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Seismic damage survey and empirical fragility curves for churches after the August 24, 2016 Central Italy earthquake

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ABSTRACT

This paper presents the results of a damage survey conducted on a wide stock of churches in Central Italy, hit by the August 24, 2016 Amatrice seismic sequence. In the weeks following the mainshock, the authors performed a damage assessment of 196 churches in the area involved by the seismic event, aiming to identify damage mechanisms and calculate damage index for each structure. Churches have similar characteristics within the analyzed area, with typical architectural elements, homogeneous structural types and similar construction materials. A discussion presents the main evidences observed during the survey and, lastly, empirical fragility functions are derived for this specific structural type.

1. Introduction

Damage reports developed after recent earthquakes demonstrated that churches are vulnerable structures, such as many other historical buildings [1–3]. This leads to the consequence that a significant portion of the Italian cultural heritage is prone to seismic risk. Indeed, these structural types were often built with unreinforced stone masonry, having significant lack of construction details. Many researchers carried out seismic damage survey of churches after past earthquakes in Italy [4,5] and in other countries prone to seismic hazard [6–8]. In this paper the results of an extensive damage survey conducted on 196 churches hit by the August 24, 2016 Amatrice earthquake of moment magnitude M_w 6.0 are presented. The epicenter of the M_w 6.0 mainshock was located between the Municipalities of Accumoli and Amatrice (42.70°N–13.24°E), in the Lazio region, by the Istituto Nazionale di Geofisica e Vulcanologia seismic network [9].

The area between Lazio, Umbria, Marche and Abruzzo regions, struck by the 2016 Amatrice earthquake sequence, is significantly prone to earthquakes: in the last 20 years, other devastating events occurred with epicenters located at about 30 km far from the actual one (April 6, 2009 M_w 6.29 L'Aquila event and 1997 Umbria seismic sequence with a M_w 5.97 mainshock). According to the *Parametric Catalogue of Italian Earthquakes* (*CPTI*15) [10], historical information reveals that the seismic activity in the Monti Sibillini area is frequent. In the past centuries, highly destructive events occurred indeed: from the eighteen century, a mean annual rate of about 0.25 events with magnitude $M_w > 4.0$ was observed. Fig. 1 shows the macroseismic intensities (in terms of macroseismic intensity $I_{O\text{-}MCS}$) historically recorded in the area of Accumoli.

First evidences of damage induced by earthquake occurrences in the area of Accumoli were related to the effects of the July 1627 Monti della Laga event [11]. It was followed by the severe October 7, 1639 [12] Amatrice earthquake, that seems very similar to the actual seismic scenario. The Accumoli area suffered extensive damage also after the most destructive January 14, 1703, and was re-struck by the May 12, 1730 Valnerina event [13]. After about 150 years, these territories were hit again by the November 7, 1883 Monti della Laga earthquake, and in the twentieth century by other significant events, with $I_{O\text{-}MCS}$ 7–8 in 1916, 1950 [14]. Table 1 lists the historical events with macroseismic intensities at least equal to $I_{O\text{-}MCS} = 5$, related to Accumoli Municipality from the 16th century.

Along this paper, results of an extensive damage survey carried out on a stock of 196 churches in Lazio, Umbria, Marche and Abruzzo regions are illustrated. The aim of this work is to give a clear overview of the main deficiencies and collapse mechanisms of the macro-elements observed after the event. In the first part, a brief overview about the surveyed structures, visual inspection criteria and mainshock earthquake scenario is provided. In the second part of the work, the most common structural types and damage observed are discussed. A key issue of this contribution is that the observed damage can be reasonably associated with the mainshock sequence, since no other significant aftershock occurred in the following 50 days, potentially leading to a remarkable damage increase hence, in such a way damage state probabilities can be directly linked to a scenario event. Lastly, empirical

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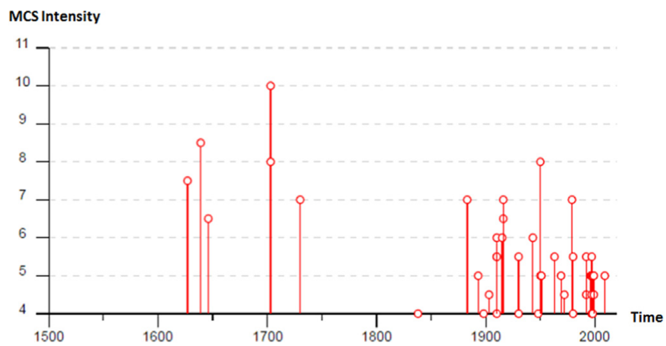

Fig. 1. Macroseismic intensity $I_{O\text{-}MCS}$ - time plot for the Municipality of Accumoli.
(source: CPTI15 [10]).

fragility functions are calibrated on the basis of the damage survey outcomes: this is the first study in which empirical fragility functions are presented for Italian churches in terms of ground motion parameters (i.e. peak ground acceleration, *PGA*), thus allowing further comparisons with future research.

