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ORIGINAL ARTICLE

Retrofitting through the loss-Based Earthquake engineering

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Abstract
The novelty of the research is the development of closed-form equations to assess the effective capacity of retrofitting interventions to reduce the seismic risk of existing buildings. The goal of the proposed procedure is to provide decision-making in the context of the Loss-Based Earthquake Engineering, whose purpose is the reduction of the seismic risk, which is herein computed through a monetary loss. The procedure consists of specifying performance targets (e.g. acceptable monetary losses, capital to invest, reduction of expected annual loss) and deriving engineering parameters, specifically the target fragility curves to achieve the established performance target. The identification of required fragility curves, in turn, allows to identify proper retrofitting interventions to mitigate the expected seismic loss. The method allows for estimating the maximum reduction of the annual average loss and the recommended capital to invest, accounting for the actual cost of the retrofitting alternatives and the nominal life of the building. In addition, it can be used to identify the payback period. With the aim of promoting the design procedure in the common practice, an existing reinforced concrete moment-resisting frame, retrofitted with three strengthening methods, is explored as case-study.

Keywords Loss-Based Earthquake Engineering · Seismic risk · Expected Annual Loss · Retrofitting · Existing buildings

1 Introduction

The economic impacts, due to damages and disruptions, such as those observed in events like the 1994 Northridge (California, US) earthquake, loss of approximately US 14 $billion, and the US $ 150 billion of the 1995 Kobe (Japan) earthquake, suggested a new conceptual way of designing to mitigate the devastating effect of earthquakes on society [1].

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Seismic codes cannot only focus on life safety and collapse prevention as highlighted by damages and consequence losses caused by recent earthquakes [2, 3]. This objective has been pursued through the Performance-Based Earthquake Engineering (PBEE) approach, which in the 1990s was integrated into the seismic guidelines. Guidelines [4–6] outlined this PBEE by relating building performance to seismic hazard levels and by integrating this approach into their acceptance criteria. Seminal applications can be found in [7, 8]. The aspects related to the monetary loss and downtime are investigated in [9–12]. The necessity to integrate these performance metrics into the PBEE characterizes the Loss-Based Earthquake Engineering (LBEE) approach. In [13–19] applications can be found to encompass risk-targeted methods. The development with respect to the classic PBEE is the intention to consider the monetary loss in both the design procedure and verification control, concerning new and existing structures, respectively.

The LBEE design approach depends on both the owner's desire for sound judgment on the costs and benefits of seismic protection and on the society's need for informed decision-making to face the seismic demand and the uncertainty of earthquake resistant capacity of structures [20]. The procedure can be combined with the possibility of privatizing the risk by offering insurance to homeowners and to export large parts of the risk to the world's reinsurance markets [21].

Nevertheless, there is still a gap between what is possible in the current state of practice via available design tools and what is needed by society. Issues like how to correlate the expected repair costs of structural and non-structural elements to building structural behavior are not well-established. In addition, a common design procedure for the mitigation of the risk by structural interventions is required [22].

A practical fragility-oriented approach for the seismic retrofit design of structures has been proposed in [23], its application requires the assessment of three points in the displacement-based ratio of capacity to life safety demand versus the median of seismic fragility relationship, for different damage states of the retrofitted building and in turn several numerical simulations. Vice versa, practitioners need an efficient analytical procedure, easily applied in common practice, to be assisted in the retrofitting process in identifying the actual benefits of strengthening interventions by performing a limited number of analyses.

This work aims to tackle these issues and to provide a design procedure, accessible in common practice, to identify proper retrofitting interventions to reduce the seismic risk of buildings. In the context of the LBEE, closed-form equations, capable of identifying the "post-retrofitting" fragility curves to achieve a target expected annual loss, are proposed. The paper concludes exploring the impact of the cost for retrofitting, considering the nominal life of the building, providing analytical expressions to identify the convenient capital to invest in the strengthening of the building and the expected recovery time.

2 Loss-Based Earthquake Engineering and risk metric

Nowadays it is widely acknowledged that seismic design should consider several performance objectives. There is a level of protection demanded by society to adequately safeguard against various types of failures that endanger human lives. At the same time, society has responsibilities in addition to life safety, including the continuing operation of critical facilities and the protection against excessive damage that may have far-reaching conse-

quences for society. The PBEE implies accepting damages in seismic events, but it should be proved that this choice is the most economical solution. The consequence-challenge for structural engineers is to be able to predict these damages and their likelihood to make informed decisions. The development of methodologies to incorporate loss estimation strategies should result in a performance that can be quantified and should provide consistent seismic protection for existing and new structures. The performance evaluation of the structure should include its components, the nonstructural systems, and the building contents. The major steps toward an integrated probabilistic design/assessment approach to PBEE, have been developed by the Pacific Earthquake Engineering Research (PEER) Center, and are the basis of the Loss-Based Earthquake Engineering (LBEE) [20]. The main objective of the LBEE is to facilitate decision-making on cost-effective risk management, providing practitioners with tools to facilitate the implementation of performance-based design.

The PEER framework [12, 20, 24–27] links the seismic response of structures to financial consequences. The analytical consequence function is shown in Eq. (1). It provides the rate of C exceeding threshold c (a given consequence, usually identified as the monetary loss):

$$\lambda\left(C>c\right)=\int_{DM}\int_{EDP}\int_{IM}P\left(C>c|\,DM\right)f\left(DM|\,EDP\right)f\left(EDP|\,IM\right)\left|d\lambda\left(IM>im\right)\right|dEDP\,dDM \tag{1}$$

where: $\lambda(C>c)$ is the rate of C exceeding the threshold c; DM is a vector damage measure indicating the discrete damage states of each component in the building; EDP is a vector of engineering demand parameters; IM is a ground-motion intensity measure; $d\lambda\left(IM>im\right)$ is the ground-motion hazard curve derivative and $f\left(A|\,B\right)=f\left(A=a|B=b\right)$ is the conditional probability distribution function for $A=a$, given $B=b$. The framework assumes conditional independence at each stage of the calculation (i.e. C is independent of EDP when DM is known).

Equation (1) can be re-arranged in Eq. (2):

$$\lambda\left(C>c\right)=\int_{IM}P(C>c|\,IM=im)\left|d\lambda\left(IM>im\right)\right| \tag{2}$$

The average annual loss or *expected annual loss (EAL=E(C))* (Eq. 3) measures the expected amount of loss experienced per year. This metric is useful in evaluating risk reduction actions, as the cost of the action can be compared with the expected reduction of loss produced by actions. It is also of interest for insurance transactions, as the annual cost of an insurance policy is influenced by the expected loss. The calculation uses the mathematical framework in Eq. (2), but with the expected consequences replacing the consequence exceedance probabilities:

$$E\left(C\right)=\int_{IM}E(C|\,IM=im)\left|d\lambda\left(IM>im\right)\right| \tag{3}$$

When the consequences are specified as conditional on a damage state and damage states are considered discrete, the assessment of the *mean consequence* (expected amount of the loss conditional on an intensity) is given by Eq. (4):

$$E\left(C|\,IM=im\right)=\sum\nolimits_{i=1}^{n}E\left(C|\,DM=dm_i\right)P\left(DM=dm_i|\,IM=im\right) \tag{4}$$

where: dm_i is the *i-th* damage state; n is the number of damage states (increasing values of i indicate more severe damages).

A consequence metric of common interest is the loss ratio $E(C|\,DM=dm_i)$, which is defined as the repair cost for the structure (cos_{repa}) with respect to the replacement construction cost (cos_{repl}) [28]. The mean associated loss ratios for the damage states are also provided by recent works [29].

Adopting Eq. (4), the expected annual loss Eq. (3), can be re-arranged in:

$$E\left(C\right)=EAL=\int_{IM}\sum\nolimits_{i=1}^{n}E(C|\,DM=dm_i)P\left(DM=dm_i|\,IM=im\right)\left|d\lambda\left(IM>im\right)\right| \tag{5}$$

Equation (5) provides information about consequences that are not conditional on the occurrence of a single *IM* level.

