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DERIVATION OF EMPIRICAL FRAGILITY FUNCTIONS FROM THE 2009 AQUILA EARTHQUAKE

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ABSTRACT

In the past 30 years, Italy has experienced multiple damaging earthquakes. These have produced a wealth of post-event damage survey data, which can be used for the construction of empirical fragility curves for the Italian building inventory. The present study focuses on the construction of empirical fragility curves using data for 24911 residential buildings collected in the aftermath of the 2009 Aquila Earthquake. A detailed GIS database is developed based on building stock information for the entire municipality territory through data made available by the Special Office for the Reconstruction of L'Aquila (USRA). It includes building usability rating, damage state, building typology and soil information derived from microzonations maps. Using soil type information at each building site, PGA values are derived through different Ground Motion Prediction Equations and compared to the ones estimated through the INGV Shakemap. Adopting an advanced non-linear regression procedure, fragility functions are then constructed in terms of usability rates for different building classes, characterised by their main construction material. The resulting curves exhibit certain anomalies compared to existing fragility functions that is shown to be related to adoption of usability data rather than damage data, for the analysis. Indeed, building safety evaluations may not reflect the sustained structural damage. Moreover it is shown that the conventional assumption that 'unusable' corresponds to 'partial collapse' or similar damage state is invalid, and the conversion between the two scales should not be adopted for the construction of fragility functions.

Keywords: Fragility Functions; Aquila Earthquake; Post-Earthquake Damage Data; Damage Scale; Building Safety Classification;

1. INTRODUCTION

Fragility curves (FCs) are key to the assessment of seismic risk of the building inventory. These curves represent the level of damage as a function of the ground motion intensity measure and the structural characteristics of the building inventory. The relative frequency of strong seismic events in Italy provides a wealth of damage data, which can be used for the empirical construction of FCs.

The present study aims to construct empirical FCs focusing on data from the 2009 L'Aquila earthquake (Figure 1). The Mw=6.3 event occurred along the Paganica Fault, a normal fault in the central Apennines. The hypocentre had been estimated with a depth of 8.3 km, whereas the epicentre (42.35N, 13.38 E) had been located only 3.4 km southwest of the city of Aquila (Rovida *et al*., 2016). The consequences of the earthquake were devastating, due to the high urban density of the area (Alexander, 2010). The event gravely damaged over 60000 buildings in 16 different municipalities, causing 308 casualties, roughly 150 injuries and 67500 people were left homeless (Alexander, 2010).

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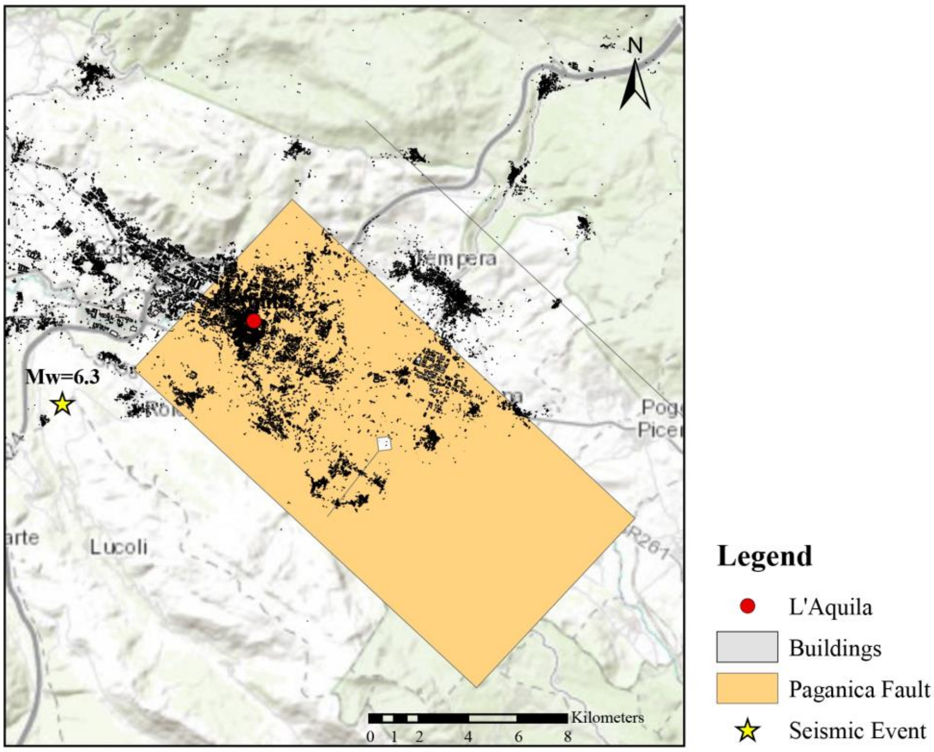

Figure 1. L'Aquila Earthquake and Paganica Fault.

