



## EVALUATION OF DIFFERENT RETROFIT STRATEGIES FOR RC SCHOOL BUILDINGS USING INTEGRATED MULTI-CRITERIA PROCEDURES

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### **Abstract**

The choice for retrofitting interventions to improve the seismic behavior of existing buildings is generally made considering a limited number of parameters and without a comprehensive and integrated comparison with other possible retrofitting solutions. Instead, for an optimal choice of a retrofitting option, it is evermore recognized that it is important to integrate different evaluation criteria to properly assess the effectiveness of each retrofitting strategy. This paper investigates various evaluation methodologies to comparatively assess retrofitting configurations for a reinforced concrete (RC) school building, assigning different weights to multiple parameters. Some of these evaluation parameters focus not only on the structural performance but also on how each intervention affects the operability of the building and future maintenance actions. The structural performance of the building was quantified in terms of seismic losses, including the contribution of non-structural elements. Such comparative performance assessment was conducted on a detailed numerical model, able to reproduce the main structural deficiencies observed during past earthquakes in RC buildings, such as inappropriate strength hierarchy of beam-column joints, non-ductile failure mechanisms or excessive deformation in critical structural elements. The different retrofitting applications were identified with the aim to solve the aforementioned structural issues and improve the overall performance of the buildings, according to the abovementioned metrics. Furthermore, a direct cost-benefit analysis was then carried out for each intervention to determine their economic feasibility. Finally, the rankings obtained by each evaluation approach are compared to the results of the performance assessment as a means of defining the most efficient retrofitting strategy for the case study building.

*Keywords: RC buildings; performance assessment; retrofit strategies; evaluation parameters.*



## 1. Introduction

Retrofitting solutions for existing buildings have been studied and adopted in diverse structures during the past decades. These strategies aimed to improve the seismic behavior of existing buildings and they can include conventional approaches and more sophisticated retrofitting methods, as indicated in ATC-40 [1]. However, in damaged buildings, it is necessary to establish if it is more convenient to repair or to demolish the structure under evaluation. However, selecting the most convenient retrofitting solution is not always a simple and straightforward task [2]. For example, Caterino *et al.* [2] have compared different approaches of a multi-criteria procedure considering structural factors, as well as social-economical aspects, in order to rank a set of possible retrofitting solutions. Moreover, additional aspects, such as invasiveness level, execution time, technical labor work, architectural impact, occupancy disruption, also have an impact on the final decision for selecting a seismic retrofit configuration. With this in mind, this paper reviews currently available evaluation methodologies of different retrofitting solutions, using a specific case-study building. The outcomes are then compared with a detailed assessment, in terms of some of the decision variables, to verify the proposed measures, obtained through these simplified approaches.

## 2. Evaluation methodologies for retrofitting strategies

From a detailed literature review on the topic, five evaluation methodologies have been identified and are outlined and reviewed here, addressing their most relevant features. A cost-benefit analysis is also included among these five approaches to understand the influence of economic aspects.

### 2.1 Multi-criteria decision making

The multi-criteria decision making (MCDM) approach is a decision-support procedure that compares a set of alternatives, when many decision variables are involved, identifying the optimal solution. The procedure uses a technique for order preference by similarity to ideal solution, known as TOPSIS method [3], along with a pairwise comparison [4] to define the importance of each decision variable. Moreover, an eigenvalue approach [5] determines the influence of each variable respect to each other. In this study, the evaluation criteria focus on economical/social and technical aspects studied by Caterino *et al.* [6], adopting an analytic hierarchy process [7].

### 2.2 Seismic resilience

The seismic resilience approach compares the seismic performance recovery, measured as the amount of losses associated to maintaining the functionality of a system to the minimum possible. This framework has been used to verify if intervention strategies can reduce the level of disruption during seismic events (Cimellaro [8] and Mahini *et al.* [9]). To briefly illustrate this approach, in Fig. 1, the resilience is presented as the normalized shaded area underneath the functionality function,  $Q(t)$ , where a linear recovery function is used. The time of occurrence of the event ( $t_{OE}$ ), control time of the system ( $T_{LC}$ ), recovery time ( $T_{RE}$ ), loss function ( $L$ ) and robustness ( $R$ ) are needed to estimate the resilience of the system.

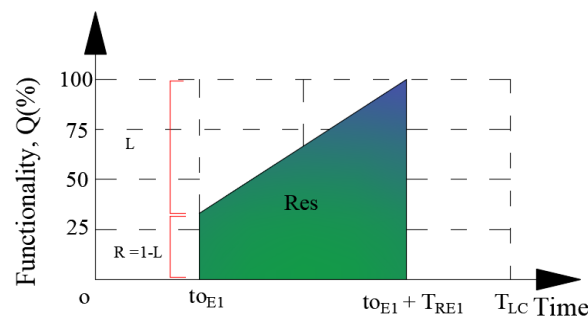


Fig. 1 – Linear recovery resilience-functionality relationship, adapted from [9]



### 2.3 Index-based method

According to the index-based method, an optimal retrofitting strategy can be determined using Eq. (1), proposed by Requena *et al.* [10], calculating a seismic retrofitting index. This method has been tested in a reinforced concrete (RC) primary school building to improve its seismic performance and the foreseen procedure considers three aspects: structural improvement, defined by the efficiency index ( $E_I$ ); retrofit cost, measured by the cost index ( $C_I$ ); and architectural impact ( $A_I$ ). These indices are then used to determine the seismic retrofitting index ( $R_I$ ), where  $\delta$ ,  $\beta$ , and  $\gamma$  are coefficients that modify the aforementioned indices according to the singularities of each solution; and  $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$  are importance factors. The retrofitting strategy for which the highest index is obtained is considered as the most convenient one.

$$R_I = \alpha_1 \cdot \delta \cdot E_I + \alpha_2 \cdot \beta \cdot C_I + \alpha_3 \cdot \gamma \cdot A_I \quad (1)$$

### 2.4 Sismabonus

The *Sismabonus* approach provides a straightforward seismic risk classification system for existing buildings in Italy. The risk classification, described by Cosenza *et al.* [11], is based on two parameters: a life safety index (IS-LS) and the expected annual losses (EAL). Each parameter receives a classification ranking and the most critical class defines the overall risk classification of a building. This methodology provides a means of comparison of structural interventions, through the number of upgraded classes achieved by each retrofit solution.

