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# Empirical seismic fragility of different typologies of precast RC industrial buildings

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ABSTRACT
In the present economy, seismic loss estimation is extremely important for planning civil protection strategies and for predicting costs for restoring or retrofitting damaged buildings after earthquakes. Fragility curves are a fundamental tool for seismic risk assessment. They can be obtained using different approaches, mainly statistical analysis of observational damage data or numerical modelling.
Observational damage data from past earthquakes are commonly used worldwide for the development of new empirical fragility curves or for validating existing ones based on mechanical models. The present paper focuses on the definition of observational fragility curves for RC precast buildings using damage data collected for almost 1800 buildings after the Emilia seismic sequence that struck the north of Italy in 2012. In particular, the building stock was subdivided into six main typologies with homogenous features. Parametric fragility curves for the different typologies and for different damage states, allowed to distinguish the fragility of the different typologies.

## 1 INTRODUCTION

The 2012 earthquake sequence in Northern Italy (Emilia earthquake) is considered the most severe seismic event in terms of damage and collapses suffered by precast RC industrial buildings.

Issues and collapses related to precast buildings were reported by many authors after past earthquakes in the world (Muguruma et al. 1995; Posada and Wood 2002; Arslan et al. 2006; Khare et al. 2011; Akpinar et al. 2014) and in Italy (Toniolo and Colombo 2012) but the extent and the severity of the collapses observed after the Emilia earthquake are unprecedented in Italy (Savoia et al. 2012; Bournas et al. 2013; Liberatore et al. 2013; Magliulo et al. 2014; Savoia et al. 2017a; Demartino et al. 2018; Titi et al. 2018; Pollini et al. 2018).

The region struck by the earthquake mainshocks is one of the most productive areas in Italy and is characterized by medium-to-small clusters of industrial buildings located in the various municipalities. The two mainshocks, caused extended damage and collapses in prefabricated RC buildings and, in some industrial areas close to the epicenters (e.g., Mirandola Nord, S. Giacomo Roncole, Cavezzo, Medolla), up to 70% of buildings were significantly damaged or collapsed (Savoia et al. 2012; Savoia et al. 2017a). The main causes of the collapses were vulnerabilities related to the structural characteristics of Italian precast buildings not designed with seismic criteria, since the region was not covered by seismic code requirements until October 2005.

After an earthquake, the collection of damage data and their inventory represents an essential tool for predicting the response of the buildings to future earthquakes. Seismic fragility is a measure of how prone a building is to suffer damage for a given intensity of the ground shaking, and it can be mathematically formulated by fragility curves, which describe the conditional probability of exceeding a certain damage level given the intensity of the ground motion.

The present paper presents fragility models for the most common typologies of Italian RC precast buildings, obtained through a critical elaboration of the data, collected by the authors after the 2012 earthquake. In order to achieve this goal, an electronic database was developed, in order to catalog observational damage data for a wide range of precast RC buildings. Both field surveys and information provided by structural engineers appointed, by owners, to design retrofit/strengthening interventions for damaged buildings were used. Damage was classified using a five-level damage scale derived from EMS-98.

The data collected were subdivided into six main typologies of precast RC buildings with homogenous features and fragility curves were developed for each of them underling their different seismic response.

Before describing, in chapter 5, the approach used by the authors to develop the typological fragility curves, chapters 2 describes the specific features of the six structural typologies and chapter 3 shows some statistical analysis on their spatial distribution and on the damage level showed after the seismic events of 2012.

## 2 TYPOLOGIES OF PRECAST BUILDINGS IN THE EMILIA REGION

### *2.1 Selection of the structural typologies*

The typical layout of a single-story industrial building is composed of a series of basic portal frames, realized as the assembly of monolithic precast elements. Each frame has precast cantilever columns clamped in pocket foundations, and precast concrete roof girders supported by the columns. Precast slab elements are also simply-supported over the roof beams. In the case of structures not designed with seismic provisions, the beam-column and slab-beam connections are typically friction-based, without any mechanical connection device and often neoprene pads in order to allow beam end-rotations under gravity loads. The stability of the structures and their capacity with respect to horizontal actions depend on the cantilever behavior of the columns (Savoia et al. 2017a).

