16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
THESSALONIKI 18 - 21 JUNE 2018

EMPIRICAL FRAGILITY ASSESSMENT OF THE ITALIAN MASONRY BUILDINGS USING DATA FROM THE EMILIA 2012 SEQUENCE OF EARTHQUAKES

Ioanna IOANNOU[1], Enrica VERUCCI[2], Vincenzo ARCIDIACONO[3], Tiziana ROSSETTO[4]

ABSTRACT

On 20th May 2012, the Emilia-Romagna region in Italy was woken up by a strong earthquake of magnitude M_w=5.9. A seismic sequence followed with more than 2,200 shocks, the most significant of which was the M_w=5.8 earthquake that struck at 09:00:03 local time (07:00:03 UTC) on 29th May. The earthquakes affected a wide area which included 59 municipalities in the provinces of Modena, Bologna, Ferrara and Reggio-Emilia. This study used a damage database which included information regarding 41,216 residential buildings surveyed mainly in the aftermath of the second event to construct a unique set of fragility curves for masonry and RC buildings based on a sequence of events which have caused cumulative damage to an unknown number of buildings. The present study highlights issues with the data quality, commonly overlooked by the literature, and proposes ways to address non-representative samples and missing data. The comparison of the fragility curves for RC buildings with their counterparts based on the 1980 Irpinia shows that there is higher overall likelihood of damage due to the sequence of events, than the one strong earthquake.

Keywords: Empirical fragility curves; Emilia; Construction Material; Masonry; RC

1. INTRODUCTION

On 20th May 2012, the Emilia-Romagna region in Italy was woken up by a strong earthquake of magnitude Mw=5.9. A seismic sequence followed with more than 2,200 shocks, the most significant of which was the Mw=5.8 earthquake that struck at 09:00:03 local time (07:00:03 UTC) on 29th May. The earthquakes affected a wide area which included 59 municipalities in the provinces of Modena, Bologna, Ferrara and Reggio-Emilia. Reconnaissance teams (e.g. Rossetto et al., 2012 and Ioannou et al., 2012) noted the substantial damage suffered by historical buildings, low-rise unreinforced masonry buildings and the industrial structures as well as the overall good performance of the RC buildings. Post-earthquake field observations from the affected Emilia-Romagna region have been used to investigate the poor performance of the pre-cast RC industrial structures (e.g. Magliulo et al., 2014). Other studies have used sophisticated numerical models in order to examine the failure mode of pre-cast RC industrial structures (Liberatore et al. 2013) and historical buildings such as: masonry churches (e.g., Milani 2013, Milani and Valente, 2013), the Finale Emilia clock tower (Acito et al., 2014) or 1900s industrial buildings (Artioli et al, 2013). Despite the importance of these studies for the reconstruction or rehabilitation plans, only Verderame et al. (2014) attempted to analytically assess the fragility of 2-storey and 4-storey RC buildings. This last study used 41,216 residential buildings in order to validate their results. Despite past efforts to learn the lessons from the Emilia-Romagna sequence of events, no study used the post-earthquake data to empirically assess the fragility of the building inventory.

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[1]Senior Research Associate, EPICentre, UCL, London, UK, ioanna.ioannou@ucl.ac.uk
[2]PhD student, EPICentre, UCL, London, UK, t.rossetto@ucl.ac.uk
[3]Researcher, Politecnico di Torino, Italy, vincenzo.arcidiacono@polito.it
[4]Professor, EPICentre, UCL, London, UK, t.rossetto@ucl.ac.uk

This study uses a large database in order to construct empirical fragility curves for the masonry building in Emilia-Romagna by applying the Global Earthquake Model framework (Rossetto et al., 2014). The database includes information regarding the damage levels as well as the structural characteristics of 41,216 residential buildings, surveyed in the aftermath of the two main Emilia-Romagna events. The use of this database is challenging as it contains data from a sequence of events which means that there are areas affected only by a single event and areas affected by the cumulative damage from both events. The database is also found to suffer from a sizeable incompleteness error as the surveyed buildings are mostly the ones that suffered damage during the sequence of events. Finally, the survey forms have been found to suffer from a non-negligible error due to missing data. The present study has two sections, in the first section, the database is described and the main steps taken to improve the quality of the database are presented. In the second section, the fragility of the masonry and RC buildings is assessed by identifying the best-fitted parametric statistical model.

