TOWARDS THE SEISMIC AND ENERGY RETROFITTING OF EXISTING SCHOOL BUILDINGS VIA AN INTEGRATED DESING PROCEDURE

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Abstract

Nowadays most of the Italian existing reinforced concrete (RC) school buildings are obsolescent and not compliant with modern requirements in terms of seismic safety, energy efficiency and living comfort. Most of them require a deep renovation in order to improve the performances in terms of overall comfort, structural safety and energy efficiency. This makes their management difficult and expensive. In the past few years, significant economic resources have been mainly invested on the improvement of facilities, systems and general decor, while neglecting structural safety. Recent Italian seismic events showed the high seismic vulnerability of the existing school buildings, which exhibited severe damage or collapse, thus yielding significant social and economic losses. Therefore, an effective renovation design cannot neglect to consider, simultaneously, both structural and energy aspects.

In this context, this research work presents a novel integrated retrofit design methodology for the structural and energy improvement of existing school buildings. An incremental retrofit approach consisting in implementing interventions with an increasing impact, increasing performance and increasing cost and benefits is herein proposed. In order to validate the proposed retrofit design approach and quantify the relevant costs and benefits, case studies typical Italian existing RC school buildings are investigated. Different retrofit solutions are discussed and compared in terms of seismic and energy performance, benefits of the intervention, level of disruption and direct costs of implementation. The outcomes of this study can be used to help the stakeholders in the selection of the most convenient retrofit solution.

Keywords: energy efficiency; strengthening; public buildings; reinforced concrete; cost-benefit;

1. Introduction

Recent devastating earthquakes occurred worldwide demonstrated the high vulnerability of existing school buildings [1,2]. Most of the school buildings in Europe are aged buildings and they are approaching their "design" end-of-life. For instance, in Italy more than 65% of existing schools were built before the 1974 [3], i.e. before the seismic or energy efficiency regulations were enforced. Nowadays, most of the school buildings are obsolete and exhibit significant degradation of structural and non-structural components frequently resulting in the partial or total collapse also without any exceptional load.

Many research studied focused on prioritization schemes, methodologies [1,4] and innovative retrofitting solutions [5,6] to improve the seismic performance of school buildings. However, it is a matter of fact that major retrofit plans were undertaken only in the aftermath of devastating earthquakes [2,5].

Recently, a number of Italian/European existing schools have been renovated with significant economic resources mainly invested in the aesthetic restyling or a small energy refurbishment, instead of a substantial retrofitting [1,7,8]. This is to comply with EU Directives and international agreements in matter of efficiency in energy use [9]. However, recent seismic events and relevant studies outlined that any actions aimed at improving energy and environmental efficiency without addressing safety at the same time is bound to failure (SAFESUST workshop, [10]). To address this issue, regional or national programs were funded to collect detailed information on the status of existing school buildings and their seismic performance [2]. In Italy, recent national investment plans specifically provides funding (about 1 billion €, [11]) for retrofitting of existing school buildings in order to improve their seismic and energy performance. The intervention should be designed according to the recently released national standards for constructions (NTC, 2018 [12]) prescribing a minimum safety level about 60% of the new building standard. However, the long time needed for the implementation of effective structural and energy retrofitting on existing school buildings, commonly lead to the interruption of the school activities for years. This is a real barrier and novel methodologies and retrofit techniques integrating the seismic and energy retrofitting are needed.

In this context, the Italian Department of Civil Protection within the framework of the PE 2019–2021 joint program DPC-ReLUIS, WP5: "Fast and Integrated Retrofit Interventions" supported the research activities to develop a proper methodology for the integrated retrofitting of existing school buildings by using fast and innovative solutions.

This work presents a novel integrated design methodology for the combined seismic strengthening and energy retrofit of existing RC school buildings. An incremental approach consisting of retrofit interventions with an increasing impact, increasing performance and increasing cost and benefit is herein proposed. The design strategy aims to firstly identify the criticisms in the seismic and energy performances; then, the combination of the retrofit interventions is discussed with reference to RC case study building typical of the Italian school building stock.

2. Methodology for the integrated retrofitting of existing RC buildings

Many of available studies or practical cases dealing with large-scale retrofit have mainly focused on single aspects, such as energy or structural performance of non- and retrofitted structures [4,13], while few works have dealt with the integration of different sustainability targets [14]. Multi-disciplinary approaches capable of maximizing the benefits of integrated retrofit strategies (i.e., encompassing the simultaneous consideration of energy, structural and possibly environmental aspects) would be fundamental in Italy where the territory and existing school buildings are characterized by: (i) high vulnerability; (ii) large areas prone to seismic risk; (iii) wide range of climatic zones with variable and significant values of energy demands for space heating and cooling. For instance, focusing on the spatial distribution in the Italian territory of Heating Degree Days, (HDD, which is referred to the heating season) and the peak ground acceleration (PGA, expected with a 10% exceedance probability in 50 years), it can be ascertained that many Italian areas (e.g. central Italy, north east Italy etc.) are prone to earthquakes and, at the same time, have high energy demands for space heating. Consequently, independent retrofit strategies aimed, for instance, to reduce energy consumption, would probably generate a waste of money or environmental resources if the retrofitted building is not able to properly resist a very likely seismic event [14].

