2016-17 CENTRAL ITALY: MACROSCALE ASSESSMENT OF MASONRY CHURCHES VULNERABILITY

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Abstract

Masonry churches hit by 2016-17 Central Italy seismic sequence confirmed their intrinsic seismic vulnerability. A detailed report of the damage data collected during the in situ surveys carried out during the emergency phases is presented. The data were recorded by filling the II level post-earthquake survey form (A-DC) with reference to masonry churches (990 cases). These inspections were coordinated by the Italian Department of Civil Protection (DPC), the Cultural Heritage Ministry (MiBACT) and the Italian Laboratories University Network of Seismic Engineering (ReL UIS). The paper is mainly aimed at: a) providing an overview of the occurred events, b) presenting and discussing the collected database, c) developing Damage Probability Matrices (DPM) for the examined churches, useful for vulnerability analyses.

Keywords: Masonry Churches, Seismic Vulnerability, Risk Mitigation, Cultural Heritage, Damage Probability Matrix.
1 INTRODUCTION

Masonry churches represent a wide portion of the Italian cultural heritage. These structures have proven to be highly vulnerable to dynamic actions. Recent Italian earthquakes, indeed, emphasized the significant intrinsic vulnerability of such structures, which resulted highly damaged even for low-intensity earthquakes [1]-[5].

The latest seismic sequence that hit Central Italy produced widespread damages all over the affected regions (i.e. Lazio, Abruzzo, Umbria and Marche) [6]-[8]. Inspections on buildings located in these regions were carried out immediately after the earthquake in order to perform usability checks. The inspections were conducted under the joint coordination of the Department of Civil Protection (DPC), the Italian Laboratories University Network of Seismic Engineering (ReLUIS), and the Ministry of Cultural Heritage (MiBACT). Within the inspected damaged buildings, this paper focuses attention on the damages suffered by masonry churches. It is worth noting, indeed, that only few testimonies on damage observed on churches after Central Italy seismic sequence can be found in the literature [9]-[12][11] and that damage classifications are generally based on observations referred to ordinary concrete and masonry buildings.

A proper form [13] was adopted by the Italian Department of Civil Protection and the Ministry for Cultural Heritage and Activities for damage assessment during the post-earthquake emergency management. The form considers the possibility of 28 mechanisms to be activated in a number of macro-elements and a specific level of damage $d_k$, ranging from 0 (no damage) to 5 (total collapse), can be assigned. The damage registered on churches after 2016-17 seismic sequence was assessed by this form which is, indeed, based on past studies on churches [1][5]. These studies evidenced the possibility of subdividing the church into macro-elements, i.e. the façade, the lateral walls, the colonnade, the vaults, the apse, the transept, the dome and the bell tower. Figure 1 shows examples of the most frequently detected damage mechanisms on old masonry churches in Central Italy.

![Figure 1: Frequently detected damage mechanisms](image_url)
This paper presents the statistical analysis of data collected in the post-earthquake emergency phases on 990 churches, in order to have useful tools for implementing vulnerability analyses on churches. The main objective is to identify a representative subset of recurring typologies of churches found in Central Italy, and to compute Damage Probability Matrices (DPMs).

2 DESCRIPTION OF THE SEISMIC SEQUENCE AND MACRO-SEISMIC SURVEYS

2.1 Central Italy seismic sequence

On August 24th 2016 a $M_w=6.0$ earthquake struck Central Italy causing casualties and significant damages. Its epicentre was located close to the city of Amatrice (lat. $42.70^\circ$ lon. $13.23^\circ$). Successively, numerous shocks were recorded in the surrounding area. The most significant shocks occurred are: $M_w=5.9$ on October 26th, $M_w=6.5$ on October 30th and additional $M_w=5.4-5.5$ events that hit this territory on January 18th 2017 in the Campotosto area.

A brief summary of the main events of the central Italy seismic sequence is reported in Table 1.

<table>
<thead>
<tr>
<th>Seismic Event</th>
<th>Date</th>
<th>Time (UTC)</th>
<th>Lat</th>
<th>Long</th>
<th>$M_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016-2017</td>
<td>1st shock</td>
<td>2016-08-24</td>
<td>01:36:32</td>
<td>42.70</td>
<td>13.23</td>
</tr>
<tr>
<td>Central Italy</td>
<td>2nd shock</td>
<td>2016-10-26</td>
<td>17:10:36</td>
<td>42.88</td>
<td>13.13</td>
</tr>
<tr>
<td>EQ</td>
<td>3rd shock</td>
<td>2016-10-26</td>
<td>19:18:05</td>
<td>42.91</td>
<td>13.13</td>
</tr>
<tr>
<td></td>
<td>4th shock</td>
<td>2016-10-30</td>
<td>05:40:17</td>
<td>42.84</td>
<td>13.11</td>
</tr>
<tr>
<td></td>
<td>5th shock</td>
<td>2017-01-18</td>
<td>09:14:09</td>
<td>42.53</td>
<td>13.28</td>
</tr>
<tr>
<td></td>
<td>6th shock</td>
<td>2017-01-18</td>
<td>09:25:23</td>
<td>42.49</td>
<td>13.31</td>
</tr>
</tbody>
</table>