2. EMILIA-ROMAGNA DAMAGE DATABASE

The Emilia-Romagna post-earthquake damage database includes information regarding the observed level of damage sustained by residential buildings, their location and their structural characteristics. The survey forms suffer from small but non-trivial percentages of missing information regarding the latter two types of information. The database includes 41,216 surveyed residential buildings in 59 municipalities the Emilia–Romagna region, which represent 20.05% of the total number of residential buildings included in the 2011 Italian census. The buildings have been surveyed with the use of the AeDES survey form after the request of the owners (Baggio et al., 2007) in order to assess the usability of their dwellings. A brief description of the three main types of information in the survey forms is provided in what follows.

2.1 Damage Scale

The section four of the AeDES survey form, which evaluates the damages of structural elements, identifies six building “components”: four structural (vertical structures, floors, stairs, and roof), one non-structural (infills-partitions), and one referred to the pre-event damages (pre-existing damages). The damage of a given component is defined with a damage scale corresponding to the one defined in the European Macroseismic Scale. It is classified in three levels of damage (plus the case of no damage, ds_0):

- ds_1: negligible to slight damage,
- ds_2-ds_3: medium-severe damage, and
- ds_4-ds_5: very heavy damage - collapse.

The component’s damage is defined as the extension (i.e., $<1/3$, $1/3$-$2/3$, and $>2/3$) of a given damage level. In order for the damage observations for each component to be useful for the fragility assessment, the individual observations are aggregated, here, into a single overall damage state according to the schemes adopted by Dolce et al. (1999) and ADPC2005.

2.2 Location

The Emilia-Romagna database includes information for buildings located in 59 municipalities of Emilia-Romagna, which have been affected by the sequence of earthquakes (see Figure 1). The database includes the municipality of each building but included their exact address only for the 89% of the surveyed buildings. This means that only 89% of the buildings can be geocoded. By contrast, the exact location within each municipality from the remaining 11% of the surveyed buildings cannot be determined.

2.3 Building class

The classification of the building inventory is necessary for the empirical assessment of the fragility. Based on the information collected by the AeDES forms, the building units can be subdivided according to the type of vertical bearing structures (reinforced concrete, masonry, steel, and mixed), the type of horizontal structure (vault with or without ties, rigid, semi-rigid, and flexible floors), the layout and quality of masonry, the number of storeys, and the construction and retrofit periods. Despite this, the drawback of improving the quality of the database is that the detailed information is of limited use and are aggregated to broad and often inhomogeneous classes based on the buildings construction, or their number of floors as data from the census are used as described in what follows.

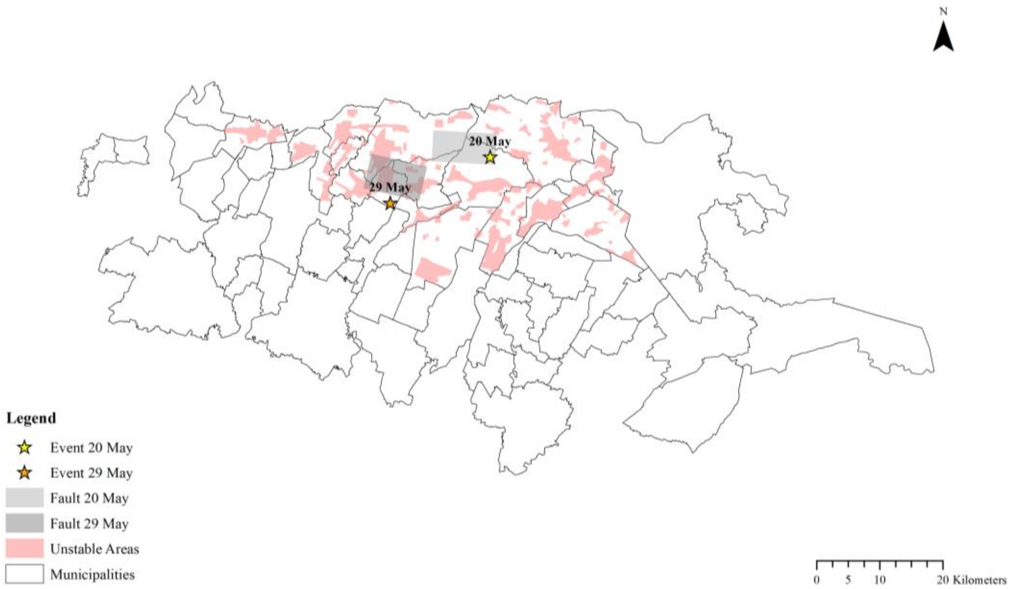

Figure 1 Map of the Emilia-Romagna showing the affected area, the two faults and the epicentres of the events of 20th May and 29th May.