The methodology presented herein aims to implement an incremental retrofit strategy that integrates energy and structural measures considering physical and social constraints of existing Reinforced concrete (RC) school buildings. In particular, only combined energy-structural interventions that are mutually compatible are considered feasible within the integrated approach. This primarily yields to the constraint that both types of interventions must be applied at the same dimensional scale of the building (e.g. component, envelope, exterior or interior etc.). In addition, eligible combined energy-structural interventions should have compatible duration in terms of practical application.

Since the definition of the optimal retrofit solutions depends on the amount of economic resources and, in the particular case of the school building, on the duration of the intervention, a tentative classification of the integrated interventions based on the total duration is proposed in this paper.

Table 1 reports the seismic and energy retrofit techniques commonly adopted on existing RC buildings. They are ordered in terms of the increasing level of disruption connected to their scale of application on site.

Table 1. Compatibility matrix of seismic and energy retrofit interventions for existing RC buildings

ENERGY EFFICIENCY INTERVENTIONS
Increasing level of disruption, increasing effectiveness

SEISMIC STRENGTHENING INTERVENTIONS
Increasing level of disruption, increasing effectiveness

		Low			**Medium**		**High**	
	Retrofit technique	Thermost. valves	Subst. of windows	Roof insulation	Insuffl ation	Thermal insulat.	New systems	Renewab. energy
Low	FRP jacket	☑	☑	☑	✓	✓	✔	✔
	Steel jacket	☑	☑	☑	✓	✓	✔	✔
	FRCM/ TRM	☑	☑	☑	✓	✓	✔	✔
Medium-to-high	RC jacket	✓	✓	✓	✓	✓	✔	✔
	Steel bracing	✓	✓	✓	✓	✓	✔	✔
	Exterior buttresses/ exoskeleton	✓	✓	✓	✓	✓	✔	✔
High	RC wall addition	✔	✔	✔	✔	✔	✔	✔
	Base isolation	✔	✔	✔	✔	✔	✔	✔

Duration of the interventions: ☑ *Short* ✓ *Medium* ✔ *Long*

Note: the level of disruption for seismic retrofit intervention is taken from fib bulletin 24 [15]. The same criterion is used to assign the level of disruption of energy efficiency interventions.

In particular, the classification proposed by the *fib* bulletin 24 [15] is used for the seismic retrofit interventions. The energy efficiency interventions are then classified by using the same criteria. Table 1 can be used to select the most appropriate integrated retrofit solution based on the level of disruption or the level of effectiveness in the retrofitting. For instance, the designer selects a seismic strengthening solution and the table can be used to identify the energy retrofit interventions with similar level of time duration or even disruption. In particular, when referring to low disruption seismic strengthening interventions (i.e. FRP, steel or TRM/FRCM jacketing), they can be applied mainly from the exterior of the building. Thus, a compatible energy retrofit solution with the same level of disruption is the installation of thermostatic valves, substitution of windows and the insulation of top roof. The reduction of energy consumptions related to these techniques is marginal when compared to the insulation of the perimetral walls or the installation of new systems. However, it is worth mentioning that the selected retrofit solutions do not provide any significant increase in the lateral stiffness of building. Thus, the installation of expensive insulation of the masonry infills without any specific protection against the earthquake damage will result in the increase of the economic value of the building exposed to earthquake hazard. Since most of the repair costs of the building damaged by the earthquake concerns the repair of infills and partitions, this will result in a significant increase of the expected annual losses (EALs) [14]. By contrast, the installation of efficient insulation systems on the perimetral walls is a viable option when seismic retrofit intervention aimed at reducing the lateral deformability of the building (i.e. RC jacketing, RC walls, steel bracing or exoskeleton) are employed.

After the selection of the integrated intervention, it should be characterized in terms of: building performance targets, dimensional scale of the application, improved performances and overall initial costs. The design strategy as-well-as the target of the retrofitting are described herein with reference to the seismic strengthening and energy retrofit. Three levels of intervention with an increasing disruption, performances and cost of installation are defined as described in the following.

2.1 Seismic strengthening

Technical studies demonstrated that local retrofit interventions aiming at increasing the overall building capacity by increasing the seismic performance of critical members without modifying global mass and structural stiffness are cost-effective retrofit solution [4]. Innovative building materials or classic retrofit solutions can be used in a local or global retrofit strategy. In order to comply with the requirements suggested by the Italian seismic code [16] for the seismic strengthening of school buildings, the target safety index ζ_E of the first level of intervention (Level 1) is set equal to 0.60. The main scope of the seismic strengthening at Level 1 is to suggest retrofit interventions with a minimum impact in terms of time of implementation and level of disruption.

