Advanced Materials Research Vols. 133-134 (2010) pp 3-17

doi:10.4028/www.scientific.net/AMR.133-134.3

Cultural Heritage Buildings and the Abruzzo Earthquake: Performance and Post-Earthquake Actions

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Abstract The architectural heritage was seriously hit by the earthquake that occurred on April 6th 2009 in the Abruzzo region, especially considering the effects on a city with the size and with historical and strategic importance as a capital of a region, L'Aquila. The activities to protect that heritage have been centralized in the structure "Protection of Cultural Heritage" at Di.Coma.C. (Command and Control Quarter), managed by the Civil Protection Department. This allowed the cooperation among different involved subjects (Ministry of Cultural Heritage officers, experts on structural engineering from Universities and Fire Brigade teams), with their own specific knowledge. Keystone of the operating process was the standardization of the damage survey and of its immediate and correct interpretation, through dedicated survey forms for churches and palaces. The experience in the field of temporary safety measures was extremely interesting: ideas for engineering the process were developed, in cooperation with the work of the fire brigade men, that are highly experienced technicians in the "emergency" field. Finally, monitoring plans for some important monuments have been set up for the control of the damage progression and the analysis of the structural behavior of buildings after the earthquake and the execution of temporary interventions: two cases (St. Mark Church and the Spanish Fortress) are discussed.

Keywords: emergency management, damage survey, safety measure, Abruzzo earthquake.

Introduction

The earthquake that struck the Abruzzo region of Italy the 6th of April 2009 at 3:32 a.m., affected a wide area among the cities of L'Aquila, Avezzano, Sulmona and Teramo. The ground morphology had an important role in the structural damage distribution and the most catastrophic effects were observed along the Aterno river valley, involving, besides L'Aquila, many historical centres like Paganica, Onna, Fossa, Sant'Eusanio Forconese, Villa Sant'Angelo and others.

The seriousness and the extension (Fig. 1) of damage on cultural heritage buildings were without precedent in the recent Italian seismic history, since an organized civil protection action had been developed. This was mainly due to the dimension and the strategic importance of L'Aquila, as capital of Abruzzo region.

Indeed, the safeguards activities for the historical and architectural heritage in emergency conditions after the seismic event requested an exceptional effort. The aim was to reduce at minimum, but efficiently, the decisional "chain" that brings from damage surveys to execution of provisional safety measures, carried out on a series of different heritage structures, that goes from ruins, nowadays only historic testimonies, to survived parts of heavily damaged constructions, where testimonies of great artistic value are still present.

With reference to the organizational aspects, the choice to centralize those activities to one figure, the deputy Commissioner with delegation for the safeguards of cultural heritage, was crucial. This choice guaranteed homogeneity in the decisional response and allowed to concentrate the work in one working group, operating on a unique objective, relieving of it the other operational working teams (C.O.M.), which were already charged with all the other emergency problems.

Figure 1: Santa Maria di Collemaggio's Basilica in the historical centre of L'Aquila (left) and view of the destroyed village of San Gregorio (in L'Aquila province - right)

The activities of Function 15 "Protection of Cultural Heritage" of the Civil Protection Department (DPC), under the direction of the delegate Commissioner, were carried out by the employers of the Cultural Heritage Ministry (MiBAC) with the help of the research centre of L'Aquila (CNR-ITC) and of a group of researchers from the University of Genova, Padova and Milano. The first objective of Function 15 was to elaborate a list, although provisory, of the protected architectural heritage to be urgently surveyed in the damaged area and to start the operation of filing the damage survey forms. This objective was crucial, as the Authority archives of L'Aquila were inside the damaged Spanish Fortress.

The survey task teams were constituted by one or two representatives of the Cultural Heritage Authority (an architect and an historian or an art expert), a structural expert from the University, an officer from the Fire Brigade. One week after the earthquake, on 14th April 09, the on-site inspections started from churches located in the historic centre of L'Aquila and the surrounding areas, with the collaboration of the structural engineers from Universities participating in the ReLUIS network (Italian Laboratories University Network of Seismic Engineering).

