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Seismic retrofit of a RC building using metallic yielding dampers: a case study

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Abstract

Many seismic dissipation devices have been proposed in the literature. However, their application in current practice is rather limited even for the general lack of simple and effective design procedures in the standard building codes. This paper presents an interesting application of metallic yielding dampers to a reinforced concrete school building in Italy. At first, the detailed investigations performed are described in detail, including geometrical, material, and soil surveys. Then, the results of the seismic performance assessment are discussed, and the structural deficiencies are highlighted. Finally, a design procedure is applied that allows an efficient design and dimensioning of dampers, and its effectiveness is demonstrated using the nonlinear response history analysis. The general design approach applied in the seismic retrofit project is illustrated. The construction phases, costs, and execution timing are described and discussed.

Keywords: Seismic retrofit; School buildings; Steel hysteretic dampers.

1. Introduction

The seismic resistance of public buildings such as hospitals or schools is a very important topic given the consequences associated with their failure. In Italy, many of these structures were designed in the '60s and '70s without seismic provisions, or in compliance with outdated seismic codes. Therefore, they don't match the characteristics of earthquake-resistant buildings. Many of them are irregular in plan and/or elevation with the consequent lateral-torsional coupling under seismic actions (Ferraioli et al. 2010). The school buildings typically have a long rectangular

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floor plan, with resisting frames along the short direction and a seismically weak direction along the internal corridor. Thus, the bi-directional resistance and stiffness requirements are not satisfied. This situation dramatically increases the seismic vulnerability of these public buildings and makes their retrofit a national emergency. Many energy dissipation systems have been proposed in the literature and applied for seismic retrofit of reinforced concrete (RC) buildings (Kasai et al. 1998, Manual JSSI 2007, Sutcu et al. 2014, Takeuchi and Wada 2017, De Matteis et al. 2018, Ferraioli et al. 2020 and 2021). These systems can be classified according to the structural type (i.e., brace, stud panel, wall panel, and shear link panel), material (steel, aluminum, shape memory alloys), yielding mechanism (i.e., axial, extrusion, yielding ring, shear panel, torsional bar). Among them, the use of steel dissipative bracing in concrete-framed structures has emerged as a leading solution since it significantly increases the energy dissipation capacity and decreases both member forces and inter-story drifts under earthquake ground motion. Moreover, it has relatively low weight, is suitable for prefabrication, and allows windows to be opened. Finally, the damper works as a structural fuse that fixes the force transferred to the main structure.

2. The case study RC school building

The case study is a school building in Vibo Valentia (Calabria-Italy) (Fig. 1a). The building was designed in 1962 according to the provisions of an outdated Italian Code (Royal Decree n. 2105, 1937). The construction site belonged to the first seismic category zone and, thus, the seismic intensity coefficient used for design was C=0.07. The allowable stress design method was used for the resistance verification. The school building is composed of three reinforced concrete frame structures (namely A, B, and C) (Fig. 1b). The seismic retrofit project has interested the structure named A in Fig. 1b, which has an L-shaped floor plan with dimensions of 17.70 x 35.50 m. All stories have the same height (3.6 m). All foundation beams have the same rectangular cross-section 50x100 cm. The floors have a mixed structure made up of reinforced concrete and tiles with a global thickness of 28 cm (25+3 cm). Some details of the original drawings are plotted in Fig. 2.

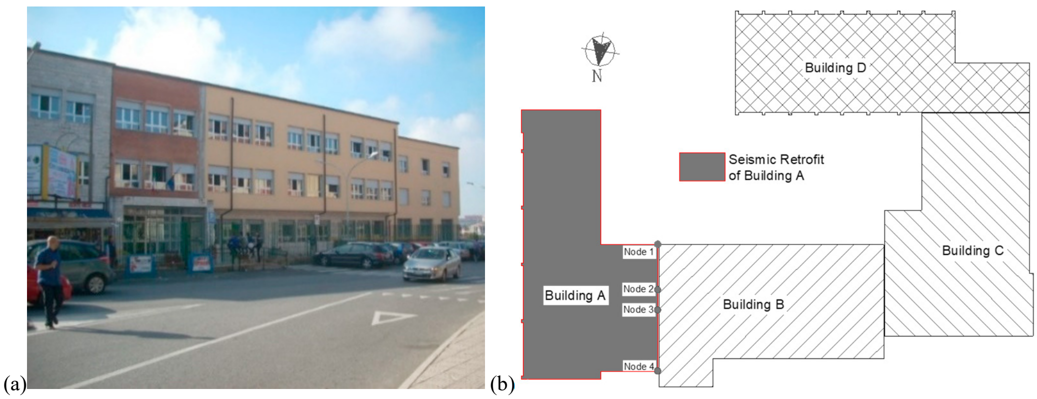


Fig. 1. (a) External view; (b) Floor Plan of the Building Structures.

