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EMPIRICAL SEISMIC FRAGILITY CURVES OF THE MARCHE REGION CHURCHES DERIVED FROM THE 2016 CENTRAL ITALY EARTHQUAKE

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Abstract: *2016 Central Italy seismic sequence seriously damaged many historical buildings of the Italian cultural heritage, especially churches. The damage of churches is due to intrinsic peculiarities of their structural systems, not capable to develop an efficient box-like resisting mechanism. Teams of technicians coordinated by the Department of Civil Protection and the Ministry of Cultural Heritage and Tourism carried out a substantial survey of churches to assess the occurred damage and their usability by registering occurred damages in a specific survey form. In this paper, a methodology for processing damage data collected in the survey of Marche Region churches is addressed in order to propose a probabilistic response model. Descriptions of the seismic sequence of Central Italy 2016 and of main characteristics of the church sample are illustrated. Churches are grouped into homogeneous typologies characterised by similar structural response, in order to derive empirical fragility curves and damage index functions. A new fragility model is proposed for the considered dataset by evaluating relevant parameters using the Maximum Likelihood Estimation. Finally the global damage index function is derived from the defined fragility curves and compared with the curve obtained by fitting data registered on field with a Sum Square Estimation technique.*

Introduction

Churches in Central Italy are widespread buildings constituting an important component of the Italian cultural heritage due to their historical and artistic value. Their architecture is characterised by recurrent structural subsystems, commonly denoted by macro-elements (e.g. façade, side walls, transept, apse, nave and side aisles), which tend to exhibit independent seismic responses (Doglioni et al., 1994). Macro-element independent behaviour is due to considerable size of the walls in plan and elevation, absence of intermediate floors, poor interlocking of the walls, presence of arches and vaults, and presence of deformable wooden roofing.

Studies carried out on damages occurred to churches following the earthquakes of Friuli 1976 (Doglioni et al., 1994), Umbria-Marche 1997 (Lagomarsino and Podestà, 2004a, b), Molise 2002 (Lagomarsino and Podestà, 2004c), L'Aquila 2009 (Lagomarsino, 2012) and Emilia 2012 (Indirli et al., 2012; Sorrentino et al., 2014) demonstrated that the damage mechanisms have recurrent characteristics, despite the uniqueness of each building.

Starting from the knowledge gained in previous studies carried out after major seismic events, in this work the authors post-processed the first data on the damages suffered by the cultural heritage of the Marche region with the goal of identifying the relationships between observed damage and earthquake intensity. A probabilistic response model is proposed by considering a subset of data collected from post-earthquake investigations of about 550 churches, carried out after the main shocks of the seismic sequence of the 2016 Central Italy Earthquakes. In this study only the set of simple plant churches are considered, making statistical observations on the possible (activated or not activated) mechanisms and on the damage. For this reduced dataset, a new probabilistic model is proposed to evaluate empirical fragility curves relevant to the overall damage, calculating the parameters by the Maximum Likelihood Estimation (MLE) (Thaut Dang et al. 2017, Straub et al. 2008, Lallemant et al. 2015). Finally global damage index function is

