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DEVELOPING SIMPLIFIED PROCEDURES FOR THE ESTIMATION OF EXPECTED ANNUAL LOSS OF RC FRAME BUILDINGS

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Abstract

The Expected Annual Loss (EAL) represents the amount one could expect to pay every year to repair earthquake damage, considering different sources of uncertainties. EAL can be a very sound and effective seismic performance indicator for a building. For that reason, it has been proposed as a global evaluation parameter of the seismic quality or resilience of existing buildings. Current methods for the estimation of EAL rely on rigorous, but very complex, probabilistic approaches. For that reason, estimation of EAL is still prerogative of a few experts.

In this paper, a simplified, practice-oriented, approach for the estimation of EAL is developed. This is achieved by introducing approximate linear relationships between monetary losses and corresponding intensity measures, calibrated based on a number of limit states, using simple methods of analysis. This way, EAL can be predicted by a closed form expression, which can be easily implemented in future seismic codes and guidelines. In this paper, the proposed approach is specialized for older RC frame buildings, designed for gravity loads only. The validity of the proposed approach is demonstrated by comparing EAL estimates with accurate results obtained following the FEMA P-58 methodology, for a number of real and archetype case study buildings.

Keywords: Seismic Performance Assessment; Expected Annual Loss; RC Frame Buildings; FEMA P-58.

1. Introduction

One of the most promising approaches that can be used to estimate economic losses due to an earthquake is the so-called Performance-Based Earthquake Engineering (PBEE) approach [1]. The integration of losses over the entire earthquake hazard range results in the quantification of the seismic performance of a building in terms of Expected Annual Loss (EAL) [2], which represents the amount one could expect to pay, on average, every year to repair earthquake damage, considering different sources of uncertainties (earthquake hazard, structural modeling and analysis, damage and loss assessment).
Recently, EAL has been proposed as a global evaluation parameter of the "seismic quality" or "seismic resilience" of existing buildings [3]. Indeed, EAL could be used for building performance classification and screening operations, to aid decision makers and other stakeholders to take rational decisions concerning the use of government incentive, estimation of insurance premiums, etc..
One of the challenge of the last years has been that of moving the frontier of PEER-PBEE forward, developing tools and methodologies accessible to engineering practice. Within this context, the ATC-58 project developed the FEMA P-58 guidelines [4] and a companion tool, referred to as Performance Assessment Calculation Tool (PACT), for the seismic performance assessment of existing buildings. PACT requires the use of suitable fragility functions for every damage state of each building component group and the definition of a set of suitable consequence functions able to translate damage into potential repair/replacement costs, repair time and casualties.
Despite the great efforts developed to make the methodology accessible to engineering practice, a correct estimation of the EAL with PACT is still prerogative of a few experts.
As a matter of fact, the probabilistic approach implemented in PACT can be followed for detailed studies on individual buildings, or strategic structures (e.g. hospitals, barracks, schools, etc.).
On the other hand, a simplified, engineering practice-oriented, mean of estimating EAL for building classes is highly desiderable. In this paper, a simplified closed-form expression for the estimation of the EAL of pre-70 RC frame buildings is proposed. The building class under consideration includes buildings realized before 1970 (i.e. before the introduction of seismic design in technical codes), featuring plain rebars and masonry infills and partitions. This class of buildings includes more than 30% of the entire RC building stock of Italy and other countries worldwide.
Whilst other proposals for simplified assessment of EAL already exist [2, 5, 6], the method proposed in this paper can be considered simpler and better aligned with current code assessment approaches and could therefore be implemented and accepted more easily in practice.
The paper is organized in three parts. In the first part, refined PACT results are reported for a number of typical pre-1970 RC frame buildings, including both archetype and real buildings. In the second part, the basic assumptions of the proposed simplified methodology are discussed and a simple closed-form expression for the estimation of EAL is proposed, considering a number of well-defined limit states. Finally, the validity of the proposed approach is demonstrated by comparing approximate predictions of EAL with accurate results obtained using refined seismic performance assessment procedures.

2. Case studies

The Reinforced Concrete (RC) frame buildings examined in this study include three archetype buildings, with number of storeys ranging from 4 to 8 (labeled with 4A, 6A, 8A in Fig. 1(a)), and a real 8-storey building (labeled with 8R in Fig. 1). The selected buildings are representative of typical residential buildings realized in Italy before '70s, characterized by one-directional RC frames (internal frames in the long/short direction for archetype/real buildings), dog-leg stairs with cantilever steps sustained by two stiff 'knee' beams, external infills with two single walls of hollow clay bricks (100 mm thickness each) separated by a cavity, and internal partitions realized with a single layer of hollow clay bricks (100 mm thickness). Steel reinforcement is realized with smooth steel rebars with end-hooks in the exterior beam-column joints and at the base of the columns. As far as the strength of materials is concerned, an average compression strength of 25 MPa and a yield strength of 325 MPa have been assumed for concrete and steel, respectively. More details on the structural characteristics of the buildings under consideration can be found in [7].

The Replacement Cost (RepC) of the building models, estimated based on current (2014) average construction cost per square meter for residential buildings, are equal to 927.655 €, 1.391.483 €, 1.855.311 € and 2.380.100 € for buildings 4A, 6A, 8A and 8R respectively. All the buildings are supposed to be located in the city of L'Aquila (central Italy), which is characterized by the highest levels of seismic hazard for Italy (0.452 g PGA with 2475 years return period on stiff soil). Reference to the data provided by the INGV (Italian Institute of Geophysics and Volcanology) for the city of L'Aquila (Italy), soil type A, has been made to derive the hazard curves for each building model, considering the relevant differences in terms of average fundamental period of vibration T*, equal to 0.77 s, 1.06 s, 1.35 s and 1.10 s for buildings 4A, 6A, 8A and 8R, respectively. It is worth observing that the high values of the fundamental period of vibration for the building models under consideration are due to the lack of internal frames in one direction.

