Seismic Retrofit of a Precast RC School Building with External BRBs in Northern Italy

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Abstract. Precast RC structures have been widely used in Italy during past 60 years and mainly adopted to host industrial and commercial activities, as well as school buildings, such as the "Ercole I d'Este" in Ferrara. For these structures, quite common features are poor connections between structural elements, along with limited shear strength and flexural ductility of columns. Many of them were designed for gravity loads only, since past regulations did not imposed earthquake loads application for the whole Italian territory. Recent seismic events have proved how much these structures are prone to premature and fragile collapse, as observed during the 2012 Emilia Earthquakes when they caused several casualties, injured people, and displaced. This study presents the application of Buckling Restrained Braces (BRBs) as advanced retrofit solution for a sustainable upgrading of precast RC structures seismic performances. BRBs are implemented to add significant damping to traditional external seismic steel bracings, and seismic forces are transferred to external bracings thanks to a proper floor and roof reinforcement. Direct displacement-based design is applied to design BRBs, optimizing their sizing and plan position. BRBs effectiveness on the RC precast structure upgrading has been investigated using nonlinear time history analysis. The designed retrofit solution provides a global improvement of the seismic performance of the building to prevent any structural and nonstructural damage with sustainable costs. The major benefit of BRBs application respect to traditional braces is the reduction of external bracing and their foundations which leads to significant savings.

Keywords: Seismic retrofit · buckling-restrained brace · RC precast structure · nonlinear time history analysis · direct displacement-based design

1 Introduction

The built environment of the Mediterranean Basin countries, such as Italy, has high seismic risk. Here, earthquakes occur with high intensity and frequency, and the building stock is extremely vulnerable and highly populated. To reduce disaster victims and reconstruction impact, national programs have been funded since 2017, based on the assignment of significant tax incentives for interventions aimed at seismic retrofit of

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structures [1]. This ambitious project requires using advanced intervention techniques that are effective, economical, and non-invasive, to be applied without even minimal downtime.

Precast RC structures are among the structural typologies with the highest seismic vulnerability. Nowadays, they are mainly used for industrial and commercial activities, as well as school and sport activities, since they allow huge spaces with limited costs and construction times. Since the 60', precast RC structures have found increasing application and diffusion in the more industrialised areas. Due to the lack of efficient seismic regulations until recent times, and an adequate assessment of national seismic hazards, an extremely high number of seismically inadequate precast RC buildings are spread through Southern Europe territories [2–4]. Dramatic evidence was observed following the 2012 Emilia Earthquakes, which occurred in a heavily industrialised area. Thousands of precast buildings suffered enormous damage, up to the collapse, producing several casualties, injured people and displaced [5]. The main deficiency of precast RC structures typically lies in structural elements connection such as beams-columns, roof slabs-beams, and cladding panels-columns [6]. The lack of strength and ductility of RC columns is also quite common. Traditional retrofit techniques usually aim to strengthen elements connection and improve columns ductility. However, this approach does not prevent structures from severe damage and downtime in the aftermath of an earthquake. In this light, the implementation of mechanical dampers is the most economical and effective strategy to reduce direct and indirect economic losses [7, 8]. Indeed, the energy dissipation approach is the most effective way to speed-up activities' recovery and, in other words, increase community resilience.

This paper presents the seismic retrofit conceptual design of "Ercole I d'Este" high school in Ferrara, Italy, making use of Buckling Restrained Braces (BRBs). BRBs are implemented to add significant damping to traditional external steel bracings, and seismic forces are transferred to external bracings thanks to a proper floor and roof reinforcement. Direct Displacement-Based Design (DDBD) is applied to design BRBs, and their effectiveness on the precast RC structure upgrading has been investigated using Nonlinear Time History Analysis (NLTHA). The designed retrofit solution provides a global improvement of the seismic performance of the building, reaching a structural safety higher than 100% of the standard safety level requested for a new building by Eurocode 8 [9] with sustainable costs.