### 2.5 Cost-benefit analysis

Sousa and Monteiro [12] quantified the cost and benefit of implementing non-structural strengthening to RC buildings through the benefit-cost ratio (BCR) approach, as indicated in Eq. (2). This approach determines the economic feasibility of an intervention by estimating the break-even point, which refers to the time needed to recover the initial investment associated with it, i.e.  $T$ , such that  $BCR(T) = 1$ , where  $T$  represents the lifespan of the building, NPV is the net present value of the amount of EAL,  $r$  presents the discount rate that accounts for the change in cash flow over time, and  $CR$  is the total cost of the retrofit.

$$BCR(T) = \frac{NPV_{as-built} - NPV_{retrofitted}}{CR} = \frac{\sum_{t=1}^T \frac{EAL_{as-built}}{(1+r)^t} - \sum_{t=1}^T \frac{EAL_{retrofitted}}{(1+r)^t}}{CR} \quad (2)$$

## 3. Case-study building

The case-study building used to apply and compare the five identified approaches consists of a RC school building located in central Italy, a region that has recently experienced numerous seismic events. The building presents two stories and one underground portion, denoted by the red contour in Fig. 2a; the construction period is estimated around 1960-1970.

### 3.1 Numerical modelling

As illustrated in Fig. 2b, the numerical model was developed in OpenSees [13] following the recommendations of O'Reilly and Sullivan [14] for simulating the structural behavior of old RC frames. The model adopts force-based beam-column elements with lumped plasticity for beams and columns and, to capture the nonlinear behavior of joints, a zero-length spring coupled with a rotational hinge at the joint centerline was implemented. The model also takes into account second-order geometry effects (P- $\Delta$ ) and assumes an inherent damping level of 5%.

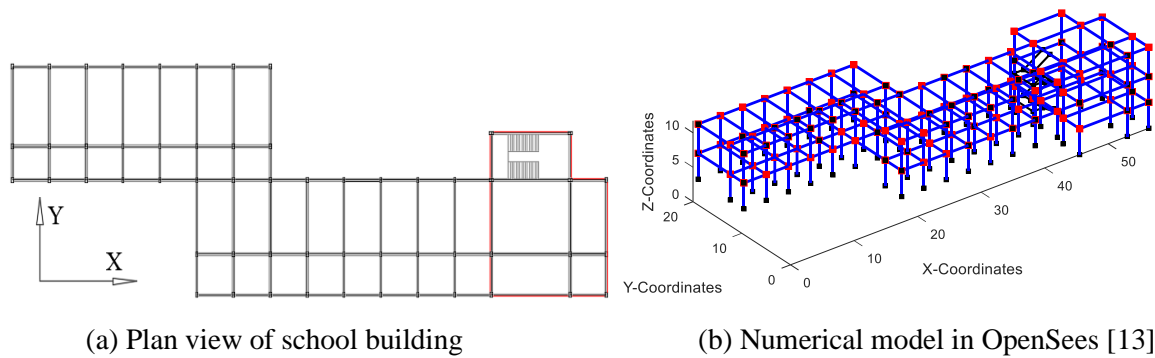


Fig. 2 – School building configuration

### 3.2 Structural response and performance

The uniform hazard spectrum (UHS) was defined for the building's location, for the four limit states specified by the Italian seismic design guidelines (NTC 2018 [15]) for a building class III, which corresponds to a nominal life of 75 years in the case of school buildings. These limit states were defined as 45, 75, 712 and 1463 years, corresponding, respectively, to SLO: operational limit state, SLD: damage limitation limit state, SLV: life safety limit state, and SLC: collapse prevention limit state [19]. Fig. 4 presents the pushover curve, in terms of base shear coefficient (base shear/seismic weight of the building) and the building roof drift (roof displacement/total building height). The capacity limit states have been identified in terms of strength and deformation capacity according to NTC 2018 [15]. A drift limit of 0.5% for rigid partition is set according to [15] to limit the damage of non-structural elements. For class III buildings, SLD and SLO are defined as this 0.5% drift limit and two-thirds of it, respectively, whereas, for SLV and SLC, the structural elements must be verified for ductile and brittle failure mechanisms according to [15, 16]. As a result, it was found that the lack of capacity of some joints takes place before reaching the SLO, meaning that all other limits states are controlled by the brittle failure mechanism of these joints. Fig. 3 illustrates the location of the different limit states in the capacity curve of the building, which are the same for all limit states due to the premature failure of joints.