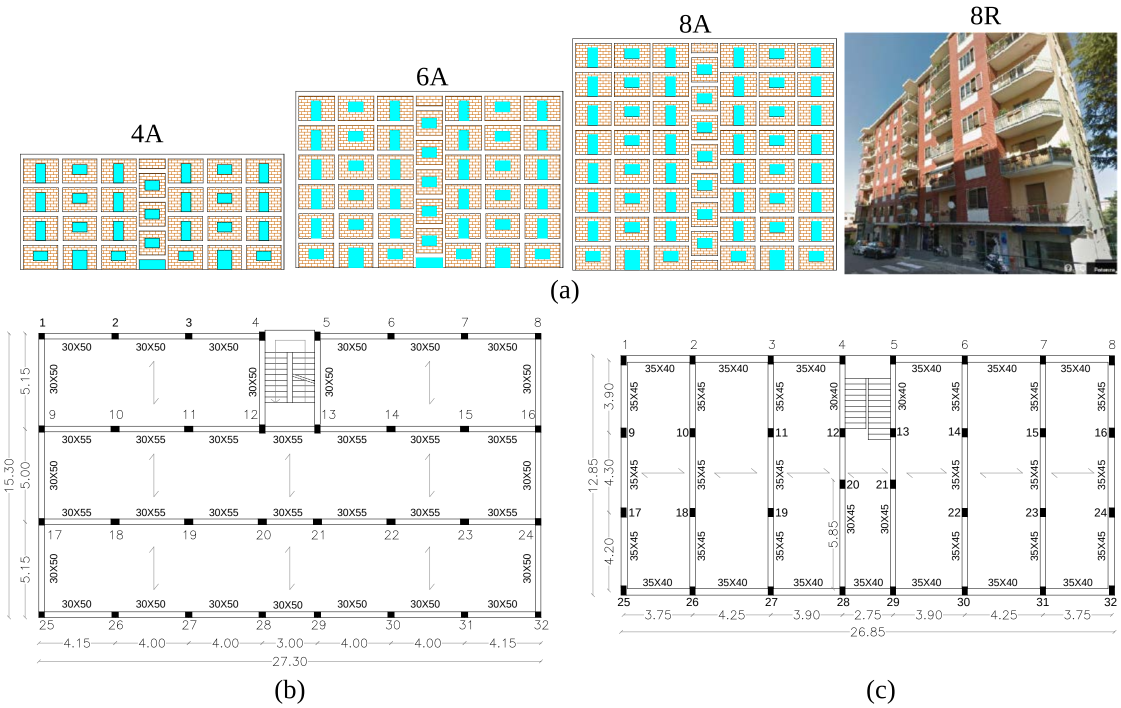


Fig. 1 – (a) Front view of the selected case-study buildings; Plan view of (b) archetype and (c) real building.

3. Seismic loss assessment with FEMA P-58

A refined evaluation of expected losses has been performed with PACT following a time-based performance assessment approach. To this end, a refined 3D lumped plasticity model has been implemented in SAP2000_Nonlinear, to accurately describe the seismic behavior of the selected case-study buildings and their possible failure modes. More details on modeling assumptions and model parameters can be found in [7]. Collapse fragility functions have been evaluated through the SPO2IDA (Static Pushover to Incremental Dynamic Analysis) tool provided in FEMA P-58, based on results of Pushover Analysis, assuming a lognormal dispersion of 0.6 [4]. Structural response has been then evaluated through Nonlinear Response-time History Analyses (NRHA) using nine sets of ten ground motion pairs, compatible with Conditional Mean Spectra [14], derived considering the M-R-ε (Magnitude-Distance-Deviation) disaggregation and a proper attenuation relationship for the city of L'Aquila. For each ground motion pair, the maximum absolute values of interstorey drifts and story accelerations have been determined and used as input in PACT to generate simulated demand sets.

Next, the building performance model has been assembled in PACT including information on building size and geometry, total replacement cost and total loss threshold beyond which building replacement is assumed more convenient than repairing. Vulnerable structural and non-structural components have been defined in PACT through the associated fragility specifications and quantity of components for each Performance Group. In particular, specific fragility and loss functions have been considered for the main structural and non-structural components of the building types under consideration [7] [8], including external and internal beam-column joints, ductile and brittle weak columns, masonry infills with and without openings. Foundations and floor diaphragms have been assumed as rugged elements. In the first approximation, also stairs have been considered rugged elements, although damage to stairs has been observed in past earthquakes. PACT analyses have been performed considering 500 realizations for each seismic intensity, assuming uncorrelated fragility groups and different values of total loss thresholds, ranging from 0.4 to 1. Building repair has been deemed to be economically and practically not feasible when residual drifts exceeded 1%. Therefore, a lognormal residual drift fragility function with median value of 1% and dispersion of 0.3 has been assumed.

In this paper, the PACT results relevant to the four buildings under consideration are further processed to derive a set of Intensity Measure (IM) vs. Monetary Losses (ML) curves. Fig. 2(a) shows the IM vs. ML curve ofor each building model considering a total loss threshold (Th) equal to 1. Each point in Fig. 2(a) represents the expected direct losses due to a spectral acceleration $S_a(T^*)$. As can be seen, for the building under consideration, monetary losses increase almost linearly as a function of IM.

In Fig. 2(b) results are normalized, in the attempt to aggregate results in a single data set. To this end, it is assumed that there is a threshold value of IM, below which minor (cosmetic) damage to the building will be not repaired and monetary losses can be assumed to be zero. This specific limit state is referred to as Zero Loss (ZL) and the associated spectral acceleration is indicated with $S_{a,ZL}(T^*)$. This way, a discontinuity in the building loss curve is introduced: ML = 0 for $Sa(T^*) < S_{a,ZL}(T^*)$ while ML = ML_{ZL} for $Sa(T^*) = S_{a,ZL}(T^*)$. The aforesaid assumption can be also adopted to capture different issues, such as the imposition of a franchise by an insurance company, government policies in granting public contributions for the reconstruction, etc.

Fig. 2(b) shows the normalized IM vs ML curves of the selected case-study buildings, obtained dividing expected monetary losses (ML) by the replacement cost of the building (RepC) and spectral accelerations (Sa(T*)) by the spectral acceleration at zero loss ($S_{a,ZL}(T^*)$). At this stage of the analysis, $S_{a,ZL}(T^*)$ has been tentatively taken equal to the average value of Sa(T*) (from the building loss curves of Fig. 2(a)) corresponding to a given value of monetary loss (M_{ZL} = 3% RepC). As can be seen in Fig. 2(b), in the proposed normalized form, the loss curves relevant to different buildings turn out to be well gathered, so that they can described by the same regression line.

