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Developing a Direct Approach for Estimating Expected Annual Losses of Italian Buildings

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ABSTRACT

A new approach, referred to as the DEAL (Direct estimation of Expected Annual Losses) method, is developed to evaluate the Expected Annual Loss (EAL) of RC buildings using results of traditional structural analyses within a closed-form expression. The DEAL method is developed here to account for buildings that may be irregular in height or have differing occupancy types along their height. By comparing loss estimates for case study buildings with a rigorous application of the FEMA P58 framework, it is shown that the DEAL method performs better than the PAM approach recently proposed in Italy for seismic risk classification.

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Expected annual loss; simplified loss assessment; performance-based earthquake engineering; seismic performance assessment; reinforced concrete buildings

1. Introduction

A building's expected annual monetary loss (EAL), associated with post-earthquake repairs, is becoming an increasingly important parameter for the seismic performance classification of buildings and general risk reduction. In Italy, recent legislation (DM 2017) has set out a seismic performance classification system in which a building's seismic rating is assigned based on its EAL and a life safety index (Cosenza et al. 2018). In parallel with this, the Italian government is incentivising seismic retrofit by offering a tax deduction of up to 85% on the retrofit cost, when a building's classification is improved such that both the life safety index and EAL satisfy certain limits. To facilitate this process, a simplified means of estimating the EAL has been provided and it will be described in Section 2. However, as shown in this paper, the EAL values obtained from the simplified approach currently used in Italy can differ significantly from those obtained using more rigorous methods, such as that outlined in FEMA P58 (2012).

This paper proposes a refined version of the approach presented in Cardone et al. (2017) for the estimation of the expected annual losses of Italian buildings. The novel approach, referred to as DEAL (Direct estimation of Expected Annual Loss), relies on suitable storey-based loss functions for the estimation of the expected loss at selected limit states or performance levels of the building. The main advantage of this important refinement is the possibility of overcoming the limitations associated with assuming given loss factors for selected limit states or performance levels. In addition, the DEAL method is capable of considering building irregularity in height and different occupancy

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types. Two sets of storey-based loss functions, specific for typical Italian pre-70 residential buildings with different non-structural layout configurations, are presented in the paper, as a practical tool for the application of the method to a wide class of buildings.

Finally, the potential implications of errors in EAL estimates obtained via different approaches are reviewed and discussed at a regional/national scale for Italy.

2. Simplified Loss Estimation

A range of loss estimation methods can be found in the literature. The FEMA/NIBS earthquake loss estimation methodology, commonly known as HAZUS (1997) could be seen as one of the first basic method for estimation of EAL and was used for mapping and displaying hazard data and the results of damage and economic loss estimates for buildings and infrastructure. The approach was supported by work by Kircher et al. (1997a, 1997b) using building damage functions developed by Whitman et al. (1997) for earthquake loss estimation. More rigorous loss estimation of buildings, as prescribed in guidelines such as FEMA P58 (2012), tends to be a time-consuming procedure and possesses a number of user-dependant steps that can greatly affect the evaluation of monetary losses (O'Reilly and Sullivan 2018a). As such, there has been a growing need for the development of more simplified loss estimation methods that can be both accessible to practitioners and univocal in their quantification of seismic performance (Koduru and Haukaas 2010). A simplified loss estimation methodology that relates hazard to selected engineering demand parameters and hence to losses without the need for classic fragility curves was proposed by Mander, Sircar, and Damnjanovic (2012) to allow computation of EAL via a closed form equation. The approach was developed for bridges and has similarities to more recent proposals by Sullivan (2016) and Cardone et al. (2017) as it proposes EAL computation via a single expression. This section describes two proposals that are aimed at providing simplified estimates of EAL for specific buildings: the recent seismic classification guidelines introduced in Italy (DM 2017) and the simplified approach of Cardone et al. (2017) which estimates the EAL in a closed-form solution. Both of these methods are then implemented in subsequent sections, where relative strengths and weaknesses are discussed followed by some further refinements to the Cardone et al. (2017) procedure based on some observations described herein.

2.1. *Estimation of EAL Using Italian Seismic Classification Guidelines*

The Italian Ministry of Infrastructure and Transport recently introduced seismic classification guidelines outlined in the D.M. 58/2017 (DM 2017) whereby the seismic performance is evaluated considering both EAL and a life safety index. These guidelines are fully integrated with the Italian Seismic Code (NTC 2018) and are therefore readily accessible to practitioners. The basic procedure is outlined in Fig. 1, where it can be seen how a static pushover analysis (Cardone 2007) is required to estimate the exceedance of relevant limit states prescribed by the assessment code.

For each of the limit states summarized, a set of prescribed loss ratios is provided in D. M. 58/2017 as shown in Fig. 1.

The EAL normalised by the building replacement cost, RepC is then simply computed from the area under the loss curve, as illustrated in Fig. 1(f). Furthermore, the life safety of

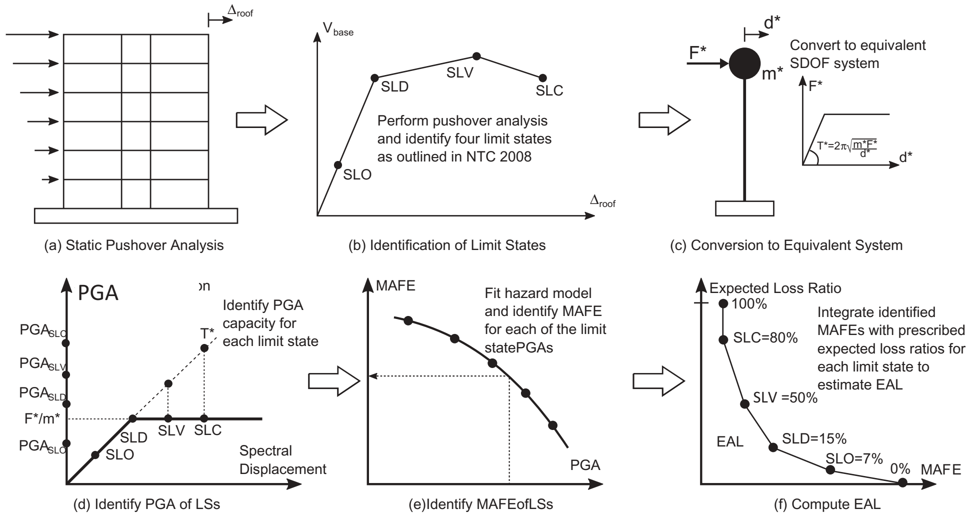

Figure 1 Overview of the main steps outlined in the Italian seismic classification guidelines D.M. 58/2017, where a static pushover analysis is required to identify limit state MAFE and following some simplifying assumptions regarding expected loss ratios, a simplified estimate EAL is derived (adapted from O'Reilly, Sullivan, and Monteiro (2018a)).

the buildings is simply computed using the capacity to demand ratio in terms of Peak Ground Accelerations (i.e. PGA_C/PGA_D) at the Life Safety limit state (SLV in Fig. 1). The overall performance rating, or classification, of the building is identified using a letter-based score system determined as the more critical of the EAL and life safety indices, which are listed in Table 1 and denoted as the Perdita Annuale Media attesa (PAM) (i.e. EAL) and the Indice di Salvaguardia Vita (IS-V) (i.e. life safety index), respectively.

While the procedure outlined in the D.M. 58/2017 is recognised as a positive step forward in the introduction of more advanced methods of seismic performance quantification, it possesses a number of limitations, as will be highlighted later in this paper and as discussed in O'Reilly et al. (2018a). Of particular relevance, is the assumption of constant loss ratios for each limit state considered. These fixed ratios have been shown by O'Reilly, Perrone, Fox, Monteiro, and Filiatrault (2018b) to be somewhat inconsistent when compared with more advanced methods of analysis to compute EAL, indicating that the fixed ratios tended to overestimate the monetary losses for RC frame buildings.

Table 1 Rating system of the seismic performance classification guidelines D.M. 58/2017, expressed as the more critical of the PAM or IS-V.

PAM Classification Range	Life Safety Index Classification Range	Classification Ranking
PAM ≤ 0.5%	1.00 ≤ IS-V	A+
0.5% ≤ PAM < 1.0%	0.80 ≤ IS-V < 1.00	A
1.0% ≤ PAM < 1.5%	0.60 ≤ IS-V < 0.80	B
1.5% ≤ PAM < 2.5%	0.45 ≤ IS-V < 0.60	C
2.5% ≤ PAM < 3.5%	0.30 ≤ IS-V < 0.45	D
3.5% ≤ PAM < 4.5%	0.15 ≤ IS-V < 0.30	E
4.5% ≤ PAM < 7.0%	IS-V < 0.15	F
7.0% ≤ PAM		G

Furthermore, the use of fixed values inherently ignores aspects such as irregularity in the structural response, which was incorporated in the procedure proposed by Cardone et al. (2017). In addition, different occupancy types are not considered using this methodology, which O'Reilly and Sullivan (2018a) note as a point for future improvement of the assessment framework. Lastly, the use of PGA and smoothed, code-based response spectra to assess the MAFE of limit states also possesses a number of simplifying assumptions related to spectral shape compared with the use of detailed site hazard information that should not be overlooked. These aspects will be considered further in later sections, where the method outlined in the next section will be expanded to incorporate a number of these refinements.

2.2. *Closed-form Evaluation of EAL*

If direct monetary losses due to earthquake shaking are assumed to increase linearly with respect to seismic intensity and if the seismic hazard curve can be reasonably represented as linear in log-space, then the expected annual loss (EAL) can be computed in a single, closed-form expression (Sullivan 2016). This approach allows the EAL to be computed knowing just the earthquake intensity level and return periods corresponding to two limit states that define the initiation of damage and complete loss of the structure. Cardone et al. (2017) extended this simplified approach introducing the concepts of a zero-loss (ZL) threshold, q, whereby an initial loss ratio to be overcome before accumulating further loss is defined, and a replacement loss threshold, m(Th), whereby the building owners may decide to replace the building even though the repair cost would be some fraction of the replacement cost. Further refinements introduced by Cardone et al. (2017) include measures to account for issues relating to non-uniform damage along the building height and bidirectional response.

The main assumptions of the Cardone et al. (2017) procedure are illustrated in Fig. 2. Fig. 2(a) shows how the seismic hazard curve may be represented as linear in log-space; this hazard curve describes the MAFE of a certain level of ground shaking as a function of the spectral acceleration at the fundamental period of vibration, $S_a(T^*)$, where T^* is taken as the mean fundamental period of vibration of each orthogonal direction of the building.

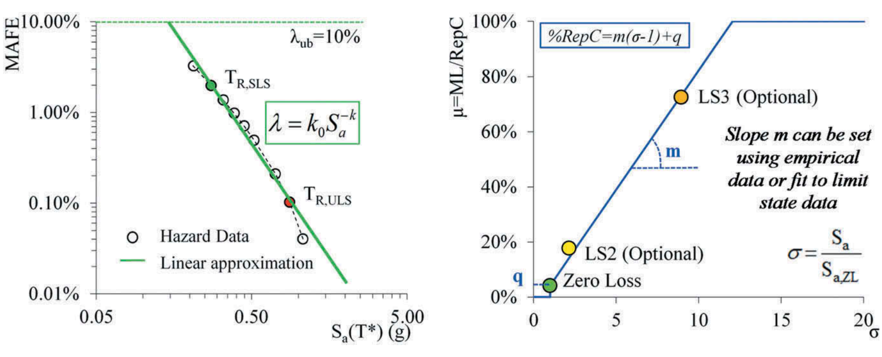

Figure 2 Main assumptions of the simplified procedure proposed in Cardone et al. (2017): (a) linear approximation of hazard curve and (b) monetary loss vs. intensity measure relationship.

Figure 2(b) shows the monetary loss curve approximated as linear with respect to $S_a(T^*)$ normalised by the zero-loss seismic intensity, $S_{a,ZL}$.