2 Case Study

"Ercole I d'Este", a high school building in Ferrara, Italy, was built in 2003 when seismic detailing was not mandatory and then the structure was designed for gravity loads only. Although seismic detailing was not respected, beam-to-column joints were provided as grouted bars cast during the beams' assembly on the top of columns. On the contrary, floor and roof tile-to-beam joints were totally lacking, and joints to connect cladding panels to columns were insufficient to seismic purposes. The building survived without damage to the 2012 Emilia Earthquakes, but just after the earthquakes a first structural upgrading was realised to eliminate the main deficiencies. Tile-to-beam joints were added, and cladding panels joints were upgraded using post-installed bars.

The building presents a rectangular base of 126 × 26 m^2 and a total height of 7.7 m. It is composed of two independent structures: the first structural body counts two storeys and hosts the school classrooms, the second one counts a single storey and hosts the laboratories. The former is the object of the present retrofit design, while the latter is considered not-interacting. The two parts of the building are divided by a staircase bay which is rigidly connected to the studied part but separated from the other one through a 7 cm seismic joint and a steel frame supporting floors. Structural plans of the body considered in the present study are presented in Figs. 1 and 2.

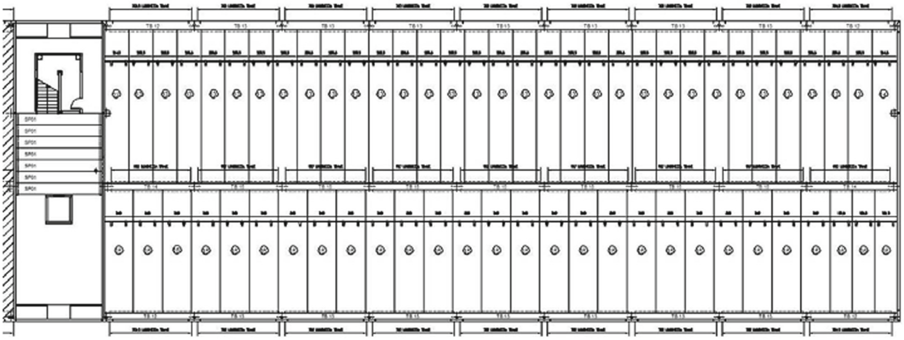


Fig. 1. Plan of the first floor.

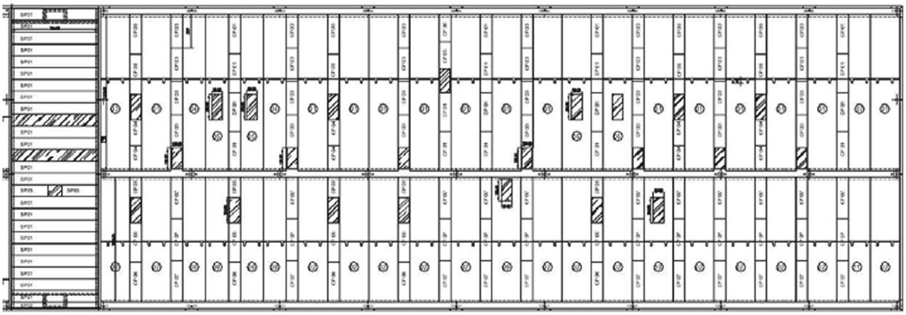


Fig. 2. Plan of the roof.

The structure is composed of precast RC columns with 45 × 45 cm^2 and 45 × 60 cm^2 sections, prestressed RC beams with "L" and "reverse T" section shape, prestressed floor and roof tiles with "π" section shape (two webs), and a RC slab of 6 cm thickness at first storey only. Columns are supported by plinth foundations with RC piles linked by plinth beams which are connected to concrete industrial pavement of 20 cm thickness. Material samples have been extracted from the structure columns and qualified by mechanical testing. Concrete average compressive strength is equal to 37.4 MPa, average elastic modulus 32.7 GPa, and steel reinforcement average yielding stress 450 MPa. Storey gravity loads in as built seismic combination are equal to 8.70 kN/m^2 and 2.40 kN/m^2 for first storey and roof, respectively. Concerning static loads, the structure is in compliance with the new buildings standards but concerning seismic loads, columns vulnerability in term of the ratio demand/capacity is about 2.8 and 3.0 due to flexural and shear failure at the base, respectively.

