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An integrated design approach for the retrofit of existing RC school buildings

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ABSTRACT

Most of the Italian existing reinforced concrete (RC) school buildings are, to date, in a severe state of obsolescence, making their safety and energy management difficult and expensive. In fact, many of them require a deep renovation in order to achieve improved performances in terms of overall comfort, structural safety and energy efficiency. In the past few years, many economic resources have been invested in this last aspect, focusing mainly on the improvement of facilities, services 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 (also related to single retrofitted systems). Therefore, an effective renovation design cannot neglect to consider, simultaneously, both structural and energy aspects.

The present work focuses on the development of an integrated retrofit design methodology for the structural and energy improvement of existing school buildings; the methodology implements proper strategies characterized by the achievement of increasing levels of building performances. In order to validate the proposed retrofit design approach and quantify the relevant costs and benefits, a case study of a typical Italian existing RC school building is investigated. An in-depth discussion on the definition of the combined design solutions and related technologies used to achieve incremental improved performances is reported.

1 INTRODUCTION

School buildings play a crucial role in modern communities. They are not only the places for education of youngest generations; they are also used for social activities and recovering after natural disasters. However, recent devastating earthquakes occurred worldwide demonstrated that many threatened communities do not yet have earthquake-resistant schools (Grant et al. 2007; Di Ludovico et al. 2017; OECD Programme on Educational Building (PEB) 2004; Taylor et al. 2009; Wang and Goettel 2007). Furthermore, most of the school buildings in Italy and in Europe are aged buildings and they are approaching their "design" end-of-life. Indeed, ANCE and Legambiente reports (2013; 2014) show that more than 65% of existing schools were built before the 1974, i.e. before the seismic regulations were enforced. Thus, 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 (Legambiente: XVII Rapporto di Legambiente sulla qualità dell'edilizia scolastica 2014).

Many research studies focused on the vulnerability of existing school buildings and the need for efficient retrofit interventions (López et al. 2008; Tena-Colunga 1996; Tesfamariam and Wang 2012). Prioritization schemes, methodologies (Frascadore et al. 2015; Grant et al. 2007) and innovative retrofitting solutions (Caverzan, Lamperti Tornaghi, and Negro 2015; Lignola et al. 2016; Di Sarno and Manfredi 2012; Takeda et al. 2013) have been also developed to improve the seismic performance of school buildings. However, major retrofit plans were carried out only in the aftermath of devastating natural catastrophes (Chrysostomou 2013; López et al. 2008; Di Ludovico et al. 2017; Takeda et al. 2013).

In order to comply with the recent EU Directives and international agreements in matter of energy efficiency in energy use (EU 2010; United Nations 2015), a great attention was also paid with regard to energy refurbishments of existing buildings. Indeed, schools and, more in general, educational buildings require quite high energy demands for heating, cooling and ventilation, having high air change rates that increase thermal loads and energy costs. Thus, well-designed energy retrofitting may allow to significantly reduce the energy consumptions (Ascione et al. 2017). Recently, 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 (Ascione et al. 2017; ENEA 2015; Grant et al. 2007; OECD Programme on Educational Building (PEB) 2004). 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, Caverzan et al. 2015). 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 (Chrysostomou 2013; Di Ludovico et al. 2017; Tesfamariam and Wang 2012). For instance in Cyprus, it has been observed that 46% of school building needs for structural retrofit interventions (Chrysostomou 2013). According to detailed studies (López et al. 2008; OECD Programme on Educational Building (PEB) 2004; Taylor et al. 2009; Tena-Colunga 1996), this percentage increases significantly in Turkey, in British Columbia (Canada), in Iran and in earthquake prone areas in Central and South America.

In Italy, recent national investment plans (MEF 2018) specifically provides funding (about 1 billion €) for seismic 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 (MIT 2018)) prescribing a minimum safety level about 60% of the new building standard for retrofit interventions on school buildings. However, the long time needed for the implementation of effective structural and energy retrofitting on existing school buildings, commonly leading to the interruption of the school activities for years, is a real barrier and innovative solutions are needed to solve this issue.

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 are discussed with reference to a real case study building typical of the Italian school building stock. Different retrofit solutions are also discussed and compared in terms of seismic and energy performance, benefits of the intervention, level of disruption and direct costs of implementation.

2 THE INTEGRATED DESIGN APPROACH

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 (Napolano et al. 2015; Jagarajan et al. 2017, Frascadore et al. 2015), while few works have dealt with the integration of different sustainability targets (Mauro et al. 2017). Multi-disciplinary approaches (Marini et al. 2017) 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 (Mauro et al. 2017) where the authors have demonstrated that the energy payback time of retrofit interventions can even double for very seismic-prone areas).

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.

The integrated intervention is then characterized in terms of: building performance targets, dimensional scale of the application, improved performances and overall costs. Several levels of retrofit can be selected on the basis of the required combination of the above mentioned characteristics (in line with an incremental rehabilitation approach). The schematic representation of the methodology is summarized in Table 1.

Table 1. Methodology for definition of the retrofit levels.

