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A suite of data-based seismic consequence assessment tools for precast buildings - Results of research project DatA ESPerT

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ABSTRACT

In order to properly manage the reconstruction process that was put into force after the 2012 Northern Italy earthquake, the public regional institution Regione Emilia-Romagna collected and stored a large number of evidences about occurred damage patterns and economic consequences. As of 2019, seven years after the seismic sequence, plenty of data is available for the researchers to be used in calibrating existing assessment tools and in creating innovate prognostic measures. In particular, it is now possible to know the location of thousands of damaged buildings, and also to identify, among other things, the total area of the buildings, the damage pattern exhibited by them, and the necessary reconstruction cost. Since 2017, a European research project, so-called DatA ESPerT, is dedicated to an in-depth investigation of one of Emilia-Romagna's databases. In particular, the data repository of funding programme SFINGE was studied, so as to develop innovative – empirical-data-based – seismic consequence assessment tools. In this work, DatA ESPerT's main results are presented. Provided data and assessment tools can contribute in innovating the existing Performance Based Earthquake Engineering framework.

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INTRODUCTION

The seismic events that, in May 2012, struck an highly industrialised geographical region of Northern Italy (Scognamiglio et al. 2012; Galli et al. 2012; Lauciani et. al. 2012; Cultrera et al. 2014; Paolucci et al. 2015), provoked not only tens of casualties and hundreds of injured people, but also vast damage to structures and infrastructures (D'Aniello et al. 2012; Parisi et al. 2012; Rossetto et al. 2012; ARR 2018). In particular, many production facilities reported significant structural damage or collapse (see Figure 1), mostly due to lack of proper seismic design (Savoia et al. 2012; Liberatore et al. 2013; Magliulo et al. 2014; Minghini et al. 2016). Of an overall assessed economic loss of EUR 13.2 billion within Emilia-Romagna region, circa 2.4 billion were due enterprises' facilities and their content. Due to the notable impact of such earthquake on the socio-economic context, soon after the dramatic events, the local public authority (Regione Emilia-Romagna), launched a funding programme aimed at supporting the enterprises in re-establishing the production lines (Pres. R E-R 2012a; Pres. R E-R 2012b). Such programme, so-called SFINGE (R E-R 2012b), made possible to collect a vast and consistent database about seismic consequences suffered by thousands of structures. SFINGE database is the first of its kind in Italy, and has relevant characteristics as: vastness, reliability, information portability, novelty and topicality (Rossi et al. 2019a). In order to exploit the relevant information contained in SFINGE, a dedicated 2-year European research project (DatA ESPerT, Rossi et al. 2016) was carried out at the *Lehrstuhl für Baustatik und Baudynamik* of RWTH Aachen University (Germany). The project was financed (from June 2017 to June 2019) within the European Marie Skłodowska-Curie Actions

Individual Fellowships initiative (grant agreement n. 743458). The main motivation of the research is the need for empirical data regarding consequences of relevant earthquakes, to be used for the development and the calibration of seismic economic assessment tools for industrial buildings. Examples of such tools are fragility functions and loss curves, that can be included into the convolution integrals of seismic performance calculation frameworks (e.g. ATC 2012). Other works about post-earthquake data collection do exist (e.g. Potter 2015, De Martino 2017, Fiorentino 2018), and were taken into consideration for this research work. To this regard, it has to be mentioned that DatA ESPerT is in some way different from the cited works, as the data repository we studied was created by an independent third party (the public institution Regione Emilia-Romagna), for administrative reasons. Such repository was accessed at the end of a vast data-collection programme that lasted for 6 years, and that required many cross-checks and refinements along the way (that contributed in ensuring both data consistency and information reliability).

In this short paper we report the most interesting results of DatA ESPerT, so to contribute in disseminating the original and innovative seismic performance assessment tools that were developed during it. Further reference can be found in (Rossi et al. 2019a; Rossi et al. 2019b; Rossi et al. 2019c).