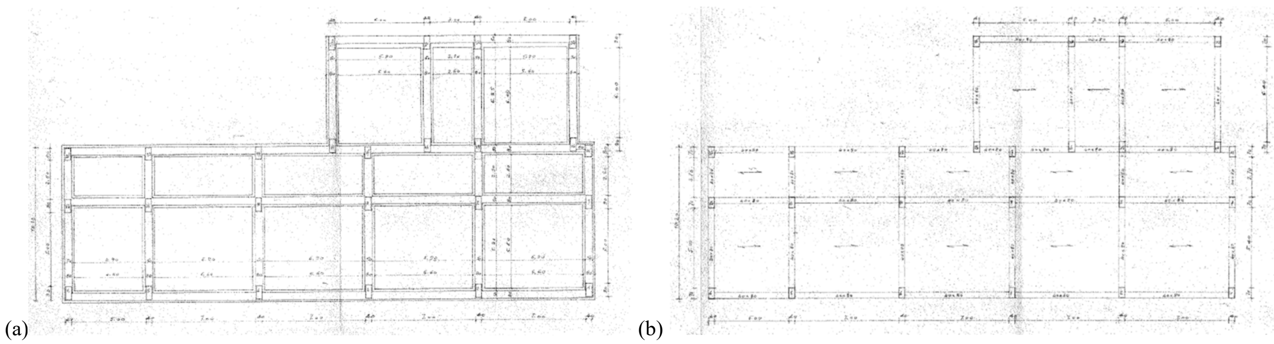


Fig. 2. Original drawings of the design floor plan. (a) Foundations; (b) First floor.

2.1. On-site and laboratory tests

Achieving an appropriate level of knowledge of the mechanical material properties is crucial to assessing the seismic vulnerability of existing structures. On-site and laboratory material tests have been calibrated to reach an accurate level of knowledge (KL3 according to NTC 2008). The mechanical proprieties of material and the characterization of structural details have been assessed by several destructive e non-destructive material tests: (a) compressive tests on concrete to get the strength of RC members (at least n. 3 concrete samples per 300 m^2 of floor area according to NTC 2008); (b) tensile tests on steel bars to get yield strength of steel (at least n. 3 steel material samples per floor for each type of structural member); (c) non-destructive tests on concrete (i.e., sclerometric and ultrasonic tests); (d) pacometric investigations for the detection of the reinforcement bars; (e) on-site inspection, thermography and endoscopy for construction details. Collected results gave a mean value of concrete strength f_{cm}=35.2 MPa and a mean value of steel rebars strength f_{ym}=408 MPa. Tab. 1 summarizes the investigations performed. Fig. 3 shows some of the tests performed: coring of a column (Fig. 3a), carbonation depth test (Fig. 3b), extraction of a steel bar sample from a column (Fig. 3c), pacometric test (Fig 3d), thermographic test (Fig 3e). The mechanical characteristics of the foundation soils have been determined using on-site Standard Penetration Tests (SPTs) and MASW (Multichannel Analysis of Surface Waves) tests.

Table 1. Material tests.

Description	On-site investigation (2009)	On-site investigation (2013)	Total
Compressive tests on concrete	6	0	6
Tensile tests on steel bars	1	2	3
Sclerometric test	9	9	18
Ultrasonic test	8	9	17
Pacometric investigations	6	60	66
Foundations surveys	0	1	1
Inspections on structures	0	13	13
Thermographic tests	0	19	19
Endoscopic tests	0	3	3

