ASSESSMENT OF THE SAN MARCO CHURCH STRUCTURAL BEHAVIOR IN SEQUENCE OF THE APRIL 2009 EARTHQUAKE IN ABRUZZO (ITALY)

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ABSTRACT

The scope of this paper is to understand the structural causes behind the almost complete collapse of the 13th century Church of San Marco, situated in the historical centre of L’Aquila, during the April 2009 earthquake. This will be achieved through the application of a 2nd level of knowledge evaluation methodology specific for this particular class of historical buildings (complex religious buildings in post seismic sceneries). The paper presents the conclusions withdrawn from the preliminary analysis, which consists on the following 3 phases: (i) historical investigation; (ii) description of the building; (iii) survey and description of the existent damage on the structure. In addition are also presented the results of a simplified limit analysis, using the software c-Sisma [9] and [10], performed to some structural elements and collapse mechanisms considered as dominant on the church behavior and individuated based on the previous gathered information. Finally will be presented and described an Automatic Monitoring System installed on the church along with some of its initial results. This type of system is useful to access the safety conditions of the structure in time, and guide more accurately the intervention process.

The knowledge attained form this type of studies is of great interest and importance, in particular for the entities that control the preservation of the built heritage, because it helps to prevents future errors and allows the definition of more efficient intervention strategies, so important for the preservation of this type of buildings in the case of another seismic event.

INTRODUCTION AND OBJECTIVES

On April 6, 2009 at 3:32 a.m. local time, an earthquake hit the central region of Italy, more precisely the region of Abruzzo near the city of L’Aquila. This earthquake presented a moment magnitude of 6.3 Mw and a shallow focal depth, of approximately 8.0 to 9.0km, according to [3]. The epicenter was located 10.0Km West of L’Aquila and 95.0km NE of Rome, [4] and [6]. This event was the strongest of a sequence that started a few months earlier; 23 earthquakes of Mw > 4 between 30/03/09 and 23/04/09 were enumerated, including an Mw 5.6 on April 7 and an Mw 5.4 on April 09, [4].

In the Abruzzo region, as in most of Italy, the historic city centers are the core of the built environment. Many different building typologies can be identified in the L’Aquila area and in the Abruzzo region. The construction began in the 13th century and continued up to the modern era, ranging from the historical stone masonry (usually not squared of irregular size and sporadic insertions of brickwork) buildings to reinforced concrete structures. Also the maintenance
conditions are very variable, on the old towns one can found a big amount of brickwork houses, inhabited but in a good state of repair.

With this seismic event, in general, all the masonry buildings suffered a great amount of damage due to this seismic event, [4] and [5].

In this paper, one of the historical center of L’Aquila emblematic masonry structures, the San Marco Church, is studied with the objective of understanding the structural causes behind its almost complete collapse during the 6th of April 2009 earthquake. This study corresponds to a posterior, more advanced phase, in what concerns the 1st level form for the damage survey of Cultural Heritage (C.H.) structures. This study is based on the application of an evaluation methodology specific for this particular class of historical buildings, which can be subdivided in six main groups from which only three were approached until this phase: (I) Historical investigation, paying special attention to the evaluative process of the building and the interventions underwent throughout the years. (II) After which, the church will be described, individualizing the main structural and constructive elements. (III) Finally it will assess the present damage state of the church and the different activated mechanisms along with its level of activation.

ANALYSIS METHODOLOGY

The methodology applied for the analysis of the churches presented in Figure 1 it’s specific for a special class of historical buildings, the complex religious buildings in post seismic sceneries and it corresponds to a second level of knowledge, being that the first level performed immediately after an earthquake, using the 1st level damage survey form for C.H. structures specific for churches, [7].

