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Procedia Structural Integrity 44 (2023) 1776–1783

Structural Integrity
Procedia

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XIX ANIDIS Conference, Seismic Engineering in Italy

Observational loss database of typological precast RC buildings damaged after the 2012 Emilia Earthquake

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Abstract

The Emilia Earthquake occurred in 2012 in a highly industrialized area, characterized by the presence of about one firm every 9 inhabitants. The industrial heart of the region hosts many important clusters, from the Motor Valley to Food, Wellbeing, Fashion and Health devices. The main activities are conducted in production districts with several different long-span buildings like storages, deposits, warehouses, factories and silos. Among these, those made of precast reinforced-concrete (RC) elements were heavily damaged by the seismic sequence, resulting in a huge amount of economic losses due to damage to structures, products and machineries, business interruption and casualties. In the aftermath of the earthquake, the Region defined the criteria for the request of funds for the reconstruction of the buildings, the restoration of the products, the reparation of the equipment, and the temporary relocation of the activities. Thus, a large number of documents was collected reporting a variety of information concerning the seismic damage, the structural properties of the buildings, and the economic costs.

In this work, through a process of progressive selection and refinement of the data, a database of seismic economic losses of damaged precast RC buildings was created. The main principles for the creation of the repository and the categorization of the information are illustrated. Hence, the losses were statistically analysed to derive useful consequence functions based on the investigation of diversified trends of the repair costs at different damage levels. The outcomes presented in this study may be adopted to perform loss assessment evaluations to guide the decision-makers in establishing priorities of structural interventions to reduce the consequences of future earthquakes in industrial areas.

Keywords: Precast RC buildings; observational database; seismic loss; 2012 Emilia earthquake; consequence functions.

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10.1016/j.prostr.2023.01.227

1. Introduction

Natural disasters cause a wide range of possible physical and socio-economic impacts, with short to long-lasting effects. In particular, earthquakes represent one of the major threats for many countries in the world, especially for Italy, as the recent events demonstrated (Dolce and Di Bucci, 2017). Nowadays, seismic loss simulations are performed to analyze the direct and indirect effects associated with the earthquake-induced structural damage, both at the local scale of a single building and at the territorial scale. Regarding the latter, the role of the indirect losses altering the business is expressed in the change of the indicators of the economic health of a territory. Indeed, recent experiences have shown that the Gross Domestic Product (GDP) of a country can suffer a significant drop after a seismic event (Daniell et al. 2011). Moreover, the Governments spend huge amount of funds in the post-earthquake phase to organize the reconstruction process of the built environment. In Italy, according to the National Risk Assessment, released by the Italian Civil Protection Department in 2018, the earthquakes caused about 5000 fatalities and over 200 billion € of economic losses in the last 50 years (Masi et al. 2021, Dolce et al. 2021). These alarming numbers are likely to increase in the next decades if adequate measures of seismic retrofit are not planned, since one of the main issues in Italy is the high vulnerability of the existing building stock (Masi et al. 2021, Di Ludovico et al. 2021).

In this context, one of the main objectives of the research is to estimate the potential losses of a natural disaster, in order to orient decision makers in the definition of suitable mitigation plans. To this aim, the empirical loss data collected after the seismic events have to be organized and analyzed in order to create repositories of sources to be used to calibrate the models. In particular, the analysis of the losses allows deriving the consequence functions that associate the seismic damage to a certain amount of loss. In Italy, a significant contribution to the analyses of the observational seismic data was presented in the book ‘Libro Bianco’ following L’Aquila Earthquake (Di Ludovico et al. 2017a and 2017b). It offers a comprehensive investigation of the repair costs at different damage levels and different structural typologies of ordinary RC and masonry buildings damaged by the earthquake.

