaluate quantitatively the progression of the damage pattern, (ii) carry out effective and urgent interventions if an unsafe displacement patterns is recorded; (iii) define an early warning procedure for the safety of the workers employed in the strengthening interventions. Monitoring can also be effective when implemented on seriously damaged buildings, if the time schedule for the interventions is difficult to be a priori planned.

In this framework, the authors and the university of Padua in collaboration with the officer of the Cultural Heritage Authority, the university of Nagoya (Japan), the National Institute of the Conservation and Restoration (ISCR) designed and installed SHM systems on six representative and emblematic CH buildings in L'Aquila after the devastating earthquake occurred on the 6th of April 2009 in the Abruzzi Region. The selected case studies SHM systems – presented in the paper – report the experience gained on the use of monitoring in "normal" conditions and after the emergency activities following a seismic event.

1 STRUCTURAL HEALTH MONITORING IN CULTURAL HERITAGE BUILDINGS

Monitoring is being more and more considered, in the field of cultural heritage buildings, as a key activity in order to increase the knowledge on the structural functioning of monuments and therefore to have a deeper insight on their conditions, allowing to intervene with more confidence with a strengthening intervention, if needed, but also to prevent the execution of unjustified intrusive repair works, Directive (2007), ISCARSAH recommendations (2005). The concurrent use of a behavioral model (e.g. FE method, or analytical) may bring a substantial contribution to the quantitative evaluation of the experimentally obtained information.

The relevance of monitoring as an appropriate tool for a correct conservationist strategy for CH buildings is now clearly specified in the "Guidelines for the evaluation and mitigation of the seismic risk for Cultural Heritage buildings – in line with the new Technical Standards for Constructions", Directive (2007), (Italian technical recommendations fitted for the assessment and repair/strengthening of CH buildings), which contain a specific paragraph on the topic [§4.1.9 Monitoring], saying: "the assessment of the building carried out on a periodic basis is a strongly advisable practice since it represents the main tool for a correct conservation strategy, allowing to program maintenance activities and to carry out on time – if quantitatively demonstrated their real necessity – repair interventions, in case of structural damage, or strengthening, aimed to prevention. To define a monitoring protocol it is necessary to preventively execute a detailed structural analysis of the structural functioning, and then to obtain an interpretation of the ongoing deterioration processes, in a way to define the most relevant parameters which, continuously acquired or with adequate time steps, allow to define their satisfactory functioning or – on the contrary – to point out possible dangerous damage processes for the stability of the whole structure or part of it.

Visual inspections, intended as a periodic check of the onset of visible crack patterns, deterioration phenomena, transformations in the structure or surrounding environment can be considered the starting point of such activities. More specific information may be collected through instrumental monitoring of some parameters which can be considered meaningful from a structural point of view (cracks movements, absolute or relative displacements of specific points of the building, rotations of walls or other elements). […] Sometimes, when the deterioration process is properly identified, and safety thresholds can be defined, SHM may represent an alternative to the structural intervention, to the benefit of conservation. […] If seismic safety is in particular addressed, being the earthquake a rare and unforeseeable event, it is clear that SHM (as intended here) does not represent an early warning procedure or a method for assess the seismic behavior of the monitored structures. The use of SHM systems may be profitably used in the post-earthquake emergency, on heavily damaged structures whose behavior has to be assessed to check the possible evolution of the identified ongoing damage processes or mechanisms, as well as to appraise the structural response of the monitored buildings to aftershocks."