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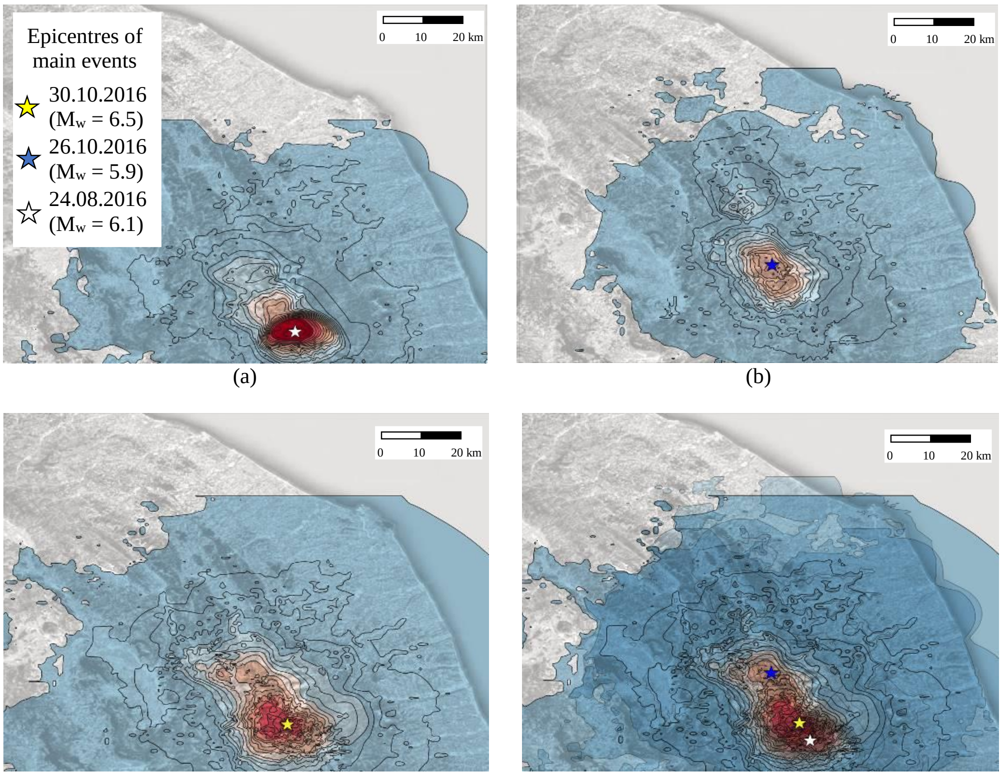
derived from the defined fragility curves and compared with the curve obtained from data fitted by means of Sum Square Estimation technique (SSE).

Central Italy seismic sequence

Seismic sequence occurred in 2016 in Central Italy began on August 24th with a M_W=6.1 earthquake, causing 299 fatalities and important damages to buildings implying huge economic losses. Its epicentre was at 1 km W from Accumoli, and the Peak Ground Accelerations (PGAs) recorded nearby the epicentre was about 0.45g. A second strong event characterised by Mw=5.9 occurred on October 26th 3 km away from Visso, extending the activated seismogenic area toward NW. Four days later, on October 30th, a third earthquake with Mw=6.5 occurred 4 km NE from Norcia. During this last mainshock, the maximum PGA recorded nearby the epicentre was about 0.48g. Moreover, the area was interested by about 6500 aftershocks with Mw ranging from 2.3 to 5.5, occurred between August 2016 and January 2017. Figure 1 shows the locations of the mainshock epicentres, the shake maps of the three main events, reporting the distribution of PGA, and their envelope. These shake maps have been obtained by handling the shake data provided by the Italian National Institute of Geophysics and Volcanology (INGV. Shake maps data) through the QGIS Opensource GIS software (QGIS. Development Team 2015). The value of PGA processed by INGV is referred to stiff soil characterised by shear wave velocity higher than 800 m/s and it is estimated by means of empirical attenuation laws starting from shakings recorded in the accelerometric stations distributed over the territory. It should be noted that the PGA estimated by INGV does not include possible local shaking amplification due to the geological conditions.



(a) (b)

(c) (d)

Figure 1. Shake maps of the main events, (a) August 24th event, (b) October 26th event (c) October 30th event, and (d) envelope of the 2016 seismic sequence.