By representing the site hazard curve in this fashion and assuming that the monetary losses can be approximated as linearly increasing with seismic intensity at a constant slope, m, following the exceedance of the initial loss threshold, q, at the zero-loss intensity, $S_{a,ZL}$, the expected annual loss expressed as a ratio of the replacement cost, EAL, is given in Cardone et al. (2017) by:

$$EAL = \frac{k_0}{S_{a,zl}^k}\left[q + \frac{m}{(1-k)}\left(\left(1 + \frac{1-q}{m}\right)^{1-k} - 1\right)\right] \tag{1}$$

where the terms k_0 and k are related to the linear approximation of the hazard curve shown in Fig. 2(a) and can be simply evaluated as:

$$k = \frac{Log\left(\frac{\lambda_{ULS}}{\lambda_{SLS}}\right)}{Log\left(\frac{S_{a,ULS}}{S_{a,SLS}}\right)} \tag{2}$$

$$k_0 = \lambda_{SLS} S_{a,SLS}^k \tag{3}$$

where λ_{SLS} and λ_{ULS} are the mean annual frequency of exceeding any Serviceability (SLS) and Ultimate (ULS) limit state imposed by the reference seismic code, and $S_{a,SLS}$ and $S_{a,ULS}$ are the corresponding spectral accelerations at T*.

Concerning the initial loss threshold, q, Cardone et al. (2017) link this to the definition of the excess on an insurance policy, whereby a certain threshold below which the damage is considered negligible is defined. Values of q ranging from around 2.5% to 5.9% the replacement cost are proposed in Cardone et al. (2017), based on results of detailed loss estimation of a number of case study buildings (Cardone, Gesualdi, and Perrone 2019; Cardone and Perrone 2017).

From an operative point of view, the zero-loss limit state can be associated with the onset of damage in non-structural members. As a consequence, it can be identified by the attainment of a given peak Inter-Story Drift (IDR) in a certain storey of the building. Recently, Cardone and Perrone (2017) developed a set of fragility curves for masonry infills with and without openings, considering four damage states. The median value of IDR for the first damage state (represented by the detachment of infill from the RC frame, with possible first diagonal crack) of the proposed fragility curves can be considered to identify the ZL limit state. As a first approximation, therefore, it is assumed that the spectral acceleration at the zero-loss limit state, $S_{a,ZL}$, is reached when the peak IDR at any storey of the building is equal to 0.075% (for masonry infills with openings) and 0.1% (for masonry infills without openings).

Lastly, the value of the slope m (see Fig. 2) is required for the computation of EAL described in Equation (1). To estimate this slope, Cardone et al. (2017) outline two approaches: the first whereby a given regression equation, as a function of the assumed loss threshold, is used based on the results of a number of case studies; and the second that uses a best-fit regression line to the three points (see Fig. 2(b)), which describe the repair costs expected at the zero loss (ZL), operational (OP) and damage control (DC) limit states, respectively. For the seismic intensities at which the OP and DC limit state loss ratios may be reached, Cardone et al. (2017) explain that these can be determined using simplified methods of analysis such as the displacement-based assessment or the so-called MIMA (Multiple inelastic Mechanism Analysis) approach (Cardone and Flora 2018), whereas the loss ratios, μ_{LSi}, may be interpreted using the results of existing loss assessment studies adjusted to account for non-uniform damage and bi-directional effects by:

$$ML_{LSi}/RepC = \alpha_{LSi} \cdot \beta_{LSi} \cdot ML*_{LSi}/RepC \tag{4}$$

where ML^*_{LSi} corresponds to the reference value of loss ratio at a given limit state. α_{LSi} and β_{LSi} are terms proposed by Cardone et al. (2017) to account for non-uniform damage along the height of the building and bidirectional effects and are defined as:

$$\alpha_{LSi} = \left(\frac{mean\left(\sum_n IDR_{i,1}; \sum_n IDR_{i,2}\right)}{0.75 \cdot IDR_{LSi} \cdot n} \right)_{LSi} \tag{5}$$

$$\beta_{LSi} = \frac{\min\left(IDR_{\max,1}; IDR_{\max,2}\right)_{LSi}}{IDR_{LSi}} \tag{6}$$

where $IDR_{i,1}$ and $IDR_{i,2}$ correspond to the interstorey drift at storey i of the two orthogonal directions of the building, $IDR_{max,1}$ and $IDR_{max,2}$ correspond to their maximum values along the height and IDR_{LSi} is the limit drift for the selected limit state (IDR_{ZL} = 0.075– 0.1%, IDR_{OP} = 0.2– 0.3%, IDR_{DC} = 0.65%, according to Cardone et al. (2017)).
While the method proposed by Cardone et al. (2017) appears very promising and effective for most building configurations, some important refinements can be made. These relate to buildings that are subjected to non-uniform damage distribution due to structural or non-structural irregularity in plan or elevation, such as buildings susceptible to a soft-storey mechanism. In addition, there is a possibility that different storeys may have different occupancy types (e.g. retail space at ground storey with residential upper storeys), changing the inventory of damageable components and subsequently the distribution of losses along the building height.

To motivate this choice, in the next paragraph the closed-form approach proposed in Cardone et al. (2017) and the conventional approach presented in the recent Italian seismic classification guidelines are applied to a number of schematic buildings, featuring different layout configurations. Loss estimates from simplified procedures are then compared with results from accurate probabilistic loss assessment (FEMA *P*-58 2012), in order to show their strengths and limitations.

2.3. *Comparison between Simplified Procedures and Accurate Probabilistic Loss Assessment*

The schematic buildings selected for this preliminary investigation were taken from a previous study by Piazza (2013) and are illustrated in Fig. 3. These buildings were designed for gravity loads only following the Regio Decreto (1939) guidelines and the construction manuals typically used in practice at the time (Pagano 1963; Santarella 1956), which are described and summarised in Vona and Masi (2004). These specified minimum areas of column reinforcement solely as function of the column area, where a reinforcement ratio, $\rho_{tot,column}$,

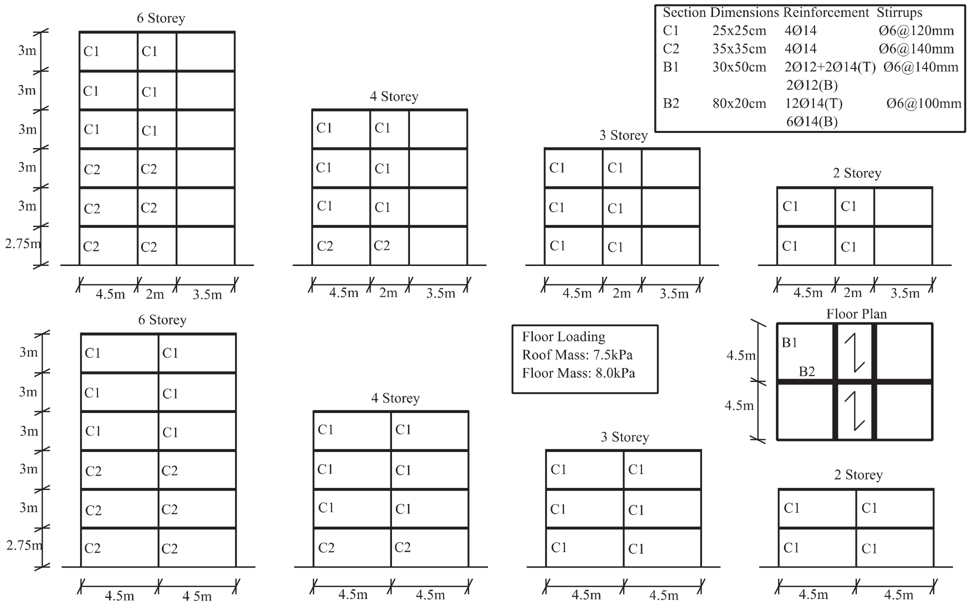

Figure 3 Piazza (2013) **case study archetype buildings.**

of at least 0.80% was required for columns with cross-sectional areas up to 2000 cm^2 and reduced to at least 0.50% for columns with cross-sectional areas over 8000 cm^2. Following these guidelines, Piazza (2013) designed the cross sections C1 and C2 (cross sectional area of 625 cm^2 and 1225 cm^2, respectively) illustrated in Fig. 3 to have reinforcement ratios of 0.99% and 0.50%, respectively, both in line with the prescriptions adopted at the time. Similarly, the beam reinforcement ratios, $\rho_{tot,beam}$, were specified as 0.51% and 1.73% for beams sections B1 and B2, respectively. These low amounts of longitudinal reinforcement in column members typically resulted in strong beam-weak column collapse mechanisms in these building typologies. It may be argued that a more constant distribution of reinforcement ratio may have been selected for the columns in these structures, but given that the same number and size of bars were used throughout the structure, whilst also satisfying the guidelines used at the time, this design was seen to be what a practitioner would have implemented at the time as no change in bar size or number would have been required between sections. Other aspects include low shear reinforcement ratios in the frame members (i.e. $\rho_{w,column}$ = 0.19% and 0.12% for columns C1 and C2 and $\rho_{w,beam}$ = 0.13% and 0.07% for beams B1 and B2), which has resulted in many instances of column shear failure during past earthquakes, and a complete lack of transverse reinforcement in beam-column joints that can lead to joint shear failures (e.g. Pampanin, Calvi, and Moratti 2002; Verderame et al. 2009). Actually, this is not a characteristic of gravity load design buildings only. The same weaknesses also affect the behavior of buildings designed according to obsolete seismic codes and located in high seismicity regions, classified as such before 1984 in Italy (e.g., L'Aquila and other areas), even if the likelihood of brittle failure can be significantly different in columns designed considering gravity versus obsolete seismic design provisions.

Three different configurations of external masonry infills are considered for the buildings illustrated in Fig. 3: fully infilled, where each bay of each storey is considered as being infilled with a 100mm thick double leaf cavity wall; partially infilled and pilotis frames, where each bay of all storeys, except the ground storey, is considered as fully infilled with the same type of infill. The partially infilled configuration is representative of buildings with commercial retail space at the first storey. The pilotis layout configuration is representative of buildings where parking is provided at the ground level.

For the buildings illustrated in Fig. 3, the numerical modelling recommendations reported in O'Reilly and Sullivan (2015, 2017a) were adopted. This involved modelling the frame members as lumped plasticity beam-column elements in order to adequately capture their strength and stiffness degradation with increasing deformation. In addition, the effects of plain reinforcing bars were considered to account for the increased chord rotation capacity of the members due to bar slippage and the increased pinching in the hysteresis typically associated with such member detailing. Furthermore, to incorporate the effects of masonry infill, the single equivalent diagonal strut models outlined in Crisafulli, Carr, and Park (2000) were adopted and the proposals of Sassun et al. (2016) for the hysteretic backbone of these struts utilised.

To estimate the expected monetary losses with respect to increasing seismic intensities, an incremental dynamic analysis (IDA) (Vamvatsikos and Cornell 2002) was performed, where a single set of ground motions is increasingly scaled to derive the relationship between structural response and shaking intensity, herein expressed in terms of the spectral acceleration at the mean value of the fundamental periods of vibration in the two horizontal directions, $S_a(T^*)$.

To characterise the evolution of structural response with increasing intensity, the buildings shown in Fig. 3 were analysed using IDA with the far-field ground motion record set described in FEMA *P*-695 (2009). This was done in despite of the hazard inconsistency that arises in adopting such an approach, but as outlined in O'Reilly and Sullivan (2018a), this simplification would not be anticipated to change the conclusions of the study had multi-stripe analyses (Baker 2015) been conducted instead. Similarly, the scope of this preliminary analysis was to outline strengths and weakness of selected simplified loss assessment procedures. Since some definition of hazard is required in both simplified and accurate methods, the impacts of using IDA is not deemed problematic for this study of relative EAL estimates since consistent definitions are used in both approaches. Regarding the collapse definition, structural collapse of the buildings under consideration has been assumed when deformations corresponded to an inter-storey drift level of 3.0% are exceeded (or numerical instability occurs). This value of drift limit has been set considering the results of Rossetto and Elnashai (2003) for European infilled RC frame buildings (i.e. expected collapse drift around 4.36%) and Masi, Digrisolo, and Manfredi (2015) for archetype pre-1970 pilotis and fully infilled buildings (i.e. expected collapse drift around 2.14% and 2.36%, respectively).

Refined loss estimation of the selected case studies has been performed using the performance assessment calculation tool (PACT) of FEMA *P*-58 (2012). For each ground motion pair, the maximum absolute values of peak storey drifts and peak floor accelerations have been determined and used as input for probabilistic loss assessment with PACT. As far as the hazard data, buildings have been assumed to be located in Italy in the city of L'Aquila with soil type C in order to maximize seismic effects (whilst noting that pre-70 gravity load design is not a fully-consistent assumption for L'Aquila). Data provided by the INGV (Italian Institute of Geophysics and Volcanology) (Montaldo and

Meletti 2007) has been used to derive the hazard curves for each building model. The performance groups of vulnerable structural and non-structural elements considered in this study have been adopted from (Cardone and Perrone 2017). In particular, fragility and loss functions for the RC members with smooth rebars were derived from Cardone (2016) while fragility and loss functions for masonry infills from Cardone and Perrone (2015). The fragility of other acceleration-sensitive non-structural elements have been taken from the FEMA P58 (2012) database.