During the filing works, the list of cultural heritage was constantly updated thanks to the notifications by municipalities, parishes and private landlords of protected constructions. The collected data were gradually recorded in a database implemented by the Ministry (MiBAC) with the support of the research centre of L'Aquila (CNR-ITC), who allowed fast access to the survey results, systematic organization of the subsequent on site inspections and the elaboration of some preliminary overall reflections on the activity progress and on the state of damage affecting the entire monumental heritage.

Figure 2: Special National Fire Brigade Groups at work on the façade of Santa Maria degli Angeli's church in Bagno (in L'Aquila municipality)

The creation of teams, made of people with different skills, allowed to fill a comprehensive survey form while giving first indications of the "emergency interventions" for the safety measures that were as much as possible respectful of the conservation principles, efficient from the structural point of view and feasible by operators, who initially were exclusively technicians of the Fire Brigade.

The Fire Brigade men had a decisive and irreplaceable role for their professional expertise, operational effectiveness and availability in the temporary safety measures. They were the only that could face extreme conditions (Fig. 2), which cannot be classified into standard and repeatable procedures, thanks to their background and to the legal provisions, in particular the possibility of acting in dispensation of the legislation on safety at work (Legislative Decree No. 81 dated 9 April 2008, on Health and Safety at Work).

Damage surveys

For the damage survey of cultural heritage, dedicated survey forms were used, prepared by the Civil Protection (G.La.Be.C. - Working group for the protection of Cultural Heritage from natural risks) respectively for churches (A-DC model, also included in the Guidelines for the evaluation and mitigation of seismic risk of the architectural heritage) and for palaces (B-DP models), approved with decree DPCM date 23 February 2006. The templates are constituted of different sections: general information; eventual presence of artworks, main dimensions, evaluation and economic quantification of structural and artistic damage; certification of fit for habitation; suggestions for temporary safety measures.

The structural damage survey is based on the identification of macro-elements that constitute a masonry building and on the evaluation of the level of activation of the kinematic mechanisms associated to the macro-element itself (Giuffré 1991). In detail, the survey form for churches identifies 28 possible kinematic mechanisms, typically detectable in this building typology; the survey form for palaces identifies 22 possible kinematic mechanisms. These are subdivided into first-way mechanisms (out-of-plane) and second-way mechanisms (in-plane) (Giuffré and Carocci 1999). In the case of churches, the mechanisms reported in the survey form were in good agreement with what was actually observed; this is due to the presence of typical elements such as façade, nave, transept, apse, vaults, etc.

The result was a form easy and quick to be filled on site, which provides a standardized evaluation on the level of building damage, substantially free of subjective evaluations by the compiler (Lagomarsino et al. 2001). The survey form used for the evaluation of the "palaces" has been used for the first time in Abruzzo region, unlike that of churches, which was already tested in previous earthquakes. The increased complexity of filling in this form for palaces is connected to the difficulty of bringing together all the non religious historic buildings into the same typology defined as "palaces". Indeed, in the case of complex structures, with different structural and geometric configuration and made of many additions, the identification of specific macro-elements is not unique for all cases.

Observed damage Almost 1677 historical buildings were surveyed, from which 973 were churches, 649 were palaces and the remaining 55 correspond to other typologies of historical buildings, such as towers, fountains, etc. The survey of the damaged churches was finished about six months after the earthquake: 240 churches were certified fit for habitation and the most urgent and serious remaining cases were selected for the first safety measures performed by the Fire Brigade.

The systematic collection and data-processing of the damage survey forms will be followed by general considerations on the behaviour and specific vulnerabilities of the different building typologies. An initial analysis, carried out on a series of churches surveyed by the University of Padova during the first three months of activity, is given by (Costa 2009) and (Modena and Binda 2009). This analysis showed how the façade (Fig. 3 left) and the overhanging elements represented the main vulnerabilities of this building typology, according also to (Doglioni 1994). A high level of damage associated with high levels of activation (greater than or equal to 3 on a scale from 1 to 5) was also obtained for mechanisms related to vaulted elements (Fig. 3 right), which typically have high intrinsic vulnerability, often worsened by the constructive technique, resorting on the use of sailor brick masonry.