Dataset of analyzed Churches

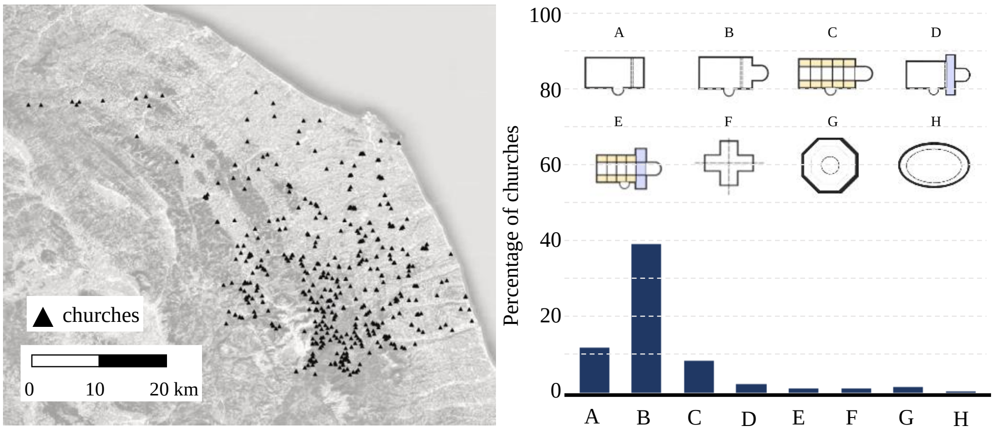
Database Construction

After the sequence of seismic events started in Central Italy on August 24th, 2016, several teams of specialized technicians were charged to examine the damage suffered by churches. Their main task was to fill in the damage survey forms, relevant to the damage detection and classification, with the aim of providing useful information for the public safety, identifying situations requiring urgent and provisional interventions.

Teams, coordinated by the Department of Civil Protection (DPC) and the Ministry of Cultural Heritage and Activities, and Tourism (MiBACT), were composed by MiBACT's officials, by structural engineers belonging to the Seismic Engineering Laboratory Network (ReLUIS), and by members of the National Fire Corps (Italy) to grant safe access to the damaged structures.

During inspections, the A-DC damage survey form (Modello A-DC PCM-DPC MiBACT, 2006) were compiled, collecting general data of the building (name, geographical position, historical dating, contained mobile goods, etc.), data of the planar-volumetric organization of the main elements of the building (e.g. central nave, apse, transept, façade) and its state of conservation. In addition, in a specific section of the survey form, the macro-elements that could be potentially activated, their relevant level of occurred damage and the nature of the damage (seismic or non-seismic) were registered. Furthermore, access restrictions and the need of urgent and provisional interventions to assure the public safety and the heritage conservation were included in the survey form.

The present study based on the sample data used in Carbonari et al. (2019), consisting of about 550 churches spread over the Marche Region except for the areas close to the epicentres, for which data relevant to inspections were not available (Figure 2a).



(a) (b)

Figure 2. (a) Churches location, (b) typological classification of churches

General Information of the Marche Region churches

A classification of the churches is provided following the one presented in Carbonari et al. (2019), considering different representative architectural typologies, useful to highlight possible vulnerabilities related to the plan organization. Thanks to this classification, it is possible to deduce information on the state of conservation of the churches, being reasonably the hypothesis that important churches were subjected to periodic maintenance. Based on the general information collected in the survey A-DC forms, eight typologies of churches are proposed according to Carbonari et al. (2019):

A. One-nave church;
B. One-nave church with apse;
C. Three-nave church with apse;
D. One-nave church with transept and apse;
E. Three-nave church with transept and apse;

F. Greek cross plan church
G. Octagonal plan church;
H. Elliptical plan church.

Based on this classification, 70% of the sample falls into typologies A and B, 22% in the C-H typologies, and remaining 8% of the sample does not belong to any classes due to a lack of data contained in the A-DC damage survey forms (Figure 2b). Distribution of the churches based on the plant area is analysed and 70% of them present an area less than 200 m^2.

According to the statistical results explained above, the sample considered now on is the one formed by the about 370 churches falling in class A or B.