3 Retrofitting procedure

The aim of the decisions, in the context of the LBEE, is the reduction of the risk and in turn of the *expected annual loss (EAL = E(C))*, Eq. (5). The goal of the work is to mitigate the seismic risk of a structure, reducing the actual = initial expected annual loss EAL_I, achieving a target = final EAL_F, identifying the required fragility curve to be achieved through proper retrofitting interventions.

Starting from the analytical expression of the *EAL* (5), and adopting the power-law relationship [30] for the ground-motion hazard curve, Eq. (6):

$$\lambda\left(IM>im\right)=k_o im^{-k} \tag{6}$$

where k_o and k are parameters defining the shape of the hazard curve and can be estimated according to [31]; the median $\Theta_{F,i}$ of the fragility function, related to the damage state dm_i, and capable of reducing the initial expected annual loss from EAL_I to EAL_F is derived by Eq. (7) (4. - Required median of the target fragility curve):

$$\theta_{F,i}=\left(\frac{\Delta E_i k_o e^{\frac{1k^2\beta_{F,i}^2}{2}}}{EAL_F-EAL_I+\Delta E_i k_o \theta_{I,i}^{-k} e^{\frac{1k^2\beta_{I,i}^2}{2}}}\right)^{1/k} \tag{7}$$

where:

$\theta_{Z,i}$ and $\beta_{Z,i}$ are the median and the standard deviation of the *ln(IM)* of the fragility functions corresponding to the building configuration Z and the damage state dm_i. $z = I$ identifies the initial configuration (pre-retrofitting = as-built) and $z = F$ the final configuration (post-retrofitting) and $\Delta E_i = E\left(C|\,DM=dm_i\right)-E(C|\,DM=dm_{i-1})$.

The potential of the Eq. (7) are summarized below:

- It allows to identify the expected median of the fragility function to achieve the target EAL_F.
- Owners and stakeholders can easily compare the invested capital *CAP* in a retrofitting intervention with the actual annual monetary return in terms of risk reduction $(EAL_I - EAL_F)$.
- Engineers can easily identify EAL_F consequent to a specific retrofitting intervention, which involves a fragility curve with median ($\Theta_{F,i}$).
- Engineers can collaborate with economists, manufacture companies etc. to identify solutions with the aim of changing the mean associated to the loss ratios with the aim of reducing the required $\Theta_{F,i.}$
- Replacing the difference between the annual average loss pre and post intervention with the invested capital $CAP = (EAL_I - EAL_F)$, Eq. (7) allows to identify the target $\Theta_{F,i}$ only by developing the fragility curve associated to the damage state *i* (pre strengthening) and identify the actual benefit of the supposed retrofitting intervention. In particular, the strengthened structure, through the invested capital (*CAP*), requires of having the median of the fragility curve greater than or equal to $\Theta_{F,i}$.
- Requiring only the knowledge of the fragility curve related to dm_i for the as-built building, it reduces the time-consuming in the risk assessment.

It is worth noting that $\theta_{F,i}$ is an acceleration and cannot be negative. Because the numerator in Eq. (7) is always positive, it involves the denominator greater than 0, Eq. 8):

$$EAL_F - EAL_I + \Delta E_i k_o \theta_{I,i}^{-k} e^{\frac{1k^2\beta_{I,i}^2}{2}} > 0 \tag{8}$$

Substituting the difference between the expected annual losses with the invested capital $CAP = EAL_I - EAL_F$, Eq. (9) is obtained:

$$CAP_{MAX,i} \approx \Delta E_i k_o \theta_{I,i}^{-k} e^{\frac{1k^2\beta_{I,i}^2}{2}} \tag{9}$$

Equation (9) provides the maximum capital ($CAP_{MAX,i}$) that is convenient to invest to get an instant profit.

Introducing the ratio between the final and initial expected loss ($EAL_{\%} = \frac{EAL_F}{EAL_I}$), and replacing $EAL_F = EAL_{\%} EAL_I$ in Eq. 8), the maximum reduction of EAL_I, which corresponds to the minimum value $EAL_{\%,MIN,i} = min\,(EAL_{\%})$, can be identified by Eq. (10):

$$EAL_{\%,MIN,i} \approx 1 - \frac{\Delta E_i k_o \theta_{I,i}^{-k} e^{\frac{1k^2\beta_{I,i}^2}{2}}}{EAL_I} \tag{10}$$

Equation (10) estimates the limit (minimum value of $EAL_{\%}$) in the reduction of the seismic risk that can be reached. Moreover, replacing the target expected annual loss with a proper value, slight greater (0.001) than the optimal solution, $EAL_F = EAL_{\%,MIN,i} EAL_I + 0.001$, the target median $\theta_{F,i,T}$ of the fragility curve, to achieve the imposed target performance objective, can be identified.

4 Application

4.1 Case-study and retrofitting techniques

The suitability of the proposed equations and the applicability of the procedure in assisting practitioners during the retrofitting design phase is highlighted through the analysis of a non-ductile RC frame, as case-study. The as-built (AB) building is a five-storeys, four-bay RC moment-resisting frame with a total height of 15 m and a uniform bay width of 4.5 m Fig. 1. The frame was designed for gravity loads according to [32]. The concrete compressive strength is 16.5 MPa, and the yield strength of reinforcing steel is 330 MPa, additional information about structural details can be found in [23].

Three strengthening techniques are investigated: FRP wrapping (FRP), Steel Jacketing (SJ), and RC Jacketing (RCJ). Figure 1 depicts RC cross-sections retrofitted through the investigated techniques. FRP wrapping and circular steel jackets are used to retrofit joints and columns, preventing shear failure and providing a higher level of confinement increasing the ductility of members. The selected FRP material consists of laminated precured sheets with high-strength carbon fibers, which are wrapped around the full height of the columns [33]. The elasticity modulus is 140 GPa, the ultimate tensile strength is 2000 MPa, and the rupture strain is 1.2%. Each FRP layer is 0.5 mm thick, and the maximum number of layers is equal to five.

The adopted steel jacketing consists of full-height circular jackets. The space between the jacket and the retrofitted column is filled with grout material. The jackets are made of structural steel grade S 235 with an average yield strength of 235 MPa and a minimum thickness equal to 1.5 mm.

RC jacketing consists of encasing existing columns with a cast-in-place RC jacket to improve confinement, ductility, shear and flexural strengths and the stiffness. Continuous

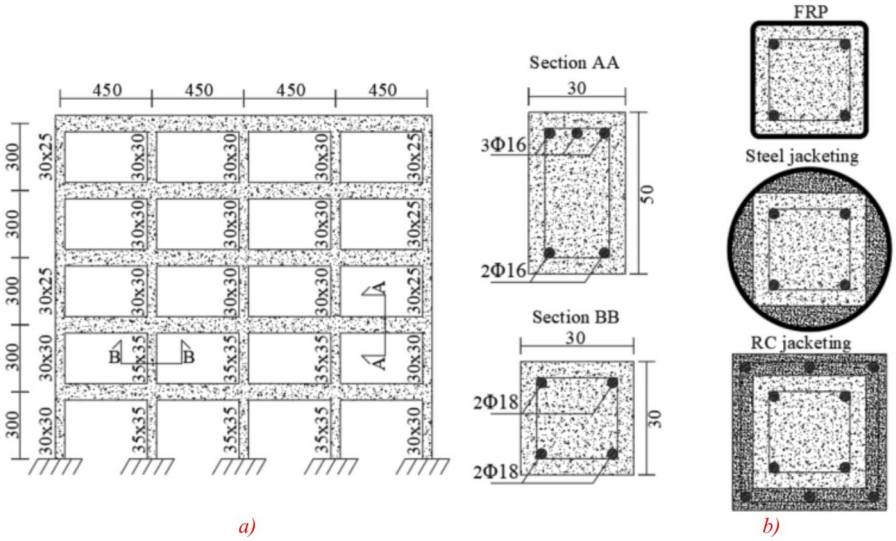


Fig. 1 **a** RC moment resisting frame adopted as case-study. **b** examples of retrofitting techniques (dimensions in centimeters)

