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Using the empirical evidences of the 2012 Emilia-Romagna earthquake for assessing the convenience of seismic retrofitting measure on long-span-beam structures

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ABSTRACT

Soon after the disastrous 2012 Northern Italy earthquake, the local public authority (Regione Emilia-Romagna) launched a vast reconstruction programme regarding private housing, infrastructures, cultural heritage, and business facilities. To this aim, databases about seismic damage and reconstruction costs – regarding both private and public buildings – were created and managed; interestingly, such data repositories, originally developed for administrative reasons, can now be accessed by researchers, and their content can be used to improve the state of the art of seismic performance assessment tools. In particular, for what concerns long-span-beam structures hosting business facilities, a consistent and reliable dataset of more than 2100 items is available. In it, reconstruction costs can be put in relation with the corresponding damage patterns and ground shaking intensity measures. Thanks to this, much can be learned in terms of structural performance and direct seismic economic consequences. In this work, available empirical evidences are used by the authors to develop innovative consequence curves. Furthermore, in the text, a first-attempt assessment tool for calculating expected economic losses is discussed.

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1 INTRODUCTION

The earthquake that struck Northern Italy in May 2012 was largely investigated and documented in numerous reports and scientific papers (e.g. Galli et al. 2012, D'Aniello et al. 2012, Parisi et al. 2012, Rossetto et al. 2012, Magliulo et al. 2014, Mucciarelli et al. 2014, Buratti et al. 2017, Savoia et al. 2017). Among the many studies on the topic, a series of recent works (Rossi et al. 2019a, 2019b, 2019c) was dedicated to the in-depth analysis of one vast and reliable database that was assembled by the public authority of the most damaged region, i.e. Regione Emilia-Romagna. Such database, so-called SFINGE, was put in place with the aim of fairly and efficiently managing the reconstruction process of business activities, to which the Italian State contributed with more than EUR 1.9 billion (ARR 2018, R E-R 2012b, Pres. R E-R 2012a, Pres. R E-R 2012b, R E-R 2018). Interestingly (details are given in Rossi et al. 2019b), gathered data include numerous informative record fields, among which: (i) building's exact location; (ii) building's area; (iii) occurred structural damage; (iv) occurred content damage; (v) assessed parametric economic loss, with regard to both structural and non-structural damage; (vi) damage-loss causal effect; (vii) cost of necessary interventions; (viii) cost of business relocation (if the case); (ix) business owners' insurance claims. In particular, structural damage was classified using a 5-pattern system (Rossi et al. 2019c), partially resembling the EMS-98 scale (Grünthal 1998). At the same time, costs were computed by taking into consideration market values and official price lists (R E-R 2012a, 2013). In total, within SFINGE, more than 4420 structures, and the seismic consequences they faced – for a corresponding total intervention cost of more than EUR 2.4 billion – were accurately documented; because of this, data can now be accessed by researchers interested in seismic consequence evaluation.

The main motivation for this research work is to make use of the discussed available information regarding the reconstruction process, so to provide the reader with statistical evidences about seismic demand, induced construction cost, occurred damage patterns and possible relations among them. Results could be integrated within existing theoretical frameworks, as the PEER's Performance Based Earthquake Engineering (PBEE) (e.g. Miranda 2003, Ramirez et al. 2009, ATC 2012), and could help improving the Italian *Sisma bonus* funding scheme as well (MIT 2017).