3 Retrofit Project

The presented retrofit project has been designed in 2021, aiming to upgrade the structural safety of the two-storey building to 100% of the standard safety level requested for a new building by Eurocode 8 [9], without interfering with the adjacent structural body. Four external steel bracings with BRBs have been adopted for each direction, installed at only one side of the building per direction, as shown in Figs. 3 and 4.

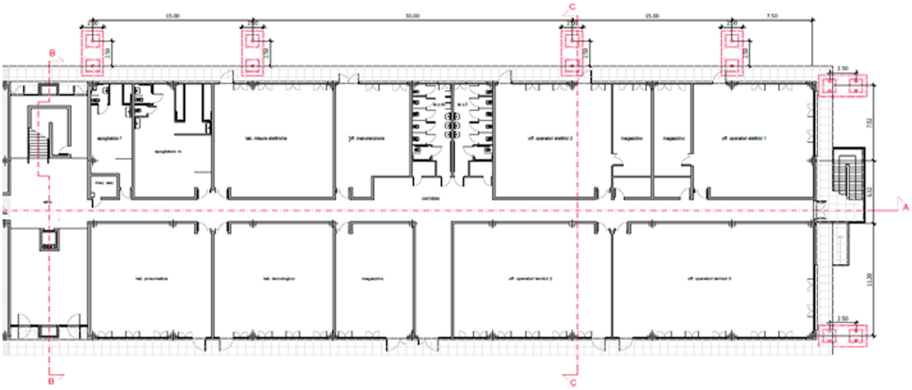


Fig. 3. Plan of the building with external bracings foundations in red. Dimensions in m.

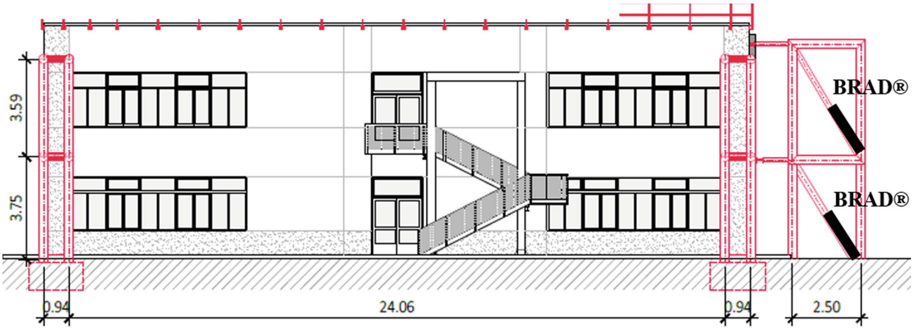
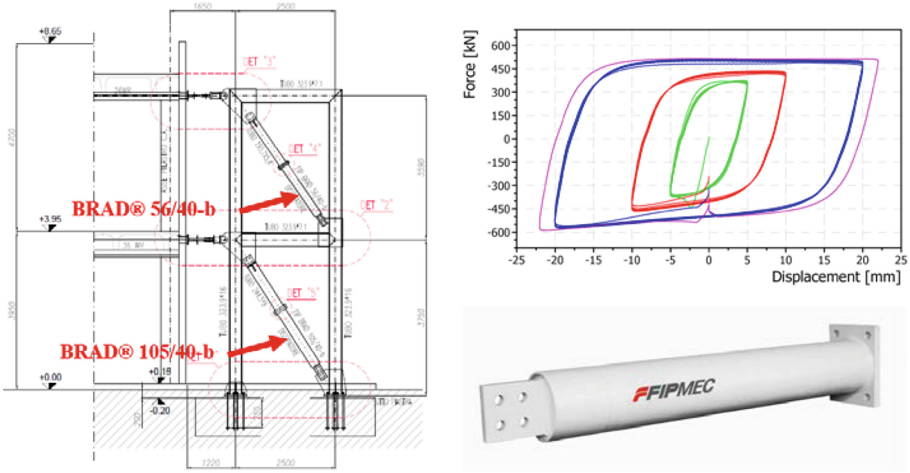


Fig. 4. Lateral view of the building with external bracings in red. Dimensions in m.