Table 1 Criteria adopted for mapping the damage states [34] and related maximum interstorey drift ratio (*MIDR*)

Level	dm_1	dm_2	dm_3
Section level	Reaching yield bending in a supporting column	The maximum bending strength of a column is reached	Reaching shear failure in any element
Component level	Reaching the yield chord rotation in a supporting column	Reaching 75% of the ultimate chord rotation in any component	Reaching the ultimate chord rotation in any component
Global level	Reaching the global yield point of the structure	Reaching the maximum strength	About 20% drop in the maximum strength
General description	Moderate structural and nonstructural damage. No significant yielding of members	Severe structural and nonstructural damage. Some residual strength and stiffness are retained	Full exploitation of strength and ductility. Low residual strength and stiffness
MIDR [%]	0.41	0.93	1.71

Table 2 Selected performance objectives for seismic retrofitting interventions

Performance objective	Description
No collapse performance	Complete collapse-prevention (dm_3)
Basic performance	Extensive damage-prevention (dm_2)
Advanced performance	Moderate damage-prevention (dm_1)

column jacketing on two consecutive floors also enhances the beam-to-column joint behavior. RC jackets with a minimum thickness of 50 mm are adopted, with at least 4 Φ 14 mm for external columns and 4 Φ 16 mm for internal ones (Φ refers to the diameter of the rebar). Stirrups have a spacing not exceeding 150 mm. The concrete material is characterized by a compressive strength of 33 MPa, while the steel yielding strength is 490 MPa.

4.2 Damage states and performance objectives

Three damage states are considered for the building's performance level: dm_1 reflects "moderate" damage level; dm_2 represents "significant" damage and dm_3 accounts for "complete" damage (near-collapse condition). Each damage occurs when the structure attains a specific engineering demand parameter defined with respect to the maximum interstorey drift ratio (*MIDR*), which is related to the first occurrence of any criterion among those listed in Table 1 [34].

The as-built (AB) structure is retrofitted aiming at selected performance objectives listed in Table 2 [23].

The structural response of the building as-built and retrofitted through investigated techniques has been assessed in [23] through static nonlinear analyses by a FE 2D numerical model via OpenSees [35]. It is worth noting that the retrofitting design can be performed by adopting alternative methods, for example designing the retrofitted structure through a linear elastic analysis, assuming the acceleration on the building (horizontal elastic response

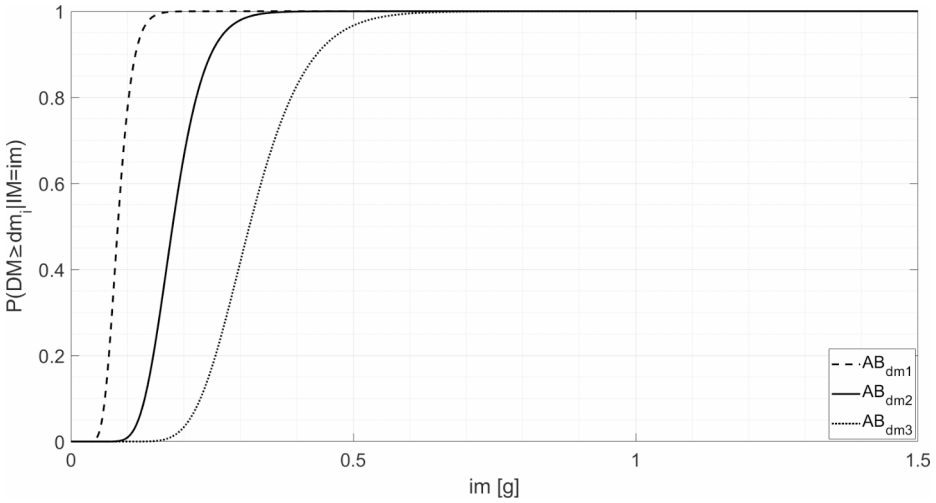


Fig. 2 Fragility curves for the AB structure and a damage state "moderate", "extensive" and "complete"

Table 3 Median Θ_i [g] and the standard deviation β_i of the ln(IM), of the fragility curves related to the damage state dm_i

Θ_1	Θ_2	Θ_3
0.083	0.18	0.316
β_1	β_2	β_3
0.25	0.25	0.25

spectrum acceleration) equal to the target median acceleration given by Eq. (7) to achieve a target performance level. Anyway, the methods for performing the retrofitting are beyond the scope of this study and therefore not investigated.

4.3 Fragility curves

Fragility curves, $P(DM \geq dm_i|IM = im) \approx P(EDP \geq edp_i|IM = im) \approx \Phi\left(\frac{ln(im/\theta_i)}{\beta_i}\right)$, for the as-built building, are shown in Fig. 2, with IM in units of [g] and median Θ_i and standard deviation β_i of the *ln(IM)* listed Table 3, for all damage states dm_i.

The probability of damage state occurrence conditional to $IM = im$, $P(DM = dm_i|IM = im) = P(DM \geq dm_i|IM = im) - P(DM \geq dm_{i+1}|IM = im)$ is shown in Fig. 3 for all identified damage states.

4.4 Consequence models for structural components

The consequence metric adopted for the analyses is the mean associated loss ratio $E(C|DM = dm_i)$, corresponding to the ratio between the repair cost and the replacement cost. The costs for repairing damaged structural elements (external beam-column joints and columns, Table 4), with smooth bars and lack transverse rebar and proper anchorage, making them susceptible to shear failure, are provided by the study developed in [36]. The required repair actions are similar for all components, including removal and disposal of

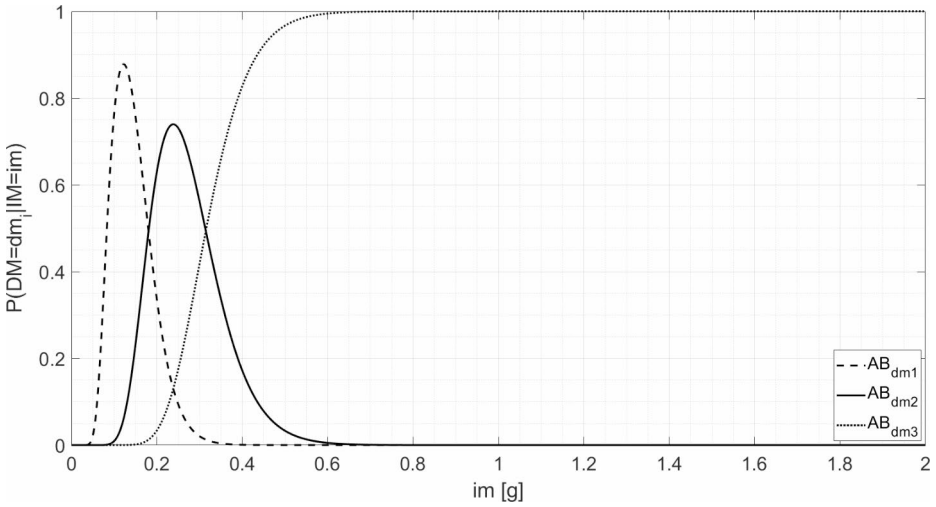


Fig. 3 Probability of damage state occurrence conditional to IM = im, for a damage state "moderate", "extensive" and "complete"

Table 4 Description of damages for structural components

Structural component	DM	Description of damage
External beam-column joints	dm_1	Cracks < 1.5 mm width at beam-joint interfaces and shear cracks in the joint panel. Additional cracks in beams and column-joint interfaces are expected to form
	dm_2	Existing cracks widen up to 5 mm. Further beam flexural cracks may form. Spalling of concrete cover covering 10% of the joint panel area is likely to happen
	dm_3	Progressive spalling occurs, covering at least 30% of the joint panel area. Buckling of column rebar might occur
Columns	dm_1	Light cracks < 1.5 mm width in the upper and lower thirds of the column
	dm_2	Extensive double diagonal cracks along the whole column height up to 5 mm width
	dm_3	Buckling of reinforcement bars and opening of large cracks along the entire column height. Potential loss of gravity load-carrying capacity

spalled concrete and buckled rebars, injection of cracks with epoxy resin, patching spalled concrete using high-cement mortar, replacing crushed concrete with an in-situ concrete mix, and replacing buckled and yielded rebars. The unit costs for each repair action have been estimated according to [37] (Table 5).