Table 1: Main shocks of the Central Italy seismic sequence since August 24th 2016 (Data from INGV - http://terremoti.ingv.it).

2.2 Macro-seismic surveys

Following each seismic event, macro-seismic field surveys were performed in order to identify macro-seismic intensity values. The surveys were conducted by the DPC, CNR-IGAG and INGV working group [14][16], according to MCS [17] and EMS98 [18] macro-seismic intensity scales. The aim of this kind of surveys is to find the different effects in terms of damages observed on various building classes. Surveys were performed after every main shock of the seismic sequence (August 2016, October 2016 and January 2017). This means that the surveys done after 18th January 2017 implicitly took into account the cumulative damage effects on the examined buildings [[16][17]. Due to the wide extension of the territory hit by the seismic sequence, several structural typologies were encountered during the inspections, as explained in the following sections.

Based on the technical reports [14][16], a macro-seismic intensity was assigned to each examined church according to both MCS [17] and EMS98 [18] scales. In particular, the maximum macro-seismic intensity registered during the whole seismic sequence prior to the inspection date of the specific church was considered. Since the intensities assigned to each church according to the different scales were very alike, in the following the MCS intensity
scale [17] was chosen as a reference [9]. In Figure 2, the MCS intensity scale map after the October 30th earthquake is reported.

![MCS intensity scale map](image)

Figure 2: MCS intensity scale map after the October 30th earthquake (4th shock) [16].

3 COLLECTED DATABASE

A detailed database made of 990 churches inspected by the University of Padova, together with the University of Naples Federico II and the University of Naples ‘Parthenope’ was constructed. The inspections were located over 14 provinces and 207 municipalities among Abruzzo (123), Marche (678), Lazio (68) and Umbria (121) regions. Out of the 990 inspections, 47 anomalies were found (ruins, churches already declared unsafe) and, thus, the remaining 943 surveys were considered for the following statistical analyses. These surveys do not coincide exactly with the examined churches, since 30 churches were inspected twice. In this framework, the first inspection was only considered, resulting in 913 different churches. Finally, 24 supplementary inconsistencies were found (i.e., churches that suffered very severe damages for extremely low value of PGA ≤ 0.1). Since these results are probably attributable to different sources of damage rather than to the earthquakes, they were excluded from the database and, thus, the final number of churches used for the following analyses is 889.

Figure 3a) shows the distribution of the churches within the regions. Most churches (68%) were located in Marche region, which resulted to be the most shocked region during the seismic sequence. Figure 3b) reports the distribution of the churches for MCS [17] macro-seismic intensity. Correlating the macro-seismic intensity to each church is very useful for subdividing the database in homogeneous areas in order to have a more consistent characterization of the inspections.
3.1 Damage observed

The inspections were performed through the filling of the A-DC survey form [13]. The most relevant outcomes of the form are the usability outcomes and the damage index. Both information are required for properly designing provisional interventions. The survey form provides a formulation for evaluating a global damage index according to Equation (1):

\[ i_d = \frac{1}{n} \sum_{k=1}^{n} d_k \]  

(1)

where \( n \) is the number of activated mechanisms and \( d_k \) is the level of damage recorded for each mechanism, that varies between 0 and 5.

The damage index \( i_d \) can be transformed into a discrete variable according to the following six damage levels individuated by the EMS scale [18], as reported in [9]:
- D0: no damage
- D1: slight damage
- D2: moderate damage
- D3: heavy damage
- D4: very heavy damage
- D5: collapse

The correlation between the damage index and the level of damage is reported in Table 2.

<table>
<thead>
<tr>
<th>Level of damage ( d_k )</th>
<th>D0</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( i_d )</td>
<td>0-0.1</td>
<td>0.1-0.25</td>
<td>0.25-0.4</td>
<td>0.4-0.6</td>
<td>0.6-0.8</td>
<td>0.8-1</td>
</tr>
</tbody>
</table>

Table 2: Correlation between level of damage \( d_k \) and damage index \( i_d \).