Figure 3: Out-of-plane overturning of the façade, church of San Giuseppe dei Minimi in the historical centre of L'Aquila (left), and collapsed vault, church of Santa Maria del Soccorso in L'Aquila (right)

The kinematic mechanisms approach adopted by the damage survey forms and also used in national codes for the seismic evaluation of existing historic buildings, is based on the monolithic behaviour of masonry structural elements. The damage survey in Abruzzo region showed that the monolithic behaviour did not develop in many cases because of the composition and the intrinsic conformation of the masonry, which has often presented poor quality, causing the collapse of entire masonry walls. This is related to the construction typology of masonry: the walls are often of considerable thickness but made with irregular stones of various sizes, irregularly arranged and jointed with a mortar of poor quality, which does not ensure effective cohesion of the units, even in the case of monumental buildings (Fig. 4). Another vulnerability element is represented by the building constructive evolution which shows an articulated construction, as often happens in the historical buildings.


Figure 4: Outside view of Sant'Eusanio church in Sant'Eusanio Forconese (left) and inside view of San Michele Arcangelo in Celano (right)

A further observation and suggestion for investigations (Binda et al. 1999), to some extent already begun (Casarin et al. 2010a, Artioli et al. 2010), comes out from the visible and sometimes very serious effects of past structural interventions. The few cases listed below represent a non exhaustive list.

The effects of the wrong use of reinforced concrete are clearly evident (Fig. 5 left; Figure 17 above), in particular the replacement of wooden trusses in the roofs, and the substitution of timber floors, with reinforced concrete trusses and gables or reinforced concrete slabs and hollow tiles.

Another intervention very often observed is the removal of the tie rods connecting orthogonal walls: emblematic examples are the Spanish Fortress and the Church of Beata Antonia (Fig. 5 right), both of great historical and artistic importance.

Figure 5: Inside view of San Marco's church (left) and of Beata Antonia's church (right) in the historical centre of L'Aquila: in the Beata Antonia's church the Fire Brigade provisional interventions repositioned the removed tie rods

Emergency interventions for safety measures

The design of temporary interventions for the safety of an historical building starts from the damage survey and from the identification of the activated collapse mechanisms. The filing in of the damage survey form is therefore the first tool to formulate an hypothesis of project for an intervention aimed to act against the specific mechanism occurring. The earthquake in the Abruzzo region was an opportunity to test on a large-scale the process of design and realization of interventions already drafted after the Umbria-Marche earthquake. This process involves three principal figures: an officer from the Cultural Heritage Authority, a structural engineer, and a team of operating Fire Brigade men. In few highly symbolic buildings, such as the Dome of the Anime Sante church (Fig. 6) and the roof of the Basilica of Collemaggio, particularly demanding works in terms of structural engineering and working conditions were carried out. Conversely, in the majority (hundreds) of badly damaged historic buildings, there was the need to quickly and effectively provide (in relation to structural safety, but also to the aftershocks occurring after the main shock), the "minimum survival conditions" of what was left after the mainshock.

Figure 6: Drum of the Anime Sante's church in the historical centre of L'Aquila (left) and special groups of National Fire Brigade Men at work on the Anime Sante's dome (right)

In particular, on about 1000 churches included in the MiBAC database, the churches certified fit to use after survey were approximately 25%, another 10% fell on other classes of use, which do not require provisional works, and about 65% needed an evaluation for safety measures. The standard procedure for their design and realization used to start by filling the damage survey form. Thereafter, the structural engineers could elaborate first project drafts, to be discussed in daily meetings at the operational core of the Fire Brigade (N.C.P., nucleus for the coordination of provisional interventions), with the engineers of the Corp and an officer of the Cultural Heritage Authority. In particular cases, the discussion might be followed by other on-site inspections. Following approval of

the final project and opening of the site, subsequent inspections, aimed to determine the best solutions accounting for historical value and cost minimization, could also take place.