Results of the damage survey

The church seismic damage is evaluated with reference to the 28 mechanisms considered in the A-DC form, according to the Italian guidelines for cultural heritage (Figure 3). Six levels of damage d_k $(k = 0 \div 5)$ have been defined according to the general observational criteria introduced by EMS-1998 (Grunthal 1998). In particular, for each macroelement, the damage levels are defined as: d_0 no damage, d_1 negligible structural damage to slight non-structural damage (few hair-line cracks in very few parts of the macroelement), d_2 slight structural damage and moderate non-structural damage (many cracks with falling of fairly large pieces of plaster), d_3 moderate structural damage and heavy non-structural damage, with large and extensive cracks (failure of individual non-structural elements if present; activation of the first out-of-plane mechanisms), d_4 heavy structural damage and very heavy non-structural damage (complete development of first-mode mechanisms), and d_5 very heavy damage (total or near total collapse of the macroelement).

The damage state of the j-th potential mechanism is denoted by $d_{k,j}$. With reference to the sample of churches falling in class A or B, Figure 4 shows the comparison between the percentage of potential mechanisms that could be activated and the percentage of mechanisms that have been actually activated with a damage level equal or higher than $d_{1,j}$. The distribution of potential mechanisms that could be activated, highlights that most of them are referred to the façade (M01-M02-M03) and to the lateral walls, both in-plane (M06) and out-of-plane mechanisms (M05-M19).

By associating a score k ranging from 0 to 5, to each damage level d_k an overall damage index i_d can be derived for each church by the expression (Lagomarsino and Podestà 2004a)

$$i_d = \frac{1}{5N_m}\sum_{j=1}^{N_m} d_{k,j} \tag{1}$$

In Equation (1), N_m is the number of potential mechanisms. This overall index has a value between 0 (undamaged state) and 1 (total collapse) and measures overall damage of each church. In order to make this damage index consistent with the classification of EMS-98 intensities defined for buildings, its range of variation is divided into six intervals associated to six damage levels d_k as shown in Table 1 (Lagomarsino and Podestà 2004a,b; De Matteis et al., 2016). Figure 5 reports, for each damage level, the percentage of churches falling within each interval; in particular 8% presents damage level d_0, 46% presents damage level d_1, 26% damage level d_2, while 15%, 3% and 2% damage levels d_3, d_4 and d_5, respectively.

