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The S. Marco Church in L'Aquila: Provisional Interventions after the 2009 Abruzzo Earthquake

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Abstract: The 6th of April 2009 a strong earthquake (rated 5.8 on the Richter scale) struck the Abruzzo region in central Italy, causing hundreds of casualties and devastating the historical city of L'Aquila and several small towns in the area. The toll in terms of structural damage was enormous, also considered that a vast amount of buildings was made of poorly arranged masonry composed by round pebbles and mortar of scarce mechanical characteristics. In particular, the buildings belonging to cultural heritage (e.g. churches and monumental buildings) were between the structures that suffered more from seismic damage, considered their dimensions, mass and general lack of adequate connections. Few weeks after the seismic event, a church in the historical city centre of L'Aquila, the S. Marco church, was "adopted" by the Italian Veneto Region, which paid and provided the necessary technical support for the first necessary provisional structural interventions. The paper describes the steps undertaken in order to provide the building with the minimum safety conditions necessary to face the aftershocks, and to survive without further collapses to be subsequently retrofitted. A static and dynamic structural monitoring system was also installed in the church since the beginning of the works, in order to control the safety conditions of the area during the execution of the interventions and to assess the damage progression or stationariness.

Keywords: Seismic damage, historical masonry buildings, provisional strengthening interventions, structural monitoring

The S. Marco Church in L'Aquila

The San Marco church is one of the first churches built in L'Aquila in the second half of the 13th century, and it is located on the hearth of the city of L'Aquila, between "Via dei Neri" and "Piazza della Prefettura" (Fig. 1). Medieval traces are preserved mainly in the external walls and in the lateral entrance, dated from the 14th century. The main façade could have been built at the beginning of the XV century (Moretti 1971, Antonini 1988).

The church presents an elongated plan, with single nave and side chapels, ending in a semicircular apse (Fig. 2). The arms of the transept do not stretch out of the width of the church. The side chapels open on the two sides, and are covered with barrel vaults of lower height respect the vaults of the nave and the arms of the transept. A shallow dome with a slightly elliptical plan covers the crossing between transept and nave. The covering of the nave, with the shape of a barrel vault, is composed by 4 brick masonry arches supporting a wooden and reed structure, with plaster covering.

The walls are composed by an irregular stone masonry, in some portions (e.g. façade, side walls in via dei Neri) provided with an external layer made of regularly cut stones (façade) and a regular facing of small-size stones, locally called "apparecchio Aquilano" (side walls).


(a) (b)

Figure 1: St. Mark church in L'Aquila city centre, before the earthquake: (a) aerial view and (b) façade

It was noted a general non homogeneity of the masonry due to different construction phases and modifications probably after past earthquakes. Arches and vaults are mainly composed by brickwork or mixed brickwork-stone masonry.

The church as it is nowadays presents several signs that indicate several transformations. The most important were: (a) the partial reconstruction of the church in 1315 after the earthquake; (b) the lateral chapels built in the XVI century covered with stone vaults, attached to the nave lateral walls; (c) the complete modification of the building in 1750 with the construction of the two bell towers and of the top part of the frontal façade.

In recent years the church underwent several structural and non structural maintenance works. The main interventions were performed in 1970, 2005 and 2007. In 1970, the church was subjected to a very intrusive intervention that consisted on the removal of the entire pre existent timber roof and its replacement with a new one made by prefabricated beams and roof slab. In 2005 different maintenance works were performed, as the replacement of the old iron ties positioned on the top part of the bell towers by more recent steel ties with a more efficient fixing mechanism. In 2007 the arches that support the dome over the presbytery area were reinforced using carbon fiber layers fixed to the arches inner face.

Reported Seismic Damage

The 6th of april earthquake induced severe damage on the church. The calculated damage index, according to the form for the damage survey of C.H. - Churches (Form for the damage survey of cultural heritage buildings 2006), corresponded to the value of 0,66 (on a scale from 0 to 1, where 0 is related to total absence of damage, and 1 to total collapse of the building), which is a relatively high value when compared to the average attained values for the others churches in L'Aquila. Different activated mechanisms of the San Marco church surveyed were analyzed in detail and a set of possible causes for its activation were hypothesized (Silva et al. 2010).