Another valuable Italian repository of seismic data is the ‘SFINGE-SISMA platform’ (Agenzia Regionale per la Ricostruzione 2018), collecting damage and loss data of buildings after the 2012 earthquake in Emilia Romagna. Specifically, SFINGE was devoted to the collection of the data regarding the business activities only, resulting in an almost unique loss database of industrial long-span buildings. The first pioneering analyses of this data were presented in Buratti et al. (2017) and Ongaretto et al. (2019), focusing on the development of empirical fragility curves at different damage levels, and for several structural typologies of precast RC buildings, respectively. In addition, Rossi et al. (2019 and 2020) proposed an extensive analysis of the losses of long-span buildings, deriving consequence functions of different components. However, the disaggregation of the data did not account for the presence of large estates with several structural units, in some case belonging to different structural typologies. Moreover, different categories of long-span buildings were considered together, such as precast RC buildings, steel buildings, ordinary RC buildings, tanks and others. Even if the majority of industrial buildings in the area are precast RC structures, there was not a differentiation of the typologies, so not allowing for a clear relationship between losses and structural features. Therefore, a comprehensive analysis of the losses of industrial buildings, such as that available in the ‘Libro Bianco’ for ordinary buildings, is not available yet.

After the events of 2012 in Emilia, the precast RC buildings have proved to be very fragile to the seismic actions (Belleri et al. 2014, Savoia et al. 2017), and a large part of the existing structures in Italy is still in an unsafe condition, even if some seismic design criteria were set. In the research to date, a minor attention was devoted to the seismic risk of precast RC buildings, compared with other structural typologies. As enhanced by Belleri et al. (2021), there is the need to develop seismic risk assessment methodologies and collect loss data on this fragile structural category, to bridge the gap with the other typologies. To this aim, an observational loss database of precast RC buildings damaged by the 2012 earthquake is described in the present work. The empirical losses are studied in a multifaceted framework of analysis, to derive useful consequence functions that can be adopted in prediction of risk models. The main criteria for the creation of the repository and the categorization of the information are illustrated. Thus, the losses are statistically analyzed to derive the consequence functions based on the investigation of diversified trends of the repair costs at different damage levels, for the main structural typologies of industrial precast buildings in the territory. The analysis of the damage and loss data offers the possibility to derive useful tools for seismic risk assessments and earthquake loss estimations in seismic prone territories. The outcomes may be adopted in the future to establish priorities of structural interventions to reduce the consequences of seismic events in industrial areas.

2. The typological-loss database of precast RC buildings

The area affected by the Emilia Romagna 2012 seismic sequence embraced 59 industrial districts, producing around the 2.5% of the National GDP (Gross Domestic Product) according to Agenzia Regionale per la Ricostruzione (2018). Before the earthquake, the industrial core hosted many important clusters: Motor Valley, Food Valley, Packaging, Tiles, Wellbeing, Health and Fashion, promoting the work of about 20'000 companies and 53'000 employees. In 2012, the GDP of the area affected by the earthquake was -3%, and the whole Region registered -2.3%. However, after this major decline due to the earthquake, the economy of the area was able to restore very soon, with +1.6% GDP compared with 0.4% of the entire Emilia Romagna Region (Caselli 2020). This positive trend was possible thanks to a huge amount of financial contributions spent for the reconstruction and the economic aid to companies, allowing to trigger new investments and to increase the employment rate.

The SFINGE-SISMA platform (Agenzia Regionale per la Ricostruzione 2018) is a valuable repository of seismic damage and loss data of industrial buildings, implemented by the Emilia Romagna Region to manage the reconstruction process after the earthquake. In particular, regarding the production companies, the 'Ordinanza Commissariale 57/2012' defined the criteria for the request of funds for the reconstruction of buildings, the restoration of products and stocks, the reparation of machineries and equipment, and the temporary relocation of the activities. In addition, the 'Bando INAIL' defined the process for the location of funds for the seismic retrofit of the non-damaged buildings, which are not treated in this work. According to the analyses of the Region, the total amount of requests accepted in SFINGE were 3450: among these, 2850 were issued for the reconstruction of the industrial buildings, while 590 were dedicated to the other elements mentioned. The first group of requests corresponds to 2105 long-span buildings, and a total amount of funds of 942'965'840,23€. A first analysis on the allocation of funds is given in Agenzia Regionale per la Ricostruzione (2018), regarding the use of the buildings, the damage scale adopted, the insurance and the national contribution given, and the surface in plan of the buildings.