In-situ post-earthquake inspections outlined that RC buildings may suffer premature shear failure at the top of the columns due to the interaction with stiff infill wall. Thus, an effective retrofitting of school building which are likely to exhibit shear failure of the RC column due to the interaction with the infills should improve the shear strength of the top-end of the columns in addition to the requirements discussed before. In this context, the seismic retrofit interventions at level 2 suggest the implementation of local strengthening solutions to improve the shear capacity of beam-column joints, the shear strength of the top-end of the columns and of the end of the beams along with column confinement. These interventions are effective in improving the local and global seismic performance as demonstrated by experimental tests and analytical studies [4].

Although local retrofit interventions can be useful to significantly improve the seismic performance of most of the existing RC buildings which were designed without proper seismic detailing, they do not change the dynamic response of the structural system. Thus, their use is restricted to the cases where there is no need for a change of the distribution of the internal actions or where the strengthening intervention is not expected to increase of the lateral stiffness of the structure. Thus, in many cases, where high performance levels are required both in terms of the increase of the safety index until the 100% of the seismic demand or where the drift demand on the structure would be contained, a global retrofit solution is needed. Thus, the Level 3 of the proposed ranking relies on a global retrofit strategy aiming at fully satisfy the seismic demand. In turn, a retrofit intervention with a significant impact on the level of disruption is needed to achieve such a significant increase in the overall building performance.

2.2 The energy retrofit

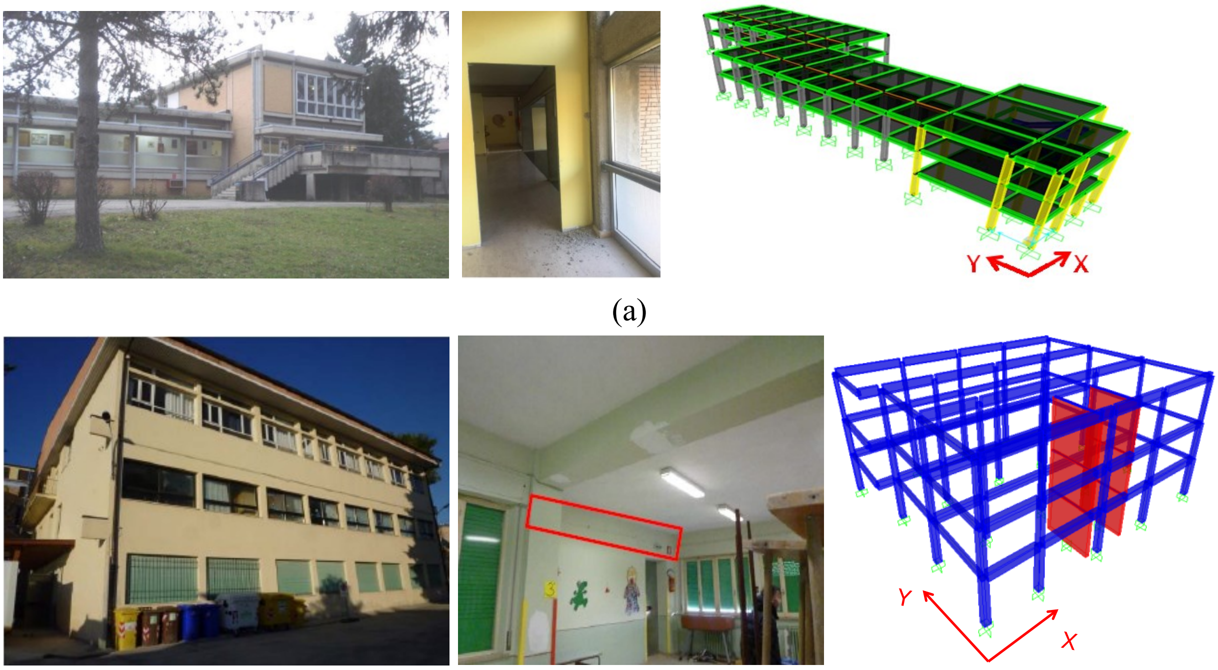
In general, energy retrofit measures (ERMs) can affect (i) the thermal behaviour of the building envelope and/or they may improve (ii) the energy performance of primary energy systems, including the exploitation of renewable energy sources (RESs). In the former case, several studied have demonstrated that the implementation of optimized packages of ERMs is able to reduce the TEDsc, thermal energy demand for space conditioning, as well as the DH, i.e. annual percentage of discomfort hours. With regard to the whole building energy performances, optimized ERM scenarios are usually evaluated by varying set point temperatures and primary energy systems; then, primary energy consumption (PEC) and global cost (GC) are assessed in order to obtain a cost-optimal curve which includes the cost-optimal retrofit solution (minimum of the cost-optimal curve). However, optimized ERMs might be not compatible with other interventions foreseen on the building, e.g. structural intervention, or be costly for a single planned activity. Indeed, rehabilitation works are typically staged over an extended period of time during which some measures can be implemented sooner and others later. For instance, structural retrofit measures could be integrated into ongoing facility maintenance projects that are routinely scheduled during the building lifetime. Similarly, in order to reduce overall costs and the disruption connected to the construction works, ERMs could be scheduled with the same maintenance interventions. In the case of school buildings, scheduled maintenance is often implemented during summer season, i.e. when the school is free of students. In the light of these considerations it is possible to propose three levels of incremental ERMs which are compatible with structural retrofit measures of levels 1 to 3 of safety index. In particular, level 1 of intervention addresses very low-invasive measures, e.g. modification of existing systems, new coverings, small components substitutions etc.; the corresponding target performance is the reduction by approximately 20% of existing school building PEC. In case of level 2, in addition to previous measures, the ERMs affect mainly the envelope thermal performances with targeted and fast interventions; the corresponding target performance is the reduction by approximately 40% of existing school building PEC. Finally in the level 3, a more intensive intervention is conducted and applied both on the envelope end existing primary energy systems; this kind of intervention includes the possibility of applying an exterior insulation and finishing system as well as highly energy-efficient systems or renewable energy systems. The corresponding target performance is the reduction by more than 60% of existing school building PEC.