Each damage state is associated with a specific set of repair activities that are required to restore the structural component to its pre-earthquake (essentially undamaged) state. The final cost includes supplementary activities (safety operations, demolition activities, clean-

Table 5 Unit costs for repair actions required for different damage state of RC members

DM	Repair Actions	Unit	Unit cost (€/unit)
dm_1	Clean area adjacent to cracks	m^2	7
	Prepare cracks to be injected	m^2	27
	Inject cracks with epoxy resin	m	156
dm_2	Remove loosened concrete, clean area adjacent to cracks	m^2	7
	Prepare cracks/surfaces to be injected /patched	m^2	27
	Inject cracks with epoxy resin	m	156
	Patch spalled concrete (if any) with mortar mix	m^2	88
	Steel jacketing	kg	4.5
dm_3	Remove damaged and potentially damaged concrete and clean adjacent area	m^2	7
	Prepare concrete surface to ensure full bond between new and existing concrete	m^2	27
	Inject cracks with epoxy resin	m	156
	Replace distorted bars (if any)	each	50
	Replace damaged concrete with rheoplastic concrete mix or high-performance mortar mix	m^2	109
	Demolition and re-construction	m^3	668

Table 6 Loss ratios for the damage states "moderate", "extensive" and "complete"

$E(C\|DM=dm_1)$	$E(C\|DM=dm_2)$	$E(C\|DM=dm_3)$
0.17	0.51	1.00

ing operations, replacement and restoration, and technical costs) which have been identified according to [36].

The replacement cost (cos_{repl}) of the building has been estimated, assuming an average unit cost of 730 euro/m^2 for each floor and 90 euro/m^2 for the foundation [36]. The loss ratios are listed Table 6 and account for only monetary direct loss, although recent research has highlighted additional parameters to quantify the seismic risk [38]. In case of complete damage (dm_3), associated with the full exploitation of strength and ductility with low residual strength and stiffness, the loss ratio has been assumed equal to one $E(C|\,DM = dm_3) = 1$ assuming to demolish and replace the building.

The expected amount of loss for a given damage state dm_i and a given $IM = im$ ($E(C|\,DM = dm_i)\,P(DM = dm_i|\,IM = im)$), is shown in Fig. 4, assuming the loss ratios listed in Table 6.

The expected amount of loss for a given $IM = im$ (Eq. (4)) is shown in Fig. 5.

Figure 6 shows the hazard curve considered in the simulation Eq. (6). The curve (k_o=0.0008183 and k=2.035) is for a site with a peak ground acceleration (PGA) of 0.27 g (at the Life Safety state), ground type A and period of 1.3 s with a damping ratio of 5%, mechanical parameters corresponding to the dynamic characteristics of the investigated building.

The correlation between the MAFE of the spectral acceleration intensity Eq. (6) and the expected amount of the loss conditional on an intensity Eq. (4) is shown in Fig. 7.

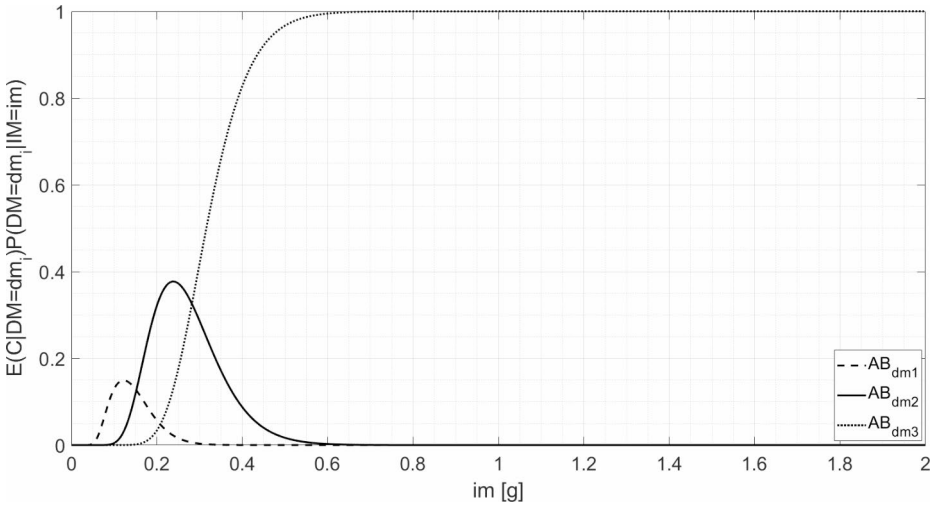


Fig. 4 Expected amount of loss for a given IM = im, for a damage state "moderate", "extensive" and "complete"

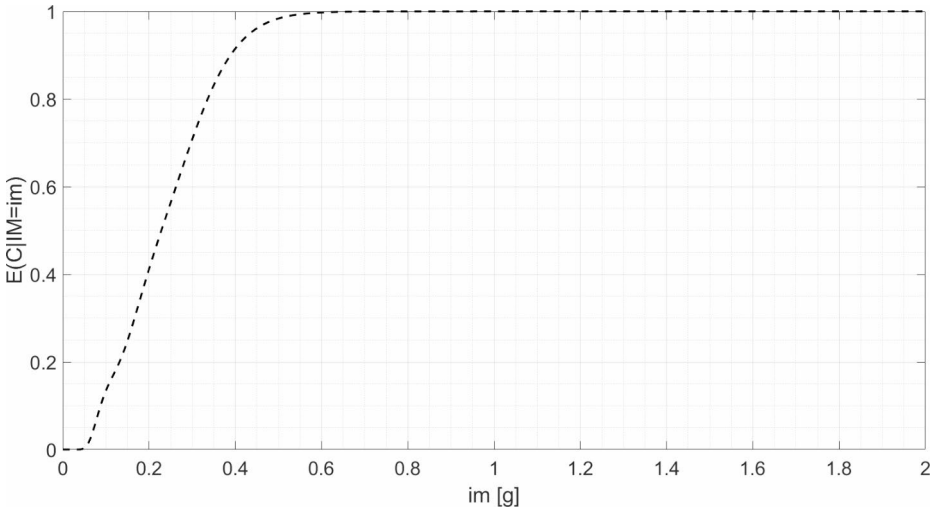


Fig. 5 Expected amount of loss for a given IM = im

The expected annual loss ($E(C) = EAL$) can be analytically approximated through the area beneath this curve (Eq. (5)) and for the case-study is $EAL_I = 4\%$.