In the present study, in order to provide a more in-depth investigation on the structural-related aspects of the seismic losses, a selected repository of seismic data was created starting from the study and selection of a sub-set of documents for the request of funds. It is a database of 600 precast RC buildings corresponding to a total amount of funds of 309'839'479,80€, which constitutes the 29% of the total amount of buildings and the 33% of the total amount of funds released, according to the SFINGE dataset. The database was created through the following process of progressive selection and refinement of the data: (i) selection of the requests corresponding to damaged one-storey precast RC buildings; (ii) study of the documents provided for the request for each reconstruction; (iii) separation of the requests presented for entire estates to provide economic data for each structural unit; (iv) depuration of all the VAT (value added tax), which is not a constant percentage in the different voices (i.e., components) of the costs; (v) identification of the coordinates of each building; (vi) evaluation of the surface in plan of each building; (vii) classification of the structural typology of precast RC building; (viii) disaggregation of the seismic losses into different components.

The diversification of the economic data (see point viii) allowed distinguishing between the following quantities:

- the Conventional costs, calculated in the phase of funding application, determined by multiplying the surface in plan with a parametric unitary loss based on the damage level, and eventually taking into account additional modifiers depending on the geometry of each building (see Table A in 'Ordinanza 57');
- the Estimated costs, which are the money actually spent for the reconstruction process, determined by the technicians delegated by the business owners considering reference unitary price lists and material and work quantities. These costs are computed through the forms called 'Computo Metrico Estimativo' (CME) – bill of quantities, which reports all the individual costs. Accordingly, the total costs can be divided into four sub-classes (see 'Ordinanza 57'):
    - A: the structural costs for the reparation of the structural components and the necessary structural and geotechnical tests;
    - B1: the technical fees not depending on the typology of intervention, such as the registration in the land-office, the environmental reports and the evaluation of conformity;
    - C: the non-structural costs due to the repair of the finishing and the ordinary systems and plants (for the reparation of the industrial machineries ad hoc requests for funds were presented);
    - D: the professionals' fees linked to the architectural and structural project;

- the insurance contribution, i.e., the amount of money given by private Insurance companies, if the building was covered by one of them;
- the final fund given, corresponding to the lowest amount between the Conventional cost and the Estimated cost minus the Insurance contribution, if present.

To ease the comparison with other documents, it is worth saying that the Conventional costs in € are called DREL in Rossi et al. (2020), and '*Importo da danno, costo convenzionale*' in Agenzia Regionale per la Ricostruzione (2018). Moreover, the Estimated costs in € are named DREC in Rossi et al. (2020), and '*Importo lavori da CME ammessi*' in Agenzia Regionale per la Ricostruzione (2018). It is important to note that the costs for the repair of particular industrial machineries and for the restoration of products are not included in the aforementioned category C. Indeed, the losses due to these quantities were collected in specific requests, which were issued for some buildings only and are not available for all the units. These spare costs, even if highly significant for industrial buildings, are not included in this work since they need to be analyzed with different criteria.

The damage scale adopted in the database is that defined by the 'Ordinanza 57', identifying five damage degrees, each of which entails a specific approach of structural intervention. The Regional damage scale, originally composed by letters, is listed with numbers for simplicity, in line with the works of Buratti et al. (2017) and Ongaretto et al. (2019). The damage levels are: D1 - local damage; D2 - widespread light damage; D3 - moderate structural damage; D4 - heavy structural damage and D5 - total or partial collapse. The damage levels considered are practically coincident with those defined in the European Macroseismic Scale EMS-98, as Buratti et al. (2017) recognized. The type of intervention suggested is either local strengthening or seismic retrofit for D1 and D2 damage levels; repair and seismic retrofit for D3 and D4; demolition and reconstruction for D5.

The typologies of one-storey precast RC buildings considered in the database are those described in Ongaretto et al. (2019) and previously defined in Savoia et al. (2017). The precast elements are strongly standardized following different technologies adopted in the years, with recurrent sections and shapes of the elements and different spans and dimensions. Thus, it is possible to categorize the structures according to several typologies based on the year of construction and the building dimensions. In the following list, the 6 most relevant typologies considered in this study are reported, among which the most common ones (and interesting from the structural point of view) are T1, T2, T3:

- T1 - buildings with double-slope precast main beams simply-supported on top of columns. On the perimeter, masonry infills or horizontal precast cladding panels placed between the columns. The roof can be made either of precast elements with hollow-clay-blocks, TT or of hollow-core concrete elements. Few or no steel connectors are present in the as-built condition. This is a typical technology adopted in the 70's and 80's;
- T2 - buildings with double-slope precast main beams simply-supported on top of columns. On the perimeter, precast cladding panels are fixed externally to columns. The cladding panels can be either horizontal or vertical, a typical technology adopted after the 80's. Like T1, T2 can be characterized by different kinds of precast roof or slab elements. Rarely, T2 may have a planar roof with straight I- or T-shaped main beams;
- T3 - buildings with a flat roof, made of long-span pre-stressed roof or floor elements. This technology was widely used after the 80's for large industrial facilities with few columns inside and large empty spaces. On average, the surface in plan is almost twice that of buildings T1 and T2. Different pre-stressed elements are adopted such as TT or Y-shaped or wing-shaped, usually longer than the main beams. The columns feature large cross-sections, and the cladding panels can be either horizontal, vertical or with a mixed layout;
- T4 - buildings with a shed roof, with different layouts; they are characterized by a very poor seismic behavior;
- T5 - buildings with a sort of irregularity (in plan or in elevation);
- T6 - buildings characterized by very uncommon characteristics.

It is evident that T5 and T6 feature two very mixed population of buildings without a homogeneous seismic behaviour. In addition, T4 buildings are not common, as demonstrated by the analysis of Ongaretto et al. (2019), whose extensive database includes only 4% of shed buildings.

The scheme in Fig. 1 illustrates the geographical distribution of the precast buildings, where each unit is identified with a coloured dot depending on the damage level. The distance from the main cities and industrial clusters can be appreciated. The position of the epicentres of the two seismic events is marked in red, together with the geographical extension of the two areas interested by the faults marked with black dot and dashed lines. Clearly, the majority of the highly damaged structures (D4 and D5) are located close to the epicentres, whereas the others are spread in the territory.

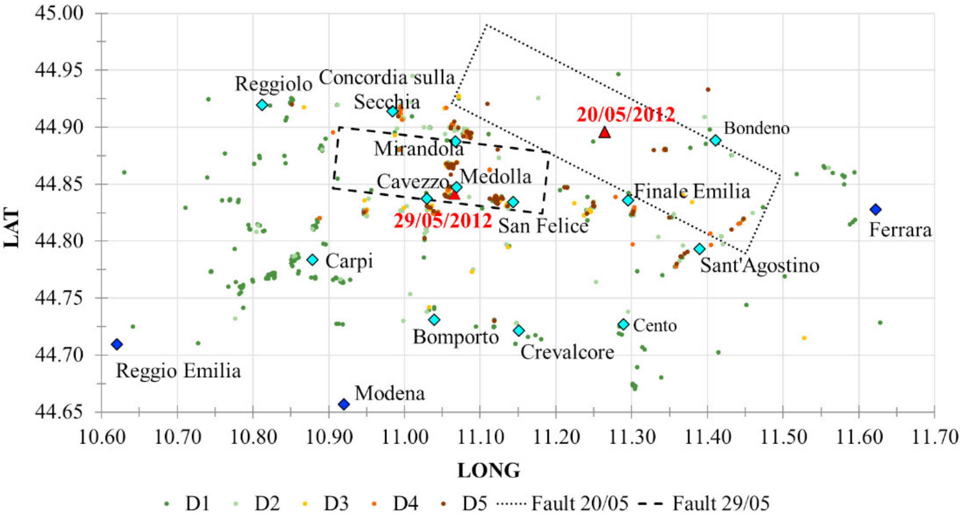

Fig. 1. Geographical distribution of the buildings with different damage levels included in the database. Position of the main cities in blue, of main industrial districts in light blue, epicenters of the main 2012 shocks in red, faults areas in black. Coordinates are in decimal degrees.