2.4 Quality of database

The quality of the Emilia-Romagna database is discussed here regarding the size of its completeness and missing data errors and ways to improve its quality are presented.

2.4.1 Completeness error

The Emilia-Romagna database includes data from the 20% of the building inventory. A residential building is surveyed by a team of engineers only after a request from the owner. This is considered to introduce a bias towards the buildings which sustained damage of any degree, as the owners of damaged buildings are more likely to request a survey. To further justify this assumption, the aggregated data in the database are compared to the 2011 Italian census as shown in Figure 2. The database appears to include a higher percentage of masonry buildings than the census as well as more buildings having 1 or 2 storeys than the census. This reinforces the initial insight that the database is biased towards the damaged buildings which tend to be the most vulnerable or low-rise masonry buildings. To reduce this bias, the 2011 census is used to provide an estimate of the undamaged buildings in the 59 municipalities. This is common practice in the empirical fragility assessment literature (e.g., Karababa & Pomonis 2010, Colombi et al. 2008).

2.4.2 Missing data

Missing data have been noted in the classification of the surveyed buildings according to their construction material and their number of floors. The percentage of buildings that have not been classified according to their construction materials and number of floor, due to missing data, is approximately 8% and 4% approximately. The former percentage (which is of interest here), although small, is not negligible and further analysis is conducted here in order to understand its mechanism and whether ignoring the buildings without defined construction material will introduce a sizeable bias in the fragility assessment.

The mechanism of the missing data is investigated in Figure 2. The proportion of buildings with missing construction material is divided over the proportion of the buildings for which the construction material is present is estimated for each damage state, municipality and the other two structural characteristics. On average, the highest the Peak Ground Acceleration from both events in the administrative centre of each municipality the lower, on average, the proportion of missing data. It can also be noted that most buildings with missing information regarding their construction material also have the number of floors missing. Missing data are more likely to be old buildings (with construction age -1919). Interestingly, the buildings with missing construction material class are more likely to have been undamaged, and to a lesser extent to have sustained collapse and heavy or moderate damage. These observations indicate that ignoring the mostly undamaged building without construction material from the database will not introduce bias in the database as the use of the census to estimate the number of the undamaged buildings for all building classes overall improves the quality of the database.