In this paper the results attained from a preliminary research that essentially comprises the first three steps of the methodology is presented: (I) Historical investigation, paying special attention to the transformation/structural interventions performed to the church throughout time. Describing in a more detailed way the existent structural interventions, assessing their efficiency and discussing how they influenced the structural behavior of the church; (II) Description of the building, through the detailed analysis of each of the architectural and structural elements, and through the survey of the geometrical and material characteristics of the structure, these last are attained using the 1st level quality form “Survey of masonry typology and masonry quality”, [12]; (III) Elaboration of a schematic synthesis of the post-seismic state of the church through an intuitive visual correlation between the overall damage state of the church, the pre-existent interventions, the material quality and the activated damage mechanisms; definition and discussion of the hypotheses for the mechanism activation based on the symptomatic signs found on the post-seismic scenario of the churches.

On a more advanced phase, further studies should and will be performed on this monument involving in-situ and laboratory tests capable of characterizing more accurately the structure, allowing therefore a more accurate assessment of the structure behavior under the seismic event. This analysis can be aided by different numerical models and modeling strategies were different hypothesis proposed on the knowledge phase can be tested.
CASE STUDY - SAN MARCO CHURCH

I - Historical Investigation

Brief Construction History

The San Marco church is one of the first churches built in L’Aquila in the second half of 13th century, whose construction was carried out due to the initiative of Pianola’s inhabitants. The church is located on the hearth of the city of L’Aquila, between “Via dei Neri” and “Piazza della Prefettura”.

The 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. The entrance on the left side is considered more ancient than the one on the main façade. The minor entrance has to be grouped with the other of identical setting present in S. Antonio, in Santa Maria del Guasto, in San Vito, in the Madonna del Carmine, etc... that presents identical structural and decorative components. In San Marco church there are four symbols of the Evangelists, three to the left and one to right, that adorn the lintel with the usual "Agnus Dei". The decoration is completed with the figures of St Abate and of San Marco’s insignia.

In the last century the internal late-baroque covering, coming from the 1700s, has been restored. The medieval structures added on the facade on the XVIII century have not changed anything of the original beauty. This beauty is increased by the presence of the gothic single ancient windows, and by the “Aquilano” texture presents in the masonry external leaf, [1] and [2].

Transformations and Interventions

The church as it is nowadays presents several signs that indicate numerous 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, Figure 2.

Throughout the years the San Marco church underwent several structural and non structural
maintenance works, Figure 3. 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-existing timber roof and its replacement with a new one made by prefabricated beams and roof slab. In order to make this roof as self-supporting as possible steel ties were placed on each of the alignments of the pre-fabricated beams. During the intervention of substitution of the roof it was also constructed over the presbytery a R.C. structure to support the new roof it in this area.

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 (Figure 3).

In 2007 the arches that support the dome over the presbytery area were reinforced using carbon fiber layers fixed to the arches inner face (Figure 3).

![Figure 2: View of San Marco church before the earthquake.](image)

![Figure 3: Main interventions on San Marco church.](image)

II - Description of the Building

The building is here described, through the (1) geometrical survey of the structure based on the measurements attained and on the geometrical info given by the L’Aquila C.H. architect; (2) detailed description of each of the composing constructive elements; (3) analyses of the material that composes the different structural elements of the church, based on a 1st level wall quality form “Survey of masonry typology and masonry quality”, [12].

Geometrical Survey

A simple geometrical survey, Figure 4, of the church was performed based on the available elements such as topographic surveys, which were later validated during the technical inspections to the building, through control measurements.
Description of the Structural Elements

The original timber trusses of the roof were substituted by R.C. elements in the second half of the last century with large clay elements between them.

A shallow dome with a slightly elliptical plan is covering the central part of the transept. The dome is supported by 4 arches made in a solid brick masonry which continue in concentric circles at the spring of the dome, while the central part of the dome is made with brick headers. At the extrados of the arches wooden tie beams are inserted in the masonry as confinement. The lateral filling of the dome is made with rather regular stones well distributed. From the analysis of the collapsed materials the dimension of the bricks was measured as 290x150x30mm.