	Performance Target [% compared to as built]		**Dimensional scale of the application**		**Level of disruption**
Level	*Structural* ζ_E [%]	*Energy* PEC [kWh/m2y]	*Nr. of Building components*	*Whole building*	*Overall duration of retrofit*
1	=60%	≅ -20%	Few	No	Short
2	≥60% <100%	≅ -40%	Several	No	Acceptable
3	≥100%	<-60%	Several + Systems	Yes	Long

The improvement of the seismic and energetic performances are considered with reference to two different indices:

- ζ_E, the safety index at life safety limit state (LSLS) defined as the PGA_c/PGA_d [%] ratio
- PEC, the Total Primary Energy Consumption, measured in [kWh/m^{2}y]

where: PGA_c is the capacity PGA defined as that required to cause the building to attain the LSLS; PGA_d is the design PGA at the building site according to the hazard map and affected by the site amplification factor. They are both calculated according to the current Italian seismic code (MIT 2018; MIT 2019). The design strategy as-well-as the target of the retrofitting are described herein with reference to the seismic strengthening and energy retrofit. The integrated design approach is later applied to a case study building to shows the results on how the two retrofit solutions can be applied in combination.

2.1.1 *Seismic strengthening*

Existing reinforced concrete buildings built in the past century were commonly designed to resist to low-to-moderate seismic actions or, more often, to gravity loads only. This results in lack of proper seismic details that may lead to premature brittle failures. Indeed, as frequently observed in the aftermath of recent seismic events, existing RC buildings are vulnerable to seismic actions because of the joint or column shear failures (Frascadore et al. 2015; Di Ludovico et al. 2008). Consequently, proper retrofit intervention should aim at improving primarily the seismic performance of beam-column joints, short columns and protecting the top end of the columns against the high shear forces transmitted by the stiff infills.

In this context, 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 is a cost-effective retrofit solution (e.g. Akguzel and Pampanin 2012; Frascadore et al. 2015, among others). Furthermore, the reconstruction processes following recent seismic events outlined that the majority of the repair cost is related to non-structural components and, in-particular, to infills and partitions (Del Vecchio, Di Ludovico, and Prota 2019). Thus, an efficient retrofit solution should aim at significantly improving both the safety index and reducing the expected annual losses (EAL) by improving the capacity of non-structural components. This concept is also stressed in the current building code (MIT 2018; MIT 2019) and in the recent guidelines for the seismic risk classification of constructions (Cosenza et al. 2018). Innovative building materials or classic retrofit solutions can be used in a local or global retrofit strategy. Proper guidelines specifically developed for the seismic retrofit of existing buildings suggest different strengthening technique to improve the seismic performance of existing RC buildings by using local retrofit strategy (DPC-ReLUIS 2011). In order to comply with the requirements suggested by the Italian seismic code (MIT 2019) for the seismic strengthening of school buildings, the target safety index ζ_E is set equal to 0.6 at Level 1. 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. This is to promote low impact interventions which can be easily applied along with the interventions for the renovation of the building façades or within the installation of energy efficient insulation envelop.

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 (Di Ludovico et al. 2008) and analytical studies (Frascadore et al. 2015).

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.

2.1.2 *The energy retrofit*

The effective design of a building energy retrofit is a complex issue that requires the consideration of a wide set of feasible measures. Generally, the most effective solution, consisting in a combination of energy retrofit measures (ERMs), is affected by numerous factors, such as available budget, time frame for the intervention, stakeholders' and owners' wills and needs as well as the scenario in which the building is located, especially the overall climatic conditions.

In general, 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 programmed 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 we propose three levels of incremental ERMs which are compatible with structural retrofit measures. In particular, the 1st level 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 the 2nd level, 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. In the 3rd level, a more intensive intervention is conducted and applied both on the envelope end existing primary energy systems; these 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 THE CASE STUDY BUILDING

The selected case study building is typical of Italian school built in 1960s – 1970s according to the old building code and without any seismic provision. It consists of RC moment resisting frames and it is made of two different buildings separated by a technical joint (see Figure 1). In the present work, only the main building where the classrooms are located is considered. The building is approximately 55 m long and 20 m width. It is a two floors building with one floor basement at the front part of the building where the main entrance is located. 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 is equal to 390.8 MPa. The structural system 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. They relies on RC rectangular columns oriented in the x direction with a cross section height about 0.6m and a width about 0.2m. They are reinforced with 4 ϕ 16 bars at the corners, while the transverse reinforcement consists of ϕ 6/150mm. The columns are connected by rectangular beams 0.6m height and 0.2 m width in the y direction. They are reinforced with 4-to-8 ϕ 16 bars at the top and 2-to-3 ϕ 16 bars at the bottom. ϕ 6 bars with a spacing varying form 80 mm to 200 mm were used as transverse reinforcement. Wide beams can be found in the interior frame in the x direction about 0.2 mm height and 0.3 m width. They are reinforced with 2 ϕ 16 bars at the top and 2 ϕ 16 bars at the top. The staircase is located at the right side of the building and it relies on RC knee beams and short columns.