For the industrial buildings struck by the 2012 Emilia earthquakes, Savoia et al. (2012) identified two main categories of precast RC structures mainly distinguished by the year of construction, span length and type of external infills/panels:

1. Buildings constructed from 1970 to 1990 (Type 1), with beam span length from 12 to 20 m, roof slab span length from 6 to 10 m, and masonry infills;
2. More recent buildings (Type 2), approximately built after 1990, featuring significantly longer spans of beams and roofing elements, and either horizontal or vertical prefabricated RC cladding panels.

These two building types approximately correspond to those identified by Casotto et al. (2015).

The construction date may represent an important factor to analyze the seismic behavior of the precast buildings struck by the Emilia earthquakes, because of the changes in construction practice and technology occurred over time. However, most of the territory struck by the earthquakes was not considered a seismic area by design codes until October 2005. As a consequence, most of the partial and full collapses were caused by the common use, both in Type 1 and Type 2 buildings, of friction-based slab-beam and beam-column connections.

The huge amount of data collected after the Emilia earthquakes and the consequent damage analysis of the structures allowed to carry out a refined structural classification of the RC precast buildings. In the present work, the number of structural typologies of precast RC buildings has been increased to six different types, indicated with T1 to T6 and described in § 2.2.

In the Emilia region, most of the precast RC buildings have a single-story structure, typically composed of a series of basic portal frames. Some buildings may have two floors, and others an intermediate floor in a portion of the building, typically along one of the two short edges, where offices are located. The present classification of building types does not consider structures with 2 or more floors since they represent less than 30% of the industrial buildings in the Emilia-Romagna region.

The six typologies of precast RC buildings identified by the authors are illustrated in the following paragraph.

### *2.2 Structural features of the six RC precast typologies*

Type 1 (T1) buildings feature double slope precast beams simply-supported at the top of the columns with masonry infills or horizontal precast cladding panels placed between the columns, along both short and long walls (Figure 1). This is a typical building technology adopted in the 70’s and in the 80’s, and also more recently for small and cheap constructions, as, for instance, agricultural warehouses. The roof can be either made of precast elements with hollow-clay-blocks or, in recent constructions, TT or hollow-core concrete elements. Columns are usually quite slender, with square cross-sections with depth and width of about 30-40 cm. No beam-column connection devices are present. Beams can be up to 2 m deep in the center, and typically have either no or little restraints against out-of-plane movements, with the exception of upper pocket supports at the top of columns. Often, the presence of an intermediate floor on one side of the building caused an irregularity in the structural behavior of the building, with negative effects during ground-motions. It is worth noticing that often there are no secondary beams to connect the main frames in transverse direction.


Figure 1. Type 1 (T1), Building with double slope precast beams simply-supported at the top of the columns and a) masonry cladding panels, b) horizontal precast cladding panels placed between the columns.

Type 2 (T2) are buildings with double slope precast beams simply supported at the top of the columns with external precast heavy cladding panels fixed externally to the columns. The external cladding panels can be either horizontal or vertical (Figure 2). This is a typical technology adopted after the 80’s. As the previous typology, T2 can be characterized by different kinds of precast roof or slab elements, based on the span lengths, as well as insulation and lightening requirements.

Type 3 (T3) are buildings with flat roof, composed of long-span prestressed roof or floor elements simply supported on (possibly prestressed) precast girder beams. This technology was widely used after the 80’s, typically for large industrial facilities requiring large empty spaces with few columns inside. On average the covered area of these buildings is almost two times that of building types T1 and T2. Planar precast RC girders are supported on columns. In order to reach significant spans in the slab direction, different kinds of prestressed elements are adopted for roofs or slabs, such as TT or Y-shaped beams (Figure 3). More recently, the use of precast vaulted thin-web elements (called “wing shaped beams”) allowed to cover roof spans over 30 m long (Savoia et al. 2012; Savoia et al. 2017). In this case, curved panels made of glass or transparent polycarbonate are placed between the structural thin-web elements with the purpose of lighting the interior of the building. When the latter solution is adopted, quite commonly in the last 20 years for large industrial buildings (spans longer than 20 m in both directions), the roof is of course highly deformable in its plane. RC columns have large cross-sections (with sides up to 60-80 cm) and must bear both vertical and horizontal loads. Cladding panels are made of reinforced concrete, externally fixed to the columns and the upper beams, and do not have any structural function. The cladding panels can be either horizontal, vertical or in some case have a mixed layout.


