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# RE-CENTERING AND DISSIPATIVE CONNECTIONS FOR PINNED-FRAME PRECAST STRUCTURES.

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## Abstract

The response of buildings not specifically designed to resist seismic actions can be generally improved by imposing the dissipation of an appropriate amount of energy. The use of passive devices to improve the seismic performance of precast structures is investigated. These devices can be successfully applied at the beam-column connections of pinned-frame structures, typical of international precast industry, in order to increase the connection degree of fixity and the dissipated energy during a seismic event. The peculiarity and efficiency of passive dissipation devices based on rotational friction with the addition of a re-centering device is analyzed. Both devices may be used in the case of one-story or multi-story existing buildings and new designed structures. Moreover, they are able to mitigate the inter-story drift demand, which often governs the seismic design of typical commercial and industrial precast buildings.

The investigated devices are applied to a selected case study, a single-story precast reinforced concrete hinged-frame building. Nonlinear time history analyses are carried out to outline the improved structural performance under seismic actions. The difference between the application of such devices to existing or new buildings is also addressed.

*Keywords: precast structures; precast connections; re-centering; energy dissipation; beam-to-column joint; hinged frame*

## 1. Introduction

Precast structures are widely recognized to provide several benefits such as the ability to cover large areas, by means of pre-stressed concrete beams, the high quality control of materials and elements, and the reduced construction time compared to traditional reinforced concrete (RC) structures. The typical structural layout of industrial and commercial precast buildings is constituted by cantilever columns pin-connected [1-3] to pre-stressed beams which support pre-stressed roof elements. The columns are placed inside cup footings or connected to the foundation by means of mechanical devices or grouted sleeves [4, 5]. Recent earthquakes in Italy highlighted the vulnerability of precast structures not designed according to modern seismic codes [6-8]. The main vulnerabilities observed are related to inadequate horizontal load transfer mechanisms between precast members which lead to the loss of support and consequent fall of both structural and non-structural elements, i.e. cladding panels, [9-12].

The beam-to-column connections considered herein are usually dry-assembled in place in order to speed up the erection sequence. This connecting system leads to more flexible structures compared to cast in place RC connections. Furthermore, the precast structures investigated herein are characterized by a lower displacement ductility demand compared to traditional RC buildings, due to the inherent story height; as a matter of fact, doubling the inter-story height reduces by half the ductility demand. The lower value of the ductility demand leads to a design focused on controlling the lateral displacement demand rather than limiting the deformation of the materials. Such a design will also contribute in controlling the displacement compatibility among adjacent structural and non-structural elements [9, 10].

The reduction of the lateral displacements, and therefore the reduction of the inter-story drift, could be achieved providing beam-to-column connections in emulation of RC structures or by the addition of passive energy dissipation devices at the beam-to-column joint. The former solution involves formworks and additional castings with consequent increase of the erection time. The latter solution is fully compatible with the traditional construction sequence, being the additional devices put in place at the end of the erection sequence. The added devices provide both additional damping to the system, therefore contributing in dissipating the seismic energy, and a degree of fixity to the beam-to-column connection, therefore contributing in reducing the lateral displacements.

The present paper considers the introduction of dissipation devices at the beam-to-column joint of both existing and new precast hinged-frames. Starting from former solutions available in the literature [13, 14, 15] regarding rotational friction dissipation devices, the introduction of a re-centering device is proposed and investigated herein. The detailing to increase the number of dissipating surfaces for the dissipating device is also addressed. The most suitable arrangements of additional devices at the beam-to-column joint have been evaluated in order to be fully compatible with the seismic deformations arising in the considered structural system. The investigated devices have been applied to a selected case study resembling the structural frame of an industrial precast concrete building. Non-linear time history analyses have been conducted and the advantages and limits of the proposed devices have been addressed.