The replacement cost, RepC, of the buildings has been estimated assuming two different unit replacement costs. The first one, equal to €900/m^2, was assumed based on the average cost of construction per square meter of similar new residential buildings (equal to €730/m2 according to CIAMI (2014)) plus the cost of demolition and disposal of materials taken (equal to €44/m^3). The second one, equal to 1200 euro/m^2, was adopted after examining the figures on the reconstruction costs relevant to the L'Aquila earthquake (Del Vecchio et al. 2018; Di Ludovico et al. 2017; Dolce and Manfredi 2015).

The PACT analyses have been performed considering 500 realizations for each seismic intensity, assuming uncorrelated fragility groups and a total loss threshold equal to unity. Collapse fragility functions have been evaluated based on the results of IDA, with a lognormal cumulative distribution fitted between the collapse probabilities defined as the number of collapses respect to the total set of ground motion records for each seismic intensity. Finally, according to FEMA 356 (2000), a lognormal residual drift fragility function with median value of 1% and dispersion of 0.3 has been assumed, to take into account that building repair is economically and practically not feasible when residual drifts exceed a certain limit. Residual drifts have been estimated as a function of the peak transient drifts, based on simplified relationships provided in FEMA *P*-58 (2012). Further details regarding loss estimation assumptions can be found in (Cardone and Perrone 2017) with details on how to account for modelling uncertainty in loss estimation for pre-1970 RC frames in Italy in O'Reilly and Sullivan (2017b, 2018b).

Table 2 shows the values of the EAL obtained from the accurate probabilistic method (EAL_{PACT}) and the two simplified procedures under scrutiny (EAL_{SIMPL} and PAM, respectively). The values of PAM have been derived following the conventional approach presented in the Italian guidelines for seismic risk [DM 57/2017], which is fully integrated with the Italian Seismic Code (NTC 2018). Details on the definition of the limit states are reported in section 5.1. Reference to a unit replacement cost of 1200 €/m^2 has been made to permit comparison between PAM and the other methods. It is also worth noting that the results reported in Table 2 already include the MAFE upper bound of 10% introduced

Table 2 Comparison between PACT results and estimates from approximate procedures (PAM and SIMPL (Cardone et al. 2017)) for different first-storey non-structural layouts.

		EAL_{PACT}			EAL_{SIMPL}		PAM		% Difference PACT-SIMPL			% Difference PACT-PAM		
Case Study	RepC* (€)	Pilotis	PI	FI	Pilotis-PI	FI	Pilotis-PI	FI	Pilotis	PI	FI	Pilotis	PI	FI
6A	609,865	0.94%	1.31%	1.99%	1.54%	2.22%	2.41%	1.31%	63%	18%	11%	156%	84%	−34%
4A	406,576	0.84%	1.35%	1.23%	1.53%	1.38%	2.29%	0.83%	81%	14%	12%	172%	70%	−33%
3A	304,932	1.24%	2.03%	0.87%	2.69%	0.96%	3.34%	0.58%	117%	32%	10%	170%	65%	−34%
2A	203,288	1.22%	2.05%	0.80%	3.83%	0.78%	2.37%	0.56%	213%	87%	−2%	94%	16%	−29%

*RepC derived assuming a unit replacement cost of 1200 €/m^2.

later in Section 3.1. This has been purposely done in order to focus on the differences between the approaches while neglecting possible errors related to the definition of hazard.

As can be seen in Table 2, the values of EAL_{PACT} are significantly affected by the building height, the structural behaviour and the non-structural layout content. In particular, EAL_{PACT} increases with the building height for the FI layout since, for these buildings, the damage and consequently monetary loss involves many floors for a given seismic intensity, as the building height increases. It then decreases with the building height for the pilotis layout configuration since the soft-storey mechanism at the first floor means that the lower the building is, the higher the influence of damage and losses of the first storey on the EAL.

For the building types and the site under investigation, PAM tends to grossly overestimate EAL for pilotis-type buildings, showing differences of up to 150%. For the fully infilled buildings considered herein, PAM underestimates the EAL, with differences of up to −34% noted. Considering the high range of differences found (from +150% to −34%), the PAM approach appears highly variable and therefore appears to possess some limitations for a simplified evaluation of EAL. The approach proposed by Cardone et al. (2017), on the contrary, gives good results for FI layout configurations, with error less than 10%, on average. This was expected considering that the reference values of loss ratio at a given limit state adopted in the simplified procedure here have been derived from similar fully-infilled buildings. However, it is noted that the closed-form expression by Cardone et al. (2017) overestimates the EAL for partially infilled and pilotis cases, with differences of 18%-87% and 63%-213% being observed. The error is notably higher for the lower buildings. In fact, this aspect has been recognised as a limitation of the simplified procedure in Cardone et al. (2017) and is one of the issues to be addressed in this study.

To better understand the differences observed when using the simplified procedure, the vulnerability curves (i.e. normalised monetary loss, μ, versus normalised IM, $\sigma = Sa(T^*)/Sa,_{ZL}$) and loss curves (i.e. μ versus MAFE) of building model 2A for (a) pilotis, (b) partially infilled and (c) fully infilled layout configurations, are shown in Fig. 4, for the case of a unit RepC of 900 €/m^2.

The vulnerability curves reported on the left-hand side of Fig. 4 clearly show that losses increase almost linearly with intensity, in accordance with the assumptions of the proposed simplified procedure. For the pilotis building 2A (see Fig. 4(a)), for which the EAL overestimation is 127%, the error appears to come from the overestimation of monetary losses at given limit states, which increases the slope of the simplified curve. Recalling that EAL is represented by the area underneath the loss curve of the building, for the partially infilled building 2A (see Fig. 4(b)), it can be seen that the overestimation of the EAL (which in this case is 36%), is concentrated at the lowest seismic intensities (MAFE > 3%). Hence, the error of the simplified procedure is generated in part also by a poor estimate of the hazard curve at low seismic intensities.

Therefore, in order to improve the simplified procedure by Cardone et al. (2017), some refinements ought to be made. These include a better method to evaluate the loss ratio at a given limit state ML_{LSi} as a function of the non-structural layout content and a better definition of the seismic hazard, especially at the lowest seismic intensities.

3. Refinements to the Simplified Procedure

The results in the previous section highlighted some limitations of the simplified procedure proposed by Cardone et al. (2017) when applied to buildings that are irregular in elevation because of non-structural components. Therefore, some refinements are needed in order to extend its applicability. They have been grouped in two categories: 1) refinements to the hazard curve; and 2) refinements to the evaluation of expected losses at a given limit state. The revised simplified procedure has been denoted as the Direct Estimation of Expected Annual Loss (DEAL) method.

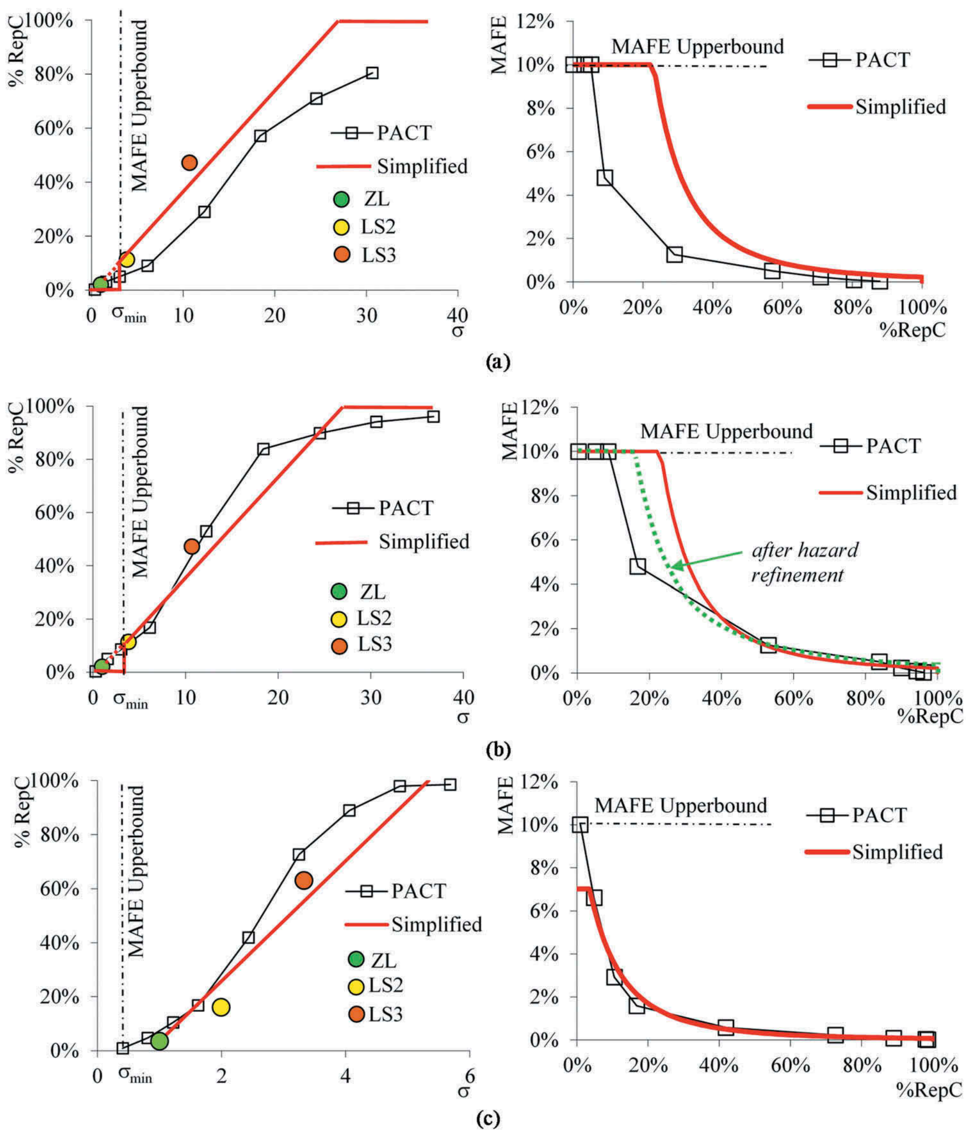

Figure 4 Comparison between PACT results and simplified procedure (Cardone et al. 2017) for the case study 2A for (a) pilotis (b) partially infilled and (c) fully infilled layout configurations.

3.1. Refinements to the Hazard Curve Fitting

In order to minimise the error introduced via the linear hazard model and maintain the relative simplicity offered by the simplified method, it is necessary to focus the fitting of these parameters more at more frequent events, especially given that these are the events that tend to contribute most to the EAL (Welch, Sullivan, and Calvi 2014). To improve the hazard estimation at the lowest seismic intensities, preserving the assumption that the seismic hazard curve can be adequately represented as linear in log-space, it is proposed that the intercept k_0 and the slope k of a line fit to site hazard data should be defined considering the points of the hazard curves corresponding to return periods of 30 years and 475 years (corresponding to the earthquake intensity levels for the verification of Fully Operational and Life-Safety limit states for residential buildings, according to the Italian seismic Code (NTC 2018)), and evaluated according to Eq. (2)-(3).

Moreover, while hazard models may be extrapolated, it is generally not wise for very low return periods due to the great uncertainties in the hazard characteristics and heavy weighting of such parameters in EAL integration. For that reason, an upper bound on the MAFE, equal to λ_{ub} = 10% ($T_R \approx 10$ years), is imposed (see Fig. 2(a)), which aligns DEAL with the recent Italian seismic classification guidelines (DM 2017).

3.2. Storey-based Loss Functions

A storey-based approach for the assessment of expected losses at different limit states is proposed in order to make the DEAL method applicable to regular/irregular buildings with different non-structural layouts for each storey. In the storey-based approach, the expected loss for the entire building at a given limit state, ML_{LSi}, is computed as the sum of the expected losses for each floor based on the relative damage attained. A storey-based approach was first proposed by Ramirez and Miranda (2009), who developed storey-based loss functions for US office buildings, which were employed also in other studies (e.g. Welch, Sullivan, and Calvi 2014). These functions are defined as a function of suitable engineering demand parameters, i.e. IDR (Inter-Story Drift Ratio) and PFA (Peak Floor Accelerations), and consist of a series of monotonically increasing functions that saturate at the expected total loss of the storey.