Types of interventions During the phase immediately following the 1997 Umbria-Marche earthquake, some types of provisional interventions and their design principles had been agreed. The main criteria were: avoiding the involvement of structures close to the building undergoing the interventions (e.g., propping of building façades made with elements acting on facing buildings); avoiding to occupy the roadways in order to allow accessibility after the earthquake; avoiding the use of interventions that could hinder the execution of subsequent works for the restoration of the structure. Other logistical considerations and operational criteria for selecting the provisional measures, already identified during the previous earthquake, focused on the choice of materials which are easy to be found and to be applied, in relation to the skills of the people involved in the interventions (VV.AA. 2007).

In designing the safety measures, besides the above mentioned logistical considerations, others of purely structural character were added concerning the static and dynamic behaviour of a building damaged by the action of the earthquake. These hints were the result of both experience gained in previous earthquakes and knowledge developed in university, through the research on earthquake engineering and specifically the behaviour of the historic buildings subjected to seismic action (Modena et al. 2008).

The most widespread provisional interventions are those referring to the so-called first-way mechanisms, i.e. out-of-plane overturning of walls. These mechanisms are characterized by a load multiplier value which activates the mechanism, and then determines the collapse of the element, which is smaller than that of second-way (in-plane) mechanisms. These latter rarely evolve until the total collapse of the element. The provisional interventions to hinder overturning mechanisms of façades and perimeter walls can be performed in two ways: through traditional propping systems using wooden poles (Fig. 7 left) or by tying with steel cables or polyester bands (Fig. 7 right). These two interventions correspond to different structural approaches: the first is intended to partially restore the stiffness of the structure; whereas in the second approach, bands (or ties) elastically connect the various stiff masonry blocks, defined by the activation of seismic damage, which form the kinematic chain (Bellizzi 2000, Bellizzi et al. 2001, Dolce et al. 2002).

Figure 7: Propping of the façade of Santa Giusta church in Bazzano (left) and polyester bands on the façade of San Giuseppe dei Minimi's church in the historical centre of L'Aquila (right)

The preference given to the second method is determined by the considerations set out above. First, road practicability: interventions performed with traditional props imply that a large portion of ground surrounding the building is to be occupied, thus preventing the passage. In addition, the dense series of props need to be removed to carry out the final repair works. Interventions performed with bands or ties do not occupy the ground space and are minimal for the structures. In addition, their application and subsequent removal is faster. However, the use of polyester bands is based on the assumption that the façade is not disassembled, and forms a clearly defined rigid rotation mechanism. From a structural point of view, an intervention with bands or ties connects rigid blocks identified by cracks due to earthquake. The damaged structure has a lower overall stiffness than before the earthquake, and

the exact positioning of the bands provides a great displacement capacity preventing collapses due to overturning.

The use of bands allows connecting perpendicular walls and thus the transfer of action from the out-of-plane loaded walls to the perpendicular walls, which act in their plan of higher stiffness. In case of high intensity aftershocks, the use of traditional props may cause pounding of the façade by the poles and thus local increase of structural damage (Calderini et al. 2004).

In most cases, the structures developed more than one collapse mechanism. The adopted design principles aimed at acting on a single mechanism, making different interventions, as much disconnected one from the other as possible, for each mechanism. This is due to the fact that "global" interventions can change the structural scheme in a non-predictable way, hence triggering different and unforeseen collapse mechanisms (Modena et al. 2000).

Figure 8: Intervention on Santa Margherita's church in the historical centre of L'Aquila

Figure 9: Intervention during works at S. Domenico's church and concluded intervention at Evangelica's church in the historical centre of L'Aquila

As an example, two main mechanisms were identified in the church of Santa Margherita: transversal response of the nave and overturning of the apse. Two separate interventions were thus carried out. The side walls were connected by metallic wire ropes anchored to a steel counter beam placed in the upper part of the walls, in correspondence of the vault (Fig. 8), the apse was connected by metallic wire ropes to the walls which separate the nave from the lateral chapels.

