A Novel Friction Damper for Seismic Retrofit of Precast RC Structures with Poor Connections

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Abstract. Precast RC structures are commonly adopted for industrial and commercial buildings, to build huge spaces with limited costs and construction times. Due to the lack of efficient seismic regulations until recent times, and adequate assessments of seismic hazard, a huge number of seismically inadequate precast RC buildings are spread through Southern Europe territories. Workers' and users' safety requirements, and the preservation of high-value facilities and stocks, demand the adoption of effective retrofit techniques for earthquake risk mitigation.

For this structural typology, connections between structural elements are often crucial for carrying lateral loads, such as earthquakes. This study presents an innovative device that acts as beam-to-column joint and as damper at once, with bidirectional dissipative capacity. Very easy to install, low cost and reusable after the main shock, this novel Bidirectional Rotation Friction Damper (BRFD) has been conceptualized and designed to improve the seismic performance of such structures by excluding the brittle failure of structural and non-structural elements. Preliminary experimental tests performed at the University of Ferrara, Italy, have proved the high-damping capacity of this novel device.

BRFD effectiveness on a precast structure has been explored using nonlinear time-history analysis accounting both low- and high-intensity Italian earthquakes. Numerical modelling has shown that no beam's slippage on column top section and no column crisis can occur in both building directions when BRFD are properly implemented. The designed devices provide a global improvement of the seismic performance of the building, preventing any structural and non-structural damage even for the more critical Near-Field events.

Keywords: beam-to-columns connections · bidirectional damping · rotational friction dampers · RC precast structures

1 Introduction

Precast RC structures have widely spread out for industrial and commercial buildings since the '60s, thanks to the possibility to cover large spans with modular quickly installable mass-product elements. During those decades of economic growth, rough seismic design regulations were available, resulting with structures mainly designed for gravity loads only. The early 2000 state-of-the-art FIB report on seismic design of precast RC buildings [1], shows the crucial relationship between structural joints and seismic

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response of such buildings. In time, only structures with efficient joints have shown good performances and a correct development and placement of plastic hinges during the earthquakes. During the 2012 Northern Italy Earthquakes a great number of precast RC buildings with poor connections, designed without seismic detailing, collapsed producing 28 casualties, hundreds of injured persons, thousands displaced and a huge damage for the regional economy, despite the low-medium intensity of the seismic events [2, 3].

The seismic rehabilitation of existing buildings with energy dissipation devices has proved to be very efficient, preventing damage of structural elements [4], and being a much cheaper solution if compared to traditional retrofit techniques [5, 6]. Several studies have been conducted on steel frames [7, 8], as well as on precast RC frames [9–11], to propose devices performing both as elements' connection and damper. These devices have proved a good structural performance in terms of both energy dissipation and base shear reduction, limitedly to the frame's plane where they are installed. Thus, orthogonal frames with added devices are required to get energy dissipation in both directions, as required by the seismic action.

In this paper, an innovative damping device is proposed to be installed in beam-to-column joints of precast RC structures, able to dissipate energy in plane and out plane of the installation main frame at once. Starting conceptually from a simple Rotational Friction Damper (RFD), and using a movable plates geometry, a Bidirectional Rotational Friction Damper (BRFD) is created producing a relevant damping effect in two main directions. The conceptualization study of the BRFD is presented in Sect. 2, where the structural layout is defined, and preliminary axial tests results are reported. The case study of a precast RC building with installed BRFDs is presented in Sect. 3. In Sect. 4 results of nonlinear time-history analyses are shown considering both Far-Field and Near-Field seismic events [12–14]. Conclusions are drawn in Sect. 5, including some consideration on different possible fields of application.

2 Conceptualization Study

2.1 Structural Layout and Design Requirements

The BRFD is formed by layered steel plates whose contact surfaces dissipates energy by friction (Fig. 1a). It is designed to be installed in beam-to-column joints with a 45° inclination from the longitudinal beam axis (Fig. 1b), depending on the available space.