(a)

(b)

Figure 1. Examples of business facilities damaged during the Emilia-Romagna sequence (a) Steel structure; (b) precast reinforced concrete structure (source: Agenzia Regionale per la Ricostruzione – Sisma 2012).

1. DATA ABOUT BUSINESS SECTOR

The main data source of project DatA ESPerT is the Emilia-Romagna's SFINGE database. In it, it is possible to directly access information about the consequence of the 2012 seismic sequence; among other things, for what concerns business premises, the following record fields are available: (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 aspects; (vi) damage-loss causal effect; (vii) cost of necessary interventions; (viii) cost of business relocation (if the case); (ix) business owners' insurance claims. For what concerns the occurred structural damage, five damage patterns were defined by Regione Emilia-Romagna (Pres. R E-R 2012b)– from P1 (*light damage*), to P5 (*structural collapse*), with some correspondence to the EMS 98 scale (Grünthal 1998); patterns definition was based on on-site observation of recurring schemes in terms of structural consequences (definitions are given in Rossi et al. 2019b). It has to be mentioned that patterns P1 and P2 were quite similar to each other, and that, for the way they were defined, patterns P3 and P4 could be considered as just one. It is worth mentioning that, in the actual definition of a damage pattern, the relative number of bearing elements reporting a structural degradation played a role (see Rossi et al. 2019b). Examples of possible damage conditions for P1-P2 and P3-P4 are given in Figure 2a and Figure 2b respectively (while pattern P5 is shown in Figure 1). In particular, in Figure 2a we see RC elements (still elastic) that were partially disconnected with each other, due to the seismic shaking; instead, in Figure 2b, a plastic deformation of an RC fork is clearly visible.

(a)

(b)

Figure 2: Examples of damage patterns according to the Emilia-Romagna's classification (a) P1-P2; (b) P3-P4 (image source: *Agenzia Regionale per la Ricostruzione – Sisma 2012*).

1.1. *Assessed losses and reconstruction costs*

By directly accessing SFINGE database, we are able to quantify the actual value of the economic consequences experienced, in 2012, by more than 2-thousand enterprises in Emilia-Romagna. In order to show results, definitions are necessary; three main independent economic variables exist: First, there is the so-called economic loss (L), that is a function of structural typology, building's total area and occurred damage level. Losses were evaluated *ex-ante*, using a reference table provided by the public authority (Pres. R E-R 2012b). Such table also takes into consideration the possible adoption of seismic improvement interventions. On the other hand, there is the real reconstruction cost (C), that was obtained – *ex-post* – by summing up the actual spent economic amounts (that had to be in compliance with in force reference price lists – R E-R 2012a; R E-R 2013). Again, if the case, improvement interventions (aimed at enhancing the seismic performance of the structures) were considered. Third, insurance claims (I), are also taken into consideration: they were used by the public institution to determine the final amount of money to be granted to the applicant (G – a dependent variable), so as to avoid overcompensation. For each of the four variables, information is classified with reference to 5 assets sub-categories (Rossi et al. 2019a):

(i) Real estate (REA): Structural and non-structural components of buildings (e.g. RC frames and cladding panels), including non-productive systems (e.g. electrical systems) and finishes (e.g. doors).

(ii) *Capital goods*, except real estate (CAP): Machinery (e.g. metal lathes), tools (e.g. compressors), equipment (e.g. cabinets) and systems for production (e.g. air purification systems); hardware in general. A CAP item was considered *reparable*, if the reparation cost was lower or equal than 70% of the replacement cost, or *to be replaced* otherwise.

(iii) *In stock goods* (STO): Raw material (e.g. glass jars), finished and semi-finished products in storage (e.g. canned food), who lost at least 20% of their initial value.

(iv) *Business relocation* (REL): Temporary relocation of the enterprise's activities to another site within the affected area. The purchase and rental of temporary structures (e.g. tents), the connection of utilities, and the moving of production facilities are also included in REL.