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 in hollow bricks and have thermal transmittance (i.e., U-value) equal to 1.23 W/m^{2}K. 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 is located in Teramo (Central Italy), a city with the following climatic scenario: climatic zone D, with 1834 heating degree days (HDDs). On the other hand, with regard to the seismic risk, the demand PGA (peak ground acceleration) is 0.294g on a B-class soil.

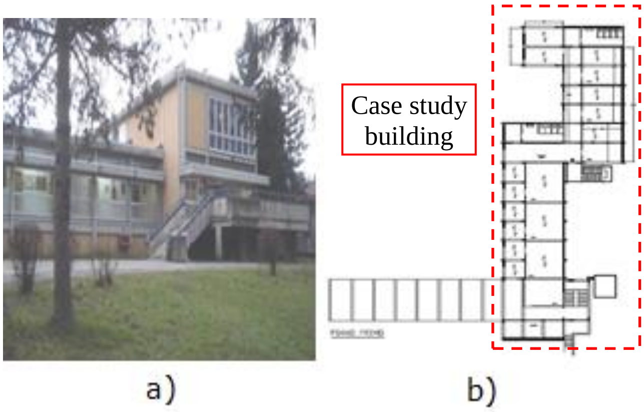

Figure 1. Building description: front view (a); plan view (b)

3.1.1 *Performance assessment*

To assess the seismic performance of the case study building, a 3D lumped plasticity nonlinear model was implemented in the SAP2000 platform (C.S.I., 2004).

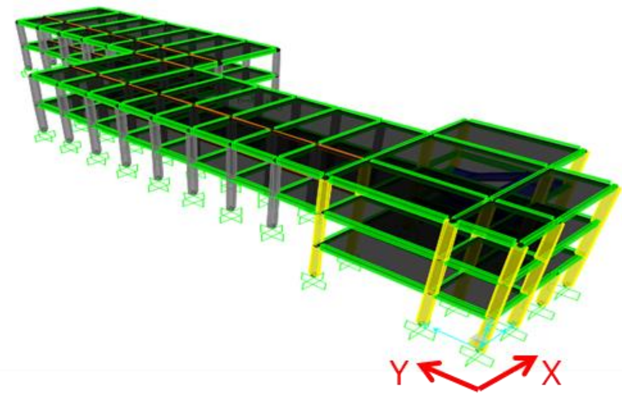

Figure 2. Numerical model

A view of the numerical model of the case study school building is reported in Figure 2. 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 (CEN 2005) and the Italian building code (MIT 2018, 2019) for the plastic hinge rotation at the yielding and at the ultimate limit state. The contribution of the joint non-linear response to the building lateral deformation is neglected in the present study. However, the joint shear failure is considered when assessing the building capacity by using a force-based approach. More details about this model can be found in (Frascadore et al. 2015). 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 is considered in post-processing the results. At each step of the capacity curve the joint shear strength (fixed at the achievement of the principal tensile stress about $0.3\sqrt{f_c}$ or at the compressive stress about $0.5f_c$, according to the Italian seismic code (MIT 2018, 2019)) is compared with the joint shear demand at each step of the building capacity curve. Similar approach is used to assess the shear strength of beams and columns. In particular, the capacity model suggested Biskinis and Fardis (Biskinis, Roupakias, and Fardis 2004) and adopted by Eurocode 8 (CEN 2005) and by the Italian building code (MIT 2018, 2019) is used since it provides reliable estimation of the shear strength for poorly detailed RC members.

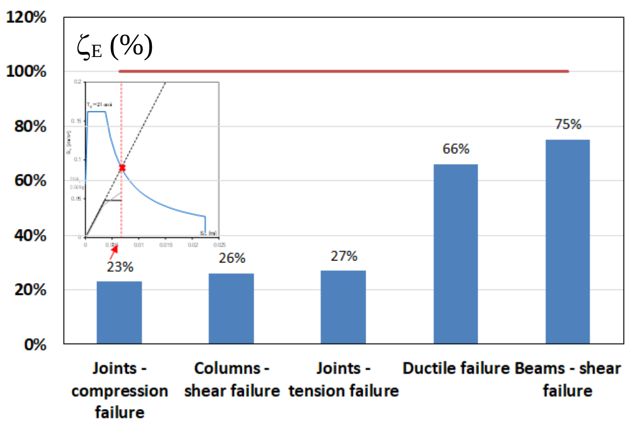

Figure 3. Seismic performance assessment of the case study building in terms of ζ_E for each type of failure.

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 at the LSLS (T_R=475) and the capacity was performed in the acceleration-displacement response spectrum (ADRS) according to the procedure suggested in the Eurocode 8 (CEN 2005) and Italian building code (MIT 2018, 2019). The results in terms of the minimum safety index at the LSLS, ζ_E, are summarized in Figure 3. The safety index is expressed as the ratio between the capacity and demand PGA at LSLS.

The seismic performance assessment outlined that the brittle failure of beam-column joints in compression and in tension is limiting the overall building performances along with the shear failure of the columns of the staircase. These failure limit the structural performance to the 23%-to-27% of the seismic demand. By contrast, the ductile failures only took place when the seismic demand reached the 66% of the design. 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 for school buildings (i.e. the 60%) can be achieved.