Figure 2. Type 2 (T2), buildings with double slope precast beams simply-supported at the top of the columns with external precast heavy cladding panels fixed externally to the columns a) horizontal panels or b) vertical panels.

Figure 3. Type 3 (T3), buildings with long span planar roof: example of exterior and interior views.

Type 4 (T4) are buildings with shed roof (Figure 4). A technology adopted from the 70’s to the 90’s but not very common. The shed roof can be realized either by means of “knee” shaped beams, or oblique beams or, less commonly, through Vierendeel or reticular type beams. This type of building is characterized by a very poor seismic behaviour, as it will be confirmed by the fragility curves illustrated in §5.

Type 5 (T5) comprises all the buildings with a sort of irregularity. The most common cases are the following:

- Irregularity in plan: L shape, T shape, etc. (Figure 5);

- Irregularity in height;
- Interaction with adjacent precast buildings built without seismic joint and characterized by a different structural typology;
- Consistent portion of the building used as offices or residential destination, usually in masonry walls and almost always located in one extremity of the precast structure;
- Precast structures with a portion cast in place.

Type 6 (T6) contains all the precast structures not belonging to one of the previous typologies since characterized by very uncommon characteristics (Figure 6).

Figure 4. Type 4 (T4), buildings with shed roof.

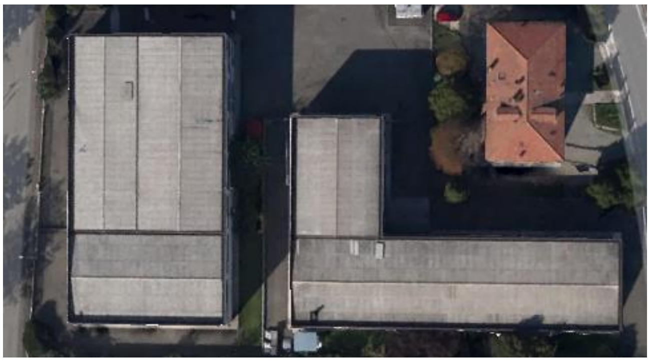

Figure 5. Type 5 (T5), buildings with plan irregularity.

Figure 6. Type 6 (T6), building not belonging to the other structural typologies.

## 3 GROUND MOTION INTENSITY

The ground-motion intensity at the building locations, required for defining fragility models, was estimated from the shakemaps published by Istituto Nazionale di Geofisica e Vulcanologia (INGV). For the definition of the fragility models presented in §5, after analyzing the ground-motion accelerograms from the recording stations and the site-to-site variability of different possible ground-motion intensity measures, the maximum horizontal PGA was chosen as measure of ground-motion intensity.

Figure 7 shows the shakemaps for the horizontal PGA referred to the 20 May and 29 May earthquakes, respectively. Discussions on the level of approximation of these shakemaps can be found in (Cultrera et al. 2014; Braga et al. 2015; Buratti et al. 2017).

Adopting the approach proposed by Buratti et al. (2017), for each building, the value of the ground-motion intensity considered in the fragility analysis was the maximum between those related to the two mainshocks of 20 and 29 May. Black dots and crosses in Figure 7 indicate the locations of the buildings in the database associated to the PGAs of 20 May and 29 May earthquakes, respectively.

a)

b)