(v) Products (PRO): Special food and agriculture products: this is the case of aged cheese and balsamic vinegar. This category – that represents quite an important term on the regional budget – is only related to enterprises in agriculture.

Data about the four variables (taken form Rossi et al. 2019a) are given in Table 1 and Table 2 and graphically summarized in Figure 3. There, information refers to all the possible business sectors; interestingly, the economic activities were classified by the authority also by business macrosector: industry, trade and agriculture. A further disaggregation is beyond the scope of this short paper (see instead Rossi et al. 2019a), but it could show that industrial activities are the most numerous among the applications and that the largest part of the economic value involved is linked to them.

Table 1. Number of application files and insurance claims

N. of items	REA	CAP	STO	REL	PRO	Total
Application files	2 847	372	180	453	17	3 869
Insurance claims	316	55	17	8	2	398

Table 2. Economic amounts of the four economic variables

(u.m.)	REA	CAP	STO	REL	PRO	Total
L (10^6€)	1967.9	258.8	48.8	89.4	47.6	2412.5
C (10^6€)	2032.4	251.8	50.8	85.4	47.6	2468.0
I (10^6€)	170.9	33.4	3.9	4.2	13.4	225.8
G (10^6€)	1600.6	187.9	24.2	42.1	27.7	1882.5

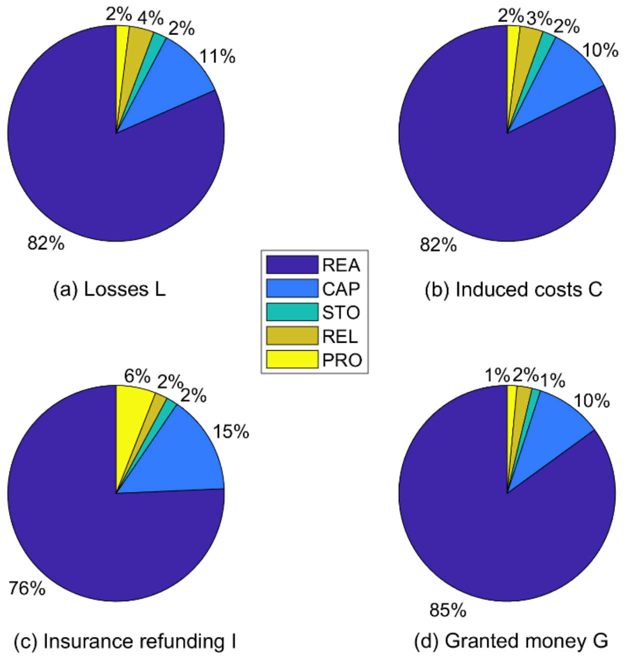

Figure 3: Distribution of economic consequence among data sub-category.

From Table 1 we noticed that most of the application files refer to real-estate items, and that capital goods were the second most important term. For what concerns insurance claims, the number of items is up to circa 10% of those of reported losses, and corresponds to less than 9% of total economic amount. Such numbers can be taken as a first approximation of the insurance penetration ratio, in business activities, within the region.