For the climatic location considered (Teramo, climatic zone D, with 1834 HDDs), EnergyPlus software was adopted as tool to run reliable energy simulations in dynamic conditions. The following assumptions are made in the energy analysis: the primary energy conversion factor was set equal to 1.95 for electricity and 1.05 for natural gas, according to current Italian law (D.M. 26/06/2015); and 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 case study investigated; as depicted in Figure 4, the energy performances of the as built RC case study building led to a low classification in terms of Italian energy efficiency class (class F). According to the proposed retrofit approach, we implemented incremental energy retrofit interventions by adopting a set of possible ERMs aiming to reduce the PEC up to 60%:

- variation of heating set point temperature (Th), which cannot be higher than 22°C according to Italian regulations (D.M. 26/06/2015);
- use of thermostatic valves;
- installation of new efficient energy systems, such as condensing boilers;
- insufflation of insulant materials inside the gap between the brick layers;
- installation of a 10 cm-thick external layer of thermal insulation (thermal conductivity = 0.026 W/m K, density = 25 kg/m^3, specific

heat = 1340 J/kg K) on the external vertical walls (the insulation layer's thickness is denoted as t_v);

- installation of a 10 cm-thick external layer of thermal insulation (see above properties) on the roof;
- replacement of the windows with energy efficient ones (i.e. double-glazed argon-filled windows with low-emissive coatings and PVC frames: U_w = 1.71 W/m^{2}K, SHGC = 0.691);
- exploitation of renewable energy sources, via the implementation of photovoltaic panels on the building roof;
- improvement of the energy efficiency of lighting systems, via the installation of LED.

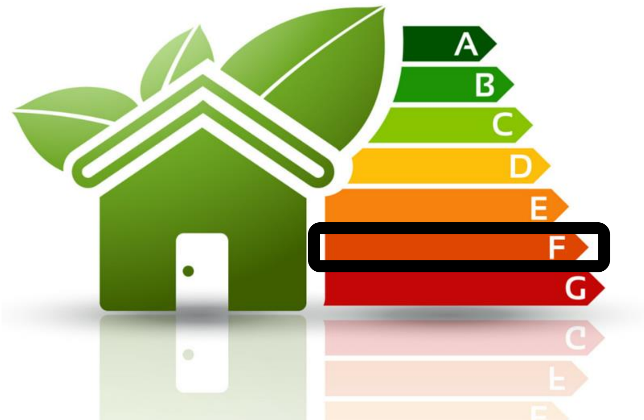

Figure 4. Energetic performance

3.1.2 *Incremental retrofit interventions*

The assessment of the case study school building outlined the poor performance against the requirements of the current seismic code or with reference to energy efficiency and modern standards of comfort. In light of this, the proposed incremental integrated design approach is applied in the design of the retrofit intervention. The proposed procedure is conceptually described in Figure 5.

The seismic performance assessment outlined that the reference case study building experienced premature shear failure at level of beam-column joints and the column of the staircase. A pushover analysis is then performed to identify the critical member that need to be strengthened to achieve the first target level of the building retrofitting proposed in the incremental integrated design approach (Level 1, ζ_E=60%).

The pushover analysis outlined that 33 exterior beam-column joints need for a tensile shear strengthening, while 7 of them need for diagonal compression shear strengthening. Furthermore, 8 columns of the staircase need for a shear strengthening. These structural members are all part of exterior frames and, thus, strengthening interventions operating from the exterior of the building can be suggested to bypass these failure and achieve the target seismic performance.

In this context, local strengthening interventions can be useful to increase the global seismic performance of the structural system. Different techniques can be used for the local strengthening of beam-column joint or short columns. FRP systems gained popularity as a fast and suitable alternative to classical strengthening solutions (Balsamo et al. 2012). They can be easily installed resulting in a very low level of disruption to the occupants. This may allow the seismic retrofit of existing school buildings to be carried out in a very short period of time, as recently demonstrated during the L'Aquila reconstruction process (Frascadore et al. 2015). At this level, 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. It was demonstrated by experimental tests to be an effective solution to improve the shear strength of the joint panel promoting more ductile failure mode.

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^{2}K, 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. The implementation of this solution is in accordance with the low disruption level of structural retrofit. The result is that PEC reduces to 145.8 kWh/m^{2}y, as reported in Table 2.

