




# The Italian guidelines for seismic risk classification of constructions: technical principles and validation

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## Abstract

The Italian “*Guidelines for the seismic risk classification of constructions*” approved in February 2017 define the technical principles for exploiting tax deductions with respect to seismic strengthening interventions on existing buildings (*Sismabonus*). Tax deductions represent a unique opportunity to improve the seismic safety of the existing Italian building stock. The guidelines are very simple and allow practitioners to deal with the sophisticated concepts behind modern seismic design, such as expected annual losses (EAL) and repair costs (expressed as a fraction of the Reconstruction Cost: %RC). The seismic risk classes of buildings and the class upgrade due to strengthening interventions can be assessed using the principles included in the guidelines. The seismic risk class is the minimum between the class defined by the building safety index at the ultimate limit state and the one related to the EAL. The latter class depends on the area under the curve of the expected losses, which is easily obtained by computing the safety index converted in the return period (annual frequency) at different limit states and the relevant %RC. This paper illustrates the technical principles at the base of the guidelines and the procedure used to calibrate the repair costs associated with the different limit states using the actual repair costs monitored in the reconstruction process following recent Italian earthquakes. Finally, simple tools to estimate the cost of the strengthening interventions to improve the seismic capacity at the life-safety limit states are provided.

**Keywords** Sismabonus · Seismic risk classification · Expected annual losses (EAL) · Strengthening · Risk reduction · Mitigation

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## 1 Introduction

Nowadays a proper quantification of the attained losses is of paramount importance in the development of sustainable and resilient communities in seismic prone areas. Indeed, estimating of the loss of lives, the monetary-losses and the resources/time for recovery of building functionality may help stakeholders (owners, governments, managers and insurance companies) to define the priority of interventions or policies for disaster prevention and, more generally, for quality and safety of constructions and infrastructures.

Recent seismic events highlighted that significant damage was attained in structural and non-structural components also under low-to-medium intensity earthquakes. The repair cost needed to restore structural and non-structural components to its pre-earthquake conditions is a relevant portion of the total reconstruction cost (De Martino et al. 2017; Del Vecchio et al. 2018a, b). These costs could be not sustainable in high-medium seismicity regions where damaging earthquakes frequently occur. In light of this evidence, a modern seismic design of new constructions or the design of retrofit interventions on existing ones needs necessarily to find the optimum between employed economic resources and expected losses (Calvi 2013; Liel and Deierlein 2013). The expected losses are becoming a key parameter to quantify and compare the building performances in its reference life. The Pacific Earthquake Engineering Research Center (PEER) presented the performance based earthquake engineering (PBEE) framework (ATC 33 1997) in a more robust methodology involving four stages: hazard analysis, structural analysis, damage analysis, and loss analysis (Cornell and Krawinkler 2000; Deierlein et al. 2003). The entire process has the scope to quantify the decision variables which measure the seismic performance of the facility in terms of greatest interest to stakeholders, whether in deaths, dollars, downtime, or other metrics (Porter 2003). Only recently, the methodology proposed by the FEMA P-58 (ATC 58 2012) addresses the full development of the PBEE framework to make it suitable for practical applications. Even though simplified methodologies (Welch et al. 2012; Ligabue et al. 2017) and computer tools (e.g. PACT, ATC 58 2012) were recently proposed, the implementation of loss-assessment in the current design practice is still challenging. Difficulties arise in the calculation of the expected annual losses (EAL) involving the building's performance assessment at increasing intensity earthquakes. This requires high scientific background and a significant computational effort and it may be not suitable for application in the common design practice, where robustness of results with respect to various possible operators is a primary requirement. Even though a proper estimation of the EAL and an optimum design of the new building/retrofit intervention were performed, difficulties would arise in communicating the benefits of a refined design procedure to the stakeholder. Thus, there is an urgent need to simplify the communication of the seismic risk of constructions and of its reduction when making seismic upgrading.

First attempts were made in Italy and in New Zealand. In 2003 in Italy the safety verification according to the seismic code of existing critical buildings was made compulsory (O.P.C.M. 3274, 2003), while a safety index given by the ratio between the capacity and the demand expressed in peak ground acceleration (PGA) was introduced (O.P.C.M. 3362, 2004). In the 2006, the New Zealand Society for Earthquake Engineering guidelines for assessment of existing building (NZSEE 2006) proposed a grading system for earthquake risk of constructions based on the seismic safety index at the ultimate limit state (percentage of New Building Standard, %NBS). However, they do not directly account for the EAL. Recently, resilient-based seismic ratings of buildings were proposed (Resilience-based Earthquake Design Initiative (REDi) rating system, Almufti and Willford 2013, and

USRC Building Ratings, US Resiliency Council 2016). They articulate the FEMA P-58 (ATC 58 2012) loss-assessment to rating the building including the building safety and time to re-occupancy of the building. More recently, Calvi (2013) proposed discrete classes of earthquake resilience based of a wide study on the influence of retrofit alternatives on the EAL and building resilience. These classes were later defined in detail to be compliant with the well-known classification of energy efficiency (Calvi et al. 2016). Although refined tools and loss assessment methodologies are currently available, refined estimations of EAL and the definition of a seismic rating for existing building typical of the Mediterranean area are still challenging (Cardone and Perrone, 2017; Ottonelli et al. 2015). This is due to the lack of data on the repair costs of structural and non-structural components of buildings typical of the Mediterranean area. Furthermore, a simple and code compliant approach to assess the building losses suitable for the application in the common design practice without performing time-consuming simulations is still lacking. To fill this gap, a proper guideline for the seismic risk assessment of constructions (Ministry Decree n.58 28/02/2017) has been recently issued in Italy in order to address the seismic risk classification of existing constructions.

This paper illustrates the guidelines focusing on the scientific background, the technical principles and the assumptions made to simplify the calculation of the EAL. Details on the derivation of EAL curves considering the actual repair costs of existing buildings damaged by recent seismic events are provided. The procedure to obtain the seismic class is discussed in detail with reference to the structural weakness typical of existing buildings and the effect of the seismic retrofitting. The influence of new seismic risk classification on a large database of case study buildings damaged by the L'Aquila earthquake and repaired/strengthened is assessed. Step-by-step solved examples on real RC and masonry buildings using the current Italian building code and the guidelines are also illustrated. Finally, simple tools to estimate the cost of the strengthening intervention to improve the seismic capacity at the life-safety limit states are provided.

## 2 The Italian perspective for seismic risk classification

The continuous upgrading of seismic code and construction practice highlights the significant effort put in by the scientific community to achieve the ambitious goal of the seismic risk reduction. The results of research and studies as well as the evidences of damage provided by recent devastating earthquakes led to the definition of building code and regulations aimed at the primary objective to protect the life of occupants. Recently, the reduction of damage due to seismic action in order to enable rapid re-use of buildings after earthquakes has been recognized as an important goal for the mitigation of the seismic risk of constructions. Including this aspect in modern design provisions may permit to strongly reduce the losses expected for future earthquakes on newly built buildings. However, a significant portion of building stock strongly suffers seismic actions and they urgently need strengthening interventions. The low risk perception (except for earthquake stricken communities) and the high cost associated to seismic strengthening interventions, negatively impact on the need to act on the existing building stock in order to reduce its vulnerability. Thus, an effective public policy for the seismic risk mitigation should both act on the people perception of risk through effective communication campaigns and on the definition of economic incentives for seismic strengthening of existing structures.

The recent devastating earthquakes, L'Aquila (2009), Emilia (2012), Central Italy (2016–2017) outlined the high vulnerability of the existing buildings in Italy. The human losses and the massive economic and social resources employed to recover and repair damaged buildings led the government to undertake actions aimed at improving building earthquake resilience at national scale as a seismic prevention strategy. In particular, a communication campaign to enhance people risk perception, “I Do Not Take Risks—Earthquake” (Postiglione et al. 2016), started in 2011. In the meanwhile, on 23 November 2013 the Minister of Infrastructures and Transportations established a Study group in charge of developing different technical methodologies targeting the seismic risk classification of constructions. The classification has to facilitate the communication to the large public and the administrators of the seismic risk of constructions and the effectiveness of the retrofit interventions aimed at upgrading the seismic class. The classification should also provide a knowledge base for Government evaluations and public policies in the field of safety and quality of constructions and disaster management. Based on relevant scientific backgrounds (Welch et al. 2012; Braga and Picchi 2017), in April 2015, the study resulted in an original document containing three different methodologies (simplified, conventional, advanced) addressing the seismic risk classification of constructions and the effectiveness of strengthening interventions. Eight seismic risk classes (from A+ to G) were introduced based on the EAL and the earthquake intensity at the reference site. From a financial standpoint, the 2017 Budget Law (IG 2017), clause 2-bis, introduces a tax deduction of 50% for expenses incurred to comply with seismic design requirements for buildings in high-risk areas carried out between 1 January 2017 and 31 December 2021, and for a total amount of up to € 96,000 per building unit. The incentive applies to homes and commercial properties and consists of 5 annual instalments of equal value each. The tax deduction for the improvement of one class is 70%; it can be raised up to 80% if the works result in an improvement of two or more classes; in case of interventions on shared parts of buildings the deduction is raised up to 75 or 85%, respectively. Another novelty is the possibility of transfer the credit from the deductions for interventions on condominium property to the contractors who carried out the work. This tax deduction was later named “*Sismabonus*” and are referred uniquely to the building components, i.e. structural and non-structural components, but not to the content. Although in some cases private buildings can also host activities implying content value or business interruption costs that are much higher than the cost of the construction, this simplification was deemed indispensable for the management of this prevention measure.

Once that the scientific principles for the seismic risk classification of constructions and the financial incentives for the strengthening interventions were defined, simple guidelines for the application in the current design practice were needed. To this scope, a technical committee was established on 10 November 2016, within the High Council of Public Works, with participation of Department of Civil Protection, Universities, professional representative (Engineers and Architects), which proposed, in a few months, a new brief document containing the technical instructions for the seismic risk classification of constructions for the Italian tax deductions.

The “*Guidelines for the seismic risk classification of the constructions*”, approved in February 2017 by the High Council of Public Works, (Ministry Decree n.58 28/02/2017), define the general principles and the technical rules to exploit tax deductions for seismic strengthening interventions on private buildings (*Sismabonus*). This represents a unique opportunity to improve the seismic safety of the Italian existing building stock, in a general perspective of risk prevention.

The guidelines are very simple and allow practitioners to deal with the sophisticated concepts of a modern seismic design such as EAL and the repair costs (expressed as a fraction of the Reconstruction Cost: %RC). The seismic risk class of buildings and the class upgrade due to the strengthening intervention can be assessed using the principles included in the current seismic technical code for constructions (MI 2008). The document refers to a conventional and to a simplified approach. A third advanced approach, which refers to displacement-based assessment (Welch et al. 2012), is currently under development. The conventional method, which requires a detailed seismic assessment of the structural system at different limit states, is the only one allowing for an upgrading of two or more seismic risk classes by using properly designed strengthening interventions. A simplified approach, based on the European Macroseismic Scale (Grünthal 1998), is also proposed for masonry buildings. The latter defines the seismic risk class based on the structural type and the potential structural deficiencies. In this case, the local strengthening interventions, properly designed according to the current seismic code, may result in an increase of only one seismic risk class. For other building typologies (i.e. RC frame structures or industrial buildings), the guidelines allow for the same tax deductions by implementing the suggested local strengthening interventions also without a proper seismic classification of the as-built capacity.