Fig. 3 shows the effect of different values of total loss threshold (ranging from 0.4 to 1) on the shape of the normalized ML vs. IM curves. As expected, at low seismic intensities (corresponding to expected monetary losses lower than 20-25% RepC) the influence of the total loss threshold is negligible. As the damage state of the building increases with increasing seismic intensity, the effect of the total loss threshold becomes significant. In particular, expected losses at a given seismic intensity increase more than linearly when the assumed total loss threshold reduces. In the first instance, such effect can by approximated by a rotation of the regression line around the ZL performance point by a quantity that depends on the total loss threshold.

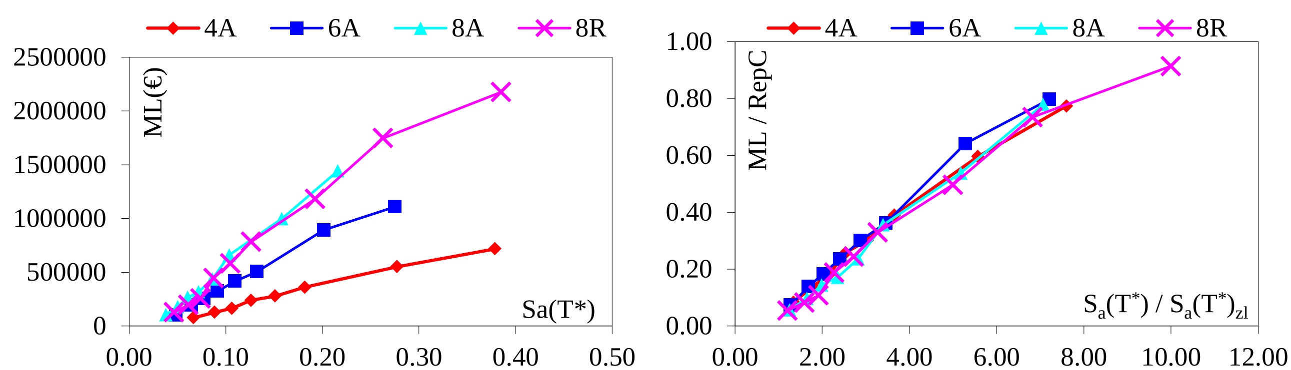


Fig. 2 – (a) IM vs. ML curves derived from PACT; (b) Normalized IM vs. ML curves.

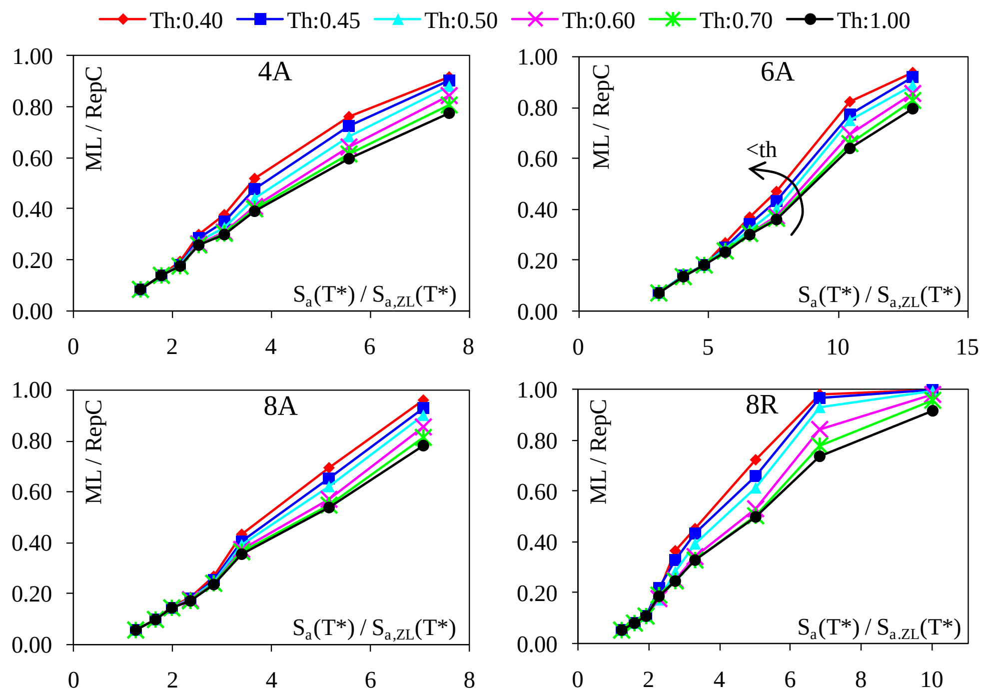


Fig. 3 – Normalized IM vs. ML curves considering different loss threshold values for: (a) 4A, (b) 6A, (c) 8A and (d) 8R building models.

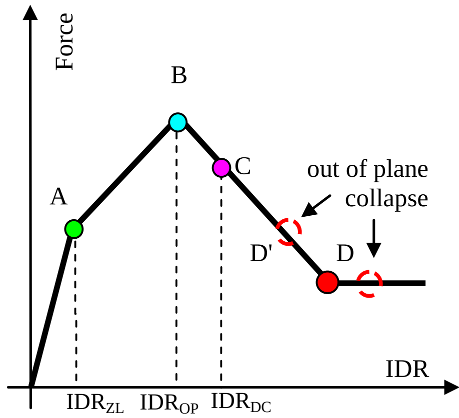
4. Simplified Evaluation of EAL

To establish a simplified expression for the EAL, it is first proposed that the direct losses for the building types under consideration can be approximated as a linear function of the seismic intensity using a number of limit states, discussed in the following section.

4.1 Limit States

In this study, three Limit States (LS) are considered: Zero Loss (ZL), Operational (OP) and Damage Control (DC). Each LS is identified considering the damage caused by the earthquake in masonry infills, in accordance with the approach described in [10]. Each LS is deemed to be attained when a given percentage of masonry infills reaches a given target point of the skeleton curve of masonry infills as shown in Fig. 4.