The barrel vault covering the nave is constituted by a mixed system: six arches in brick masonry divide five spans made with reed, (Figure 5a).

The thickness of the arches is probably 290mm and they are similar to the arches supporting the dome. Also in their case timber tie rods are present at the extrados inserted in the masonry. The lateral filling of the barrel vault is made with mixed brick and stone masonry regularly positioned.

The vaults of the aisles are made with mixed brick and stone masonry. The lateral filling is made with loose pieces of bricks and stones without any mortar. The semi dome of the apse is badly damaged and it was probably made with a mixed brick and stone masonry, (Figure 5b).

All the examined load-bearing walls are made by a multiple leaf masonry with no connection between the leaves. All the pictures show a high non homogeneity of the masonry due to different construction phases and modifications probably after past earthquakes, (Figure 5c).

The base of the walls and the left lateral wall are made externally by irregularly cut stone, while the right lateral wall and the facade are externally made with regularly cut stones.
**Material Quality**

The survey of the different types of masonry present in the church was performed during the technical inspections to the church. To systematize the collected information, a specific form developed at Politecnico di Milano (POLIMI) was used (1st level wall quality form “Survey of masonry typology and masonry quality”), [12], for each type of masonry present in the structure. The survey sites, (Figure 6), were chosen taking into consideration the historical information and consequently the different constructive phases. All the different surveyed materials present in Table 1 were defined through a macroscopic analysis.

In some cases the walls are composed by more than one type of masonry, as so, and according to its composition a weighted average of the properties as to be considered, especially in what concerns the use of this properties in simplified analysis.

Further surveys, especially to the walls section, weren’t possible due to the poor safety conditions presented by the church, with possibility of localized collapses.

![Figure 6: Masonry quality survey points on San Marco church.](image)

**Table 1:** Type of material and respective characteristics according to the 1st level wall quality form “Survey of masonry typology and masonry quality”, [12] and [13].

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ord. 3274/2005 (Circ. NTC08, 2009) Reluis</td>
<td>( f_m )</td>
<td>( \tau_0 )</td>
<td>( E )</td>
</tr>
<tr>
<td>SP1/SP2/SP3/SP4 Uncut stone masonry with facing walls of limited thickness and infill core</td>
<td>Uncut stone masonry, of variable dimensions, with prevalingly horizontal layers</td>
<td>200</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td>5.1</td>
</tr>
<tr>
<td>SP5/SP6 Dressed rectangular (ashlar) stone masonry</td>
<td>Dressed rectangular (ashlar) non-soft stone masonry</td>
<td>600</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800</td>
<td>12.0</td>
</tr>
</tbody>
</table>

**III – Crack pattern survey and description of the damage**

The several technical inspections to the church during the months following the earthquake allowed the creation of detailed internal and external crack pattern maps, (Figure 7). The interpretation of the crack pattern can be of great help in understanding the state of damage of the structure, its possible causes and the type of survey to be performed, provided that the
development history of the building is already known.

Figure 7: Crack pattern map of the nave left lateral façade.

In this case the crack pattern maps allowed an easy and intuitive assessment of the damage during the seismic event. The overall damage of the church is very high. The most severe damages are: the total collapse of the apse vault, (Figure 8a); a wall portion located on the upper part of the nave left lateral façade, (Figure 8b); part of the chapels adjacent to this façade, (Figure 8c); some of the arches that support the nave vault and also approximately 80.0% of the nave vault, (Figure 8d).

It is also worth noticing the separation between the internal and external masonry of the nave right lateral façade, probably due to the lack of interlock, as they belonged to two different constructive phases, Figure 9a.

The dome over the presbytery presents an advanced crack pattern map, Figure 9b. 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 presents an out-of-plane deformation characterized by the presence of vertical cracks in correspondence with intersections between the main façade and the nave lateral walls. This façade presents also important in-plane shear damage passing through the entire thickness of the wall, Figure 9d.

Figure 8: Collapse damages on the church.