Several studies have looked at the large amount of data on the earthquake consequences that was collected in the aftermath of the event for the development of empirical FCs (e.g. Liel & Lynch, 2012, De Luca *et al*., 2015; Del Gaudio *et al*., 2017). Different sample sizes of the affected damage buildings have been used in each study, and with the exception of Liel & Lynch (2012) who collected their own damage data, most past FC studies for L'Aquila (e.g. De Luca *et al*., 2015; Del Gaudio *et al*., 2017) have used data derived from post-earthquake safety assessments made by the the Department of Civil Protection (DCP). The latter conducted post-earthquake surveys of buildings using the AeDES forms described in Baggio *et al*. (2007), with the primary aim of assessing the 'usability' of ordinary, typically residential, buildings in the emergency phase following the earthquake.

Prompted by the 2009 earthquake, a detailed microzonation study was carried out by a working group comprising the DCP and several universities (MS-AQ Working Group, 2010) to better understand geologic, geomorphologic, geotechnical, and geophysical features of the L'Aquila's area. Despite this, all the aforementioned FCs have adopted as their ground motion intensity measure peak ground acceleration (PGA) estimated through the INGV Shakemap (http://shakemap.rm.ingv.it/shake/index.html), which is only a first-order assessment of the experienced ground shaking (Michelini *et al*., 2008). In addition, novel and statistical data analysis techniques have been proposed by the GEM Guidelines (Rossetto *et al*., 2014). These constitute a considerable improvement compared to the statistical models used in the aforementioned studies.

In the present research, the GEM methodology is adopted to construct empirical FCs for masonry and reinforced concrete (RC) buildings using data from 24,911 buildings collected from both the parametric forms of the Special Office for the Reconstruction of L'Aquila (Ufficio Speciale per la Ricostruzione dell'Aquila, USRA) and the DPC's safety classification map. The focus of this research is the sensitivity analysis of the derived functions to the ground motion prediction method (i.e. Shakemaps vs GMPE), and an evaluation of the suitability of safety evaluation data for use in FC construction. In the next section, a detailed description of the post-disaster database adopted from this study is presented followed, in Section 3, by the statistical analysis of the dataset and Conclusions in Section 4.

2. THE 2009 L'AQUILA EARTHQUAKE DATABASE

The 2009 earthquake affected an area in the central section of the Apennines mountain chain, which runs the length of the country. The main municipality affected was L'Aquila, a moderate-sized city (466 km2) located in Central Italy approximately 100 km northeast of Rome. The city itself is enclosed by medieval walls, surrounded by high-density quarters, and more sparsely populated suburbs such has Coppito and Pettino. The surrounding area, always within the municipal borders, also includes several scattered villages like Onna, Paganica, and Tempera which were severely damaged by the event (Ricci *et al*., 2011).

In what follows, the multiple sources of the adopted data are discussed together with the main variables used for the construction of FCs, namely: the usability scale, the buildings characteristics and the intensity measure are presented.

2.1 Data Sources

Building data related to the L'Aquila earthquake are available from multiple sources. The AeDES forms and the ReLUIS database are identified as the best data for analysis, but unfortunately, a number of constraints on availability of these data meant that they could not be used in this study. Other sources of data provided by the USRA office and L'Aquila Council are instead adopted.

Detailed building information is made available through the Special Office for the Reconstruction of L'Aquila (USRA) parametric forms. This dataset (received in mid-October 2016 and still ongoing) contains 775 masonry and 88 RC buildings. It enclosed data regarding typology, usage, material, number of floors, volume, year of construction, seismic code adopted, and strengthening interventions effected. It also categorises building using the EMS-98 damage scale (Grunthal, 1998). However, the number of buildings with damage information corresponds to only 2.87% of the total number presented in the cadastral map (30,082 buildings) on which the dataset is based, resulting in a limited amount of data. Compared to this relatively small damage dataset, a significant amount of data based on the safety classification are accessible. Indeed, L'Aquila Council has implemented the DCP map developed in agreement with the AeDES forms into the Cadastral one, resulting in 26697 buildings (88.75% coverage) being attributed a usability rating.

The database used for the current research is developed building-by-building starting from the Cadastral map made available in GIS format from L'Aquila Council. All data from the various sources previously mentioned are joined in ArcGIS to enable each building to be characterised by as much detailed information as possible. The map is then cross-referenced with the Regional Technical Map (CTR) to eliminate special types of structures (e.g. monuments, churches, and barns). After the cleaning procedure, the database contains information for a total of 24,911 buildings.

The database obtained can be evaluated as high quality for its coverage. It presents the entire building stock of L'Aquila and, for each building, geographical coordinates are known. The sample size is one of the most important features that determine the reliability of the mean FCs (Rossetto & Ioannou, 2017). The availability of a such large dataset is indeed in contrast with the majority of the studies available in the literature, which tends to aggregate data into 'bins' of similar ground motion intensities values (e.g. Rota *et al.*, 2008). However, a limitation of the present database is the lack of building height, age, and typology, which are not available for all buildings. Also, residential buildings are not easily distinguished from other construction types, such as schools and hospitals. Indeed, only structures with similar characteristics should be included in a database to avoid uncertainties in the fragility assessment, as suggested in Rossetto and Elnashai (2003). An improvement for the database could be achieved through an extensive analysis of the USRA parametric forms when the reconstruction process will be completed, and this information becomes available.