### 3 The conventional approach

The Conventional approach described in the Guidelines (Ministry Decree n.58 28/02/2017) relies on Performance Based Earthquake Engineering concepts currently adopted in modern seismic design codes worldwide (i.e. Eurocode 8, CEN 2004, 2005, Italian building code, MI 2008). Indeed, it can be easily implemented by structural engineers who are familiar with technical principles of current standard for seismic design/assessment of buildings at different Limit States: Operational (OLS) and Damage Limitation (DLLS) at Serviceability Limit State (SLS); Life Safety (LSLS) and Collapse (CLS) at Ultimate Limit States (ULS) according to the current Italian building code (MI 2008). Once the seismic capacity of the reference building is assessed at SLS and ULS, by means of standard procedures already implemented in commercial software, the seismic risk class of the building can be computed using “conventional” and robust simple formulations proposed in the guidelines.

From a technical standpoint, the only novelty is the introduction of two conventional Limit States, called “Initial Damage” (IDLS) and total loss or “Reconstruction” (RLS). The former accounts for low intensity and high frequency seismic events, which may result in a slight “initial” damage to the building components or services. The Guidelines conventionally assumes that this Limit State occurs for seismic events having 10 years return period ( $T_r$ ). The RLS limit state refers to a seismic event causing a monetary loss corresponding to the total value of the construction. It refers to a new building subjected to a very destructive earthquake, having a virtual infinite return period, exploiting the maximum possible damage and monetary losses corresponding to 100% of reconstruction cost.

The seismic risk class of the building is defined as the minimum between two classes: the one associated to the Safety Index of the structure at the LSLS (namely SI-LS, in the following) and the one related to the EAL (namely *Perdita Annuale Media attesa*, PAM, in the Italian guidelines, Ministry Decree n.58 28/02/2017). The consideration of SI-LS also is needed because considering only EAL does not provide adequate guarantees for the

safety of people living inside. Indeed, highly stiff fragile constructions can have low EAL values, corresponding to a good EAL class, while having inadequate safety with respect to collapse conditions, implying loss of life of many occupants (Dolce and Moroni 2017).

The first index, SI-LS, is the ratio  $PGA_D/PGA_C$ ;  $PGA_D$  is the design PGA at the building site according to the hazard map and affected by the site amplification factor (MI 2008), and  $PGA_C$  is the capacity PGA defined as that required to cause the building to attain the LSLs. The  $PGA_C$  can be conventionally evaluated according to the standard design methodology that accounts for the attainment of the LSLs due to brittle or ductile failure modes. For instance, on existing RC buildings typical of the Mediterranean area, it is commonly governed by the attainment of brittle failures on unconfined (i.e. exterior or corner) beam-column joints or columns (Fracadore et al. 2015; Del Vecchio et al. 2016, 2018a, b). Whereas in existing masonry buildings the attainment of brittle failure in the spandrel or piers should be considered (Parisi et al. 2014, Cattari et al. 2014).

Although the human losses were, intentionally, not converted in terms of economic losses, it is essential to consider the building performance at LSLs in the definition of the seismic risk class of the construction. As said above, this parameter was introduced by the Italian code O.P.C.M 3274 (2003) following the San Giuliano di Puglia earthquake (2002) to assess the building performance at the LSLs. It was used in the recent reconstruction processes to define the safety threshold (i.e. SI-LS=60%) to have access to the financial contributions for the reconstruction of severely damaged non-strategic buildings (see Di Ludovico et al. 2017a, b and Ministerial Decree 477 of 27/12/2016 for more details). To assess the building performance at the LSLs, the designer may use the preferred analysis complying with MI 2008, provided that it properly accounts for the brittle failures that commonly affect the seismic performance of existing buildings.

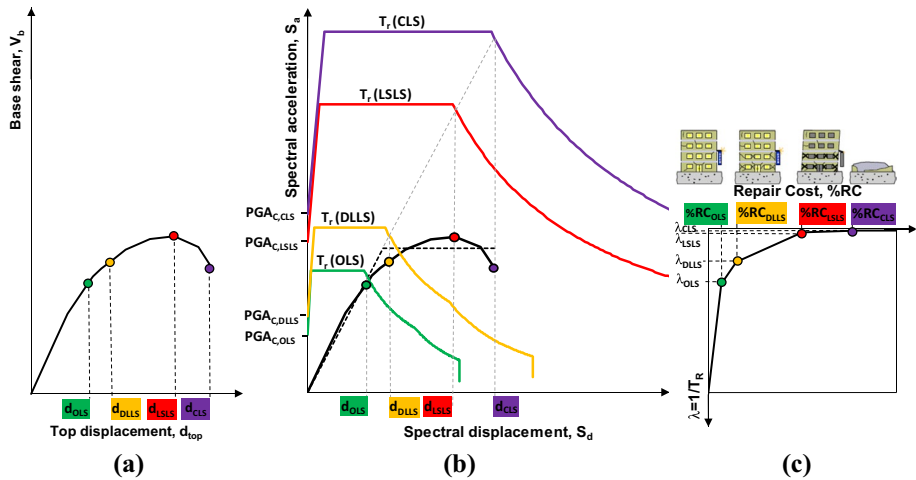
Once that the SI-LS has been assessed, the constructions can be classified according to the seven classes,  $Class_{SI-LS}$ , summarized in Table 1.

The second index, EAL or PAM in Italian, estimates the overall behaviour of the construction in terms of expected economic annual losses. To determine EAL, it is necessary to compute the performance of the structure for different earthquake intensities/return periods  $T_r$ , in the reference life of the construction (expressed in terms of the mean annual frequency of exceedance,  $\lambda = 1/T_r$ ) and the relevant repair costs, %RC. By connecting the points ( $\lambda$ , %RC) representative of each limit state, the EAL curve is obtained. The area above the curve represents the EAL.

Figure 1 schematically shows the steps to convert a classic force–displacement capacity curve (Fig. 1a), to a  $\lambda$ –%RC relationship (Fig. 1c), through the assessment of the structural performance at SLS and ULS in terms of  $PGA_C$  (Fig. 1b).

**Table 1** Building Life-Safety Index classes, SI-LS

Life-safety index (SI-LS)	Class $_{SI-LS}$
$100\% \geq SI-LS$	A <sup>+</sup> <sub>SI-LS</sub>
$80\% \leq SI-LS < 100\%$	A <sub>SI-LS</sub>
$60\% \leq SI-LS < 80\%$	B <sub>SI-LS</sub>
$45\% \leq SI-LS < 60\%$	C <sub>SI-LS</sub>
$30\% \leq SI-LS < 45\%$	D <sub>SI-LS</sub>
$15\% \leq SI-LS < 30\%$	E <sub>SI-LS</sub>
$SI-LS \leq 15\%$	F <sub>SI-LS</sub>



**Fig. 1** Non-linear static analysis (pushover curve) and limit states: Force–displacement scheme (a); Capacity vs. demand in the ADRS plane (b); and change of the variables to those used in the guidelines (c)

For instance, by using the non-linear static analysis to assess the building performance (Fig. 1a depicts a typical pushover curve), the spectral acceleration,  $S_{a2}$  and the corresponding PGA related to the capacity at OLS, DLLS, LSLs, and CLS can be computed by using the capacity spectrum method (ATC 1996), the N2 method (Fajfar 2000) or the Coefficient Method (FEMA 356 2000). This process is depicted in Fig. 1b in the Acceleration Displacement Response Spectrum (ADRS) plane with reference to the N2 method in the case of  $T > T_c$ . The PGA associated to the building capacity at different limit states can be evaluated by scaling the response spectrum until the displacement demand matches the capacity at the reference limit state.

Each  $PGA_c$  corresponds to a given return period and a relevant mean annual frequency of exceedance,  $\lambda$ . Given the  $PGA_c$ , the return period of the relevant seismic event can be computed using the seismic hazard maps provided by the reference building code. However, the Italy hazard maps developed by the National Institute of Geophysics and Volcanology (INGV) and the Department of Civil Protection (DPC) refer to nine return periods (30, 50, 72, 101, 140, 201, 475, 975, 2475 years). Thus for the intermediate return periods (i.e. for  $PGA_c$  that does not match exactly with those nine return periods), the Guidelines (Ministry Decree n.58 28/02/2017) suggests an approximate formulation, applicable on the entire national territory:

$$T_{rC} = T_{rD} (PGA_c / PGA_D)^\eta \quad \text{with } \eta = 1/0.41 \tag{1}$$

This formulation allows calculating the return period corresponding to the building capacity,  $PGA_c$ , once the demand return period,  $T_{rD}$ , and the demand  $PGA_D$  for a given Limit State are known.

In order to have more refined estimations of the return period, the parameter,  $\eta$ , can be selected as a function of the maximum acceleration on rigid soil,  $a_g$  ( $\eta = 1/0.49$  if  $a_g \geq 0.25$  g;  $\eta = 1/0.43$  if  $0.25$  g  $\geq a_g \geq 0.15$  g;  $\eta = 1/0.356$  if  $0.15$  g  $\geq a_g \geq 0.05$  g;  $\eta = 1/0.34$  if  $0.05$  g  $\geq a_g$ ). Note that, for a reference existing construction, the  $PGA_c$  on the rigid soil leading to the fulfillment of each of the Limit States can be computed by the structural



engineer by means of preferred analysis option between the code compliant approaches (linear/non-linear; static/dynamic).

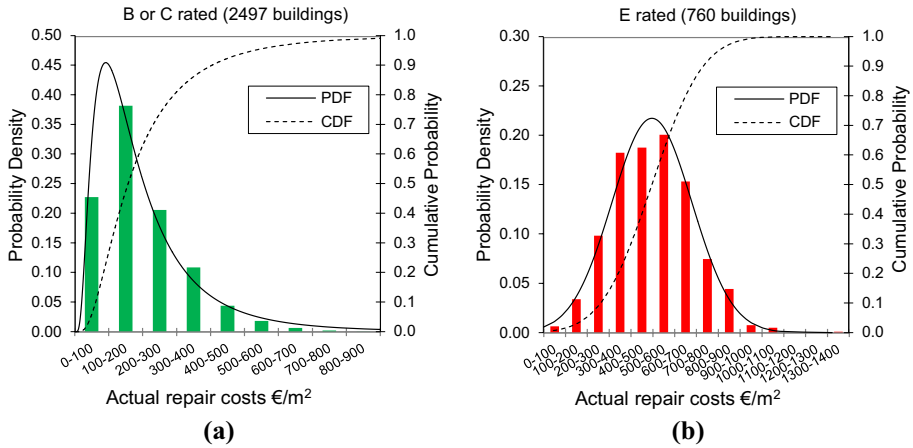
Once the building performance associated to specific limit states is known in terms of  $\lambda = 1/T_r$ , ranging from 0 to 1, or 0 to 100% (vertical axis of Fig. 1c), a reliable correspondence between each  $\lambda$  and the relevant %RC, including the repair/reconstruction cost of structural and non-structural components, is needed. The  $\lambda$ -%RC curve is defined by linearly connecting the performance points ( $\lambda$ ; %RC) and the EAL can be computed as the area under the EAL curve. In order to avoid time consuming and complex calculations to estimate the %RC at different limit states, the “*Guidelines for the seismic risk classification of the constructions*” (Ministry Decree n.58 28/02/2017) provides conventional repair costs in terms of %RC for each limit state, properly calibrated to include all the repair actions associated to a specific damage level.