It is worth noting that, the curve in Fig. 7 can be approximated by a curve on three points [22]: one related to the ground motion intensity inducing a first onset of damage (index *o*), one related to the intensity inducing structural collapse or total economic loss [39] (index *c*) and an intermediate one controlling the shape of the resulting curve (index *f*). The use of an approximated curve has been adopted in the seismic loss assessment of many different kinds of buildings [40–45] with reliable results. An approximated curve to estimate EAL_I

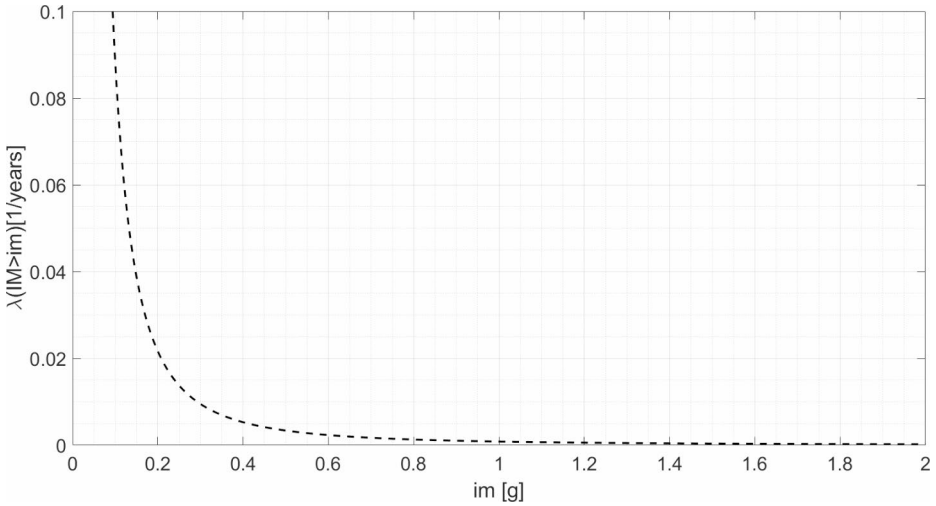


Fig. 6 Spectral acceleration hazard curve providing the mean annual frequency of exceeding a particular spectral acceleration

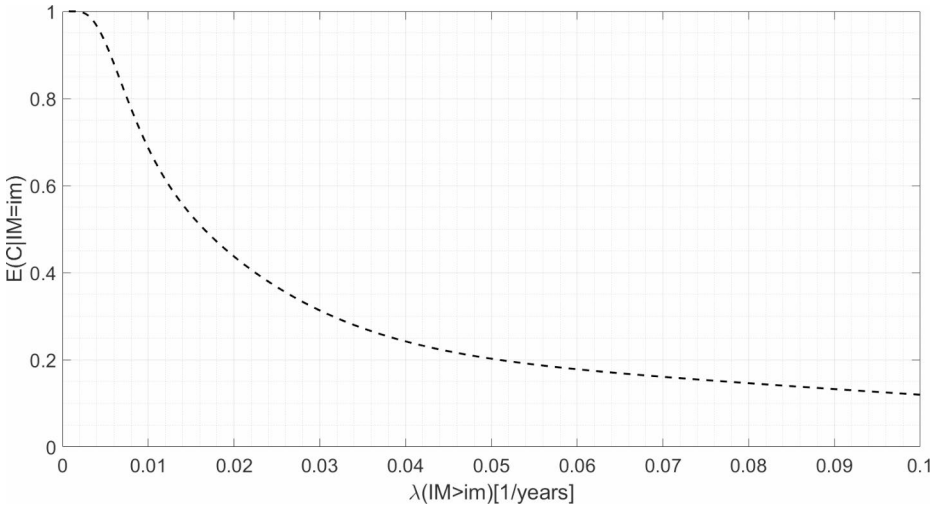


Fig. 7 Expected level of damage and subsequent loss versus mean annual frequency of exceedance of the ground motion intensity

reduces the time-consuming and promotes the application of the proposed approach Eq. (7). Moreover, as confirmed in [22], the resulting *EAL* is strongly influenced by the selection of the (*f*) point, while it is less sensitive to the assumption on the onset of damage (*o*) and almost insensitive to the assumption on collapse (*c*). Sensitivity studies are performed in [46, 47, 48].

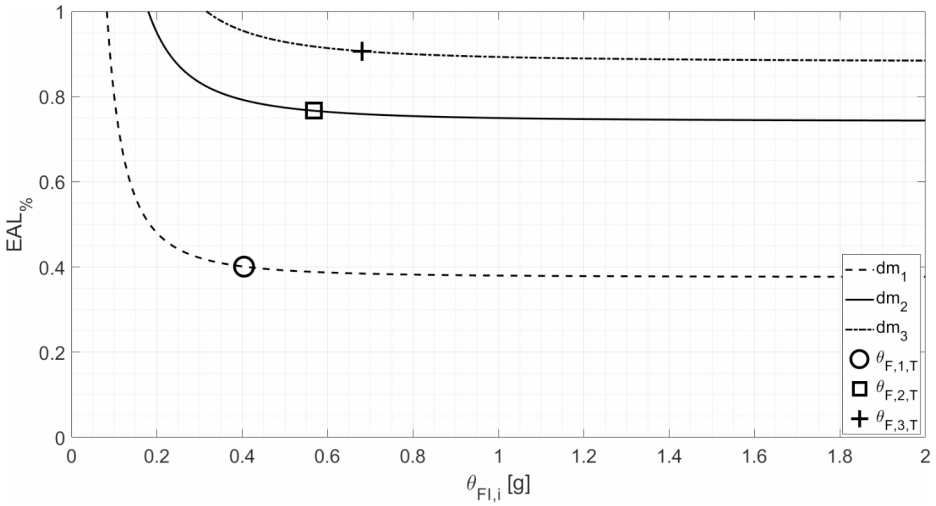


Fig. 8 Ratio between the final and the initial expected annual losses $EAL_{\%} = \frac{EAL_F}{EAL_I}$ versus the median of the fragility curve in the final configuration ($\Theta_{F,i}$), for all damage state

Table 7 Minimum value of EAL_F/EAL_I ($EAL_{\%,MIN,i}$, Eq. (10), which corresponds to the maximum reduction of the seismic risk modifying the fragility curve related to the damage state dm_i, recommended maximum capital to invest $CAP_{MAX,i}$ and approximation of the target median $\theta_{F,i,T}$ of the fragility curve corresponding to a the achievement of the plateau in the $EAL_{\%,i}$ trend

$EAL_{\%,MIN,1}$	$EAL_{\%,MIN,2}$	$EAL_{\%,MIN,3}$
0.38	0.74	0.88
$CAP_{MAX,1}$	$CAP_{MAX,2}$	$CAP_{MAX,3}$
0.025	0.010	0.005
$\theta_{F,1,T}$ [g]	$\theta_{F,2,T}$[g]	$\theta_{F,3,T}$[g]
0.404	0.568	0.680

4.5 Retrofitting procedure

4.5.1 Target expected annual loss (EAL_F), capital to invest (CAP_{MAX}) and target median of fragility curve ($\theta_{F,i,T}$)

High values [39, 46] of $EAL > 1\%$ are not desired in new structures but can characterized existing buildings [49, 50]. By Eq. (7), the mean of the fragility curve post strengthening $\Theta_{F,i}$ and related EAL_F can be evaluated. The value of $\Theta_{F,i}$, Eq. (7), versus $EAL_{\%} = \frac{EAL_F}{EAL_I}$ is shown in Fig. 8, for all damage states dm_i.

Figure 8 allows to identify the fragility curve with the greater impact on *EAL*, that, for the case-study, is related to the "moderate" damage (dm_1). In fact, by modifying the fragility curve related to this damage state (from $\Theta_{I,1} = 0.083$ g to $\Theta_{F,1} = 0.4$ g) EAL_I reduces by about 40% (Fig. 8).

The best solution, minimum value of EAL_F/EAL_I, corresponds to $EAL_{\%,MIN,i}$, it is evaluated by Eq. (10) and listed in Table 7, for all damage states dm_i.

Results confirm that it is convenient to improve the structural response of the building related to the damage dm_1. The proposed procedure also allows to identify the actual benefit of the retrofitting intervention. In particular, for a given $\Theta_{F,i}$ the final expected annual loss (EAL_F) can be evaluated by reversing Eq. (7).

Assuming to transfer the invested capital in the reduction of EAL_I, the maximum capital $CAP_{MAX,i}$ that is recommended to invest for having a profit on the year, is given by Eq. (9) and listed in Table 7 for all damage states.