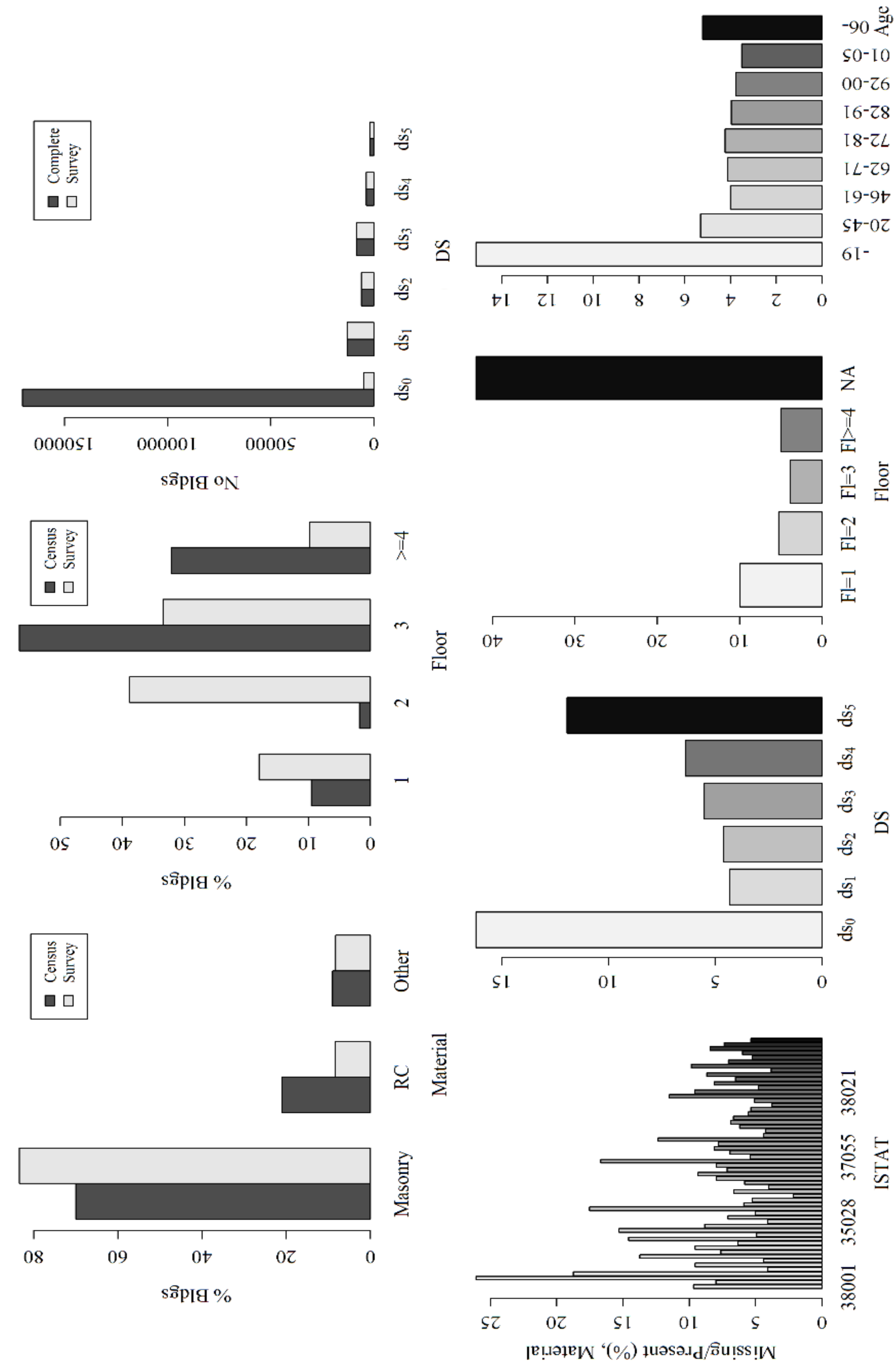

Figure 2 (Top row) Comparison of the database data with the2011 Italian census and the distribution of the buildings to the 6 damage states and (bottom row) examining the missing data mechanism.

2.5 Ground motion and ground failure

The 59 municipalities of Emilia-Romagna experienced damage by two earthquakes which struck on 20th and 29th May 2012. Reconnaissance teams identified areas, which were mostly affected by the first event or the second event. However, these surveys tend to concentrate on a small number of observations from the street. On the other hand, the speed and objectives of the post-earthquake survey based on the AeDES forms meant that buildings were surveyed only once and overwhelmingly (~96%) in the aftermath of the second strong event on 29th May. Therefore, for most buildings it is not possible to infer, without perhaps unrealistic assumptions, whether a building has been damaged in the first or the second strong event and which its damage state was after the first event. It should be mentioned that a small (4%) percentage of buildings were surveyed after the 1st event but they have not been revisited after the second event. These data are removed from the post-earthquake database in order avoid bias in the empirical assessment of the buildings' fragility, which is concentrated only on the majority of surveys.

Reconnaissance teams also reported damage caused both by ground shaking as well as ground failure most notably liquefaction. In what follows, the main assumptions regarding the ground shaking and ground failure are presented.

2.5.1 Ground shaking

The ground motion intensity for each event is measured here in terms of *PGA* (in g), which is a ground intensity type commonly used in the empirical fragility assessment literature. Given the lack of a dense network of ground motion intensities, the intensity measure levels are estimated by the Ground Motion Prediction Equation (GMPE) proposed by Bindi et al. (2011). Given that the data are aggregated at municipality level, the intensity levels at the administrative centre of each municipality are estimated for the two events. Implicit in this, is the assumption that each municipality is treated as an isoseismic unit. Given the size of the municipalities, this assumption appears to be problematic as the ground motion intensity appears to range rather widely. Nonetheless, this assumption is in line with common approaches followed in the literature. To further simplify the problem, a single ground motion intensity is assigned to each centre. This intensity is considered equal to the maximum of the PGA for the two events.

2.5.2 Liquefaction

Emilia-Romagna area mostly affected by the sequence of events is located in the Po Plain between the Southern Alps and the northern Apennines, which have considerable saturated alluvial soil deposits. Figure 1 depicts the areas which were considered as unstable and caused liquefaction during the sequence of the two events.