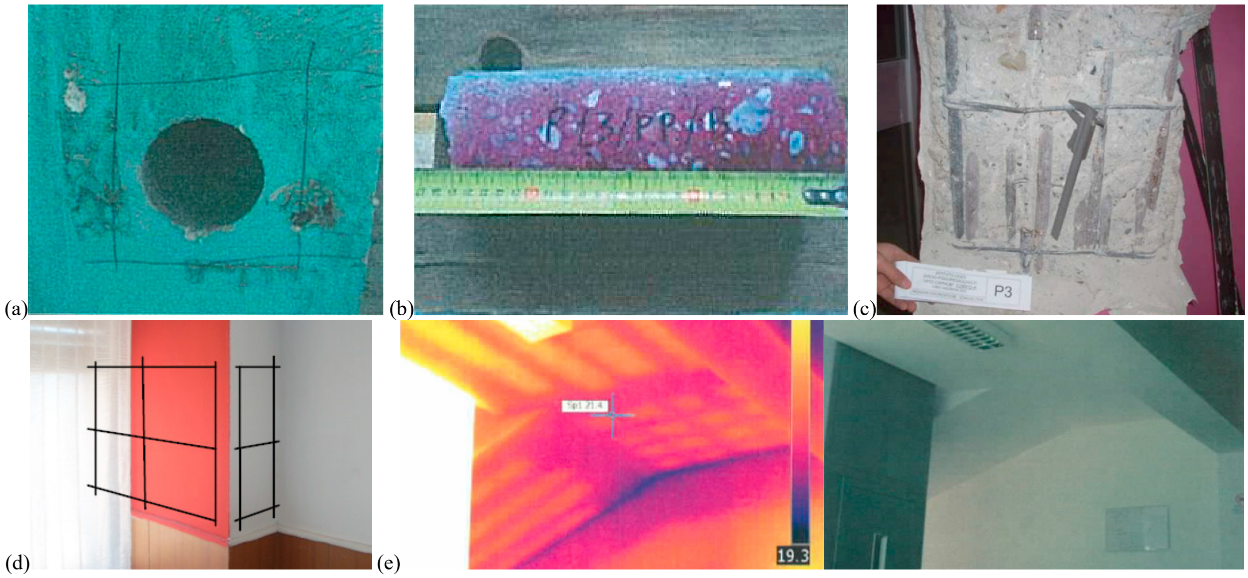


Fig. 3. (a) Coring of RC column; (b) Carbonation Depth Test; (c) Extraction of a steel bar sample from a column; (d) Pacometric test on a column to verify the positioning of steel bars; (e) Thermographic tests.

2.2. Seismic assessment

The seismic assessment was carried out according to the current Italian Code. For each limit state (i.e., Immediate Occupancy (IO), Damage Limitation (DL), Life Safety (LS), and Collapse Prevention (CP) the capacity peak ground acceleration is divided by the corresponding demand giving the risk index (I_R). The existing building shows the following deficiencies: 1) Inadequate stiffness for the limit states IO (I_R=0.822) and DL (I_R=0.940); 2) Poor shear capacity of brittle components; 3) Torsional effects that activate partial failure mechanisms; 4) Inadequate member chord rotation capacity for the LS Limit State (I_R=0.691); 5) Inadequate seismic gap from adjacent building structures. More details about the seismic performance assessment can be found in Ferraioli et. al. (2018).