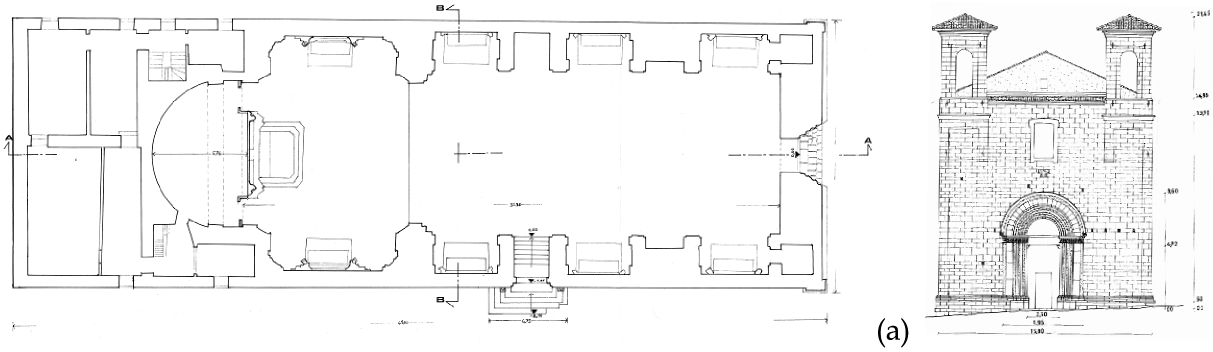

(a) (b)

Figure 2: Geometry of the St. Mark Church: (a) plan and (b) façade

Figure 3: St. Mark church after the 2009 earthquake: (a) external and (b) internal views; (c) collapse of the nave vaults,(d) of the apsidal vaults and (e) severe damage in the pillars sustaining the dome

Even if the external appearance of the church seems to indicate an almost untouched structure, the inner view of the church clearly reveal the seriousness of the situation (Fig. 3). The most severe damages corresponded to the total collapse of the apse vault, of a wall portion located on the upper part of the longitudinal left walls of the nave, part of the chapels adjacent to this last, of some of the arches that support the nave vault and the main part of the nave vault. It is also worth noticing the separation between the internal and external masonry layers of the longitudinal right wall, probably due to the lack of interlock, as they belong to two different constructive phases, as well as the separation between the whole wall and the right side chapels.

The dome over the presbytery presents an advanced crack pattern map. The supporting structure is compromised: one of the arches that support this dome collapsed, while the other three are heavily damaged. As for the main façade, it is mainly affected by in-plane shear damage passing through the entire thickness of the wall.

The Provisional Strengthening Intervention

The initial provisional strengthening intervention was financed by the Veneto Region of Italy, which paid 240.000,00 € as a first instalment. Works started the 4th of July 2009 and were completed in November of the same year. This first intervention aimed at counteracting the most critical collapse mechanisms, such as the apsidal and transept walls overturning. Further interventions involved the hooping of the facade, the sustaining of a wide walls portion of the right longitudinal side of the church, and the strengthening – by means of wooden trusses - of the valuable stone main portal. These interventions were the first and the most urgent in emergency time, and were carried out by working outside the church – considered the serious risk of collapse of further elements of the structure, especially in the period of continuation of seismic events (aftershocks) with non negligible magnitude.

The initial intervention entailed the construction of a sound scaffolding made by hollow pipe steel trusses (Fig. 4), constituting a portal spanning across the church, in order to inhibit the prosecution of the overturning of the apses and transepts walls. 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.