1.1 SFINGE's LSB subset

In SFINGE, a consistent subset of 2104 structures exists: That of long-span-beam buildings (in the following referred to as "LSB"), to which the present work is dedicated. LSB items are mostly (but not only) RC precast structures, with beams whose length is between 10 and 20 m; they are delimited by infill masonry or concrete walls, these latter being connected to the main structure via small metal parts (see for example Bonfanti et al. 2008). In general, for what has been discussed on the topic by many authors (e.g. Savoia et al. 2012, Magliulo 2014, Minghini et al. 2016), such structures present little structural overcapacity and limited ductility (an example of damaged LSB building is given in Figure 1a). In Emilia-Romagna, in many cases, damage was due to the lack of proper connection between columns and beams (see Figure 1b) – among other things, the lack of a metal dowel to effectively link vertical elements to horizontal ones was crucial. For what concerns vulnerability, it has to be considered that a large share of the existing Italian LSB building stock was built during the '60s, '70s and '80s (see also Bellotti 2014), well before the relevant advancements of the national building code in terms of seismic design (MIT 2008). Due to their relevance for the business sector (they are largely adopted both in industrial and commercial activities), performance of LSB structures can make the difference on the economic impact of a seismic event.

(a)

(b)

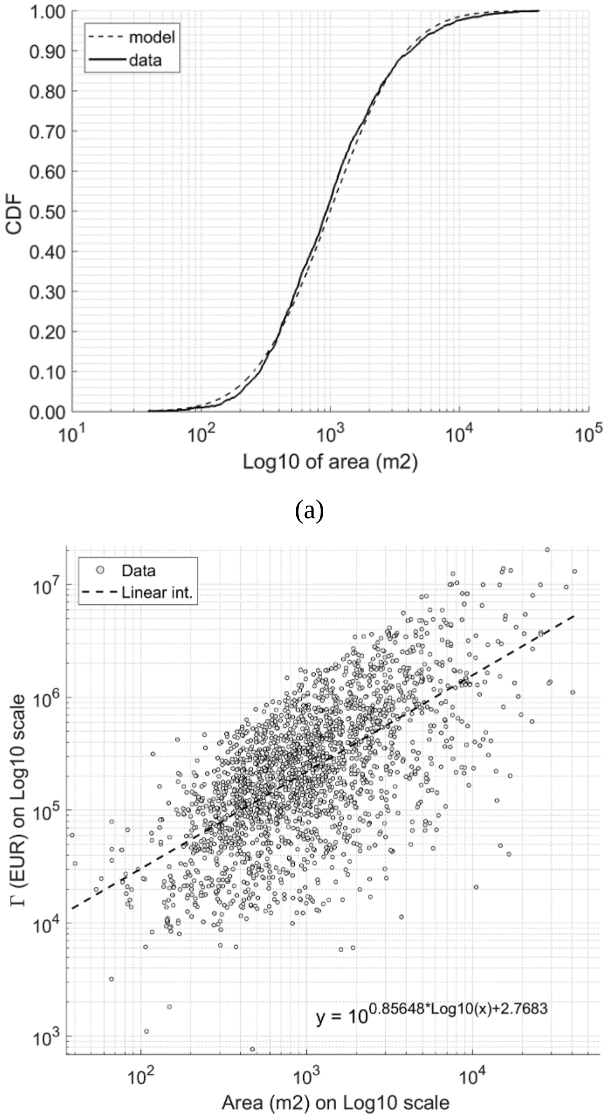
Figure 1. (a) A damaged LSB building in Emilia-Romagna. (b) Detail of a heavily-damaged precast beam-column joint in a LSB structure (source: Agenzia regionale per la ricostruzione – Sisma 2012).

2 SUMMARY OF RECENT STUDIES ON EMILIA-ROMAGNA'S DATABASE

For what concerns the damage states of LSB buildings, after the 2012 earthquake, recurrent patterns were observed by on-site investigations; as a consequence, the regional public authority (Regione Emilia-Romagna), while establishing the set of rules for providing public financial help, defined a 5-pattern damage description system: from P1 ("light damage"), to P5 ("building's collapse") – details are given in Rossi et al. 2019c. Interestingly, in the database, the occurred damage pattern of a structure is associated to the actual cost of necessary post-earthquake construction works.