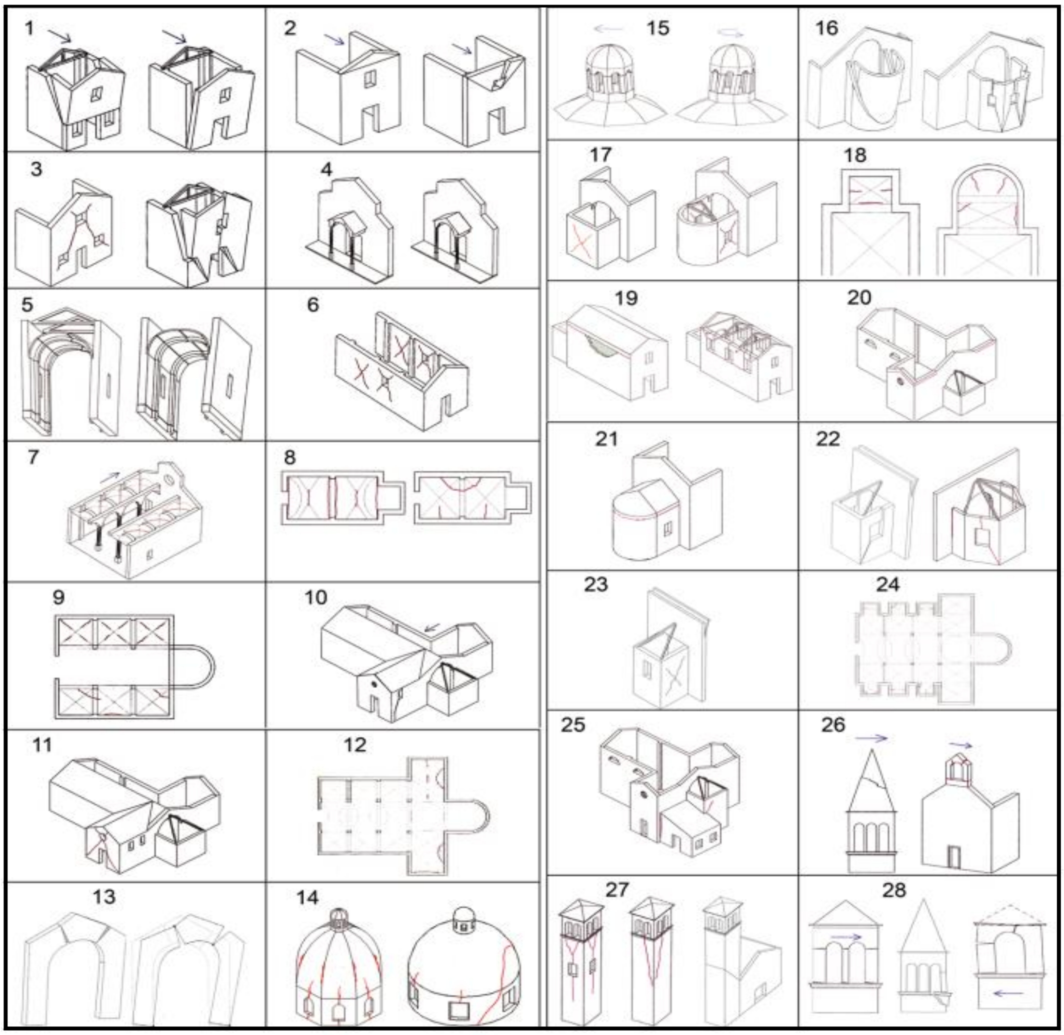


Figure 3. Damage mechanisms for churches provided in the A-DC 2006 form (Modello A-DC PCM-DPC MiBACT, 2006).

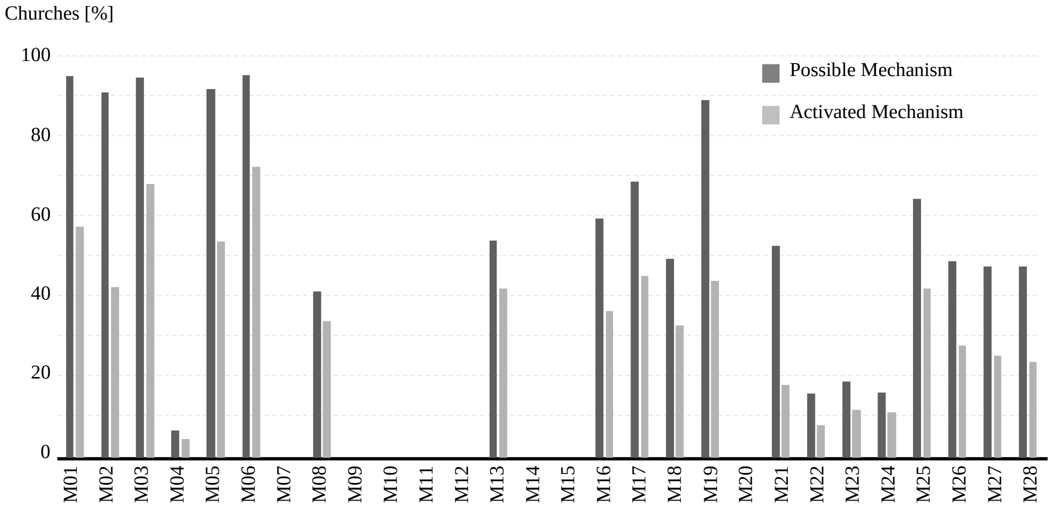
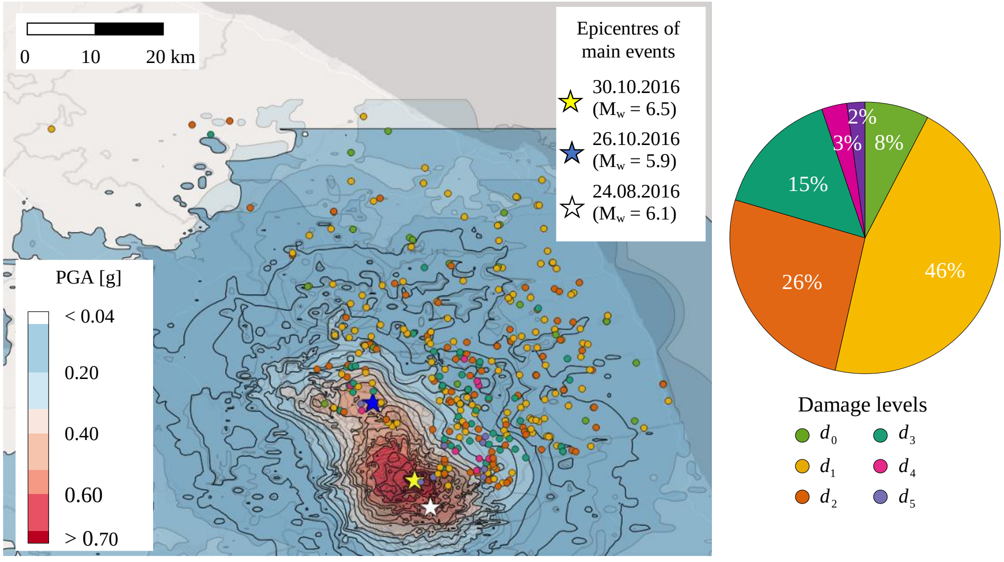