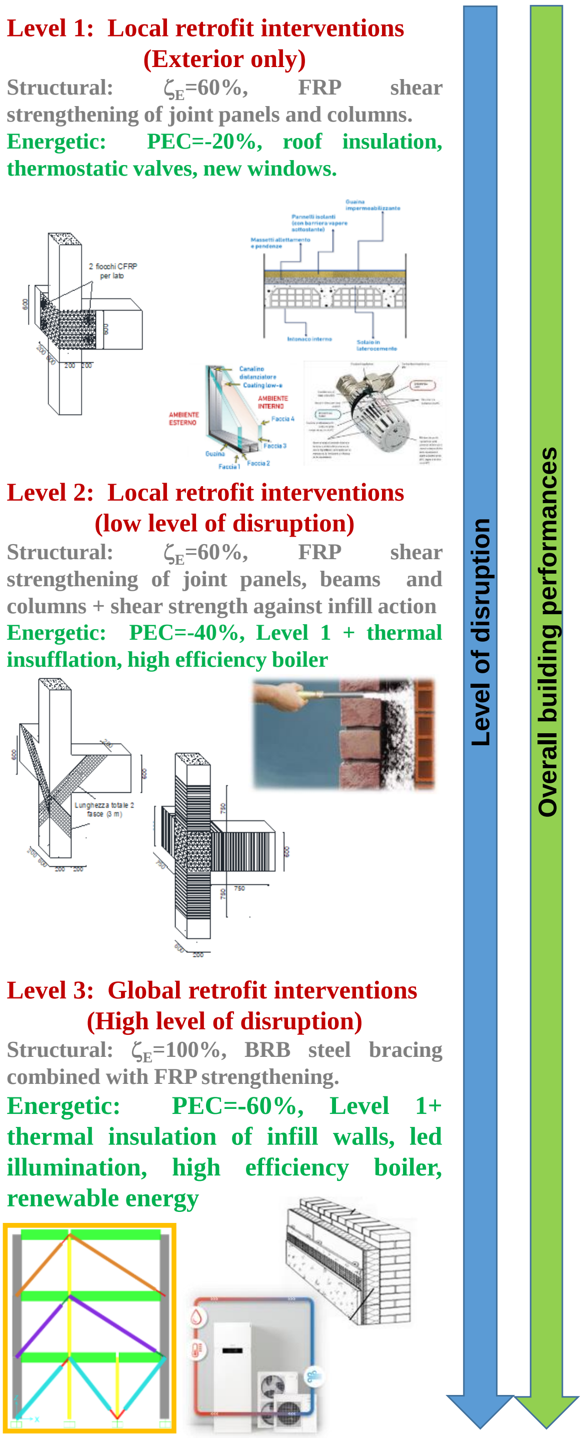

Figure 5. Conceptual design of the incremental retrofit interventions

According to the ReLUIS guidelines for the seismic strengthening of existing RC members (DPC-ReLUIS 2011) in order to effectively improve the seismic performance of the joint subassemblies in a local strengthening strategy the shear strengthening and confinement of the RC members framing into the joint is suggested. At first level only joint panel strengthening is suggested by means of quadri-axial CFRP sheets. To ensure the effectiveness of such solution and to reduce the disruption the application of spike at panel corners is suggested to proper anchor FRP sheets, see Figure 5. At the second level of the proposed incremental retrofit the full retrofit scheme suggested by the ReLUIS guidelines (DPC-ReLUIS 2011) is considered. Apart for the joint 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. The solution also involves the CFRP Uni-axial wrapping of column ends and beam ends to improve the column confinement and increase the shear strength of the beam. The latter solution has been extensively validated by means of analytical and experimental studies (Frascadore et al. 2015). Although the disruption level is low, the application of the strengthening solution 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 proposed by Del Vecchio et al. (2015) and recently included in the Fib Bulletin 90 (2019). In particular the shear demand in the joint panel is obtained from the static nonlinear analysis considering the design target ζ_E=60%. This resulted in different number of layers on the joints because of the variable joint shear demand. In this case study, most of the joint have been retrofitted by using one layer of quadri-axial CFRP, while 4 joints need to be strengthened by using 2 layers and 2 joints with 3 layers. To increase the joint shear strength in diagonal compression a section enlargement of the joint panel is designed. However, this interventions interests only 7 perimeter joints and its application will not significantly affect the degree of disruption and the duration of the intervention.

The second level of energy retrofit affects a reasonable number of building components and is conducted 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 which allow for primary energy demand reduction. The implementation of these energy measures determine a PEC reduction to 108.9 kWh/m^{2}y, as reported in Table 2.

Debonding phenomena may limit the effectiveness of the FRP shear strengthening. Indeed it is widely recognized that more than three layers are commonly not effective to achieve further increase of the joint shear strength. This assumption is supported by the analytical calculation performed by using the design formulation proposed by Del Vecchio et al. (2015). Thus, to achieve a seismic performance higher than the previous level a change of the retrofit technique is needed. In this case study, to achieve a ζ_E = 100% the use of buckling restrained axial dampers (BRAD) is selected (Di Sarno and Manfredi 2012). 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 criteria 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. 975 years) instead of the one at the DLS, as suggested by the Italian seismic code. The design procedure resulted in a diameter of the dissipative part of the brace of ranging from 168 mm to 273 mm depending from the direction and the floor. The braces were installed on 8 perimeter bays in the x direction and 4 perimeter bays in the y direction in order to limit the level of disruption. 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 (i.e. ζ_E = 100%).

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. Also in this case, the intervention is conducted in association with the same working activities foreseen for structural retrofit. 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. The implementation of these energy measures determine a significant PEC reduction to 42.6 kWh/m^{2}y leading to the achievement of the highest level of energy efficiency (A3), as reported in Table 2.