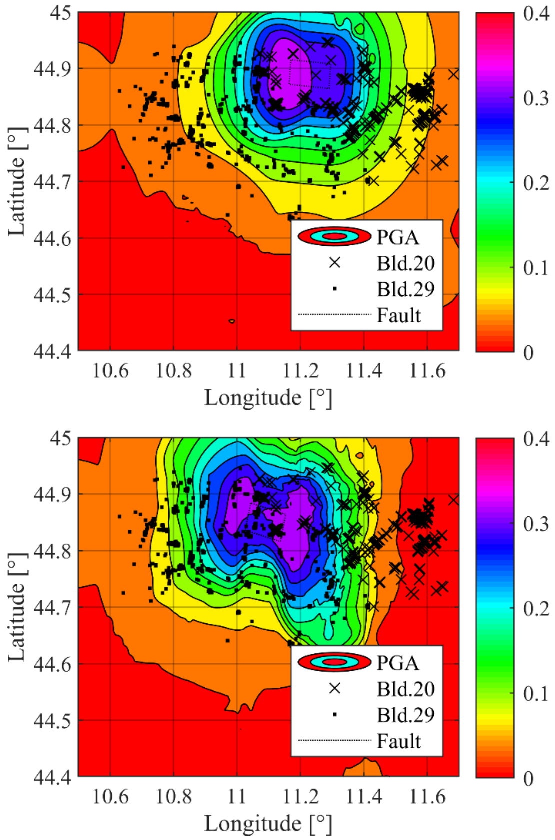


Figure 7. Shakemaps in terms of PGA for a) the 20 May 2012 and b) the 29 May 2012 earthquakes.

## 4 DAMAGE DATA ANLYSIS FOR THE DIFFERENT STRUCTURAL TYPOLOGIES OF PRECAST BUILDINGS

The buildings analysed in the present paper are 1767. This number is slightly lower than that considered by the authors elsewhere (Buratti et al. 2017) since here two floor buildings are excluded, as well as buildings with arch roof or steel roof. The buildings examined are located at epicentral distances not larger than 30 km and represent about 30% of the total stock of industrial buildings in the area. Figure 8 shows the percentage of each of the 6 types of precast buildings in the database. This pie chart clearly indicates that type T2 is the most common within the database (27 %), followed by T1 (25%) and then by T3 (20%). It's worth noticing the high percentage of irregular buildings (T6) in the area (18%).

Damage data were gathered form reports prepared by engineers, representing building owners, as partial requirement for obtaining regional funds for either reconstruction or retrofit, in accordance with Regional Decree 57/2012 [31]. Funding was available also for retrofitting non-damaged buildings, and that retrofitting of industrial buildings with structural deficiencies (e.g. lack of mechanical connections between elements) was mandatory. The damage in these buildings was classified as in Buratti et al. (2017), i.e. using a five level damage scale derived from EMS-98 (Minghini et al. 2016). Table 1 shows the number of buildings for each damage level, starting from $D_0$ (no damage) to $D_5$ (collapse).

Table 1. Number of buildings analyzed for each damage level after grouping the structures by type.

| Damage level | $D_0$ | $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ |
|---|---|---|---|---|---|---|
| No. of buildings | 880 | 375 | 159 | 88 | 79 | 186 |

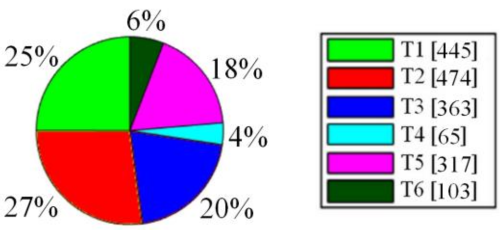


Figure 8. Percentage of each of the 6 types of precast buildings in the database.

Figure 9 shows the percentage of each damage level for each type of building and Figure 10 the percentage of each type of building for each damage level. Obviously it is not possible to infer about the fragility of the different types of buildings form these figures, because the ground motion intensities to which they were exposed is not uniform – being the different building types not uniformly distributed in the area (Minghini et al. 2016; Savoia et al. 2017b)– whereas these plots allow to analyse the completeness of the damage database. As an example, damage levels D1 to D4 contain very few T4 buildings, therefore the reliability of their fragility models for those damage levels will be limited.

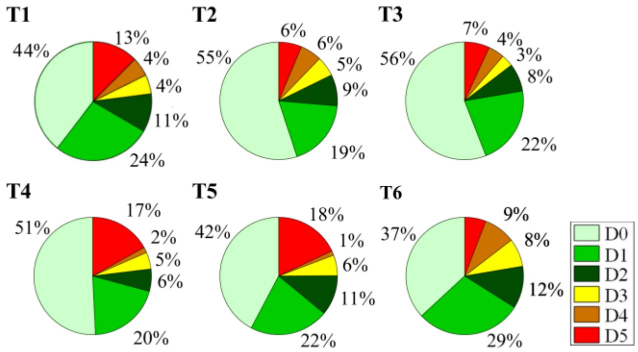


Figure 9. Percentages of the different damage levels for the six building types.