3. Application to existing school buildings

The selected case study buildings are representative of Italian school building stock built in 1960s – 1970s and in the 1950s – 1970s for the Case study 1 and 2, respectively. They were designed according to the old building code and without any seismic provision. They have been selected to be representative of two of the most diffused archetype school buildings in Italy, namely a two-storey building with large extension in plan (55 m long and 20 m width, see Fig. 1a) and a three-storey building with small in plan extension (22,6 m long and 18,6 m width Fig. 1b). They both relies on RC moment resisting (see Fig. 1).

The material properties were investigated by means of in-situ destructive and non-destructive tests. The mean concrete compressive strength (f_{cm}) is equal to 16.6 MPa and the reinforcing steel yielding stress (f_{ym}) is equal to 390.8 Mpa for the case study building 1, while for the case study building 2 f_{cm} = 20 MPa and f_{ym} = 370 MPa. The structural system of the case study 1 consists of RC frames in both the directions. The RC frames in the short x direction have two bays with length about 6.9 m and 2.7 m and a story height about 3.8m. The case study building 2 relies on RC frames in the x direction. The lateral resisting system in the y direction consists of two RC shear walls and RC perimetral frames. Both the buildings have lack of transverse reinforcement (i.e. 6/8 mm diameter stirrups 150/200 mm spaced in beams and columns and no stirrups in the joint panel), as typically found in existing RC buildings in the Mediterranean area.

The building envelope has low thermal resistance, like a large part of Italian existing buildings (built before 1980) and this implies inadequate energy performance given the high entity of energy demand for space conditioning. In this regard, the vertical external walls are made by hollow bricks and have thermal transmittance (i.e., U-value) equal to 1.23 W/m^2K. The horizontal envelope is in mixed brick-reinforced concrete and the U-value is equal to 1.2 W/m^{2}K. Finally, the windows are double-glazed and have U-value equal to 5.7 W/m^{2}K. The school building 1 is located in Teramo (Central Italy), a city with the following climatic scenario: climatic zone D, with 1834 heating degree days (HDDs), while the case study 2 is located in Macerata (Central Italy) with climatic zone E and HDDs of about 2150. On the other hand, with regard to the seismic risk, the demand PGA (peak ground acceleration) for a return period of 712 years (life safety limit state for a class III building with reference life 75 years) is 0.294g and 0.240g on a B-class soil, respectively for the case study 1 and case study 2 according to the Italian building code [12].