## 2. Beam-to-column connection devices

In order to select the most appropriate additional devices suitable for installation at the beam-to-column joint of new and existing precast concrete structures, a preliminary investigation of their required characteristics has been carried out:

1. the device should be compatible with the considered structural typology, i.e. hinged frame, and construction methodology, i.e. dry-installed connections;
2. the device should be placed at the side or underneath the beam, in order to do not interfere with the floor activities;
3. the device should be able to provide dissipative capacity without being affected by phenomena like "sliding-shear" and "pinching";

4. the device should represent the main source of energy dissipation in the building and it should be fully replaceable after an earthquake;
5. the damage in the beams and in the columns should be limited, with the exception of the plastic hinge at the base of the columns;
6. re-centering ability should be preferred.

On the basis of the aforementioned optimal characteristics, two devices have been selected. Such devices have different behaviors and they could be applied separately or acting in parallel. The first device, whose potential has been already investigated under both analytical and numerical point of view [14], is able to dissipate energy through the friction generated by the relative rotation of steel plates with interposed brass plates. The dissipation of energy significantly increases the damping of the system and it is therefore advantageous especially in the case of seismic events which do not present "near field" characteristics, i.e. conditions in which the maximum deflection of the system is reached before fully engaging its dissipative capacity. As a matter of fact, the maximum efficiency of a dissipation device is associated to a steady-state response, as evidenced in the concept of equivalent viscous damping [16].

Therefore it is envisaged that the proposed system will be able both to dissipate energy and to provide an appropriate degree of fixity of the joint in order to reduce the displacement demand of the building. This is possible by the introduction of the second device proposed herein which is also able to limit the residual deformations by means of pre-compressed springs. The two proposed devices can be coupled and calibrated to dissipate a sufficient amount of energy, and to allow re-centering of the connection after an earthquake.

The optimal position of the devices has been selected in order to maximize their performance under a seismic event. A kinematic analysis has been carried out whose results are represented in Fig. 1a. The position of the friction-rotation dissipation devices, shaded circles in Fig. 1a, is selected as to form an articulated quadrilateral after the activation of the static friction load; this configuration does not significantly increase the lateral stiffness of the system. The position of the stiffening / re-centering device is selected in order to create an isostatic triangle with the beam and column ends; this configuration is characterized by a high stiffening effect. It is worth noting that the stiffening device could be substituted by friction-linear or other hysteretic systems to provide both energy dissipation and stiffening effect. The results of such solution are not presented herein. Fig. 1b shows the arrangement of the devices considered in the following case study.

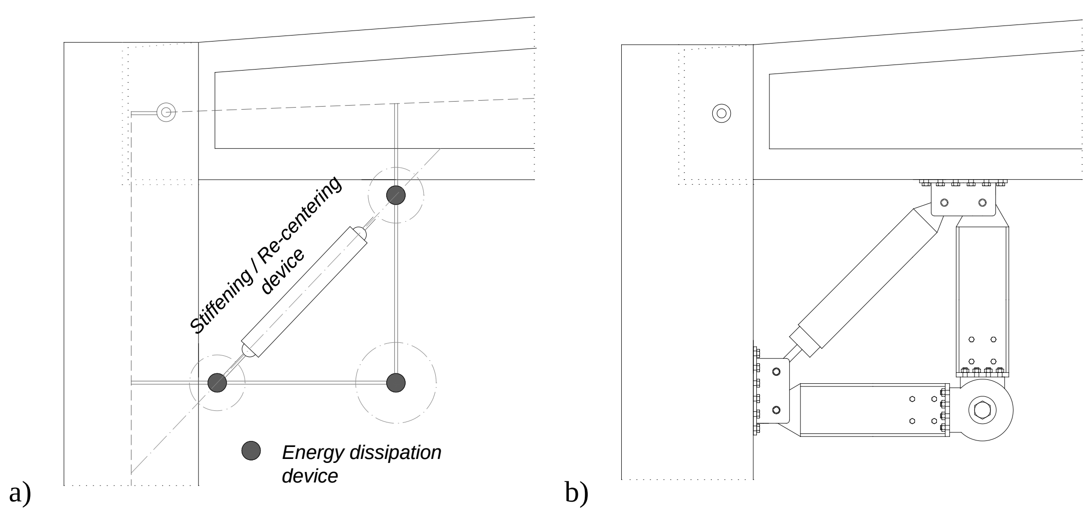


Fig. 1 – Beam-to-column device: a) optimal placement; b) possible solution.