2. DATA ABOUT PRECAST STRUCTURES

In SFINGE, it is possible to get direct access to a series of records regarding a total of 4423 building units. Of these, 2319 are house-type (or similar), while 2104 are so-called *long-span-beam* (LSB). That of LSB is an internally consistent, scientifically interesting, subset: buildings' elements are mostly – but not always – RC precast components (cast-in-place and steel ones also exist), with slender beams of length between 10 and 20 m. Sometimes, the columns are made of masonry too. The plan is often rectangular, or a simple combination of few rectangles. The building's perimeter is closed by concrete-made, simply-supported panels, as well as by infill masonry walls. In Italy, such building typology is definitely common, especially in industrial areas (Bonfanti et al. 2008; Toniolo et al. 2012); many building units of this kind have been built during the '60s, '70s, and '80s (Bellotti et al. 2014), well before Emilia-Romagna was classified as "prone to seismic risk", and a modern seismic code was introduced in Italy (MIT 2008). Many recent studies are dedicated to the seismic performance of precast structures in Emilia-Romagna, e.g. (Savoia et al. 2012; Liberatore et al. 2013; Magliulo et al. 2014; Minghini et al. 2016; Buratti et al. 2017; Savoia et al. 2017). From the cited studies emerges that, among the various vulnerabilities, the lack of a proper column-beam connection is one of the most relevant. Such interesting previous works mostly rely on information collected during on-site inspections, as well as on vulnerability reports that were written soon after the emergency phase. On the contrary, in our study, we accessed data that went through the entire evaluation process of SFINGE; this means that: (i) Data were cross-checked many times from public delegates working on the funding applications; (ii) Information about the application files is complete, as we accessed the database at a time when the funding call was closed (June 2018). (iii) We got a comprehensive view on the damaged building stock, as the information was organised and gathered in a final worksheet. In the following, we summarize some of most relevant results about our investigation on 2104 LSB structures (see also Rossi et al. 2019b, and Rossi et al. 2019c).

First of all, in Figure 4 the reader can see the distribution of damaged LSB and house-type buildings, within the municipalities of Emilia-Romagna that were struck by the 2012 sequence.

Even if the scale of representation does not allow a fully clear understanding, it is possible to notice that building units are more densely located, as we can expect, between the towns of Mirandola, Cavezzo, Medolla, and San Felice sul Panaro (close to the epicenters).

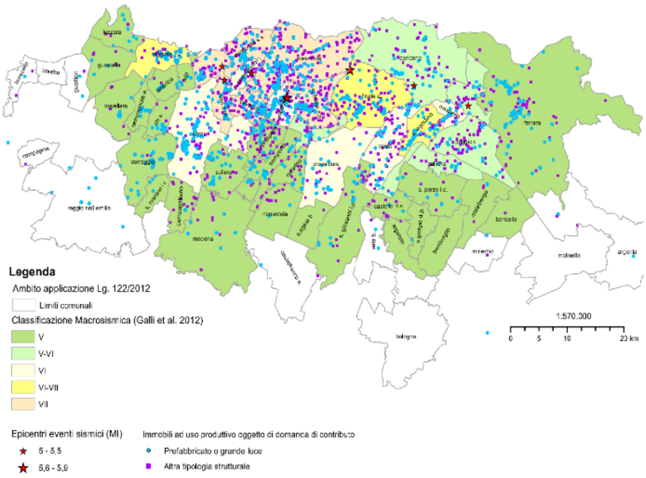

Figure 4: Distribution of LSB and house-type buildings within the area of Emilia-Romagna that was struck by the 2012 earthquake (image source: *Agenzia Regionale per la Ricostruzione – Sisma 2012*).

For what concerns the total number of LSB structures – damaged and undamaged – within the territory affected by the 2012 seismic sequence, we assessed it to be in the order of 16700 units (see Rossi et al. 2019c), circa 8 times the ones we see in SFINGE.

Buildings' area is one of the record field that is possible to explore. From data we see that the business premises that suffered seismic damage used to have quite different size: Typical business activities in the region are small-medium enterprises (SME), but very big ones also exist. In numbers: The area mean value is up to 1885 m^2, with a standard deviation of circa 3209 m^2 (the buildings' area grand total, for all the listed items, being equal to 3.966 million of m^2). Once on the Log10 scale, the area variable resembles the lognormality (see Figure 5, where the model was drawn using mean and standard deviation of logarithmic values).