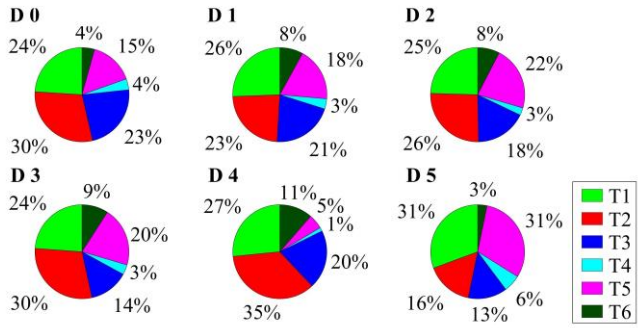


Figure 10. Percentages of the different buildings building types for each damage level under consideration.

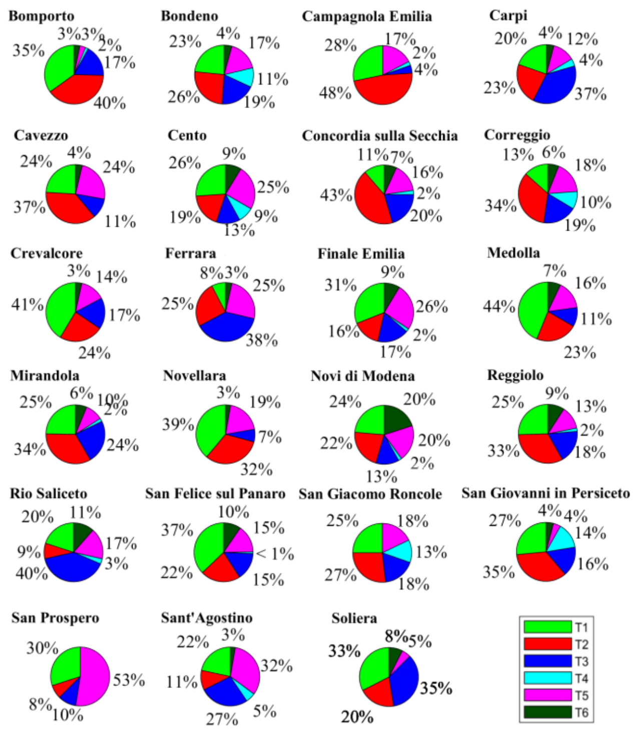


Figure 11. Percentages of the building types in the main industrial clusters present in the area struck by the 2012 Emilia earthquakes.

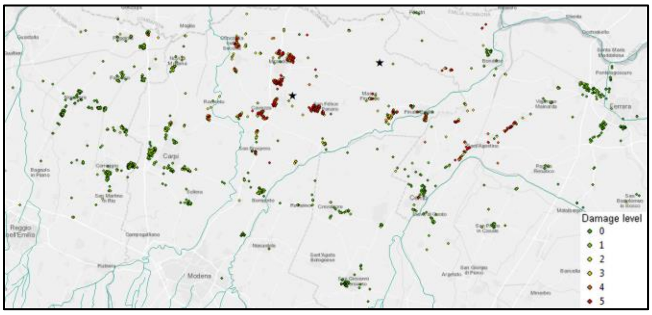


Figure 12. Geographic representation of the spatial distribution of the buildings in the damage database.

Concerning the spatial distribution of the buildings, Figure 11 shows the percentage of each building type for the main industrial clusters in the area struck by the 2012 Emilia earthquakes, while Figure 12 shows a geographic description of the whole database. Figure 11 shows that all the industrial clusters have at least 50% of the precast buildings classified as types T1, T2, T3 but with different proportions between cluster and cluster. Some industrial cluster show an high predominance of type T1, as San Felice sul Panaro, Crevalcore e Medolla; others an high predominance of type T2 as Cavezzo and Concordia sulla Secchia; finally, some clusters show a predominance of type T3 as Carpi and Ferrara. It's worth noticing the very low percentage of building T1 in the cluster of Ferrara.

Fragility curves for different typologies will be illustrated in chapter 5. Nevertheless, Figure 13 and Figure 14 show a preliminary analysis of the seismic behavior of different typologies, evaluating the damage levels distribution for each type of building considering three ranges of PGA.