Figure 9: Activated mechanisms on the church.
**Damage Mechanisms**

Different activated mechanisms of the San Marco church surveyed according to the “1st level form for the damage survey of C.H. - Church” were analyzed in detail and a set of possible causes for its activation were hypothesized. This conclusion was possible by the correlation of the mechanisms with all the previously gathered information, such as material quality, crack pattern, interventions, transformations, etc..., [8]. In Figure 10, the different mechanisms activated on the church along with its respective level of activation are presented.

![Figure 10: Activated collapse mechanisms vs Level of activation of the mechanisms.](image)

From the graph presented in Figure 10, it can be easily concluded that the San Marco church is severely damaged. From the possibly activated mechanisms on this church almost all of them are in fact activated (21 out of 22) with an average level of damage activation of 3.5 that corresponds to a serious to very serious overall state of damage. The highest level of damage activation (collapse level) appeared on the mechanisms 5 (nave transversal response), 8 (mechanism of the central nave vaults), 13 (triumphal arch), 18 (presbytery and apses vaults) and 21 (apses roof elements). The damage index ($I_d$) of the church is given by equation (1), [7], where $d$ represents the total damage score for all the activated mechanisms, and $n$ is the number of the possibly activated mechanisms. The possibly activated mechanisms of this church are 22, while the total damage amounted to 73 resulting on a 0.66 damage index, which is a relatively high value when compared to the average attained values for the others churches in L’Aquila.

$$I_d = \frac{1}{S_n} \sum_{i=1}^{28} d_k$$

(1)

**Analysis of the mechanisms**

The analysis of the mechanism was performed using the program c-Sisma, [9] and [10]; like some others available it allows calculating automatically the collapse coefficients ($c=a/g$) related to a single elementary kinematism of macro elements, which can be individuated in the masonry buildings. The minimum value of $c$ corresponds to the first mechanism that will be activated, between the ones considered on the analysis, considering the imposed initial conditions. This program allows also the safety verification based on the Updated Italian Technical Norms for Construction, [11].

In order to perform this analysis it was necessary first to define the initial general parameters related with the characterization of the seismic action, the particular geometrical and material properties and the applied loads of each analyzed mechanisms. The applied loads were defined based on the geometrical and material properties of the church. Some of the loads such as the
self-weight were automatically calculated by the program c-Sisma, as for the others were calculated separately and inserted on the program as input data.

Based on the analysis of the activated damage mechanisms on the church the most vulnerable structural elements and correspondent collapse mechanisms (Figure 11), to which perform this kinematic analysis using the program c-Sisma, were chosen.

![Figure 11: Structure elements and collapse mechanism chosen to be analyzed with c-Sisma.](image)

**Table 2:** Results of the mechanism analysis using c-Sisma.

<table>
<thead>
<tr>
<th>Macro Elements</th>
<th>Mechanisms (c-Sisma)</th>
<th>Collapse Coefficient (c)</th>
<th>Linear Analysis ((\alpha^*))</th>
<th>(\Delta d)</th>
<th>(\Delta d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal Façade</td>
<td>1.2</td>
<td>0.0038</td>
<td>0.00346 KO</td>
<td>0.0129</td>
<td>0.5134 KO</td>
</tr>
<tr>
<td></td>
<td>4.1</td>
<td>0.2667</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Right Lateral Façade</td>
<td>1.2A</td>
<td>0.0105</td>
<td>0.00879 KO</td>
<td>0.0188</td>
<td>0.3958 KO</td>
</tr>
<tr>
<td></td>
<td>1.2B</td>
<td>0.0151</td>
<td>0.01653 KO</td>
<td>0.0232</td>
<td>0.3408 KO</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>0.2101</td>
<td>0.1574 KO</td>
<td>0.3926</td>
<td>0.4384 KO</td>
</tr>
<tr>
<td>Left Lateral Façade</td>
<td>1.2A</td>
<td>0.0127</td>
<td>0.2101 KO</td>
<td>0.0205</td>
<td>0.3275 KO</td>
</tr>
<tr>
<td></td>
<td>1.2B</td>
<td>0.0134</td>
<td>0.0119 KO</td>
<td>0.0233</td>
<td>0.3119 KO</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>0.2165</td>
<td>0.1687 KO</td>
<td>0.5223</td>
<td>0.4269 OK</td>
</tr>
<tr>
<td>Transept Extremity Façades</td>
<td>2.2</td>
<td>0.0210</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Apses</td>
<td>1.1</td>
<td>0.1480</td>
<td>0.1575 KO</td>
<td>0.1580</td>
<td>0.2309 KO</td>
</tr>
</tbody>
</table>