Core plates and core connection plates, as well as the four preload bolts that keep them coupled (Fig. 1a), constitute the BRFD main elements that host the friction interfaces. BRFD activation force and initial stiffness are highly influenced by core plates geometry, bolts preload, and mechanical properties of the constitutive elements. Once the BRFD is activated, core central and side plates' ends rotate around the preload bolts, and the energy dissipation occurs thanks to friction generated by the plates' contact.

Two guides with slotted holes have been placed at the top and at the bottom of the device (Fig. 1a) to keep preload bolts lined-up with the central bolt during the motion. The selected structural layout allows a double component of displacement, longitudinal and transversal respect the device main axis, enhancing its efficiency.

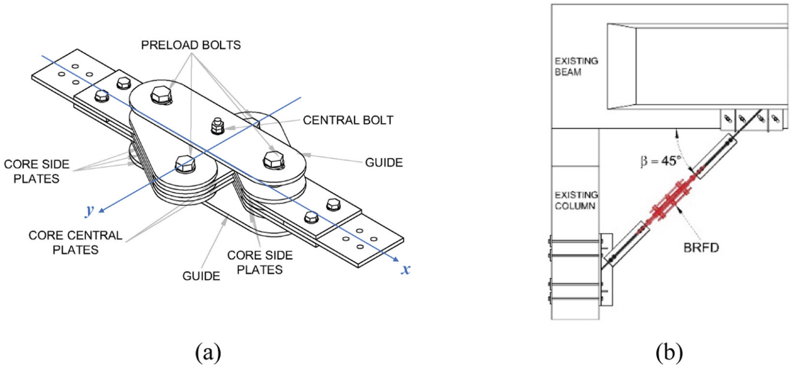


Fig. 1. BRFD a) axonometric view and b) example of installation as beam-to-column connection.

Under any circumstances, the BRFD design is driven by two main conditions:

1. RC beams and columns cannot slide on each other during the seismic motion even if a mechanical fastening is not installed.
2. RC beams and columns shear, and flexural demand cannot exceed their capacity.

2.2 Prototype Preliminary Axial Test Results

The design of the BRFD prototype has firstly requested the selection of a proper coupling surfaces able to develop a reliable and steady friction coefficient μ. To this aim, a preliminary tribological investigation was performed at the Metallurgy Laboratory (Engineering Department, University of Ferrara, Italy) [15, 16]. The obtained results brought to select nickel-coated steel and bronze surfaces for a proper surface coupling and to define a suitable running-in test to be performed, able to increase significantly the overall μ steadiness.

Preliminary axial tests have been performed on the BRFD prototype at the Structural Integrity Laboratory (Engineering Department, University of Ferrara, Italy) using an MTS 810 (Mod. 318.25) testing machine and control system. The testing procedure has been set according to EN15129 [17]. After the execution of the running-in test, the BRFD has been subjected to oscillatory displacements with maximum values of 10, 20 and 40 mm, applied with frequencies of 0.05, 0.5 and 1 Hz. The BRFD hysteretic behavior has been modelled using the Coulomb law with constant $\mu = 0.4$ and bolts torque of 100 Nm. The obtained experimental and analytical results have been compared and they have shown a very good agreement for the considered displacements and frequencies. Figure 2 shows the comparison between the experimental (E) and analytical (A) hysteresis cycles performed at 0.05 Hz. The experimental curve displays a steady and reliable behaviour and matches with such simple analytic prevision. As a result, the numerical implementation of the BRFD can be obtained using a simple hysteretic model.

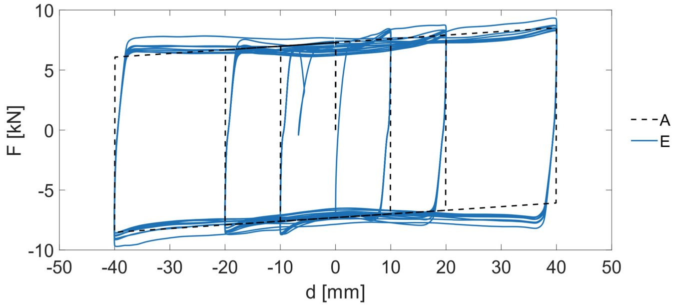


Fig. 2. BRFD hysteresis cycle: comparison between analytic (A) and experimental (E) results.