### 3.1 Calibration of the %RC

Reliable loss assessment of existing buildings under seismic events is a challenging task and it commonly requires complex probabilistic analysis not suitable for the application in the common design practice. The difficulties increase exponentially moving from the building level to regional/national scale. In order to simplify the monetary loss assessment in the conventional approach, research studies based on macroseismic analysis were performed (Braga and Picchi 2017). Given the earthquake intensity, this study combines the probability of achieving an earthquake damage defined by using the European Macroseismic Scale (Grünthal 1998) and the repair costs. The repair costs of structural and non-structural components provided by the FEMA E-74 (2004) are used in the calibration, while the actual repair costs monitored during the L’Aquila reconstruction process reported in the “White book” (Dolce and Manfredi, 2015) are used in the validation. They resulted in a rough estimation of the repair costs depending on the intensity of the earthquake event (namely Seismic Zone). In particular, at the DLLS in Seismic Zone 1 ( $PGA \geq 0.25$  g in Italy) the estimated loss in terms of %RC ranged between 13.6% and 15.9% of the %RC. Conversely, at the LSLs the estimated %RC ranged between 45.8% and 51.5% of the %RC.

In order to validate such predictions, the %RC were compared to the actual repair costs monitored in the reconstruction process of private residential buildings outside the historical center damaged by L’Aquila earthquake (2009) (ReLUIS “White book” on the reconstruction process in L’Aquila edited by Dolce and Manfredi 2015, Di Ludovico et al. 2017a, b). It is worth mentioning that these costs strictly depend on the earthquake damage experienced by buildings rather than on the intensity of the earthquake event. This permits to extend, with reasonable accuracy, the actual repair costs to the entire Italian territory, if normalized by the building reconstruction cost in L’Aquila. Results similar to those outlined by the macro-seismic assessment were found. In particular, in the aftermath of the L’Aquila earthquake, the overall building damage to structural and non-structural components was classified by in situ inspections using the AeDES form (Baggio et al. 2007). In the following, the practitioners engaged by owners defined the repair actions considering the earthquake damage and the relevant costs according to regional price lists. Component-by-component, the designer selected the repair actions or the component replacement. The estimates (and actual repair costs) were reviewed, amended and then approved by a technical and financial committee established by the Italian government to oversee the funding requests (Di Ludovico et al. 2017a, b). It resulted that the repair cost related to DLLS can be assumed equal to the repair cost related to 2497 buildings, 1598 reinforced concrete





**Fig. 2** Frequency distribution of the actual repair costs for building damaged by the L'Aquila 2009 earthquake: B or C rated buildings (a); E rated buildings (b)

**Table 2** Actual repair cost of private residential buildings monitored during the L'Aquila reconstruction process

Rating	N. buildings (–)	Mean (€/m <sup>2</sup> )	CoV (%)	Median (€/m <sup>2</sup> )	16th percent. (€/m <sup>2</sup> )	84th percent. (€/m <sup>2</sup> )
B or C	2497	195.7	64	165.3	81.7	314.7
E	760	497.9	37	496.2	309.9	684.8

and 899 masonry buildings, which experienced slight damage. They were classified as B or C (limited or no structural damage and slight-to-severe non-structural damage, namely B/C buildings in the following) in the aftermath of the earthquake according to the AeDES form.

The distribution of the actual repair costs of the B or C rated buildings is reported in Fig. 2a, while Table 2 reports the relevant statistics. The Probability Density Function (PDF) and the Cumulative Distribution Function (CDF) are also reported. A log-normal function well fits the frequency distribution of actual repair costs for B or C rated buildings (see Fig. 2a), while the actual repair costs of E rated buildings can be described by using a normal distribution (see Fig. 2b).

The mean repair cost of B/C rated buildings resulted about 196 €/m<sup>2</sup>. Considering that the mean reconstruction cost of buildings in L'Aquila was about 1200 €/m<sup>2</sup>, the repair cost at the DLLS, expressed as %RC, is about 16%. On the other hand, at LSLs, the analysis involved 760 buildings, 447 reinforced concrete and 313 masonry buildings, classified with E rating in the AeDES forms (i.e. buildings with severe structural and non-structural damage). The mean repair cost of these buildings resulted 498 €/m<sup>2</sup> corresponding to %RC about the 42%. Considering that the buildings rated E also included severely damaged buildings that did not completely achieved the performances required at the LSLs, is reasonable to assume %RC = 50% at the attainment of the LSLs.

Based on such analysis and taking into account both studies based on macro-seismic analyses as well as post-earthquake observational data, the %RC associated to DLLS and LSLs were set equal to %RC = 15% and %RC = 50%, respectively.

Large dispersion characterizes the actual repair costs used to calibrate the %RC. Indeed, Table 2 reports a coefficient of variation (CoV) about 64% and 37%, respectively for B or C and E rated buildings. This reflects the building-to-building variability of the earthquake damage and, in turn, of the actual repair costs. Detailed description and statistical analyses of the earthquake damage exploited by RC and masonry buildings, classified by using the AeDES form in the aftermath of the L’Aquila (2009) earthquake, are reported in De Martino et al. (2017) and Del Gaudio et al. (2017). These studies showed that buildings classified with the same rate could have experienced different damage in terms of the specific components (i.e. vertical structure, floors, stairs, roof, infill and partitions), damage severity (i.e. null, slight, medium-severe, very heavy) and damage extent (i.e. < 1/3, 1/3–2/3, > 2/3). In particular, the damage factor, DF, which accounts for the damage extent and the weight of the damage on the different components (De Martino et al. 2017), shows approximately the same variability of the repair cost. A direct correlation between observed earthquake damage and the actual repair costs is also proposed in De Martino et al. (2017). These uncertainties may affect the estimation of the EAL and proper statistical analyses are needed to quantify their influence on the  $EAL_{class}$ . Further research studies are needed to correlate the observed earthquake damage with code compliant LS in order to refine the estimation of the actual repair costs and of the EAL.

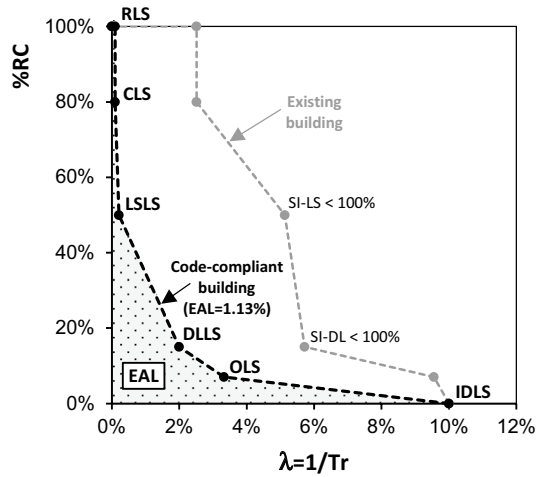
The repair costs (%RC) associated to the Initial Damage Limit State (IDLs) and total loss or “Reconstruction” Limit States (RLS), conventionally related to a fixed  $\lambda = 10\%$  and  $\lambda = \lambda_{CLS}$ , were assumed equal to the 0 and 100%, respectively. Moreover, the %RC for OLS and CLS were set %RC = 7% and %RC = 80%. The former was conventionally set about the half of the %RC related to DLLS. Note that it does not significantly affects the EAL estimate. The %RC at the CLS was set 80% because, even if the collapse limit state implies that the structure is no more usable, the conventional attainment of collapse limit state based on theoretical calculations may not correspond to the actual complete collapse of the building.

The repair costs at different limit states expressed as %RC are reported in Table 3. The table also includes the return period,  $T_r$ , and the frequency,  $\lambda$ , for a residential building, having 50 years reference life and seismic performances compliant to current seismic code provisions (i.e. the capacity at each limit state exactly matches the relevant demand). Figure 3 shows the EAL curve for such building (the dashed line connecting the performance points,  $\lambda$ -%RC, related to each limit state). Note that the trend of the loss curve from %RC = 80% to %RC = 100% is vertical (same frequency of exceedance,  $\lambda_{RLS} = \lambda_{CLS}$ ) and once the RLS is achieved, the %RC = 100% is constant for all the lower frequencies,  $\lambda$ . The

**Table 3** Building repair cost (%RC) and mean annual frequency of exceedance ( $\lambda$ ) associated to each LS

Limit State	%RC	$T_r$ (years)	$\lambda = 1/T_r$ (%)
RLS	100	$\infty$	0.00
CLS	80	975	0.10
LSLS	50	475	0.21
DLLS	15	50	2.00
OLS	7	30	3.33
IDLs	0	10	10.00

**Fig. 3**  $\lambda$ -%RC relationship and EAL



area under the curve represents the EAL; Fig. 3 shows a possible  $\lambda$ -%RC relationship (gray dashed line) for an existing building with seismic performance not compliant with current code provisions having the SI-LS < 100% and the safety index at the DLLS SI-DL < 100%.

### 3.2 Assessment of the expected annual losses (EAL)

The assessment of EAL, resulting in the calculation of the area below the curve of losses (see Fig. 3), is crucial to classify the seismic risk of construction with the conventional approach. This area represents the possible losses related to earthquake events with different intensity, different return period and, thus, different mean annual frequency. It corresponds to the area of a rectangle having height equal to the mean EAL and base equal to  $\lambda = 100\%$ . Considering all the possible events that may occur in the range of  $\lambda$  between 0 and 100%, the area corresponds to the expected loss distributed on the entire reference life of the structure, namely the mean expected losses.

The area under the  $\lambda$ -%RC relationship can be easily calculated as follows:

$$EAL = \sum_{i=2}^5 [\lambda(LS_{i-1}) - \lambda(LS_i)] * [\%RC(LS_i) + \%RC(LS_{i-1})] / 2 + \lambda(CLS) * \%RC(RLS) \tag{2}$$

where the “i” index represents the generic Limit State (i=5 for CLS and i=1 for IDLS).