In order to reduce the number of external bracings, rigid diaphragms floors are needed. While the first storey is already provided by a RC floor slab, a new RC slab has been designed to be cast on the top of the roof floor. The added weight on the roof storey is 1.00 kN/m^2 and can be carried by the structural elements without static reinforcement. Designing non-dissipative external braces would have required massive steel elements and new foundations with long piles to support the overturning moment. Thanks to the application of BRBs, the structural elements size has been reduced consistently, and consequently the cost of braces and their foundations.

Buckling-Restrained Axial Dampers (BRAD®), produced by FIP MEC S.r.l. (Padova, Italy) have been implemented in BRBs, one for each storey. The BRAD® are located along the diagonals of bracings (Figs. 4 and 5).



a) b)

Fig. 5. a) Detailing of external bracings with BRBs, dimensions in mm; b) Experimental hysteresis cycles of BRAD® 56/40-b at different amplitudes and BRAD® picture [15]

The selected BRAD® are type 105/40-b and 56/40-b. Type 105/40-b is installed at lower level and offers a yielding force of 900 kN at 2.03 mm of axial displacement and an ultimate force of 977 kN at 20 mm of axial displacement. Type 56/40-b is installed at upper level and offers a yielding force of 479 kN at 1.98 mm of axial displacement and an ultimate force of 519 kN at 20 mm of axial displacement (Fig. 5). BRAD® have been certified by the manufacturer in accordance with EN15129 [10].

External bracings are made of S355 round steel tubes of 323.9 mm diameter and 7.1 mm thickness for beams, 323.9 mm diameter and 16 mm thickness for columns, 244.5 mm diameter and 8 mm thickness for lower diagonals, and 193.7 mm diameter and 5.4 mm thickness for upper diagonals. Their capacity is protected by an overstrength factor equal to 1.25 over maximum actions transferred by dampers. Each brace in transversal direction and each brace couple in longitudinal direction have an independent plinth foundation with eight RC piles of 40 cm diameter and 23 m length and of 40 cm diameter and 15.5 m length, respectively. The choice of coupled bracings in longitudinal direction has been driven by economic reasons, to reduce the number of acceptance testing as requested by EN15129 [10].

The design of dissipative bracings has been performed with Direct Displacement-Based Design [11] optimizing their sizing and plan position. The designed retrofit solution aims to provide a global improvement of the seismic performance of the building to prevent any structural and nonstructural damage, therefore an appropriate design inter-storey drift ratio (IDR) is selected equal to 0.5%. Under this drift limitation, structural damage is prevented since structural elements connections integrity is safeguarded, and no steel yielding and shear failure of columns occur. Also, non-structural damage is prevented since infilled panels damage probability keeps lower than 5% [12–14]. To reach such performance, an equivalent damping coefficient of 21% must be provided by BRBs.

4 Numerical Analyses

NLTHA have been performed in order to accurately evaluate the structural performance of the retrofitted structure under the design seismic action. The considered building is located in an Italian medium seismic risk zone, characterized by a Peak Ground Acceleration (PGA) of 0.15 g and Soil Amplification Factor of 1.46 for Life Safety (LS) limit state and of 0.20 g and 1.40 for Near Collapse (NC) limit state. A group of seven natural ground motions have been selected, orthogonal effects have been coupled with the 100:30 rule [9] and then applied in switched direction for a total of fourteen NLTHA. A preliminary check executed on RC beams and tiles, accounting the vertical component of ground motion, has shown that seismic vertical actions are not relevant if compared to the gravity load actions at Ultimate limit state.

Spectral compatibility shown in Fig. 6 has been checked by comparison of the selected records mean spectrum with the target elastic spectrum using Rexel software [16]. The average and maximum values of selected ground motion scale factors are equal to 1.9 and 2.8, respectively. NLTHA have been carried out using the commercial FEM code Midas/Gen [17]. The Rayleigh damping coefficient has been set to 5% and the analysis time step assumed 0.01 s, that is lower than 1/20 of the fundamental period.

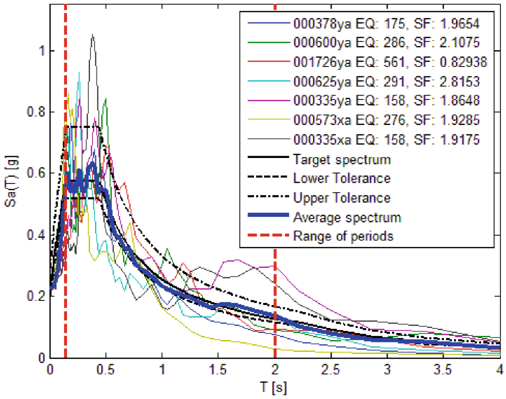


Fig. 6. Elastic spectra of selected natural ground motions with scale factors.