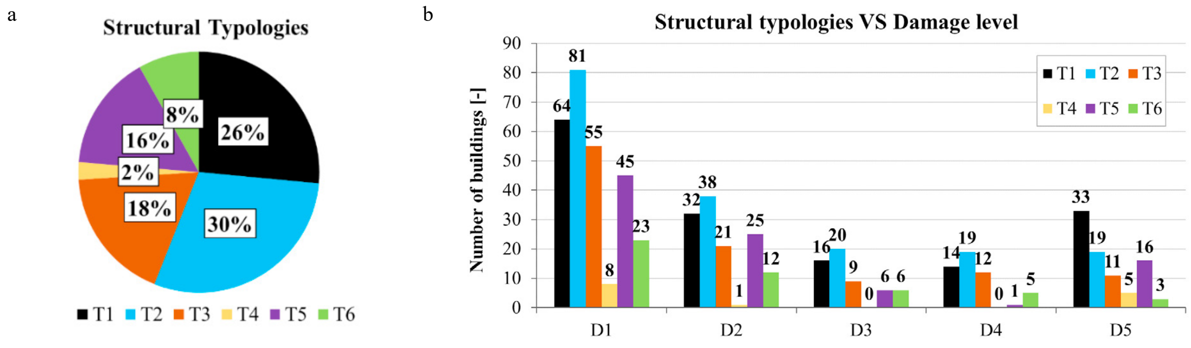

Fig. 2. (a) Percentage of the six structural typologies in the database; (b) number of buildings at different damage levels, for the six typologies.

The percentage distribution of typologies T1-T6 in the database are given in Fig. 2a: the most significant ones are T1, T2 and T3, constituting the 74% of the database, while T4 is almost negligible. Fig. 2b reports the number of buildings belonging to the different typologies, at different damage states. There is a higher number of buildings belonging to damage levels D1 and D2, like in the distributions observed in Agenzia Regionale per la Ricostruzione (2018) and Buratti et al. (2017).

3. Analysis of the estimated losses

In this Section some significant results of the analysis of the database are presented. The actual costs estimated by the technicians, i.e., the total estimated costs, have been analysed for different damage levels considering all the structural typologies of precast RC buildings together. The outliers of the losses in €/mq of surface in plan have been removed at each damage state with the following rule: a data is considered outlier if it is equal or greater than 1.5 interquartile ranges above the 75° percentile, or below the 25° percentile. The empirical continuous distributions of the monetary losses have been derived by fitting the observational data with lognormal functions, and the main descriptors of the curves (μ and σ) have been computed with an iterative last-squares estimation, so obtaining an estimate of the consequence functions at different damage states.

It is worth noting that the values of losses at damage states D1 and D2 have been further divided into two sub-groups. Indeed, the buildings subjected to these damage states could have been retrofitted if the vulnerability (i.e., the ratio between seismic capacity and demand PGA_c/PGA_d calculated by the technicians) in the as-built condition was estimated to be lower than 0.6 or, only repaired with local interventions, if it was higher or equal to 0.6. This separation leds to quite different results between the two sub-groups, in terms of distribution of losses. Some examples of common retrofit solutions for precast RC buildings can be found in Minghini and Tullini (2021) aimed at the strengthening of columns, the interventions or substitution of cladding panels, or the use of steel bracing systems. Moreover, it is worth mentioning the use of seismic dissipative devices, such as that described in Praticò et al. (2021).

In addition, the losses have been calculated dividing the amount in € by the surface in plan of the buildings in the pre-earthquake condition, following the indications defined by the Region. However, at D5, a process of demolition and reconstruction was engaged, and, in some cases, this led to a higher surface in plan in the post-earthquake condition. Hence, the losses at D5 have been calculated considering the post-reconstruction surface.

Table 1 reports the statistical analysis of the data at different damage levels. In Fig. 3, the distributions of the data in €/mq are plotted together with the fitting continuous lognormal functions. The logarithmic main descriptors of each function are indicated in the figures with letters μ and σ. The bin-width considered in the histograms is 25 €/mq for losses at damage levels D1 and D2, and 50 €/mq for losses at D3, D4, D5. In general, the losses at D1 with local interventions are lower than those at D1 with retrofit, and the same occurs at damage level D2. The local strengthening interventions aim at increasing the stiffness and/or the ductility of some structural elements only (typically the columns and the connections), while a complete retrofit increases the seismic capacity of the entire buildings. The latter approach results in a more complex procedure affecting the overall seismic behaviour of the structure, often involving the application of different techniques; therefore, it is expected to be more expensive. In this light, the evidences found in this work are in line with those found in Di Ludovico et al. (2017a) after L'Aquila earthquake. The fitting curves at D3, D4 and D5 follow different distributions with increasing mean values, as expected. At D5, the buildings were entirely reconstructed leading to a huge increase of the average loss compared with the previous damage states.