3. Seismic retrofit using steel yielding dampers

3.1. The adopted "Participatory design approach"

To overcome the criticalities that emerged from the seismic assessment, a structural retrofit intervention was designed based on dissipative steel bracing. The choice of the most appropriate retrofit strategy depends on the characteristics of the school building (e.g., architectural distribution of the classrooms), availability of financial costs, temporary disruption of school activities, etc. The choice of the methodology of analysis and intervention on existing structures cannot depend strictly on engineering issues, but should necessarily optimize the cost/benefit ratio in the various aspects involved. In this specific case study, the use of dissipation devices has been directly requested by the Public Authority to reach the seismic retrofitting of the building by using innovative technologies. The objective has been also to use a highly visible solution to give a strong educational value given the following reasons: awareness of living in a very high seismic zone but, at the same time, attending a "Seismic-Safe School"; knowledge of the existence of innovative technologies able of improving safety conditions; recognition that the adopted solution made use of metal materials that are recyclable and respectful of the environment. In these circumstances, it has been important to adopt the so-called "participatory design approach" including all the parties involved. In addition to the Public Authorities that are generally engaged in the technical and economic aspects, also the School Management system played an important role in the functional and programmatic aspects. This approach includes, during the planning phase, several on-site meetings with the School Management, which explains the real needs of structures useful for the growth and educational training of students. Taking inspiration from the findings expressed by all the involved stakeholders, it is possible to proceed with a primary general approach to the project and to verify exactly the real needs to be satisfied, all of this in the perspective of an ever-increasing social awareness regarding a seismic safety that at the same time is respectful of various aspects such as full compliance with technical regulations, the comfort of the school building and completeness of construction works on schedule and within budget. As extensively proven through past experiences based on the designs of seismic retrofitting of school buildings, the close interactions between the Public Authority and the other parties involved (including teachers) were found to be particularly fruitful, to identify the needs of the school, so to ensure a high level of user satisfaction throughout the entire process of design and construction works. In conclusion, when these (fortunate) circumstances occur, it has been seen that each person can improve progressively the design process by distilling his personal experiences and insights: the **Technician** highlights compliance with the technical rules; the **User** brings the daily experience of using the school building; the **School Manager** evaluates the duration of works looking for minimizing the disruption of educational activities; the **Public Authority** looks at the maintenance of the asset and promotes the awareness of seismic safety.

3.2. Seismic design and structural details

The seismic design was carried out using a specific procedure giving the optimal distribution and sizing of dampers. All the details about the retrofit design method and subsequent performance assessment through **non-linear dynamic analysis** can be found in Ferraioli et al. (2018). Fig. 4 shows the views of the existing and retrofitted structures. Fig. 5 illustrates the layout in plan of the damped braces and some significant sections, which also show the foundations retrofit using micro-piles and RC plates. Fig. 6 shows some significant structural details and construction phases. The new foundations were built with micro-piles and RC plates (Fig. 6a). To make the micro-piles, a small machine to enter the classrooms on the ground floor was used (see Fig. 6a-6b-6d). Fig. 6b shows the connection of the damped brace to the RC beam using metal plates bolted to the center of the beam (Fig. 6c). The connection of the damped brace to foundations was carried out using metal plates that are fixed with bars inserted into the concrete (Fig. 6g). The metallic yielding dampers used represent special passive seismic protection systems that, unlike traditional bracing, show a greater dissipative capacity when subjected to inelastic cyclic deformations such as those induced by seismic actions. The use of dissipative bracing allows to maximize the safety level and, at the same time, minimize costs by limiting interventions on existing structural elements to a minimum. Moreover, it allows obtaining great flexibility and adaptability thanks to the possibility of inserting the braces along the perimeter of the casing (Fig. 7) or hiding them inside internal dividers between rooms (Fig. 6e-6f). This last characteristic is fundamental for schools where it is often required to keep the divisions of rooms unchanged to preserve the distributions of existing functions and plant networks. The implementation of the intervention involved the demolition and localized reconstruction of the interfering non-structural elements (such as cladding and partitions). This aspect, in addition to maintenance needs, was also used as an opportunity to give the intervention a **strong educational value**. It was decided to reconstruct the dividers between the classrooms by creating inspection hatches in plexiglass to make the intervention "visible" (Fig. 6h and 6i).

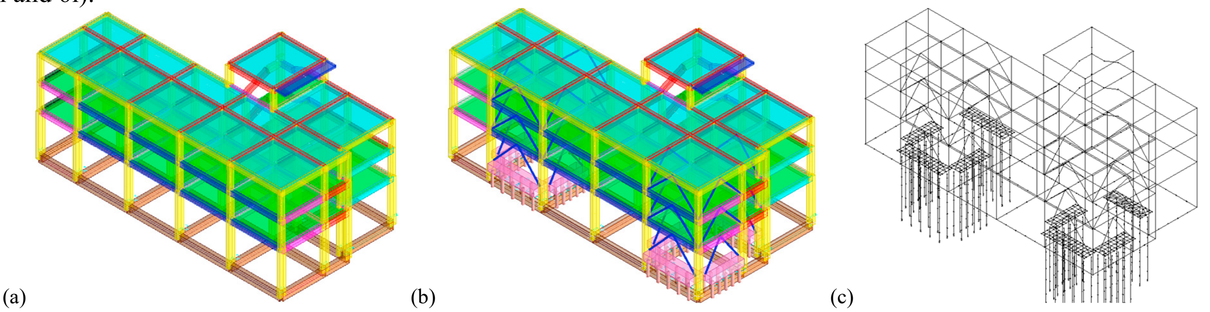


Fig. 4. (a) 3D view of the original building; (b) 3D view of the retrofitted building. (c) Fem model of the retrofitted building.