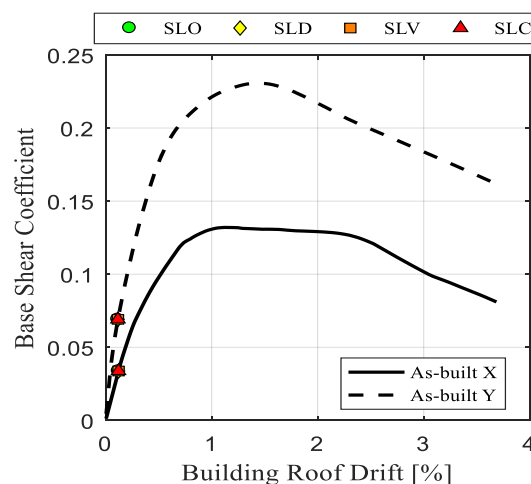


Fig. 3 - Lateral capacity of the building normalized by the total building weight, and displayed the capacity points for each the limit state.

To assess the building's performance, the N2 method was used, following the guidelines of Fajfar [17]. The serviceability limit states (SLO and SLD) were assessed referring to the drift limits, i.e. 2/3 of 0.5% and 0.5%, respectively. Fig. 4a illustrates how the building does not fulfil the code requirements based on drift limitation. Likewise, for the ultimate limit states (SLV and SLC), some drift concentrations are observed in



Fig. 4b, which take place in the second story for the X direction and in the third story for the Y direction. Moreover, several beam-column joints do not follow a ductile failure mechanism, as described by Tasligedik *et al.* [18].

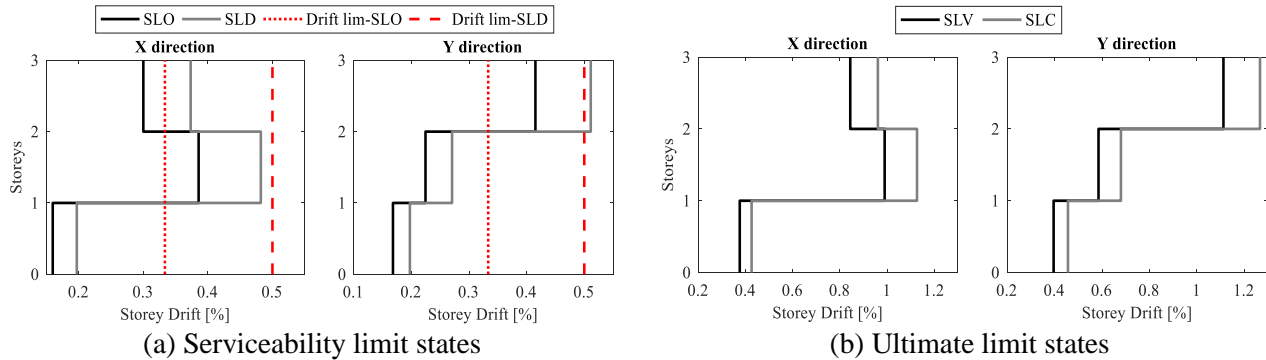


Fig. 4 - Maximum story drift profiles for different limit states

#### 4. Retrofitting schemes applied to the case-study building

Three retrofit options are proposed, aimed at improving the building's global performance. Furthermore, these alternatives were defined strategically to consider the different cost of implementation, execution time and architectural impact.

##### 4.1 Description of retrofitting strategies

The first alternative (A1 in Fig. 5a) foresees FRP bars and FRP wrapping to the columns to increase their flexural capacity, as well as their shear resistance and confinement. Additionally, FRP strips are placed in the joints to improve their shear resistance. A1 is aimed to provide an adequate strength hierarchy that ensures a ductile failure mechanism in the column-beam joints [18]. The properties of the FRP material were adopted from [19], while the flexural capacity of the retrofitted structural members was derived from [20] and from [21, 22] for the specific case of the joints.

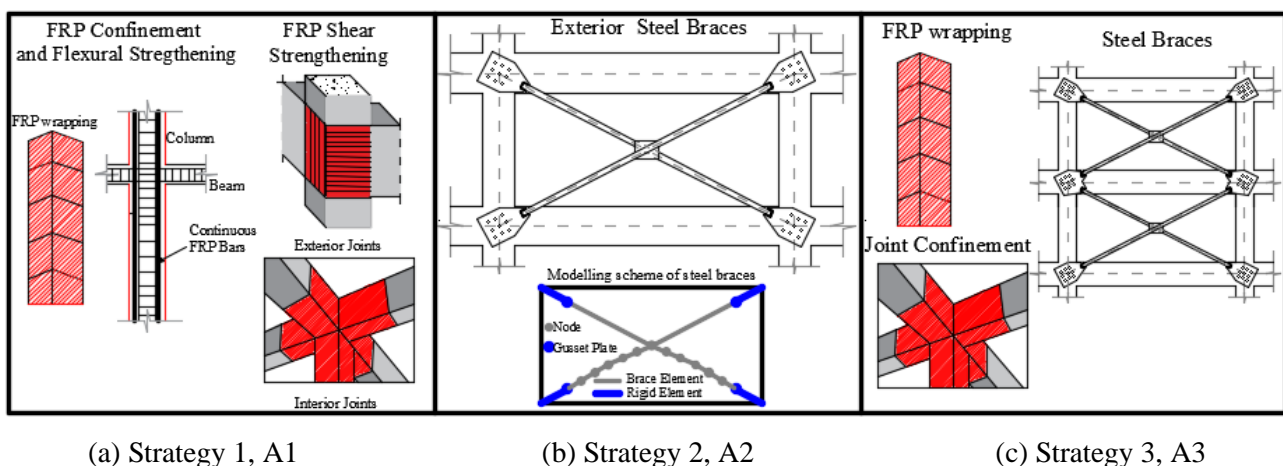


Fig. 5 – Retrofitting schemes

The second alternative (A2 in Fig. 5b) consists of the installation of external steel braces, which are connected in the middle of their length to minimize the unbraced length and improve the overall post-buckling resistance, as illustrated in Fig. 5b. The steel braces are aimed to increase the lateral resistance and the stiffness of the building and thereby reduce the buildings' displacement demand. The design of the braces