In mid-2017, a research project funded by the European Commission (so-called DatA ESPerT, see Rossi et al. 2016), was dedicated to the study of Emilia-Romagna's database; in this section, we summarize some scientific results of such project, so to introduce the further research step we want to discuss here.

First of all, the total area of the 2104-unit building stock is circa 3.97 million m^2, with a mean of 1885 m^2 and a standard deviation of circa 3209 m^2. The large dispersion in the original dataset is due not only to the different buildings' usage and aim, but also to the different size of the involved business activities (in this context, small-medium enterprises coexist with extremely large production sites). Once on the Log10 scale, the area variable resembles a normal distribution (see Figure 2a). For every area entry it is possible to know the corresponding value of the reconstruction cost variable; the variable definition would be: *direct real estate-related economic cost* (DREC) – here referred to with the Greek letter "Γ" – as the main action included in it is the money spent to fix or rebuild the structural elements. Nonetheless, the term Γ also includes what was due for engineers' design, as well as works supervision, final testing, on-site safety measures, geological and material surveys, and VAT (if the case). Figure 2b shows the area-Γ scatterplot in the Log10 plane. From the figure, it emerges that Γ is linearly proportional to area, but a large dispersion exists within the dataset.



(a)

(b)

Figure 2. (a) CDF of the Log_{10} of the area variable. (b) Area-Γ scatterplot, on Log10 plane. (Rossi et al. 2019c).

The total value of Γ for the whole dataset is up to EUR 1224 million, with a mean of EUR $5.825 \cdot 10^5$ and a standard deviation of EUR $1.262 \cdot 10^6$. A more portable information is obtained by dividing each Γ entry by the corresponding building's area – so to get the *relative DREC* (or "γ"). Once on the Log10 scale, the cumulative distribution function (CDF) of γ partially resembles that of a normal distribution (Figure 3). Additionally, it is also possible to have a CDF for each of the five damage patterns P1, ..., P5 (see Figure 4) – the number of items per damage pattern is given in Table 1. The user interested in developing a statistical model of the seismic economic consequences on LSB structures, could do the following: (i) For a given reference time span, he/she assesses the absolute probability of each of the five different damage patterns $p(DP = P_i)$, with i = 1, ..., 5 and of having no damage at all ($p(DP = P_0)$); (ii) by reading the curves' ordinates in Figure 4, and multiplying them for the assessed $p(DP = P_i)$, he/she can then obtain the absolute probability of having γ between two reference values of interest (γ_{inf} and γ_{sup}).

$$p(\gamma_{inf} < \gamma \le \gamma_{sup}) = \\ = \sum_{i=1}^{5} [\Phi_i(\gamma_{sup}) - \Phi_i(\gamma_{inf})] \cdot p(DP = P_i) \qquad (1)$$

In doing so, the user has to remember that in Figure 4 we assumed that one of the five damage patterns P1, ..., P5 actually occurred; in other words, the curves we provide express a conditional probability p(A|B) – see Formula 2. Following this first approach, the user takes care of modelling the structural response of a target building, and then gets the information regarding reconstruction cost variability from the empirical evidences of Emilia-Romagna. In other words, we suggest a way of by-passing the consequence model for direct economic consequences for what concerns LSB structures.

