SEISMIC VULNERABILITY ASSESSMENT OF MASONRY CHURCHES THROUGH THE APPLICATION OF PROBABILISTIC METHODS

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Abstract. The 2009 seismic event occurred in L’Aquila (Italy) caused many losses, with severe damage of the whole monumental heritage of the Abruzzi Region and in particular for churches.

The current paper reports the main results of a research campaign carried out by the authors after the 2009 L’Aquila earthquake. This has been focused on the religious buildings belonging to the Sulmona-Valva diocese, a territorial area located at the boundary of L’Aquila district, which undertook slight-medium damages during the seismic events.

In a first stage, a detailed investigation, carried out on the basis of observations on a population of twenty-six three nave churches, is presented aiming to define local and global levels of damage according to the criteria introduced by the EMS-98 macro-seismic scale. Therefore, the collected data-set is managed from the statistical point of view in order to obtain Damage Probability Matrices (DPMs).

Then, a predictive model based on the identification of the main fragility indicators and anti-seismic devices of the studied churches is dealt with. It is defined according to the methodology proposed by the Italian Guidelines on cultural heritage in order to retrieve back vulnerability indices that are properly used for assessing the mean damage due to potential earthquakes.

The obtained outcomes prove that the adopted model is particularly suitable for reproducing the observed damage scenarios, it resulting a reliable and efficient tool that can be used for future risk mitigation analyses at regional level that can be implemented for evaluating intervention priorities and management strategies for the seismic protection of the regional religious heritage.
1. INTRODUCTION

The seismic event occurred in L’Aquila on the 6th of April 2009 provoked heavy consequences and losses from the social, economic and administrative point of view, involving both local and national entities in the process of emergency management. After five years, the capital city of the Abruzzi region still presents the closure of its old historic centre, which was partially destroyed by the earthquake.

The historical architecture in the large L’Aquila territorial area, where the epicenter of the earthquake was located, represents one of the most important cultural resource of the region; this valuable heritage has been deeply affected by several types of damages, mainly due to the poorness of the materials, the defects of both structural design and constructional process, as well as the alterations applied to the original buildings during their life. The early inspections carried out in the aftermath of the 2009 seismic event, under the responsibility of the governmental Department for the Environment and Historical Buildings [1], highlighted several collapses and irreversible situations. A meaningful example is the important Romanesque basilica of Collemaggio, founded by the Pope Celestino V in the 1287, whose façade represented the maximum masterpiece of the Abruzzi art.

In this framing, this paper aims to define suitable probabilistic models to be used for setting up future risk mitigation analyses and to predict potential damages level on churches belonging to the whole territorial area of Abruzzi. Such models are calibrated on the basis of the damage scenarios observed after the 2009 seismic event on the three naves masonry churches of the Sulmona-Valva diocese, which is a wide ecclesiastic area located in the south-east part of the L’Aquila district.

The proposed study is therefore a classical example of positive exploitation of a dramatic situation for setting up suitable tools finalized to the achievement of a proper awareness of the current vulnerability of existing churches.

2. DAMAGE OBSERVATION (three nave churches of the Sulmona-Valva Diocese)

The Sulmona-Valva diocese territory takes up one third of the whole L’Aquila District, with about 1800 square kilometers of area; it is constituted by forty-nine small towns, among which Sulmona is the most important city, it representing the bishop seat.

In a first step, the entire stock of churches of the area (see figure 1, where the MCS intensity related to the 2009 seismic event is also represented) has been classified owing to their typological and architectural features. It has been recognized that, on a total number of 251 churches, only the 14% (26 buildings) are characterized by three naves (figure 2a). These have been selected for this study, as they represent a stock that can be considered homogeneous in terms of materials, geometric ratios, architectural typology. Moreover, these have been subjected to a further classification in relation to their foundation date (figure 2b), so to individuate the construction techniques and the main structural typologies and that are characterized by recurrent vulnerability types, which usually are related to the construction period.