Finally, assuming $EAL_F = EAL_{\%,MIN,i}EAL_I + 0.001$, which almost corresponds to the best solution ($\approx EAL_{\%,MIN,i}$), the minimum target median of the fragility curve $\theta_{F,i,T}$, related to the damage state dm_i, can be assessed by Eq. (7). $\theta_{F,i,T}$ corresponds to the point where $EAL_\% = \frac{EAL_F}{EAL_I}$ reaches the constant minimum value and it is related to building retrofitted to avoid the damage related to investigated performance level (dm_i, target objective).

Table 7 confirms that is recommended to modify the fragility curve related to the moderate damage (dm_1) to have the lowest target expected annual loss $EAL_{\%.MIN,1} = 0.38$ and the maximum recommended capital for the retrofitting intervention, for having an immediate profit, is about 2.5% the cost of the building as-built ($CAP_{MAX,1} = 0.025$).

It is worth noting that for the sake of simplicity, it is assumed that the variability of the fragility curves does not change pre and post-retrofitting ($\beta_{F,j}=\beta_{I,j}$) for all damage states; and, on the safe side, the retrofitting intervention only affects the fragility curve related to the investigated damage state (i), which in turn means $\Theta_{F,j}=\Theta_{I,j}$ for all damage states, with $j \neq i$.

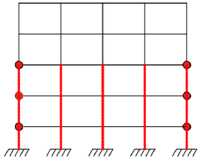
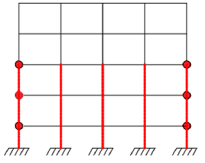
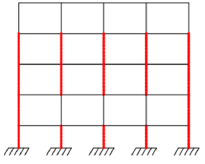
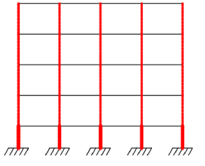
4.6 Performance assessment for the strengthened structures

Table 8 shows the details, layout, and number of retrofitted elements using the retrofitting techniques to achieve two investigated performance objectives (basic (dm_2) and advanced (dm_1), Table 2) with the minimum possible amount of intervention. Table 8 shows that the advanced performance objective cannot be achieved using FRP wrapping or steel jacketing because they mainly only improve ductility through confinement and increase shear strength. Their contribution to the lateral strength and stiffness is negligible and enhancing these parameters is essential with respect to moderate damage (dm_1). The advanced performance objective is achieved, by RC jacketing, which provides a significant overall enhancement for the stiffness and strength. Nevertheless, as illustrated in Table 8, achieving the advanced performance level requires of strengthening the entire columns of the building, resulting in a global retrofit intervention rather than local, which might be expensive and technically challenging.

The fragility curves for the as-built and retrofitted cases are shown in Fig. 9. The fragility parameters (median Θ_i and standard deviation β_i of the *ln(IM)*) are listed Table 9 for all damage states dm_i.

The achievement of a basic performance (extensive damage-prevention dm_2) is related to $\theta \approx 0.5$ g while the achievement of the advanced performance (moderate damage-prevention dm_1) is related to $\theta \approx 0.4$ g. Values which are close to the minimum target medians of the fragility curves $\theta_{F,i,T}$ (Table 7), analytically estimated by Eq. (7), and corresponding to the achievement of the plateau in the $EAL_\%$ versus $\theta_{F,i,T}$ curve (Fig. 8). Simultaneously, the preliminary evaluation of $\theta_{F,i,T}$, related to the achievement of a performance objec-

Table 8 Description of retrofitting for different performance objectives and techniques

Technique	Performance objective	First period [s]	Description of retrofitting	Graphical illustration
FRP	Basic	1.31	Strengthening of external beam-column joints (1st – 2nd – 3rd floor). One layer for the 2nd floor columns. Four layers for the 1st floor and internal columns in 3rd floor and five layers for the 3rd floor external columns	
	Advanced	NA	NA	NA
SJ	Basic	1.27	Strengthening of external beam-column joints (1st – 2nd – 3rd floor) 1.5 mm jacket for the columns of 2nd floor. 2.5 mm jacket for the 3rd floor and external columns of 1st floor. 3 mm jacket for the internal columns in 1st floor	
	Advanced	NA	NA	NA
RCJ	Basic	1.14	50 mm jackets for the external columns in the 1st to 4th floor with 4Φ14. 50 mm jacket for the internal columns in 1st, 3rd, 4th floors with 4Φ16.	
	Advanced	0.94	100 mm jacket with 8Φ16 and 1Φ8/100 mm hoops for external, 12Φ22 and 1Φ10/80 for the internal columns of 1st floor. 50 mm jackets with 8Φ20 and 1Φ8/150 mm hoops for external columns with 8Φ22 and 1Φ8/150 for the internal columns of 2nd floor. 50 mm jackets with 8Φ14 and 1Φ8/150 mm for the 3rd, 5th and external columns of 4t^{h} floor. Similar jackets but with 8Φ16 mm for internal columns of the 4th floor	

tive, allows to identify a conservative value in the reduction of the expected annual loss ($EAL_{\%,MIN,1}$= 0.38 and $EAL_{\%,MIN,2}$=0.74, Eq. (7) and Fig. 8). Although, Table 9 highlights that the effective reduction of the expected annual loss $\frac{EAL_F}{EAL_I}$ is lower than the predicted one, because the adopted retrofitting interventions involve a reduction in the fragility for all damage states, results confirm the reliability and quick application of the proposed procedure.

4.7 Impact of the retrofitting cost

The cost-benefit analysis can be improved considering the cost of each retrofitting alternative (cos_{ret}) and the nominal life of the building T_N (50 years for the case-study), being the expected annual loss the economic loss that, on average, occurs every year.

The cost for the column steel jacketing [51] is assumed equal to the total weight of steel, used to arrange a steel jacketing cage, times the cost per unit weight, estimated at 4.5 €/kg. The costs for the FRP-wrapping and RC-jacketing methods are evaluated according to [37]. Considering the basic performance level, the mean value of the steel jacketing is 2355 €/column; the price for the FRP-wrapping is about 2771 €/column and that for the RC jacketing 1155 €/column, confirming the analyses carried out in [52]. It is worth noting that the achievement of an advanced performance requires to strength a greater number of structural members and in turn a greater overall cost. Compared with the other two techniques, RC jacketing is the most traditional and common technique in practice as it is characterized by a low cost and does not require specialized labor, but it poses the highest level of invasiveness, by increasing the size of existing columns, an aspect that is not investigated herein.

The effective reduction of the seismic risk involves:

$$\mathrm{EAL}_{\%} + \frac{\mathrm{COS}_{RET}}{T_N EAL_I} \leq 1 \tag{11}$$

where: $\mathrm{COS}_{RET} = \frac{cos_{ret}}{cos_{repl}}$ is the retrofitting loss ratio and corresponds to the cost for the retrofitting (cos_{ret}) normalized respect to the replacement cost of the as-built structure. Equation 11) allows for assessing the recommended limit in the retrofitting loss ratio $\mathrm{COS}_{RET,LIM}$, accounting for the nominal life of the building T_N:

$$\mathrm{COS}_{RET,LIM} = \frac{cos_{ret,LIM}}{cos_{repl}} \leq T_N EAL_I(1 - EAL_{\%}) \tag{12}$$

Moreover, rearranging Eq. 11), the actual recovery time of the investment for the retrofitting (T_{rec} [years], or payback period), which corresponds to the amount of time it takes to recover the cost of the investment, and involves $\frac{COS_{RET}}{T_{rec}} + EAL_F = EAL_I$, can be evaluated:

$$T_{rec} = \frac{\mathrm{COS}_{RET}}{EAL_I(1 - EAL_{\%})} \tag{13}$$

The limit for the retrofitting loss ratio versus the ratio between the final and initial expected annual loss ($COS_{RET,LIM}$ *vs.* $EAL_{\%}$) is shown in Fig. 10. The trend of the recovery time (T_{rec} *vs.* $EAL_{\%}$) is shown in Fig. 11. Symbols identify the actual retrofitting loss ratio