$$\Phi_i(\gamma_0) = p(\gamma \le \gamma_0 \mid DP = P_i) \qquad (2)$$

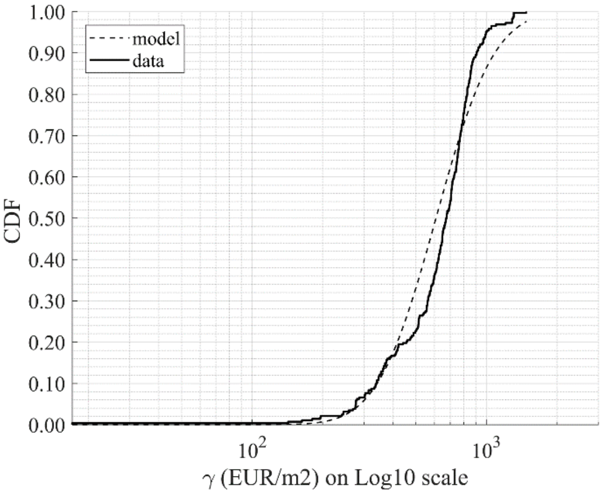
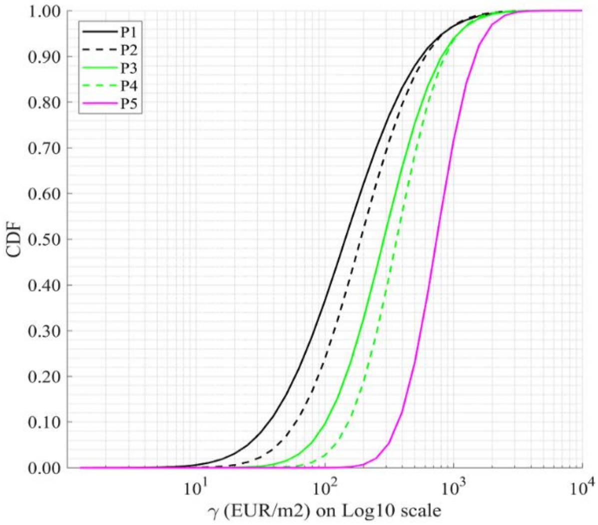


Figure 3. CDF of γ for the entire dataset (Rossi et al. 2019c).



(b)

Figure 4. CDF of γ by damage pattern (Rossi et al. 2019c).

Table 1. Number of damaged buildings by damage pattern.

	P1	P2	P3	P4	P5	Other	Total
#	1042	434	180	139	288	21	2104

3 COST OF WORKS AND DEMAND RETURN PERIOD

As an additional – original – research step, it is possible to use the information in SFINGE database so to put together the cost of works (in terms of γ) and the return period (T_R) of the corresponding recorded seismic intensity. To this aim, we will assume the following hypotheses:

(i) The Peak Ground Acceleration (PGA) is the elected intensity measure; this makes possible to directly relate γ items – obtained from the studied database – to the return period of corresponding seismic intensity values. This can be done, for example, by using the information about seismic hazard already included in the Italian building code (MIT 2018).

(ii) The 2104 LSB buildings listed in SFINGE database can be considered as a representative sample of the existing Italian LSB building-stock; this means that the empirical data reported in the database can be used so to create an archive of PGA-γ pairs, to be taken as a reference for future assessments in practical applications.

First of all, LSB items are grouped by damage pattern, and the values of both γ and PGA are evaluated. For what regards the first, values of both Γ and area size were directly provided by Regione Emilia-Romagna within a special scientific agreement (Pres. R E-R 2015); the second term is instead obtained from the buildings' geographical coordinates, by using the shakemap of Figure 5; such figure reports the envelopment of 47 shakemaps (taken from INGV's official website, also considering Lauciani et al. 2012 and Cultrera et al. 2014), corresponding to those seismic events with magnitude (Mw) equal to or greater than 4.0. Epicenters of the considered events are represented on the map with a star symbol (in red the two biggest shocks, in black the others). A graphic representation of PGA's statistical distribution by damage pattern is given in Figure 6. In this first example, for the way damage patterns P3 and P4 were defined by Regione Emilia-Romagna (see also Pres. R E-R 2012a, and R E-R 2012b), we will consider them as one single damage pattern (in the following named P3-4).