When structural elements develop both in-plane shear mechanisms and out-of-plane overturning mechanisms, the monolithic nature of the overturning element is damaged and must be secured with an intervention, which is preliminary to tying for hindering the out-of-plane mechanism. This intervention can be made by wooden grids and bands (Fig. 9), which first are used to strengthen the wall in its plane, and then are connected to the orthogonal walls by tying, thus preventing the overturning.

The local collapses due to poor quality and irregularity of masonry suggested to intervene extensively by consolidating the non-collapsed portions of masonry with a surface rendering, based on natural hydraulic lime mortars with fast hardening and reduced shrinkage, which can be subsequently integrated into the restoration interventions (Fig. 10).

Figure 10: Surface rendering on the apse wall of the Madonna della Prata church in Tussillo village: realization of the intervention (left) and concluded intervention (right)

The methodological approach used for the temporary safety measures adopted on churches could be then used on a larger scale for intervening on historic buildings and palaces. The greater number of the latter, compared to churches, suggested to operate with the more rapid and less invasive methods. Interventions tested on churches, with bands or tie rods associated with wooden grids, appeared to be the best suited because they do not occupy the building entrances and the roadways, but they also achieve a better response to additional seismic actions. In historic centres, where streets are usually narrow, shoring systems acting on facing buildings (Fig. 11), which cause interactions and pounding between different structures, were as much as possible avoided.

Figure 11: Three types of safety measures on façades in the historic centre of L'Aquila: wooden grids and ties, traditional props, shoring systems acting on facing buildings

Structural monitoring of damaged heritage buildings

The enormous structural damage on heritage buildings caused by the earthquake posed not only the problem of providing the minimum safety conditions by means of temporary interventions, but also the problem of future strengthening and retrofitting interventions, to be carried out on the buildings. This problem is dual: on one hand, there is the need to define adequate materials and techniques to intervene on these buildings, and to define proper strategies when it has to be dealt with buildings of high historic and artistic values, but with extensive portions of collapsed vertical and horizontal structures. On the other hand, it is evident that many monuments in L'Aquila and in the surrounding areas will not undergo the final works before some years from the seismic sequence of 6th April 2009.

In this context, the use of structural monitoring has been proposed and agreed, with the various involved authorities (MiBaC, Civil Protection, Local Authorities) to control eventual damage progression, to understand the structural behaviour of buildings after the earthquake and the execution of temporary interventions, and to evaluate the structural modifications that will occur with the final interventions. Different strategies are being employed in smaller churches and buildings on a more diffused scale, and in more emblematic buildings. In the following, two cases of the latter type (St. Mark Church and the Spanish Fortress) are discussed.

St. Mark Church The St. Mark church, located in 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 building was completely restructured around 1750, after the 1703 devastating earthquake. The two bell towers enclosed in the façade belong to that period (Casarin et al. 2010b).

Figure 12: St. Mark church in L'Aquila: external (left) and internal (right) views

The church reported severe damage in the apsidal and transept area, where the external walls manifested a visible outward overturning, involving the four pillars sustaining the dome. Also the transversal response of the church proved to be inadequate, since most of the vaults collapsed, such as a big portion of the external wall, at the clerestory level (Fig. 12 left). Severe damage was finally reported in the vaults of the apse, of the presbytery, in the triumphal arch (Fig. 12 right).

In this church, such as in many others of the area, the original roof had been replaced by a heavy and stiff roof made by precast reinforced concrete beams and hollow tiles, with an upper layer composed by a concrete slab.

The initial provisional strengthening intervention was financed by the Veneto Region: works started on 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. This intervention entailed the construction of a retaining scaffolding made of hollow pipe steel trusses, constituting a portal spanning across the church. Two lattice towers were built on the two sides of the church, subsequently connected at their top by an open web girder, in its turn connected to the masonry structures of the church.