2 UNIVERSITY OF PADUA & NAGOYA APPLICATIONS

Since several years the Department of Structural and Transportation Engineering of the University of Padua, Italy, in line with the enunciated needs for CH building conservation, is employing SHM systems and procedures for the assessment of the

structural functioning of building and monuments, together with reference behavioral models, to have a more sound understanding of their structural functioning and capacities, especially with reference to their seismic performance. Several systems applied on CH buildings are currently managed by the Department in different parts of Italy and abroad, both in "regular" conditions (i) and after the occurrence of a major earthquake (ii), striking the central part of Italy on April 2009. Systems belonging to the first group are: 1) St. Sophia church in Padua (inst. 1999), 2) Cansignorio della Scala stone tomb in Verona (inst. 2006), Qutb Minar tower in New Delhi, India (inst. 2006), 3) Bertoliana Public Library in Vicenza (inst. 2010), 4) Scrovegni Chapel in Padova (inst. 2011), 5) Arena of Verona (inst. 2010-11), 6) Conegliano Cathedral (to be inst. 2011), 7) David Tower, old city of Jerusalem (to be inst. 2011). Systems belonging to the second group after L'Aquila Abruzzi 6th of April 2009 earthquake are: 1) St. Mark church (inst. 2009), 2) Spanish fortress (inst. 2009), 3) St. Biagio and St. Giuseppe churches (inst. 2011) 4) St. Agostino church (inst. 2010), 5) St. Silvestro church (inst. 2010), 6) Civic Tower (inst. 2010), these last three being provided by the Nagoya City University of Japan and installed in cooperation with the University of Padua, Italy.

2.1 Monitoring strategy

The installed SHM systems are aimed at the control of static and dynamic parameters related to the structural functioning of the selected buildings and monuments. The monitoring strategy is conceived both to collect data at predetermined time-intervals (periodic monitoring, i.e. cracks opening, changes in the dynamic response) and to automatically start to save data in case of significant external events (such as seismic events). Such controls will permit to appreciate possible variations in the assessed structural functioning with the passing of time and to have a record of the dynamic behavior during severe events.

The acceleration transducers are placed in suitable positions in relation to the mode shapes of the structures, with reference to the numerical modeling / dynamic identification previously implemented, with reference sensors fixed at the base for the record of the ground acceleration both in operational conditions (i.e. evaluation of the traffic induced vibrations) and during seismic events. Static sensors are located in areas of interest with reference to the structural aspects to be considered (e.g. displacement transducers are positioned across significant cracks, tiltmeters on out-of-plumb walls, and so on).

3 SHM OF CH BUILDINGS IN "REGULAR" CONDITIONS

3.1 The stone tomb of Cansignorio della Scala, Verona, Italy

The monitoring systems installed in the stone tomb of Cansignorio della Scala, in Verona (Fig. 1), Gaudini et al., (2008), is composed by a central unit (National Instruments PXI) provided with controller and 16/24 bit data acquisition cards, connected to accelerometers, displacement transducers, temperature and relative humidity sensors. The installation of the SHM system was provided in parallel with studies and repair interventions carried out in the years 2006-2009, and the aim of the monitoring system was to propose experimental feedback for the structural assessment and the light strengthening interventions carried out.

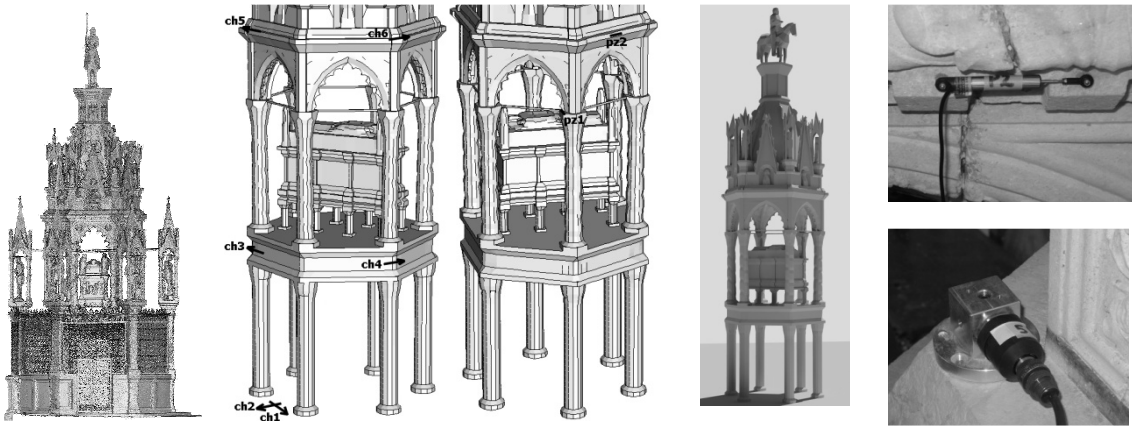
A couple of reference acceleration transducers is fixed at the base for the record of the ground acceleration both in operational conditions (i.e. evaluation of the traffic induced vibrations) and during seismic events. The remaining 4 dynamic sensors are placed on two levels for the evaluation of the vibration in the NS and EW direction (bending modes) and in the horizontal planes (torsion modes). A temperature/relative humidity sensor is fixed at the intrados of the marble slab (first level). The displacement transducers are positioned across significant cracks (Fig. 2). The central unit is provided with a Wi-Fi router for remote data transmission.