## 2.1 Dissipative device

The dissipative device considered herein could be applied in correspondence of the three hinges indicated in Fig. 1a. Such device dissipates energy through friction due to the relative rotation of its elements. The performance of the device is optimized by the insertion of brass discs. The choice of brass discs was dictated both to maximize the dissipated energy, i.e. high coefficient of friction, and to decrease the difference between static and dynamic coefficient of friction, respectively 0.51 and 0.44, in order to obtain a stable and uniform hysteretic response, especially at cycle reversal. Increasing the number of the sliding surfaces (Fig. 2) represents a simple strategy to increase the system energy dissipation. Such an increase could be obtained with the detailing in Fig. 2 for the steel discs, which are bolted to the flange of the beam element by means of horizontal slotted connections. This detail assures a uniform transferring of the pre-tension load to the brass discs.

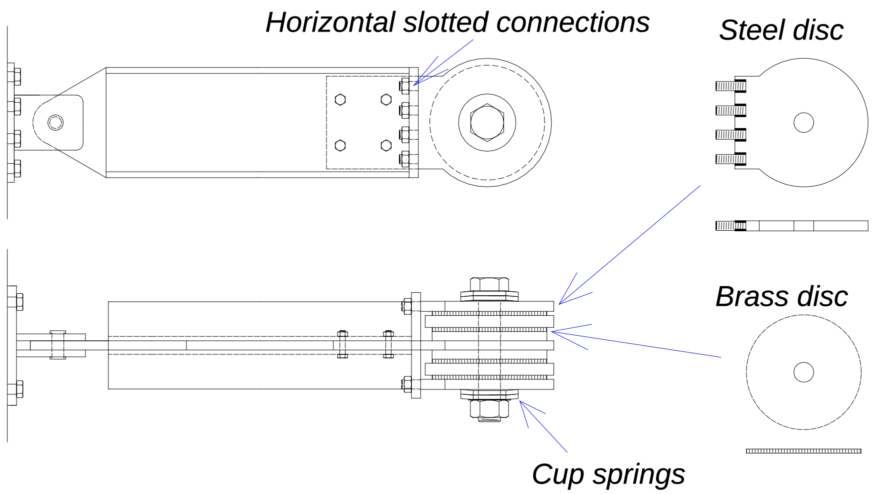


Fig. 2 – Friction-rotation dissipative device

The bending moment associated to the sliding of the brass surfaces in dynamic conditions is:

$$M = \int_{\rho=R_i}^{R_e} \int_{\theta=0}^{2\pi} \rho^2 \cdot \mu \cdot \frac{N}{\pi\left(R_e^2 - R_i^2\right)} \cdot d\rho d\theta = \frac{2}{3}\mu \cdot N \cdot \frac{R_e^3 - R_i^3}{R_e^2 - R_i^2} \tag{1}$$

where:

$\mu$ coefficient of friction

$N$ Bolt pre-tension load

$R_e$, $R_i$ external, internal radius of the brass disc

The characteristics of the device in order to reach an activation moment in the range 40-120 kNm are presented in Table 1; the bolt class is 10.9 [17].