Further interventions in the façade area were made to counteract the overturning of a significant portion of the right side wall external veneer. Wooden struts were employed to counteract this mechanism and to sustain the stone elements of the valuable church portal, disconnected by the seismic motion. The façade was hooped on two levels with steel cables, positioned to avoid the progression of shear damage. Finally, several openings were propped, and the façade bell-towers were hooped at the level of the belfry (Fig. 13).

In parallel to the execution of the interventions, the structure was controlled by means of an automated low-cost monitoring system. This system is continuously acquiring data, and stores hourly the readouts coming from 5 linear displacement transducers, positioned across the main cracks of both apse and transept, where the worst damage scenario is observed (Fig. 14).

Data are correlated to the environmental parameters recorded by a temperature – relative humidity sensor. A couple of acceleration sensors is located at the base of the structure, in order to record any seismic event, of even 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 system is able to automatically store the data when the acceleration in one of the sensors exceeds a predefined threshold, both in time and frequency domain, and to periodically record the data (e.g. at a 12-24 hrs intervals), to carry out sequential dynamic identifications and measure eventual variations in the modal parameters, with the progression of the strengthening interventions.

The monitoring system was installed the 10th of August 2009. Displacement transducers data – up to January 2010 - are plotted in the graph of Fig. 15. In these first months, any worsening of the crack pattern can be excluded, confirming the effectiveness of the adopted provisional interventions.

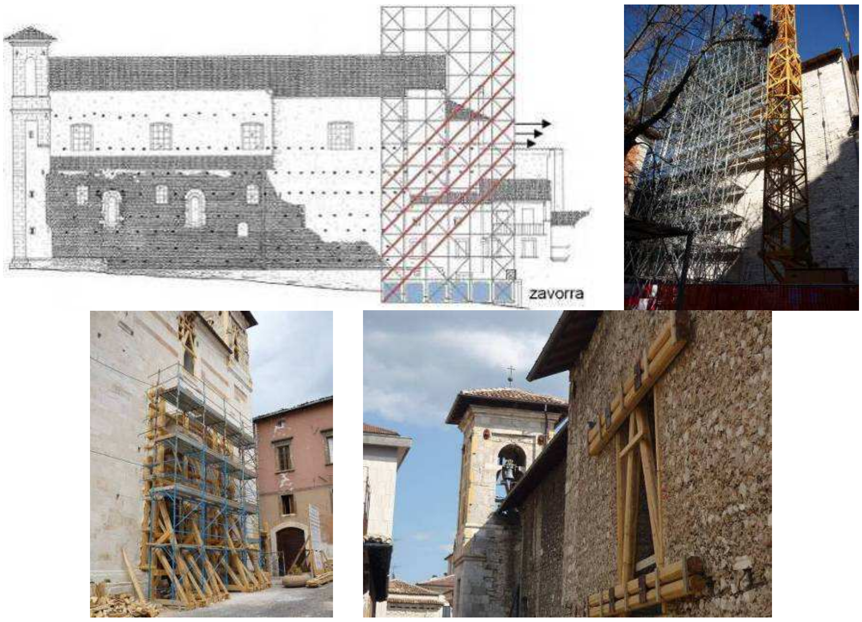

Figure 13: St. Mark Church: initial provisional strengthening interventions

Figure 14: view of the apsidal area of St. Mark church: displacement and Temperature-Relative Humidity sensors positioning

The Spanish Fortress The Spanish Fortress of L'Aquila (Fig. 16) is one of the most impressive Renaissance castle in Central and Southern Italy. It was built starting from 1534, when L'Aquila had become the second most powerful city in the Kingdom of Naples, under the Spanish domination, to punish the citizens for their rebellion. The Fortress was never used in a battle, and, between 1949 and 1951, was restored and transformed into the National Museum of Abruzzo.

The structure is made of four bastions connected through mighty walls, 60 meters long, with a thickness of 30 metres at the bottom and 5 meters at top. All around the fortress was a ditch (never filled with water), 23 meters wide and 14 meters deep, aimed at defending the foundations from the enemy's artillery (Casarin et al. 2010b).