was conducted through an equivalent single-degree-of-freedom system, as described by Di Cesare and Ponzo [23]. Additionally, the effect of global buckling was modelled using the recommendations of Lignos *et al.* [24] and the guidelines of Uriz and Mahin [25]. The third retrofitting alternative (A3 in Fig. 5c) is based on a hybrid strategy that combines the effects of FRP with steel braces. This configuration is expected to provide a proper strength hierarchy in the joints and to decrease the lateral displacements.

#### 4.2 Performance assessment and loss estimation

All the retrofitting strategies increased the lateral resistance of the school building. As illustrated in Fig. 6, A1 (blue lines) develops a higher strength capacity and moves the capacity points of the building to larger displacements, indicating a reduction of the seismic vulnerability of the structure. Similarly, A2 rises the strength and the lateral stiffness of the building considerably, but it does not achieve a substantial improvement in terms of the capacity of the elements (capacity points). On the other hand, A3 improves significantly the structural behavior of the building, demonstrated by the largest shifting of the capacity points.

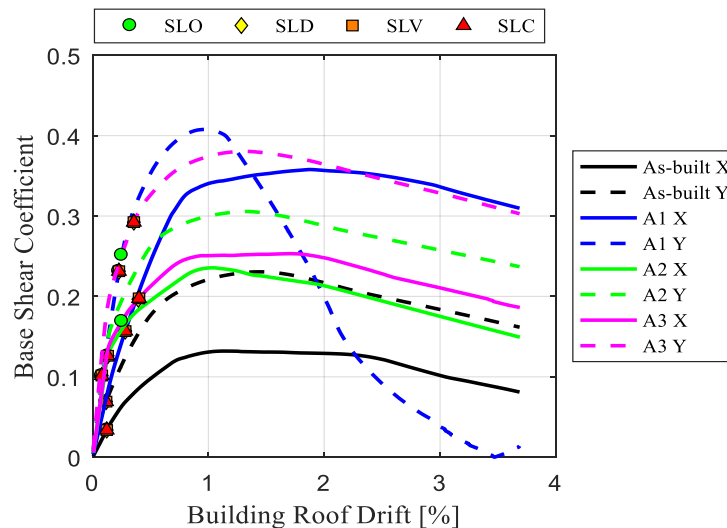


Fig. 6 – Lateral strength comparison of different strategies

Moreover, structural performance can reflect the effectiveness of the strategies in terms of drift profiles. For instance, considering the serviceability limit states (SLO and SLD), all the retrofitting strategies reduce the magnitude of the drift profiles, which are now comply with the standard recommendations [15], as shown in Fig. 7. In the case of the ultimate limit state (SLV and SLC), the story drifts are also more under control, mitigating the drift concentration observed for the as-built configuration.

Collapse assessment and loss estimation analyses were also conducted through a multiple-stripe analysis (MSA) approach. The software OpenQuake [26] was used to perform the probabilistic seismic hazard analysis (PSHA) and disaggregation for the site location. The source Model MPSO4 [27] and ground motion model of Akkar *et al* [28, 29] were adopted. The ground motion selection was carried out in terms of average spectral acceleration (AvgSA) [30], as intensity measure, since the different numerical models (i.e. as-built configuration and retrofitting strategies) presented period variations. As such, to include these differences, the AvgSA was selected for a range of  $0.2T - 1.5T$  [30], where  $T$  was taken as the geometric mean of the periods of the two fundamental modes. A set of 20 pairs of ground motion records in two horizontal components were downloaded from the Engineering Strong-Motion database (ESM) [31].