Figure 4 shows the correlation between the damage index \( i_d \), as representative of the damages suffered by each structures, transformed into a discrete variable through the correlation of Table 2, and the macro-seismic intensity \( I_{MCS} \), registered at each church location. This is a direct comparison between the damage observed and the seismic input. It can be noted that for increasing values of macro-seismic intensity the damage increases. For \( I_{MCS} \geq \text{VIII} \) about 50% of churches present damage index higher than 0.4.
The A-DC survey form [13] also provides the possibility of assigning a usability outcome to each examined structure. Figure 5 clearly highlights that for an increasing value of seismic input (i.e. IMCS ≥ VII) there is a substantial increase of unsafe conditions (more than 70% of the sample). Nevertheless, unsafe conditions were observed also for low values of macro-seismic intensity (45% for IMCS = VI, 20% for IMCS ≤ V). This could be due to the fact that is more complex to describe a proper correlation between the seismic input and the usability outcome, depending on both the vulnerability of the building and the ground motion characteristics. It is worth noting that the vulnerability of the building could also be related to already existing maintenance problem not directly connected with the seismic event.

Figure 4: Correlation between the damage index and the macro-seismic intensity recorded.

Figure 5: Usability outcomes for different intervals of macro-seismic intensity.

A further study on the possible and activated mechanisms was carried out, as reported in Figure 6. The considered mechanisms are the ones reported in the A-DC survey form.

Figure 6 shows that for the examined database of churches there is a very high possibility of activation for the façade (M1-M2-M3), nave (M5-M6-M8) arches (M13), apses (M16-M17-M18), roof (M19-M21), chapels (M25) and bell tower (M26-M27-M28). The possibility of a mechanism to be activated depends on the presence of the macro-element in the church. For this reason it is more useful to analyse the activated mechanisms, i.e. the mechanisms that were characterized by damage level higher than 0. The highest probability of activation was
encountered for the shear mechanisms of façade and nave lateral walls (M3 and M6). Those macro-elements result to be the most vulnerable to the seismic actions. Conversely, the less frequent mechanisms were porch and narthex (M4), vaults of the lateral naves (M9), transept mechanisms (M10- M11- M12), collapse of the dome and the tiburio and of the lantern (M14 and M15) and hammering and damage in the transept roof (M20). Figure 7 reports some of the most recurrent façade mechanisms found on central Italy churches.

Figure 6: Possible and activated local mechanisms of collapse for the inspected churches.

Figure 7: Façade mechanisms: a) façade overturning in Tempietto Monumentale dell’Assunta church (Ascoli Piceno); b) gable overturning in San Flaviano and San Lorenzo church (Collespada, Accumoli); shear mecha-
nism in the façade of c) SS Cosma and Damiano church (Mozzano, Ascoli Piceno) and d) San Lorenzo church (Cesaventre, Accumoli).

Figure 8 shows further frequent mechanisms found in churches.

Figure 8: Transversal vibration of the nave and shear mechanism on the nave lateral walls in: a) San Bartolomeo (Fonte del campo, Accumoli) and b) San Lorenzo (Cesaventre, Accumoli) churches; c) mechanism in the triumphal arches in Tempietto Monumentale dell’Assunta (Ascoli Piceno); d) shear failure of the apses and presbytery walls in San Bartolomeo (Fonte del campo, Accumoli) church; overturning of the apses in e) San Lorenzo (Cesaventre, Accumoli) and f) San Bartolomeo (Fonte del campo, Accumoli) churches; global collapse of the bell tower of San Bartolomeo (Fonte del campo, Accumoli) church.

3.2 Typological analysis

A detailed analysis on the church typologies was also performed in order to individuate the most significant ad recurrent ones. The first subdivision of the database was made according
to the plan shape of the churches. The seven types of plan shape reported in Table 3 were considered. Most churches from central Italy are characterized by one-nave, with or without apse and/or transept (i.e. type 1, 2 and 3 which totally represent the 71.2% of the whole database).

<table>
<thead>
<tr>
<th>Church typologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Nave churches</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>3 Nave churches</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Circular plan</td>
</tr>
<tr>
<td>Not available</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Table 3: Plan shape distribution

The tower bell typology, the façade and the masonry type were also taken into account for individuating the most recurrent typologies. Four types of façade were identified: triangular, gabled, quadrangular/rectangular and polygonal. Most churches are characterized by a triangular façade (57.3%), as reported in Figure 9a,b. A gabled façade is reported in Figure 9c).