From an operative point of view, each LS can be identified by a given value of peak inter-story drift (IDR_{LSi} in Fig. 4), selected according to the fragility curves for masonry infills with and without openings proposed in [8]. In particular, the median value of IDR for Damage State DS1 (i.e. detachment of infill from the RC frame, possible first diagonal crack) and DS2 (i.e. extensive diagonal cracking) of the proposed fragility curves can be used to identify ZL and OP limit states, respectively. In first approximation, therefore, it is assumed that ZL limit state occurs when a peak interstorey drift (IDR_{ZL}) equal to 0.075-0.1% (depending on the type of opening) is reached and OP limit state when a peak interstorey drift (IDR_{OP}) equal to 0.2-0.3% (depending on the type of opening) is attained. As far as the DC limit state is concerned, based on the NRHA results presented in Section 3, a damage scenario similar to that described in Fig. 4 (i.e. no more than 30% of the panel reaches point C) is observed for peak interstorey drifts of the order of 0.6-0.75%. This value is very similar to the median value of IDR associated with yielding of beam-column joints of pre-70 RC frame buildings [7]. In accordance with [11], it is then assumed that DC limit state occurs when the first structural component yields. For pre-70 RC frame buildings, this happens for peak interstorey drift (IDR_{DC}) of the order of 0.65%. It is worth noting that the aforesaid assumptions are valid for RC pre-70 buildings, designed for gravity loads using smooth rebars as steel reinforcement, and featuring hollow clay bricks infills and partitions. The aforesaid assumptions may change for RC frame buildings with different structural details and/or non-structural components, although the proposed simplified method for the evaluation of EAL can be still valid.



LS	Description	Partition Damage	IDR_{LSi}
Zero Loss (ZL)	Onset of partition/infill damage	First panel reaches point A	0.075-0.1%
Operational (OP)	Light non-structural damage. Immediate Reoccupancy.	First panel reaches point B	0.2-0.3%
Damage Control (DC)	LS Between OP and LS. Building can be repaired.	No panel reaches D (or D'). Not more than 30%of the panels reaches point C.	0.65%

Fig. 4 – Definition of Zero Loss, Operational and Damage Control Limit States on partition/infill panels.

4.2 Theoretical formulation

As explained in [9], EAL can be expressed as a function of the expected loss in a building ($ML[L_T|S_a]$ in Eq. (1)) and the Mean Annual Frequency of Exceedance (MAFE) ($H(S_a)$ in Eq. (1)), through the following expression:

$$EAL = \int_0^\infty ML\left[L_T|S_a\right] dH\left(S_a\right)| \tag{1}$$

To establish a simplified expression for the EAL, in first approximation it is assumed that both the seismic hazard and direct losses could be approximated as a linear function of the seismic intensity measure $S_a(T^*)$. This proposal builds on ideas first presented in [6]. It is well known that, under certain hypothesis, the hazard curve $H(S_a)$ can be approximated with a linear regression in log-log coordinates. The simple power-law can be expressed as follows [12]:

$$H(S_a) = K_0 (S_a)^{-K_1} \tag{2}$$

where K_0 and K_1 are positive real numbers, representing the intercept and the slope of the fitted line. Eq. (2) is commonly recognized for its use in the probabilistic SAC-FEMA assessment approach [13]. As observed in Fig. 2, also direct losses can be approximated with a linear function in the normalized (IM vs. ML/RepC) format. More precisely, the model proposed herein can be expressed as follows:

$$ML/\mathrm{Rep}C = \begin{cases} 0 & for\ \mathrm{S_a/S_{a,ZL}} < 1; \\ m\left(\mathrm{S_a/S_{a,ZL}} - 1\right) + q & for\ 1 \le \mathrm{S_a/S_{a,ZL}} \le \left(1 + \left(1-q\right)/m\right); \\ 1 & for\ \mathrm{S_a/S_{a,ZL}} > \left(1 + \left(1-q\right)/m\right); \end{cases} \tag{3}$$

where m and q are the slope of the building loss curve and the monetary loss at the Zero Loss (ZL) limit state (ML_{ZL}/RepC), respectively. It is worth nothing that the loss model proposed in Eq. (3) assumes that no losses are incurred until the seismic intensity exceeds a given threshold limit, herein defined as the ZL limit state. Next, losses are assumed to increase linearly until the replacement cost of the building is attained.

A benefit of the model proposed in Eq. (3) is that, in principle, only three parameters are required to define the whole building loss curve: the slope m, the spectral acceleration at zero loss $S_{a,ZL}$ and the corresponding normalized expected loss $q=ML_{ZL}$/RepC. To take into account possible pre-determined cap to repair efforts, the coefficient m can be conveniently expressed as:

$$m = \gamma_{Th}\, m_1 \tag{4}$$

where m_1 is the coefficient corresponding to the assumption of a total loss threshold equal to 1, and γ_{Th} is a magnification factor, depending on the assumed total loss threshold (see Fig. 3). Substituting Eq. (2) and Eq. (3)

in Eq. (1), a closed form expression for EAL_{RepC} (i.e. the expected annual loss normalized with respect to the Replacement Cost of the building) is obtained, as a function of the parameters $S_{a,ZL}$, q, m, K_0 and K_1 :

$$EAL_{RepC} = \frac{K_0}{S_{a,zl}^{K_1}}\left[q + \frac{m}{(1-K_1)}\left(\left(1+\frac{1-q}{m}\right)^{1-K_1} - 1\right)\right] \tag{5}$$

Despite the simplicity of the proposed model, some crucial issues arise concerning the following two aspects: (i) the correct definition of the ZL limit state, through the estimation of the corresponding intensity level $S_{a,ZL}$ and monetary loss $q=ML_{ZL}/RepC$, and (ii) the representativeness of the slope m considering the different situations that can be found in common practice. For this reason, in this paper two alternative approaches (Approach 1 and Approach 2) are proposed to evaluate the main parameters of the proposed simplified model. A schematic representation of the ML vs. IM curves derived following Approach 1 and Approach 2 is shown in Fig. 5(a) - 5(b), respectively. The common philosophy of both approaches is that, the loss vs. intensity relationship is linked to a limited number of limit states (LS) (see Sect. 4.1), easily understood by engineers, being presented in current codes. For each LS, the corresponding spectral acceleration $S_{a,LSi}$ can be evaluated with a suitable structural analysis. For each LS, moreover, a pre-determined monetary loss, expressed in terms of given percentages of RepC (i.e. $ML_{LSi}/RepC$), can be reasonably assumed, based on results of previous accurate analyses on a adequate number of buildings representative of that typology.