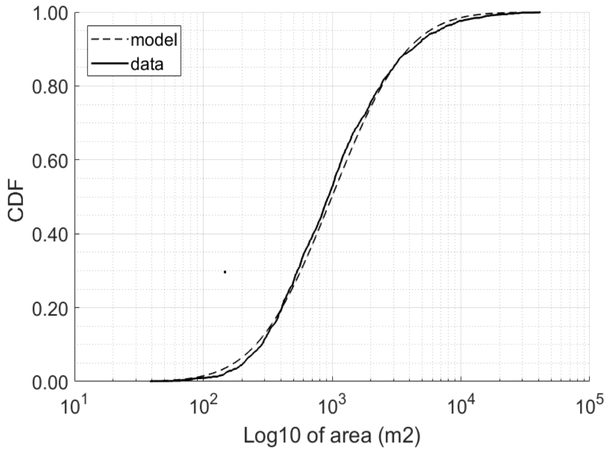

Figure 5: Theoretical and empirical CDF of the area variable.

Using the information about both area (A) and cost of interventions (Γ), for each LSB item it is possible to calculate the corresponding unitary cost of intervention (γ). In Table 3 and Figure 6 we report the mean values of γ by damage pattern (P1, ..., P5).

Table 3 – Cost of works by damage patterns

Damage pattern	P1	P2	P3	P4	P5
Num. of items	1042	432	180	139	288
μ_γ (€/m^2)	225	267	390	442	823

According to the regulations in-force in Emilia-Romagna after the emergency, in case of light damage (P1, P2) the business owners had the opportunity to apply seismic improvement interventions (SII) on top of the necessary reparation works. This influenced significantly the unitary cost of reconstruction, as is visible in Figure 6: On average, reconstruction works for a P2 damage pattern that included SII, could have a cost not far from serious damage patterns, as P3 or P4.

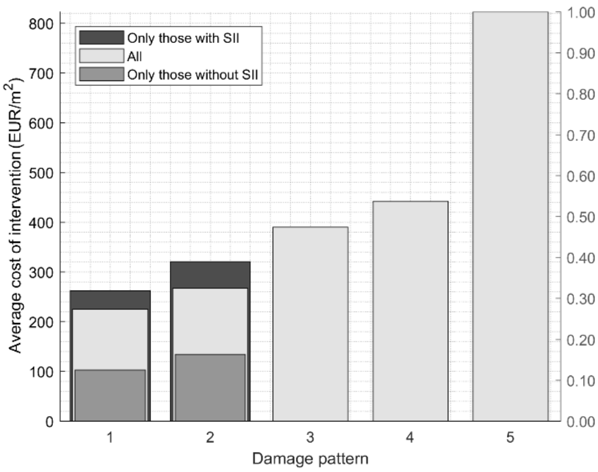

Figure 6: Average cost of interventions by damage pattern.

Additionally, the unitary reconstruction cost – γ – can be statistically described, by damage pattern, as reported in Figure 7. In the box plot, 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. As visible in Figure 7, despite outliers exist for all the five damage conditions, the size of the central 50th percentile is nonetheless comparable among the presented cases.

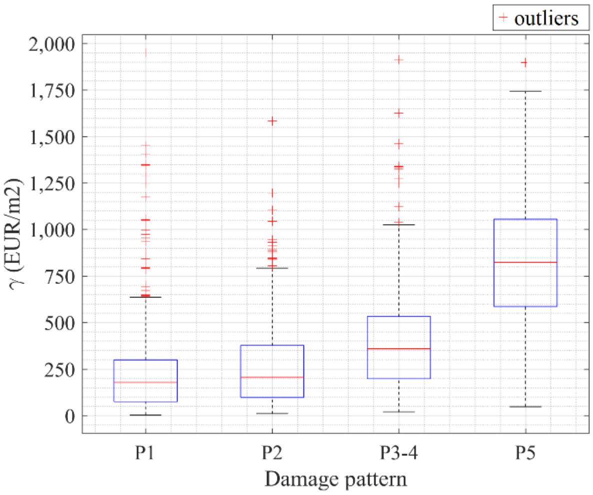

Figure 7: Box plot of unitary reconstruction cost.