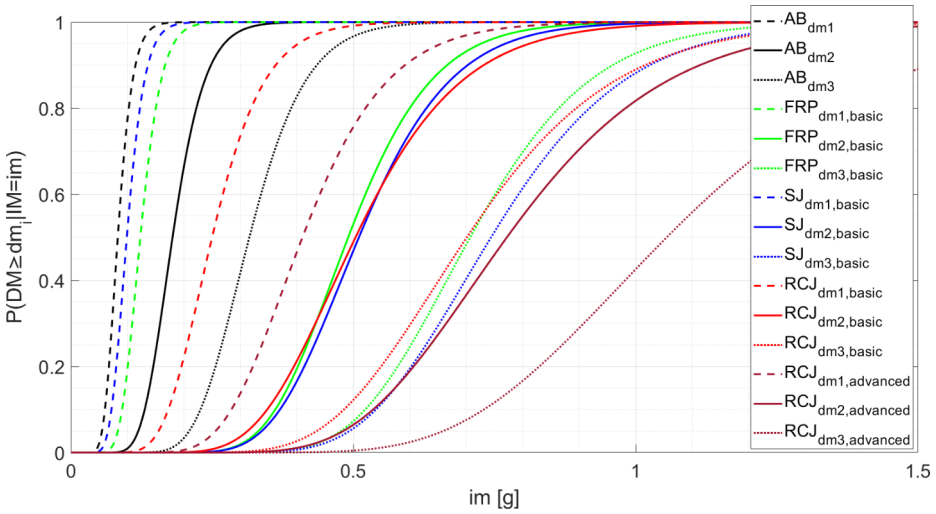


Fig. 9 Fragility curves for the as-built (AB) and retrofitted building through FRP wrapping (FRP), Steel Jacketing (SJ) and RC Jacketing (RCJ) to achieve different performance objectives (basic and advanced)

Table 9 Fragility parameters of the as-built and retrofitted cases for different performance objectives

Damage state	Basic performance			Advanced performance
	FRP wrapping	Steel jacketing	RC jacketing	RC jacketing
	Θ [g] - β	Θ [g] - β	Θ [g] - β	Θ [g] - β
dm_1	0.123–0.238	0.099–0.247	0.250–0.290	0.410–0.286
dm_2	0.491–0.238	0.510–0.247	0.504–0.290	0.772–0.286
dm_3	0.707–0.238	0.744–0.247	0.701–0.290	1.055–0.286
EAL_F	0.013	0.020	0.005	0.002
EAL_F/EAL_I	0.332	0.487	0.126	0.049

COS_{RET} and the recovery time $T_{rec,}$ for all investigated retrofitting methods, and they are listed in Table 10.

Figure 10 confirms that the cost for each retrofitting intervention is lower than the recommended one. The cost for the RCJ (basic performance level target) is the lowest while the costs for the retrofitting through FRP and SJ are similar. The recovery time for RCJ is 8 years with respect to 15 and 21 years related to FRP and SJ, respectively (Fig. 11). Table 10 provides a quantitative information to assist all interested parties in making risk management decisions. The quantitative measure of the economic loss, accounting for the impact of the retrofitting cost, provides the interested parties with an improved level of information regarding seismic performance and can become the basis for more rational decision-making as part of risk management strategies. Engineers can optimize the retrofitting interventions through the proposed closed-form equation for achieving a target EAL_F or vice-versa to identify the actual beneficial effect due to an assumed strengthening to achieve a target performance objective. Insurers can compare the annual earthquake insurance premiums (IP) to annual expected losses $IP = EAL + p$, to estimate the profit per year (p) [53]. Owners and stakeholders can decide the level of economic loss that they are willing to accept, which in

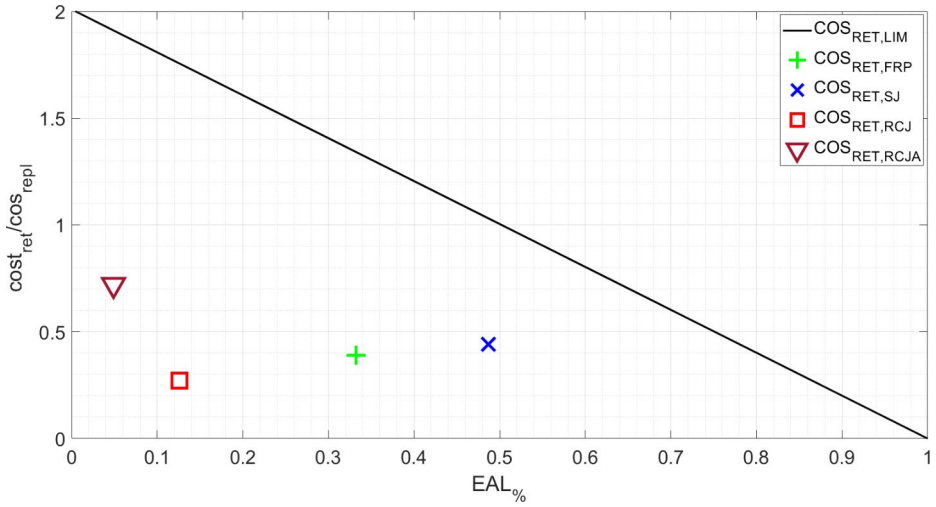


Fig. 10 Limit for the retrofitting loss ratio versus the ratio between the final and initial expected annual loss ($COS_{RET,LIM}$ *vs.* $EAL_{\%}$)

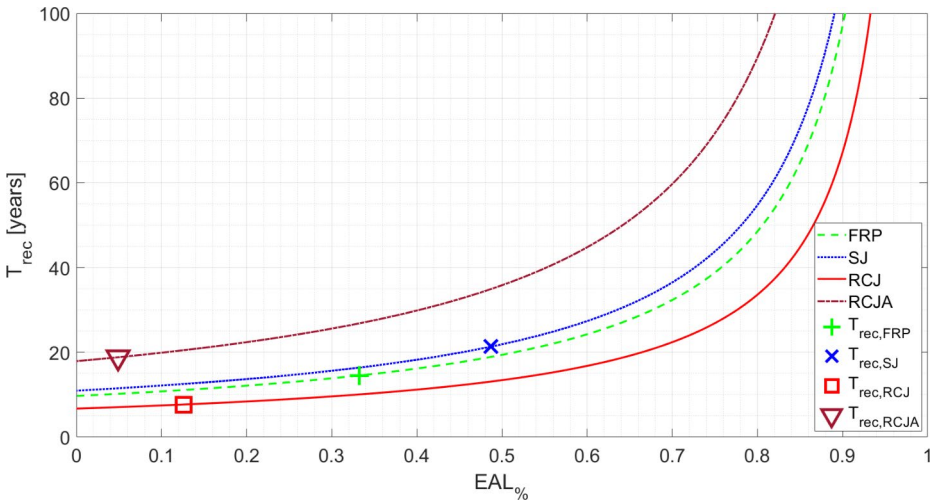


Fig. 11 Recovery time versus the ratio between the final and initial expected annual loss (T_{rec} vs. $EAL_{\%}$)

Table 10 Retrofitting ratios for adopted techniques (COS_{RET}), and time of recovery for invested capitals (T_{rec}), considering investigated performance levels

Parameter	Basic performance	Advanced performance
$\mathrm{COS}_{RET,FRP}$	0.39	NA
$\mathrm{COS}_{RET,SJ}$	0.44	NA
$\mathrm{COS}_{RET,RCJ}$	0.27	0.72
$T_{rec,FRP}$ [years]	15	NA
$T_{rec,SJ}$ [years]	21	NA
$T_{rec,RCJ}$ [years]	8	19

turn can lead them to decide whether or not to make the investment in the building, considering the expected payback period.