Table 1 – Dynamic friction moment of the dissipative device

| Bolt diameter (mm) | Bolt pre-tension (kN) | Activation moment (kNm) |
|---|---|---|
| 2 sliding surfaces – Disc radius 125 mm | | |
| 39 | 530 | 40 |
| 48 | 794 | 60 |
| 4 sliding surfaces – Disc radius 125 mm | | |
| 39 | 530 | 80 |
| 48 | 794 | 120 |

## 2.2 Stiffening / Re-centering device

The stiffening/re-centering device has the function of creating a degree of fixity at the beam-to-column joint and to minimize the residual deformations after a seismic event. In this paper the use of cup springs is explored, although other solutions could be adopted, as for instance ring springs or shape memory alloys. The peculiarity of the device proposed herein is its ability to exploit the behavior in compression of the springs for actions that tend both to shorten and lengthen the device itself. As depicted in Fig. 3, the internal springs will undergo a compression when the device is subject to compression or tension.

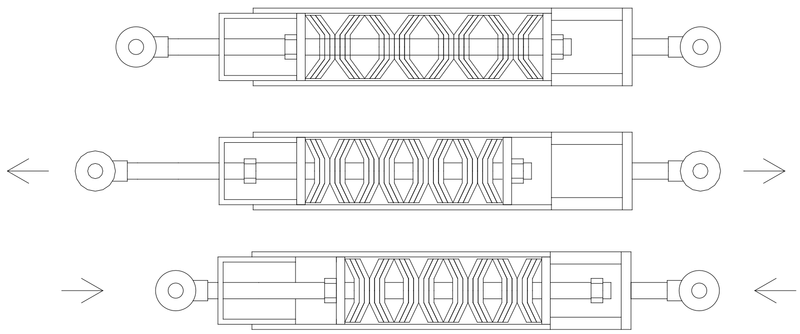

Fig. 3 – Scheme of the stiffening / re-centering device

It is possible to use the cup springs with or without an initial pre-compression. In the first case the device will act as a rigid system until the pre-compression of the springs is reached; while in the second case the device is acting as a spring depending on the amount and type of cup spring stacks. The available stroke is related to the number of spring stacks in series, while the number of springs in parallel determines the resistance. In the case of pre-stressed springs, the evaluation of the available stroke is obtained subtracting the displacement already assigned to pre-compress the springs. It is important to provide adequate displacement capacity to the device, in order to avoid full packing of the springs. Herein, the 90% of the available stroke of the springs is selected in order to sustain a lateral drift of the system of 2.5%. Based on these conditions, the characteristics of the re-centering device in selected configurations are presented in Table 2.

Table 2 – Characteristics of the re-centering device (device length 1.12m).
Note: $d_e$ external diameter; $d_i$ internal diameter; $t$ spring thickness; $k$ device stiffness.

| $d_e$ (mm) | $d_i$ (mm) | $t$ (mm) | n° springs per stack | n° stacks | $N$ (kN) | $k$ (kN/mm) |
|---|---|---|---|---|---|---|
| Without pre-compression | | | | | | |
| 50 | 25.4 | 3 | 5 | 14 | 70 | 4.7 |
| 50 | 25.4 | 3 | 10 | 14 | 125 | 9.5 |
| 80 | 36 | 4 | 10 | 7 | 250 | 15.1 |
| 80 | 41 | 5 | 13 | 9 | 500 | 35.3 |
| With pre-compression | | | | | | |
| 100 | 41 | 4 | 5 | 9 | 70 | 4.1 |
| 100 | 41 | 4 | 9 | 9 | 125 | 7.4 |
| 125 | 51 | 5 | 11 | 8 | 250 | 12.3 |
| 150 | 61 | 6 | 17 | 6 | 500 | 33.1 |

## 2.3 Coupling dissipative and re-centering devices

The coupling of the two devices could bring significant benefits to the system, reducing the system demand in terms of both lateral displacement demand and residual deformations in case of earthquake. The activation moment of the energy dissipation device and the activation load of the re-centering device could be selected in such a way that the resulting behavior of the system, in terms of moment-rotation relationship, assumes a flag shape hysteresis (Fig. 4). The full re-centering of the connection is possible if the moment generated by the re-centering device is greater than the activation moment of the dissipative device.