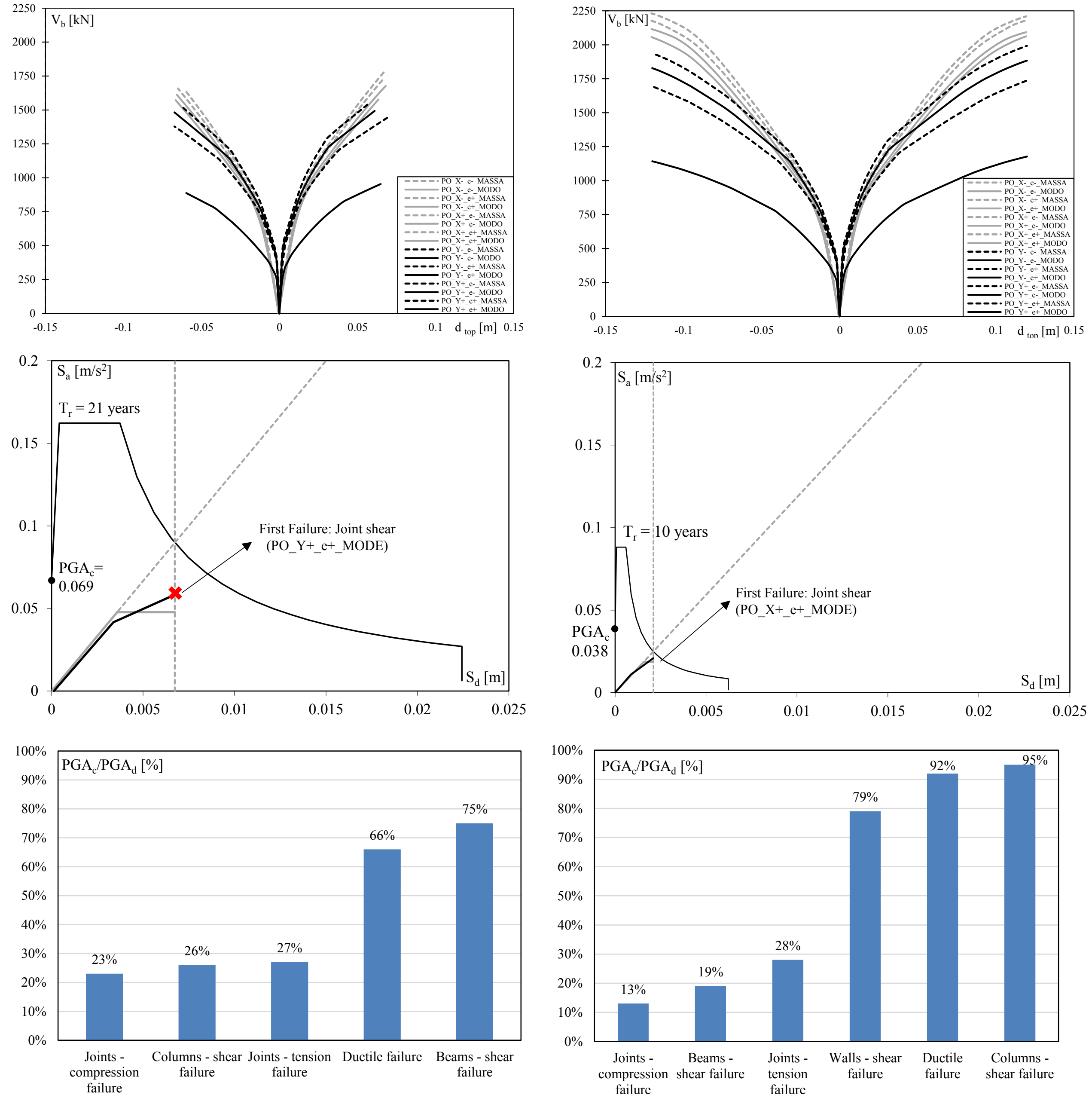
(a)

(b)

Fig. 1 – Front view and plan view of the case study school buildings: Case Study 1 (a); Case Study 2 (b).

3.1 Performance assessment

To assess the seismic performance of the case study buildings, a 3D lumped plasticity nonlinear model was implemented in the SAP2000 platform [17]. A view of the two numerical models is reported in Fig. 1. The non-linearities of beams and columns are concentrated at the member's ends. The plastic hinge properties are characterized by using the capacity models suggested by the Eurocode 8 [18] for the plastic hinge rotation at the yielding and at the ultimate limit state. Two different load profiles applied in the two different directions and considering the Eurocode 8 suggestion on the eccentricity of the center of the mass were considered to develop the push-over curves. The comparison of the seismic demand and the capacity was performed in the acceleration-displacement response spectrum (ADRS) according to the procedure suggested in the Eurocode 8 [19]. The results in terms of pushover curves, the minimum safety index (PGA_c/PGA_d) at the limit state of life safety, LSLS, and the sequence of failures by increasing the demand once the first failure is attained are summarized in Fig. 2. Given the seismic demand, the attainment of ductile failures (i.e. maximum rotational capacity in the beams or columns) or brittle failures (i.e. joints, columns or beams shear failure) in the RC members are checked in compliance with widely recognized capacity model suggested in the Eurocode 8 [18] and Italian building code [16]. The seismic performance assessment of both the case study buildings outlined that the brittle failure of beam-column joints in compression and in tension defines the overall building performances along with the shear failure of the columns of the staircase for building 1 and beam-shear failure for building 2. These failures limit the structural performance to the 23% and 13% of the seismic demand, respectively for the case study 1 and 2. By contrast, the ductile failures only took place when the seismic demand reached a safety index higher than the threshold of the 60% imposed by Italian building code. This remarks that, if the shear strength of beam-column joint and of the short columns is improved, a safety index higher than the minimum allowed in case of seismic strengthening of school buildings according to Italian current code (i.e. the 60%) can be achieved.