2.2 Building Classes

Building structural and non-structural characteristics need to be defined to class together buildings with similar seismic performance to obtain reliable FCs. The building classification is influenced by the type of data available and must consider that a too narrow classification will decrease the sample-size of the data on which to base the FC for each class (Rossetto & Ioannou, 2017). In light of the lack of data on building height and age for all buildings, in this paper, a building classification based only on the material type is adopted.

According to ISTAT (2001), the building inventory in L'Aquila area includes two predominant building typologies: masonry (68%) and reinforced concrete (RC), (24%). Masonry buildings are typically 2-4 storeys high constructed of local stone masonry with mortar joints. RC buildings are present mainly beyond the boundaries of the medieval centre and in the suburban areas, built mostly from the 1970s to 1990s (Tertulliani *et al*., 2011; Rossetto *et al*., 2009).

In the current database, the building typology is known for buildings which were included in the USRA parametric forms. For the ones with missing material type, an assumption based on their location is made which considered buildings in the historical centres as masonry, and those immediately outside the centres as RC (corresponding to urban residential expansion in the 1960s and 1970s). Rural housing are also considered to be of masonry construction. Other material types, including steel, are not considered in this classification, given that they made up just 8% of structures according to ISTAT (2001). As a result, 60% of buildings in the database are considered of masonry and the remainder RC.

The resulting trend is in general agreement with the ISTAT (2001) statistical data. However, the database includes slightly fewer masonry structures, and a higher number of RC structures, a bias created given the engineering assumptions made for the estimation of the material class. In contrast, the previously mentioned studies, such as Del Gaudio *et al*. (2017) who selected only RC buildings from the AeDES forms or Liel & Lynch (2012) who directly inspected the buildings, do not present this bias. For this reason, the current database is considered as low quality for building materials based on GEM Guidelines (Rossetto *et al*., 2014).

2.3 Usability Scale

The current database adopts the building safety classification as a proxy for damage, given its common use during Italian reconstruction processes for the distribution of funds for building interventions (see Baggio *et al.*, 2007 for a full definition of each usability rating). All usability classes (A to F) are present in the database, with 50% of the buildings in Class A (usable), approximately 30% in class E (unusable) and 15% in Class B (Temporarily unusable). Less than 5% of buildings are in C (Partially Unusable) and F (Unusable due to external risks) and just 1% in class D (temporarily unusable because further investigations are needed). Approximately 18% of data presents no information and, hence, are assumed to be in Class A (Usable).

The safety classification as defined in Baggio *et al.* (2007) presents some shortcomings for the purpose of deriving FCs. It is not based on an ordinal scale increasing in intensity from Class A to Class F, and these rates are not mutually exclusive. Thus, to perform a fragility analysis, buildings have been re-aggregated in three classes ('usable', 'partially unusable', and 'unusable'). In addition, the defined usability classes cannot be converted into the EMS-98 damage states. The common assumption that 'unusable' is equivalent to 'partial collapse' or similar damage state is invalid. This is evident in the small dataset provided by the Special Office for the Reconstruction of L'Aquila (USRA) for which both safety and damage classification are presented at each building site. In particular, if the distribution of damage states amongst buildings assigned to Class E is considered, a spread of damage states between D0 (i.e. undamaged - possibly classed as unusable due to a peril posed by an adjacent structure) and D5 (i.e. collapse) is shown (Figure 2). This also means that FCs derived using safety classifications should not be converted to equivalent damage state fragilities.

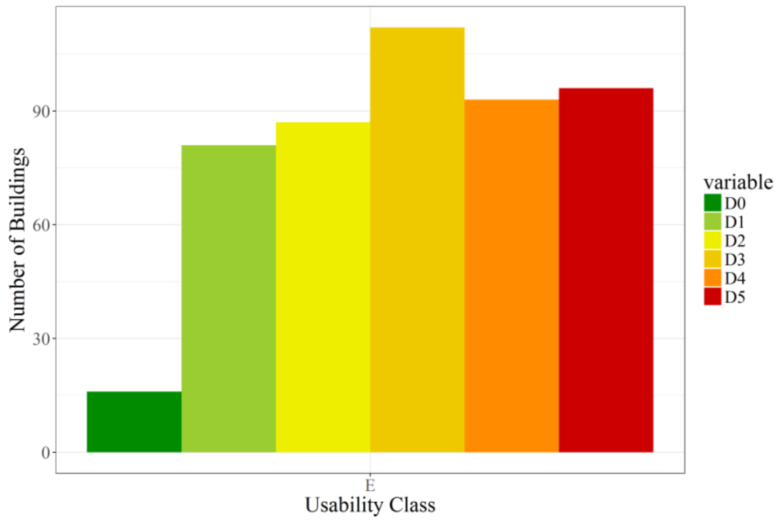

Figure 2. Usability classes E vs Damage State Limits.