Figure 4. Comparison between possible/activated damage mechanisms for A and B churches typologies.

Level	Damage Score	Description
d_0	$i_d \leq 0.05$	No damage: light damage only in one or two mechanisms
d_1	$0.05 < i_d \leq 0.25$	Negligible to slight damage: light damage in some mechanisms
d_2	$0.25 < i_d \leq 0.40$	Moderate damage: light damage in many mechanisms, with one or two mechanisms active at medium level
d_3	$0.40 < i_d \leq 0.60$	Substantial to heavy damage: many mechanisms have been active at medium level with severe damage in some mechanisms
d_4	$0.60 < i_d \leq 0.80$	Very heavy damage: severe damage in many mechanisms, with the collapse of some macroelements of the church
d_5	$i_d > 0.80$	Destruction: at least 2/3 of the mechanism exhibit severe damage

Table 1. Definition of structural damage levels based on damage index i_d (Lagomarsino and Podestà, 2004b).



(a) (b)

Figure 5. (a) Shake maps of PGA and indications of overall damage of A and B churches (b) distribution of the damage levels for A and B churches.

Definition of fragility curves

Fragility curves describe the probability of exceedance of a given damage level as a function of the intensity measure of the seismic ground motion. Generally, the damage state is described by a discrete variable d_k $(k = 0,1,..,N_D)$ which denotes the damage within a finite number $N_D + 1$ of ordered possible damage states. By denoting by D the random variable that describes the church damage, the fragility curve $G_D(d_k \mid i)$ $(k = 1,..,N_D)$ describes the probability that, for a seismic intensity i, the damage state is equal or higher than d_k. Usually, the fragility curves are efficiently approximated by the two-parameter function (Singhal et al. 1996, Ibarra et al. 2005, Bradley et al. 2008):

$$G_D\left(d_k \mid i\right) \approx \Phi\left[\frac{\ln\left(i\right) - \mu_k}{\beta_k}\right] \tag{2}$$

where Φ is the cumulative normal distribution function, i is the intensity measure expressed in PGA and μ_k and β_k are the two-parameters associated to the response of the structure.

Data observed from churches consist of pairs $\left(d_m, i\right)$ where the measure of experienced damage state d_m, is derived from the damage index i_d on the basis of the equivalences reported in Table 1, and the intensity measure i if obtained from the shaking registered on site.