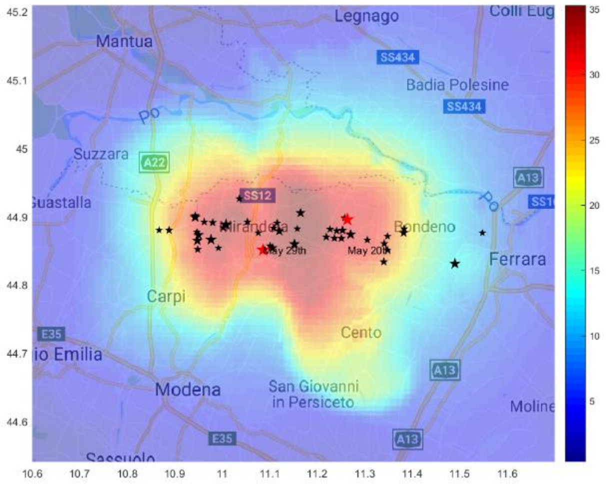


Figure 5. Envelopments of 47 shakemaps of the 2012 Emilia-Romagna sequence (Rossi 2019b).

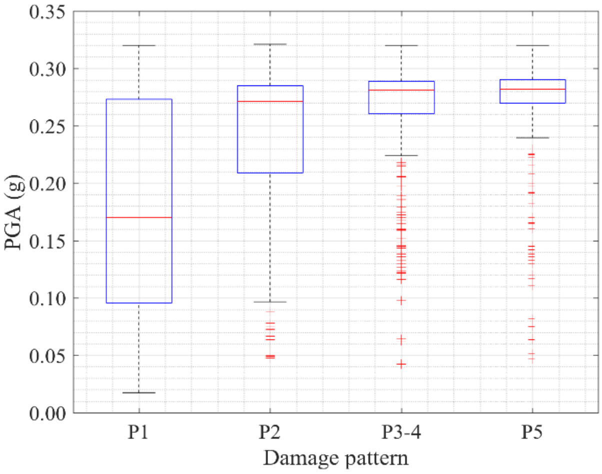


Figure 6. Boxplot of PGA values, by damage pattern.

In Figure 6, a red line represents the set's median value, while bottom and top blue edges stay for 25th and 75th percentiles, respectively. The whiskers show the most extreme data points not considered outliers; finally, each outlier is plotted individually (in red) as a "+" symbol. From the figure, the reader will notice how PGA variability reduces as the damage state worsens. Furthermore, we also see that: (i) medians of damage patterns 2, 3-4 and 5 are close each other, but the 25th percentile limit makes the difference; (ii) PGA of items for which DP = P_5 has a quite symmetric distribution and a relative little dispersion. Dually to Figure 6, in Figure 7 we show a boxplot of γ by damage pattern.

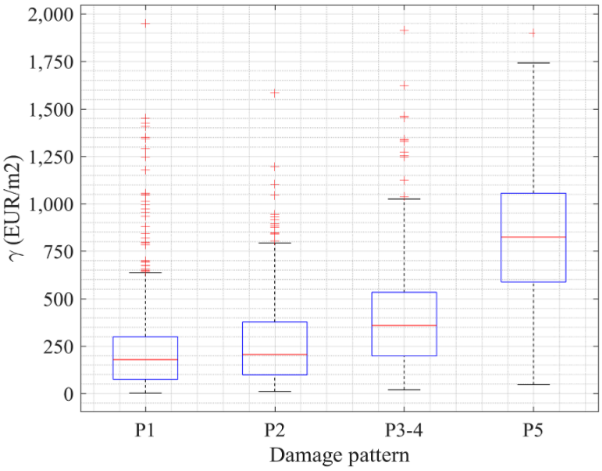


Figure 7. Boxplot of γ values, by damage pattern.

From Figure 7, we learn that: (i) as expected, median value of γ grows as damage pattern worsens. (ii) In the four boxes, both the distances of 25th and 75th percentiles from median are comparable: This is not in contrast with the idea that dispersion of cost core values is similar within the different damage patterns. (iii) Damage pattern P1, the one standing for "light damage", presents a relatively high number of outliers; in other words, a light damage can also lead to high unitary cost of works. To this regard, it has to be mentioned that, for what concerns P1 and P2, the necessary repair actions were sometimes followed by seismic improvement interventions (see Rossi et al. 2019c).