Since the data presented so far do not account for the disaggregation into structural typologies, Table 2 reports the loss data of typology T1, T2 and T3, together with μ and σ of the corresponding functions. Clearly, the number of data after the disaggregation is smaller for the various categories. From the data, it is possible to infer that typology T1 is characterized by higher repair costs than T3, but lower reconstruction costs (those at D5). The mean value of the reconstruction costs (at D5) of typology T3 is significantly higher compared to those of typologies T1 and T2. Typology T2 occupies an intermediate position at the first three damage levels, while it is characterized by the lower losses at D4 and D5. This aspect may be due to the structural and geometrical features of the buildings. Indeed, T1 represents a class of older buildings with lower span dimensions, thus, a higher number of columns per surface unit, while T3 represents industrial buildings with larger span dimensions and broad empty internal spaces with fewer columns. Therefore, with reference to the losses in €/mq, the repair costs of typology T3 are lower than T1 and T2 (whose geometries are similar) considering, for instance, a local strengthening intervention of all the columns. This means that the higher density of columns in T1 buildings may lead to an increase of the costs for all the structural retrofit that involve operations on the columns. Those kinds of retrofit techniques were highly adopted in the reconstruction and retrofit phase after 2012 (Minghini and Tullini 2021).

Table 1. Statistical analysis of the estimated losses at different damage levels.

	D1-ret	D1-int	D2-ret	D2-int	D3	D4	D5
Mean [€/mq]	197.13	58.05	268.35	105.14	293.76	389.22	915.51
Max [€/mq]	529.31	396.63	650.87	318.92	641.06	781.01	1952.53
Min [€/mq]	13.99	8.06	44.65	11.67	25.97	66.23	369.94
Standard deviation [€/mq]	123.54	59.54	147.75	72.13	155.91	181.19	287.81
Number [-]	201	67	88	38	55	49	84
16° percentile [€/mq]	61.02	19.69	105.79	54.05	130.84	177.15	626.59
84° percentile [€/mq]	325.18	91.57	402.10	167.42	463.07	544.11	1194.97
CoV [%]	62.7	102.6	55.1	68.6	53.1	46.6	31.4