The investigation activities carried out (dynamic identification) proposed experimental evidences for the calibration of behavioral models of the monument, implemented on the basis of the laser scanner survey. FE linear and non linear models were used to predict the static and dynamic behavior of the building, and were successively tuned on the basis of the experimental activities. The Structural Health Monitoring System gave the possibility to continuously evaluate the conditions of the monument by recording significant indicators (environmental parameters, dynamic response, cracks opening) for 5 years now. The systems also allowed to check the dynamic response of the structure to traffic or seismic events, recording some real however moderate earthquake during its functioning.

Outcomes of the static and dynamic monitoring indicate a certain stability for the observed or calculated parameters, since dynamic data (Fig. 2a) denotes a reversible (cyclic) frequencies tendency – in line with the temperature change – as well as the crack mouth opening, shown in Fig. 2b. Displacement transducer PZ1 seems to indicate a tendency to open – for the observed crack – but in the last year such trend seemed to significantly reduce.

3.2 The Scrovegni Chapel, Padova, Italy

The Scrovegni Chapel, dedicated to St. Mary of the Charity, frescoed between 1303 and 1305 by Giotto, is one of the most important masterpieces of Italy (Fig. 3). The frescoes, which narrate events on the lives of the Virgin Mary and Christ, cover the entire walls. In may 2011 the Municipality of Padua gave the task to the Dept. of Structural and Transportation Engineering to install a static SHM system in order to keep controlled the visible crack pattern in the vault in occurrence of initial dewatering operations in close by areas, for the construction of the new auditorium of the city of Padua.



a) b) c) d)

Figure 1. The stone tomb of Cansignorio della Scala: a) laser scanner survey; b) sensors positioning layout; c) linear FE model rendered view; d) displacement (PZ2) acceleration (CH6) transducers.

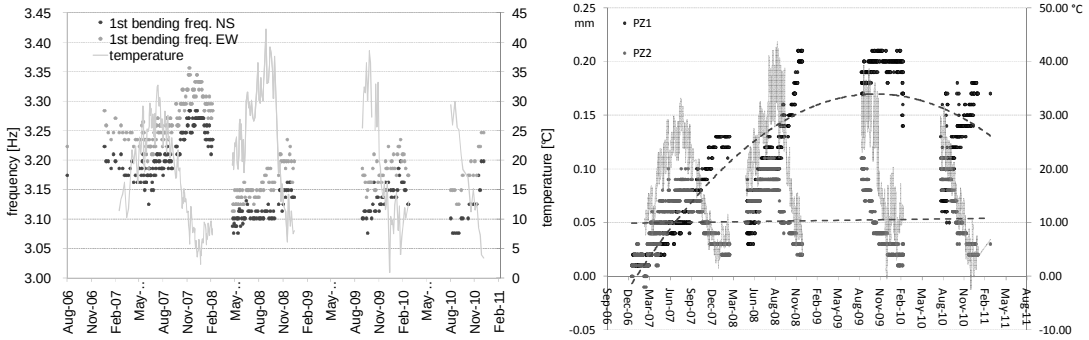


Figure 2. The stone tomb of Cansignorio della Scala: left – dynamic monitoring, 1st and 2nd frequencies vs. time; right – static monitoring, crack mouth opening vs. time.