In order to define the  $\lambda$ -%RC relationship and the relevant EAL of a building, the practitioner should calculate the building capacity expressed in terms of the annual frequency at the CLS, LSLS, DLLS, and OLS. In order to simplify this procedure, the “Guidelines for the seismic risk classification of the constructions” (Ministry Decree n.58 28/02/2017) suggests easy formulations to determine the capacity of the structure at OLS and CLS once those at DLLS and LSLS have been computed. In particular, the mean annual frequency of exceedance at OLS and CLS can be computed according to the following simplified formulations:

$$\lambda_{OLS} = 1.67\lambda_{DLLS} \quad \lambda_{CLS} = 0.49\lambda_{LSLS} \tag{3}$$

The coefficient 1.67 and 0.49 were calculated as the ratio between design return periods (50 years reference life) at DLLS and OLS,  $T_r(\text{DLLS})/T_r(\text{OLS}) = 50/30 = 1.67$ , and at LSLs and CLS,  $T_r(\text{LSLS})/T_r(\text{CLS}) = 475/975 = 0.49$ , respectively, in accordance with the NTC 2018 (MIT 2018). The use of these simplified formulations, derived considering a code compliant buildings designed to perfectly match the requirements at different limit states, may lead to clear approximations for the case of existing buildings. By using the Eq. (3), Eq. (2) becomes  $EAL = 0.4965\lambda_{\text{LSLS}} + 0.34,025\lambda_{\text{DLLS}} + 0.0035$ . The latter can only be used if  $\lambda_{\text{OLS}} = 1.67 \lambda_{\text{DLLS}} \leq 10\%$ .

Accordingly, the designer may evaluate only the building performance at the DLLS and LSLs. Conventionally, the building performance at the DLLS can be assessed by evaluating the maximum interstorey drift (CEN 2005, MI 2008). For instance, the upper bound limit to the interstorey drift for DLLS of stiff infills in RC structures suggested in current standards (CEN 2004, Circolare n.617 2009) is about 0.5%. The revised draft of the Italian Building Code (MIT 2018), establishes an additional limit about the 0.75% in case that the infill is properly protected to support in-plane and out-of-plane displacement. This approach is extremely functional but the use of a unique parameter, the interstorey drift, to assess the performance of all the non-structural components, including ceilings or the hydraulic and electrical systems, may result not always accurate.

It is worth noting that the theoretic minimum EAL, 0%, corresponds to a building that is not susceptible to any damage at the OLS and the DLLS. This could be the case of a perfectly isolated structure. The theoretical upper bound of EAL is about 10%, which corresponds to a structure that collapses under a very low intensity earthquake (in this case the one corresponding to the IDLS, having a return period  $T_r = 10$  years and  $\lambda = 10\%$ ). Conversely, to be compliant with the criteria suggested for the construction of the EAL curve, the minimum EAL is 0.35% and the maximum is 8.215%. Indeed, Fig. 4a shows that the minimum area above the curve is the area of the triangle connecting the origin (0%; 0%RC), the IDLS ( $\lambda = 10\%$ ; 0%RC) and the OLS (0%; 7%RC), assuming that the reference structure achieves the OLS for the strongest earthquake having an infinite return period. By contrast, the maximum area below the EAL curve is attained for a structure that achieves the LSLs for a very low intensity earthquake (i.e.  $\lambda = 10\%$ ), see Fig. 4b. The area of the trapezoid connecting LSLs, CLS and RLS, has to be subtracted to the area of the

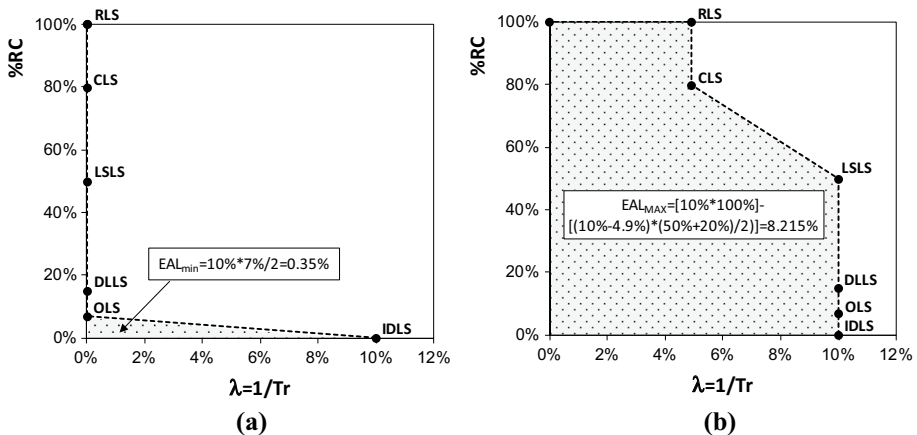


Fig. 4 Theoretical minimum EAL (a); and maximum EAL (b)

**Table 4** Building EAL classes

Expected annual losses (EAL)	CLASS <sub>EAL</sub>
$EAL \leq 0.50\%$	A <sup>+</sup> <sub>EAL</sub>
$0.50\% < EAL \leq 1.0\%$	A <sub>EAL</sub>
$1.0\% < EAL \leq 1.5\%$	B <sub>EAL</sub>
$1.5\% < EAL \leq 2.5\%$	C <sub>EAL</sub>
$2.5\% < EAL \leq 3.5\%$	D <sub>EAL</sub>
$3.5\% < EAL \leq 4.5\%$	E <sub>EAL</sub>
$4.5\% < EAL \leq 7.5\%$	F <sub>EAL</sub>
$7.5\% \leq EAL$	G <sub>EAL</sub>

rectangle defined with sides  $\lambda = 10\%$  and  $\%RC = 100\%$ , respectively. This is because the guidelines assume that the CLS is achieved with a mean annual frequency,  $\lambda$ , lower than LSLS,  $\lambda_{CLS} = 0.49\lambda_{LSLS}$ .

The building performance in terms of EAL can be determined using eight EAL classes reported in Table 4.

The percentage variation of EAL is uniform for groups of similar classes. Indeed, one class upgrade corresponds to a reduction of the EAL of about 1% for the intermediate classes C<sub>PAM</sub>, D<sub>PAM</sub> and E<sub>PAM</sub> and 0.5% for classes A<sup>+</sup><sub>PAM</sub>, A<sub>PAM</sub> and B<sub>PAM</sub>. This to attain a uniform reduction of the seismic risk, which does not depend on building site and on seismic hazard. For instance, with reference to a residential building (50 years reference life) designed according to recent seismic codes and perfectly satisfying all the Limit States, the EAL curve can be constructed using the return period, T<sub>r</sub>, and the mean annual frequency,  $\lambda$ , reported in Table 3. The area under the EAL  $\lambda$ -%RC relationship is about 1.13% corresponding to B<sub>EAL</sub> class (see Fig. 3). In particular, the weighted contribution of the LSLS, DLLS and OLS to the total EAL of a code-compliant building, is about the 9%, 60% and 31%, respectively. In turn, to achieve an EAL class upgrade from B<sub>EAL</sub> to A<sub>EAL</sub> or A<sup>+</sup><sub>EAL</sub>, the designer has to increase the performances at the DLLS. It is worth mentioning that new buildings compliant with modern seismic code provisions certainly belong to class A<sub>EAL</sub> or A<sup>+</sup><sub>EAL</sub>. This is because the DLLS (conventionally assessed by comparing the maximum interstorey drift of the bare frame with the code limitation of the 0.5%) is commonly satisfied with significant safety margin. Indeed, by assuming an elastic structural behaviour, the interstorey drift is a linear function of the PGA; thus, an interstorey drift slightly higher than the 0.5% (specifically 0.55%) is sufficient to achieve the A<sub>EAL</sub> class.

For existing buildings, the performances at the LS may be significantly lower than current code compliant buildings (see Fig. 3). This implies that the  $\lambda$ -%RC relationship moves to the right side and the relevant EAL increases. Indeed, existing buildings designed for gravity loads only or according to obsolete seismic codes may suffer a lack of lateral stiffness leading to poor seismic performances at the DLLS or premature brittle failure and insufficient dissipation capacity leading to poor seismic performances at the LSLS.

According to theoretical calculations the attainment of DLLS may occur for a mean annual frequency lower than that related to LSLS (i.e.  $\lambda_{DLLS} < \lambda_{LSLS}$ ). However, it is arguable that a building achieving the LSLS (namely significant damage) did not achieved the DLLS, commonly associated to light damage. For this reason, in such cases the guidelines prescribes  $\lambda_{DLLS} = \lambda_{LSLS}$ , see Fig. 4b. A lower bound limit to the capacity at different LS has been set to  $\lambda = 10\%$  (i.e. return period T<sub>r</sub> = 10 years).

This is because the lowest  $T_r$  at the IDLS is conventionally set equal to 10 years and it is assumed that a building achieving the DLLS, LSLS, CLS (namely significant damage) also achieved the IDLS. According to such limitations, if  $\lambda_{LSLS} = 10\%$ , the corresponding structural performance at DLLS and OLS are  $\lambda_{DLLS} = \lambda_{OLS} = 10\%$ .

The proposed procedure relies on the assumption that the repair costs at the DLLS and LSLS are known and equal to 15% and 50%, respectively. However, the frequency distributions depicted in Fig. 2 outline that the actual repair costs may significantly differ from the mean of the distributions, especially for DLLS. To investigate on the influence of the variability of the actual repair costs on the EAL and the relevant seismic risk class, a statistical analysis was carried out for case study buildings (represented by specified values of the SI-LS and SI-DL). In particular, a Montecarlo analysis considering two independent distributions of the repair costs at DLLS (Fig. 2a) and at LSLS (Fig. 2b) is used. The procedure consists of a repeated random sampling simultaneously from the two distributions of the repair costs at the DLLS and LSLS. Then for each of the 100.000 sets of the repair costs ( $\%RC_{DLLS}$ ;  $\%RC_{LSLS}$ ), the EAL curve can be computed along with the relevant  $EAL_{class}$ . The results are evaluated in terms of the probability of obtaining a class different from the one computed by using the mean repair costs.

The results of this study outlines that for a code-compliant building (SI-LS = 100% and SI-DL = 100%, belonging to B class) the probability of obtaining a class different from B is about 72%: in most of the cases (63%) the building fall into class A; while in the remaining 9% the class is C. Thus, the error is limited to one class and mostly lead to conservative predictions. Moreover, with reference to existing buildings typical of the Mediterranean area designed to withstand low-to-moderate seismic actions but exhibiting lack of proper seismic detailing (SI-LS ranging between 10% to 30% and SI-DL = 100%) the probability to obtain a seismic risk class different from G or F is negligible. This is because the influence of the variability of the %RC on the EAL curve typical of an existing building (see Fig. 2b) is very low since the DLLS and LSLS are aligned along the same vertical. Thus, the repair costs variability slightly affects the definition of the seismic risk class of existing buildings confirming the robustness of the procedure.

The proposed procedure to compute the EAL relies on the assumption that repair costs (%RC) at the different limit states are constant for all types of buildings without distinction at component level. This allow to simplify the procedure and to have a design-oriented approach suitable for common practice applications. In fact, an effective strategy for seismic risk mitigation at national scale should aim at reducing the seismic vulnerability of the highest number of buildings by using reliable and simple procedures.