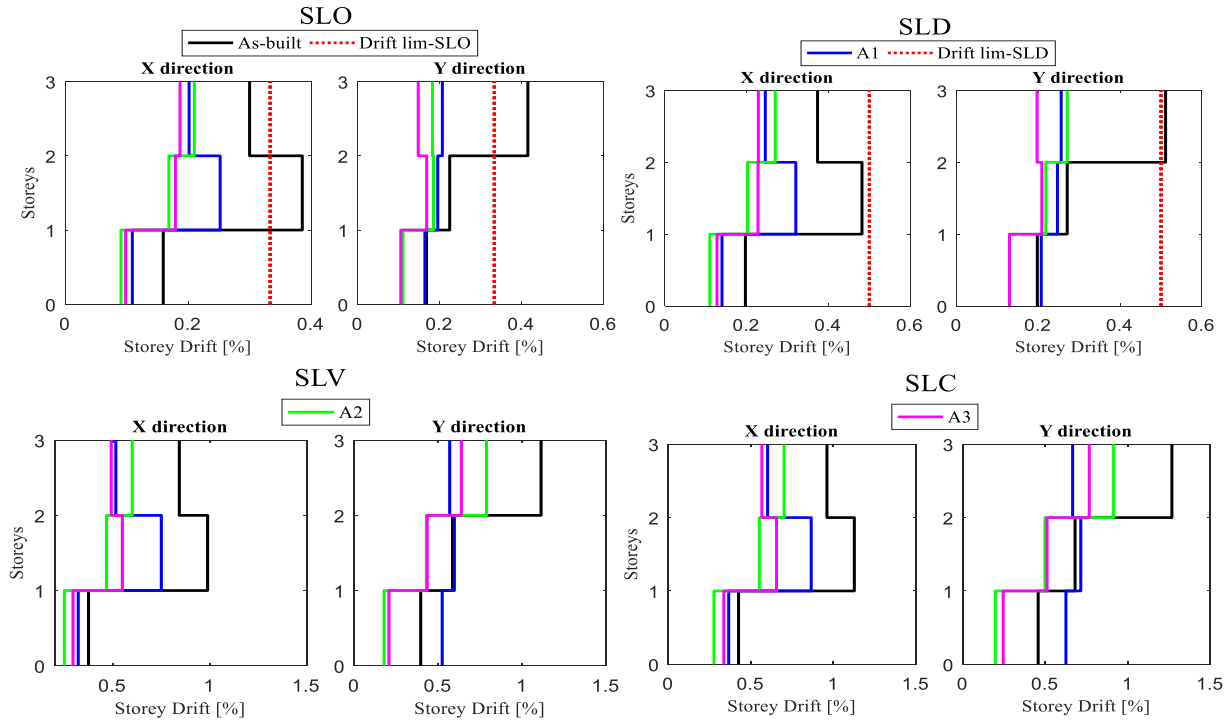


Fig. 7 – Comparison of maximum story drift profiles for different limit states

The collapse criteria for elaborating the collapse fragility function of each numerical model was based on NTC 2018 [15]. As observed in Fig. 8, the as-built configuration is very vulnerable already for low spectral acceleration (i.e.  $S_a(T)$  lower than 0.2g). Nevertheless, the retrofitting strategies deal with this issue by shifting the collapse fragility function to a higher range of intensity levels (i.e. larger  $S_a(T)$ ). As outlined in Table 1, the median collapse intensity for all retrofitting alternatives is larger than the one obtained with the as-built model. The collapse margin ratio (i.e. the ratio between the median collapse intensity and the intensity level associated to the collapse limit state), is a performance criterion that can be used to evaluate the collapse vulnerability level. Even though all alternatives present higher CMR in comparison to the original configuration, A3 is the only strategy presenting a CRM higher than unity. Therefore, A3 is the best alternative, when it comes to collapse safety.

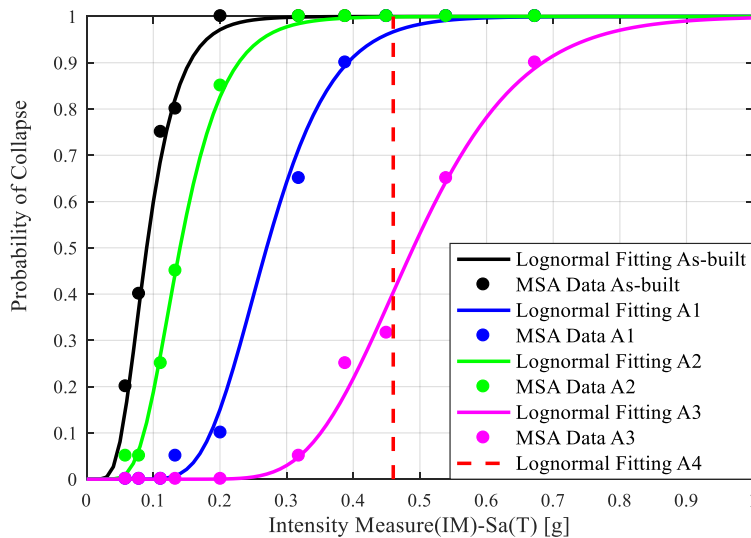


Fig. 8 - Collapse fragility functions



Additionally, Table 1 lists the expected annual losses (EAL) for each model. All the alternatives decrease EAL, but only A1 and A3 achieve a considerable reduction. Despite A1 and A3 present almost the same EAL, A1 reached a lower one hence this alternative can be considered as the most effective for decreasing EAL.

Table 1- Median collapse intensities, collapse margin and expected annual losses, for retrofitted case study school buildings

Model	Median collapse intensity [g]	Sa at SLC [g]	Collapse margin ratio (CMR)	EAL [%]
As-built	0.09	0.46	0.20	1.56
A1	0.27	0.46	0.59	0.54
A2	0.14	0.46	0.30	1.15
A3	0.49	0.46	1.07	0.60

In summary, from the detailed performance assessment (SLO, SLD, SLV and SLC) and considering the collapse vulnerability and loss estimation analyses (CMR and EAL), A3 results as the most satisfactory retrofitting intervention. This alternative is able to meet the code requirements for strength and serviceability criteria. Additionally, it improves the overall performance of the building by reducing its collapse vulnerability and expected losses. Although A2 and A1 cannot reduce the collapse vulnerability to a safe margin (i.e. CMR >1.0), these alternatives improved the other criteria parameters therefore the retrofitting alternatives can be preliminarily ranked as A3-A1-A2 according to the most efficient to the less adequate strategy.

## 5. Application of evaluation methodologies and comparison

### 5.1 Ranking of retrofitting strategies

For the implementation of the multi-criteria decision making (MCDM) approach, the necessary decision matrix is presented in Table 2. The installation costs ( $C_1$ ) were estimated from published information [19, 32] and following recommendations by practitioners and manufacturers. The maintenance costs ( $C_2$ ) and execution time ( $C_3$ ) were estimated from the study in [6] which deals with similar retrofitting strategies. Functional compatibility ( $C_4$ ) and technology level ( $C_5$ ) were conducted through qualitative criteria, following the TOPSIS method [3]. The alternative A1, consisting of FRP, is less invasive than the implementation of steel braces (A2 and A3) however, it requires a higher level of specialization of the workers. The intervention at the foundation ( $C_6$ ) was determined as the ratio of the maximum vertical reaction of each alternative to the maximum vertical reaction of the as-built configuration. The significant damage risk ( $C_7$ ) and damage limitation risk ( $C_8$ ) were taken from the hazard curves at SLV and SLD.