3.1 *From consequence data to loss assessment*

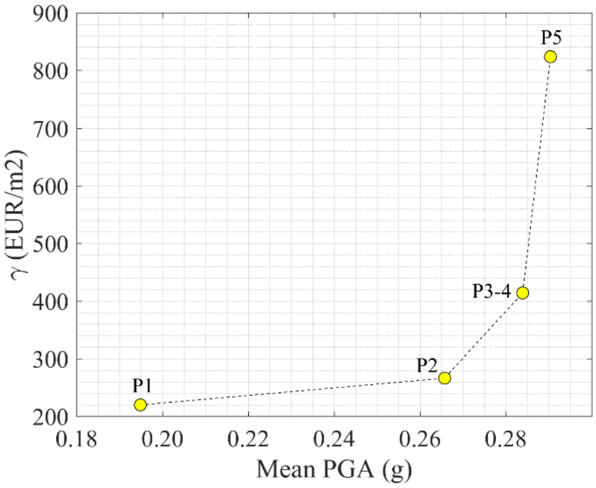
As a further step, we obtained a set of PGA-T_R pairs, by taking into consideration the mean values of the two variables for the five damage patterns. The user looking for reference (mean) values about seismic economic consequence on LSB structures, can obtain first-attempt indications from Table 2 (to this regard, more information is provided in Rossi et al. 2019c).

Table 2. Mean values of γ, PGA and T_R by damage pattern.

Damage patter (-)	Mean of γ (EUR/m^2)	Mean PGA (g)	Mean T_R* (year)
P1	220	0.195	283
P2	267	0.266	685
P3-4	414	0.284	834
P5	824	0.290	887

*site-dependent, considering S = 1.5.

Information given in Table 2 can also be represented graphically (see Figure 8 and Figure 9): On one hand, Figure 8 shows the mean values of γ, as a function of the mean values of PGA. Apparently, the function is a constantly increasing one, and its shape resembles the exponential.



(a)

Figure 8. Mean γ, by damage pattern, as a function of mean PGA.

On the other hand, Figure 9 shows a γ–λ function – where λ = $1/T_R$: In this case, values of return period were obtained by assuming a reference geographical location (Lon. = 11.04° E; Lat. = 44.41° N), for which ground acceleration-return period (ag-T_R) pairs are known (MIT 2008), and considering an amplification factor S = 1.50 (MIT 2018), i.e. so that ag = PGA/1.50.

For a site of interest, and using the same set of γ-PGA pairs, it will be possible to obtain a local instance of the γ-λ curve. From it, one can get a first-approximation value of the Expected Annual Loss (EAL). This can be done because – for a time span of one year – the inverse of the return period is equivalent to the probability of exceedance (Kottegoda 2008). To this aim, one can apply the definition of expected value, so to get EAL by using Formula 3.

$$\mathrm{EAL} = \sum_{\mathrm{i}=1}^{\mathrm{N}} [\lambda(\gamma_{\mathrm{i,inf}}) - \lambda(\gamma_{\mathrm{i,sup}})] \cdot \bar{\gamma}_{\mathrm{i}} \qquad (3)$$

In Formula 3, N is the number of segments forming a finite partition of the γ domain; λ is the value of absolute probability of exceedance, calculated at each interval's extremes; $\bar{\gamma}_{\mathrm{i}}$ is the mean value of variable γ in the i-th interval.

As an additional step, the interested reader could get a first-attempt value of the Lifetime Expected Loss, by computing the probability of exceedance with Poisson's formulation, in a reference time span V_R (see Formula 4, where s is the number of exceeding events within V_R).

$$p_{VR}(s \geq 1) = 1 - p_{VR}(0) = 1 - e^{(-\frac{VR}{TR})} \quad (4)$$

In Formula 4, $p_{VR}(0)$ is the probability of exceeding zero times the intensity level corresponding to a return period T_R, during the life span of interest (V_R). This second formulation poses the problem of evaluating γ for multiple occurrences of relevant seismic events, during the structure's life-cycle; such problem goes beyond the scope of this short paper and is then ignored in the following.