The oldest building, the St. Pietro ad Oratorium abbey, dates back to the VIII century. This is a single example of pure Romanic architecture and represents one of the most important monumental buildings of the Region. Subsequent marginal stratifications have been applied in the XII century, which are recognizable on the decorations, but the global plant is today identical to the original one.

In a second period (XI-XII-XIII-XIV centuries) the Romanic style developed in this area. It is identifiable on a large number of churches, about the 50% respect of the whole population. The main peculiarity is the basilica plan with timber trusses on the cover and a remarka-
The seismic vulnerability assessment of masonry churches through the application of probabilistic methods

ble poorness of decorations. Some of these churches have today a different aspect from that of the past, due to post-interventions on the structures.

In the XV, XVI and XVII centuries some new churches were built. Most of them are characterized by a typical Renaissance plant, represented by the Latin plan covered by arches, barrel vaults and domes.

In the XVIII century the occurrence of the 1706 earthquake changed the whole scenario of the religious buildings in Abruzzi. More than one-third of the old churches were totally or partially rebuilt (figure 2 c). For churches of this period elliptical vaults and lavish decoration, typical of the Baroque style, are recognizable.

On the basis of the above description, the whole sample of three-naves churches can be mainly classified into three different classes, with reference to their architectural and structural features, as well as to the related seismic response experienced during the 2009 earthquake.
The first class concerns the oldest churches, characterized by the original rectangular plant covered by timber truss and composed by a good quality of the masonry pattern, made of regular stones. These churches generally did not present large damage, as the absence of thrusting vaults and the presence of good quoins connections prevented the activation of collapse mechanisms. Some shear failure cracks have been sometimes recognized on the lateral walls, while compressive damages have been found on the external wythe of the columns (figure 3) mainly made of filled masonry not composed by monolithic stones.

![Figure 3: Damages on columns of Romanic churches.](image)

The second group of churches dates back to the Renaissance period. These are characterized by a rectangular plan, three naves covered by heavy vaults crossed by transept and surmounted by dome.

Finally, the third class of churches is characterized by buildings that have undertaken structural transformations during their life, generally recognizable on the vaults section, on the façade and on the bell tower. For both the last two groups, the most recurrent damage occurred during the 2009 earthquake was represented by cross diagonal cracks. These have been frequently found on lateral walls, bell towers and domes (figure 4a), owing to the composition of the masonry fabric, which, in the great part of cases, resulted poor and chaotically organized. As far as the vault system is concerned, the elliptical types resulted particularly vulnerable. In fact, for these elements, fractures along both the diagonal directions and the circular springlines have been highlighted (figure 4b). With regard to the pillars, vertical cracks due to crushing phenomena have been sometimes surveyed, as in the case of St. Gemma church in Goriano Siculo [2]. These have been probably induced by the increasing compression stresses, due to the earthquake vertical component, which, even far from the epicenter, resulted significant during the 2009 seismic event.

Heavy sliding damages have been detected on the churches where reinforced concrete roof or beams have been built in past years (figure 4c). This obsolete practice was the cause of damage on arches (figure 5a), due to the outward thrust of the heavy roof amplified by the horizontal seismic component. The presence of iron ties certainly constrained this effect; nevertheless, in some cases, ineffectiveness due to punching phenomena involving the anchors (figure 5b) or breaking of ties have been detected (figure 5c).

For the churches under investigation, three main out-of-plane phenomena have been recognized: the rigid façade overturning (fig. 6a) and the transept façade top-corner overturning (fig. 6b) for the St. Gemma church in Goriano Siculo, and the apse overturning (fig. 6c) in the St. Martino church in Gagliano Aterno.
The seismic vulnerability assessment of masonry churches through the application of probabilistic methods

Figure 4: Diagonal cracks on the lateral walls on the St. Gemma Church, b) shear failures on the elliptical vaults on the St. Maria Nova Church and c) sliding mechanisms at the top of wall due to reinforced concrete bond beam on the St. Gemma Church.

Figure 5: a) damages on arches, c) punching phenomena of anchors and d) tie breaking.

Figure 6: a) Rigid façade overturning and b) transept corner overturning in the St. Gemma church in Goriano Sicoli and c) Apse overturning in the St. Martino church in Gagliano Aterno.