Reconnaissance surveys (Rossetto et al., 2012), however, reported relatively small areas of loose sands, alluvial soils and reclaimed deposits, which suffered extensive liquefaction near the two epicentres. Liquefaction was mostly caused by the 20th May event and affected the locality of Mirabello, Sant'Agostino, San Prospero, Cento and Finale Emilia as well as the villages of Bondeno and San Martino (2013). On the other hand, the liquefaction caused by the second 29th May event was limited to the areas outside the villages of Moglia and Quistello and Cavezzo. Liquefaction in San Felise sul Panaro was reported to have been caused by both events. Reports from different reconnaissance teams agree that the liquefaction is localised in both clusters and alignments (Ioannou et al, 2012). Given, however, the aggregation of data at municipality-level this study is not able to explore the impact of liquefaction and incorporate this explanatory variable in the statistical model.

3. EMPIRICAL FRAGILITY ASSESSMENT

Having addressed the main issues with the Emilia-Romagna damage database, the next step is to identify the parametric statistical model which fits the data best.

3.1 Statistical Model Selection

The construction of a statistical model is based on the results of an explanatory analysis which is not presented here due to the limited space. This analysis showed that the increase in the max*PGA* also increases the likelihood of damage, which indicated that the selected intensity measure is capable to depict an expected trend in the data. It was also found that the masonry buildings are the most vulnerable and the RC buildings are the least vulnerable. The explanatory analysis showed that the individual fragility curves vary both in their intercept as well as their slope, indicating the need to develop of statistical model which accounts for the construction materials as well as their interaction with the max*PGA*.

Following the main observations of the exploratory analysis, the fragility of Emilia-Romagna's building stock is empirically assessed here. The assessment includes the construction of a partially ordered probit model. The random component of this model can be written as:

$$DS = \{ds_0, ds_1, ds_2, ds_3, ds_4, ds_5\}, \quad DS \mid \max PGA = x \sim Multinomial\left(P\left(DS = ds_i \mid x\right)\right) \tag{1}$$

where,

$$P\left(DS = ds_i \mid x\right) = \begin{cases} 1 - P\left(DS \geq ds_i \mid x\right) & i = 0 \\ P\left(DS \geq ds_i \mid x\right) - P\left(DS \geq ds_{i+1} \mid x\right) & 0 < i < 5 \\ P\left(DS \geq ds_i \mid x\right) & i = 5 \end{cases} \tag{2}$$

The systematic component is determined as:

$$P\left(DS \geq ds_i \mid x\right) = \begin{cases} \theta_0 + \theta_{1i}x + \theta_2 class + \theta_{3i} xclass & .1 \\ \theta_0 + \theta_{1i}x + \theta_2 class & .2 \\ \theta_0 + \theta_{1i}x & .3 \end{cases} \tag{3}$$

where *class* is a categorical unordered variable, expressed either in terms of the construction material, construction age or number of floors; $\theta_{0\text{-}3}$ are the unknown regression coefficients of the model. The systematic component Eq.(3.1) is selected as it allows the slope as well as the intercept of the fragility curves to vary with the damage state and the structural class. Two additional systematic components are considered in order to perform a sensitivity analysis which will identify which is the best fitted model. The component expressed by Eq.(3.2) ignores the interaction term and the Eq.(3.3) ignores the influence of the construction material to the shape of the fragility curves. The three modes are then fitted to the database completed by the 2011 Italian census.

The best fitted model is identified by comparing the three AIC values, presented in Table 1. The ‘Model1’ has the smallest AIC value and is identified as the model which it’s the data best.

Table 1 AIC values for the three models.

<table>
<tr><td rowspan="2">Model</td><td colspan="2">Component</td><td rowspan="2">AIC</td></tr>
<tr><td>Random</td><td>Systematic</td></tr>
<tr><td>Model1</td><td rowspan="3">Eq.(1)</td><td>Eq.(3.1)</td><td><u>206203</u></td></tr>
<tr><td>Model2</td><td>Eq.(3.2)</td><td>206930</td></tr>
<tr><td>Model3</td><td>Eq.(3.3)</td><td>210875</td></tr>
</table>

The differences are small and likelihood ratio tests (see Table 2) are also conducted in order to examine whether the changes of the slope of the fragility curves due to the construction material are statistically significant (i.e. compare ‘Model1’ and ‘Model2’) and whether the influence of the construction material on the intercept of the fragility curves is also statistically significant (i.e. compare ‘Model2’ and ‘Model3’). The *p*-values are well below the 0.05 threshold which indicates that both the construction material as well as the interaction term are statistically significant variables.

Table 2 Likelihood ratio test summary.