More accurate estimations of the EAL can be obtained by using rigorous loss-assessment procedures such as the FEMA P-58 methodology (ATC 58 2012). It consists of the complete development of the PBEE framework (Cornell and Krawinkler 2000; Deierlein et al. 2003; Porter 2003) in order to estimate the engineering demand parameter and the attained damage states/costs by a refined quantitative modelling of the building. The predicted repair cost at building level can be obtained by summing the repair cost of all structural and non-structural components. However, since significant uncertainties characterize the seismic input, the building performance, the component performance and the relevant repair costs, the procedure to derive repair costs should be implemented in a probabilistic framework. The component-based approach makes the FEMA methodology flexible and open to possible continuous improvements. Recent research studies (Cardone and Perrone 2017; O'Reilly and Sullivan 2018; Del Vecchio et al. 2018b) demonstrated that it is suitable for application to the building stock typical of the Mediterranean area. However proper fragility and consequence functions should be employed to account for

the major differences between US and Italian standard components. A detailed discussion on this aspect is reported in Del Vecchio et al. (2018b). This study demonstrates that a further research effort is needed to achieve accurate loss assessment estimations by using the FEMA P-58 methodology since the fragility functions, reflecting the performance at component level, and the consequence functions, including the repair actions, repair time and repair costs, significantly differ from those proposed in the original database.

#### 4 The “simplified” approach

The guidelines for seismic risk classification of constructions (Ministry Decree n.58 28/02/2017) suggests also a simplified approach to compute the seismic risk class of constructions and identify the strengthening intervention allowing for the seismic performance upgrade. As demonstrated by Lagomarsino and Giovinazzi (2006) and discussed in Giovinazzi and Pampanin (2017), this approach could be a viable solution to estimate the seismic risk class of constructions where a limited knowledge on the building geometry and structural details is available. It was specifically developed for unreinforced masonry buildings where in certain cases (e.g. urban aggregates) a reliable characterization of the seismic performances is arguable. This approach is based on the European Macroseismic Scale (Grünthal 1998) defining the seismic risk class based on the type of masonry, stiffness of the slabs and the potential structural weaknesses (Braga and Picchi 2017). In particular, the vulnerability class (from  $V_1$  to  $V_6$ ) and the dispersion of the class estimation can be identified based on the type of masonry and the stiffness of the slab. The presence of dangerous structural weaknesses, such as low quality mortar, poor construction quality, existing damage or degradation, lack of connection between the slab and the vertical walls or between orthogonal walls, possible out-of-plane mechanisms and big openings results in a high vulnerability class (from  $V_i$  to  $V_{i+1}$ ). The seismic risk class is defined comparing the vulnerability class and the seismic hazard zone. To identify the vulnerability class and the seismic risk class simple tables are provided in the guidelines (Ministry Decree n.58 28/02/2017). The guidelines also suggest the strengthening interventions to upgrade the seismic risk class considering the original vulnerability class and the main structural weaknesses. When the simplified approach is used to classify the seismic risk class and to define the seismic strengthening interventions, the upgrade of only one seismic risk class is allowed. This limitation accounts for the high uncertainties in the use of a simplified approach and the low confidence in the estimation of the effectiveness of the strengthening interventions. It is worth mentioning that, according to the 2017 Budget Law (IG 2017), the upgrade of one seismic risk class results in a maximum tax deduction of 70% that can be raised up to 75% for interventions on shared parts of buildings.

The simplified approach was also extended to industrial building and residential reinforced concrete buildings. In these cases, even though the guidelines do not provide a methodology to classify the seismic risk class, they allow for the upgrade of one seismic risk class when local strengthening interventions are adopted. The local strengthening interventions suggested for industrial buildings consist in the improvement of the connection between structural members and between the structure and the exterior cladding panels. Furthermore, the stability of interior non-structural components whose collapse may influence the failure of structural members should be improved. In reinforced concrete residential buildings, the local strengthening intervention consists of the strengthening of exterior partially confined beam-column joints and the installation of a connection system between the perimetral infill walls and the



structural system to avoid their out-of-plane mechanisms (Fracadore et al. 2015). Furthermore, the degraded or damaged parts of the building should be repaired.

### 5 Operational procedure for the conventional approach and examples

The procedure for the seismic risk classification of construction according to the conventional approach is summarized in the flow-chart depicted in Fig. 5. Once that the construction and the seismic hazard are defined, the seismic assessment procedure permits to evaluate the seismic performance at the reference limit states expressed by means of the safety index (SI). The SI at the life safety limit state (SI-LS) is used to define the  $Class_{SI-LS}$ . To define the EAL curve, the user has to characterize the building performance at the different limit states (OLS, DLLS, LSLs, CLS) in terms of the frequency,  $\lambda = 1/T_r$ . The return period,  $T_r$ , corresponding to building performance at the different limit states can be computed by using Eq. (1). Alternatively, the calculation of the frequency,  $\lambda$ , can be limited to the LSLs and DLLS deriving the frequency at the CLS and OLS by using Eqs. (3). The compatibility of the calculated frequency of exceedance,  $\lambda$ , at the different limit states should be checked considering the constrains  $\lambda_{i+1} \leq \lambda_i$  and  $\lambda_i \leq 10\%$ . Once that the building performances are known, the EAL curve can be easily defined using the repair costs (%RC) provided in Table 3. The area under the EAL curve, computed by using Eq. (2), is  $EAL$ , which allows the  $Class_{EAL}$  to be defined (see Table 4). The seismic risk class of a construction is defined as the minimum between  $Class_{SI-LS}$  and  $Class_{EAL}$ . The stakeholder may decide to upgrade the seismic risk class of the reference building by using seismic strengthening interventions. In this case, the interventions should be designed to remove the main structural weaknesses outlined by the seismic performance assessment at different limit states.

The conventional approach of the guidelines (Ministry Decree n.58 28/02/2017) suggests to assess the building performance of the strengthened configuration (*post-operam*)

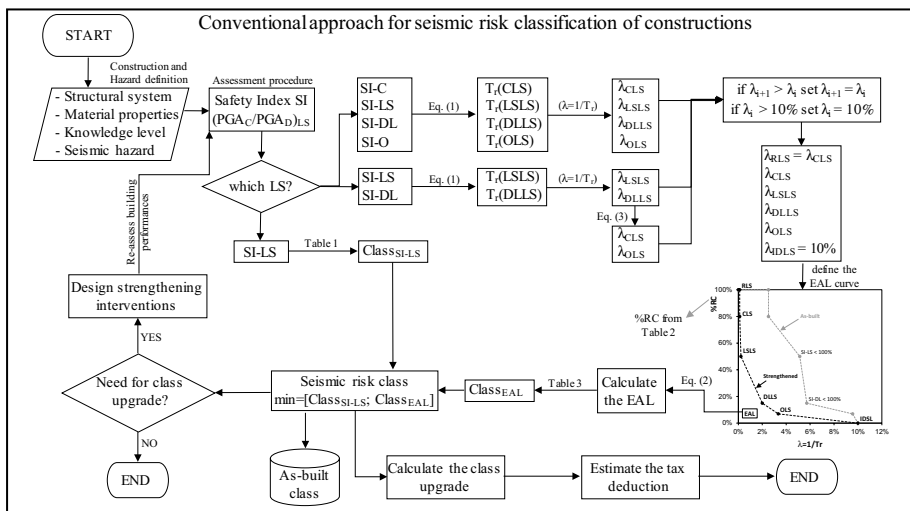


Fig. 5 Flow-chart of the procedure for seismic risk classification of the construction

consistently with the procedure adopted for the original configuration (*ante-operam*). Thus, the same process described above should be repeated for the strengthened building resulting in a new seismic risk class. The seismic risk class upgrade can be evaluated comparing the class of the building in the *ante-operam* and *post-operam* configuration. The latter establishes the tax deduction for the strengthening interventions depending if an increase of one or more classes has been attained.

In order to validate the proposed procedure three case study residential buildings, typical of the Mediterranean area, damaged by the L'Aquila earthquake and then repaired and strengthened (Di Ludovico et al. 2017a, b) are considered. The buildings experienced severe damage to structural and non-structural components (E-rated according to the AeDES form, Baggio et al. 2007). The assessment of the seismic capacity and the design of repair and strengthening interventions were carried out by the practitioners engaged by the owner. It is worth noticing that these buildings were unusable at that time (E-rated), thus the selection and design of the retrofit solution was made considering the possibility to operate on the full building (interior and exterior). The buildings data are summarized in Table 5. The buildings front view and the layout of strengthening interventions are reported in Fig. 6 for Building 1 and 2 and in Fig. 7 for Building 3.