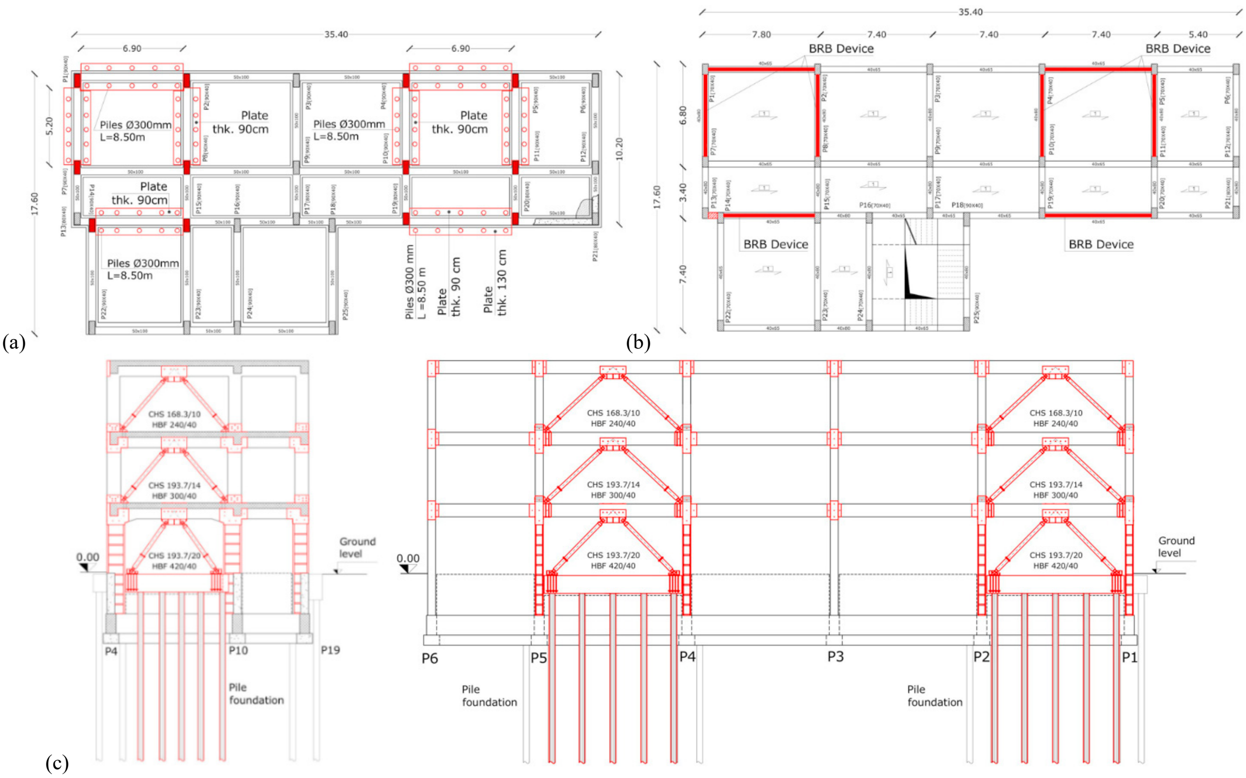


Fig. 5. (a) Retrofit of existing foundations; (b) Layout in plan of the damped braces; (c) Section views.