Furthermore, Cumulative Distribution Functions (CDF) of γ can be obtained from data – results in this sense are reported in Figure 8. Such curves can be intended as the probability of experiencing a given γ, considering that a specific damage pattern occurred; in formulas:

$$p(\gamma \leq \gamma_0 \mid DP = P_i) \qquad (1)$$

Results of Figure 8 could be included in Performance Based Earthquake Engineering (PBEE) models (Miranda et al. 2003; Aslani 2005; ATC 2012; Syner-G Consortium 2013; GEM Foundation 2018).

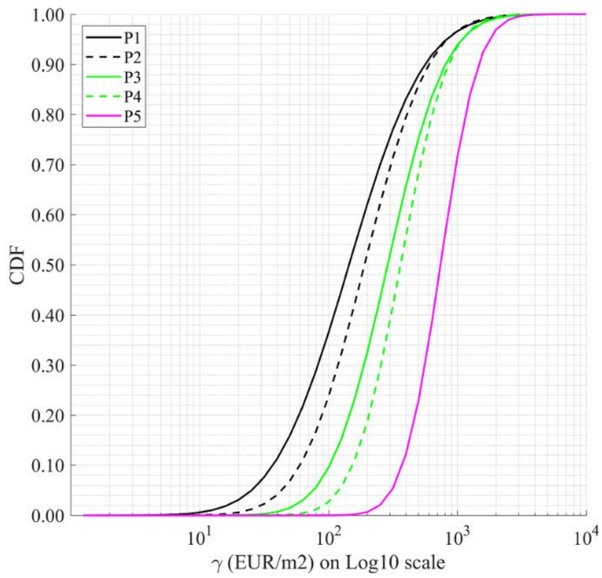

Figure 8: CDF for γ, by damage pattern.

1.1. *Buildings' location and events' shakemap*

From buildings' geographical position and events' shakemap, it is possible to determine a consequence map like the one we show in Figure 9. First of all, in the figure, we considered the envelopment of 47 PGA-shakemaps, that we collected on INGV's website and refer to those shocks with magnitude equal or greater than M_w 4.0. Secondly, we plot the LSB items we had on the envelopment map, distinguishing by damage pattern. As the reader can see, worse damage conditions are more frequent in the reddish area, while light damage is located in the peripheral zones.

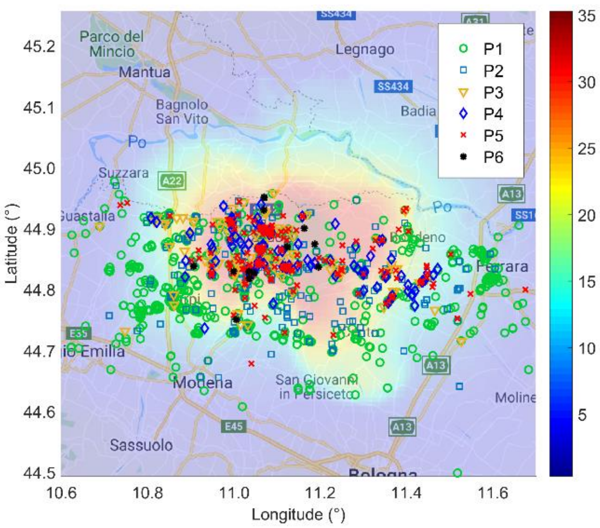

Figure 9: Consequence maps in terms of PGA (%g).

Knowing buildings' location, and considering the position of the sequence's two main events (May 20th and 29th, 2012), we obtained the chart presented in Figure 10. In this figure, δ represents the minimum distance between an LSB item and the two epicenters;

on the Y-axis instead we show the normalised cumulative value of reconstruction cost Γ. As the reader can see, most of Γ occurred for δ values lower or equal than 30 km. In other words, the 2012 Emilia-Romagna earthquake provoked quite a local effect, for what concerns direct economic losses on LSB structures.