5 Conclusions

A procedure to assist practitioners in the decision-making process in the context of seismic risk management is proposed. Closed-form equations are developed to identify the proper retrofitting intervention to reduce the expected annual loss of existing structures. Equations are based on the Loss-Based Earthquake Engineering and allow for evaluating the median of the fragility curves to reach a target building performance objective and providing a preliminary assessment of the expected annual loss for the retrofitted building. The proposed procedure, easily applied in common practice, goes beyond the concept of seismic risk assessment and can be adopted for the preliminary identification of proper strengthening alternatives. The method allows to identify the minimum expected annual loss as dependent on the adopted solution and to evaluate the maximum capital that is convenient to invest.

In the context of the seismic risk mitigation of existing structures, the proposed framework allows for identifying the optimal economic solution, considering the nominal life of the building and the impact on the economic revenues due to the cost of retrofitting.

The procedure has been applied to an existing non-ductile RC moment-resisting frame, used as case-study, which is retrofitted through three techniques: FRP wrapping, steel jacketing, and RC jacketing. Identifying the specific fragility median to obtain a target benefit, in terms of reduction in the expected annual loss or building performance level, the provided closed-form equations will drive the designer in the preliminary retrofit design of structures with the advantage of drastically reducing the number of numerical analyses, leading to a significant reduction in both time and costs.

In the analysis, the total annual loss, which on average affects the structure, results from the repair and replacement of structural damaged components in the building, so the potential for significant indirect losses resulting from downtime and interruptions still needs to be addressed, despite its relevance, and could be investigated in further studies.

Appendix

Required median of the target fragility curve

The expected annual loss for a structure in the actual = initial (I) configuration can be written as:

$$E_I(C) = \sum_{i=1}^{n} \int_{IM} E(C|\, DM = dm_i) P(DM = dm_i|\, IM = im)\, |d\lambda\,(IM > im)|$$

with n the number of damage states.

The probability of damage state occurrence (i.e., of being in a particular dm_i) can be computed by subtracting the exceedance probabilities for sequential damage states:

$$P(DM = dm_i|\, IM = im) = P(DM \geq\ dm_i|\, IM = im) - P(DM \geq\ dm_{i+1}|\, IM = im)$$

Adopting the lognormal cumulative distribution function for estimating the probability of a structure of reaching a damage state or worse (4., Fragility function) and using the analytical formulation for the damage hazard curve (4., damage hazard curve):

$$E_I(C) = \sum_{i=1}^{n} E(C|\, DM = dm_i) \left(k_o \theta_{I,i}^{-k} e^{\frac{1k^2 \beta_{I,i}^2}{2}} - k_o \theta_{I,i+1}^{-k} e^{\frac{1k^2 \beta_{I,i+1}^2}{2}} \right)$$

with $\Delta\, E(C|\, DM = dm_i) = E(C|\, DM = dm_i) - E(C|\, DM = dm_{i-1})$:

$$E_I(C) = \sum_{i=1}^{n} \Delta\, E(C|\, DM = dm_i) \left(k_o \theta_{I,i}^{-k} e^{\frac{1k^2 \beta_{I,i}^2}{2}} \right)$$

Assuming to modify the median of the fragility curve related to the damage state j, the final ($_F$) expected annual loss can be evaluated by:

$$E_F(C) = \Delta\, E(C|\, DM = dm_j) \left(k_o \theta_{F,j}^{-k} e^{\frac{1k^2 \beta_{F,j}^2}{2}} \right) + \sum_{i=1}^{n} \Delta\, E(C|\, DM = dm_i) \left(k_o \theta_{I,i}^{-k} e^{\frac{1k^2 \beta_{I,i}^2}{2}} \right)$$

with i≠j. It gives:

$$E_F(C) = \Delta\, E(C|\, DM = dm_j) \left(k_o \theta_{F,j}^{-k} e^{\frac{1k^2 \beta_{F,j}^2}{2}} \right) + E_I(C) - \Delta\, E(C|\, DM = dm_j) \left(k_o \theta_{I,j}^{-k} e^{\frac{1k^2 \beta_{I,j}^2}{2}} \right)$$

and the final median of the fragility curve $\theta_{F,j}$ can be obtained by:

$$\theta_{F,j} = \left(\frac{\Delta E(C|\, DM = dm_j) k_o e^{\frac{1k^2\beta_{F,j}^2}{2}}}{E_F(C) - E_I(C) + \Delta E(C|\, DM = dm_j) \left(k_o \theta_{I,j}^{-k} e^{\frac{1k^2\beta_{I,j}^2}{2}} \right)} \right)^{1/k}$$

Fragility function

The *fragility function* characterizes the probability of a structure reaching a damage state or worse [27, 54, 55], the incremental dynamic analysis (IDA) procedure [56] is often adopted for its estimation and a lognormal cumulative distribution function is frequently used to analytically describe its curve [57-59]:

$$P(DM \geq dm_i |\, IM = im) \approx P(EDP \geq edp_i | IM = im) \approx \Phi \left(\frac{ln(im/\theta_i)}{\beta_i} \right)$$

where: Θ_i is the median of the fragility function and β_i is the standard deviation of the *ln(IM)* level at which failure of damage dm_i occurs; $\Phi(\cdot)$ is the standard Gaussian comultative distribution function of $(\cdot)$. In the Equation, as usually happen in decision-making procedures concerned with the total risk estimation, $EDP \approx DM$ and then the engineering demand parameter is assumed as correspondent to the physical damage, which will be correlated to an economic damage (loss ratio). The multiple damage states are typically assumed to be mutually exclusive and collectively exhaustive.

Damage hazard curve

For a lognormal variable, possible values range from 0 to ∞:

$$\lambda(DM > dm_i) = \int_{IM} P(DM > dm_i |\, IM = im) \left| d\lambda(IM > im) \right|$$

$$= \int_0^\infty P(DM > dm_i |\, IM = im) \left| d\lambda(IM > im) \right| = \int_0^\infty \Phi \left(\frac{ln(im/\theta_i)}{\beta_i} \right) \left| d\lambda(IM > im) \right|$$

applying the integration by parts and assuming the term to be close to zero for the integration limits (i.e. very small and very large *IM* values) and using the power function for the seismic hazard curve, it follows:

$$= \int_0^\infty \frac{\mathrm{d}\Phi \left(\frac{ln(im/\theta_i)}{\beta_i} \right)}{dim} \left| \lambda(IM > im) dim \right|$$

$$= \int_0^\infty \frac{1}{im\beta_i} \varnothing \left(\frac{ln(im/\theta_i)}{\beta_i} \right) k_o im^{-k} dim$$

where $\varnothing\ (u) = \frac{1}{\sqrt{2\pi}} exp\left(-\frac{1}{2}u^2\right)$ is the Gaussian probability density function and then:

$$= \int_0^{\infty} \frac{1}{im\beta_{\,i}} \frac{1}{\sqrt{2\pi}} exp\left(-\frac{1}{2}\left(\frac{ln\,(im) - ln\,(\theta_{\,i})}{\beta_{\,i}}\right)^2\right) k_o im^{-k} dim$$

$$= k_o \int_0^{\infty} \frac{1}{im\beta_{\,i}} \frac{1}{\sqrt{2\pi}} exp\left(-\frac{1}{2}\left(\frac{ln\,(im) - ln\,(\theta_{\,i})}{\beta_{\,i}}\right)^2\right) exp\left(-\frac{1}{2}2k\ ln\,(im)\right) dim$$

$$= k_o exp\left(\frac{1}{2}k^2{\beta_{\,i}}^2\right) exp\,(-k\ ln\,(\theta_{\,i})) \int_0^{\infty} \frac{1}{im\beta_{\,i}} \frac{1}{\sqrt{2\pi}} exp\left(-\frac{1}{2}\left(\frac{ln\,(im) + k{\beta_{\,i}}^2 - ln\,(\theta_{\,i})}{\beta_{\,i}}\right)^2\right) dim$$

$$= k_o exp\left(\frac{1}{2}k^2{\beta_{\,i}}^2\right) exp\,(-k\ ln\,(\theta_{\,i}))\ 1$$

$$= k_o {\theta_{\,i}}^{-k} e^{\frac{1k^2{\beta_{\,i}}^2}{2}}$$

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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