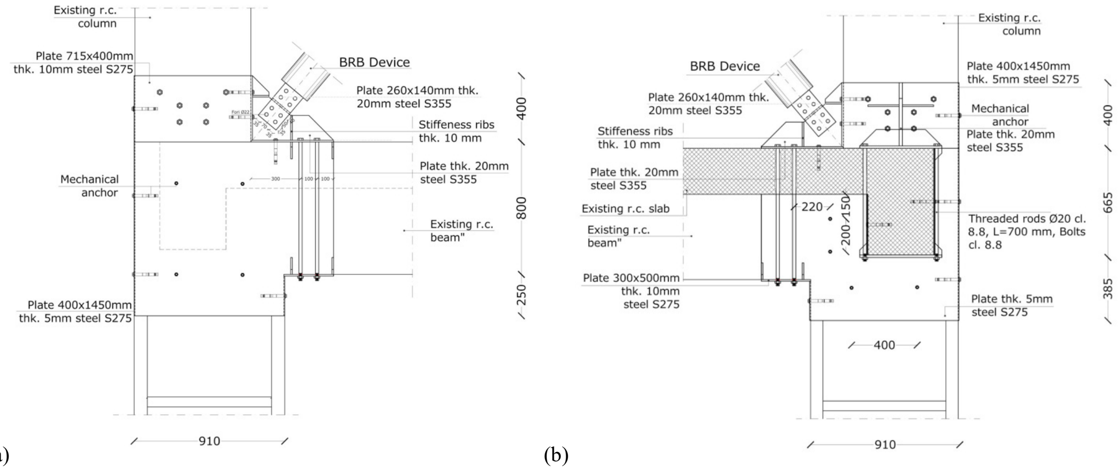
Fig. 6. (a) Excavations in foundation; (b) Construction of micropiles; (c) Connecting plates of damped brace to beam; (d) Rebars in foundation slab; (e) Internal damped braces; (f) Construction of partitions; (g) Connection of damped brace to foundation; (h) - (i) Visible dampers.

Fig. 7. External views after retrofit implementation

All of this was designed to raise awareness among young students, making them aware of living in a seismic area but at the same time attending a safe school, and making them aware of the existence of innovative technologies capable of improving safety conditions. The connections of the damped brace to columns (Fig. 8a-8b), beams (Fig. 9a), and foundations (Fig. 9b) is a very important aspect to treat in detail because they should transfer the seismic action from the brace to the main structure. Finally, some local interventions were required to avoid brittle failure modes. Fig. 10 describes the shear strengthening of beam-column joints using steel plates.

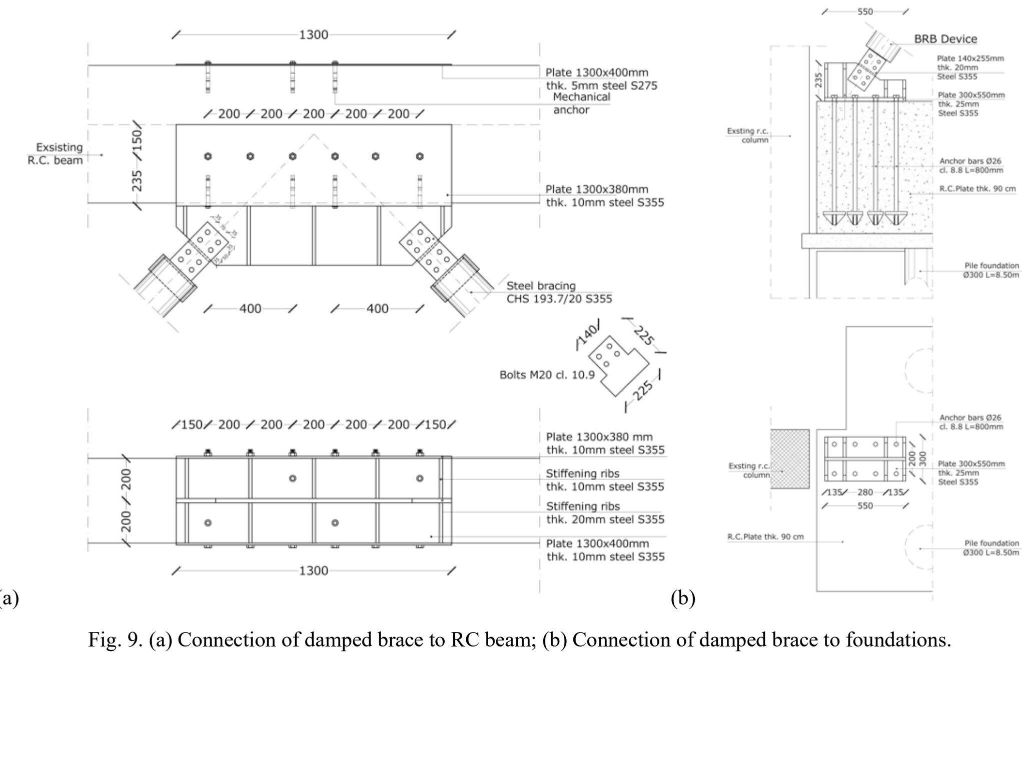
3.3. Construction phases, costs, and project execution times