The main differences with respect to Ramirez and Miranda (2009) are that the storey-based based loss functions proposed in this study: (i) include loss contributions from both collapse and non-collapse cases, (ii) are derived for drift sensitive and acceleration sensitive components, without distinguishing between structural and non-structural components, (iii) are defined separately for three different floor types, i.e. 1st floor, typical floor and top floor, and (iv) three different architectural layouts (pilotis, partially infilled and fully infilled, respectively) are considered for the 1^{st} floor. Using these storey-based loss functions, the simplified approach proposed by Welch, Sullivan, and Calvi (2014), using prescribed limit states and storey-based loss functions, has been integrated with the approach of Cardone et al. (2017), to obtain a more versatile and unified procedure. In the proposed storey-based loss assessment procedure, the expected loss of each generic limit state, ML_{LSi}, is computed as:

$$\mu_{LSi} = ML_{LSi}/\mathrm{Rep}C = \sum_j \mu_{LSi,j} RepC_j/RepC \tag{7}$$

where μ_{LSi} is the expected loss of the i^{th} limit state normalised by RepC and $\mu_{LSi,j}$ is the expected loss at the j^{th} storey, normalised with respect to the replacement cost of each storey $RepC_j$. For each storey, $\mu_{LSi,j}$ can be evaluated as:

$$\mu_{LSi,j} = \frac{ML_{LSi,j}}{RepC_j} = \left(\mu_{LSi,D}\right)_{IDR_{LSi,j}} + \left(\mu_{LSi,A}\right)_{PFA_{LSi,j}} \tag{8}$$

where $(\mu_{LSi,D})_{IDR,LSi,j}$ and $(\mu_{LSi,A})_{PFA,LSi,j}$ are the normalised expected loss from drift-sensitive and acceleration-sensitive elements. In order to account for the bidirectional nature of building response, the IDR and PFA associated with the expected loss at a given limit state, can be evaluated as:

$$\begin{aligned} IDR_{LSi,j} &= IDR_{LSi,j,1}w_1 + IDR_{LSi,j,2}w_2 \\ PFA_{LSi,j} &= PFA_{LSi,j,1}w_1 + PFA_{LSi,j,2}w_2 \end{aligned} \tag{9}$$

where $IDR_{LSi,j,1}$ and $IDR_{LSi,j,2}$ are the IDR values at the j^{th} storey, attained at LSi in the two orthogonal directions of building response, respectively. Similarly, $PFA_{LSi,j,1}$ and $PFA_{LSi,j,2}$ are the PFA values at the j^{th} storey, attained at LSi in the two orthogonal directions of building response, respectively. The terms w_1 and w_2 are weights defined based on the distribution of non-structural elements in the two orthogonal directions of the building. As a first approximation, $w_1 = w_2 = 0.5$ can be assumed. It is worth noting that through the above approach, the complete drift profile in both directions are inherently considered. Therefore, the terms α_{LSi} and β_{LSi} originally used in the first version of the simplified procedure (Cardone et al. 2017) to account for non-uniform damage along the height and bidirectional effects (see Equations (5) and (6)) are no longer necessary.

Two sets of storey-based loss functions are presented here for typical residential buildings realized in Italy from the '50s to early '70s, with different non-structural layout configurations. The storey-based loss functions under consideration have been derived by disaggregating accurate results of loss assessment with PACT on a set of archetype pre-70 RC frame buildings (see Fig. 5) (Cardone, Gesualdi, and Perrone 2019), as a function of the corresponding IDR. It's worth specifying that these buildings are different from those considered in section 2.3, as they are 3D models with non-squared RC columns.

Two different unit replacement costs (900 €/m^2 and 1200 €/m^2, respectively) and different layouts of masonry infills (and partitions) at the ground storey of the buildings have been considered. The latter, indeed, may have different usages (e.g. commercial retail space, garage or car parking), as shown in Fig. 5(b–d)), whereas the upper storeys would be typical of residential usage (see Fig. 5(e)).

The disaggregated loss estimates derived from PACT have been fitted by a linear regression relationship to get a practice-oriented tool to be used within a simplified loss assessment approach such as DEAL.

Figure 6 shows the storey-based loss functions derived for (a) first storey, (b) upper (typical) storeys and (c) top storey, for a unit RepC of 900 €/m^2. Table 3 summarize the storey-based loss function parameters for both 900 and 1200 €/m^2 unit RepC.

The storey-based loss functions of the first storey (see Fig. 6(a)) are specialized for three different architectural configurations (i.e. pilotis-type (no infills), partially infilled and fully infilled). Each point in Fig. 6 represents the expected total loss (including both repair and replacement costs, with the latter being due to cases of collapse or attainment of excessive

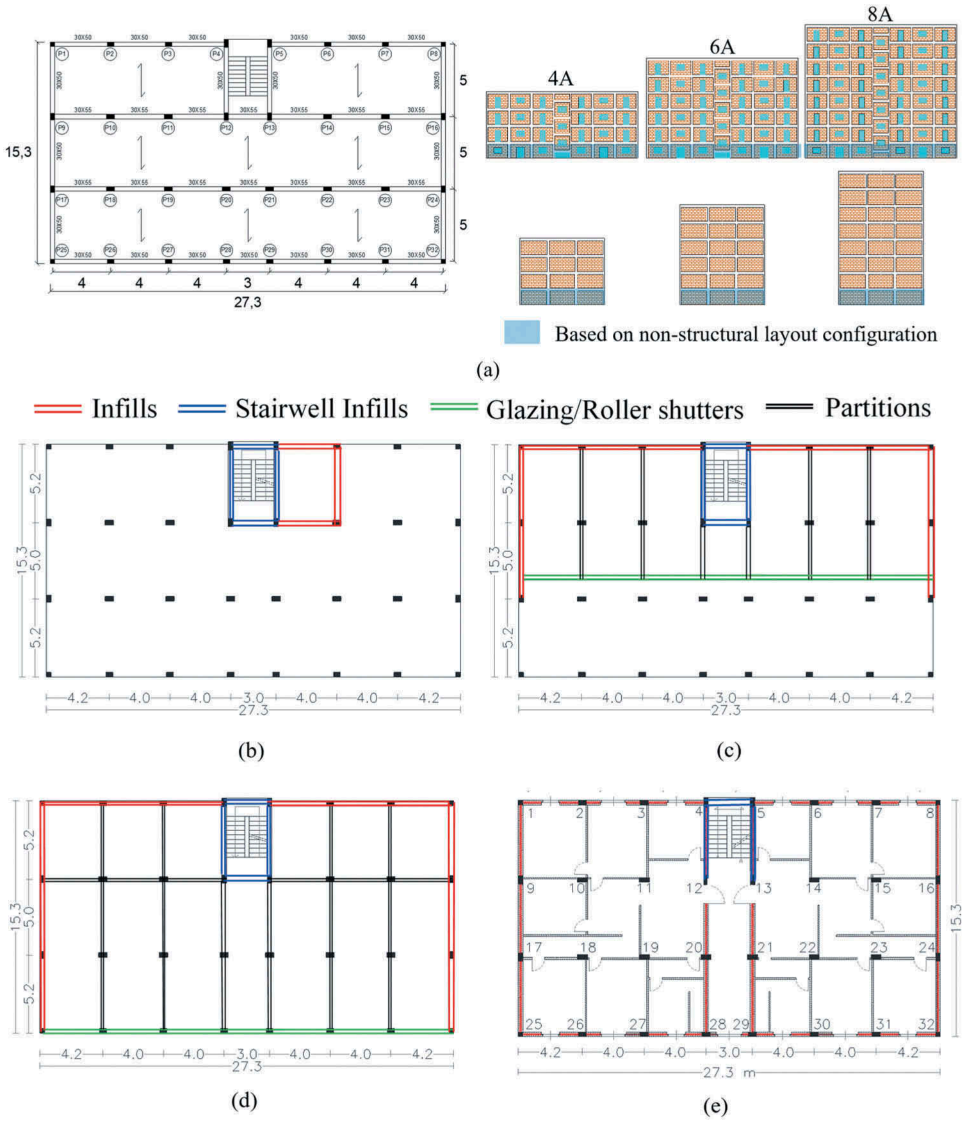

Figure 5 (a) Front view and plan view of the archetype pre-70 RC frame buildings investigated in Cardone, Gesualdi, and Perrone (2019); First-storey non-structural layout configurations considered in this study: (b) pilotis-type (i.e. no infill); (c) retail (partially infilled); and (d) garage (fully infilled); (e) upper storeys typical layout for residential use.

residual drifts) observed in the j-th storey (μ_j), for a given seismic intensity, normalized with respect to the relevant $RepC_j$, as a function of the corresponding interstorey drift (IDR_j).

As can be seen in Table 3, the proposed storey-based loss functions are characterised by: (i) an IDR lower threshold (IDR_{in}) below which expected losses can be neglected, (ii) a linear relationship between IDR and expected losses and (iii) an IDR upper threshold (IDR_{fin}) beyond which the expected loss is equal to $RepC_j$ (i.e. μ_j = 100%). The upper threshold therefore corresponds to a drift at which it is no longer considered economical

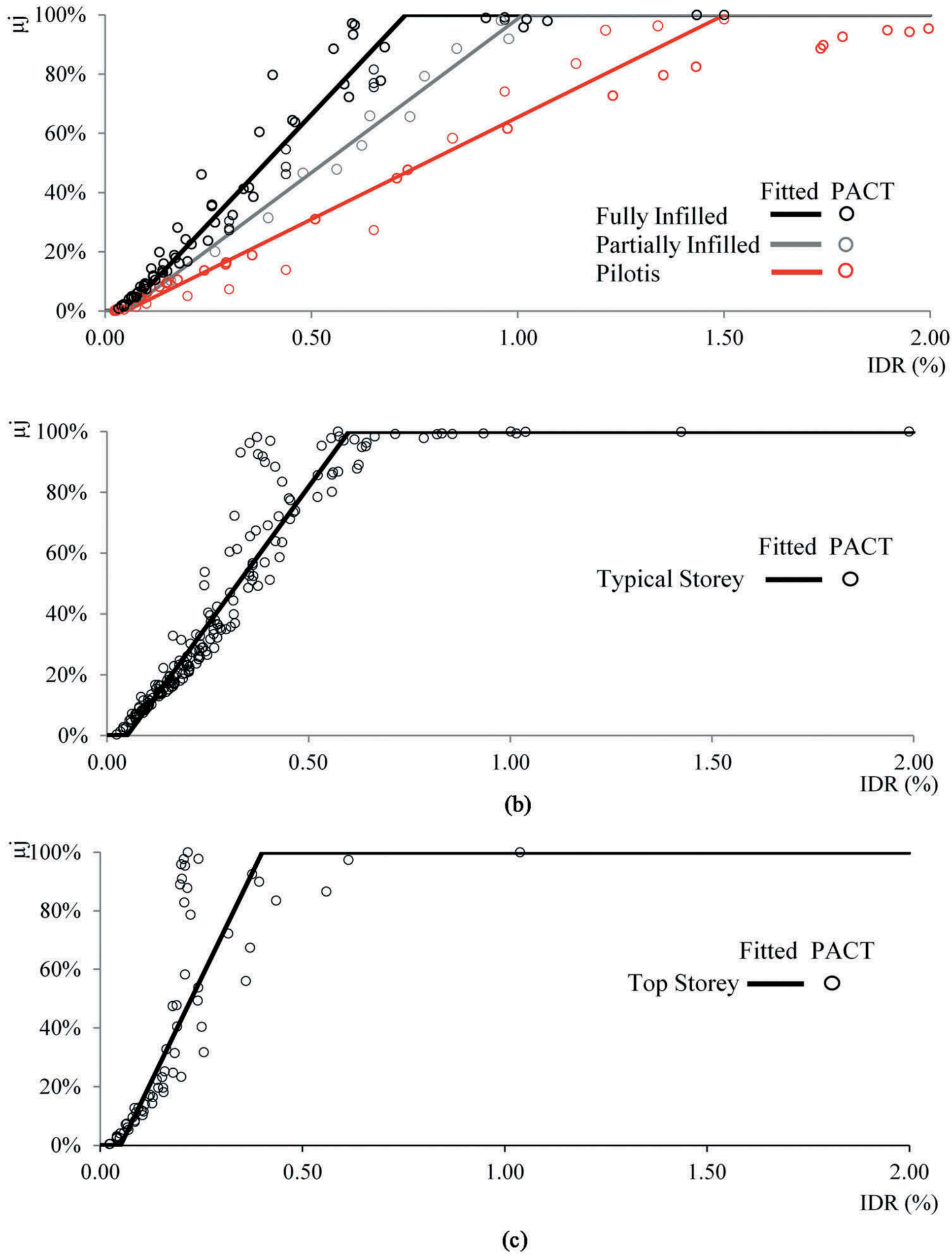

Figure 6 Storey-based total loss functions for residential pre-1970 RC frame buildings: (a) Ground storey: Pilotis, i.e. no infill, partially infilled and fully infilled layout configurations. (b) Typical storey residential; (c) Top storey residential.

to undertake repair works. This can occur when only a limited number of structural and/or non-structural elements are damaged but the cost of the repair work required for the damaged elements is high.