2. Structural characteristics of the analyzed churches

A peculiar structural type characterizes the stock of analyzed churches in the area hit by 2016 Amatrice earthquake, which significantly differs from the ones damaged in the 2009 L'Aquila and the 2012 Emilia Romagna earthquakes. In the current case, urban areas mainly consist of small municipalities, each with numerous, sparse and few populated hamlets: for example, the Municipality of Amatrice, one of the most affected centers, is divided into 49 hamlets, with a total population of 2650 inhabitants. These villages are essentially groupings of houses, located on hilltops, small valleys or plateaus, and most of them have a small local church situated right at the center. These churches were often built by members of the community, with poor quality local materials, and were based on simple architectural forms, typically much smaller than traditional Italian ones. The historical seismicity significantly influenced structural type evolution of churches in this area, leading in many cases to the construction of small single nave churches. Indeed, about 90% of the surveyed churches are characterized by a single nave plant, often without apses (Fig. 2), with recurrent geometrical and structural characteristics. Typically windows are located on the two long sides of the church, and on the short side, opposed to the main façade. The remaining 10% of the churches refers to those situated in the main cities (i.e. Norcia, Cascia, Camerino etc.), of which geometry is more complex than the previous ones.

Side walls of the "Apennine church" type are generally made of stone masonry, and in most cases are unplastered. Longitudinal walls support wooden trusses, which are the bearing structure for the double-pitched roof. The front façade has instead a rose window over the main entrance, and often there is also a triangular or rectangular parapet, whose height exceeds the ridge of the roof. In many cases a bell tower or a two-dimensional element is also present.

3. Dataset of analyzed churches and visual inspection methodology

A total number of 196 churches were surveyed in the area hit by the 2016 Amatrice earthquake. Appendix A lists the identification number (*ID*) and municipality for each church. The majority of the structures (136/196) were located in small villages, as stated in Section 2. Fig. 3 shows the shake map of the event in terms of *PGA* distribution, and the location of the inspected churches within the hit region. The *PGA* shake map provided by the Italian Institute of Geophysics and Vulcanology (*INGV*) was used as a reference representation of the ground shaking of the event, necessary for the following calibration of empirical fragility functions. Since this area is historically prone to seismic events, a suitable number of record stations was installed over the years for a reliable monitoring of the seismicity. However, for improving the accuracy in ground motion distributions, the ShakeMap program uses also predicted values in those areas with an insufficient number of recordings. This allows to stabilize contouring and minimize misrepresentation due to lack of data [15]. In spare regions, peak motion amplitudes are indeed estimated from the event magnitude and epicenter coordinates, through proper attenuation curves [16].

Table 1
Accumoli historical seismic catalogue ($I_{O\text{-}MCS} \geq 5$). (source: CPTI15 [10]).

Year	Month	Day	Area hit by the event	Epicentral intensity ($I_{O\text{-}MCS}$)	Intensity felt in Accumoli (I_{MCS})	M_w
1627	07	–	Monti della Laga	7–8	7–8	5.33
1639	10	07	Monti della Laga	9–10	8–9	6.21
1646	04	28	Monti della Laga	9	6–7	5.90
1703	01	14	Valnerina	11	10	6.92
1730	05	12	Valnerina	9	7	6.04
1883	11	07	Monti della Laga	7	7	5.10
1893	08	02	Valnerina	5–6	5	4.55
1910	12	22	Monti della Laga	5–6	5–6	4.30
1910	12	26	Monti della Laga	6	6	4.56
1915	01	13	Marsica	11	6	7.08
1916	07	04	Monti Sibillini	6–7	6–7	4.82
1916	11	16	Alto Reatino	8	7	5.50
1930	04	07	Monti Sibillini	5–6	5–6	4.50
1950	09	05	Gran Sasso	8	8	5.69
1951	09	01	Monti Sibillini	7	5	5.25
1963	07	21	Monti della Laga	7	5–6	4.71
1979	09	19	Valnerina	8–9	7	5.83
1980	02	28	Valnerina	6	5–6	4.97
1992	10	24	Monti della Laga	5–6	5–6	4.08
1997	10	20	Appennino laziale-abruzzese	5	5	4.36
1997	09	26	Appennino umbro	7–8	5	5.66
1997	09	26	Appennino umbro	8–9	5–6	5.97
1997	10	06	Appennino umbro	–	5	5.47
1997	10	14	Valnerina	–	5	5.62
1998	03	21	Appennino umbro	–	5	5.00
1999	11	29	Monti della Laga	5–6	5	4.15
2009	04	06	Aquilano	9–10	5	6.29