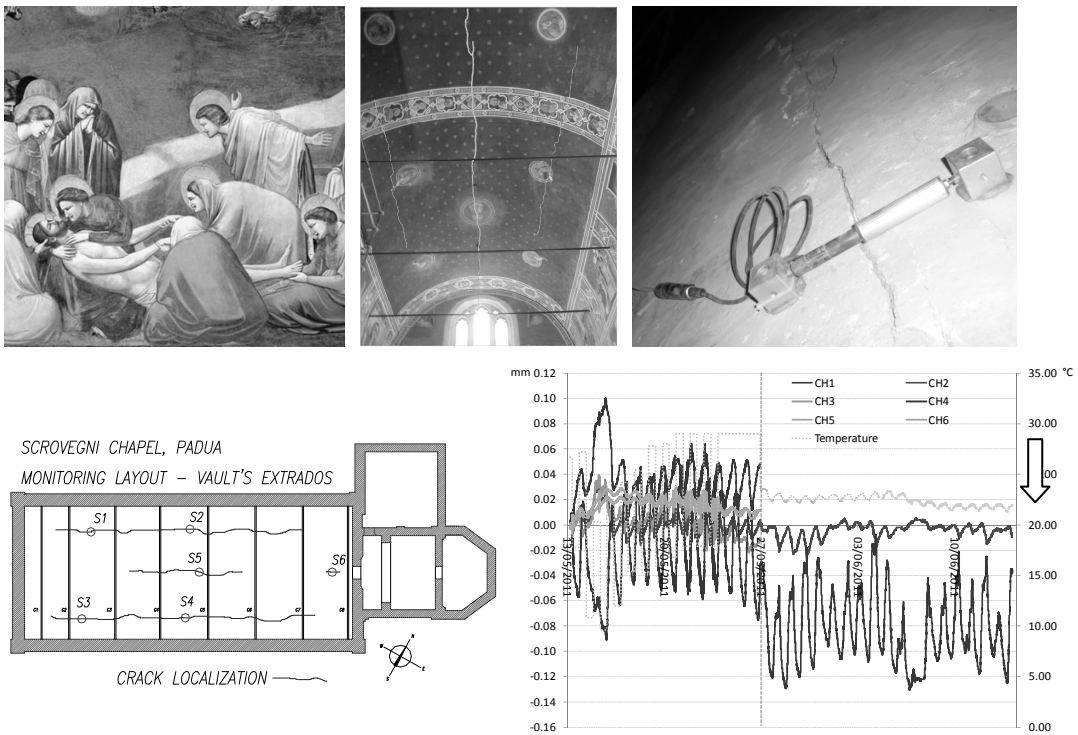


Figure 3. The Scrovegni Chapel in Padua, adorned with masterpieces frescoes of Giotto: cracks at the extrados of the vault, displacement transducer, sensors' layout and monitoring results (May-June 2011).

The SHM system is composed by a low cost central acquisition unit provided with six displacement transducers (0-25 mm, precision 0,01 mm) and a temperature and relative humidity sensor, connected via USB to a laptop. Fig. 3 shows the magnified crack pattern, the displacement transducers, the SHM layout and the outcomes of the first weeks of monitoring, in correspondence of the dewatering operations (white arrow): no significant variations were found (the daily deformation is in fact the only visible data variation), and thus the construction works may continue, always keeping an eye on the Chapel's crack pattern.

4 SHM SYSTEMS ON CH BUILDINGS AFTER THE EARTHQUAKE

4.1 The 6th of April 2009 L'Aquila earthquake

The earthquake that struck the Abruzzi region of Italy the 6th of April 2009 (MI 5.8 on the Richter scale), affected a wide area between the provinces of L'Aquila, Avezzano, Sulmona and Teramo. The earthquake was felt throughout Abruzzi; as far away as Rome, other parts of Lazio, Marche, Molise, Umbria, and Campania. The landscape morphology played a very important role in the damage distribution – by amplifying or decreasing the seismic motion effects – with the most severe damages recorded in the Aterno river valley, in small towns like Onna, Fossa, Sant'Eusanio Forconese, Villa Sant'Angelo and others, besides severely striking the city of L'Aquila.