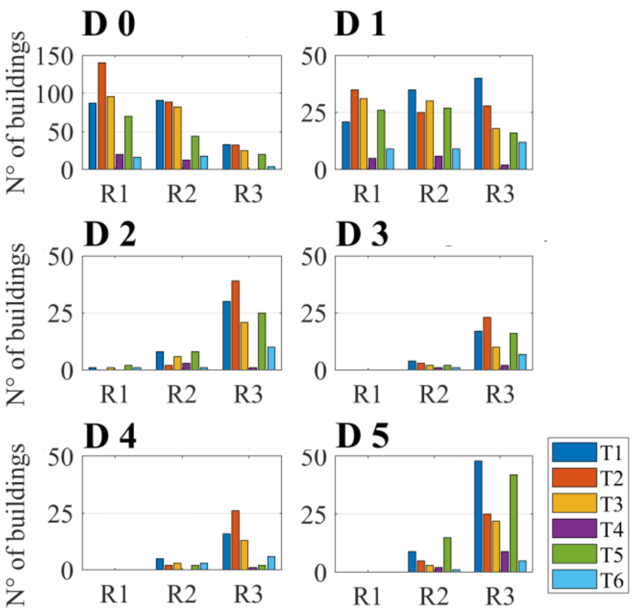


Figure 13. Number of buildings belonging to each interval of PGA, for each type of building and for each damage level.

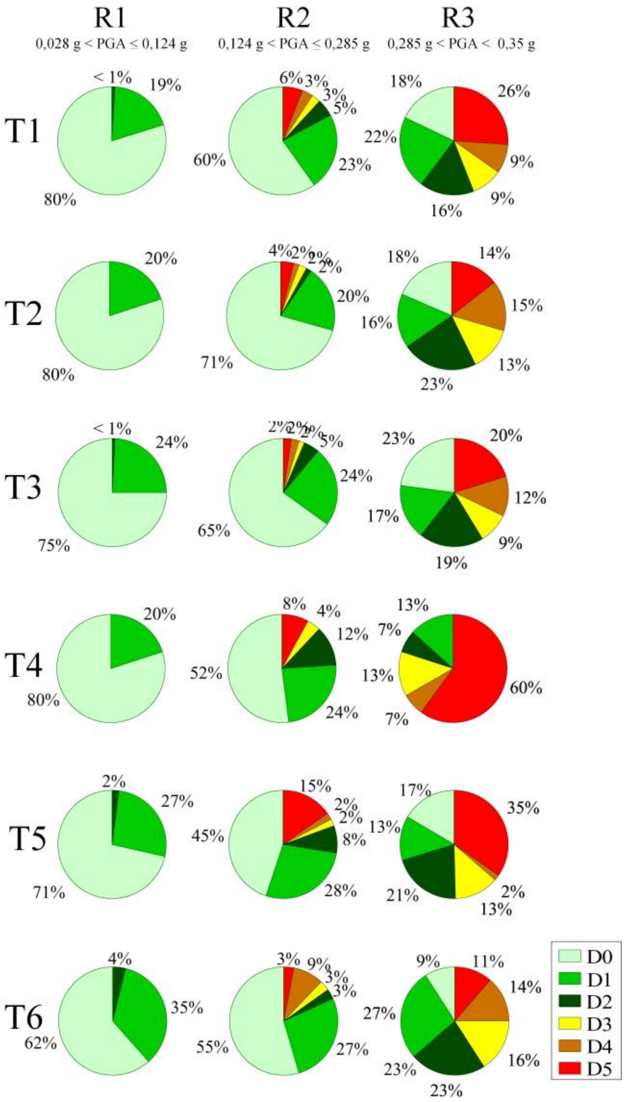


Figure 14. Percentages of damage levels distribution for each building type as a function of PGA.

These ranges, named R1, R2 and R3 were selected in order to group almost the same number of buildings.

- R1: 0,028 g < PGA ≤ 0,124 g
- R2: 0,124 g < PGA ≤ 0,285 g
- R3: 0,285 g < PGA < 0,35 g

Figure 14 indicates that Type T4 (shed roof) seems to be the most vulnerable typology, followed by type T5 (Irregular buildings), type T1 (double slope roof - infills), type T3 (flat roof) and type T2 (double slope roof - external panels).

## 5 FRAGILITY CURVES FOT DIFFERENT TYPES OF PRECAST BUILDINGS

Parametric fragility models were fitted using on the damage data described in the previous Section. Lallemant et al. (Lallemant et al. 2015) discussed the most commonly used methods for fitting fragility curves from observational data. In this work the maximum likelihood estimation method was adopted to calibrate the models.