3 Case Study

To evaluate the efficacy of the BRFD, the case study of a single-story single-bay precast RC structure shown in Fig. 3 is considered. Main frames are composed by I-shaped prestressed beams and by square columns 7 m height from the foundation. Figures 3c and 3d shows the reinforcement detailing of columns and beams while the material properties are assessed by on-site sampling: concrete has 38 MPa cylindrical compressive strength and 33 GPa Young modulus, reinforcing steel bars have 544 MPa yielding stress and 200 GPa Young modulus, prestressed steel bars have 1670 MPa yielding stress and 200 GPa Young modulus. Main frames (*X* direction) are connected in out-of-plane direction (*Y* direction) by three PI-shaped prestressed slabs with 17.30 m span long, so that a proper frame in *Y* direction is lacking.

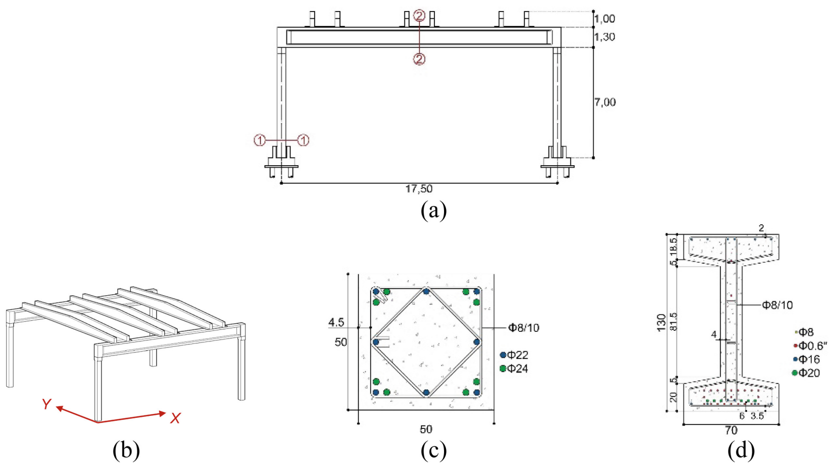


Fig. 3. Precast RC structure a) main frame and b) 3D view (dimensions in m) and detailing of c) column and d) beam at mid-span (dimensions in cm).

BRFDs are installed in the main frames only (*X* direction) and positioned at the corner between beams and columns, as shown in Fig. 1b. It is worth noting that the devices implementation changes the structural behaviour, increasing the beam-to-column joint stiffness and providing energy dissipation in both X and Y directions. When the device is active, concentrated actions occur on both beams and columns at connections, and beams might slip on columns top section. For this reasons, beams and columns shear capacities, as well as beams slipping forces, are part of the design parameters.

Seismic design of BRFDs was carried-out considering Damage Limitation (DL), Severe Damage (SD) and Near Collapse (NC) limit states, according to Eurocode 8 [18], and selecting Italian low-risk and high-risk seismic zones, Zone 3 (Z3) and Zone 1 (Z1) respectively. For each seismic zone, an optimization analysis based on nonlinear time-history simulation has been conducted to select the most effective device, with the smallest geometry and lower construction costs [19, 20]. The optimization target has been set on columns drift reduction and beams and columns damage control (no-yielding, no-shear-failure, and no-slipping condition). The optimized geometry of BRFDs for the selected seismic zones are reported Table 1 and Table 2.

A group of seven spectrum-compatible natural ground motions with two components were selected for each limit state and seismic zone assuming soil type C and building Importance Class III, according to Eurocode 8 [21]. Figure 4 shows the acceleration response spectra of the selected accelerograms and the target spectrum for each limit state and seismic zone considered.