The severity and the extent of damages caused by the earthquake to the cultural heritage was never reached before in the recent Italian earthquakes history. The measures undertaken in order to protect the architectural heritage in post-seismic emergency conditions, also taking advantage of the previous recent earthquakes management (especially in the 1997 Umbria-Marche scenario), requested a remarkable effort in terms of defining the right procedures and framework in order to maximize the effectiveness of the provisional strengthening interventions.

4.2 The SHM network in the city center of L'Aquila

In the emergency period after the seismic event, the Local Office of the Ministry of Culture entrusted by the Italian prime minister with the task of the initial stabilization activities for CH buildings, collaborated with the Civil Protection Agency, the special squads of the Italian Fire Brigades and the Universities specialized in seismic engineering for the first safeguard activities on CH buildings. Such activities consisted – after the damage survey and cataloguing – in carrying out the first provisional stabilization interventions (especially with the aid of specialists from the Firemen and the Universities), to avoid the worsening of the structural conditions of buildings and monuments already severely damaged by the main shock of the 6th of April 2009.

In some significant monuments (e.g. the Spanish fortress, seat of the museum of the Abruzzi region) , SHM systems were soon provided in order to control the progression or stationariness of the damage pattern already assessed. In a second step, further systems were applied on CH buildings, also during the stabilization works execution, in order to appraise the effectiveness of the interventions carried out, or to denounce their inadequacy. After more than two years, with the "heavy" reconstruction process at its beginning, a small network of SHM systems was set up by the Dept. of Structural and Transportation Engineering and the Nagoya City University (Fig. 4), whose data – also containing several aftershocks records – will constitute a sound database for investigation in the field of CH structures response and strengthening procedures. In the following paragraph, a SHM system installed in an emblematic structures is briefly discussed.

4.3 The St. Marco church

The St. Marco church, located in the L'Aquila city centre, was severely damaged by the 6th of April 2009 earthquake. The first construction of the church dates back to the end of the 13th century - beginning of the 14th century. The main façade was likely built at

the beginning of the XV century. The building was completely restructured around 1750, after the 1703 devastating earthquake. The two bell towers belong to that period.

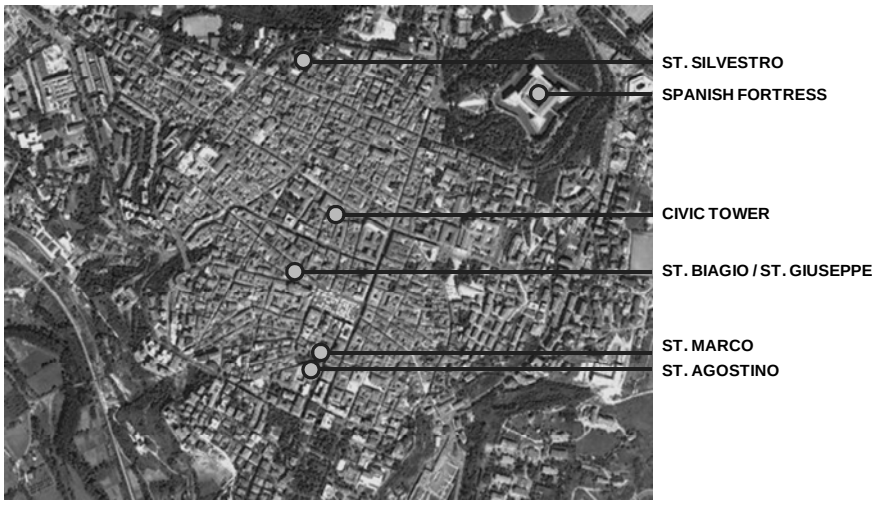


Figure 4. Network of SHM systems in the city center of L'Aquila managed by the University of Padua / Nagoya City University.