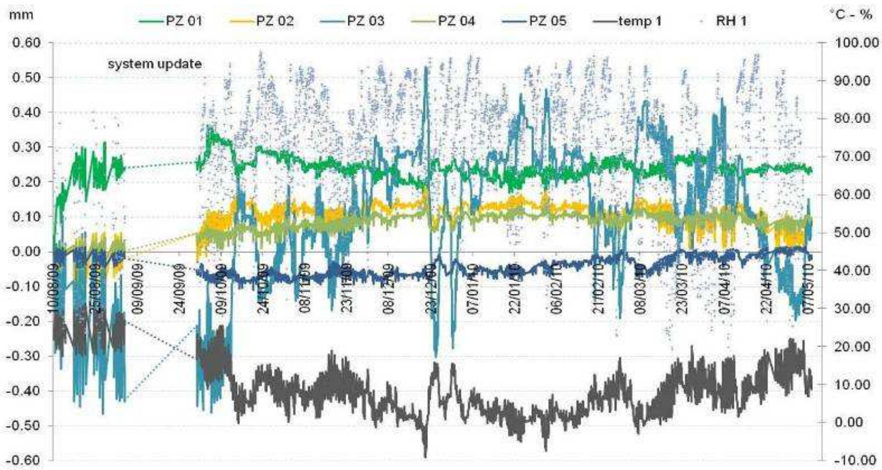

Figure 15: St. Mark monitoring system: plots of the displacement sensors data vs time

Figure 16: Aerial view of the Spanish fortress of L'Aquila before the earthquake

Following the 6th of April 2009 earthquake, the fortress was seriously damaged, especially in the upper floors. According to the damage survey form for palaces used in the inspections (Model B-DP PCM-DPC MiBAC 2006), overturning and flexural mechanisms on the external walls, shear damage in the external and internal walls, damage to vaults and arches, local collapses of floors and vaults, corresponded to the worst activated mechanisms (Fig. 17). Damage was remarkable both for intensity and distribution, and was considered so serious to likely prejudice the overall stability of the building.

Provisional interventions were carried out on the S-East and S-West wings of the fortress, by groups of specialized Fire Brigades men. The structural stability was provided by connecting the internal and external façade by means of stainless steel cables, to avoid the incipient overturning mechanisms. In the S-East wing the roof was partially rebuilt using hollow section steel trusses and light wooden covering structures. In the S-West wing, steel frames were positioned in contrast to the external and internal façades before tensioning the cables (Fig. 18).

Between 17th and 19th December 2009 a dynamic monitoring system was installed in the fortress, following a first investigation campaign carried out in September, including dynamic identification of the structure. The system complements a static monitoring system installed during the first months after the earthquake by the ISCR (National Conservation and Restoration Institute) of Rome, which controls the crack pattern and the environmental parameters. The dynamic system is composed by an acquisition unit connected to eight high sensitivity piezoelectric accelerometers. The central unit, located at the second floor of the fortress, in the S-East wing, is provided with a WiFi router for remote data transmission.

Two reference sensors are fixed at the base of the structure, in two orthogonal horizontal directions, to record the ground accelerations in both operational conditions and during seismic events. The positions of the acceleration sensors on the elevation of the S-East wing was based on the results of

the previous dynamic identification. According to the predominant motion direction, sensors were fixed orthogonally to the façade, on the internal and external façades (Fig. 19).

Figure 17: Above: view of the L'Aquila castle (Spanish fortress) before and after the earth-quake; below: severe damage recorded in the internal area of the S-East wing

Dynamic data are collected both at fixed time intervals to allow sequential dynamic identification of the structure with different environmental conditions, and on a trigger basis, when the signal, on one of the acceleration channels, gets over a predefined threshold, on the time and/or frequency domain.

Figure 18: Provisional interventions: connection of the internal and external façades

The frequencies and mode shapes emerged from the experimental investigation activities carried out before the installation of the monitoring systems (September 2009) are reported in Fig. 20. During the period of monitoring no significant seismic events were recorded (a power line suspension between 4th and 14th of January did not allow to record the 12th of January 2010 Ascoli Piceno events). Monitoring results show that the dynamic response of the monument vary with the environmental conditions. The natural frequencies tend to increase with the temperature (Casarin et al. 2010b), but fortunately a change in the structural response due to worsening of the damage state can be excluded, at present.