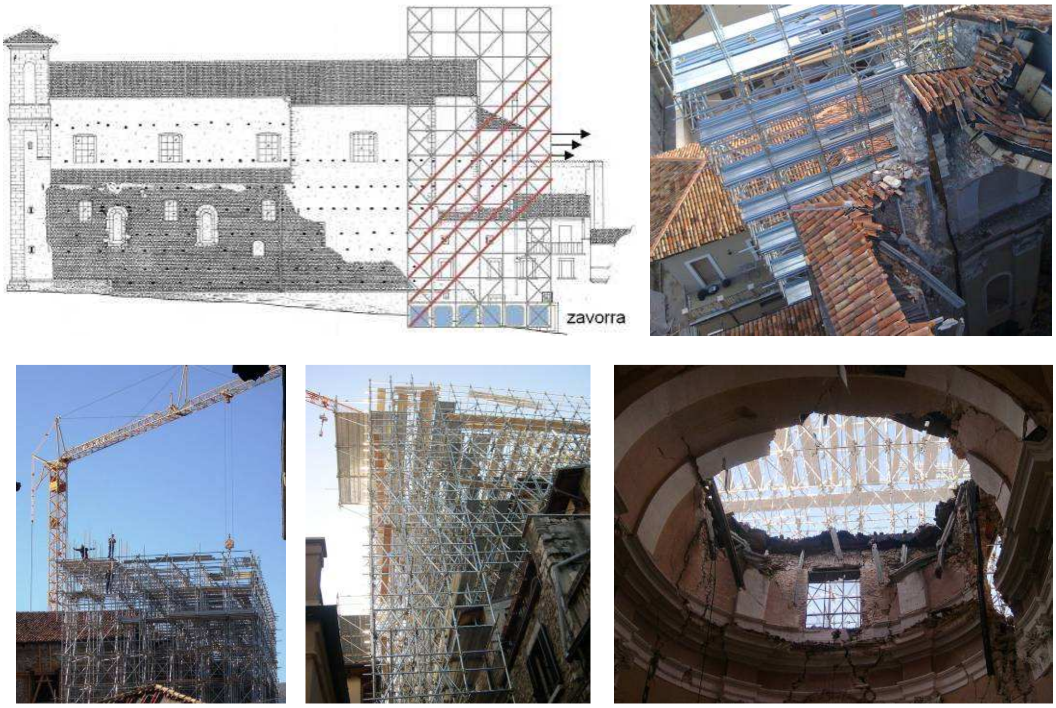


Figure 4: St. Mark church in L'Aquila: erection of the structural scaffolding in the apsidal area

In the façade area, wooden struts were employed in order to counteract the overturning of a remarkable part of the right wall external veneer, and to sustain the stone elements of the valuable church portal, disconnected by the seismic motion (Fig. 5). The façade was hooped on two levels with steel cables, also positioned to avoid the shear damage progression. Finally, several openings were propped by means of wooden trusses, and the façade bell-towers were hooped at the level of the belfry.

The continuation of the works (2010-2012), with further instalments provided by the Veneto Region for a total of 5 Millions of Euros, will entail the "internal" works – also considered that the aftershocks are today substantially of negligible magnitude. Works will consist in the removal (with sorting of valuable and reusable materials) of the internal debris, the construction of a lattice steel tower sustaining the breach in the wall on Prefettura square, and then in the main internal provisional intervention, consisting in the creation of steel "portals" in lattice structure, used to prop the still unstable masonry vertical elements, mainly in order to avoid the risk of flexural collapse at mid height of the pillars. This metallic hollow pipe structure will be designed in a way to be the base for the definitive strengthening interventions and local reconstruction of masonry elements.

The Structural Monitoring System

In parallel to the execution of the interventions, the opening of the main cracks was controlled by means of an automated low-cost structural monitoring system (Casarin et al. 2010).

Figure 5: St. Mark church in L'Aquila: strengthening interventions in the façade area

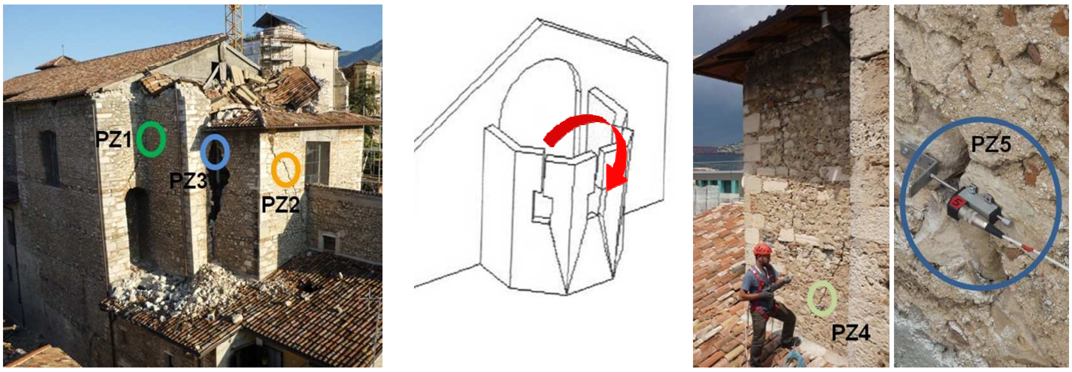


Figure 6: view of the apsidal area of St. Mark church displacement and T-RHumidity sensors positioning

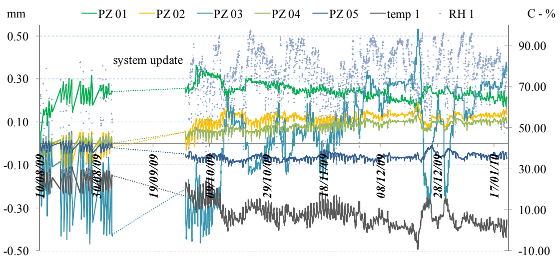
The monitoring system is continuously acquiring data, and stores hourly the readouts coming from 5 linear displacement transducers positioned in the external area of both apse and transept, where the worst damage scenario is observed (Fig. 6). Data are correlated to the environmental parameters recorded 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 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) with the aim of the repetition of the dynamic identification, to measure possible variations in the modal parameters of the structure with the progression of the strengthening interventions. Sensors, both at the base and at the top, are positioned orthogonally to each other, measuring accelerations in the horizontal plane. The monitoring system was installed the 10th of August 2009. Displacement transducers data – up to February 2010 - are plotted in the graph of Fig. 7a. In the first months 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. The elaborated response spectra of some recorded minor seismic events in the L'Aquila area (Fig. 7b), scaled to the local peak ground acceleration as given by the Italian seismic code (Norme Tecniche per le Costruzioni – Ministerial Decree 14/01/2008), corresponding to the value of 0,364 g, indicate a local resonance with very high peaks around the frequency of 5 Hz (especially in the far source seismic events), in a frequency band where several structural eigenvalues are noted.