4 COMPARISON OF RETROFIT LEVELS

In order to compare the retrofit alternative a cost-benefit analysis is needed (Caterino et al. 2008). In this paper only a first direct comparison of the improved seismic performance both in terms of seismic performances and energy efficiency is provided to the reader along with the relevant costs needed for the implementation of the retrofit solutions. The results are summarized in Table 2 in terms of: the seismic risk index, ζ_E, and the Total Primary Energy Consumption, PEC indices in the as-built and retrofitted configuration; the type of intervention; the level of disruption, the seismic risk class and the energy efficiency class assessed by using the Italian guidelines for seismic risk assessment of constructions (Cosenza et al. 2018; Ministry law n.58 28/02/2017) and the guidelines for energy performance classification (D. M. 26/06/2015). 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 needed for the implementation of the proposed retrofit solution is calculated. The latter has been estimated by using the regional price list of the Abruzzo region (LL.PP. 2017). 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.

Table 2. Building performances for different retrofit solutions

Level	Type of intervention	Level of disruption	ζ_E (%)	PEC [kWh/m²y]	Seismic risk class *	Energy efficiency class **	Cost of integrated intervention *** (€/m²)
As-built	None	None	23%	182.0	E	F	-
1	Local strengthening	Exterior only	60%	145.8	B	D	258.84
2	Local strengthening	Low	60%	108.9	B	B	401.02
3	Global retrofit	Medium	100%	42.6	A+	A3	647.96

* According to D.M. n°65 07/03/2017, "Linee guida per la classificazione del rischio sismico delle costruzioni".
** According to D.M. 26/06/2015, "Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici".
*** 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.

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 improving the seismic performance of the case study school building. In particular, the safety index significantly increases from 23% to 60% for Level 1 and 2 or to 100% for Level 3. This allows to significantly increase the seismic risk class from E to B for Level 1 and Level 2 or to A+ for Level 3. Similarly, 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. This can be useful to drive the designer in the selection of the most convenient retrofit solution based on the desired performance or on the available economic budget. It is worth remarking that the results of this study cannot be generalized since they are limited to this case study. Further research effort is needed to apply the proposed incremental procedure to different case studies in order to collect data on the performance and the related costs which may allow to draw generalized conclusions.

5 CONCLUSIONS

The present analytical work deals with the retrofit of existing school buildings accounting for both the enhancement of seismic performance and energy efficiency. An incremental integrated design approach is proposed. Retrofit interventions with an increasing level of disruption, increasing performance and increasing costs and benefits are proposed. Integrated retrofit interventions are proposed and discussed with reference to a real case study building typical of the Italian school building stock. The selected case study building exhibited poor seismic and energetic performances This is mainly related to the lack of proper seismic detailing and the obsolescence of energy systems and enclosures. This makes the building very vulnerable to seismic actions (i.e. ζ_E, 23%, corresponding to E seismic risk class) and high energy consumption (180.0 kWh/m^2 corresponding to the F energy class).

The retrofit solutions are compared in terms of seismic and energy performance, benefits of the intervention, level of disruption and direct costs of implementation. With reference to the case study building, the following conclusions can be drawn:

- The Level 1 consists in light retrofit interventions which can be quickly applied from the exterior of the building. FRP strengthening of the joint panel along with roof insulation and the installation of new windows and thermostatic valves allow a significant increase in the seismic performance (i.e. ζ_E = 60%, corresponding to B seismic risk class) and a significant reduction of high energy consumption (-20% PEC, corresponding to the D energy class) to be attained;
- In case that the interaction with stiff infill wall is triggering column shear failure, SRP

sheets have been combined with the FRP one to improve the seismic capacity of the structure. Furthermore, FRP sheets were extended to columns and beam ends to definitely avoid brittle failure on the sub assemblage and improve the columns' ductility. This allowed a satisfactory seismic performance (i.e. ζ_E = 60%, corresponding to B seismic risk class) to be achieved. The seismic strengthening intervention at the Level 2 are combined with thermal insufflation of the infill walls, the installation of high efficiency boiler to achieve a significant reduction of high energy consumption (≈-40% PEC, corresponding to the B energy class). All these interventions can be made operating with a low level of disruption;

- In case that high seismic and energy performance are required to this building, a global retrofit solution with a significant level of disruption is needed. In this case, the installation of steel braces applied on few perimeter frames to contain the level of disruption is used. This allow the design seismic demand (i.e. ζ_E = 100%, corresponding to A+ seismic risk class) to be fully satisfied. An in-depth renovation of the energy systems and envelope is proposed at this level to significantly increase the overall thermal performance (i.e. PEC- 60% corresponding to A3 class);
- The cost of the building retrofit at the proposed three levels increases with the increasing performance from 258.84 €/m^2 at Level 1 to 647.96 €/m^2 at level 3. In all the cases they 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. However, 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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REFERENCES

Akguzel, Umut and Stefano Pampanin. 2012. "Assessment and Design Procedure for the Seismic Retrofit of Reinforced Concrete Beam-Column Joints Using FRP Composite Materials." *Journal of Composites for Construction* **16**(1), 21–34.