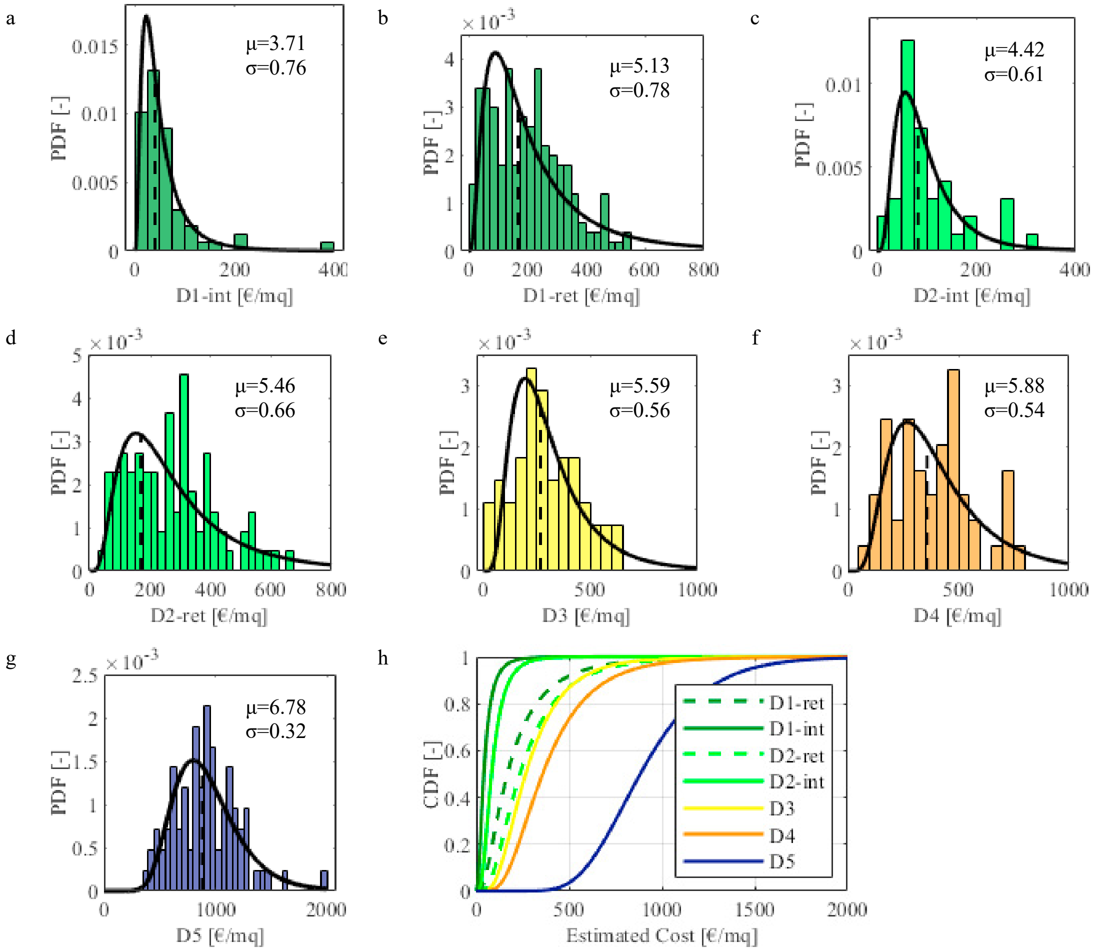

Fig. 3. Probability distributions of the estimated losses for damage levels: (a) D1 with local interventions; (b) D1 with retrofit; (c) D2 with local interventions; (d) D2 with retrofit; (e) D3; (f) D4, (g) D5. (h) Cumulative density functions. The main descriptors of the functions are reported.

Table 2. Mean, standard deviation and number of data of estimated losses of typologies T1, T2, T3 and main descriptors of the functions.

		D1-ret	D1-int	D2-ret	D2-int	D3	D4	D5
T1	Mean [€/mq]	224.11	74.64	267.42	142.63	316.92	439.99	866.93
	Standard deviation [€/mq]	132.22	56.83	146.61	78.35	138.18	151.08	241.24
	Number [-]	45	14	24	8	15	14	32
	μ; σ [ln(€/mq)]	5.28; 0.77	3.96; 0.81	5.44; 0.62	4.68; 0.61	5.66; 0.52	6.08; 0.32	6.75; 0.27
T2	Mean [€/mq]	199.12	46.43	224.97	91.98	309.37	373.59	870.73
	Standard deviation [€/mq]	121.68	27.62	116.79	82.42	137.99	190.24	243.35
	Number [-]	59	21	24	14	19	18	19
	μ; σ [ln(€/mq)]	5.14; 0.74	3.64; 0.75	5.24; 0.62	4.15; 0.74	5.60; 0.36	5.75; 0.53	6.73; 0.29
T3	Mean [€/mq]	142.84	38.72	253.02	76.07	204.30	349.76	998.29
	Standard deviation [€/mq]	90.81	30.84	185.06	26.84	165.57	187.20	296.99
	Number [-]	41	14	11	9	9	12	10
	μ; σ [ln(€/mq)]	4.77; 0.80	3.28; 0.84	5.11; 1.03	4.18; 0.34	4.67; 1.41	5.66; 0.64	6.83; 0.35

4. Conclusions

In this work, a repository of seismic loss data of damaged one-storey precast RC buildings is presented, assembled through the detailed examination of the documentation collected after the 2012 Emilia earthquake. The loss database has been analysed focusing on different aspects of the losses of the 600 buildings considered, classified into 6 structural typologies. The analysis of the total estimated costs has been presented, allowing to provide the distributions of the losses of precast buildings for different damage levels. Moreover, the losses were disaggregated considering the most common structural typologies (T1, T2 and T3), obtaining a comprehensive panorama of the repair and the reconstruction costs. The lognormal consequence functions derived for various damage levels are useful tools to be used in seismic loss and risk assessment of typical typologies of precast RC buildings.

The future developments of this work will be addressed to the examination of the distributions of other relevant loss parameters, and the cost data disaggregation into structural and non-structural components. Moreover, the correlation of the losses with the intensity measure (such as the PGA at the construction sites of the buildings) will be object of future analyses.

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