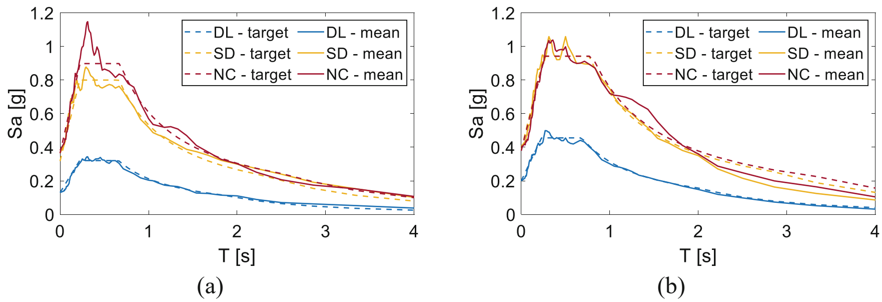


Fig. 4. Spectrum-compatibility of the selected group of natural ground motions for the considered a) Z3 and b) Z1 seismic zones.

4 Structural Performance Assessment with BRFDs

Nonlinear time-history analyses were carried out using the commercial FEM code Midas/Gen [22], while MATLAB [23] software was used for pre- and post-processing of data. Nonlinear links with bilinear hysteresis models [22] have been used for numerical simulation of BRFDs in both longitudinal (x) and transverse (y) directions of the device. The first branch of this model is defined by the activation force F_a and initial stiffness K and the second branch by a post-yield stiffness ratio of 10^{-4}.

4.1 Far-Field Hypothesis (FFH)

According to the optimization analysis, two devices have been selected, for Z3 and Z1 seismic zones, respectively. The selected BRFDs main properties for FFH are reported in Table 1, where *l*, *w* and *t* are the length, the width, and the thickness of the core plates, respectively.

Table 1. Selected BRFD's main properties for FFH.

Seismic Zone	*l* [mm]	*w* [mm]	*t* [mm]	Bolt size [24]	$F_{a,x}$ [kN]	$F_{a,y}$ [kN]	K_x [kN/m]	K_y [kN/m]
Z3	340	140	10	M24	151	87	1.47E + 05	8.46E + 04
Z1	340	120	18	M30	192	111	1.66E + 05	9.59E + 04

The global structural performance before and after the device's installation is schematically represented in Figs. 5 and 6 using ADRS format [25], where ρ_s is ratio between the horizontal component of BRFD's activation force F_a and the beam-column shear-slipping capacity, ρ_d is ratio between columns drift demand and capacity, and ξ is the equivalent damping coefficient in per cent.

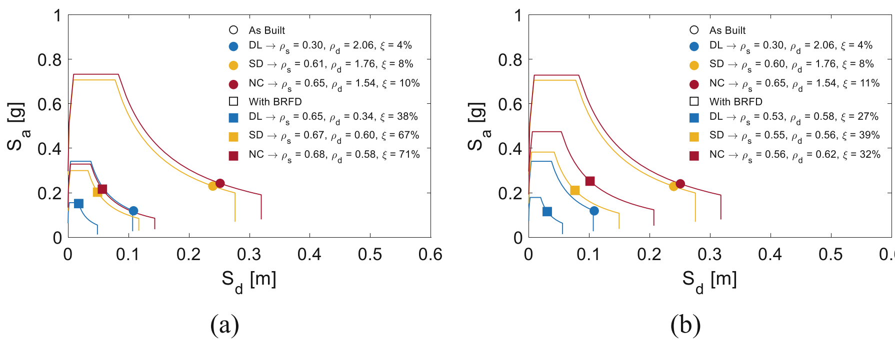


Fig. 5. Structural performance in Z3 with and without BRFDs (Table 1) under FFH: (a) *X* direction and (b) *Y* direction.