Table 3 Storey based loss function parameters for typical pre-70 buildings.

		Unit RepC 900€/m^2		Unit RepC 1200€/m^2	
Storey	Destination of use	IDR_{in}	IDR_{fin}	IDR_{in}	IDR_{fin}
Ground Floor	Pilotis	0.05%	1.50%	0.05%	1.90%
Ground Floor	Partially Infilled	0.05%	1.00%	0.05%	1.25%
Ground Floor	Fully Infilled	0.05%	0.8%	0.05%	1.00%
Typical Floor	Residential	0.05%	0.60%	0.05%	0.75%
Top Floor	Residential	0.05%	0.40%	0.05%	0.50%

The IDR lower threshold complies with the concept of the initial loss threshold used in the DEAL approach. Herein, it has been rounded to 0.05% for all the storey-based loss functions.

The IDR upper threshold (IDR_{fin}) changes with building storey and architectural configuration. In particular, it is of the order of 0.65% for the typical storey of an Italian residential building, while it increases from 0.8% to 1.5% for the first storey, passing from fully infilled to pilotis-type configurations, due to the different non-structural contents and layouts. For the top floor, finally, it turns out to be in the order of 0.4%.

From an analytical point of view, the proposed storey-based loss functions are given by the following expressions:

$$\begin{cases} \mu_j = 0 & for \quad IDR_{LSi,j} < IDR_{in} \\ \mu_j = \left(IDR_{LSi,j} - IDR_{in}\right) / \left(IDR_{fin} - IDR_{in}\right) & for \quad IDR_{in} \leq IDR_{LSi,j} \leq IDR_{fin} \\ \mu_j = 1 & for \quad IDR_{LSi,j} > IDR_{fin} \end{cases} \tag{10}$$

where μ_j, $IDR_{LSi,j}$, IDR_{fin}, IDR_{in} and IDR_j are defined above.

As far as acceleration Sensitive components are concerned, the repair cost for a number of acceleration sensitive non-structural components (Electrical service and distribution, Ceramic tiles, Water and sanitary system Skirting Sanitary Ware and Plumbing fixtures) are incorporated directly in the repair cost of infill and partition walls, because in the Italian construction practice they are commonly installed within partition and infill walls. Other acceleration-sensitive non-structural components (e.g. roof coverings, chimneys, pendant lightings and piping systems), do not contribute significantly (less than 5% in terms of replacement cost) to the total loss of typical Italian residential buildings, as shown in (Cardone and Perrone 2017). For this reason, they have been neglected.

Finally, it is worth noting that even if the shape of the storey-based loss functions may appear rather simple, it is compatible with the scope of the DEAL method. Obviously, other storey-based loss functions can be assembled and implemented in DEAL for different structural and non-structural configurations. Moreover, different approaches (either analytical or semi empirical) can be followed to derive such storey-based loss functions and different trends (bilinear, quadratic, …) can be assumed. In this sense, the simplified DEAL approach can be adopted for any building type and any structural/non-structural content configuration. It is then clear that further studies would be desirable to derive new sets of storey-based loss functions for the application of the DEAL method to different building types.

3.3. Simplified Evaluation of EAL Using Storey-based Loss Functions

The simplified evaluation of EAL via DEAL through the use of storey-based loss functions can be done through the following steps:

In the first step, structural analysis is carried out to assess the engineering demand parameters expected over the height of the building at attainment of a number of limit states: ZL, LS2, LS3 (optional). It is worth nothing that, given the formulation of storey-based loss functions, LS2 and LS3 can be selected (almost) arbitrarily. The selection of LS2 and LS3 corresponding to the Operational (OP) and Damage Control (DC) limit states introduced in Cardone et al. (2017) is suggested. Then, the expected drift profiles, $IDR_{LSi,j,1}$ and $IDR_{LSi,j,1}$, and the corresponding spectral acceleration $S_{a,LSi}$ for each limit state are evaluated. The PFA along the building height must be estimated (e.g. through code-conforming closed-equations) if acceleration-sensitive losses need to be considered. Finally, IDR profiles are computed using Equation (9), based on the derived IDR profiles in each orthogonal direction and the distribution of non-structural elements.

In the second step, the expected loss ratio, $\mu_{LSi,j}$, for each storey is evaluated as a function of $IDR_{LSi,j}$ considering an appropriate storey-based loss function (see Fig. 6). Then the expected loss ratio at each limit state, μ_{LSi}, is evaluated with Equation 7.

In the third step, the simplified normalized intensity, σ, vs expected loss ratio, μ_{LSi}, curve is derived as a function of the linear relationship's slope m and the expected loss ratio at the ZL limit state, μ_{ZL} = q. The coefficient m is evaluated from a best-fit linear regression analysis considering the performance points previously identified, ensuring that the regression line passes through the ZL point.

In the last step, the coefficients k_0 and k are identified using Equations (2) and (3) with the hazard curve of the site and also considering the refinements of Section 4.1, where the data at lower intensities is utilised.

The EAL is then evaluated using Equation (1), which is rewritten here to include the MAFE upper bound outlined in Section 4.1 as:

$$EAL = \lambda_{\min} q_{\min} + \frac{k_0}{S_{a,ZL}^k}\left[\frac{m}{1-k}\left(\sigma_{TL}^{1-k} - \sigma_{\min}^{1-k}\right)\right] \tag{11}$$

$$q_{\min} = m(\sigma_{\min} - 1) + q \tag{12}$$

$$\sigma_{TL} = \left(\frac{1-q}{m} + 1\right) \tag{13}$$

$$\sigma_{\min} = \frac{S_{a,\min}}{S_{a,ZL}} = \max\left(1; \frac{1}{S_{a,ZL}}\left(\frac{\lambda_{ub}}{k_0}\right)^{-\frac{1}{k}}\right) \tag{14}$$

where σ_{TL} corresponds to the intensity at which the expected losses reach 100% of RepC, λ_{ub} is the MAFE upper bound, $\sigma_{\min}$ corresponds to the maximum (normalized) seismic intensity between the ZL limit state and the spectral acceleration corresponding to the MAFE upper bound and $q_{\min}$ is the corresponding expected loss.

Using the DEAL approach for the buildings examined in Section 3, their performance can be checked for the fully infilled and pilotis configurations. The results are summarised in Table 4 and in Fig. 7. As can be seen, differences between PACT and DEAL are very

Table 4 Comparison between PACT results and estimates from approximate procedures (PAM and DEAL) for different first-storey non-structural layouts.

		EAL_{PACT}		DEAL		PAM		% Difference PACT-DEAL		% Difference PACT-PAM	
Case Study	RepC* (€)	Pilotis	FI	Pilotis	FI	Pilotis	FI	Pilotis	FI	Pilotis	FI
6A	609,865	0.94%	1.99%	0.83%	1.96%	2.41%	1.31%	−12%	−2%	156%	−34%
4A	406,576	0.84%	1.23%	0.85%	1.23%	2.29%	0.83%	0%	0%	172%	−33%
3A	304,932	1.24%	0.87%	1.38%	0.77%	3.34%	0.58%	11%	−11%	170%	−34%
2A	203,288	1.22%	0.80%	1.50%	0.77%	2.37%	0.56%	23%	−4%	94%	−29%

*RepC derived assuming a unit replacement cost of 1200 €/m^2.

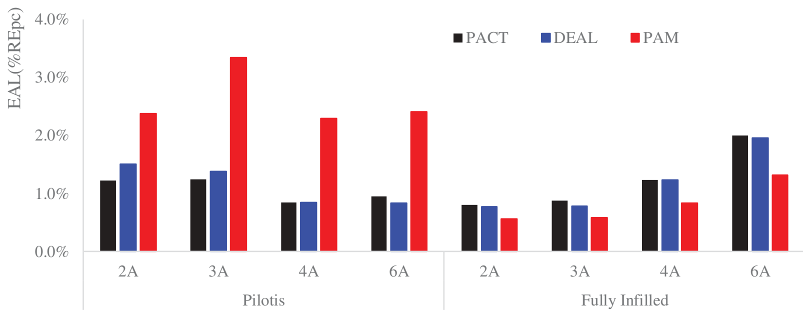

Figure 7 Comparison between PACT results and approximate procedures PAM and DEAL for fully infilled and pilotis configurations.

small and, on average, less than 10% for both pilotis and fully infilled buildings. The PAM results previously presented in Table 2 are included again in Table 4 for convenience.

4. Application to Real Case Study Buildings

4.1. *Overview*

In order to assess the effectiveness of the DEAL method, a realistic case study building is analysed. The building has been defined considering the typical dimension and structural characteristics of typical pilotis-type RC frame buildings located in a residential neighborhood of L'Aquila, Italy. The archetype building thus derived has 21.05 × 9.30m plan dimensions and storey height equal to 3.8m for the first storey and 3.3m for upper storeys. Each storey presents a floor area of approximately 200 m^2 (see Fig. 8) and a seismic mass of approximately 200 tons. The RC frame structural system features 23 columns with cross section dimensions equal to 300x300mm at each level, three frames in the longitudinal direction (X-direction) and four frames in the short direction (Y-direction), including the two frames of the staircase, with beam dimensions equal to 250x400mm. The dog-legged stair with cantilever steps is supported by 200x550mm knee-beams. An average compressive strength of 25MPa and yield strength of 325MPa (considering Aq42 steel type) have been assumed for concrete and steel, respectively, in accordance with (Verderame, Manfredi, and Frunzio 2001a, 2001b). Smooth bars with poor detailing have been assumed and longitudinal reinforcement ratios ranging from 0.5% to 0.68% for the beams and from 0.5% to 0.73% for the columns. Transversal reinforcement consists of 6mm diameter

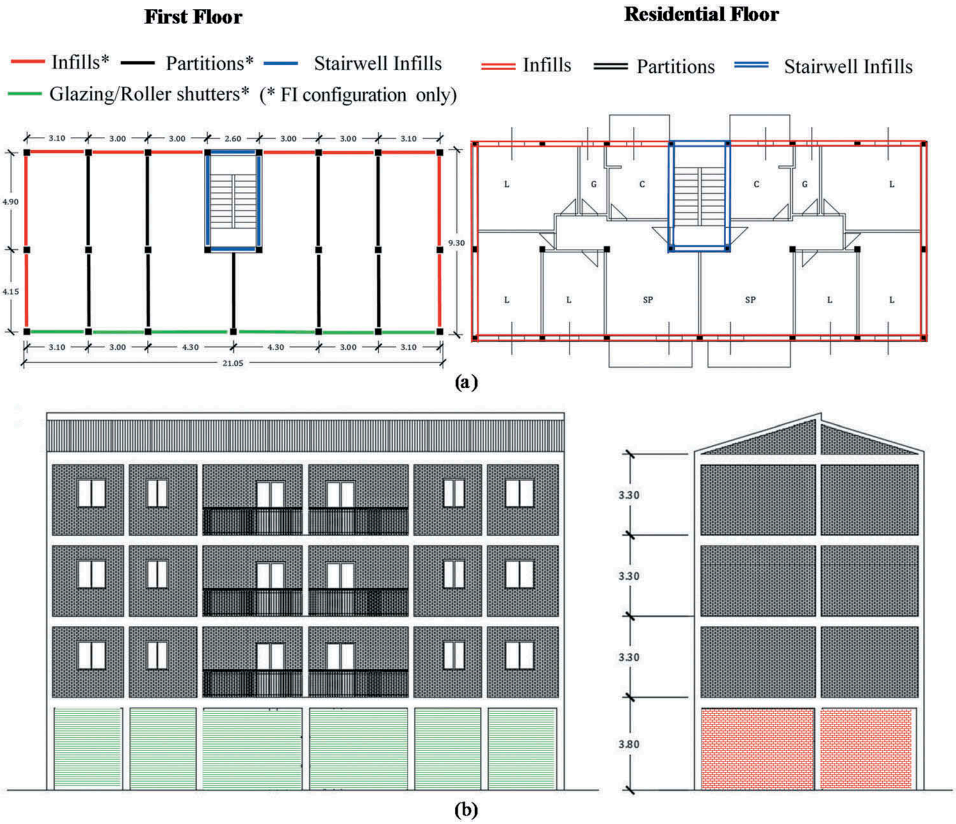

Figure 8 (a) Plan and (b) frontal elevations of the case study buildings, considering two different non-structural layout configurations (Pilotis and fully infilled).

stirrups with 200mm spacing for both beams and columns. The building features external infills made of hollow clay bricks arranged in two single walls of 120mm and 80mm thickness, respectively, separated by an air cavity of 70mm. Internal partitions with a single layer of hollow clay bricks with 100 mm thickness have been considered. The building has been examined in two non-structural layout configurations (see Fig. 8): (i) 4R_Pilotis in which the first storey is used as car parking whereas other storeys have a residential use, and (ii) 4R_FI in which the first floor has commercial retail spaces, and the other floors have residential use. The replacement cost, RepC, of the building has been estimated assuming a unit cost of 1200 €/m^2. A value of RepC of about 885,000 € has been thus obtained in both the cases.