\(\alpha^*\) = Spectral acceleration to activate the mechanism  
\(\Delta d\) = Ultimate displacement capacity of the system  
\(\Delta d\) = Displacement demand of the system

As a result of the kinematic analysis of the considered mechanisms, it was attained that the first mechanism that can be activated on the church, i.e., the one that corresponds to the lowest value of
the collapse coefficient (c), is the out-of-plane movement of the façade. However, the seismic action acted mainly on the transversal direction of the church. This fact can explain why in reality this mechanism didn’t present a high level of activation when compared with the others. As so if we neglect the collapse coefficient value attained for the façade it is possible to conclude that the out-of-plane movement of the lower part of the right lateral wall \((c=0.0105)\) and the out-of-plane movement of the higher part of the left lateral wall \((c=0.0127)\) are the ones that present the lowest value for the collapse coefficient and as so are the weakest and most relevant mechanism. In reality if we observe the present in situ state of the church, we can easily recognize that in fact these two mechanisms are the ones that present the highest level of activation. Furthermore, the non linear analysis confirmed the considerations presented above.

**Monitoring System (Static and Dynamic)**

During the emergence work performed to render the San Marco Church secure/stable, it was thought necessary to monitor the behavior/evolution of some of the main damages, i.e., check the safety conditions in time using an Automatic Monitoring System, Figure 12. This system acquires automatically the data from 5 Displacement Transducers, positioned on the exterior part of the apses and transept area, Figure 13. Also, the system is capable of acquiring acceleration signals - periodically and under environmental vibration conditions and automatically in case of an important seismic event - through 4 high precision acceleration transducers, 2 placed on the base of the structure and other 2 placed on the top part. All the acquired data is correlated with the environment parameters attained with the Temperature and Humidity Sensor.

![Figure 12: Automatic Monitoring System installed on the San Marco church.](image)

![Figure 13: Location of the sensor on the church.](image)
The system was installed on August 10th 2009. From the first results attained (displacement transducers - Figure 14), it’s possible to observe that the measures show stability - taking into account the normal variation due to the environment conditions - the exception is the sensor PZ3 placed on the crack of largest dimension on the apse; however, this variation may be due to the dimension of the crack in which this sensor is positioned.

![Figure 14: Results from the static monitoring.](image)

In this particular case the dynamic system is only being used for research purposes to assess the structure dynamic response and its amplification in case of a seismic event.

**FUTURE DEVELOPMENTS**

This methodology followed the first approach performed using the “1st level form for the damage survey of C.H. - Church”. It aims to achieve a more detailed level of knowledge concerning the structure. This type of knowledge is of great importance for the definition of the final restoration solution, because it helps to prevent future errors, and allows the definition of more efficient intervention strategies, that are so important for the preservation of this type of buildings in the case of another seismic event. The final intervention will consider the preservation of the original material and construction techniques as much as possible.

Although the course of work is not completely defined, during a subsequent phase, the execution of laboratory and in-situ tests, capable of characterizing more accurately the structure, is planned, allowing therefore a more accurate assessment of the structural behavior under a seismic event. This analysis can be supported by different numerical models and modeling strategies, where different assumptions proposed during the knowledge phase can be tested.

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