In the *As Built* configuration, base shear ranges between 200 and 410 kN for Z3 and between 260 and 480 kN for Z1 in both directions and different limit states without reaching the shear-slippage limit ($\rho_s < 1$). Beams and columns register a percentage of shear work that average, respectively, around 73% and 42% for Z3 and around 73% and 50% in Z1. Column top displacement range between 11 and 25 cm for Z3 and between 15 and 33 cm for Z1 in both directions and different limit states. These values are associated to a high damage level in SD and NC limit states for both the considered seismic zones ($\rho_d > 1$), confirming the plastic behaviour of the columns. Finally, limited values of ξ

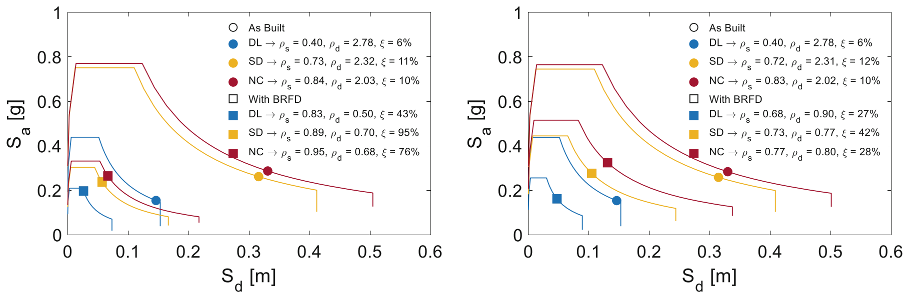


Fig. 6. Structural performance in Z1 with and without BRFDs (Table 1) under FFH: (a) *X* direction and (b) *Y* direction.

are obtained, ranging between 4 and 11% for Z3 and between 6 and 12% for Z1 in both directions and different limit states.

In the *With BRFD* configuration, base shear ranges between 190 and 430 kN for Z3 and between 270 and 550 kN for Z1 in both directions and different limit states without reaching the shear-slippage limit ($\rho_s < 1$). Beams and columns register a percentage of shear work that average, respectively, around 60% and 43% for Z3 and around 62% and 52% in Z1. Column top displacement range between 2 and 10 cm for Z3 and between 4 and 11 cm for Z1 in both directions and different limit states. These values are associated to no-damage level in all the limit states and for both the seismic zones ($\rho_d < 1$). Finally, high values of ξ are obtained, ranging between 27 and 71% for Z3 and between 27 and 76% for Z1 in both directions and different limit states.

As a summary, an overall performance improvement in terms of spectral accelerations and displacements can be observed in both *X* and *Y* directions, avoiding structural damage with a significative damping effect. It is worth noting that in the *With BRFD* configuration the interstorey drift remarkably decreases up to 80% in *X* direction and 66% in *Y* direction, and the associated base shear slightly increments up to 2% in *X* direction and 3% in *Y* direction. This result is successfully in line with the assumed design objectives.

4.2 Near-Field Hypothesis (NFH)

The selection of the optimal BRFD has been revised considering the increment of the vertical component of the seismic action in the case of NFH. The selected BRFDs main properties for NFH are reported in Table 2.

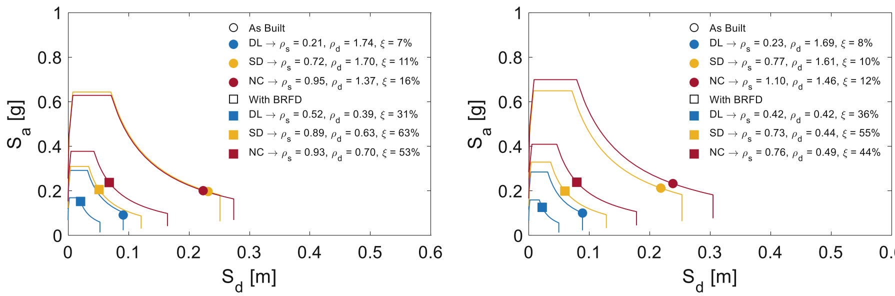
The global structural performance before and after the device's installation is schematically represented in Figs. 7 and 8 using ADRS format [25].

In the *As Built* configuration, base shear ranges between 150 and 390 kN for Z3 and between 200 and 450 kN for Z1 in both directions and different limit states, reaching the shear-slippage limit ($\rho_s > 1$) for SD and NC limit states in *Y* direction. Beams and columns register a percentage of shear work that average, respectively, around 37% and 48% for Z3 and around 51% and 43% in Z1. Column top displacement range between

Table 2. Selected BRFD's main properties for NFH.