<table>
<tr><td>Model</td><td>p-value</td></tr>
<tr><td>Model1</td><td rowspan="2"><2.2e-16</td></tr>
<tr><td rowspan="2">Model2</td></tr>
<tr><td rowspan="2"><2.2e-16</td></tr>
<tr><td>Model3</td></tr>
</table>

The analyses showed the Model1 is the model which fits the data best. The fragility curves as well as the 90% confidence intervals are depicted in Figure 3 for the three construction materials: Masonry, RC and Other. The latter class is a non-homogenous and relatively small class, which includes a wide range of residential buildings such as mixed RC and masonry buildings and steel buildings.

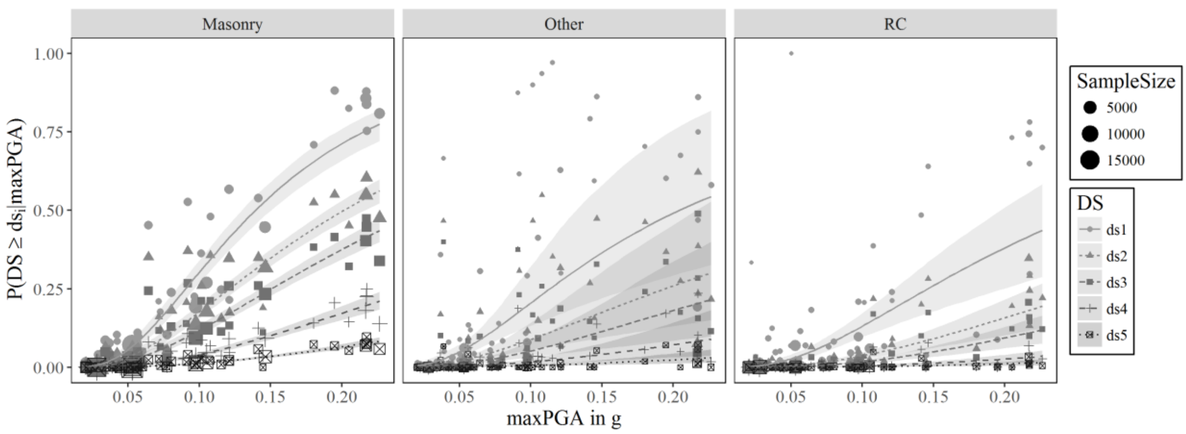

Figure 3 Fragility curves for the buildings inventory of Emilia obtained by fitting ‘Model1’ to the data.

3.2 Discussion

The need to aggregate the data into three broad classes led to fragility curves which depict average trends among the three classes and are not able to provide a deeper insight over the impact of the sequence of events in the Italian inventory. Overall, the study of the fragility curves in Figure 3 confirms what is observed from other Italian earthquakes; the masonry buildings are overall the most vulnerable buildings and the RC buildings are the least vulnerable. It can also be noted that the relatively small confidence intervals for the curves corresponding to all 5 damage states for masonry buildings can be attributed to the fact that this building class has the highest number of buildings. By contrast, the relatively small number of Other and RC buildings produced fragility curves which overlap considerably and lead to not very informative fragility curves.

Overall, the Emilia-Romagna building inventory appears to be typically over 30 years old. The poorer performance of the masonry buildings can be attributed to the fact that they are mostly unreinforced. Despite their typical regular layout, the masonry buildings in the affected areas are more likely to have flexible horizontal structure (i.e., timber floors), which increases their seismic fragility. These types of buildings represent the 66% of the surveyed buildings. It is not uncommon for masonry buildings in this area to have a combination of wooden roof with rigid floors. A common failure type for these buildings involves the collapse of the roof due to poor quality of materials or slenderness of the façade. In the historical centres of the affected areas, it is common to see a mixture of timber floors and vaults. The vaults are typically on the first floor and supported by the portico, a common architectural feature in the North of Italy. The majority of masonry buildings have a regular layout. In the historical centres of the affected areas, brick masonry buildings with regular layout ranging from 1 to 5 stories high and good quality material and construction techniques are common.

The vulnerability of most masonry buildings in Emilia-Romagna is also reduced by the lack of tie beams or rods. Tie beams or rods appear to be lacking from the 67% of the surveyed buildings. Overall, masonry buildings with tie rods or beams performed better during the sequence of the earthquakes. However, this intervention improves the seismic performance of the masonry building if the rods are regularly spaced over the façade at all floor levels and at the roof and their correct anchored through to the orthogonal walls or the floor structures (Ioannou et al., 2012).