Table 2 – Multi-criteria decision making (MCDM) approach decision matrix.

Alternative	Economical/Social Aspects				Technical Aspects			
	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	$C_6$	$C_7$	$C_8$
A1	€1,494,443.52	€1,501,561.15	72 days	0.550	0.582	2.90	0.022	0.291
A2	€7,583.52	€1,6161.58	9 days	0.210	0.109	15.18	0.024	0.002
A3	€645,548.36	€657,164.87	42 days	0.240	0.309	2.97	0.04	0.172

Following the analytic hierarchy process [7], the ranking of the retrofitting strategies resulted as shown in Table 3.  $C_i^*$  represents the relative closeness to the ideal solution hence the alternative with the highest  $C_i^*$  is considered as the optimal strategy according to the parameters evaluated in the MCDM [6].



Table 3 – Ranking of alternatives using analytic hierarchy process [7].

Alternative	C <sub>i</sub> *	Rank
A1	0.497	III
A2	0.503	II
A3	0.526	I

For what concerns the seismic resilience-based approach, it has been conducted for the SLO. For this limit state, the standards prescribe that the building should remain operative after an event of such intensity level. Table 4 outlines the parameters needed for estimating the resilience. The expected losses (L) and recovery time (T<sub>REI</sub>) were obtained from the loss assessment for the return period corresponding to SLO, using the software PACT [33]. All retrofitting strategies reduced substantially the recovery time respect to the as-built model and increased the resilience of the building. The ranking presented in Table 6 is based on the alternative achieving the highest resilience level.

Table 4 – Parameters to estimate the seismic resilience for SLO [9].

Model	T <sub>REI</sub>	L	1-L	Resilience	Rank
As-built	130	0.07	0.9300	96.6%	---
A1	7	0.018	0.9820	99.1%	II
A2	8	0.022	0.0980	98.9%	III
A3	5	0.016	0.0984	99.2%	I

Subsequently, the index-based method was implemented and the parameters used in Eq. (1) are outlined in Table 5. The efficiency index (E<sub>I</sub>) is the ratio between the shear capacity of the retrofitting solution and the shear capacity of the as-built model;  $\delta$  represents the ratio between the displacements of the retrofitted configuration to the displacement of the original configuration, obtained from the performance points. The construction cost index (C<sub>I</sub>) represents the ratio between the construction cost of the cheapest retrofitting solution and the cost of the assessed one. The parameter  $\beta$  is the importance of the cost, according to Requena *et al.* [10]  $\beta$  is taken as 1.00 when one building is assessed). The architectural index (A<sub>I</sub>) presents the architectural impact of the retrofitting strategy, evaluated through a table reported in [10], ranging from 1 (for the highest architectural impact) to 1.4 (for the lowest impact). The parameter  $\gamma$  relates the importance of the building in terms of protection (i.e.  $\gamma=1.00$  for the case of school buildings [10]). Requena *et al.* [10] suggests to consider the efficiency (E<sub>I</sub>) as the most important factor for sites with significant seismic hazards. Consequently,  $\alpha_1$ ,  $\alpha_2$ ,  $\alpha_3$  were adopted as 0.6, 0.2 and 0.2, respectively [10]. The most convenient solution is the one with the highest R<sub>I</sub>.

Table 5 - Evaluation of parameters for obtaining the retrofitting index [10].

Alternative	$\delta$	E <sub>I</sub>	C <sub>I</sub>	A <sub>I</sub>	R <sub>I</sub>	Rank
A1	2.30	4.64	0.01	1.20	6.64	II
A2	1.07	3.73	1.00	1.00	2.79	III
A3	3.31	5.84	0.01	1.00	11.79	I

Regarding the Sismabonus guidelines [11], Table 6 outlines the resulting seismic risk classification. IS-LS is computed as the ratio between the capacity and demand peak ground accelerations (PGA) for the life-safety limit state (SLV), whereas the EAL is estimated through the mean annual frequency of exceedance (MAFE) of the PGA for each limit state. This procedure is comprehensively illustrated in O'Reilly *et al.* [34]. The ranking is provided according to the number of the upgraded classes achieved by each intervention.



Table 6 - Seismic risk classification of the different models [11].

Alternative	IS-LS Classification	EAL Classification	Overall Classification[30]	Rank
As-built	0.18 (E)	8.22% (G)	G	---
A1	0.62 (B)	0.77% (A)	B (5↑)	II
A2	0.24 (E)	4.56% (F)	F (1↑)	III
A3	1.01 (A)	0.51% (A)	A (6↑)	I

Finally, a cost-benefit analysis is conducted for each strategy to determine the economic feasibility of implementing each of the alternatives. Assuming a rate of return of 2% and setting the lifespan of the building as 100 years, a cost-benefit-ratio was carried out as illustrated in Fig. 9.