As can be seen in Fig. 5, both approaches require the evaluation of the spectral acceleration $S_{a,ZL}$ and the assumption of a suitable value for the monetary loss $q=ML_{ZL}/RepC$. Values of $S_{a,ZL}$ can be evaluated by modal analyses or Displacement Based Assessment (DBA) procedures. The main difference between Approach 1 and Approach 2 is on how the coefficient m is evaluated. In the Approach 1 (see Fig.5(a)), the values of m are pre-determined, being expressed as a function of the assumed total loss threshold only. In the Approach 2 (see Fig. 5(b)) the coefficient m_1 is derived from a best-fit linear regression analysis (Least Squares Method), considering three performance points corresponding to ZL, OP and DC limit state of the building under scrutiny, assuming the passage of the regression line through the ZL point. Similarly to the ZL limit state, values of $S_{a,OP}$ and $S_{a,DC}$ can be evaluated based on modal analysis, pushover analysis or through DBA procedure. Herein, preliminary estimates of $ML_{OP}/RepC$ and $ML_{DC}/RepC$ are tentatively proposed based on the results of accurate loss assessment analyses with PACT on the four building models described in section 2.. In first approximation, the variation of the coefficient m with the total loss threshold is assumed to be the same as in the Approach 1.

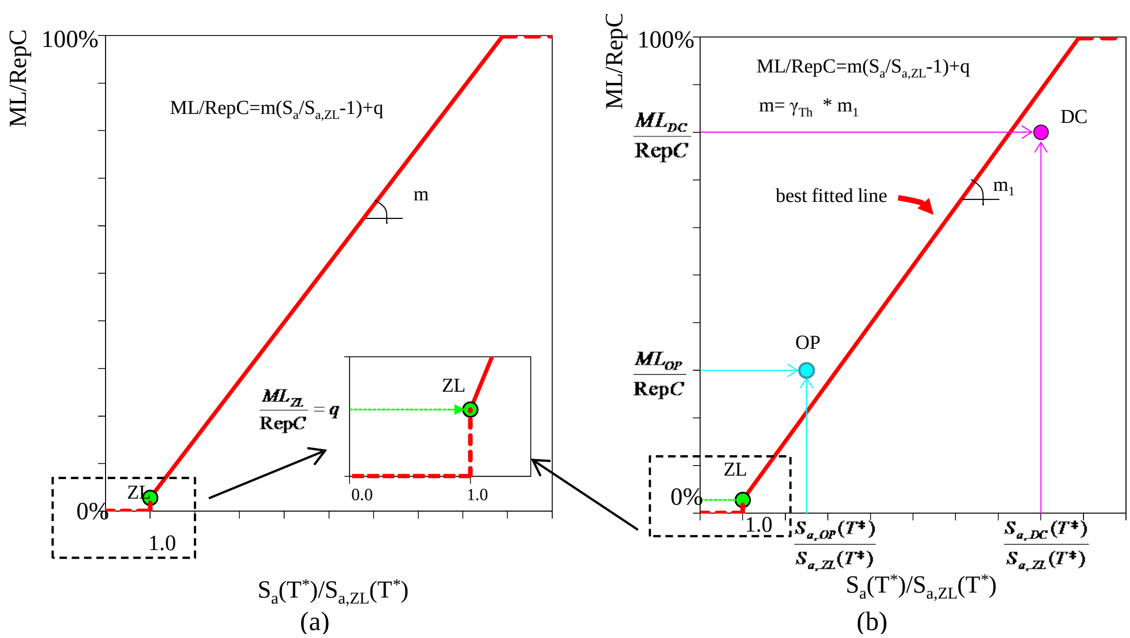


Fig. 5 – Derivation of normalized ML vs. IM curves: (a) Approach n. 1 and (b) Approach n.2.

The key point of both approaches is the definition of the normalized monetary losses (ML_{LSi}/RepC) that, for selected building typologies, are expected to incur (under typical conditions) for each LS. From this point of view, the operative definition of LS given before is not exhaustive, being associated with the occurrence of a given drift limit in the first structural or non-structural component. The expected total loss should be necessarily related (in some way) to the "shape" of the entire drift profile, in both directions. In the example of Fig. 6(a), it is apparent that the expected monetary losses for Building A will be greater than for Building B, due to the different profile of interstorey drifts. Similarly, in the example of Fig. 6(b), it is clear that, in buildings where the in-plane distribution of structural and non-structural components is almost uniform, damage will be different in the two directions, due to differences in the drift values. With the above in mind, the expected losses of a building for a given LS shall be estimated taking into account the shape of the drift profile and the differences in the two directions, with the following expression:

$$ML_{LSi} / RepC = \alpha_{LSi} \cdot \beta_{LSi} \cdot ML^*_{LSi} / RepC \tag{6}$$

where ML^*_{LSi}/RepC is a reference value of expected losses calibrated based on accurate analyses on selected building models, representative of that building typology (see. Section 5.2), α_{LSi} and β_{LSi} are modification factors accounting for shape and bidirectional effects, respectively. The shape factor α_{LSi} can be defined as:

$$\alpha_{LSi} = \left(\frac{mean\left(\sum_n IDR_{i,x} h_i ; \sum_n IDR_{i,y} h_i\right)}{0.8 IDR_{LSi} H} \right)_{LSi} = \left(\frac{mean\left(D_{top,x}; D_{top,y}\right)}{0.8 IDR_{LSi} H} \right)_{LSi} \tag{7}$$

where $IDR_{i,j}$ is the interstorey drift at the i-th storey in the j-direction, obtained from structural analysis, H is the height of the building, h_i is the interstorey height, IDR_{LSi} is the limit drift for the selected limit state. The coefficient 0.8 is introduced to convert the limit drift IDR_{LSi} in the median value of the drift profile of a typical shear-type building with column tapering (from first to upper storeys), subjected to an inverted triangular distribution of inertial forces. The bidirectional factor β_{LSi} can be defined as:

$$\beta_{LSi} = \frac{\min\left(IDR_{\max,dir1}; IDR_{\max,dir2}\right)_{LSi}}{IDR_{LSi}} \tag{8}$$

where $IDR_{max,dir1}$ and $IDR_{max,dir2}$ are maximum interstorey drifts in the two directions.