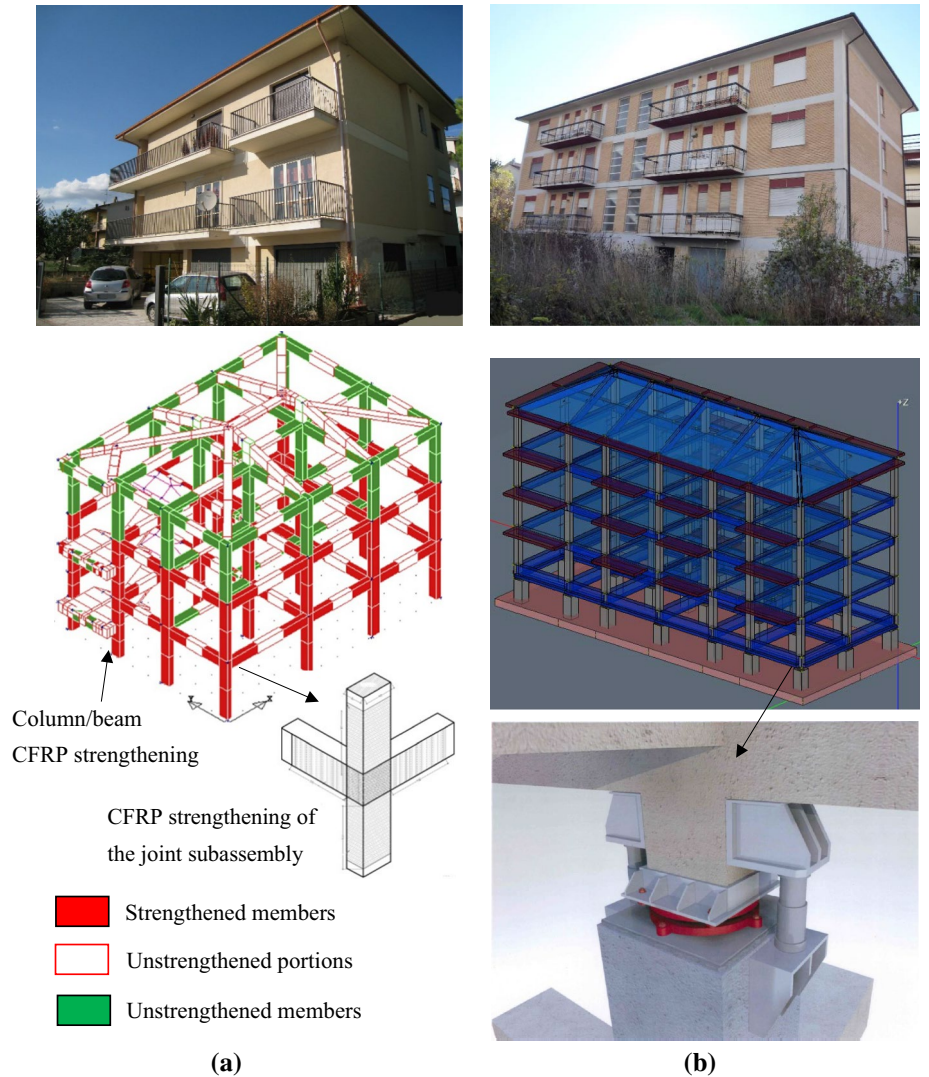
Buildings 1 and 2 rely on reinforced concrete moment resisting frames (RC-MRF). They were built in 1973 and in the range 1961–1972, respectively. Thus, they have reinforcement details not compliant with current seismic code provisions. The lack of transverse reinforcements commonly results in the premature shear failure of columns or beam-column joints, as commonly found in the aftermath of major seismic events. Non-linear static analyses were conducted to assess the building capacity in terms of push-over curves. Lumped plasticity models assuming the concentration of nonlinearities at the member ends were adopted. The plastic hinge length and moment–curvature relationships were defined according to the Italian building code (MI 2008 and Circolare 617, 2009). Pushover analyses in the longitudinal and transverse directions were carried out by subjecting the structure to a monotonically increasing pattern of lateral forces proportional to the fundamental mode of vibration and mass distribution. Lateral loads were applied at the centres of floor mass in the model. The structural capacity against brittle failures was checked according to capacity models suggested by the code (variable truss inclination model for the shear strength of beam and columns and principal tensile stress approach for the shear capacity of beam-column joints). In turn, the ductile push-over curve was limited at the first brittle failure. More details on the determination of push-over curves according to 2008 Italian building code are reported in Frascadore et al. (2015). The seismic assessment of the structural systems showed the premature shear failure of beams, beam-column joints and short columns in relationship to the staircase. For both the RC case studies, brittle failures characterized the lateral response at very low intensity of the seismic demand anticipating the activation of ductile failure modes (yielding of perimeter beams).

Building 1 was strengthened by using FRP systems applied on the beams, columns and beam-columns joints of the first two storeys (red tagged members in Fig. 6a). CFRP quadriaxial fabric was used to strengthen the joint panel, while uniaxial CFRP was applied in the complete wrap and U-wrap configuration at the portion end of columns and beams, respectively. More details and the experimental validation of this strengthening configuration can be found in Di Ludovico et al. (2018a, b), DPC-ReLUIS (2009) and Del Vecchio et al. (2018c). By contrast, Building 2 was retrofitted by using a base isolation system consisting of Friction Pendulum System (FPS) bearings.

Building 3 is a three storeys unreinforced masonry building. It was originally built before 1919, by using irregular stone masonry with low quality mortar and then it was

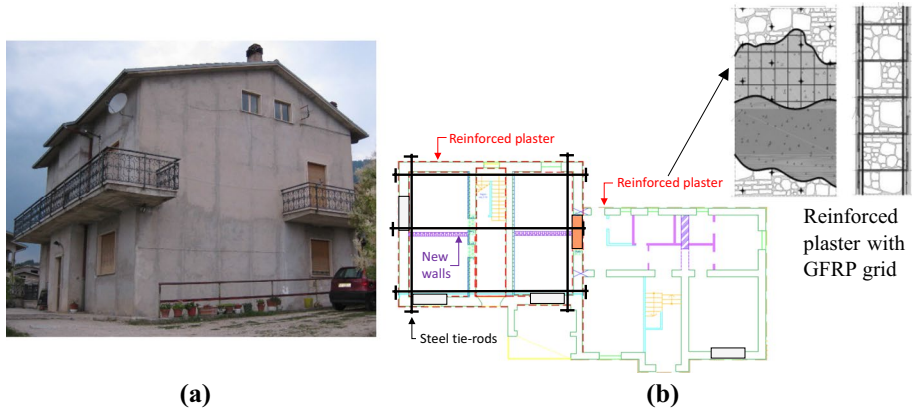
**Table 5** Description of the case study buildings

Building	Structural system	Year of construction	No. of storeys	Footprint [m <sup>2</sup> ]	Residential units	Structural weaknesses	Strengthening system
1	RC-MRF	1973	3	544	2	Lack of transverse reinf Strong beams-weak columns Poor quality of concrete	FRP wrapping
2	RC-MRF	1961–1972	4	1540	7	Lack of transverse reinf Poor quality of concrete	Base isolation
3	Unreinforced Masonry	< 1919	3	859	3	Deficient connections of perimetral walls	Steel tie-rods + reinforced plaster



**Fig. 6** View of the case study RC buildings: Building 1—FRP strengthened (a) and Building 2—base isolated (b)

subjected to renovation and extension. The horizontal slab and the roof, substituted during renovation works, are made of cast in situ reinforced concrete elements. In the old part of the building, the lack of proper connections between the slab and the masonry wall and between orthogonal walls may lead to first mode failure mechanisms of slender masonry walls (out-of-plane mechanism). This building was strengthened by using steel tie-rods at the level of the slabs, reinforcing composite bars grouted into drilled holes to connect the orthogonal masonry walls, reinforced plaster on perimetral walls and the inclusion of new walls in the structural system (see Fig. 7).



**Fig. 7** View of the case study masonry building (Building 3) (a) and adopted strengthening interventions (b)

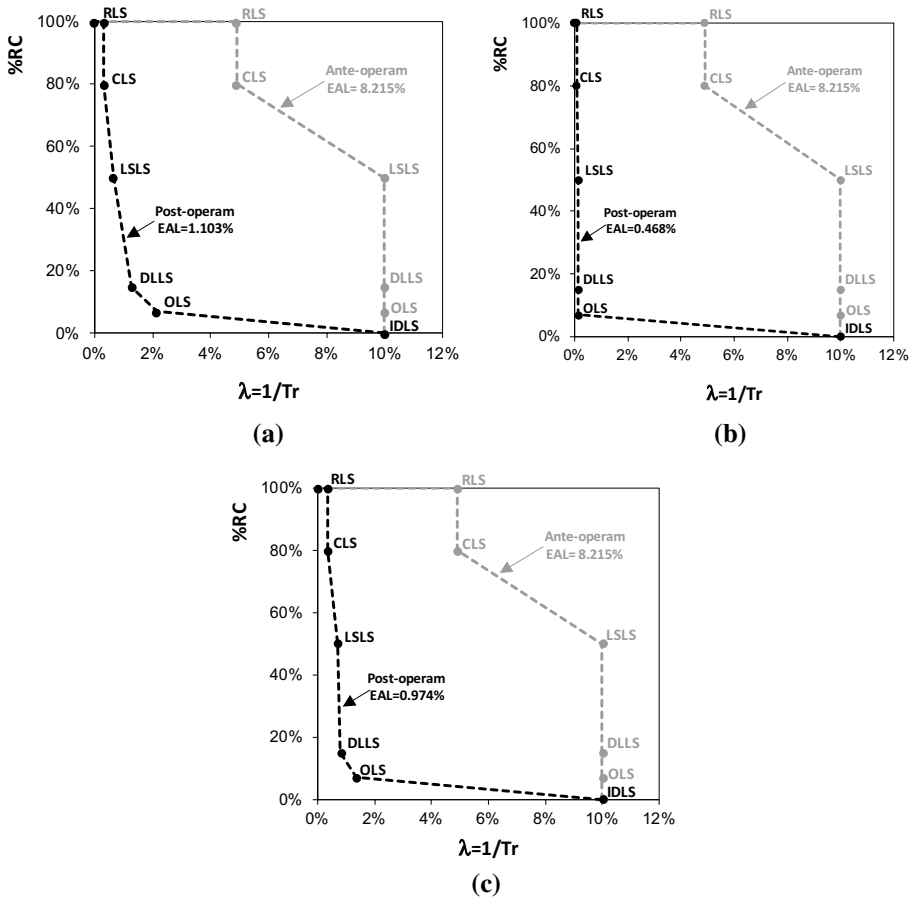
The results of the assessment procedure on the case study buildings carried out according the Italian building code prescriptions (MI 2008) are summarized in Table 6. It includes all parameters needed to define the seismic risk class: the ratio ( $PGA_D/PGA_C$ ), the return period,  $T_r$ , and frequency of exceedance,  $\lambda$ , both at the LS and DL limit states, the EAL, the  $Class_{SI-LS}$  and the  $Class_{EAL}$  both for the *ante-operam* and *post-operam* configurations.

The seismic capacity at the LS limit state of both Building 1 and 2 is limited by the shear failure of the beam-column joints. This significantly limited the lateral capacity of the buildings resulting in a  $PGA_C$  equal to about 0.033 g and 0.053 g, respectively for Building 1 and Building 2. Considering that the  $PGA_D$  at the two reference sites on B-type soil is 0.261 g (MI 2008), the SI-LS is about 12.5% and 20.3% for Building 1 and Building 2, respectively. According to the classification reported in Table 1, they belong to  $F_{SI-LS}$  and  $E_{SI-LS}$  class. The building performance at the damage limit state (conventionally assessed by comparing the maximum interstorey drift of the bare frame with the code limitation of the 0.5%) satisfies the requirement of current seismic code. In particular, the SI-DL is about 120 and 100% for Buildings 1 and 2, respectively. However, due to the constrains  $\lambda_{i+1} \leq \lambda_i$  and  $\lambda_I \leq 10\%$  the corresponding  $\lambda$  is 10%. The safety indices are converted in  $T_r$  and  $\lambda$ . The seismic performance at the OLS and CLS are computed by using Eqs. (3) as function of the  $\lambda_{SI-LS}$  and  $\lambda_{SI-DL}$ , respectively. Existing RC buildings typical of the Mediterranean area may suffer for premature shear failure of the primary structural members (i.e. beam-column joint, columns or beams) as commonly observed in the aftermath of recent seismic events. This may strongly affect the lateral capacity of the buildings resulting in very low SI-LS (Fracadore et al. 2015). According to the procedure for the definition of the EAL curve suggested by the guidelines, the maximum possible value of  $\lambda$  is 10%, which corresponds to  $T_r = 10$  years and  $SI-LS = 20.54\%$  computed by using Eq. (1). Thus,  $\lambda_{SI-LS}$  is set equal to 10% for all the buildings having a  $SI-LS \leq 20.54\%$ . In these cases, the EAL does not depends by the performance of the building at the DLLS and OLS, since the guidelines assumes that a building that achieved LSLs (namely significant damage) has also achieved the DLLS and OLS, commonly associated to light damage. This is guaranteed by the constrain  $\lambda_{i+1} \leq \lambda_i$  and in these examples,  $\lambda_{SI-LS}$ ,  $\lambda_{SI-DL}$  and  $\lambda_{SI-O}$  are fixed at 10%, because the actual  $\lambda$  exceeds the maximum  $\lambda$ . In all these cases, the EAL curve will be equal to those depicted in Fig. 8a,b resulting in the EAL about 8.215% belonging to the