2.4 Ground Motion Intensity

The database is completed with ground motion intensities necessary for the derivation of FCs. Despite the availability of PGA shake-maps, multiple GMPEs are used in the current research to assess the impact of ground-motion variability and soil type on empirical fragility.

In particular, Bindi *et al.* (2011), Akkar *et al.* (2014) and Kotha *et al.* (2016) are selected among the numerous relationships available in the literature for the prediction of PGA intensities at each building site given their coherence with the L'Aquila seismic event and tectonic environment. The Joyner-Boore distances employed in these GMPEs are estimated in ArcGIS assuming as fault coordinates and characteristics the ones provided by INGV Database of Individual Seismogenic Sources (DISS Working Group, 2015). Soil type according to Eurocode 8 (CEN, 2004, par. 3.1.2) classification and $V_{s,30}$ at each building location is added to the geodatabase through the interpretation of microzonation studies carried out in the aftermath of the L'Aquila earthquake (MS-AQ Working Group, 2010). This information is integrated with individual geotechnical inspections effectuated by professionals for the reconstruction process and provided by the Special Office for the reconstruction of L'Aquila (USRA). For areas not covered by the previous two sources, soil types are classified manually using Italian Geological Map (ISPRA, 2009) as a reference.

The INGV Shakemap in terms of PGA levels (http://shakemap.rm.ingv.it/shake/index.html) is imported into the current GIS database for comparison. This map has been generated automatically after the event considering an approximation of the $V_{s,30}$ value according to the national geological map (scale 1:100 000) and then correct with data coming from the National Accelerometric Network (RAN) recording stations (Michelini *et al*., 2008). It is available directly in shapefile format, which facilitates the extrapolation of intensities at each building site and this might explain its extensive adoption in empirical studies (e.g. De Luca *et al*., 2015; Del Gaudio *et al*., 2017). Even though this map is a valuable scientific resource, it reports only a first-order assessment of the experienced ground shaking with PGA levels aggregated in bins of 0.4g, and the INGV itself declines any responsibility for its use.

3. EMPIRICAL FRAGILITY ASSESSMENT

This section of the paper describes in greater detail the empirical fragility assessment of the building stock. First, a brief overview of the different GMPEs implemented in the database is presented. Then, the statistical models adopted are described. Next, the results of an exploratory analysis of the database are reported to examine the relevance of PGA as an IM for the database and to provide a first assessment of the effect of using GMPEs instead of the INGV Shakemap in the derivation of empirical FCs. Lastly, the model which best fits the database is discussed highlighting the influence of the adopted building classification.

3.1 Ground Motion Prediction Equations

The ground motion intensity is measured in the present research in terms of PGA and is estimated at the location of each building using both the INGV ShakeMap, as described in the previous section, and three different GMPEs, namely: Bindi *et al.* (2011), Akkar *et al.* (2014) and Kotha *et al.* (2016).

GMPEs proposed by Bindi *et al.* (2011) have been derived using a database of only Italian data with 769 records from 213 Italian seismic events, including the 2009 L'Aquila earthquake. Their use is suggested within 200 km distance range, and for M_w between 4.1 and 6.9. The functional form of the GMPE (for M_w <= 6.75) is:

$$log_{10}(Y) = e_1 + F_D(R_{JB}, M_w) + F_M(M_w) + F_S + F_{sof} \quad (1)$$

where Y is the PGA in cm/s^2, e_1 is a constant term (=3.672), $F_D(R_{JB}, M_w)$, $F_M(M_w)$, F_S and F_{sof} represent the distance function, the magnitude scaling, the site amplification and the style of faulting correction, respectively, given by:

$$F_D(R_{JB}, M_w) = \left[c_1 + c_2(M_w - M_{ref})log_{10}\left(\sqrt[2]{R_{JB}^2 + h^2/R_{ref}}\right) - c_3\left(\sqrt[2]{R_{JB}^2 + h^2} - R_{ref}\right)\right] \quad (2)$$

$$F_M(M_w) = b_1(M_w - 6.75) + b_2(M_w - 6.75)^2 \quad (3)$$

$$F_S = s_j C_j \quad (4)$$

$$F_{sof} = f_i E_j \quad (5)$$

with $M_{ref} = 5$, $R_{ref} = 1, C_j$ dummy variables used to denote the five different Eurocode 8 soil type (CEN, 2004), and E_j dummy variables used to denote the different fault classes. The values adopted for the other coefficients are: $c_1 = -1.940$, $c_2 = 0.413$, $h = 10.322$, $c_3 = 1.34 \cdot 10^{-4}$, $b_1 = -0.262$, $b_2 = -0.0707$, $s_A = 0$, $s_B = 0.162$, $s_C = 0.240$, $s_D = 0.105$, $s_E = 0.570$, $f_1 = -5.03 \cdot 10^{-2}$, $f_2 = 0.105$, $f_3 = -5.44 \cdot 10^{-2}$ and $f_4 = 0$.