Numerical models of the two buildings were assembled in OpenSees (McKenna, Scott, and Fenves 2010) and the RC frame elements were modelled using finite-length plastic hinge beam-column elements with plastic hinge behaviour characterised by a tri-linear cyclic behaviour described by the modified Ibarra-Medina-Krawinkler (IMK) deterioration model with pinched hysteretic response (Ibarra, Medina, and Krawinkler 2005). The skeleton curves of plastic hinges have been calibrated on a moment-curvature analysis of the critical cross sections of beams and columns, considering axial load interaction and bar slipping effects, as described in (Cardone, Gesualdi, and Perrone 2019; Cardone and

Perrone 2017). For RC members liable to premature shear failure (which are identified a-priori), the same IMK model has been considered, with the difference that the ultimate rotation capacity has been defined by the intersection between the shear associated with flexural behavior and the shear resistance of the specific element. Preliminary analyses showed a negligible influence of exterior beam-column joint behaviour and therefore, they have been neglected in the analysis.

External masonry infills have been modelled with a single equivalent compression-only diagonal strut, featuring a three-linear skeleton curve (Cardone, Gesualdi, and Perrone 2019; Cardone and Perrone 2017). This choice was purposely done in order to limit the complexity of the model and, as a consequence, the analysis time. The single-strut approximation does not allow the local interaction between infills and RC columns to be captured but it has been presumed that the likelihood of failures potentially induced by this interaction could be considered negligible for this research.

The influence of openings (i.e. windows or doors) in masonry infills have been taken into account reducing the strength and lateral stiffness of the panel with the reduction factors proposed in (Dolsek and Fajfar 2008). More details on the structural modelling can be found in (Cardone, Gesualdi, and Perrone 2019; Cardone and Perrone 2017).

Non-linear response-time history analyses were performed using ten ground motion pairs for nine seismic intensities, corresponding to return periods ranging from 30 to 2475 years. Ground motion pairs have been selected according to a set of nine conditional spectra developed considering the local site hazard disaggregation for the spectral acceleration corresponding to the average fundamental period of the structure, which is about 0.7s. The site hazard information was taken from the INGV hazard model (Montaldo and Meletti 2007) for the city of L'Aquila and soil type C was assumed. Using these results, the PACT analysis was performed under the same hypotheses described in Section 2.3. More precisely, loss estimation options and the collapse fragility curve have been defined according to the process described in section 2.3.

The PAM and DEAL approaches have been applied following the steps described in Sections 3.1 and 4.3, respectively. For simplicity, the same structural model and the same analysis method have been considered, although DEAL and PAM are intended to be used with simpler analysis methods (i.e. linear static/dynamic analyses, etc.). This has been purposely done to compare the EAL results coming from different approaches, avoiding bias due to different models and/or methods of analysis.

As far as the PAM approach is concerned, the conventional approach described in the Italian guidelines for the seismic risk classification of buildings has been followed. In analogy with PACT, incremental dynamic analysis considering the nearest set (on the side of the lower intensity) of ground motion pairs has been carried out to identify the earthquake intensity levels associated with the Operational (SLO), Damage Limitation (SLD), Life Safety (SLV), and Collapse Prevention (SLC) limit states. The definition of limit states in PAM fully complies with that reported in the Italian Seismic Code (NTC 2018) and summarized in Table 5 for completeness. More precisely, for masonry infills, it is assumed that SLD and SLO are attained for a drift limit equal to IDR_{SLD} = 0.3% and 2/3 IDR_{SLD}, respectively. For RC structural elements, limit states are identified as a function of the yield and ultimate chord rotation (θ_u and θ_y in Table 5), also considering the possibility of premature shear failure. The Italian guidelines for seismic risk classification introduces two additional limit states: the "Initial Damage" (SLID) and the total loss or

Table 5 Limit states evaluation according to Italian seismic code (NTC 2018) and definition of seismic and loss performances according to DM (2017).

Limit State	Performance Levels: Infills	RC-Ductile	RC-Brittle	T_{rC} (years)	MAFE (%)	%RepC
Initial Damage (SLID)	-	-	-	10	10%	0%
Operational (SLO)	2/3IDR_{SLD}	2/3 θ_y	-	$T_{rD}(PGA_C/PGA_D)^n$	≈1/TR_C	7%
Damage Limitation (SLD)	[a]IDR_{SLD}	[b]θ_y	-		≈1/TR_C	15%
Life Safety (SLV)	-	3/4 θ_u	-		≈1/TR_C	50%
Collapse Prevention (SLC)	-	[c]θ_u	[d]V_R, [e]σ_{jt}/σ_{jc}		≈1/TR_C	80%
Reconstruction (SLR)	-	-	-	∞	0%	100%

a. Iterstorey drift ratio for SLD; b. Yield chord rotation; c. Ultimate chord rotation; d. Ultimate shear resistance of beams/columns; e. Ultimate diagonal tension/compression of beam-column joints.

"Reconstruction" (RLS) limit states, which are conventionally assumed to have 10 years and a virtually infinite return period (i.e. MAFE = 0), respectively (see Table 5). Expected total loss ratios of 0%, 7%, 15%, 50%, 80% and 100% are assumed in PAM for the six limit states mentioned above (see Fig. 1 and Table 5). PAM is then computed integrating the aforesaid expected loss ratios weighted by the MAFE associated with each limit state.

The storey-based loss functions summarized in Table 3 have been used to implement the DEAL method considering the Zero Loss (ZL), Operational (OP) and Damage Control (DC) limit states defined according to Cardone et al. (2017). Table 6 shows the results of the DEAL approach, including: (i) the spectral accelerations at the fundamental period of vibration (T*) for each limit state (i.e. $Sa(T^*)_{ZL}$, $Sa(T^*)_{OP}$, $Sa(T^*)_{DC}$, respectively), (ii) the corresponding expected loss ratios (i.e. μ_{ZL}, μ_{OP}, μ_{DC}) evaluated using the storey-based loss functions associated with a unit replacement cost of 1200 €/m^2; (iii) the values of MAFE foe each limit state (i.e. $MAFE_{ZL}$, $MAFE_{OP}$, $MAFE_{DC}$) and (iv) the EAL value.

As can be seen, the expected loss ratio associated with the zero loss limit state is of the order of 3% for fully infilled residential buildings, while it reduces to about 1% for pilotis-type buildings because damage is concentrated at the first floor only. It's worth noting that the MAFE corresponding to the initial loss threshold is always equal to 10%. This means that, for the case-study buildings under consideration, considering the high seismicity of the reference site, non-structural damage begins for earthquake intensity levels with return period lower than 10 years. Obviously, such damage/loss estimates are likely to be dependent on home-owner repair decisions and appetite to live with minor damage. Indeed, some very minor cracking might not be deemed necessary to repair. Another interesting observation is that the expected loss ratios associated with a damage control limit state range between 27% to 75%. This means that for this limit state, corresponding to the onset of damage in the main structure, expected losses can change considerably not only due to the layout and content of non-structural elements but also due to the shape of the drift profile in the two horizontal directions.

Table 6 Results of the DEAL approach.

Case Study	T* (g)	$S_{a,ZL}$ (T*) (g)	$S_{a,OP}$ (T*) (g)	$S_{a,DC}$ (T*) (g)	μ_{ZL} = q (%RepC)	μ_{OP} (%RepC)	μ_{DC} (%RepC)	$MAFE_{ZL}$	$MAFE_{OP}$	$MAFE_{DC}$	EAL_{DEAL} (%RepC)
4R_PI	0.67	0.026	0.069	0.210	0.71%	5.38%	23.78%	10%	10%	2.5%	2.19%
4R_FI	0.67	0.034	0.091	0.270	3.16%	13.73%	48.85%	10%	10%	1.4%	3.35%

Table 7 Comparison between EAL values derived from PACT, DEAL and PAM.

Case Study	RepC (€)	PACT (Risk Class)	DEAL (Risk Class)	PAM (Risk Class)	% Difference PACT-PAM	% Difference PACT-DEAL
4R_Pilotis	885 427	2.06% (C)	2.19% (C)	3.40% (D)	55%	6%
4R_FI	885 427	3.17% (D)	3.35% (D)	2.42% (C)	−28%	6%

Table 7 compares the values of EAL derived from PACT with those derived from the proposed DEAL method and PAM approach. Comparing PACT and DEAL results, it can be seen how the latter is quite effective with differences less than 6%. Conversely, differences between PACT and PAM are very high for the pilotis building (55%) but are still acceptable for the fully infilled building (−28%). Table 7 also shows the seismic rating derived according to the seismic performances classification guidelines. As can be seen, seismic ratings derived from DEAL are in good agreement with PACT, while the seismic rating derived with PAM is overestimated for the case study 4R_Pilotis and underestimated for the case study 4R_FI.

To better understand the effectiveness of the DEAL and PAM approaches, the results are plotted in Fig. 9 in terms of vulnerability and loss curves for the 4R_Pilotis (Fig. 9(a)) and the 4R_FI (Fig. 9(b)) cases. It is confirmed again that monetary losses increase almost linearly as a function of intensity. Furthermore, the DEAL curves are in good accordance

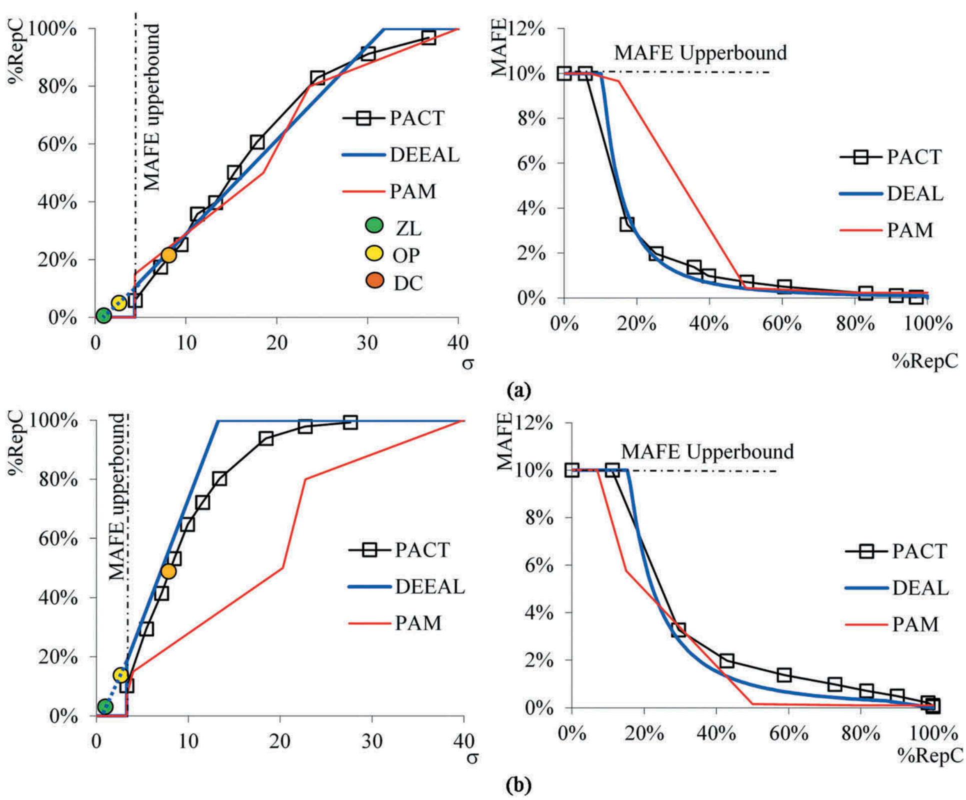

Figure 9 Comparison between PACT, DEAL and PAM results: (left) vulnerability curves and (right) loss curves for the (a) pilotis and (b) fully infilled configurations.

with the PACT results for both pilotis and fully infilled building configurations. This implies that the evaluation of the ZL point and the slope m derived from DEAL are quite accurate, independent of the ground storey occupancy type. Regarding the PAM results, Fig. 9 highlights how assigning prescribed expected loss ratios for each limit state, without considering the damage distributions along the floors and or non-structural layout of each floor, results in erroneous estimations of building vulnerability and loss curves, with consequent overestimation or underestimation of the EAL.