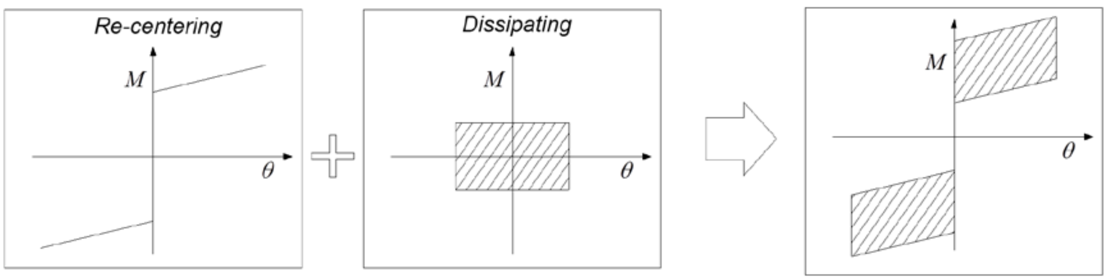


Fig. 4 – Coupling of dissipative and re-centering devices.

The use of the proposed device, applied to a precast hinged frame, leads to a gradual increase of the elastic stiffness of the structural system (Fig. 5). The system with the addition of the investigated dissipative devices has a behavior and stiffness comparable to a hinged frame, with no significant increase of the load demand at the beam-to-column joint. The addition of dissipative devices is therefore suitable as a retrofit solution for existing buildings, without significant strengthening measures at the beam and column ends. The use of re-centering devices leads to a structural stiffness similar to a portal frame with rigid connections, with a load distribution at the beam and column ends completely different from the initial hinged frame solution. The addition of such devices is therefore suitable for new buildings rather than for the recovery of existing structures. However, it is possible to use re-centering devices also in existing buildings provided that appropriate strengthening measures are applied to the beam and column ends to withstand the new load demand.

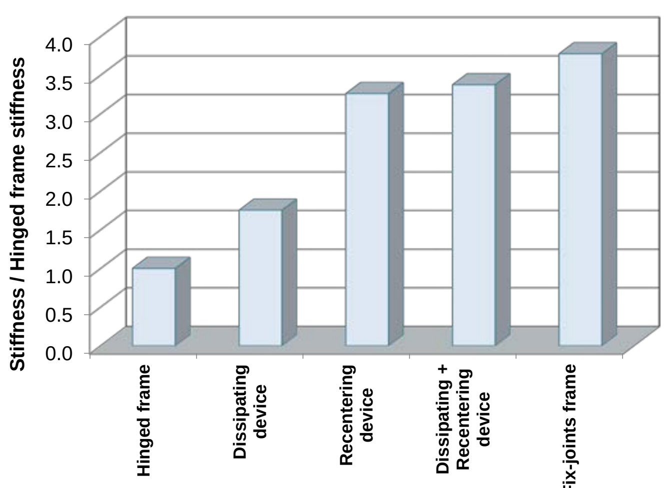


Fig. 5 – Structural stiffness based on the additional devices adopted.

## 3. Application to a selected case study

The considered devices have been applied to a selected case study. A portal frame resembling an existing precast industrial building is considered (Fig. 6), with a tributary roof mass equal to 104’000kg. The site seismicity is in accordance to EN 1998–1 [18] type 1 spectrum, soil type C, and $a_g$=0.25 g (ground acceleration on rock). Non-linear time history analyses are conducted on the selected portal frame by means of a spectrum-compatible artificial record, generated with the SIMQKE-1 algorithm [19]. The columns have square cross section (60x60cm) reinforced with twenty 16mm diameter rebars. Fiber elements are used to model the columns (concrete $f_{ck}$ = 45MPa, steel $f_{yk}$ = 450MPa) while non-linear springs are used to model the additional dissipative and re-centering devices.