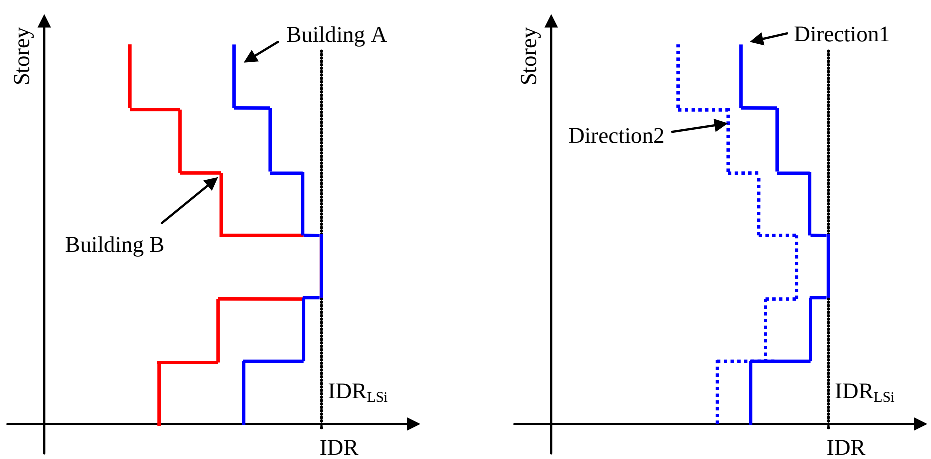


Fig. 6 – Influence of (a) shape and (b) bidirectionality of IDR profile on expected losses.

5. Calibration of the proposed procedure

5.1 Estimates of monetary losses for different limit states

In this section, estimates of the monetary losses expected at ZL OP and DC limit states are derived in PACT based on corresponding drift and acceleration profiles obtained from a simplified displacement-based procedure, inspired to the principles of the Displacement Based Assessment (DBA) method, described in [5]. In particular, the expected monetary losses losses at ZL OP and DC limit states have been evaluated assuming, in accordance with Section 4.1, values of IDR_{SLi} equal to 0.075%, 0.3% and 0.65% and a total loss threshold (Th) equal to 1. The corresponding results, normalized with respect to the Replacement Cost of the buildings, are summarized in Table 1. As can be seen, considering the three archetype buildings, expected losses show a slight tendency to decrease with the number of storeys for ZL while increasing for OP and DC. The reason is that, in the probabilistic framework of PACT, the percentage of masonry infills/partitions that exceeds the drift limit IDR_{ZL} decreases while increasing the number of storeys. For OP and DC, even if the percentage of infills/partitions that exceeds drift limits IDR_{OP} and IDR_{DC} tends to decrease while increasing the number of storeys, a growing percentage of non-structural elements reach lower damage states. In addition, it is apparent that monetary losses for the case study 8R are much lower compared to those experienced by the case study 8A. This can be ascribed to differences in the structural scheme (basically, arrangement of internal frames and layout of infills), previously outlined in Section 2, which determine significant differences in the shape and magnitude of the IDR profiles in the two directions.

Based on the results of this study, the following reference values of monetary losses (ML*/RepC in Eq. (6)) can be tentatively assumed for the selected limit states of pre-70 residential RC frame buildings: 3% (ZL), 30% (OP) and 80% (DC). As discussed in section 5.1, a shape modification factor (α_{SLi}) and a bidirectional modification factor (β_{SLi}) have to be applied to the aforesaid reference values to take into account the shape of the drift profiles in the two orthogonal directions. The values of ML_{SLi}/RepC thus obtained (together with the values of the applied modification factors α_{SLi} and β_{SLi}) are summarized in Table 2 for each building model. The comparison between "exact" and approximate values of expected losses is satisfactory (compare Table 1 and 2), as differences are (on average) lower than 15%. It is also worth noting the values of the modification factor, which are around 1 for the archetype buildings, while considerably lower (ranging from 0.74 to 0.85) for the real building, characterized by a different structural scheme and infill layout (see Fig. 1).

Table 1 – Expected losses for different limit states of the selected buildings derived with PACT (Th=1).

Limit State	IDR_{LSi}	$Sa_{,LSi}$				ML_{LSi}/RepC			
		4A	6A	8A	8R	4A	6A	8A	8R
Zero Loss	0.075%	0.050 g	0.038 g	0.031 g	0.038 g	4.48%	3.97%	3.51%	1.43%
Operational	0.30%	0.141 g	0.121 g	0.116 g	0.096 g	30.07%	30.24%	35.85%	18.42%
Damage Control	0.65%	0.284 g	0.273 g	0.274 g	0.186 g	72.45%	79.62%	85.38%	46.38%

Table 2 – Values of α_{LSi}, β_{LSi} and corresponding ML_{LSi}/RepC for the selected case studies.

Case study	α_{ZL}	α_{OP}	α_{DC}	β_{ZL}	β_{OP}	β_{DC}	ML_{ZL}/RC	ML_{OP}/RC	ML_{DC}/RC
4 A	1.07	1.03	0.94	1.00	0.94	0.76	4.26%	29.04%	57.58%
6 A	1.02	1.02	0.98	0.99	1.00	0.91	4.05%	30.55%	71.14%
8 A	0.97	1.01	1.02	0.90	0.99	0.99	3.50%	29.97%	80.67%
8 R	0.80	0.78	0.74	0.85	0.83	0.74	2.73%	19.47%	43.56%

5.2 Influence of total loss threshold

As discussed in section 4.2, the simplified evaluation of EAL requires the assignment of a suitable value of the slope coefficient m. Since it can assumed that the point at zero loss is not affected by the value of the total loss threshold (see Fig. 3), only the slope coefficient m incorporates the effects of changes in the total loss threshold.