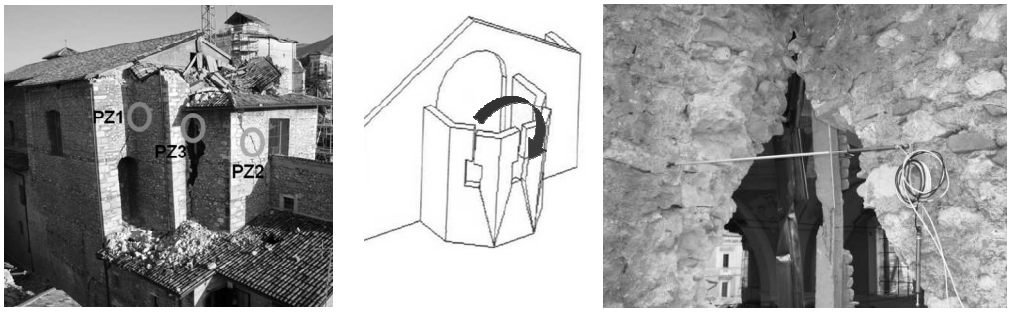


Figure 5. St. Marco church in L'Aquila: observed damage and displacement transducers localization

After the earthquake the church reported severe damage in the apsidal and transept area, where a critical crack pattern was noticed in the external walls, which manifested a visible outward overturning, involving the four pillars sustaining the dome. Also the transversal response of the church proved to be inadequate, since the most part of the vaults collapsed, such as a big portion of the external wall, at the clerestory level. Severe damage was finally reported in the vaults of the apse, of the presbytery, in the triumphal arch (Figure 5). The initial provisional strengthening intervention started the 4th of July and were completed in November 2009. This first intervention aimed at counteracting the most critical collapse mechanisms, such as the apsidal and transept walls overturning.

In parallel to the execution of the interventions, the opening of the main cracks was controlled by means of an automated low-cost SHM system which is continuously acquiring data, storing hourly the readouts coming from 5 linear displacement transducers positioned in the external area of both apse and transept, where the worst damage scenario is observed (Figure 5). Data are correlated to the environmental parameters recorded by a temperature – relative humidity sensor positioned at the base of the scaffolding.

A couple of acceleration sensors is located at the base of the structure, in order to record any relevant data in terms of seismic events – also of low-moderate energy - and other two sensors are positioned at the top of the North wing of the transept, to store the structural response (amplification) of the church. The monitoring system was installed the 10th of August 2009. Displacement transducers data – up to April 2011 - are plotted in the graph of Fig. 6.

In almost 2 yrs. of observation no worrying displacement-trends were noticed, thus excluding the worsening of the crack pattern, and confirming the effectiveness of the adopted provisional interventions. Sensors 1 and 3 denote non negligible displacements (up to 0,5 mm) from the first readouts, being however strictly connected to the temperature variations.

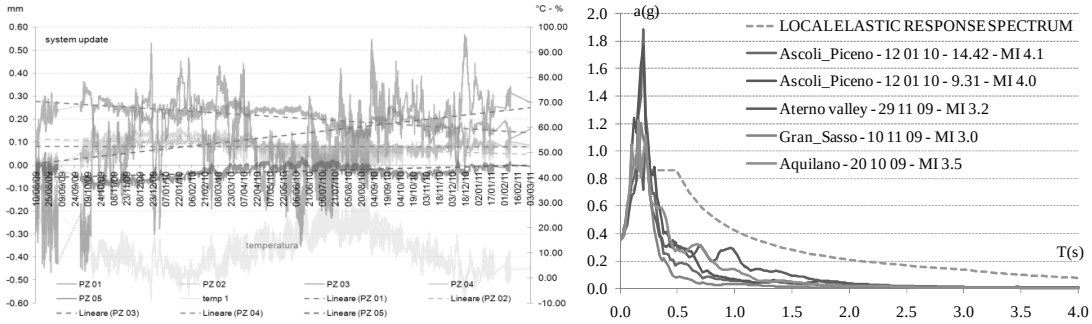


Figure 6. St. Marco monitoring system: plots of the displacement sensors data vs. time; Scaled to the local PGA value horizontal elastic response spectra calculated from the low magnitude recorded accelerograms