On the basis of the assumed probabilistic model, given an intensity measure i, the probability to observe a damage d_m equal or higher than d_k can be expressed as:

$$p\left[d_m \geq d_k \mid i\right] = G_D\left(d_k \mid i\right)^y \left(1 - G_D\left(d_k \mid i\right)\right)^{1-y} \tag{3}$$

where y is a binary variable that is equal to 1 if $d_m \geq d_k$, 0 otherwise. Considering a number of observations $\left(d_{m,l}, i_l\right)$ with $l = 1,..,N$ where N is the total number of observed churches and assuming that data are independent and identically distributed, the associated likelihood function L_k for the general damage level d_k can be defined as follows (Thaut Dang et al. 2017, Straub et al. 2008, Lallemant et al. 2015).

$$L_k\left(\mu_k, \beta_k\right) = \prod_{l=1}^{N} p\left[d_{m,l} \geq d_k \mid i_l\right] \tag{4}$$

The values of μ_k and β_k are obtained maximizing the likelihood function L_k for each damage level d_k:

$$\left(\hat{\mu}_k, \hat{\beta}_k\right) = \arg\max\left(L_k\left(\mu_k, \beta_k\right)\right) \tag{5}$$

Figure 6 reports the fragility curves obtained considering the expression proposed in Equation 2 and 5 pairs of parameters $\left(\hat{\mu}_k, \hat{\beta}_k\right)$ estimated by Equation 5 and reported in Table 2.

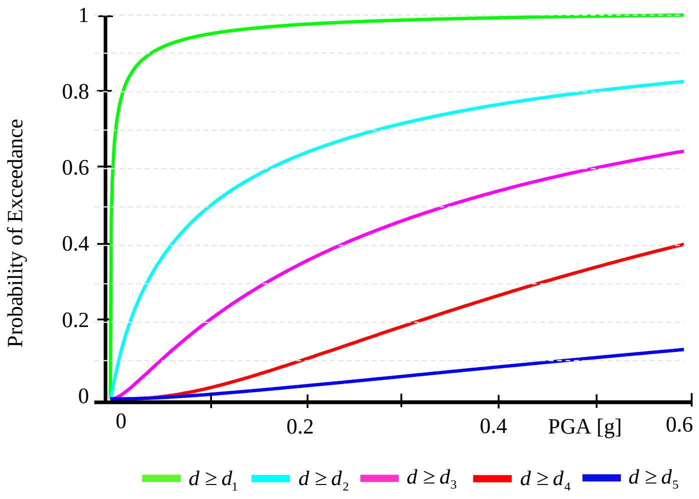


Figure 6. Fragility curves for damage levels from d_1 to d_5

	$d \geq d_1$	$d \geq d_2$	$d \geq d_3$	$d \geq d_4$	$d \geq d_5$
$\hat{\mu}_k$	-6.6175	-2.2346	-1.0242	-0.2291	1.2783
$\hat{\beta}_k$	2.8691	1.9379	1.4893	1.0708	1.5663

Table 2. Parameters of the fragility curves derived by the MLE

Global damage function

In this section, the relationship between the seismic intensity i and the expected overall damage index i_d is analysed. This information can be recovered by computation from the probabilistic model defined in the previous section or can be directly determined by interpolation techniques, starting from surveyed pairs $\left(i_{d,j}, i_j\right)$. The results coming from the two approaches are compared in the following. The damage functions, derived by the former and latter approach, are denoted by $I_C(i)$ and $\overline{I}_C(i)$ respectively. For what concerns the former approach, the probability $f_D\left(d_k \mid i\right)$ that a church is in the *k*-th damage state, given the intensity i, can be derived from the previous fragility curves as follows:

$$f_D\left(d_k \mid i\right) = \begin{cases} 1 - G_D\left(d_1 \mid i\right) & k = 0 \\ G_D\left(d_k \mid i\right) - G_D\left(d_{k+1} \mid i\right) & k = 1, 2, .., N_D - 1 \\ G_D\left(d_{N_D} \mid i\right) & k = N_D \end{cases} \tag{6}$$

The model provided by the fragility curves collects, in each damage state d_k, values of the overall index i_d belonging to the intervals reported in Table 1 and does not provide information about the distribution of i_d values within each interval. In order to estimate the mean response for each intensity i, it is assumed that the mean of the indexes belonging to each interval, coincides with the centre of the interval itself. Consequently, the mean damage indexes for the six damage states are: 0.025, 0.15, 0.325, 0.50, 0.70, and 0.90.