3. DAMAGE CLASSIFICATION

3.1 Damage levels

In order to identify the most recurrent damage mechanisms, the structural response of single macro-elements have been analyzed for each church. This allowed to note that, apart from those cases in which retrofitting techniques have been applied, the churches having the same distance from the earthquake epicenter and characterized by both the same geometrical ratios
and architectonic features (type of vaults, pillars cross section shape, etc.) experienced similar
damage typologies and severities during the 2009 seismic event.

The classification of the observed damages has been carried out accounting for 28 mecha-
nisms referred to the main macro-elements (i.e. façade, colonnade, vaults, apse, transept,
dome and bell tower), according to the Italian Code “Guidelines for Cultural Heritage” [3].
For each mechanism, six levels of damage $d_k$, ranging from 0 to 5, have been considered and
attached to each macro-element/mechanism by means of observations, according to the crite-
ria introduced by Grunthal [4]. Obviously, $d_k=0$ means that no damage has been observed for
the macro-element (or that the macro-element is not present), whereas $d_k=5$ means fully col-
lapse.

Then, in order to evaluate a global damage level ($D_k$) referred to each of the anlaysed
churches, a global damage index ($i_d$) has been calculated, according to equation (1).

$$i_d = \frac{1}{5} \sum_{k=1}^{28} \rho_{k,i} \cdot d_{k,i}$$

where $(\rho_{k,i})$ is a weight score, ranging from 0 to 1, based on the influence that the mechanism
$i$ has on the global structure stability. Thus, the transformation of the indices into discrete var-
iables has been carried out, linking the damage index $i_d$ to the global damage level $D_k$, by cor-
relations introduced by Lagomarsino and Podestà [5], which are provided in Table 1. The elab-
orated results are shown in figure 7.

Table 1: Definition of structural damage levels for the churches, based on the damage score.

<table>
<thead>
<tr>
<th>Damage Level ($D_k$)</th>
<th>Damage Index ($i_d$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$i_d \leq 0.05$</td>
</tr>
<tr>
<td>1</td>
<td>$0.05 \leq i_d \leq 0.25$</td>
</tr>
<tr>
<td>2</td>
<td>$0.25 \leq i_d \leq 0.4$</td>
</tr>
<tr>
<td>3</td>
<td>$0.4 \leq i_d \leq 0.6$</td>
</tr>
<tr>
<td>4</td>
<td>$0.6 \leq i_d \leq 0.8$</td>
</tr>
</tbody>
</table>

Figure 7: Damage levels for the 26 observed churches.
The seismic vulnerability assessment of masonry churches through the application of probabilistic methods

3.2 Damage Probability Matrices

Damage Probability Matrices (DPMs) have been outlined, based on the frequency of occurrence of each damage level $D_k$ (from 0 to 5). These obtained frequencies permitted to assess, with reference to the analyzed territory, the probability of occurrence of an expected damage scenario for a seismic event similar to the one of 2009.

In addition, it has been observed that the collected frequencies are well fitted by means of the binomial distribution expressed in eq. 2 [6].

$$p_k = \frac{5!}{k!(5-k)!} \left( \frac{\mu_d}{5} \right)^k \left( 1 - \frac{\mu_d}{5} \right)^{5-k}$$  \hspace{1cm} (2)

In the above equation $k$ ranges from 0 to 5, depending on the considered levels of damage, and $\mu_d$ is the mean damage, calculated according to equation (3):

$$\mu_j = \frac{\sum_{k=0}^{5} D_{k,j}}{n}$$  \hspace{1cm} (3)

where $n$ is the number of churches and $D_{k,j}$ is the level of damage observed for the generic church $j$. In figure 8 the comparison between the obtained DPMs and the related binomial distribution is shown for two cases. The former is referred to the whole population of churches and provides damage scenarios when earthquakes of macro-seismic intensity (in MCS scale) ranging from 4 to 7 occur. The latter provides the same damage scenarios for buildings divided into two groups: Group 1 is composed by churches located in zones that during the 2009 events were hit by MCS 4 and MCS 5 intensities; Group 2 is formed by churches belonging to territories for which damages according to the grades MCS 6 and MCS 7 have been observed, according to Galli et al. [7].