The second most popular construction material is RC. Epicentre's reconnaissance teams (Rossetto et al., 2012; Ioannou et al., 2012) rapidly surveyed a small sample of RC buildings and concluded that these buildings have been affected in larger numbers and more severely in the May 29th event than the May 20th event, which had mainly inflicted non-structural damage to infill walls of clay block or brick masonry. With regard to the damage observed in the second event, failures included failures in columns, beams and joints, and examples of damage due to lap-splice failure were also noted. Damage to non-structural elements was also common and included: i) balcony wall failures; ii) masonry infill wall damage; iii) minor damage in cold joints due to pounding between the buildings. Soft storey mechanisms were also noted. Evidence of inadequate reinforcement detailing of joints and insufficient concrete confinement in joints has also been noted. Despite the poor performance of some RC buildings, the empirical fragility assessment performed in this study showed that their seismic performance was better than the other two classes.

Finally, the fragility curves for the ´Other´ buildings highlight that these buildings overall performed better than the masonry and worse than the RC buildings.

The fragility curves obtained for the 2012 Emilia sequence of events are compared to their counterparts obtained by the 1980 Irpinia earthquake. The data from the second event are also aggregated at the centre of 41 municipalities and the GMPE proposed by Bindi et al. (2011)

has been used to estimate the PGA level at the centre of each municipality accounting for the soil conditions. It should be noted that it was not possible to assess the completeness of the 1980 Irpinia data and it was assumed that all buildings were surveyed in each municipality. The comparison is limited to the fragility of RC buildings which can be considered to be the most homogenous building class, including engineered buildings designed without seismic code or with a low seismic code. The comparison presents a complex picture, which is not surprising given the complexity of the Emilia events and issues of data quality for both databases. Overall, the fragility curves based on the 2012 Emilia events appear to be steeper than their 1980 Irpinia counterparts. For moderate and extreme damage (i.e., ds_{2-4}), Emilia's RC buildings appear to be more vulnerable, which can be, partially at least, attributed to the cumulative damage sustained by these buildings during the sequence of events. For ds_1, the flatter 1980 Irpinia fragility curves raise questions regarding that the database was complete. By contrast, the differences in the likelihood of collapse of RC buildings are not notable, which could be attributed to the very small number of RC buildings which collapsed in the two earthquakes.

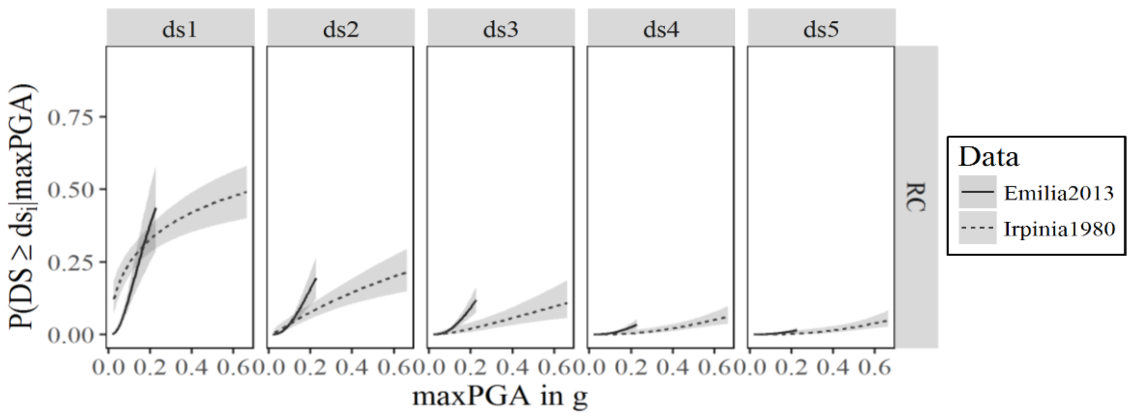

Figure 4 Fragility curves for RC buildings based on post-disaster data from the 2012 Emilia sequence of events and the 1980 Irpinia earthquake.

4. CONCLUSIONS

A post-earthquake damage database of residential buildings affected by the Emilia-Romagna sequence of events is adopted here for the construction of fragility curves based on the construction material of the inventory. The main challenge faced in this study has been the improvement of the quality of the database, which was found to suffer from a substantial completeness error and a notable missing data error. The results show that the masonry buildings were the most vulnerable. By contrast, the RC buildings have been the least vulnerable in the building inventory. The comparison of the fragility of these buildings with the RC buildings affected by the 1980 Irpinia showed that there is higher overall likelihood of damage due to the sequence of events, than the one strong event. One of the main issues in need of further study is how to incorporate into the model the areas which suffered liquefaction during the sequence of events.