To this purpose, for each damage state $D_j$, the observed damage data was transformed into a binary variable $y_{ij}$ which is set equal to 1 if the damage the *i*-th building is greater or equal to $D_j$ and 0 otherwise. Assuming these binary variables as independent and identically distributed, the likelihood function $L_j$ for the damage state $D_j$ is defined as (Lallemant et al. 2015; Buratti et al. 2017; D'Amico and Buratti 2018):

$$L_j = \prod_{i=1}^{N} \left(1 - p_{i,j}\left(IM_i, \mathbf{b}_j\right)\right)^{\left(1-y_{i,j}\right)} p_{i,j}\left(IM_i, \mathbf{b}_j\right)^{y_{i,j}} \tag{1}$$

where $N$ is the total number of buildings in the database, $p_{i,j}\left(IM_i, \mathbf{b}_j\right)$ indicates the exceedance probability for the damage state $D_j$ for the ground motion intensity $IM_i$ (PGA in this case) associated to the *i*-th building and $\mathbf{b}_j$ is a vector of unknown regression parameters, which, in the present work, represent building types and the effect of the ground motion intensity. Equation (1) corresponds to assuming that $y_{ij}$ follows a Bernoulli distribution, with probability $p_{i,j}\left(IM_i, \mathbf{b}_j\right)$. In the present work a log-logit (LL) multivariate regression model is used in order to write the exceedance probability for the *j*-th damage level (D'Amico and Buratti 2018)

$$\ln\left(\frac{p_{i,j}\left(IM_i, \mathbf{b}_j\right)}{1 - p_{i,j}\left(IM_i, \mathbf{b}_j\right)}\right) = \beta_{1j} + \sum_{k=2}^{6} \beta_{kj} T_{ki} + \beta_{7j} \ln\left(IM_i\right) \tag{2}$$

,

where $T_{ki}$ is a dummy variable set to 1 if the *i*-th building is of type *k* and 0 otherwise. Therefore, the vector of unknown regression parameters of the model is $\mathbf{b}_j = \left[\beta_1, \ldots, \beta_7\right]$. For each damage level the estimates of the parameters are the values that maximize the likelihood function (Eq. 1) of the observed damage data. It should be noticed that type T1 is used as reference and is associated to the constant term of the model $\beta_{1j}$. Therefore, the values of the coefficients $\beta_{2j}$ to $\beta_{6j}$ provide an indication of the relative fragility of the different building types with respect to T1, i.e. a negative value of $\beta_{kj}$ indicates that building type *Tj* is less fragile that T1 for the damage level $D \geq D_j$.
The estimates of the regression parameters are reported in Table 2. The effect of the various building types was evaluated by means of statistical significance tests on the terms $\beta_{2j}$ to $\beta_{6j}$.