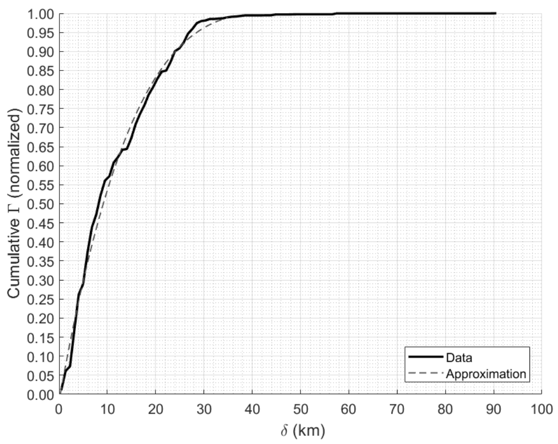

Figure 10: Cumulative (normalised) Γ as a function of δ.

We think that values we reported in the tables and figures may serve as a reference for first try assessment of reconstruction costs for LSB structures.

3. DISCUSSION

The presented results can be considered as an innovative step forward for Performance Based Earthquake Engineering (PBEE), but this does not rule out that limitations of this work exist. For example, on one hand, the quality of information can be considered as *good*, because it was first collected locally, under a bottom up approach, and then independently cross-checked in-depth by the public authority, with the help of appointed reviewers. On the other hand, data describe a well-defined socio-economic context, i.e. that of Emilia-Romagna 2012: This means that, in order to adopt obtained results in different contexts, economic values have to be translated in space and time, thus considering both the site-dependent purchasing power and the inflation rate over years. Another shortcoming regards the missing structures, i.e. those who were not listed in SFINGE, but that suffered damage as well. This problem was faced in (Rossi et al. 2019b): We are indeed convinced that the most part of the damaged units were included in SFINGE. Indeed, as funding from the state also covered expenses carried out by the applicant for experimental tests and professional fees, application was meaningful also for small buildings and light damage. In the text, we provided an assessed total amount of buildings in the area. This point poses a further problem, that is quite relevant for the investigation: In counting the undamaged structures, where is geographical limit at which we have to stop? In (Rossi et al. 2019b) it was decided to consider as possible source of undamaged buildings all those towns at which at least one structure was damaged. A further critical aspect of this study refers to the intensity measure parameter that was selected in DatA ESPerT as a reference for getting the fragility maps: i.e. PGA. First, for every map we took from INGV's website, we considered just one PGA value, without any additional uncertainty. Second, PGA is easily tractable for what concerns demand return periods (see for example the ag-return period tables attached to MIT 2008) but, obviously, it is not a sufficient descriptor of a seismic event. To this regard, given the dynamic characteristics of the studied set of buildings, further investigation may lead to fragility maps in terms of spectral acceleration at a reference vibration period (e.g. 1.0 s), and include input variability.

4. CONCLUSIONS

In this paper we presented the main scientific results that were obtained during the 2-year European research project DatA ESPerT. First of all, we provided a short description of the database that served as a main reference for the study. We then put the focus on the project's main target, i.e. the economic losses of enterprises. To this regard, we gave indications about the amount of parametric assessed losses (L), the actual reconstruction costs (C), the insurance claims (I) and, finally, the money granted by the Italian state (G). In a second step, we focused on consequences regarding a specific kind of buildings, i.e. long-span-beam (LSB) structures. For them, we analysed the cost of structural intervention (that we called Γ) and its value per square meter (γ). On one hand, we showed the mean and the statistical distribution of γ, as well as the cumulative distribution functions, by damage pattern. On the other hand, we introduced the buildings' geographical position, so to create a fragility map (in terms of PGA) and a Γ cumulative spatial distribution function.

Despite limitations exist, among which the specific socio-economic context in which the data were generated, we think that discussed results represent an innovative and original step forward in the field of seismic economic consequence assessment.

Further research may extend DatA ESPerT's results: (i) First, better data disaggregation is possible (at the cost of additional in-depth analysis of the data source); (ii) Second, obtained models can now be adopted in practical numerical simulations aiming at assessing economic consequences for selected locations of interest.

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