The influence of the imposed total loss threshold on the slope coefficient m can evaluated through linear regression analysis, based on the normalized ML vs. IM curves derived with PACT using NRHA results (see Fig. 3). The values of m thus obtained are reported in Fig. 7 (a). As expected, the slope coefficient m decreases as the total loss threshold increases, ranging from approximately 0.17 to 0.12. Negligible differences in terms of m (less than 10%) are observed between the selected case-study buildings, for a given value of total loss threshold. In first approximation, the values of m reported in Fig. 7(a) can be further processed to derive the coefficients m_1= 0.125 and γ_{Th} to be used in Eq. (4) for the evaluation of EAL within the first approach (Fig. 7(b)). It is worth noting that γ_{Th} remains almost constant for Th $\geq$ 0.7, while it increases linearly from 1 to approximately 1.25 as Th decreases from 0.7 to 0.4 (see Fig. 7(b)). As explained in section 4.2, following the Approach 2, the slope coefficient m_1 is identified through a best fit regression analysis, based on the performance points at ZL, OP and DC limit states of the building under scrutiny. The same relationship of γ_{Th} can be reasonably used also in this case to take into account the influence of the total loss threshold. Fig. 8 compares the lines derived following Approach 1 and Approach 2, assuming Th=1, for the four case-study buildings examined in this study.

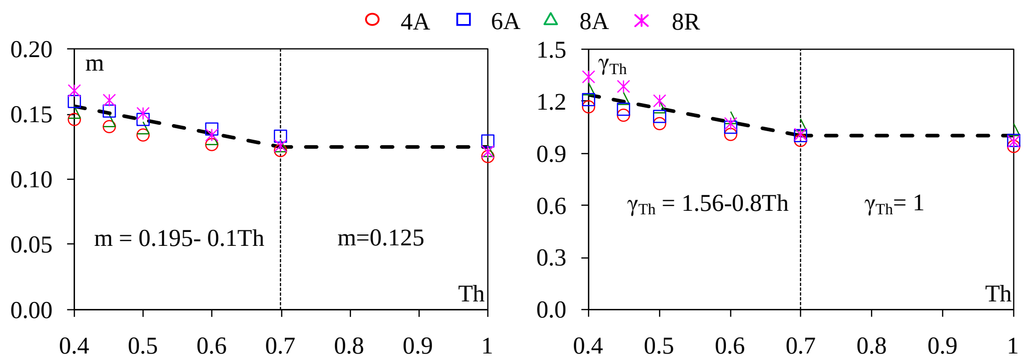


Fig. 7 – (a) Variability of m with Th; (a) Trend of γ_{Th} as a function of Th.

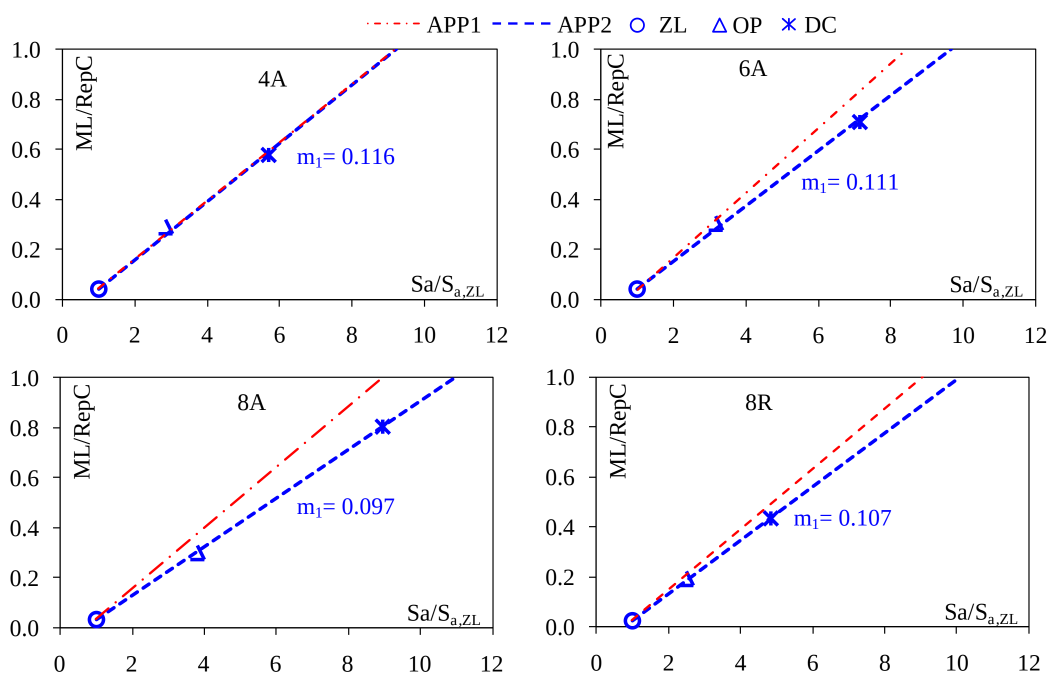


Fig. 8 – Linear Regression of Normalized IM vs ML for Approach 1 and Approach 2.

6. Results

Fig. 9 compares the approximate values of EAL_{RepC} derived following the proposed methodology (Eq. (5)) with the "exact" values derived from PACT based on NRHA results (see Fig. 9). Generally speaking, the proposed methodology gives good results with errors, on average, lower than 20% for Approach 1 and lower than 10% for

Approach 2, respectively. The Approach 1 tends to be conservative, especially for low-rise buildings. In any case, the maximum error does not exceed 30%, for building 4A, and 20% for the other buildings. Following the Approach 2, errors do not exceed 7%, except for building 4A for which differences of the order of 20% are found. The reason why approach 2 turns out to be more accurate than approach 1 is that it is able to capture the change of slope with buildings height.

Approach 2 is certainly more versatile than Approach 1 because the slope of the loss curve is evaluated considering the performance of the building at three limit states (ZL, OP and DC) instead of one limit state only (ZL) like in Approach 1. Bearing that in mind, Approach 2 should be preferred, when retrofit interventions are envisaged.