On the other hand, the second approach is based on the definition of a reference curve starting from the experimental data. The data were fitted considering a two-parameter function (Baker, 2015)

$$\overline{I}_C(i) = \Phi\left(\frac{\ln(i) - \overline{\mu}}{\overline{\beta}}\right) \tag{7}$$

and the parameters $\overline{\mu}$ and $\overline{\beta}$, evaluated through the Sum Square Estimation technique (SSE) assume the values -0.523 and 2.991, respectively. In this case no statistical meaning can be associated to the curve obtained.

Figure 7 reports the global damage index function obtained from the fragility functions (blue curve), and the dot points represents the expected damage index derived from fragility curves for the sample of churches considered. The red curve depicts the empirical damage index fitted by the SSE technique. The global damage index evaluated starting from the fragility curves is in agreement with the one obtained from the data fitted with the SSE.

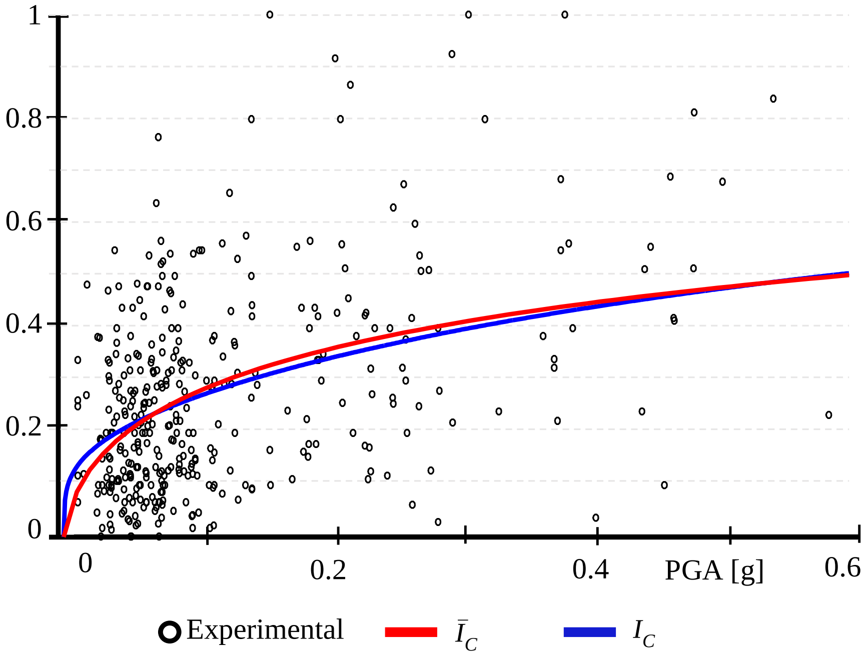


Figure 7. Global damage index functions obtained from the fragility functions and from the experimental data fitted by SSE

Conclusions

The problem of defining probabilistic damage models for churches is approached by exploiting data provided by the survey carried out after the seismic sequence of the 2016 Central Italy Earthquake. A methodology to process data aimed at defining relationships between the observed damage and the seismic intensity, has been proposed. The sample consists of churches characterised by the most diffused typologies in the Central Italy territory that have similar structural response.

A statistical processing of the major possible/activated mechanisms has been presented and synthetically discussed highlighting the most diffused ones.

A new form of fragility model has been proposed by evaluating relevant parameters using the Maximum Likelihood Estimation for the selected dataset.

The relationship between the seismic intensity and the expected overall damage index are defined, by using two different strategies. The first one is based on the computation of a global damage index function from the model provided by the fragility curves previous defined. The second one is obtained with a simple interpolation technique based on the Sum Square Estimation technique by assuming a two parameter functions as mathematical model. A good agreement is observed between the two approached.

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