GMPEs proposed by Akkar *et al.* (2014) present a more complex functional form. They have been derived using a subset of Reference Database for Seismic Ground-Motion in Europe (RESORCE), which consists of 1041 records from 221 earthquakes from the Mediterranean and Middle East Regions. Their functional form (for M_w <= 6.75) is:

$$ln(Y) = ln(Y_{ref}) + ln[S(V_{s,30}, PGA_{ref})] \quad (6)$$

where $ln(Y_{ref})$ is the reference ground-motion model:

$$ln(Y_{ref}) = a_1 + a_2(M_w - c_1) + a_3(8.5 - M_w)^2 + [a_4 + a_5(M_w - c_1)]ln\sqrt[2]{R^2 + a_6^2} + a_8 F_N + a_9 F_R \quad (7)$$

and $ln[S(V_{s,30}, PGA_{ref})]$ is the non-linear site amplification function:

$$ln[S(V_{s,30}, PGA_{ref})] = \begin{cases} b_1 ln\left(\frac{V_{s,30}}{V_{ref}}\right) + b_2 ln\left[\frac{PGA_{ref} + c(V_{s,30}/V_{ref})^n}{(PGA_{ref} + c)(V_{s,30}/V_{ref})^n}\right], & for\ V_{s,30} \leq V_{ref} \\ b_1 ln\left[\frac{\min(V_{s,30}, V_{CON})}{V_{ref}}\right], & otherwise \end{cases} \quad (8)$$

In these equations, Y is the ground motion intensity measured in g; R is the source-to-site distance measure for which R_{JB} is admitted; F_N and F_R dummy variables used to denote the different fault classes, V_{ref} and V_{CON} are the reference $V_{s,30}$ in the non-linear site model and the limiting $V_{s,30}$ after which the site amplification is a constant of $750\ m/s$ and $1000\ m/s$, respectively. The values adopted for the other coefficients are: $a_8 = -0.1091$, $a_9 = 0.0937$, $a_2 = 0.0029$, $a_5 = 0.2529$, $a_6 = 7.5$ and $a7 = -0$, $a1 = 1.85329$, $a3 = -0.02807$, $a4 = -1.23452$, $b1 = -0.4199$, $b_2 = -0.28846$, $c = 2.5$ and $n = 3.2$.

Similarly to Akkar *et al.* (2014), GMPEs proposed by Kotha *et al.* (2016) have been derived from a subset of the RESORCE database with 1251 recordings (of which 378 from Italy). However, these relationships differ from the former ones as they take into account regional differences in the ground motion scaling while maintaining a relatively simple functional form close to the one proposed by Bindi *et al.* (2011):

$$ln(Y) = e_1 + F_D(R_{JB}, M_w) + F_M(M_w) + \delta B_s \qquad (9)$$

where $F_D(R_{JB}, M_w)$ is the distance scaling component:

$$F_D(R_{JB}, M_w) = [c_1 + c_2(M - M_{ref})]ln\left[\frac{\sqrt[2]{R_{JB}^2+h^2}}{R_{ref}} + (c_3 + \Delta c_{3,Italy})\left(\sqrt[2]{R_{JB}^2 + h^2} - R_{ref}\right)\right] \qquad (10)$$

$F_M(M_w)$ is the magnitude scaling component:

$$F_M(M_w) = \begin{cases} b_1(M - 6.75) + b_2(M - 6.75)^2, for\ M < 6.75 \\ b_3(M - 6.75), otherwise \end{cases} \qquad (11)$$

and δB_s is a random effects component describing the between-station variability:

$$\delta B_s = (g_1 + \Delta g_{1,Italy}) + (g_2 + \Delta g_{2,Italy})lnV_{s,30} \qquad (12)$$

where Y is the ground motion intensity expressed in m/s^2, M_{ref} and R_{ref} are the reference magnitude and reference R_{JB} distance set at 5.5 and 1 km respectively. The other regression coefficient are: $e1 = 2.982$, $b_1 = -0.363$, $b_2 = -0.195$, $b_3 = -0.406$, $c_1 = -1.231$, $c_2 = 0.272$, $c_3 = -0.00395$, $h = 6.390$, $\Delta c_{3,Italy} = -0.00326$, $g_1 = 1.407$, $g_2 = -0.234$, $\Delta g_{1,Italy} = -0.360$, $\Delta g_{2,Italy} = 0.063$. Finally, it is noted that these last GMPEs are recommended for distances up to 200km and events of magnitude M_w ranging from 4.0 to 7.6.

3.2 The statistical model

In order to examine the importance of the PGA and material typology in predicting the probability of reaching or exceeding a given usability state, a cumulative linear model termed partially ordered probit model is fitted to the data. This model is adopted given that it is found to have provided the best fit elsewhere in the empirical fragility literature.