For the 4R_Pilotis building, expected losses at the lowest limit states are significantly overestimated by PAM (see Fig. 9(a)). This is because at lowest limit states, damage and losses are located principally in the ground storey level and consequently total losses are expected to be low with respect to a fully infilled building, where damage may be expected to be distributed more uniformly along the height. Since PAM gives prescribed expected loss ratios for each limit state independent of the building configuration, this key difference in structural behaviour and damage is overlooked. For the 4R_FI building, expected losses are consistently underestimated by PAM (Fig. 9(b)) and therefore, the EAL evaluated via PAM tends to be underestimated.

4.2. *Influence of Seismic Hazard and Soil Conditions*

In order to evaluate the influence of seismic hazard and soil conditions on the accuracy of the proposed DEAL approach, the results shown in the previous section have been extended to the entire Italian region, considering the 4R_Pilotis and 4R_FI case study buildings located on Soil Type A (stiff soil) and Soil C (soft soil), respectively. This essentially involves updating the site hazard terms and incorporating them with the vulnerability curves previously developed. In addition, the EAL derived from PACT and PAM have been compared in order to identify with more accuracy the sources of the discrepancies observed in Sections 2.3 and 4.1. It is recognised that this extension implies some approximations with regard to ground motions, site hazard and soil properties. However, it is noted that the absolute values are not of direct interest here, but rather the relative difference between the different methods. As such, the general conclusions drawn herein are not anticipated to be affected by such an assumption.

The EAL for the case study building under consideration (with both pilotis-type and fully infilled configurations, see Fig. 8) has been evaluated with PACT, DEAL, and PAM approaches, over the entire region of Italy, considering the specific hazard curve for each grid point (10751 points in total) of the INGV hazard map. As explained above, the seismic response (and loss) of the building for a given intensity was assumed to be independent of the site hazard, while the corresponding MAFE is instead site-specific. Subsequently, this permits the seismic rating to be evaluated according to the seismic performance classification guidelines D.M. 58/2017 presented in Table 1. Figure 10(a–c) show the seismic ratings obtained for the seismic hazard across Italy according to the seismic performance classification guidelines, based on the EAL values derived from each method for the case study 4R_Pilotis on soil type C. As expected, the distribution of seismic rating is influenced by the hazard of each site. For example, the seismic regions with highest hazard (e.g. north eastern Italy in Friuli, Central Italy in Abruzzo, Umbria and south Italy in Calabria and eastern Sicily) exhibit the more critical seismic ratings. However, significant differences in seismic rating are found comparing the relative results derived from PAM, PACT and DEAL.

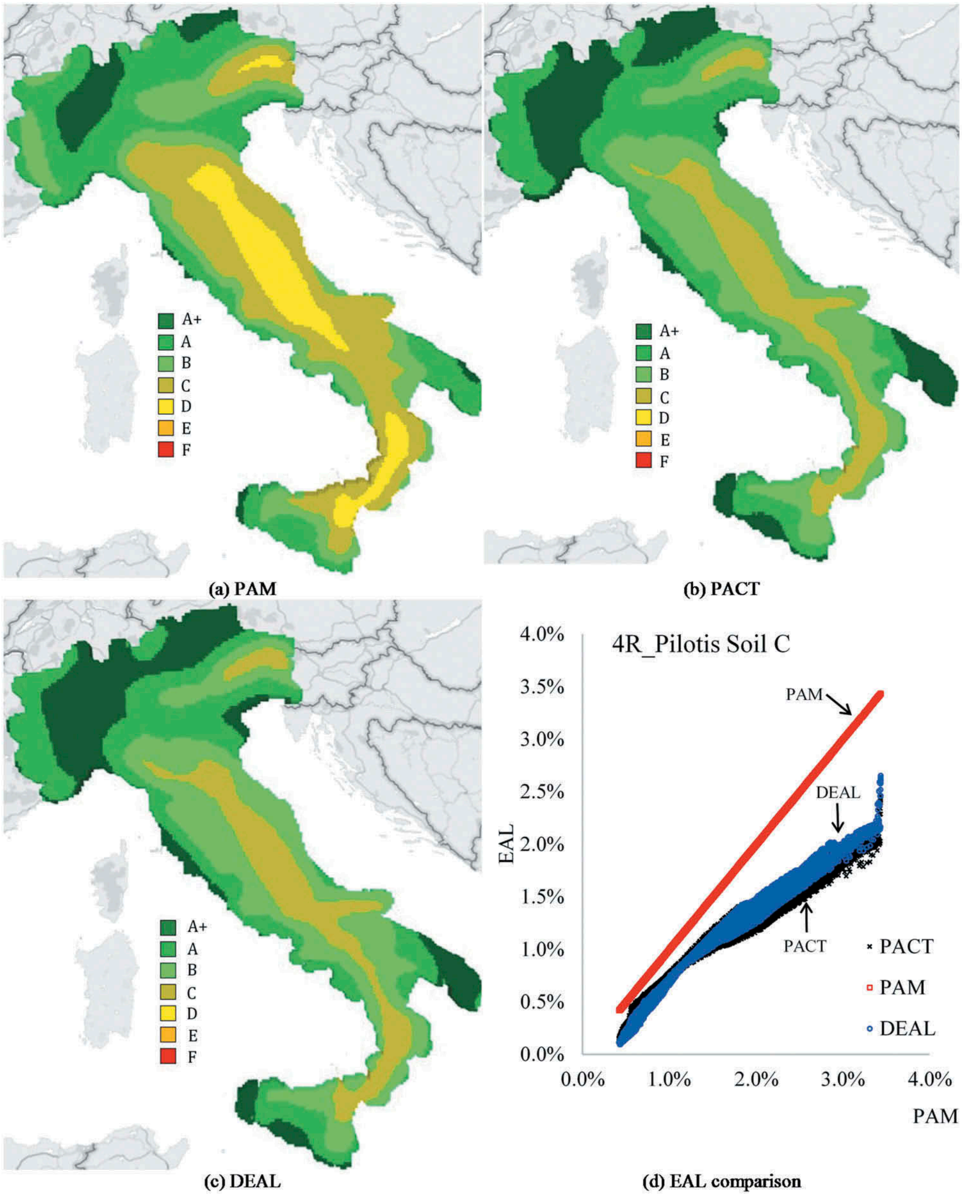

Figure 10 Seismic risk rating based on EAL, varying seismic hazard across Italy, considering (a) PAM, (b) PACT and (c) DEAL; (d) comparison between EAL values as a function of PAM for the case study building 4R_Pilotis located on soil type C.

Figure 10(d) compares the corresponding values of EAL derived from PACT, PAM and DEAL, as a function of PAM for each location considered over the entire Italian region. It can be seen that EAL computed using DEAL is in good agreement with the values derived using PACT, with percent differences not exceeding 20% (and relative differences lower than 0.18%). On the contrary, the values of EAL derived with PAM are significantly different with respect to PACT and generally overestimated. For the lower values of EAL, indeed, percent differences even exceed 100%, although the absolute difference is always lower than 0.4%. For the higher values of EAL, instead, percent differences are around 50–60% and the absolute differences are as high as 1.4%.

Similar results are reported in Fig. 11 for the case study building 4R_FI on soil type C. In this case, seismic risk ratings ranging from Class A+ to Class E are observed. Similar to Fig. 10, significant differences in seismic risk rating are found comparing the results

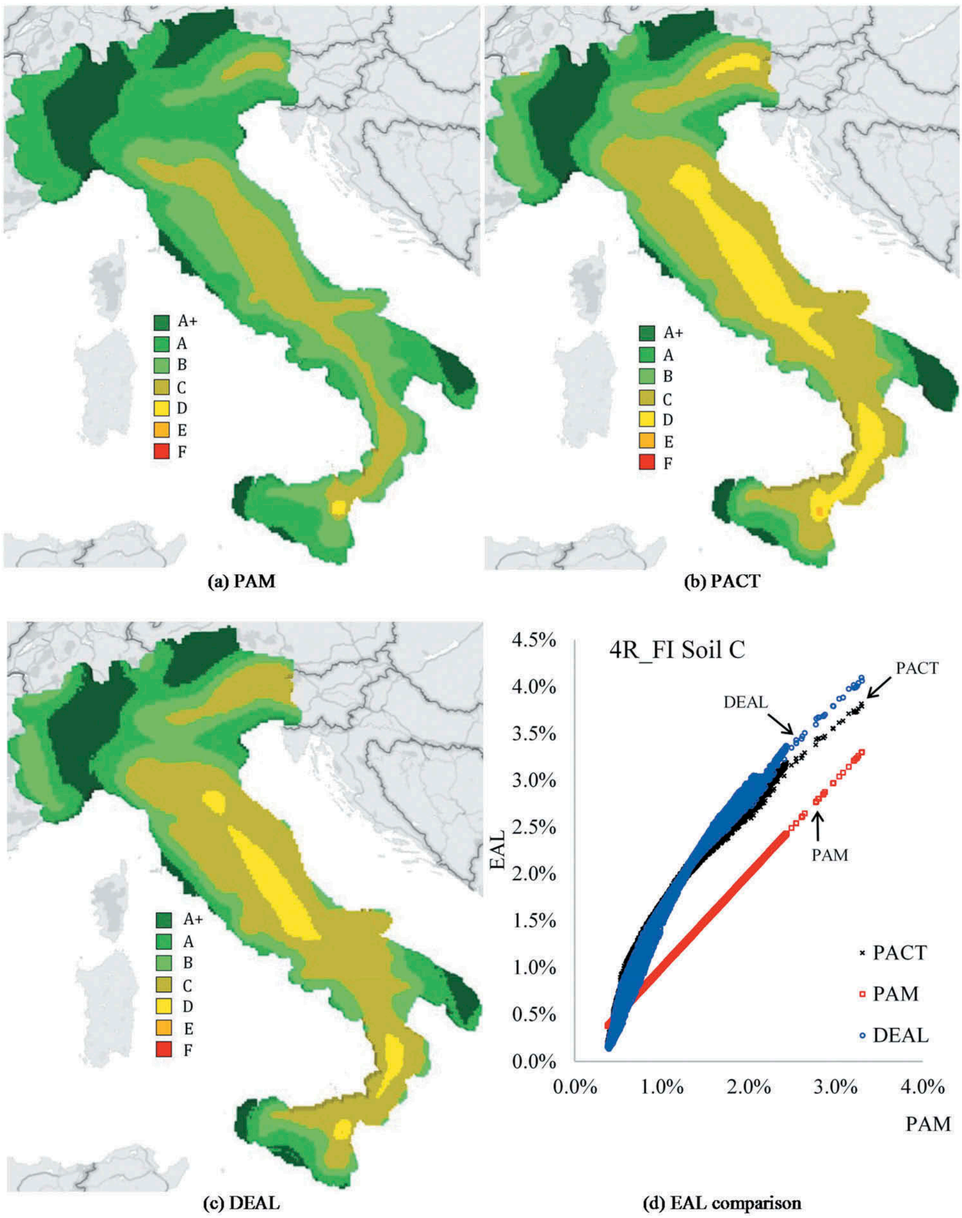

Figure 11 Seismic risk rating based on EAL, varying seismic hazard across Italy, considering (a) PAM, (b) PACT and (c) DEAL; (d) comparison between EAL values as a function of PAM for the case study building 4R_FI located on soil type C.

derived from PAM, PACT and DEAL. Also for the case study 4R_FI on soil type C, EAL values evaluated with DEAL are in good agreement with the expected values derived from PACT with percent differences ranging approximatively from +7% to −10% (absolute differences are lower than 0.10% for EAL <1% and do not exceed 0.3% for EAL>3%). On the contrary, the EAL values derived with PAM are underestimated (except for EAL<0.5%) compared to PACT, with percent differences of around −40% and absolute differences of up to −0.8 % for EAL>3%.