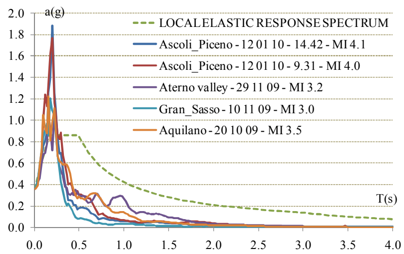
Conclusions

The design of a provisional strangthening intervention for historical buildings in case of seismic events is based on the outcomes of the post-seismic damage survey, and in particular from the identification of the collapse mechanisms activated by the earthquake, as emerged from the compilation of the "forms for the damage survey of Cultural Heritage Buildings", fitted for churches and palaces. The damage observation is then the first step in the process of designing an intervention suitable to counteract the individuated collapse mechanisms.

The Abruzzo earthquake gave the possibility to test on a wide scale a process of damage assessment and design of provisional interventions introduced after the Umbria-Marche earthquake (1997). In fact, after the 1997 event, the procedures for the damage assessment and some principles for the design of the provisional interventions were setted. Such principles indicated, where possible, to avoid heavy interventions of propping, e.g. the façades of the churches, or to interact with the adjacent buildings, and also to reduce to a minimum all of the interventions that may occupy the streets interfering with the accessibility of the rescue vehicles, and to avoid interventions which may lead to onerous works of removal when carrying out the definitive strengtening interventions.



(a)



(b)

Figure 7: St. Mark monitoring system: (a) plots of the displacement sensors data vs. time; (b) scaled to the local PGA value horizontal elastic response spectra calculated from the recorded accelerograms

Beyond these needs, further issues related to the dynamic and static response of historical buildings damaged by the earthquake were considered after the Abruzzo earthquake (Modena et al. 2008, Modena et al. 2010).

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 intrusive repair works, if they are not justified by an experimentally demonstrated worsening of the structural conditions of the structure (Guidelines for evaluation and mitigation of seismic risk to cultural heritage with reference to technical constructions regulation Italy). 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, acting also as an early warning procedure for the safety of the workers employed in the strengthening interventions.

References

[1] (2006) Modello A-DC / B-DP PCM-DPC MiBAC – Form for the damage survey of cultural heritage buildings – churches and palaces. Available: http://www.protezionecivile.it/ (in Italian)

[2] Antonini, O. (1988). "*Architettura religiosa aquilana*." L'Aquila, Italy: Edizioni del Gallo Cedrone.

[3] Casarin, F, da Porto, F, and Modena, C, (2010). "Structural monitoring of damaged cultural heritage buildings after the April 2009 Abruzzo earthquake," in *Proc. 3rd int. workshop on Civil Structural Health Monitoring*, Ottawa, Canada.

[4] *Guidelines for evaluation and mitigation of seismic risk to cultural heritage with reference to technical constructions regulation*, Ministry for Cultural Heritage and Activities, General Direction of Architectural Heritage and Landscape – Dept. of Civil Protection Agency (Italy)

[5] Modena, C, and Binda, L, (2010). "Edilizia storica monumentale. Salvaguardia degli edifici di interesse storico artistico nell'emergenza post-sisma."in *Progettazione Sismica 03-09*, 107-115. IUSS Press (in Italian)

[6] Modena, C, Valluzzi, M R, da Porto, F, Casarin, F, Munari, M, Mazzon, N, and Panizza, M (2008). "Assessment and improvement of the seismic safety of historic constructions: research and applications in Italy," in *Proc. I Congreso Iberoamericano sobre Construcciones Históricas y Estructuras de Mampostería*, Bucaramanga, Colombia

[7] Moretti, M (1971). "*Architettura medioevale in Abruzzo*." Roma, Italy: De Luca.

[8] *Norme Tecniche per le Costruzioni* – Ministerial Decree 14/01/2008 (Italian Standards)

[9] Silva, B, Magi, J, Casarin, F, Modena, C, Valluzzi, M R, Condoleo, P, Cardani, G, and Binda, L (2010). "Assessment of the San Marco church structural behavior in sequence of the April 2009 earthquake in Abruzzo (Italy)," in *Proc. 8th MONUBASIN Symposium*, Patras, Greece.