The model has two components: the random and the systematic component. With regard to the random component, the categorical probability distribution is adopted to determine the probability that building, affected by ground motion intensity im_j will be in one of the three usability states uc_i:

$$y_{ij} \sim \prod_{i=0}^{n} \frac{m_j!}{y_{ij}!} P(UC = uc_i|im_j)^{y_{ij}} \qquad (13)$$

The categorical distribution is fully determined by $P(UC = uc_i | im_j)$, which can be estimated as:

$$P(UC = uc_i | im_j) = \begin{cases} 1 - P(UC \geq uc_i | im_j) & for\ i = 0 \\ P(UC \geq uc_i | im_j) - P(UC \geq uc_{i+1} | im_j) & for\ 0 < i < 1 \\ P(UC \geq uc_i | im_j) & for\ i <= n \end{cases} \tag{14}$$

Finally, the systematic component is estimated as:

$$\Phi^{-1}[P(UC \geq uc_i | im_j)] = \eta \begin{cases} \theta_{0i} + \theta_{1i} \ln(im_j) + \theta_2 class + \theta_3 \ln(im_j)\, class & (15) \\ \theta_{0i} + \theta_{1i} \ln(im_j) + \theta_2 class & (16) \\ \theta_{0i} + \theta_{1i} \ln(im_j) & (17) \end{cases}$$

where $[\theta_{0i}, \theta_{1i}, \theta_2, \theta_3]$ is the vector of the 'true', but unknown parameters of the model; θ_{1i} is the slope, and θ_{0i} is the intercept of a fragility curve corresponding to uc_i; θ_2 is the parameter for the building class; θ_3 accounts for the interaction term which increases or decreasing the slope of a fragility curve according to the building class; η is the linear predictor; $\Phi^{-1}[.]$ is the inverse cumulative standard normal distribution, expressing the probit link function.

Overall, three models of decreasing complexity are considered in this study. Model 1 (M1) accounts for the PGA as well as the building class. For this model, the building class can change both the intercept as well as the slope of the fragility curve for each usability class. To identify the best-fitted model, two less complex expressions of the systematic component are considered. In Model 2 (M2), the interaction term is omitted and only the contributions of PGA and building class on the intercept are accounted for. In Model 3 (M3), the influence of the construction class is omitted altogether, and only the influence of PGA is accounted for. The model that best fits the data is then identified by comparing their Akaike's information criterion (AIC from here on) values. In general, the smaller the AIC value of a model the better its fit. To further explore the goodness-of-fit of the models, likelihood ratio tests are performed. These compare M1, M2 and M3, in order to test whether the addition of more parameters (i.e. the construction material) leads to a better fit.

3.3 Results from the exploratory analysis

An exploratory analysis according to the model M3 is performed on the data aiming to examine the importance of the PGA in predicting the probability of reaching or exceeding a given usability state. The obtained fragility curves, as well as their 90% intervals, are depicted in Figure 3.

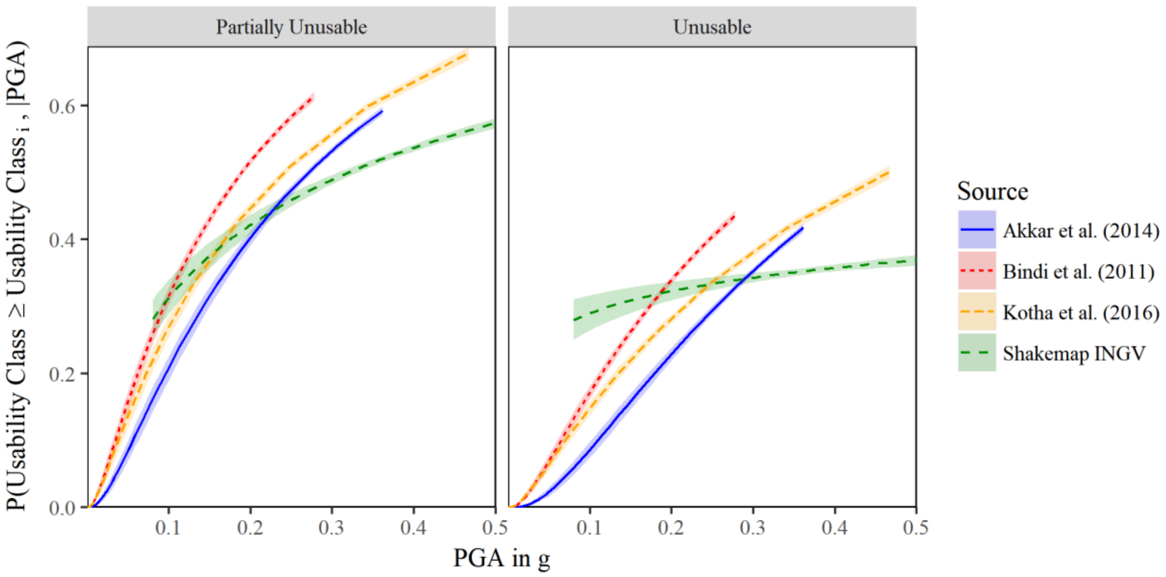

Figure 3. Fragility Functions according to GMPEs by Akkar et al. (2014), Bindi et al. (2011), Kotha et al. (2016) and INGV Shakemap.