The construction works were carried out without any particular problems with the project schedule and within budget. The total cost of the intervention, including repair works related to the aesthetic and functional aspects, was around € 490.000 (340 €/m^2). This amount is decidedly lower than the unit cost that can be estimated for a traditional retrofit of an existing building and is generally valued at around 800-900 €/m^2. The works lasted about one year and the interference with the educational activities was almost nil also considering that the supervision of works was able to compartmentalize and separate it from the building. Indeed, in the initial phase of the construction works some rooms of the school management and secretariat remained in use on the ground floor. This was possible given the type of intervention that allows working separately on the various floors and without the need to start from the bottom to the top. What was foreseen in the design phase regarding the minimum invasiveness with the existing structures and systems, the ease and speed of installation of the bracing, and reduced interference with the activities in progress, were confirmed during the execution of the works, requiring aesthetic/functional restoration and plant engineering interventions reduced to the essentials.



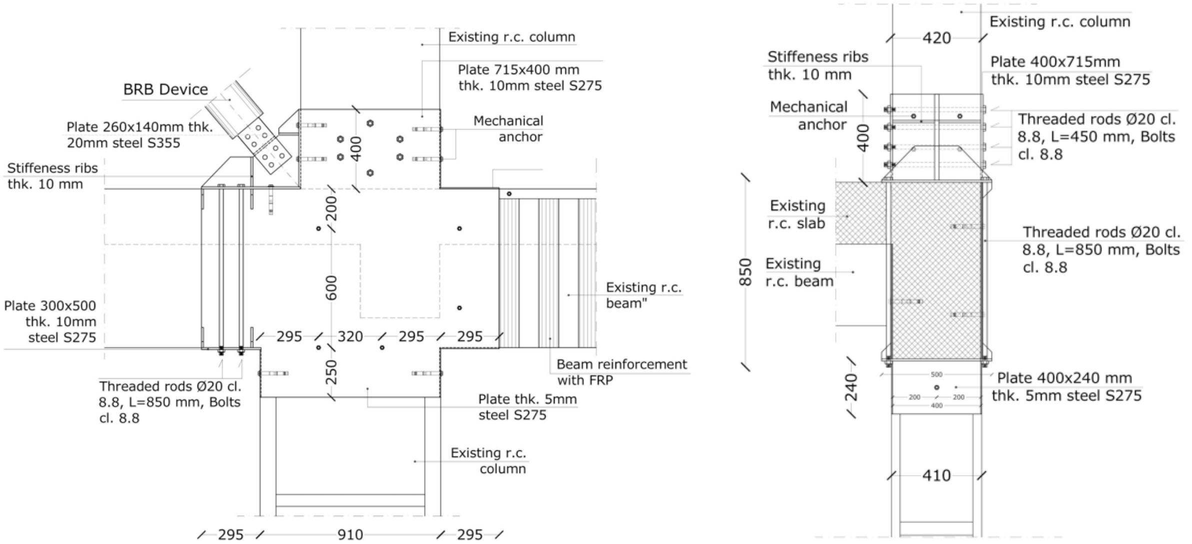
(a) (b)

Fig. 8. (a) Connection of damped brace to column: (a) Front view; (b) Section view.



(a) (b)

Fig. 9. (a) Connection of damped brace to RC beam; (b) Connection of damped brace to foundations.



(a) (b)

Fig. 10. Shear strengthening of beam-column joint with steel plates: (a) Front view; (b) Section view.

4. Conclusions

This paper presents an emblematic case study of a reinforced concrete school building retrofitted with steel yielding dampers. The entire design process, starting from the initial on-site and laboratory tests and seismic performance assessment to retrofit design and construction has been described in detail. The choice of the most appropriate retrofit strategy has been carried out using the so-called “participatory design approach” that includes all the parties involved and tries to reconcile engineering issues and cost/benefit optimization. The structural details, construction phases costs, and execution times are described in detail. General considerations for retrofit projects of school buildings are discussed.

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