(a) Case Study 1 (b) Case Study 2

Fig. 2 - Seismic performance assessment of the case study buildings.

For the climatic location considered (Teramo, climatic zone D, with 1834 HDDs), energy simulations in dynamic conditions were carried out. The main assumptions are reported in Table 2. The IWEC (international weather for energy calculations) weather data file related to Pescara was used. In this regard, accredited weather data files were not available for Teramo, but the use of Pescara file provides a good approximation as well, since these two locations are very close (the distance is around 47.6 km) and characterized by similar climatic conditions (1718 HDDs climatic zone D). As far as the baseline energy performance is concerned, Table 2 reports primary energy consumption for the investigated case studies. The energy performances of the as built buildings led to a low classification in terms of Italian energy efficiency class (class F for both the case studies).

Table 2. Energetic performance assessment of the case study buildings

	Case study 1	Case Study 2
Location	Teramo (TE), Italy	Loro Piceno (MC)
Climatic zone	D (1834 HDDs)	E (2150 HDDs)
Design external temperature (°C)	Winter (0°) Summer (32°)	Winter (-2°) Summer (31°)
Primary energy conversion factors	1.95 (for electricity) 1.05 (natural gas)	1.95 (for electricity) 1.05 (natural gas)
PEC [kWh/m2y]	182	187
Energy class	F	F

3.2 Incremental retrofit interventions

The simultaneous enhancement of the seismic and energetic performances are evaluated with reference to two different indices, the safety index at life safety limit state (LSLS) defined as the PGA_c/PGA_d [%] ratio and the PEC, the Total Primary Energy Consumption, measured in [kWh/m2y] calculated according to the Italian regulations [12,16,20]. The proposed procedure is conceptually described in Fig. 3.

In particular, the three levels of interventions, the techniques adopted for the retrofitting along with the performance targets and comments on the combination of the intervention in the philosophy of the integrated design are schematically reported in Fig. 3.

In line with the objective of the Level 1 interventions, light seismic strengthening schemes with low level of disruption and mainly applicable from the exterior of the building are preferred. Local strengthening interventions can be used for this scope. In order to minimize the cost of the intervention, the level of disruption and the time needed for the implementation, only the joint panel is strengthened in shear by means of a quadri-axial CFRP fabric. To ensure the joint panel strengthening efficiency a proper anchorage system made by FRP spikes is also adopted in the strengthening solution; this solution has been recently validated by means of experimental tests on poorly detailed beam-column joints [21]. Furthermore, the FRP shear strengthening is applied to the short-columns of the staircase for both the buildings. The first level of energy retrofit affects few components of the building and can be classified as local, i.e. with a very low level of disruption. In particular, external roof, internal heating elements and windows are targeted for the energy performance improvement. These components can be easily accessed and do not imply any interruption of school activities. Roof insulation is implemented by means of the installation over the building roof of a 10 cm-thick external layer of insulating material (i.e. extruded polyurethane material with thermal conductivity = 0.026 W/mK); existing windows are replaced with energy efficient ones (i.e. double-glazed argon-filled windows with low-emissive coatings and PVC frames: U_w = 1.71 W/m^2K, SHGC = 0.691) by means of operations which can be completed inside the buildings; the overall energy intervention is completed by introducing thermostatic valves to reduce heat waste and align with the predefined heating set point temperature.

At the second level of the proposed incremental retrofit strategy, the full retrofit scheme suggested by the ReLUIS guidelines [22] is considered for beam column joints. Apart for the joint panel shear strengthening, this scheme allows to improve the shear strength of the top of the column to contrast the infill action by using uniaxial steel FRP fabric. Furthermore, the quadri-axial CFRP fabric is applied on the joint panel and extended for 20 cm at the ends of the framing beams as in the previous case but anchored by means pf CFRP Uni-axial wrapping which also improve the end beam shear capacity. The solution also involves the CFRP Uni-axial wrapping of column ends and beam ends to improve the column confinement. The latter solution has been extensively validated by means of analytical and experimental studies [4].