A significant difference in the FC slope is visible in Figure 3 between the best-estimate FCs for PGA estimated by the three GMPEs and that from the INGV shakemap. This observation suggests that for the former three cases, PGA appears to be an efficient intensity measure which clearly depicts the increase in the partially or totally unusable buildings with increasing IM. The shift of the fragility curve along the IM axis that is observed when different GMPE's are used suggests that the choice of GMPE affects the overall fragility estimate. In particular, the fragility curves estimated by Bindi *et al.* (2011) appear to be shifted to the left for both usability classes, resulting in a higher estimate of fragility. By contrast, use of Akkar *et al.*(2014) results in a lower estimated fragility of the building inventory with the curves mostly shifted to the right. The initial steep curve of these FCs is possibly due to the large number of buildings present in the database that are also associated with low values of PGA.

The estimation of PGA levels using the INGV ShakeMap results in a substantial increase in the flatness of the fragility curves, suggesting that the PGA is no longer an efficient measure of the usability of the building inventory. In particular, this flatness might be due to insufficient data for buildings at higher intensity values of PGA. Also, the INGV shakemap does not allow to take into consideration the peculiarity of L'Aquila. Therefore, even though the adopted GMPEs have not been calibrated with the values of the recording stations, their flexibility in considering the different soil conditions for each building site and their variability of the reported PGA values result in a better fit of the resulting FCs with the building dataset.

The resulting shape can be associated with the specific conditions of the Italian building typology, which are characterised by poor construction techniques and a lack of maintenance (Di Pangrazio & Clemente, 2015). The implication of this is the possibility of buildings being in an unusable or partially unusable class even at extremely low IMs. Finally, it should be noted that due to the use of building-by-building data much narrower confidence intervals are obtained in the current research compared to FC's derived from aggregated data (e.g., Rota *et al.*,2008; Ioannou *et al*., 2008), which typically suffer from substantial over-dispersion.

3.4 Results: the best-fitted model

As far as the best-fitted model is concerned, M1 is identified as the model that fits the data best. Indeed, the AIC values reported in Table 1 for all three models for the four assumptions used in the current study to estimate the PGA level at the location of each building are smaller for model M1.

Table 1. AIC values.

Component		**Model**	**AIC values**			
Random	**Systematic**		**Akkar *et al.* (2014)**	**Bindi *et al.* (2011)**	**Kotha *et al.* (2017)**	**INGV Shakemap**
Eq.(13)&Eq.(14)	Eq.(15)	M1	**47693.30**	**47735.87**	**47973.27**	**48924.46**
	Eq.(16)	M2	47850.94	47826.54	48065.33	48938.76
	Eq.(17)	M3	49325.39	49438.55	49608.69	50748.86

Model M1, which considers a different slope is seen to fit better the data compared to model M2. Also, models M1 and M2, which consider the additional parameter of the material typology, result in smaller AIC values compared to model M3, suggesting the relevance of introducing an additional parameter for the description of the building stock.

The performance of the best-fitted models also depends on the assumption made for the estimation of the PGA level. FCs derived from GMPEs are seen to provide a better fit to the data than those using the INGV shakemap: the smallest AIC score is achieved by Akkar *et al.* (2014), whereas Bindi *et al.* (2011) are the worst among the different GMPEs selected. Nevertheless, the differences are small and decrease from model M3 to model M1, highlighting the impact of adding a construction material term for the better fit of FCs with the building dataset. This means that a better definition of the local site characteristics should not exclude a more detailed building typology classification.

The statistical significance of the construction material is also confirmed by the P-values reported in Table 2. These P-values are always below 0.05, and hence the more complex model fits better the data.

Table 2. Lrtest results.

Case	**M1**	**M2**	**M3**	***p*-value**
Akkar *et al.*	v	v		2.2e-16
		v	v	2.2e-16
Bindi *et al.*	v	v		2.2e-16
		v	v	2.2e-16
Kotha *et al.*	v	v		2.2e-16
		v	v	2.2e-16
INGV ShakeMap	v	v		0.0001062
		v	v	2.2e-16

Indeed, the construction material strongly affects both the intercept and the slope of the FCs for all cases, as illustrated in Figure 4.