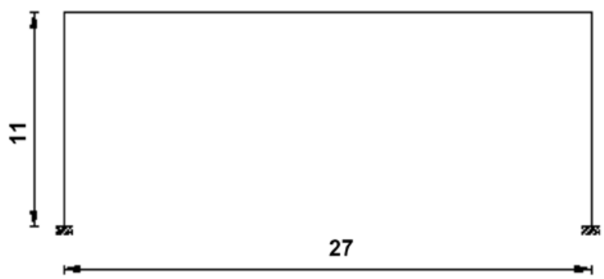


Fig. 6 – Considered portal frame (measures in m).

Three additional configurations are considered (Fig. 7) based on the introduction of dissipative and re-centering devices at the beam-to-column joint: a) dissipative devices (activation load 40 kNm and 120 kNm), b) re-centering devices (activation load 250 kN), c) dissipative plus re-centering devices. The results of the analyses are expressed in terms of roof displacement (Fig. 8) and energy dissipated at the column base (Fig. 9). Such figures show how the investigated additional devices contribute in reducing both the roof lateral displacements and the energy dissipated at the column base, therefore limiting the damage both to structural and non-structural elements. It is worth noting that the additional load arising at the beam-to-column joint due to the considered devices might require substitution or retrofit of the exiting beam-to-column pin connection. At this regard the results of the analyses in terms of maximum additional load demand at the beam-to-column joint are reported in Table 3. Compared to the hinged frame solution it is observed, as expected, an additional load demand in terms of bending moment and shear in both the beam and column at the connection joint, associated to the change of the static scheme from hinged frame to portal frame. These loads need to be accounted for when designing such elements, in the case of new buildings, and when designing the retrofit intervention, in the case of existing structures.


Fig. 7 – Scheme of the additional beam-to-column devices.

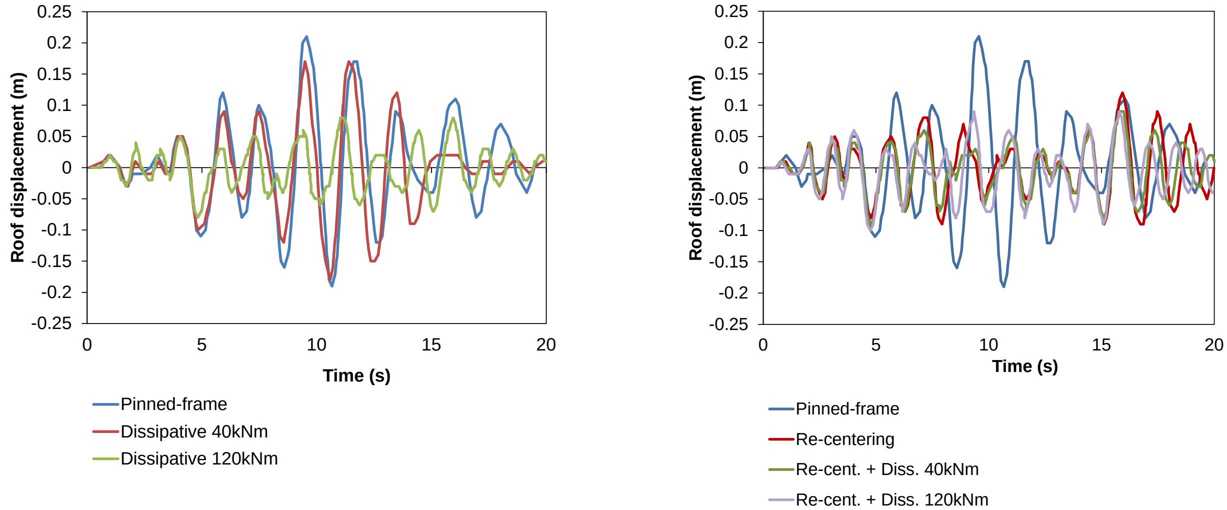


Fig. 8 – Non-linear time history analyses results in terms of roof displacement.