ANCE (Italian association of constructors). 2013. *Audizione Dell'Ance Sulla Situazione Dell'edilizia Scolastica in Italia*.

Ascione, Fabrizio, Nicola Bianco, Claudio De Stasio, Gerardo Maria Mauro, and Giuseppe Peter Vanoli. 2017. "CASA, Cost-Optimal Analysis by Multi-Objective Optimisation and Artificial Neural Networks: A New Framework for the Robust Assessment of Cost-Optimal Energy Retrofit, Feasible for Any Building." *Energy and Buildings* **146**, 200–219.

Balsamo, Alberto, Marco Di Ludovico, Gian Piero Lignola, Andrea Prota, Gaetano Manfredi, and Edoardo Cosenza. 2012. "Composites for Structural Strengthening." in *Wiley Encyclopedia of Composites, Second Edition*, edited by L. Nicolais and A. Borzacchiello. John Wiley & Sons, Inc.

Biskinis, Dionysis E., George K. Roupakias, and Michael N. Fardis. 2004. "Degradation Of Shear Strength Of Reinforced Concrete Members With Inelastic Cyclic Displacements_Biskinis_2004.Pdf." *ACI Structural Journal* **101**(6), 773–83.

C.S.I. Computers and Structures Inc. 2004. "SAP 2000, Static and Dynamic Finite Element Analysis of Structures."

Caterino, Nicola, Iunio Iervolino, Gaetano Manfredi, and Edoardo Cosenza. 2008. "Multi-Criteria Decision Making for Seismic Retrofitting of RC Structures Multi-Criteria Decision Making for Seismic Retrofitting of RC Structures." *Journal of Earthquake Engineering* **12**, 555–83.

Caverzan, A., M. Lamperti Tornaghi, and P. Negro. 2015. "A Roadmap for the Improvement of Earthquake Resistance and Eco-Efficiency of Existing Buildings and Cities." Pp. 1–136 in *Proceedings of SAFESUST Workshop*. JRC, Ispra: JRC science hub.

CEN. 2005. *"Design of Structures for Earthquake Resistance - Part 3: Assessment and Reofitting of Buildings" EN-1998-3, Eurocode 8.* Brussell: European Committee for Standardization.

Chrysostomou, C. Z. 2013. "Seismic Retrofitting and Health Monitoring of School Buildings of Cyprus." *The Open Construction and Building Technology Journal* **7**(1), 208–20.

Cosenza, Edoardo, Ciro Del Vecchio, Marco Di Ludovico, Mauro Dolce, Claudio Moroni, Andrea Prota, and Emanuele Renzi. 2018. *The Italian Guidelines for Seismic Risk Classification of Constructions: Technical Principles and Validation*. Vol. 16. Springer Netherlands.

Del Vecchio, Ciro, Marco Di Ludovico, and Andrea Prota. 2019. "Repair Costs of RC Building Components: From Actual Data Analysis to Calibrated Consequence Functions." *Earthquake Spectra* in press.

Del Vecchio, Ciro, Marco Di Ludovico, Andrea Prota, and Gaetano Manfredi. 2015. "Analytical Model and