It has to be noticed that the curve showed in Figure 9 was defined by taking as a reference Emilia-Romagna's data – for this reason, in the following we will refer to it as ER_λ. Dually to ER_λ, by taking the provided γ values as fixed, the future user could represent the corresponding capacity curve C_λ of a given structure of interest, by inputting the λ values obtained from structural analysis. We show an example of C_λ curve in Figure 10, where the X and Y axes are now reverted (and Y is also normalized), so to resemble the layout used in a typical chart of the Italian *Sisma bonus* scheme (MIT 2017). Indeed, from the proposed chart, it would be possible to compute a value corresponding to the annual expected loss per square meter. Dividing that value for an assessed unitary monetary worth (in EUR/m^2) of the building of interest, one can get something comparable to what in (MIT 2017) is referred to as PAM or, in Italian, *Perdita Media Annua attesa*.

With regard to Figure 10, for a given C_λ curve, the larger the λ value at which a damage pattern is reached, the worse the structure is performing. In other words, the larger λ, the smaller the return period of the event for which a conventional damage pattern manifests itself. The user's four points, that define the piecewise curve C_λ, will be placed along the horizontal dashed lines that characterize the chart of Figure 10; this means that the cost of interventions are considered fixed. Then, by comparing ER_λ and C_λ, the reader can learn how good the target structure is performing with respect to the Emilia-Romagna's building stock, the latter being *virtually* translated to the considered location. Here, the word "virtually" is used as we consider Emilia-Romagna's actual values of γ and PGA, together with return periods that now depend on the seismic hazard of the considered site of interest. As a term of comparison, in Figure 10 we also represented (with red dashed lines) the percentages of total reconstruction cost corresponding to the five limit states considered by the Italian building code (see MIT 2018). As expressed in the official documentation about *Sisma bonus* (MIT 2017), the limit states, and the associated percentages of total reconstruction cost are: (i) SLO, 7%; (ii) SLD, 15%; (iii) SLV, 50%; (iv) SLC, 80%; (v) SLR, 100%. Considering this, two observations can be made: (1) The lower limit state seem to be well below the minimum value of actually experienced mean reconstruction cost, γ. This is due to the fact that P1 and P2 incorporate some extra costs, generated by seismic improvement interventions (SII) that were put in place by the business owners after the necessary damage reparations (see Rossi 2019c). A further data disaggregation will allow the authors to isolate the cases of buildings that underwent SII. This will make possible a direct comparison of both P1 to SLO, and P2 to SLD. (2) The reconstruction cost corresponding to SLV (life-safety limit state), seems to be well calibrated to P3-4's mean value. This fact is particularly interesting as the two conditions could be considered comparable from the point of view of the damage condition they refer to.

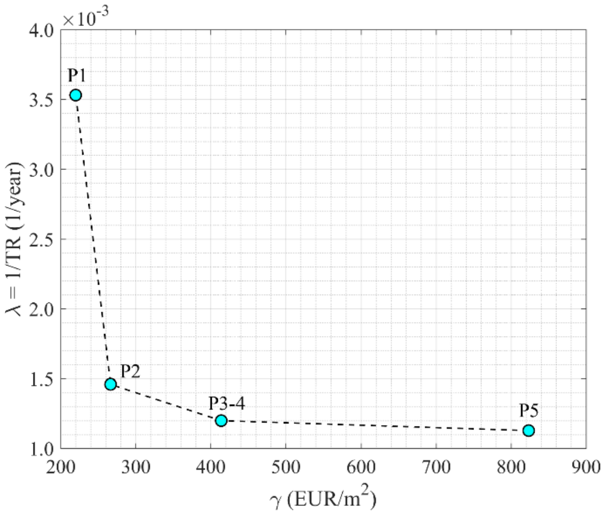


Figure 9. Mean γ, by damage pattern, versus mean λ.