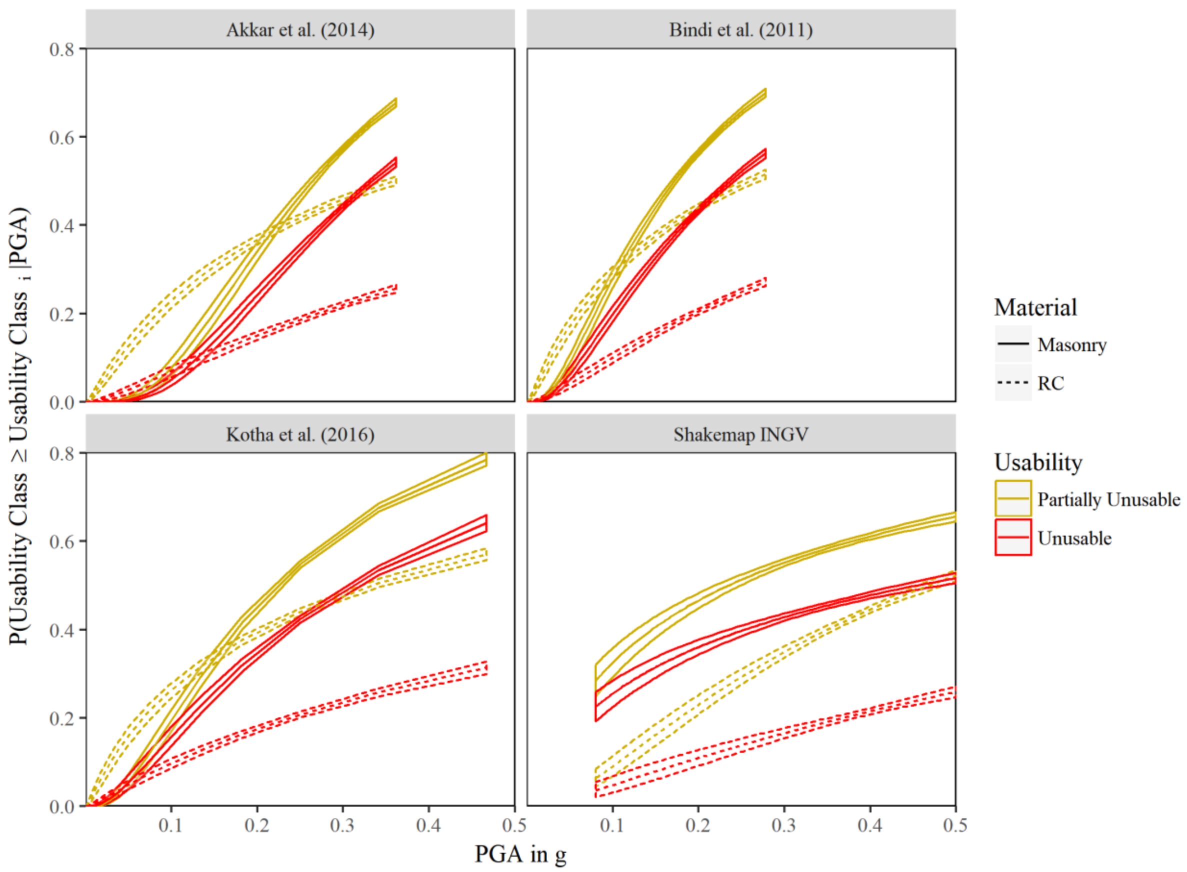

Figure 4. Fragility Functions according to GMPEs by Akkar *et al.* (2014), Bindi *et al.* (2011), Kotha *et al.* (2016) and INGV Shakemap.

Figure 4 shows that when the INGV Shakemap is used for the IM evaluation, the expected trend that masonry structures are more fragile than RC structures is maintained throughout the IM range, which is in-line with existing literature. Instead, when the GMPEs are used for estimating the PGA, in all cases RC structures appear more vulnerable than masonry at low PGA values, whilst masonry structures are more fragile at higher PGA values. Also, for a given IM, the difference between 'unusable' and 'partially usable' is quite narrow, especially for lower PGA values. It is postulated that these trends are due to three possible issues: 1. that PGA is not a good IM for use with mid-rise RC structures that can be affected by the frequency content of the ground motion, 2. Erroneous assumptions have been made to classify buildings by material classes, and 3. Misclassification errors exist in the core database due to biases in the way that masonry and RC buildings were assigned a usability rating. The latter is a particular worry, as demonstrated in Figure 2, as it is seen that a wide range of damage states exist within one usability class, and hence that usability classes are not mutually exclusive.

4. CONCLUSIONS

This study has presented empirical FCs for both masonry and RC buildings derived applying the GEM methodology to 24,911 damaged buildings data from the 2009 L'Aquila earthquake. It first describes the database collected from the USRA parametric forms and the DPC's safety classification map. In this regards, it is shown that the safety classification, which is typically adopted for the allocation of reconstruction funds, can misinterpret structural/non-structural damage. The second part of the study investigates the sensitivity of the derived functions to the ground motion prediction method (i.e. Shake-maps vs GMPE). As expected, the higher variability of PGA levels of the GMPEs, which take into consideration the local soil conditions, results in higher quality FCs, compared to the ones derived from the INGV Shakemap which provide only a first-order approximation of the experienced ground shaking. However, a better-defined building classification system compared to the one here adopted would result in FCs which describe better the building stock. This step could be easily achieved analysing all the parameters included in the USRA database once the reconstruction process will be finished.

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