RC columns and beams, steel frame and external steel bracings have been modelled as elastic *beam* or *truss* elements, BRBs as nonlinear *spring* with a bilinear shape. Column's ends have been modelled with lumped plasticity adopting simplified normal bilinear hysteretic hinge to check whether their behaviour is limited to elastic field. Beams are simply supported by columns which work as cantilevers. Floor and roof tiles have been simulated as rigid diaphragms. Cladding panels have not been modelled because they do not interact with the structure as the building presents wide ribbon windows. An isometric view of the numerical model is shown in Fig. 7.

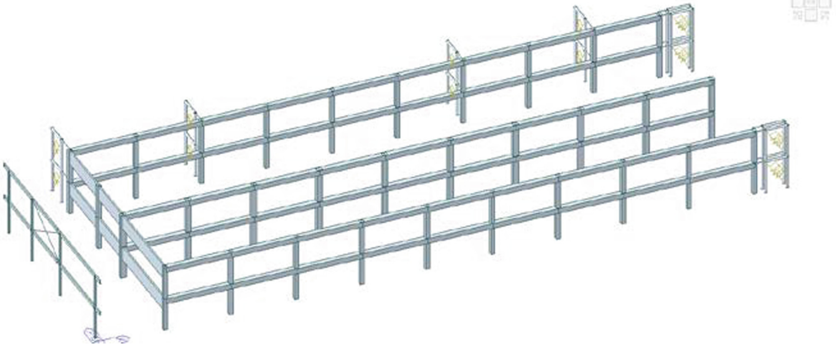


Fig. 7. 3D scheme of numerical model.

5 Results and Discussion

The adopted retrofit solution through BRBs has been validated by NLTHA which have confirmed the adequacy of the building seismic performance to prevent any structural and nonstructural damage, and to fulfill the limitation of IDR $\leq 0.5\%$.

Thanks to the BRBs introduction, a regular dynamic behavior is established, and a significant reduction of top displacements d, *IDRs*, and shear forces in columns V_{col} is obtained in both transversal and longitudinal directions, as reported in Table 1. It is noted that the overall base shear V_b of the retrofit project is almost 30% higher than of the as built, due to the increased stiffness provided by braces, and the consequent reduction of main vibration period T_1. However, more than 40% of V_b is supported by the new external bracings with BRBs. Seismic adequacy of the building has been obtained and all demand/capacity ratios for top displacement, shear and flexure are reduced to less than one, as shown in Table 2.

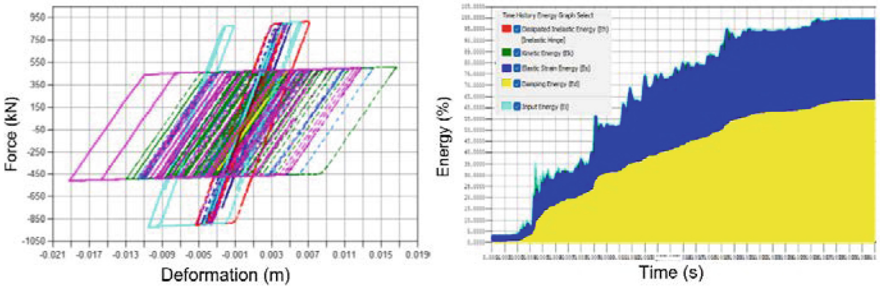
In Fig. 8 hysteretic cycles of BRBs recorded during NLTHA are shown, with reference to all the considered earthquakes in NC limit state. According to EN1998 and EN 15129 [10], maximum axial displacements do not exceed ultimate values suggested by the manufacturer [18]. In Fig. 8b the energy balance during the 000355xa earthquake in LS limit state is reported. No energy from inelastic hinges is released, and energy dissipation produced by BRBs is about 60% of the input energy.

Table 1. Structural response average results of as built and retrofitted building.