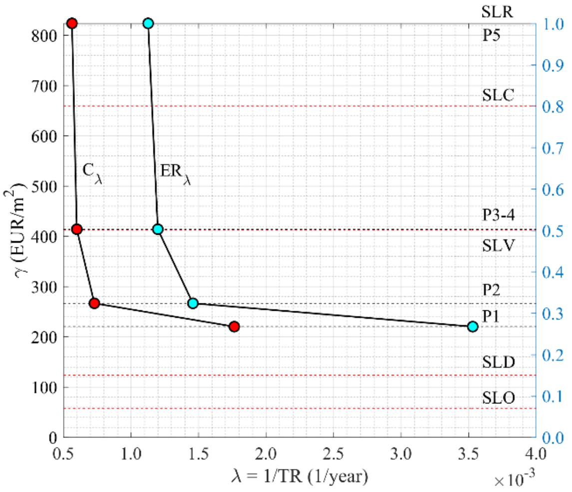


Figure 10. Examples of ER$_\lambda$ and C$_\lambda$ curves.

In a nutshell, the information we provided here (in tables and charts), may be used in two ways: (i) On one side, it can help the user wanting to assess the seismic economic losses (in a given time span) for a given LSB building. (ii) On the other hand, it can be adopted by public institutions wanting to improve the way they allocate money to support structures retrofitting. To both these aims, additional investigation and data disaggregation are envisaged as necessary further research steps.

4 LIMITATIONS

The Emilia-Romagna's database represents a unique chance of getting up-to-date, first-class, information about the reconstruction cost of an industrialized area of Italy. Nonetheless, the results here presented face some general limitations: (i) The PGA values we considered are the maximum values recorded at every location; this means that we cannot be sure about the actual intensity at which the damage patterns were activated. To this regard, for damage patterns below collapse, the only thing we can take for granted is that the seismic demand was not strong enough to activate the following damage pattern. (ii) The data we analyzed are influenced by the socio-economic context in which they were generated, i.e. the geographical area of Emilia-Romagna (Italy), as of 2012. This second drawback can be overcome by adopting cost correction coefficients that translate prices both in time (considering inflation) and in space (correcting the values by local purchase power), respectively. (iii) Finally, the damage patterns here considered (P1, ..., P5) do not resemble those defined in the Italian building code. Nonetheless, they can be considered as representative of the way LSB structures actually get damaged by an earthquake.

5 CONCLUSIONS

First of all, in this paper we introduced the main results of a 2-year research project focused on the in-depth analysis of a seismic consequence database. The studied database was created by Italian public authority Regione Emilia-Romagna after the 2012 seismic sequence, so to fairly manage public compensations. Among the results presented, there are the cumulative distribution functions (CDF) of the cost of post-earthquake construction works on long-span-beam structures; such functions, that were developed for a set of frequently recurrent damage patterns, can be used by the PBEE reader in assessing the direct economic consequence of an earthquake on precast RC structures. A second relevant result is the statistical analysis of the PGA values that induced the different damage patterns. Dually, we also reported a boxplot summarizing the statistical analysis of unitary reconstruction cost by damage pattern. As a further step, we showed a chart in which economic consequences and PGA are put in relation. Finally, such chart is translated into a new one, having the inverse of the return period on one axis. This latter represents the first attempt of a consequence assessment tool that public institutions could use in two ways: (i) To assess possible economic consequences, by events' return period. (ii) To calibrate their spending, when promoting seismic retrofitting of undamaged LSB buildings.

In the text, we discussed possible limitations of the proposed tools: Nonetheless, Emilia-Romagna's data represent a unique opportunity for improving the state of the art of seismic performance assessment tools.

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