In order to extend the analysis, Fig. 12 shows the comparison between EAL values as a function of PAM for the case studies 4R_Pilotis (Fig. 12(a)) and 4R_FI (Fig. 12(b)) on soil type A. As can be seen, DEAL is again in good agreement with PACT, with percent differences that do not exceed ±20% and absolute differences lower than 0.1%. On the contrary, PAM still overestimates excessively the EAL especially for the pilotis configuration (percent differences higher than 100% for EAL < 0.5% and around 30% for EAL>1%, and absolute differences ranging between 0.15% and 0.35%). For the fully infilled configuration, PAM tends to overestimate the EAL when it is lower than 0.5% but, more importantly, it considerably underestimates the EAL (percent differences up to −50% and relative differences up to −0.6%) when it is greater than 0.6%.

In order to understand why PAM tends to excessively under or overestimate the value of EAL, specific cases have been extracted from the previously discussed results. In the following discussion, it is useful to remember that the vulnerability curves shown in Fig. 9 for the considered case study buildings are invariant with respect to the site soil conditions and seismicity. Figure 13(a–c) shows the loss curves for the 4-storey pilotis building whereas Fig. 13(d–f) shows the same for the 4-storey fully infilled building, for different sites (all on soil type C) characterized by (i) low (northern Trentino region), medium (northern Rome), and high (north-eastern Sicily) seismicity. For the case shown in Fig. 13 (a–d), the EAL derived from PACT is equal to 0.10% and 0.15%, respectively, while that from PAM is 0.43% and 0.39% (percentage differences equal to 342% and 185%), respectively. In these cases, PAM overestimation is due to the assumption of an initial non-structural loss threshold associated with a MAFE of 10%, independently from the hazard of the site. Even if this assumption may be reasonable for medium to high seismic

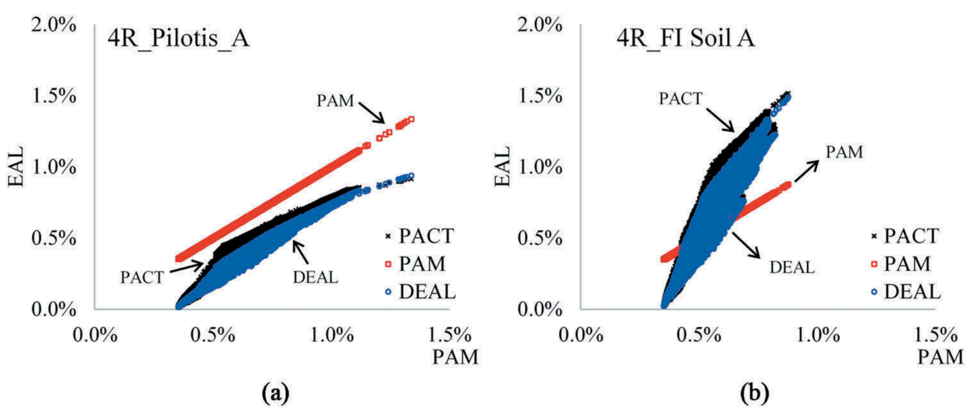

Figure 12 Comparison between EAL values obtained from PAM, DEAL and PACT for: (a) Case Study 4R_Pilotis on soil type A and (b) Case Study 4R_FI on soil type A.

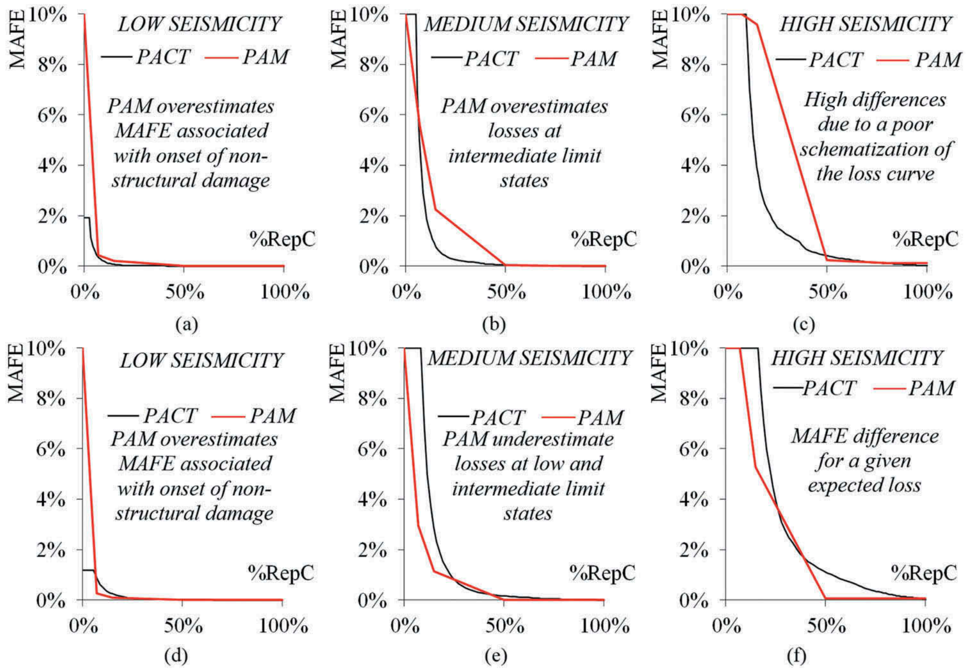

Figure 13 Loss curves for: (a) to (c) 4-storey pilotis building, and (d) to (f) 4-storey fully infilled building located in low, medium, and high seismicity sites, on soil type C.

zones, for low seismic hazard zones it may be too conservative. For instance, for the case shown in Fig. 13(a), the spectral acceleration at a return period of 30 years (MAFE = 3.3%) is 0.016g while the initial non-structural damage (derived from structural analysis) is expected at a value of 0.026g, corresponding to a return period of about 50 years. Nevertheless, both PACT and PAM give the same seismic risk rating (A+), which can be sufficient for the objectives of the Italian seismic classification guidelines. On the contrary, if the objective is a correct evaluation of EAL, some adjustments to the PAM procedure would be required.

For the cases shown in Fig. 13(b,c), EAL values derived from PACT are equal to 0.88% and 1.82%, whereas the EAL derived from PAM is 1.27% and 3.27% (percent difference equal to 41% and 66%), respectively. A somewhat reverse result is obtained for the cases shown in Fig. 13(e,f), for which the EAL values derived from PACT are equal to 1.46% and 2.89%, while the EAL derived from PAM is equal to 0.82% and 2.27% (percent difference equal to −42% and −25%), respectively. Such differences imply an error in the identification of the seismic risk classes (B instead of A and D instead of C for the pilotis building on medium and high seismicity site, and A instead of B for the fully infilled building on medium seismicity site).

The aforementioned discrepancies arise from a series of aspects. First of all, the accuracy of PAM is conditioned by the assumption of prescribed loss levels for each limit state. For a given limit state, the difference in terms of monetary loss between PAM and PACT is constant (it does not depend on the site), being associated with the same earthquake intensity level. Obviously, when the site changes, the MAFE associated with this earthquake intensity level changes. As a consequence, the differences in terms of MAFE (between one site and another) result in a greater or lower differences in the EAL. In addition, the multi-linear loss curve implicit to PAM (being derived from four points only) can be a cause of significant differences when compared to the more continuous loss curve in PACT. For instance, for the pilotis building (see Fig. 13(b–c)), assuming a monetary loss of 15% (corresponding to the attainment of the damage limit state according to (DM 2017)) differences in terms of MAFE are 1.5% for the medium seismicity site and 5.8% for the high seismicity site. On the other hand, under the same assumptions, the differences are 1.5% and 4.72%, respectively, for the fully infilled building (see Fig. 13(e–f)). Similarly, assuming a MAFE of 2% (corresponding to a return period of 50 years), the differences in terms of monetary losses are +8% for the medium seismicity site and +30% for the high seismicity site. On the other hand, under the same assumptions, the differences are −6% and +3 %, respectively, for the fully infilled building (see Fig. 13(e–f)).

5. Conclusions

A building's Expected Annual Loss (EAL), associated with post-earthquake repair costs, is recognised as an effective parameter for the seismic performance classification of buildings and for the selection of cost-effective seismic retrofit measures.

Recently, a number of simplified approaches have been proposed to estimate the EAL of a building without the need to compile an inventory of damageable components and with the possibility of using practice-oriented (e.g. linear instead of nonlinear) structural analysis methods. In Italy, a simplified approach (referred to as PAM) for the estimation of expected annual loss was recently published by the Italian Ministry of Infrastructure and Transport for the purposes of providing buildings with a seismic performance classification. The PAM approach is simple, but it is shown in this work that the loss estimates it provides can differ greatly from those obtained using more accurate but time-consuming methods, such as the FEMA *P*-58 (2012) approach. As a matter of fact, PAM possesses some limitations of applicability. This is mainly due to a number of assumptions and simplifications such as fixed values of limit-state loss ratios, which inherently ignores aspects such as irregularity in the structural response, in addition to bidirectional effects and different storey occupancy types.

This article has taken a step in addressing this gap by developing a novel approach, referred to as DEAL (Direct estimation of Expected Annual Losses), for the evaluation of EAL in RC buildings, which exploits results of traditional structural analyses (e.g. response spectrum analyses, displacement based approaches, …) within a closed-form expression to compute direct losses. The DEAL procedure represents an extension of the simplified approach proposed by Cardone et al. (2017), with the most significant refinement being the introduction of a set of storey-based loss functions (after (Ramirez and Miranda 2009)) to evaluate expected losses considering different layouts of non-structural elements. Using storey-based loss functions, the DEAL procedure can be applied to irregular buildings and buildings with different storey occupancy types. This makes the DEAL procedure much more versatile and accurate than currently available simplified methods for the estimation of the EAL.

Based on comparisons between loss estimates obtained from PAM and DEAL, for a number of case study buildings located in Italy, with results of rigorous probabilistic seismic performance assessment (FEMA P-58 2012), it is concluded that:

- The PAM method, currently in use in Italy, can provide what appear to be erroneous EAL values that are significantly larger or smaller than those obtained via the more rigorous but time-consuming PACT approach. For sites with low values of EAL, percent differences can even exceed 100%. For sites with higher values of EAL, percent differences were as large as ±50% and absolute differences in EAL were up to 1%.
- The overestimation of EAL by the PAM method at the lowest values of EAL can be attributed to the assumption of an initial non-structural loss threshold associated with a MAFE of 10%, independently from the hazard of the site. At the higher values of EAL, instead, the accuracy of PAM appears to be conditioned by the assumption of prescribed loss levels for each limit state that, in combination with the differences in terms of MAFE (between one site and another), result in greater or lower estimates of the EAL. In addition, the multi-linear nature of the PAM loss curve (set from four points only) was identified as another reason for the differences in loss estimates compared to PACT, which uses a more continuous loss curve.
- The DEAL method provides EAL estimates that are similar to those obtained via the more rigorous but time-consuming PACT approach, with percent differences not exceeding 20% (absolute differences in EAL lower than 0.3%) for the case study buildings examined.

The results of the comparison between PAM and DEAL presented in this paper have referred to a set of case study buildings only. Moreover, the values of EAL derived following the probabilistic seismic loss assessment approach described in FEMA *P*-58 are not benchmarked with actual repair costs from real Italian buildings (although fragility and consequence functions typical of Italian building components have been used). As such, the EAL values presented here should only be considered as a representative indication of the EAL for Italian buildings, recognizing that some variations could be anticipated for different building typologies. Nevertheless, the DEAL approach has been shown to offer significantly more accurate estimates of EAL than the PAM approach and hence merits consideration as a possible alternative for seismic risk classification in Italy.

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