Project/Direction	*d* [mm]	*IDR*	V_b [kN]	V_{col} [kN]	T_1 [s]
As Built/Longitudinal	58	0.009	3000	3000	1.22
Retrofit/Longitudinal	32	0.005	3850	2200	0.74
Difference (%)/Longitudinal	**−45%**	**−44%**	**28%**	**−27%**	**−39%**
As Built/Transversal	63	0.010	2900	2900	1.41
Retrofit/Transversal	32	0.005	3700	2150	0.77
Difference (%)/Transversal	**−49%**	**−50%**	**28%**	**−26%**	**−45%**

Table 2. Columns' demand/capacity ratios of the retrofit project.

Direction	d_{max}/d_{gap}	V_{max}/V_{Rd}	M_{max}/M_{Rd}
Longitudinal	0.91	0.91	0.95
Transversal	0.91	0.93	0.92



a) b)

Fig. 8. a) Hysteretic cycles of BRBs at 1st and 2nd storey for all earthquakes in NC limit state. b) Energy balance during 000355xa earthquake in LS limit state

The total cost of the proposed retrofit solution in 2021 has been estimated about 730 k€ equal to about 190 €/m^2 of the usable area. The economic impact of different works in per cent over the construction total cost is reported in Fig. 9. The cost of steel bracings with BRBs, including foundations and acceptance testing, amounts to 49% of the total. BRBs economic impact is limited to 17% of the external bracings total cost, and 8% of the construction total costs. A traditional retrofit solution without BRBs would have been costed from 30 to 50% more, due to bigger bracing structures and longer foundation piles, without fulfilling the no-damage requirement. For this reason, the school building owner approved and funded the proposed retrofit solution.

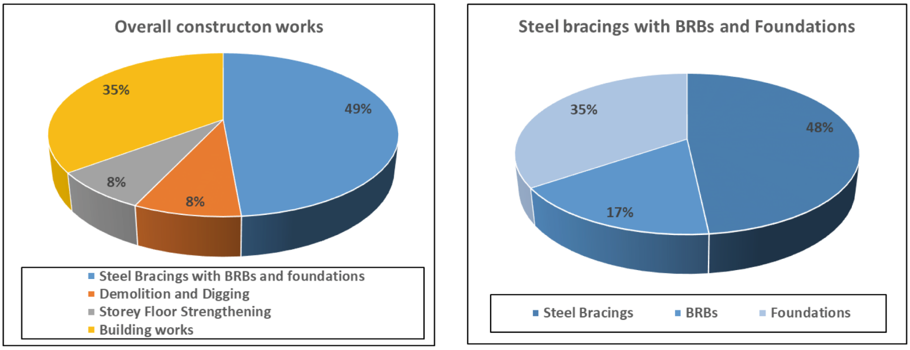


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Fig. 9. a) Economic impact of different works in per cent over the construction total cost b) Economic impact of BRBs in per cent over the external bracings total cost

6 Conclusions

This study presents the application of BRBs as advanced retrofit solution which allows a sustainable upgrading of seismic performances of a precast RC school building in Ferrara, Italy. BRBs have been designed to add significant damping to traditional external steel bracings. A proper strengthening of storey floors has been designed to ensure their behavior as rigid diaphragm.

DDBD has been applied to design BRBs, optimizing their sizing and plan position in order to prevent any structural and non-structural damage. The retrofit design effectiveness has been investigated using fourteen NLTHA, implementing elastic structural elements except for lumped plasticity at columns' ends and nonlinear springs to simulate BRBs. Numerical modelling results have confirmed that no yielding and shear failure occur in structural elements, nor pounding with the nearby building, and that IDRs keeps lower than 0.5% at LS limit state. The designed retrofit solution provides a global improvement of the seismic performance of the building, which is now in compliance with new buildings standards. The retrofit project prevents both structural damage and non-structural damage of infills and plants in LS limit state.

Besides, external braces with BRBs are minimally invasive because built with new external foundations and linked with the existing structure at floor and roof level only, so that internal equipment must not be removed during the works. The benefit of BRBs respect to traditional braces is the relevant reduction of the external bracing size and piles' length of new foundations which leads to significant savings, making them a competitive and sustainable solution.

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