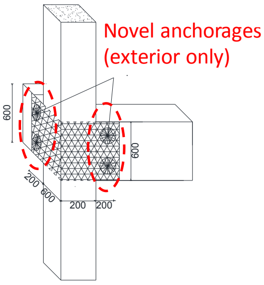
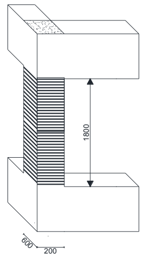
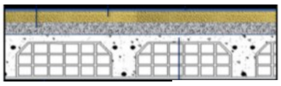
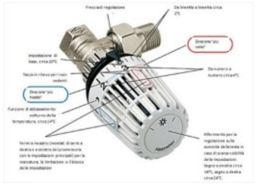
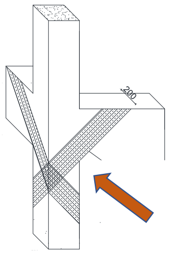
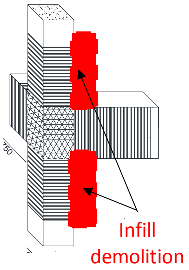
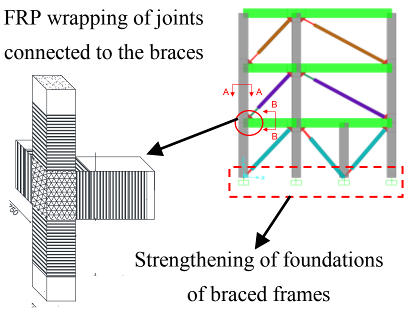
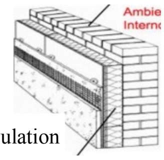
Level of disruption	Performance target	Seismic retrofit technique	Energy efficiency
Low (Level 1)	Seismic strengthening ($PGA_c/PGA_d = 60\%$) Energy efficiency (PEC = - 20%)	FRP strengthening of perimetral joints  FRP wrapping of columns of the staircase  	Roof insulation  Thermostatic valves  New windows (double glazed) 
		Notes: the interventions applicable from the exterior of the building and with low level of distruption are selected in order to avoid the interruption of the activities	
Medium-to-high (Level 2)	Seismic strengthening ($PGA_c/PGA_d = 60\%$) Energy efficiency (PEC = - 40%)	SFRP wrapping to resist infill action  FRP wrapping of joint subassembly  FRP wrapping of columns of the staircase	Interventions of level 1 + Insufflation of perimetral infills  High efficiency boiler 
		Notes: the selected interventions are applicable mainly from the exterior of the building, except for minor demolitions at the corner of the infills for the wrapping of beam and columns. This openings can be used for the insufflation. This requires the closure of some portions of the buildings for few weeks.	
High (Level 3)	Seismic strengthening ($PGA_c/PGA_d = 100\%$) Energy efficiency (PEC = - 60%)	Steel bracing of perimetral frames  	Interventions of level 1 +   Thermal insulation of infills New systems  Renewable energy 
		Notes:the braces can be placed at the exterior frames. The strength and deformability of the slab under horizontal loads should be checked. The strengthening of fundations creates high level of distruption and thus the building can be closed for few months. For this reason new systems and renewable energies are also installed.	

Fig. 3 - Definition of the retrofit interventions for the case study buildings

Although the disruption level is low, the application of the strengthening solution in such a case require that a limited portion of infill should be removed and then replaced. Both for level 1 and level 2 the amount of CFRP plies needed for the shear strengthening of the joint panel is calculated by using the design formulation recently included in the Fib Bulletin 90 [23].

The second level of energy retrofit affects a reasonable number of building components and it is carried out in association with the same working activities foreseen for structural retrofit. Indeed, in addition to the measures of the previous level of intervention, operations on infills (already included in the working activities of structural retrofit) and systems are implemented. In particular, the insufflation of a foaming insulating material (i.e. polyurethane foam with thermal conductivity = 0.026 W/mK) is executed inside the gap between the brick layers, leading to an overall improvement of energy performances of the building envelope. Existing heating systems are also replaced with condensing boilers that allow for primary energy demand reduction.

In order to achieve a seismic performance higher than that achieved in the previous level, a change of the retrofit technique is needed. A different strategy based on the insertion of new structural systems increasing both stiffness and energy dissipation is required in this case to achieve such goal; note that the increase of lateral stiffness certainly improves the performance at damage limit state but lead to higher foundation demand with respect to the as-built configuration. In this case study, to achieve a PGA_c/PGA_d = 100% the use of buckling restrained axial dampers (BRAD) is selected [6]. In order to contain the degree of disruption and the duration of the application the steel braces will be applied on to some of the perimeter frames of the building in both the directions. The design procedures consisted in the definition of the increased stiffness needed to regularize the dynamic response of the structural system and contain the torsional effects. Furthermore, the building lateral stiffness in both the directions has been increased to improve the seismic response of the school building to low magnitude (i.e. frequent) earthquakes. This may have a significant impact on the expected annual losses by containing the expected damage to non-structural components. To match this criterion the achievement of the damage limit state (DLS) corresponding to an interstorey drift about the 0.5% is considered. The design of the stiffness of the steel bracing consisted in setting the target return period where the 0.5% drift is achieved for an earthquake with return period at the LSLS (i.e. 712 years) instead of the one at the DLS, as suggested by the Italian seismic code. The strengthening of the foundation system by section enlargement and the introduction of micro-piles is also needed. The CFRP shear strengthening of few beam-column joints and some columns were also needed to achieve the target seismic demand. The third level of energy retrofit affects the overall building and, for this reason, is characterized by a high level of disruption in terms of down time and suspension of building occupancy. In particular, an external insulating system is applied to the entire building over its external walls. In terms of systems, beside the replacement of existing boiler with a more efficient one, renewable energy sources are also implemented by using photovoltaic panels on the building roof; in addition, the improvement of the energy efficiency of lighting systems is achieved via the installation of LED.