Design Approach for FRP Strengthening of Non-Conforming RC Corner Beam-Column Joints." *Engineering Structures* **87**, 8–20.
DPC-ReLUIS. 2011. *Linee Guida Per Riparazione E Rafforzamento Di Elementi Strutturali, Tamponature E Partizioni (in Italian)*. Doppiavoce. edited by M. Dolce and G. Manfredi.
Di Ludovico, M., A. Digrisolo, F. Graziotti, C. Moroni, A. Belleri, S. Caprili, C. Carocci, A. Dall'Asta, G. De Martino, S. De Santis, B. Ferracuti, D. Ferretti, G. Fiorentino, A. Mannella, A. Marini, C. Mazzotti, A. Sandoli, A. Santoro, S. Silvestri, L. Sorrentino, G. Magenes, A. Masi, A. Prota, M. Dolce, and G. Manfredi. 2017. "The Contribution of ReLUIS to the Usability Assessment of School Buildings Following the 2016 Central Italy Earthquake." *Bollettino Di Geofisica Teorica Ed Applicata* **58**(4), 353–76.
Di Ludovico, M., G. Manfredi, E. Mola, P. Negro, and A. Prota. 2008. "Seismic Behavior of a Full-Scale RC Structure Retrofitted Using GFRP Laminates." *Journal of Structural Engineering* **134**(5), 810–21.
Di Sarno, L. and G. Manfredi. 2012. "Experimental Tests on Full-scale RC Unretrofitted Frame and Retrofitted with Buckling-Restrained Braces." *Earthquake Engineering & Structural Dynamics* **41**, 315–33.
ENEA. 2015. *Rapporto Annuale Efficienza Energetica*. Casaccia, Roma.
EU. 2010. *Directive 2010/31/EU: The Energy Performance of Buildings*.
fib bulletin 90. 2019. *Externally Applied FRP Reinforcement for Concrete Structures*. Fédération internationale du béton (fib), 2019.
Frascadore, R., M. Di Ludovico, A. Prota, G. M. Verderame, G. Manfredi, M. Dolce, and E. Cosenza. 2015. "Local Strengthening of RC Structures as a Strategy for Seismic Risk Mitigation at Regional Scale." *Earthquake Spectra* **31**(2), 1083-1102.
Grant, Damian N., Julian J. Bommer, Rui Pinho, G. Michele Calvi, Agostino Goretti, and Fabrizio Meroni. 2007. "A Prioritization Scheme for Seismic Intervention in School Buildings in Italy." *Earthquake Spectra* **23**(2), 291–314.
Legambiente: XVII Rapporto di Legambiente sulla qualità dell'edilizia scolastica, delle strutture e dei servizi. 2014. *Ecosistema Scuola*.
Lignola, Gian Piero, Luigi Di Sarno, Marco Di Ludovico, and Andrea Prota. 2016. "The Protection of Artistic Assets through the Base Isolation of Historical Buildings : A Novel Uplifting Technology." *Materials and Structures* **49**(10), 4247–63.
LL.PP., Servizio Tecnico Regionale dei. 2017. *Abruzzo Region Price List "2017 Edition."*
López, O. A., J. J. Hernández, A. Marinilli, Ricardo Bonilla, Norberto Fernández, J. Dom\'\inguez, Trino Baloa, Gustavo Coronel, Salvador Safina, and Ramón Vielma. 2008. "Seismic Evaluation And Retrofit Of School Buildings In Venezuela." *14 Th World Conference on Earthquake Engineering: Innovation Practice Safety* 1974(López).
Marini, Alessandra, Chiara Passoni, Andrea Belleri, Francesca Feroldi, Giovanni Metelli, Paolo Riva, Ezio Giuriani, Giovanni Plizzari, Alessandra Marini, Chiara Passoni, Andrea Belleri, Francesca Feroldi, Giovanni Metelli, Paolo Riva, Ezio Giuriani, and Giovanni Plizzari. 2017. "Combining Seismic Retrofit with Energy Refurbishment for the Sustainable Renovation of RC Buildings : A Proof of Concept." *European Journal of Environmental and Civil Engineering* **8189**, 1–21.
MEF. 2018. *D.M. 3 Gennaio 2018: Programmazione Nazionale in Materia Di Edilizia Scolastica per Il Triennio 2018-2020. (18A02319) (GU Serie Generale n.78 Del 04-04-2018) (in Italian)*.
Ministry law n.58 28/02/2017. n.d. *ALLEGATO A: LINEE GUIDA PER LA CLASSIFICAZIONE DEL RISCHIO SISMICO DELLE COSTRUZIONI (in Italian)*. Italy: Italian Ministry of Infrastructures and Trasport.
MIT. 2018. *Aggiornamento Delle «Norme Tecniche per Le Costruzioni» (in Italian). Supplemento Ordinario n. 8 Alla GAZZETTA UFFICIALE Del 20-2-2018*. Italy.
MIT. 2019. *Istruzioni per l'applicazione Dell'«Aggiornamento Delle "Norme Tecniche per Le Costruzioni"» Di Cui Al Decreto Ministeriale 17 Gennaio 2018.* Italy.
MIT 2019. "Circolare Del Ministero Delle Infrastructure e Dei Trasporti, n.7 Del 21 Gennaio 2019: "Istruzioni per l'applicazione Dell'aggiornamento Delle Norme Tecniche per Le Costruzioni Di Cui Al D.M. 17 Gennaio 2018." *Consiglio Superiore Dei Lavori Pubblici. G.U. n.35 Del 11.02.2019*.
OECD Programme on Educational Building (PEB). 2004. *Keeping Schools Safe in Earthquakes*.
Takeda, Kiyoji, Kyoya Tanaka, Toshiaki Someya, Asao Sakuda, and Yoshiteru Ohno. 2013. "Seismic Retrofit of Reinforced Concrete Buildings in Japan Using External Precast, Prestressed Concrete Frames." *PCI* 41–61.
Taylor, Graham, Carlos E. Ventura, Freddy E. Pina, and W. D. Liam Finn. 2009. "Performance-Based Retrofit of School Buildings in British Columbia, Canada." Pp. 234–45 in *ATC&SEI conference on Improving the Seismic Performance of Existing Buildings and Other Structures*.
Tena-Colunga, Arturo. 1996. "Some Retrofit Options for the Seismic Upgrading of Old Low-Rise School Buildigns in Mexico." *Earthquake Spectra* **12**(4), 883–902.
Tesfamariam, S. and Y. Wang. 2012. "Risk-Based Seismic Retrofit Prioritization of Reinforced Concrete Civic Infrastructure: Case Study for State of Oregon Schools and Emergency Facilities." *Natural Hazards Review* **13**(3), 188–95.
United Nations. 2015. "Adoption of the Paris Agreement." Pp. 1–32 in *Framework Convention on Climate Change - Conference of the Parties - Twenty-first session*. Vol. FCCC/CP/20.
Wang, Yumei and Kenneth A. Goettel. 2007. *Enhanced Rapid Visual Screening (E-Rvs) Method for Prioritization of Seismic Retrofits in Oregon*.