Figure 19: L'Aquila castle: localization of the acceleration transducers (left) and base acceleration transducers (CH1, 2) and acquisition unit (right)

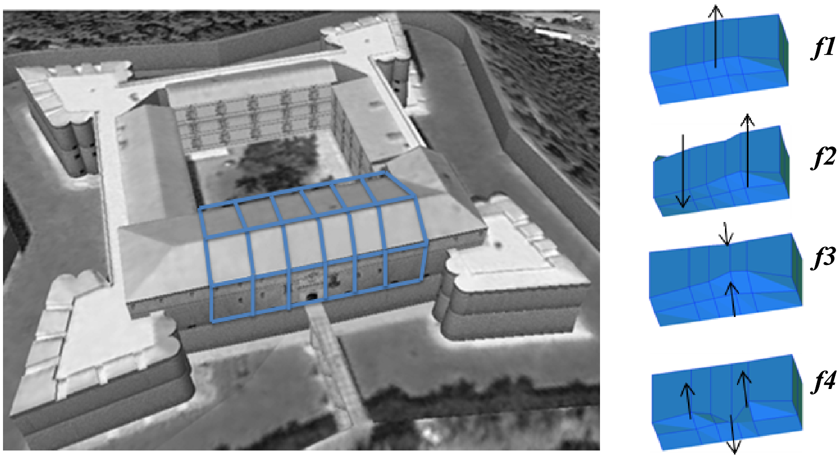

Figure 20: Mode shapes emerged from the dynamic data acquisition

Conclusion and perspectives

The earthquake that hit the Abruzzo region on April 6th provided an opportunity to test a methodology for the damage survey of monuments and historic buildings. This method, already implemented during previous earthquakes, has largely proved its reliability. The damage and seismic vulnerability survey allowed to conduct a preparatory analysis to the design of provisional interventions. The study of provisional interventions made during previous earthquakes, showed how the adopted methodological choices and solutions are sometimes in contrast with any purpose and design criteria for safety measures. Thanks to the activity carried out at a larger scale during this earthquake, it was also possible to prepare guidelines for their design (N.C.P. 2009).

After this experience, the survey forms for damage assessment can be further refined, particularly in relation to the definition of synthetic damage index, the evaluation of economic damage, and the simplification of the palace survey form. The systematization of the observed damage will also hopefully bring new insight into the seismic behaviour of historic structures. In the case of temporary interventions, specific and systematic research activities are also necessary to optimize the measures for heritage buildings, through theoretical, numerical and experimental research (Liberatore et al. 2009).

The extent to which the city of L'Aquila and the surrounding towns have been hit by the earthquake, will require deep studies and a long time before all of the historic buildings will be repaired. In this contest, monitoring, which is being more and more considered as a key activity to increase knowledge on the structural behaviour of monuments, is being proposed as a tool for the post-emergency phase. In case of the seismic sequence of L'Aquila, monitoring can show the eventual

progression of damage, can be a warning tool in case of sudden worsening of structural conditions, and allows minimizing and tailoring the repair works, when these will be carried out. The low cost distributed monitoring that is being implemented can also provide a tool to create a time-schedule for the most needed interventions.

Deep studies and analyses are needed to interpret correctly the peculiar damage mechanisms observed and the effect caused by past interventions, to select proper intervention techniques, and to adjust them or prove their compatibility to the local structural types, construction elements, and materials (Modena et al. 2009). On one hand, attention has to be paid in avoiding unnecessary interventions, on the other hand, it will be necessary to determine some shared criteria to intervene on badly damaged buildings, where large portions of the original structural elements collapsed.

Acknowledgments:

The authors wish to thank all the researchers, collaborators, Ph.D. candidates and students for their significant help during the activities in L'Aquila. The activity was supported by ReLUIS.

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