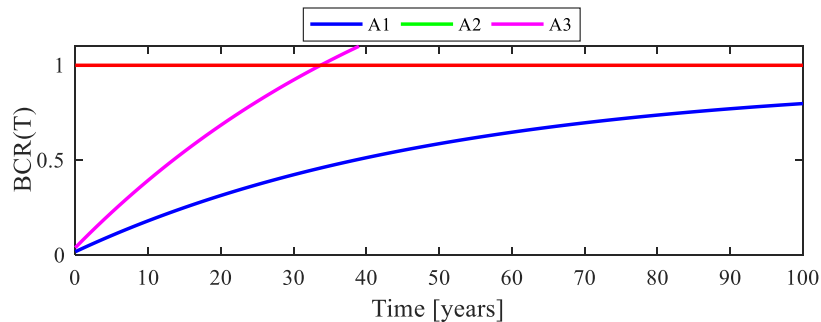


Fig. 9 - Cost-benefit analysis of studied retrofit strategies

The replacement costs reported in Table 7 were estimated using a general cost per floor area, rather than an individual component-based cost summation approach, remaining therefore unchanged for all models. The retrofit cost associated with A2 is 0.3% of the total replacement cost of the building. From an economic point of view, the A2 could represent a very attractive strategy, since the amortization time is virtually immediate. On the other hand, A1 needs more than 100 years to amortize the investment fully, thereby, this strategy is not economically favorable. Finally, the implementation cost of A3 would be amortized entirely after 34 years, which is a reasonable period, since it represents less than half of the lifespan of the building.

Table 7 - Detailed of replacement costs and cost of retrofit interventions

Model	Replacement Cost [€]	EAL [%]	Cost of Retrofit Intervention [€]	Breakeven time [years]	Rank
As-built	2,652,465.00	1.56%	---	---	---
A1	2,652,465.00	0.54%	1,494,443.52	>100	III
A2	2,652,465.00	1.15%	7,583.52	0.0	I
A3	2,652,465.00	0.60%	645,548.36	34.0	II

## 5.2 Discussion of results

As stated in section 4.2, A3 is considered the most effective retrofitting solution for improving the global structural risk performance of the building. However, when merging both structural and economic criteria,



the alternatives were ranked as A3-A1-A2, listed from the optimal to the unfavorable one. The same ranking was obtained by the approaches of Sismabonus, seismic resilience and index-based method whereas the cost-benefit ratio methodology determined A2 as the most convenient alternative from an economic point of view. This outcome is due to the low retrofitting cost of this intervention. Moreover, the MCDM considered A2 as the second-best solution, when considering costs of implementation, maintenance, execution time and functionality, which, indeed, gives more benefit to A2 than A1. Even though the Sismabonus agrees with the ranking provided by the detailed assessment, the EAL are overestimated and do not follow the same pattern (i.e. EAL of A1 higher than EAL of A3).

## 6. Conclusions

The application of five different evaluation methodologies enabled the critical review and comparison of currently available procedures to select the most efficient retrofitting solution among a set of different options, using an existing school building as illustrative case-study. It was observed that, among three different options, the retrofitting alternative based on FRP and steel braces was the most suitable strategy for the case study building since it improves the overall performance of the building considerably. This outcome was indeed confirmed by four of the tested methodologies. On the other hand, the retrofitting alternative based on steel bracings is the less desirable alternative, as it is not able to meet code requirements. The only contrasting approach was the cost-benefit analysis, which identified the solution based on steel braces, only, as the most convenient strategy from an economic point of view. These different evaluation methodologies are useful for selecting the best retrofitting intervention from a group of alternatives when a detailed assessment is not conducted (performance assessment and loss estimation) however, even though most of them, for this specific case-study building, identified the same best retrofitting option, non-homogeneous outcomes were found for the ranking of the remaining strategies. Moreover, some procedures strictly depend on the adopted coefficients, which deserve future developments for their calibration.

## 7. Acknowledgements

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## 8. References

- [1] Applied Technology Council (ATC) (1996): ATC-40: Seismic evaluation and retrofit of concrete buildings. United States.
- [2] Caterino N, Iervolino I, Manfredi G, Cosenza E (2009): Comparative analysis of multi-criteria decision making methods for seismic structural retrofitting. *Comput-Aided Civ Infrastruct Eng*, 24 (1):14.
- [3] Hwang CL, Yoon K (1981): Multiple Attribute Decision Making, Lecture Notes in Economics and Mathematical Systems 186, Springer-Verlag, Berlin.
- [4] Shapira, M, Goldenberg M (2005): AHP-based equipment selection model for construction projects. *ASCE Journal of Construction Engineering and Management*, **131** (12), 1263–1273.
- [5] Saaty TL (1980): *The Analytic Hierarchy Process* McGraw-Hill, New York.
- [6] Caterino N, Iervolino I, Manfredi G, Cosenza E (2008): Multi-criteria decision making for seismic retrofitting of RC structures. *Journal of Earthquake Engineering*, 12, 555-583. DOI: 10.1080/13632460701572872.
- [7] Geoff Coyle: Practical strategy. Open Access Material (2004): AHP. The analytic hierarchy process (AHP). *Pearson Education Limited*.
- [8] Cimellaro GP (2008): Seismic resilience of a regional system of hospitals. Multidisciplinary Center for Earthquake Engineering Research (MCEER) publication, <http://mceer.buffalo.edu/publications/resaccom/07-SP05/01Cimellaro.pdf>.
- [9] Mahini S, Hadigheh, SA, Setunge S. (2015). Seismic resilience of retrofitted reinforced concrete buildings.
- [10] Requena M, Morales A, Durand P, Estêvão J (2019): An index-based method for evaluating seismic retrofitting techniques. Application to a reinforced concrete primary school in Huelva. *PLoS ONE*, 14 (4), e0215120, <https://doi.org/10.1371/journal.pone.0215120>. 2019.