5. REFERENCES

Acito, M., Bocciarelli, M., Chesi, C., Milani, G. (2014). Collapse of the clock tower in Finale Emilia after the May 2012 Emilia Romagna earthquake sequence: Numerical insight. *Engineering Structures*, 72, 70-91.

Artioli, E., Battaglia, R., Tralli, A. (2013). Effects of May 2012 Emilia earthquake on industrial buildings of early ’900 on the Po river line. *Engineering Structures*, 56, 1220-1233.

Baggio, C., Bernardini, A., Colozza, R., Corazza, L., Della Bella, M., Dolce, M., Goretti, A., Martinelli, A., Orsini, G., Papa, F., Zuccaro, G. (2007). Field manual for the post-earthquake damage and safety assessment and short term countermeasures (AeDES). European Commission—Joint Research Centre—Institute for the Protection and Security of the Citizen.

Bindi, D., Pacor, F., Luzi, L., Puglia, R., Massa, M., Ameri, G., Paolucci, R. (2011). Ground motion prediction equations derived from the Italian strong motion database. *Bulletin of Earthquake Engineering*, 9(6), 1899-1920.

Charvet, I., Ioannou, I., Rossetto, T., Suppasri, A., Imamura, F. (2014). Empirical fragility assessment of buildings affected by the 2011 Great East Japan tsunami using improved statistical models. *Natural Hazards*, 73(2), 951-973.

Colombi, M., Borzi, B., Crowley, H., Onida, M., Meroni, F., Pinho, R. (2008). Deriving vulnerability curves using Italian earthquake damage data. *Bulletin of Earthquake Engineering*, 6(3), 485-504.

Dolce, M., Masi, A., & Goretti, A. (1999). Damage to buildings due to 1997 Umbria–Marche earthquake. Seismic damage to masonry buildings. *Balkema, Rotterdam.*

Emergeo Working Group (2013). Liquefaction phenomena associated with the Emilia earthquake sequence of May-June 2012 (Northern Italy). *Natural Hazards and Earth System Sciences*, 13(4), 935.

Ioannou, I., Borg, R. C., Novelli, V., Melo, J., Alexander, D., Kongar, I., Rossetto, T. (2012). The 29th May 2012 Emilia Romagna Earthquake.

Karababa, F. S., & Pomonis, A. (2011). Damage data analysis and vulnerability estimation following the August 14, 2003 Lefkada Island, Greece, Earthquake. *Bulletin of Earthquake Engineering*, 9(4), 1015-1046.

Liberatore, L., Sorrentino, L., Liberatore, D., & Decanini, L. D. (2013). Failure of industrial structures induced by the Emilia (Italy) 2012 earthquakes. *Engineering Failure Analysis*, 34, 629-647.

Lombardi, D., & Bhattacharya, S. (2014). Liquefaction of soil in the Emilia-Romagna region after the 2012 Northern Italy earthquake sequence. *Natural hazards*, *73*(3), 1749-1770.

Magliulo, G., Ercolino, M., Petrone, C., Coppola, O., & Manfredi, G. (2014). The Emilia earthquake: seismic performance of precast reinforced concrete buildings. *Earthquake Spectra*, *30*(2), 891-912.

Milani, G. (2013). Lesson learned after the Emilia-Romagna, Italy, 20–29 May 2012 earthquakes: a limit analysis insight on three masonry churches. *Engineering Failure Analysis*, *34*, 761-778.

Rossetto, T., Alexander, D., Verrucci, E., Ioannou, I., Borg, R. C., Melo, J., Kongar, I. (2012). The 20th May 2012 Emilia Romagna Earthquake.

Rossetto, T., Ioannou, I., Grant, D. N., & Maqsood, T. (2014). Guidelines for Empirical Vulnerability Assessment Report produced in the context of the Vulnerability Global Component project. Pavia Google Scholar.

Rota, M., Penna, A., & Strobbia, C. L. (2008). Processing Italian damage data to derive typological fragility curves. *Soil Dynamics and Earthquake Engineering*, *28*(10-11), 933-947.

Verderame, G. M., Ricci, P., De Luca, F., Del Gaudio, C., & De Risi, M. T. (2014). Damage scenarios for RC buildings during the 2012 Emilia (Italy) earthquake. *Soil Dynamics and Earthquake Engineering*, *66*, 385-400.