The response spectra scaled to the local peak ground acceleration elaborated from recorded minor seismic events in the L'Aquila area and some higher however moderate magnitude in different seismic districts (Ascoli Piceno, at a distance of 100 km from L'Aquila), are represented in Fig. 6. Such plots indicate a local resonance with very high peaks around the frequency of 5 Hz, in a frequency band where several structural eigenvalues are noted.

5 CONCLUSIONS

Monitoring is being more and more considered, in the field of cultural heritage buildings, as a key activity in order to increase the knowledge on the structural functioning of monuments and therefore to have a deeper insight on their conditions. In case of a seismic event, monitoring can furthermore prove its usefulness in quantitatively evaluating the progression or stationariness of the damage pattern of selected buildings, in order to keep controlled their structural behavior and to allow to intervene in an effective way and more urgently if an unsafe displacement patterns is noticed, also as an early warning procedure for the safety of the workers employed in the strengthening interventions.

If a vast amount of buildings is seriously damaged and the time schedule for the interventions is difficult to be a priori planned, a low cost distributed monitoring can provide evidence of needs to proceed more urgently on selected monuments – if necessary because of the worsening of their structural conditions – or to postpone the interventions in a successive step, if the assessed damage pattern maintains an acceptable stability.

Between the available techniques that may be profitably used to control the response of a historic masonry building, dynamic identification proves to be a very effective tool, since it allows to experimentally measure parameters related to the global structural behavior. The combined use of dynamic identification procedures and "local" controls (besides the monitoring of the environmental parameters), providing quantitative information on local conditions of structural elements (e.g. cracks opening), can be an important asset in the effort of attaining a deeper degree of awareness on the "real" structural functioning of the monuments.

6 REFERENCES

Directive of the Prime Minister oct-12-2007 "Guidelines for the evaluation and mitigation of the seismic risk for Cultural Heritage buildings – in line with the new Technical Standards for Constructions" (Italy)

ICOMOS - International scientific committee for analysis and restoration of structures of architectural heritage – (2005) *recommendations for the analysis, conservation and structural restoration of architectural heritage*

F. Casarin, M.R. Valluzzi, F. da Porto, C. Modena (2008), *Structural monitoring for the evaluation of the dynamic response of historical monuments*, RILEM Symposium on On Site Assessment of Concrete, Masonry and Timber Structures - SACoMaTiS 2008, eds. L. Binda, M. di Prisco, R. Felicetti, ISBN 978-2-35158-061-5, pages 787 – 796, Publisher RILEM Publications SARL

G. Gaudini, C. Modena, F. Casarin, C. Bettio, F. Lucchin (2008), *Monitoring and strengthening interventions on the stone tomb of Cansignorio della Scala, Verona, Italy*, 6th Int. Seminar on Structural Analysis of Historical Constructions, 2-4 July 2008, Bath, UK

F. Casarin, C. Modena, M. R. Valluzzi, F. da Porto (2010a), *Structural monitoring of damaged cultural heritage buildings after the April 2009 Abruzzi earthquake*. Proc. 3rd Euro Mediterranean Symposium On Advances in Geomaterial and Structures, AGS'10 - Djerba, Tunisia, 10-12 May 2010

F. Casarin, C. Modena, F. da Porto (2010b), *Structural monitoring of damaged cultural heritage buildings after the april 2009 abruzzo earthquake*, proc. 3rd International Workshop on Conservation of Heritage Structures Using FRM and SHM (CSHM-3 2010), Ottawa Canada, 11-13 Aug 2010