As it can be observed, the probabilistic approach provides a correct prediction of the results of the empirical analysis, with a light disagreement for the first level $D_1$. This is probably due to the difficulty of correctly evaluating damage levels ranging from 0 to 2. In fact it is complex to exactly assess the absence of damage or the presence of slight damage, in particular for masonry buildings, where elements affected by defect due to aging are always present. On the other hand, the evaluation of the levels $D_3$, $D_4$ and $D_5$ is generally more objective, being the structural damages evident and unmistakable.

![Figure 8: a) Damage Probability Matrix vs binomial distribution for a) the 26 observed churches and for b) Groups 1 and 2 of churches.](image)
4. CALIBRATION OF PREDICTIVE MODELS

The application of predictive models, calibrated on the basis of empirical methods, is of utmost importance for the seismic risk evaluation of a population of buildings. As it has been shown in the previous chapter for the analyzed churches, the binomial distribution is able to retrieve back the probability of having a certain level of damage when a determined hazard occurs. This is a significant outcome, as the above distribution depends on one parameter only, namely the mean damage. Thus, the definition of predictive models for forecasting possible damage scenarios has been pursued by the setting up equations able to correlate the expected mean damage to those characteristics affecting the vulnerability of the churches of the analyzed population.

To this purpose, each church has been partitioned into macro-elements, taking onto account the 28 likely mechanisms described in the previous chapter. For each potential mechanism, fragility indicators and possible protection devices have been defined and associated to a score ranging from 0 to 3. In detail a score \( v_{ki} \) of 0 to a fragility indicator defined for a certain mechanism means that the mechanism itself does not represent a source of vulnerability for the building, whereas a score of 3 means that it is characterized by the maximum fragility, or rather that it is prone to experience damage also for moderate earthquakes. At the same way, a score \( v_{k,p} \) of 0 to a protection device applied to the generic mechanism \( i \) means that it is absent or completely un-effective for the elimination of that mechanism. On the contrary, a score of 3 indicates the maximum effectiveness of the protection device.

In the proposed study, the evaluation of each score has been implemented by the definition of specific coefficients (i.e. \( z \), \( w \), \( f \) and \( \eta \)), according to eqs. (4) and (5) for the fragility indicators and the anti-seismic devices scores, respectively:

\[
v_{k,i} = \sum_{i=1}^{n} w_i \cdot z_i \cdot f_i
\]

\[
v_{k,p} = \sum_{i=1}^{n} w_i \cdot z_i \cdot \eta_i
\]

In the above equations \( z \) is a Boolean coefficient, which can be equal to 1 or 0, depending on the presence/absence of the fragility indicator or of the protection devices, for eq. (4) and (5), respectively. The \( w \) coefficient is an importance factor and ranges from 0 to 2. In eq. (4) it represents the potentiality of the fragility indicator in determining the vulnerability of the mechanism, while in eq. (5) it is a measure of the capability of the applied protection device typology. For example, when the vulnerability is induced by irregularities, situations in which they concern both plan and elevation are to be considered more important (influencing) than those one in which one irregularity only is present. At the same way, constraining devices, as the buttresses or the ties, can be of difference importance for out-of-plane mechanisms of a wall. The fragility coefficient \( f \) measures the effectiveness of the indicator and it ranges from 0 (in the case of the indicator does not influence the failure activation) to 1.5 (in case of fully vulnerability with respect to the onset of the failure). Similarly, the efficiency coefficient \( \eta \) measures the effectiveness of the anti-seismic system that mitigated the possible failure. It also ranges from 0 to 1.5.