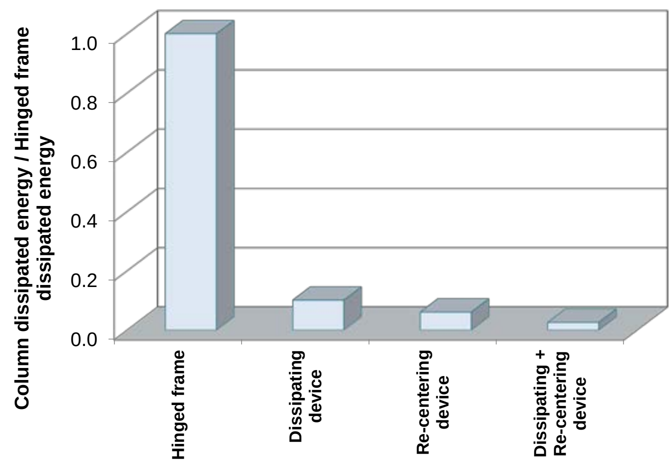


Fig. 9 – Non-linear time history analyses results in terms of column base dissipated energy.

Table 3 – Non-linear time history analyses results in terms of **additional load demand** on existing elements.
Note: ED-*xx* = energy dissipation device with *xx* kNm activation moment;
RD-*xx* = re-centering device with *xx* kN activation load;

| *ID* | $V_{base\_column}$ (kN) | $F_{beam\text{-}column\ connection}$ (kN) | $M_{top\_column}$ (kNm) | $V_{top\_column}$ (kN) | $M_{top\_beam}$ (kNm) | $V_{top\_beam}$ (kN) |
|---|---|---|---|---|---|---|
| ED-40 | 4 | 140 | 94 | 73 | 62 | 77 |
| ED-120 | 9 | 329 | 192 | 184 | 182 | 227 |
| RD-250 | 15 | 348 | 175 | 164 | 217 | 271 |
| RD 250 + ED-40 | 23 | 441 | 227 | 229 | 271 | 338 |
| RD 250 + ED-120 | 33 | 631 | 335 | 364 | 379 | 473 |

## 4. Conclusions

The paper presented the use of two devices to be applied at the beam-to-column joint of typical precast hinged frames in order to dissipate seismic energy and to reduce residual deformations. Such devices are compatible with the construction practice and typical precast elements being installed after completing the erection phase. The installation after the erection phase allows taking advantage of the pre-stressing of precast concrete beams. As a matter of fact, in a first phase the pre-stressed beams act as simply supported elements, subjected to gravity loads; in a second phase, in the case of seismic event, the devices provide a degree of restraint at the beam-to-column joint and a bending moment demand arises at the column and beam ends.

The first device, namely the dissipative device, has the purpose of dissipating energy through friction by the relative rotation of steel and brass discs; the hysteretic damping of the system is therefore increased with a consequent reduction of the load demand in the structural elements. This device has been already investigated under an analytical and numerical point of view; the detailing to increase the number of dissipating surfaces for the dissipating device has been addressed herein. The second device, namely the re-centering device, provides a stiffening of the beam-to-column joint and reduces the residual deformations of the system. The two devices could be used in parallel and designed so as to lead to a flag-shape hysteresis of the coupled system, similarly to what is effectively obtained by means of post-tensioning. The introduction of a re-centering device has been proposed and investigated herein. The use of the devices leads to a gradual increase of the system stiffness associated to a gradual shift of the beam-to-column joint from a pin to a fixed connection. During an earthquake, the advantages resulting from the use of the devices are the reduction of the load demand in the structural elements, the reduction of the lateral displacement demand and the control of the residual deformations at the beam-to-column joint. It is worth noting that the increase of the joint stiffness leads to an increase of the load demand, in terms of bending moment and shear, which needs to be accounted for, especially if the devices are envisaged as a retrofit measure for existing structures. The connection at the beam-to-column joint is also subjected to a load demand increase.

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