A comparison of the performance achieved by using the three different levels of integrated retrofitting is reported in Table 3 in terms of seismic performances and energy efficiency along with the relevant costs needed for the implementation of the retrofit solutions. The seismic risk class and the energy efficiency class assessed by using the Italian guidelines for seismic risk assessment of constructions [24] and the guidelines for energy performance classification [20] are also included. The seismic risk class is here used to compare the seismic performance improvement, even though the references guidelines mainly refers to residential buildings. Furthermore, the direct monetary cost, expressed as euro per square meter of total building covered surface, needed for the implementation of the proposed retrofit solution is calculated according to regional price lists. It includes the all the direct costs needed for the implementation of seismic and energy efficiency retrofit interventions, the cost of the installation of the construction field and safety measures, all the supplementary and complimentary activities, the contractors overhead. It does not include the V.A.T. and the cost of the professional fees.

The comparison between the performance of the school building in the as-built configuration and the retrofitted ones outlines that the proposed retrofit solutions are capable of significantly improve the seismic performance of the case study school buildings. In particular, the safety index significantly increases from

13% or 23% to 60% for Level 1 and 2 or to 100% for Level 3. This allows to improve the seismic risk class from E to B for Level 1 and Level 2 or to A+ for Level 3. Note that although the retrofit interventions designed at Level 2 have additional works compared to the Level 1 (i.e. shear strengthening of columns to sustain the infill actions, column confinement and beam shear strengthening) the same safety index is achieved. This is because the numerical model does not account for the infill actions as commonly found in the design practice. However the retrofit schemes adopted at Level 2 is designed based on experimental evidences from recent earthquakes, clearly showing that for those structural systems interested by a significant infill-to-structure interaction, the shear failures due to the infill action may significantly limit the global building performance [22]. Similarly to seismic retrofit, the proposed energy efficiency retrofit interventions allows to increase the original energy efficiency class F to D, B or A3, for Level 1, 2 or 3 interventions, respectively with a significant reduction in building energy consumption (from 65 kWh/m^{2}y to 25 kWh/m^{2}y). According to the proposed incremental design philosophy, increasing the seismic and energetic performances the level of disruption, the duration of the retrofit intervention and the relevant costs also increase. Thus, the owner and the designer may choose the target level of the retrofit intervention by knowing the target performances, the degree of disruption and the associated cost of intervention. It is worth remarking that the results of this study cannot be generalized since they are limited to this case study.

Table 3. Comparison of the proposed retrofit solutions for the case study buildings

Case study	Surface (m^2)	Level	Level of disruption	Type of intervention	PGA_c/ PGA_d (%)	PEC [kWh/m^{2}y]	Seismic risk class*	Energy efficiency class**	Total cost of intervent.*** (€/m^2)
1	1470	As-built	None	None	23%	182.0	E	F	-
		1	Exterior	FRP local	60%	145.8	B	D	276
		2	Low	FRP local	60%	108.9	B	B	462
		3	Medium	Steel bracing	100%	42.6	A+	A3	665
2	1200	As-built	None	None	13%	187.0	G	F	-
		1	Exterior	FRP local	60%	141.3	B	D	193
		2	Low	FRP local	60%	103.0	B	B	335
		3	Medium	Steel bracing	100%	n.a.	A+	n.a.	n.a.

* According to D.M. n°65 07/03/2017 [24], ** According to D.M. 26/06/2015 [20], *** Total cost of interventions includes: direct cost of structures and energy efficiency interventions; the cost for the installation of construction field and safety measures. It does not include the V.A.T. and professional fees.

4. Conclusions

The present analytical work has dealt with the retrofit of existing school buildings accounting for both the enhancement of seismic performance and energy efficiency. A novel methodology for the integrated design of the global retrofit of school buildings is proposed and combined retrofit interventions with an increasing level of disruption, increasing performance and increasing costs and benefits are discussed. This approach is then applied to two case study school buildings representative of the reinforced concrete school building stock of the Mediterranean area.

According to the proposed incremental design philosophy, increasing the seismic and energetic performances the level of disruption, the duration of the retrofit intervention and the relevant costs also increase. Three different performance levels are proposed to drive the stakeholders and the designers to choose the target level of the retrofit intervention by knowing the target performances, the degree of disruption and the associated cost of intervention. In all the cases, the costs of the intervention are significantly lower than the cost of demolition and reconstruction.

Further research effort is needed to generalize the results of this work and to provide useful data to drive the designer in the selection of the most convenient retrofit solution based on the desired performance or on the available economic budget. The results of the presented work may provide useful preliminary insights to practitioners and public authorities approaching the complex and urgent task of seismic and energy retrofit of existing school buildings.

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