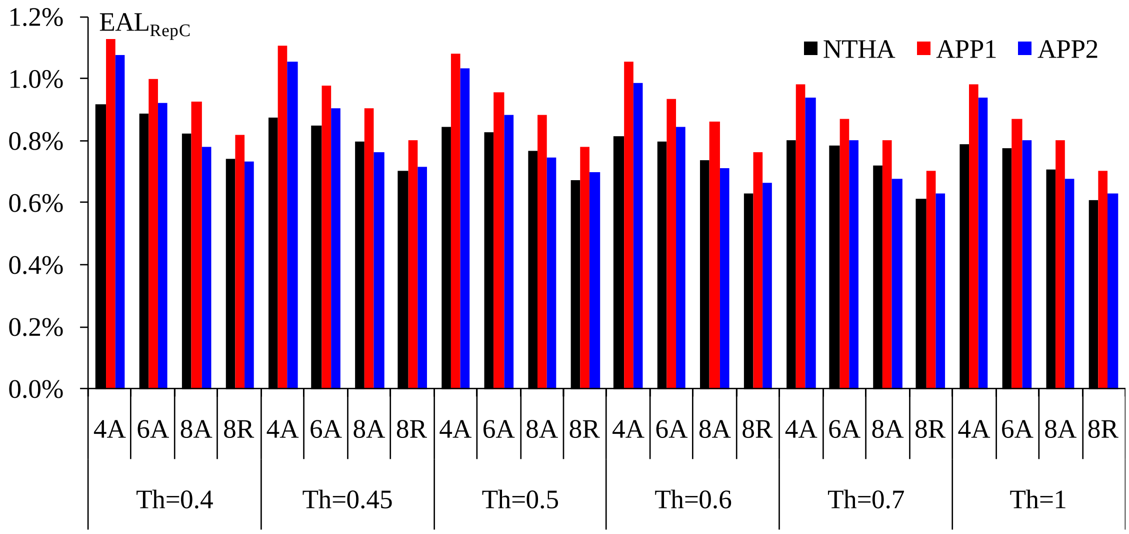


Fig. 9 – Comparison between the values of EAL_{RepC} derived from PACT and those obtained following the proposed simplified methodology for different loss threshold values.

7. Conclusions

The Expected Annual monetary Loss (EAL) is a powerful seismic performance indicator for a building as it quantifies repair and replacement costs considering a wide range of possible earthquake scenarios. Despite the great effort developed to make the methodology accessible to engineering practice, a correct estimation of EAL is yet prerogative of a few experts. Therefore, a simplified engineering practice-oriented means of estimating EAL is needed.

In the first part of the paper, the performance-based seismic assessment methodology proposed in FEMA P-58 has been applied to a number of archetype and real case-study buildings representative of typical pre-70 RC frame buildings, for a refined evaluation of EAL, based on comprehensive non-linear response-time history analyses. “Exact” results provided the basis for the development of simplified approaches for the evaluation of EAL.

In the second part of the paper, a simplified closed-form expression for the evaluation of EAL has been proposed. The proposed approach is based on two gross approximations: (i) the repair costs of a building increase linearly with seismic intensity after the zero-loss limit state is exceeded, and (ii) the hazard curve can be represented by a linear model in log-log space. By formulating the proposed simplified loss assessment approach in terms of a limited number of limit states, it is made reasonably accessible to engineers and easy to implement in practice.

In the third part of the paper, the results of the proposed simplified method have been compared to those obtained following accurate seismic performance assessment approaches. Comparisons have shown that the proposed formulation gives good results with errors that result on average lower than 10% on the safe side.

As part of future research, further efforts are needed to extend the proposed procedure to other building categories, bearing in mind the final goal, which is to use this approach to quickly identify, in the preliminary steps of a project, the design or retrofit choices that could be more effective in reducing monetary losses.

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References

[1] Porter KA (2003): An Overview of PEER's Performance-Based Earthquake Engineering Methodology, *9th Conference on Applications of Probability and Statistics in Engineering*, San Francisco, CA.

[2] Porter KA, Beck JL, Shaikhutdinov RV (2004): Simplified performance-based earthquake engineering estimation of economic risk for buildings, *Earthquake Spectra*, **20**(4), 1239-1263.

[3] Calvi GM, Sullivan, TJ, Welch, DP (2014): A Seismic Performance Classification Framework to Provide Increased Seismic Resilience, *Chapter 11 in Perspectives on European Earthquake Engineering and Seismology*, A. Ansal (ed.), Geotechnical, Geological and Earthquake Engineering **34**, DOI: 10.1007/978-3-319-07118-3_11.

[4] Applied Technology Council (ATC), FEMA P-58, (2012): Next-generation Seismic Performance Assessment for Buildings, Volume 1 and Volume 2, *Federal Emergency Management Agency*, Washington, D.C.

[5] Cardone D, Flora A (2016): Developing displacement-based approaches for seismic performance assessment of RC frame buildings within FEMA P-58 framework, *Engineering Structures*, under review.

[6] Sullivan TJ, (2016): Use of limit state loss versus intensity models for simplified estimation of expected annual loss, *Journal of Earthquake Engineering*, DOI: 10.1080/13632469.2015.1112325.

[7] Cardone D, (2016): Fragility curves and loss functions for RC structural components with smooth rebars, *Earthquakes and Structures*, accepted for publication (in press).

[8] Cardone D, Perrone G (2015): Developing fragility curves and loss functions for masonry infill walls, *Earthquakes and Structures*, **9**(1), 257-279

[9] Cardone D, Perrone G (2015): Damage and Loss Assessment of Pre-70 RC Frame Buildings with FEMA P-58, Journal of Earthquake Engineering, in press, DOI: 10.1080/13632469.2016.1149893.

[10] Calvi GM, Bolognini D, Penna A (2004): Seismic performance of masonry-infilled r.c. frames: benefits of slight reinforcements. *Sismica 2004, 6th Portoguese Congress on Seismology and Earthquake Engineering, Guimaraes, Portugal*.

[11] Welch DP, Sullivan TJ, Calvi GM, (2014): Developing Direct Displacement-Based Procedures for Simplified Loss Assessment in Performance-Based Earthquake Engineering, *Journal of Earthquake Engineering*, **18**(2), 290-322.

[12] Kennedy RP, Short, SA (1994): Basis for seismic provisions of DOE-STD-1020. Rep. No. UCRL-CR-111478, Lawrence Livermore National Laboratory, Livermore, Calif., and Rep. No. BNL-52418, Brookhaven National Laboratory, Upton, N.Y.

[13] Cornell CA, Jaylayer F, Hamburger RO, Foutch DA (2002): Probabilistic basis for 2000 SAC Federal Emergency Management Agency Steel Moment Frame Guidelines, *Journal of Structural Engineering* **128**(4), 526–553.

[14] Baker JW (2011): Conditional Mean Spectrum: Tool for ground motion selection, *Journal of Structural Engineering*, **137**(3), 322–331.