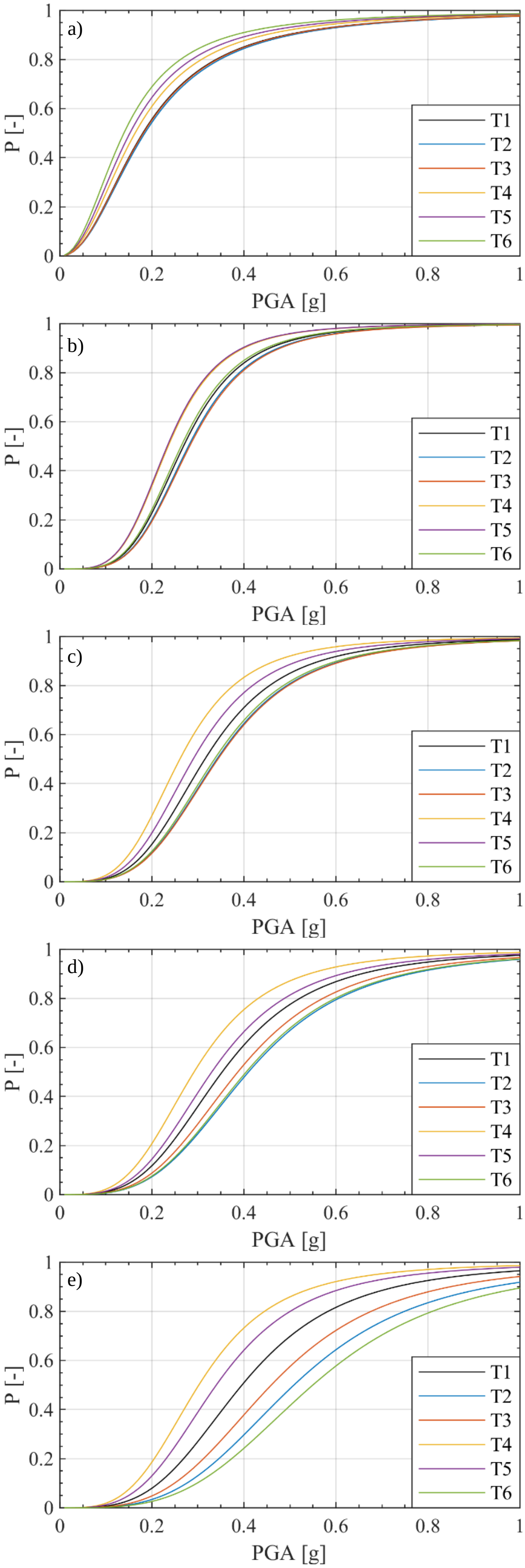

Figure 15. Fragility curves for a) $D \geq D_1$, b) $D \geq D_2$, c) $D \geq D_3$, d) $D \geq D_4$ and e) $D \geq D_5$.

Table 2. Estimates of the regression parameters of the fragility models.

| | $D \geq D_1$ | $D \geq D_2$ | $D \geq D_3$ | $D \geq D_4$ | $D \geq D_5$ |
|---|---|---|---|---|---|
| $\beta_1$ | 3.75 | 5.46 | 4.34 | 3.70 | 3.32 |
| $\beta_2$ | -0.05 | -0.16 | -0.30 | -0.53 | -0.90 |
| $\beta_3$ | -0.02 | -0.20 | -0.32 | -0.33 | -0.53 |
| $\beta_4$ | 0.21 | 0.55 | 0.71 | 0.68 | 0.97 |
| $\beta_5$ | 0.37 | 0.58 | 0.32 | 0.23 | 0.55 |
| $\beta_6$ | 0.57 | 0.08 | -0.24 | -0.49 | -1.18 |
| $\beta_7$ | 2.19 | 4.15 | 3.76 | 3.55 | 3.58 |

Table 3. p-values for the regression parameters of the fragility models.

| | $D \geq D_1$ | $D \geq D_2$ | $D \geq D_3$ | $D \geq D_4$ | $D \geq D_5$ |
|---|---|---|---|---|---|
| $\beta_2$ | 0.73 | 0.38 | 0.12 | 0.01 | <0.01 |
| $\beta_3$ | 0.92 | 0.32 | 0.13 | 0.15 | 0.05 |
| $\beta_4$ | 0.50 | 0.16 | 0.06 | 0.08 | 0.01 |
| $\beta_5$ | 0.04 | 0.01 | 0.13 | 0.28 | 0.02 |
| $\beta_6$ | 0.03 | 0.78 | 0.42 | 0.14 | 0.01 |
| $\beta_7$ | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |

The p-values of the regression parameters are reported in Table 3. Low p-values correspond to a statistically significant term. This Table clearly shows that, at least with reference to the most severe damage states, the data analysed suggests significant differences among the fragilities of various building types. On the other hand, for low damage levels ($D \leq D_2$) the difference among some building types are not significant. The fragility curves obtained are plotted (using Eqn. 2) in Figure 15. These fragility models clearly indicate that, with reference damage levels $D_2$ to $D_5$, the most fragile building type is T4, followed by T5, T1, T2 and T2. Building type T6 is associated to low fragilities but, since this type contains buildings with different features, it is not possible to draw general conclusions on their structural behaviour.

## 6 CONCLUSIONS

A database containing seismic damage data and geometric parameters for almost 1800 precast RC buildings was assembled using data collected after the 2012 Emilia earthquake. After a detailed analysis of the structural features of the buildings in the database a subdivision into six categories was proposed. Then, the seismic behaviour of these different types of buildings was analysed by fitting parametric fragility models by means of logistic regression. Statistically significant differences were observed in the fragility curves for the different building types, in particular for the most severe damage levels.

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