- [11] Cosenza E, Del Vecchio C, Di Ludovico M, Dolce M, Moroni C, Prota A, Renzi E. The Italian guidelines for seismic risk classification of constructions: technical principles and validation. *Bulletin of Earthquake Engineering*. 2018; 16:5905–5935, <https://doi.org/10.1007/s10518-018-0431-8>.
- [12] Sousa L, Monteiro R (2018): Seismic retrofit options for non-structural building partition walls: impact on loss estimation and cost-benefit analysis. *Engineering Structures*. 161, 8–27, <http://dx.doi.org/10.1016/j.engstruct.2018.01.028>.
- [13] McKenna F, Scott MH, Fenves GL (2010): Nonlinear finite-element analysis software architecture using object composition. *J Comput Civ Eng*, 24, 95–107, [http://dx.doi.org/10.1061/\(ASCE\)CP.1943-5487.0000002](http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000002).
- [14] O'Reilly GJ, Sullivan TJ (2017): Modeling techniques for the seismic assessment of the existing Italian RC Frame Structures. *J Earthq Eng*. 1–35, <http://dx.doi.org/10.1080/13632469.2017.1360224>.
- [15] NTC (2018): Norme Tecniche Per Le Costruzioni. Rome, Italy.
- [16] Supplemento ordinario n. 5 alla Gazzeta Ufficiale (2019): Roma.
- [17] Fajfar P (2000): A nonlinear analysis method for performance based seismic design. *Earthquake Spectra*, **16** (3), 573-592.
- [18] Tasligedik S, Akguzel U, Kam W, Pampanin S (2016): Strength hierarchy at reinforced concrete beam-column joints and global capacity. *Journal of Earthquake Engineering*. 1-34.
- [19] Mugahed Y, Rayed A, Raizal S, Hisham A, Hunge C (2018): Properties and applications of FRP in strengthening RC structures: A review. *Structures*. 16, 208-238, <https://doi.org/10.1016/j.istruc.2018.09.008>.
- [20] EN 1998-3 (2005): Eurocode 8: Design of structures for earthquake resistance – Part 3: Assessment and retrofit of buildings. Brussels, Belgium.
- [21] Del Vecchio C, Di Ludovico M, Prota A, Manfredi G (2015): Analytical model and design approach for FRP strengthening of non-conforming RC corner beam-column joints. *Engineering Structures*. 87, 8-20,
- [22] Akguzel U, Pampanin S (2012): Assessment and design procedure for the seismic retrofit of reinforced concrete beam-column joints using FRP composite materials. *ASCE, J. Compos. Constr.* **16** (1), 21-34.
- [23] Di Cesare A, Ponzo F (2017): Seismic retrofit of reinforced concrete frame buildings with hysteretic bracing systems: design procedure and behaviour factor. *Shock and Vibration*, <https://doi.org/10.1155/2017/2639361>.
- [24] Lignos DG, Karamanci E, Martin G (2012): A Steel database for modelling post-buckling behavior and fracture of concentrically braced frames under earthquakes. *15th World Conference on Earthquake Engineering*, Lisbon, Portugal.
- [25] Uriz, P, Mahin, SA (2008): Toward earthquake-resistant design of concentrically braced steel-frame structures. *PEER Report 2008/08*, Berkeley, California.
- [26] GEM (2019): The OpenQuake-engine User Manual. *Global Earthquake Model (GEM) Open- Quake Manual for Engine version 3.7.0*. 183, doi: 10.13117/GEM.OPENQUAKE.MAN.ENGINE.3.7.0.
- [27] Meletti C, Galadini F, Valensise G, Stucchi M, Basili R, BarbaS, Vannucci G, Boschi E (2008) : A seismic source zone model for the seismic hazard assessment of the Italian territory. *Tectonophysics*. 450, 85-108, doi:10.1016/j.tecto.2008.01.003
- [28] Akkar S, Sandikkaya M, Bommer J (2014): Empirical Ground-Motion Models for Point- and Extended-Source Crustal Earthquake Scenarios in Europe and the Middle East. *Earthquake Engineering*.
- [29] Sandikkaya M, Akkar S, Bard P (2013): A nonlinear site-amplification model for the next Pan-European ground-motion predictions equations. *Bulletin of the Seismology Society of America*. **130** (1), 1-32, doi: 10.1785/0120120008
- [30] Kohrangi M, Bazzurro P, Vamvatsikos D, Spillatura A (2017): Conditional spectrum-based ground motion record selection using average spectral acceleration. *Earthquake Engng Struct. Dyn.* DOI: 10.1002/eqe.2876.
- [31] Luzi L, Puglia R, Russo E & ORFEUS WG5 (2016): Engineering Strong Motion Database, version 1.0. *Istituto Nazionale di Geofisica e Vulcanologia, Observatories & Research Facilities for European Seismology*, doi: 10.13127/ESM".
- [32] Mazzolani F, Formisano A, Vaiano G (2018): Adeguamento sismico di edifici in cemento armato: BRB e FRP. *Costruzioni metalliche*.
- [33] FEMA P58-3 (2012): Seismic Performance Assessment of Buildings Volume 3—Performance Assessment Calculation Tool (PACT) Version 2.9.65 (FEMA P-58-3. 1). vol. 3. Washington, DC.
- [34] O'Reilly G, Perrone D, Fox M, Monteiro R, Filiatrault A (2018): Seismic assessment and loss estimation of existing school buildings in Italy. *Eng Strt.* 168,142-162, <https://doi.org/10.1016/j.engstruct.2018.04.056>.