**Table 6** Parameters for seismic risk classification of the case study buildings

Building	Configuration	SI-LS (%)	$T_1$ (SI-LS) (year)	$\lambda_{SI-LS}$ (%)	SI-DL (%)	$T_1$ (SI-DL) (year)	$\lambda_{SI-DL}$ (%)	EAL (%)	Class <sub>SI-LS</sub> (-)	Class <sub>EAL</sub> (-)	Class (-)
1	Ante-operam	12.5	3	10.00*	120	78	10.00*	8.22	F <sub>SI-LS</sub>	G <sub>EAL</sub>	G
	Post-operam	63.5	157	0.64	120	78	1.28	1.10	B <sub>SI-LS</sub>	B <sub>EAL</sub>	B
2	Ante-operam	20.3	10	10.00	100	50	10.00*	8.22	E <sub>SI-LS</sub>	G <sub>EAL</sub>	G
	Post-operam	114.7	664	0.15	>289	>664	0.15*	0.47	A <sub>SI-LS</sub>	A <sub>EAL</sub>	A <sup>+</sup>
3	Ante-operam	8.0	1	10.00*	18	1	10.00*	8.22	F <sub>SI-LS</sub>	G <sub>EAL</sub>	G
	Post-operam	61.0	142	0.70	145	124	0.81	0.97	B <sub>SI-LS</sub>	A <sub>EAL</sub>	B

\* Constrains  $\lambda_{i+1} \leq \lambda_i$  and  $\lambda_i \leq 10\%$



**Fig. 8** EAL curves related to *ante* and *post-operam* configuration for the case studies: reinforced concrete Building 1 (a), reinforced concrete Building 2 (b), unreinforced masonry Building 3 (c)

class  $G_{EAL}$ . The seismic risk class of Building 1 and Building 2 is G. This remarks the need for seismic strengthening interventions to reduce the high seismic risk of this construction.

In order to improve the seismic performance of Building 1 at the LSLS, strengthening interventions by using composite materials (FRP) applied on the joint panels and at the portion ends of columns and beams were adopted (see Fig. 6a). This allows the shear failure of poorly detailed members to be delayed, resulting in a significant improvement of the seismic capacity,  $SI-LS = 63.5\%$  ( $B_{SI-LS}$  class). The strengthening intervention significantly affects the EAL (about 1.1%,  $B_{EAL}$  class) as result of the translation to the right side of the EAL curve (see Fig. 8a). This results in a seismic risk class upgrade of about 5 classes from G to B.

Building 2 was strengthened by using FPS bearings installed at the base of each column and designed according to the Italian Building code (MI 2008) to fulfil the displacement demand at the CLS. This resulted in the elongation of the fundamental period of the structure and, in turn, in a significant reduction of the seismic actions transmitted to the super-structure. According to the calculations performed by the practitioner engaged by



the owner, the seismic capacity of the super-structure at the LSLS is about 115%. At this stage, the maximum interstorey drift is lower than the limit corresponding to the DLLS (for base isolated structures it can be conventionally assumed at  $2/3 \cdot 0.5\%$ ). The use of a base isolation system allows to improve the seismic capacity both at the LSLS resulting in a significant reduction of the EAL to 0.47% belonging to  $A_{EAL}^+$  class (see Fig. 8a). This result in a seismic risk class upgrade of about 7 classes from G to  $A^+$ .

With reference to the masonry case study (Building 3), the seismic capacity was assessed by mean of non-linear analyses on the entire structural system to assess the global response of the building and assuming a perfect connection between the orthogonal walls and the walls and the slabs. Furthermore, first mode mechanisms resulting in the local out-of-plane failure of masonry panels were evaluated by means of linear analyses since they commonly limit the lateral performance of existing masonry buildings (more details can be found in ReLUIIS, DPC, CNR-ITC (2009) at [http://www.reluis.it/doc/emergenza\\_terremoto\\_abruzzo/CINE\\_1.0.4.xls](http://www.reluis.it/doc/emergenza_terremoto_abruzzo/CINE_1.0.4.xls)). The seismic performance assessment of Building 3 outlined that the local out-of-plane failure mechanism limits the SI-LS to the 8% ( $PGA_C$  about 0.022 g). This failure mechanism also characterizes the seismic performance at the DLLS (SI-DL=18%). The corresponding  $T_r$  and  $\lambda$  are reported in Table 6. Also in this case, they are fixed at 10% to account for the limitation on the maximum  $\lambda$  value. The EAL curve is depicted in Fig. 8c resulting in the EAL about 8.215% belonging to the class  $G_{EAL}$ . The seismic risk class of Building 3 is G.

The strengthening interventions designed by the practitioner engaged by the owner consisted in the installation of steel tie-rods and reinforcing composite bars grouted into drilled holes to avoid the out-of-plane failure mechanism of slender walls. Furthermore, to improve the global behaviour of the construction, the outside walls were strengthened by using reinforced plaster and new masonry walls were also included (see Fig. 7). The strengthening interventions resulted in a significant increase of the seismic performance both at the LSLS and DLLS (SI-LS=61%,  $B_{SI-LS}$  class, and SI-DL=145%). This significantly modified the EAL curve (see Fig. 8b) resulting in an EAL of about 0.97% ( $A_{EAL}$  class). This result in a seismic risk class upgrade of about 5 classes from G to B.

The actual repair costs of the selected case studies are 53, 56 and 37% of the reconstruction costs for Building 1, 2 and 3, respectively. The mean repair cost for the three case studies is equal to about the 49% of the reconstruction costs, which is similar to %RC suggested by the guidelines (Ministry Decree n.58 28/02/2017) at the LSLS (50%). Indeed, the selected case study buildings were rated E because of the significant structural and non-structural damage due to the L'Aquila 2009 earthquake. The variability of the actual repair is related to the different damage extent and severity experienced by the different building components, which are difficult to include in a simplified design-oriented methodology for the loss-assessment. This difference between the actual repair percentages given by these case studies and the 50% percentage suggested by the guidelines does not produce any significant change of the  $EAL_{class}$ . This is confirmed also in the case of Building 3 showing an actual repair cost about the 37% of the reconstruction cost which significantly differs from the 50% suggested by the guidelines.

## 6 Costs for strengthening: SI-LS class upgrade

In order to have an insight on the role of the SI-LS index in the seismic risk classification, the SI-LS classes of buildings severely damaged by the L'Aquila earthquake (i.e. E rating according to AeDES form) before the earthquake (*ante-operam* configuration) and after seismic strengthening interventions (*post-operam* configuration) are evaluated in Tables 7 and 8. The data were collected in the framework of a technical support that ReLUIS performed on behalf of Government Institutions responsible for reconstruction of L'Aquila and other municipalities hit by the earthquake of April 6, 2009. The preliminary analyses of these data are reported and discussed in the “White book” (Dolce and Manfredi 2015) and in Di Ludovico et al. 2017a, b. These studies were partially performed in the framework of PE 2014–2016 joint program DPC-ReLUIS. The SI-LS has been computed by practitioners and it refers to undamaged structure (i.e. as before the earthquake) and to the strengthened structure according to design projects (see also Di Ludovico et al. 2017a, b). The practitioners used different structural analyses, static or dynamic, linear or nonlinear compliant with the MI 2008 seismic code. This, along with different retrofit strategies, techniques and materials adopted in the design of the structural retrofit may led to a significant building-to-building variability of the strengthening costs. Further research studies are needed to analyse the influence of these variables on the strengthening costs.

Tables 7 and 8 refer to 527 and 410 reinforced concrete and masonry buildings, respectively. They show that no buildings belonging to classes safer than  $C_{SI-LS}$  (even though L'Aquila was classified as seismic territory since 1915, R.D.L. n. 573, 1915) were found in the original *ante-operam* configuration while the strengthening interventions, allowed to attain in the *post-operam* configuration SI-LS classes in the range  $B_{SI-LS}$ – $A^+_{SI-LS}$  (i.e. safety index  $SI-LS \geq 60\%$ ). Note that, it was mandatory to achieve by strengthening interventions SI-LS values higher than or at least equal to 60% to have access to the public grant in the L'Aquila earthquake reconstruction process. According to the Guidelines classification (Ministry Decree n.58 28/02/2017), achieving the SI-LS equal to or higher than 60% results in  $B_{SI-LS}$  or higher class.

**Table 7** SI-LS class for reinforced concrete buildings damaged by L'Aquila earthquake

		527 reinforced concrete buildings		
		No. of buildings post operam		
		$A^+_{SI-LS}$	$A_{SI-LS}$	$B_{SI-LS}$
No. of buildings	$C_{SI-LS}$	–	2	16
Ante Operam	$D_{SI-LS}$	7	24	267
Class $SI-LS$	$E_{SI-LS}$	8	7	94
	$F_{SI-LS}$	–	8	94

**Table 8** SI-LS class for masonry buildings damaged by L'Aquila earthquake

		410 Masonry buildings		
		No. of buildings post operam		
		$A^+_{SI-LS}$	$A_{SI-LS}$	$B_{SI-LS}$
No. of buildings	$C_{SI-LS}$	–	3	70
Ante Operam	$D_{SI-LS}$	–	1	202
Class $SI-LS$	$E_{SI-LS}$	1	4	53
	$F_{SI-LS}$	–	5	71