The scores described above have been used in order to obtain, for each building, the vulnerability index given in eq.(6), which is calibrated in order to retrieve back values ranging from 0 to 1. The obtained results for single church are given in figure 9.
The seismic vulnerability assessment of masonry churches through the application of probabilistic methods

\[ i_v = \frac{1}{6} \sum_{k=1}^{28} \rho_{k,i} (v_{k,i} - v_{k,p}) + \frac{1}{2} \]  

Values ranging between \( i_v=0.376 \) (Madonna della Libera church) and \( i_v=0.571 \) (St. Gemma church) have been therefore calculated.

![Vulnerability Index](image)

Figure 9: Vulnerability indexes for the 26 observed churches.

Once that the average of the vulnerability indices calculated for each of the twenty-six churches has been obtained (\( \bar{i}_v=0.463 \)), the following formulation (eq. 7) has been used in order to predict the expected mean damage \( \mu_{D,0} \) provoked by an earthquake of intensity \( I \):

\[ \mu_D = 2.5 \left[ 1 + \tanh \left( \frac{I + 3.4375 \cdot \bar{i}_v - 8.9125}{3} \right) \right] \]  

The reliability of the above formulation has been proved by Lagomarsino et al. [8] on the basis of a first version provided by Sandi et al. [9]. Moreover, it has been able to return the same mean damages observed on the population of churches analyzed in the present study.

5. FRAGILITY CURVES

The variation of the macroseismic intensity \( I \) in eq. (7) (from 0 to 12 MCS) has allowed to get twelve mean damages related to likewise damage scenarios. They have been obtained by using the binomial distribution of eq. (2), which, for each intensity allowed to get the probability of having differentiated levels of damage.

Thus, the fragility curves for each of the 5 damage levels introduced in Chapter 2 have been plotted (figure 10), they representing the probability \( P(D>D_k|I) \) of exceeding of a certain level of damage, when seismic intensity \( I \) occurs.

The proposed curves can be well interpreted by means of the performance levels for monumental buildings defined by the Italian Guidelines on Cultural Heritage that, as described in table 2, have been linked to each of the damage levels given in table 1.

As an example, the performance demand for the Damage Limit State (DLS), which corresponds to the admissible standard of failure for monumental buildings of architectural significance has been related to the damage level D2, as, according to Grunthal, this damage level
refers to moderate damage (slight structural damage, moderate non-structural damage) characterized by cracks in many walls, fall of fairly large pieces of plaster and partial collapse of chimneys. Thus, the proposed predictive model allows to state that whether an earthquake of intensity 6 MCS occurs, there is a probability of about 45% that the considered buildings exceed the Damage Limit State (D2).

![Fragility Curve](image.png)

Figure 10: Fragility curves for three nave churches in the Sulmona-Valva diocese.

<table>
<thead>
<tr>
<th>Damage Level $(D_k)$</th>
<th>Limit State</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Damage Limit State for Cultural Heritage (CHLS)</td>
<td>During an earthquake of the appropriate level, the decoration system (i.e. frescoes, paintings and sculptures) suffer small damages which can be restored without a significant loss of cultural value.</td>
</tr>
<tr>
<td>2</td>
<td>Damage Limit State (DLS)</td>
<td>Under the effect of seismic action the structure does not present severe damage that justify the interruption of use.</td>
</tr>
<tr>
<td>3</td>
<td>Life Safety Limit State (LSLS)</td>
<td>The structure, while undergoing major damage, retains a residual strength and stiffness against horizontal actions and the entire load-bearing capacity in relation to vertical loads.</td>
</tr>
<tr>
<td>4-5</td>
<td>Collapse Limit State (CLS)</td>
<td>The high level of damage does not permit the use of the buildings.</td>
</tr>
</tbody>
</table>
6. CONCLUSIONS

In the current paper predictive models for forecasting potential damage scenarios on Abruzzi churches have been provided.

In a first stage, Damage Probability Matrices have been proposed through the data set collected by means of in-field inspections carried out in the immediate aftermath of the 2009 L’Aquila earthquake. On the basis of these outcomes, a predictive model, according to the methodology given by the Italian Guidelines for Cultural heritage, has been proposed. This allowed to get fragility curves to be used for forecasting potential damage scenario determined under the occurrence of earthquakes of variable intensity on the considered population of buildings.

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