![Figure 9: Statistical distribution of a) façade type: b) San rocco church (San Severino Marche) triangular façade; c) San Filippo neri church (Camerino) gabled façade.](image)

About the bell tower, on almost a half of the inspected churches the presence of a bell gable was found (43%), while for the 51% of the database the bell tower was present and integrated in different parts of the church (Figure 10).

Finally, most churches were characterized by stone masonry (376 churches out of 889), as shown in Figure 11.

It can be concluded the most common church in Central Italy is characterized by one-nave (plan shape 1 or 2), with or without apse, a simple triangular façade, a bell gable and made of stone masonry. The identification of a typical church allows the analysis of a more homoge-
nous dataset, which provides more reliable vulnerability results. For this reason, the following analysis will be presented for the subset made of one-nave churches (633 out of 889).

![Figure 10: Statistical distribution of a) bell tower type: b) San Paolo church (Sefro) bell gable; b) San Lorenzo church (Viterbo) isolated bell tower; c) San Francesco church (Ascoli Piceno) integrated bell tower.](image1)

![Figure 11: Statistical distribution of a) masonry type: a) Abbazia SS Benedetto and Mauro (Monsanpolo del Tronto, AP) brick masonry church; c) Santa Maria Assunta (Frunti, AP) stone masonry church.](image2)

4 DAMAGE PROBABILITY MATRICES (DPMS)

Damage Probability Matrices (DPMs) were computed for the subset of one-nave churches. DPMs are an efficient tool for performing reliable vulnerability analysis [19]-[23]. Through the DPMs it is possible, indeed, to obtain a correlation between the seismic input and the damage observed during the inspections. In order to have homogeneous categories of damaged churches, the database of 633 churches was divided according to four intervals of macro-seismic intensity. The first group ($I_{MCS} \leq V$) counts 360 churches, the second group ($I_{MCS} = VI$) counts 112 churches, the third group ($I_{MCS} = VII$) counts 41 churches while the last group ($I_{MCS} \geq VIII$) counts 93 churches. The statistical elaboration about the observed damage level $d_k$ allowed to obtain the DPMs reported in Figure 12, which shows the percentage of occurrence of a certain damage level for a fixed intensity value. The DPMs were also compared to a binomial distribution, since past studies [9],[24]-[26] showed that it is representative of the distributions obtained from the statistical analysis of damages. The binomial law is reported in Equation (2):
where $p_k$ is the probability of having a $k$-level damage ($k = 0, 1, 2, 3, 4, 5$) and $i_{dm}$ is the mean damage index for each homogeneous group of macro-seismic intensity. According to Figure 12, the binomial law seems to be well representative of the damage distribution.

![Figure 12: DPMs according to different intervals of MCS macro-seismic intensity.](image)

It is important to note that churches characterized by a low macro-seismic intensity ($I_{MCS} \leq V$), suffered low damage (damage level D1-D3). On the other hand, for higher macro-seismic intensities, the percentage of more severe damage (D4-D5) significantly increases to about 50% for churches with $I_{MCS} \geq VIII$.

## 5 CONCLUSIONS

The 2016-17 Central Italy seismic sequence caused numerous damages to the masonry churches located in the four hit regions (Abruzzo, Lazio, Marche, and Umbria). This paper presents some statistical analyses about the damage distribution in a collected database made of 889 churches, which were inspected during the immediate emergency phases following each earthquake.
The seismic events causing damages were examined according to a quantitative approach in terms of macro-seismic intensities based on the MCS scale. Damages were recorded by means of the A-DC survey form and were synthesized by a global damage index. Both damage index and usability outcomes were analysed in function of the recorded macro-seismic intensities. Despite some exceptions, the results showed that safe cases decrease for increasing seismic actions. Nevertheless, it is important also to take into account the previous building safety conditions for assessing the correct seismic vulnerability of the church.

The analysis of the mechanisms evidenced that the most activated ones are M3 and M6, referred to Figure 6.

Successively, a typological description of the inspected churches was performed with reference to: plan shape, tower bell typology, façade and masonry type. The statistic analysis shows that the typical church of central Italy is characterized by one-nave plan, made of stone masonry, with or without apse, a simple triangular façade, a bell gable. For a reduced database only including one-nave churches, Damage Probability Matrices were also produced. The relationship between the observed damage and the seismic action in terms of macro-seismic intensity showed that churches characterized by a low macro-seismic intensity suffered low damage (damage level D1-D3), while for higher macro-seismic intensities more severe damage (D4-D5) was observed.

The computation of DPMs is an essential tool for setting up fragility curves for a homogeneous class of churches, which will be further investigated, in order to define the best strategies for interventions.

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