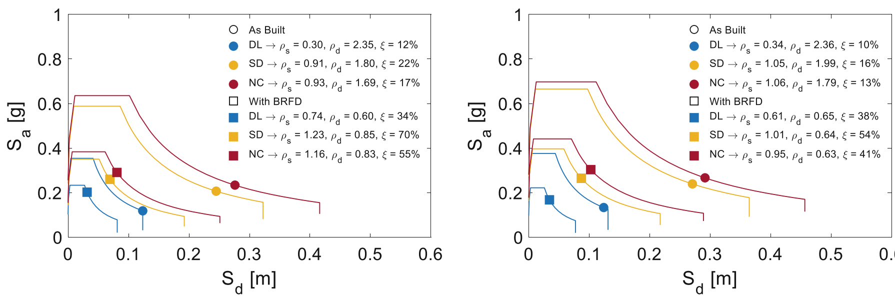
Seismic Zone	l [mm]	w [mm]	t [mm]	Bolt size [24]	$F_{a,x}$ [kN]	$F_{a,y}$ [kN]	K_x [kN/m]	K_y [kN/m]
Z3	340	140	10	M24	151	87	1.47E + 05	8.46E + 04
Z1	300	120	14	M24	146	84	1.88E + 05	1.09E + 05

9 and 24 cm for Z3 and between 12 and 29 cm for Z1 in both directions and different limit states. These values are associated to a high damage level in SD and NC limit states for both the considered seismic zones ($\rho_d > 1$), confirming the plastic behaviour of the columns. Finally, ξ values range between 7 and 16% for Z3 and between 10 and 22% for Z1 in both directions and different limit states.



(a) (b)

Fig. 7. Structural performance in Z3 with and without BRFDs (Table 2) under NFH: (a) X direction and (b) Y direction.



(a) (b)

Fig. 8. Structural performance in Z1 with and without BRFDs (Table 2) under NFH: (a) X direction and (b) Y direction.

In the *With BRFD* configuration, base shear ranges between 210 and 400 kN for Z3 and between 250 and 530 kN for Z1 in both directions and different limit states without reaching the shear-slippage limit ($\rho_s < 1$). Beams and columns register a percentage of shear work that average, respectively, around 50% and 45% for Z3 and around 55% and 57% in Z1. Column top displacement range between 2 and 8 cm for Z3 and between 3 and 12 cm for Z1 in both directions and different limit states. These values are associated to no-damage level in all the limit states and for both the seismic zones ($\rho_d < 1$). Finally, high values of ξ are obtained, ranging between 31 and 63% for Z3 and between 33 and 63% for Z1 in both directions and different limit states.

As a summary, an overall performance improvement in terms of spectral accelerations and displacements can be observed in both *X* and *Y* directions, avoiding structural damage with a significative damping effect. It is worth noting that in the *With BRFD* configuration the interstorey drift remarkably decreases up to 69% in *X* direction and 64% in *Y* direction, and the associated base shear slightly increments up to *12%* in *X* direction and 26% in *Y* direction. This result is successfully in line with the assumed design objectives, highlighting the BRFD efficacy even for NFH.

5 Conclusions

In this study the performance of a new BRFD device has been investigated with the aim to improve the overall performance of precast RC structures with poor or no connections. BRFD is meant to solve connection deficiencies acting as beam-to-column joint and damper at once, so that RC structural elements are kept in the elastic field. Nonlinear time-history analyses have been performed on a common precast RC structure before and after the BRFD installation to evaluate the effectiveness of this innovative device. The main findings are summarised as follows:

- The BRFD can improve the overall structural performance in terms of spectral accelerations and displacements in both the main structural directions *X* and *Y*, considering seismic zones Z3 and Z1, and both field hypothesis FF and NF, with an equivalent damping coefficient ranging between 32% and 69%.
- The BRFD can significantly decrease the interstorey drift in both *X* and *Y* directions, up to 80% in FFH and 69% in NFH with a maximum base shear increase limited to 3% in FFH and 26% in NFH.

Further step of the ongoing research will be the experimental characterization of BRFD, that will include the execution of 2D mechanical and 3D shaking table testing.

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