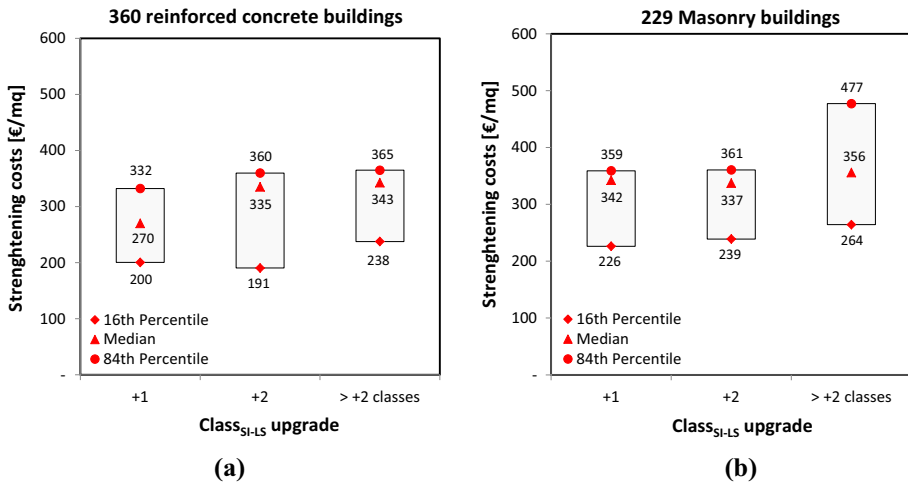


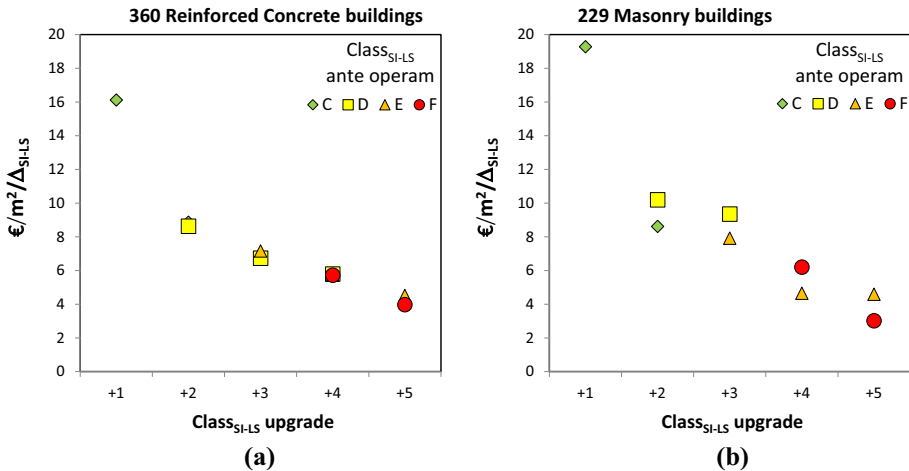
Fig. 9 Unit strengthening costs function of the upgrades of the SI-LS class

Figure 9 summarizes the unit costs (i.e. costs per square metre of the overall building gross surface area, including fees for design and the technical assistance of practitioners, and not including VAT) for strengthening intervention aimed at upgrading the SI-LS class by one, two or more classes. Figure 9 refers to a subset of 360 and 229 reinforced concrete and masonry buildings for which data costs were fully available. The median, 16<sup>th</sup> and 84<sup>th</sup> percentile unit costs are reported. The figure shows an increasing trend of the median unit costs for reinforced concrete buildings and a pseudo-constant trend for masonry ones.

The unit costs to have an upgrade of one SI-LS class result €270/m<sup>2</sup> and €342/m<sup>2</sup> for reinforced concrete and masonry buildings, respectively. Their unit costs range from a minimum of €191/m<sup>2</sup> (16th percentile for a two classes upgrade) to a maximum of €365/m<sup>2</sup> for reinforced concrete (84th percentile for upgrading more than two classes) and from €226/m<sup>2</sup> to €477/m<sup>2</sup> for masonry ones. Note that a significant dispersion affects each category of cost (i.e. costs for a given class upgrade). This is due to the use of different strengthening techniques but also to the different increase of the SI-LS for buildings belonging to the same class upgrade. Indeed, the upgrade of one or more classes may correspond to different safety index increase (see Table 1). Analysing the available data, the unit costs of Fig. 9 refers to mean percentage SI-LS increase of: +21, +37, and +53% for one, two and more than two steps increase in case of reinforced buildings and +18, +33, and +53%, for masonry ones.

Note that the cost for strengthening of masonry buildings to achieve an increase of one seismic risk class is higher than the one for RC buildings. This may be surprising considering that for masonry buildings, mortar injections and connections by steel tie rods are easily applicable and may significantly increase the risk class. However, it should be considered that all the masonry buildings of the dataset with an increase of one seismic risk class started from C<sub>SI-LS</sub> class meaning that mostly they did not suffer for local failures and an extensive in plane strengthening intervention (e.g. reinforced plaster) was needed.

In order to normalize the unit costs, the mean unit cost to increase the SI-LS index by one percentage unit (i.e. the strengthening cost normalized by the % increase of the



**Fig. 10** Average unit cost to increase the SI-LS index by one percentage unit function of the upgrades of the SI-LS class: reinforced concrete buildings (a); masonry buildings (b)

SI-LS) has been computed with reference to a subset of 360 and 229 reinforced concrete and masonry buildings. It has been computed as the ratio between strengthening unit cost, €/m<sup>2</sup>, and  $\Delta_{SI-LS} = (SI-LS)_{post\ operam} - (SI-LS)_{ante\ operam}$ . It resulted equal to €7.8/m<sup>2</sup> and €10.7/m<sup>2</sup> for reinforced concrete and masonry buildings, respectively.

Figure 10 shows the mean unit cost to increase the SI-LS index by one percentage unit, (€/m<sup>2</sup>)/Δ<sub>SI-LS</sub>, for buildings belonging to different *ante operam* Class<sub>SI-LS</sub> (i.e. between C and F) as a function of the Class<sub>SI-LS</sub> upgrade (i.e. between +1 and +5).

Figure 10 clearly shows that the higher the Class<sub>SI-LS</sub> upgrade is, the lower is the mean unit cost to increase the SI-LS index by one percentage unit. This highlights that a rationale investment should aim at increasing as much as possible the safety because the fixed costs due to the installation of a construction site significantly affect the total costs. The data of Fig. 10 may allow to easily predict the cost of the strengthening intervention to reduce the vulnerability of existing buildings once the initial SI-LS index is known. However, some caution should be taken because they refer to data derived from L'Aquila 2009 post-earthquake reconstruction process and thus they are obviously representative of such type of buildings and construction practice.

## 7 Final remarks

The Guidelines for the seismic risk classification of constructions (Ministry Decree n.58 28/02/2017) represents a challenge for the Italian earthquake engineering. Indeed, Italy is the first country in Europe adopting a methodology explicitly correlating the seismic risk, the performance of structural and non-structural components and the expected losses.

The seismic risk class of a building, ranging from A+ to G, is the minimum class between the EAL and SI-LS class. It is worth noticing that buildings compliant with Italian current seismic code that exactly match the required performance at different Limit States without any safety margin, are certainly classified as “A+” in the SI-LS class (see Table 1).

By contrast, it belongs to the EAL class “B” (EAL=1.13%, see Fig. 3). Nevertheless, as already stated, it is extremely unlikely that all the Limit States are reached without any further margin; therefore, the construction will probably attain an EAL Class higher than “B”. This is the case of isolated structures that reach the OLS and DLLS at very low frequencies,  $\lambda$ .

A suitable strengthening strategy on existing buildings should aim to a homogeneous EAL and SI-LS class upgrade; indeed, a strengthening intervention mainly aimed at upgrading the EAL class could not affect the final risk class of the building and vice versa.

The DLLS clearly affects the EAL class as also confirmed by the significant economic losses related to the damage on non-structural components in the recent earthquakes. The development and the application in the construction practice of low-damage infill and partition systems for reinforced concrete frame structures are strongly encouraged in the future to reduce the earthquake losses.

The assessment of the Seismic Risk Class of a building is operatively very simple. A committee specifically set up for monitoring the procedure and to evaluate the effectiveness of the proposal, will suggest proper modifications to the Guidelines, if necessary. At the same time, the study and the calibration of advanced methodologies, which could better gather the DLLS and OLS are desirable. However, they should comply with methodologies currently available in the technical literature to be easily and uniformly applicable by practitioners.

In conclusion, according to the approach outlined in the Guidelines for the seismic risk classification, the practitioner is free to choose the strategy and the relevant strengthening technique to upgrade the seismic Risk Class of a building. The selection and the design of proper strengthening interventions aimed at improving the performances at different Limit States is a challenging task. One of the main issue for existing buildings is a reliable estimation of the cost of the strengthening intervention. This aspect is of paramount importance in a cost–benefit framework to compare the amount of economic resources to invest in the seismic protection of buildings and the related benefits measured as the upgrade of the SI-LS and the reduction of the EAL. To have a reliable estimation of the costs of the strengthening intervention an in-depth analysis of 348 reinforced concrete and 229 masonry buildings, for which actual strengthening costs are available, has been carried out. This study points out that the mean cost of strengthening intervention to increase the SI-LS index by one percentage unit is about €7.8/m<sup>2</sup> and € 10.7/m<sup>2</sup> for reinforced concrete and masonry buildings, respectively. Furthermore, it can be concluded that the higher the Class<sub>SI-LS</sub> upgrade is, the lower is the average unit cost to increase the SI-LS index by one percentage unit.

## 8 Conclusions

This paper illustrates the recent Italian Guidelines for seismic risk classification of constructions for exploiting tax deductions with respect to seismic strengthening interventions on existing buildings. Emphasis is given to the technical principles considered in the developments, calibration and validation of the conventional approach. An in-depth discussion on the procedure to evaluate the seismic risk class is provided focusing on the role of safety index at the life safety limit state (SI-LS) and on the expected annual losses (EAL). Practical considerations on the application of the conventional approach to newly designed and existing buildings by using the technical principles of the current seismic

codes are provided. An operational procedure is proposed and applied to three case study buildings typical of the Italian building stock damaged by the L'Aquila 2009 earthquake and then repaired and strengthened. The effectiveness of different strengthening interventions improving the building performances and the seismic risk class is demonstrated. In conclusion, a statistical analysis of the actual strengthening costs monitored in the L'Aquila reconstruction process for a wide database of RC and masonry buildings is carried out. The results are reported and discussed referring to their application in the seismic risk classification and cost–benefit frameworks. The paper remarks that:

- the procedure proposed by the Italian guidelines for seismic risk classification of constructions is simple and applicable in the common design practice since it relies on the technical principles contained in the modern seismic design codes. In fact, well established design/assessment procedure at different limit states could be used to define the seismic risk class;
- the calibration of the %RC at different limit states by using the actual repair costs monitored in the recent reconstruction processes simplified the calculation of the EAL. This allows practitioners to deal with the sophisticated concepts of a modern seismic design such as EAL and the repair costs;
- large uncertainties characterize the actual repair costs used in the calibration of this procedure. These uncertainties reflect the building-to-building variability of the earthquake damage and, in turn, of the repair costs. However, it is demonstrated that they do not significantly affect the assessment of the building class since the error is limited to one class and mostly lead to conservative predictions;
- the procedure is suitable for application to existing RC and masonry buildings typical of the Mediterranean area. Indeed, a direct validation by applying the conventional approach to three case study buildings is proposed and discussed;
- one of the main issue for existing buildings is a reliable estimation of the cost of the strengthening intervention. In this paper, the actual strengthening costs of 348 reinforced concrete and 229 masonry buildings are analysed and discussed considering their application seismic risk classification framework.

Further research studies are needed to improve the prediction of the EAL. Although more refined methodologies are available, a further research effort is needed to extend their application to buildings typical of the Mediterranean area since the fragility and consequence functions of structural and non-structural components still need a calibration and validation against actual data. The committee specifically set up for monitoring the procedure and to evaluate the effectiveness of the proposal will suggest proper modifications to the Guidelines, if necessary.

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