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SEISMIC RETROFITTING OF SINGLE-STORY RC PRECAST BUILDINGS THROUGH A NOVEL METALLIC HYSTERETIC DEVICE

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Abstract

Structural joints are generally the most critical parts of RC precast structures in terms of seismic assessment, especially in existing buildings, where friction connections can be often found. This issue, widely highlighted in the aftermath of recent earthquakes in Europe, have brought the scientific community to develop retrofitting techniques improving the seismic performance of the connections. The presented work deals with a dissipative hysteretic device, made of two steel rods, arranged as a three-hinged arch, and provided with moon sickle shaped items. It is applied at the beam-to-column connection level and it is intended for both restraining the relative displacements between the joined structural elements and dissipating energy coming from the earthquake. In the presented study, the innovative device is described in detail along with its numerical model, as applied to an existing single-story RC precast structure with beam-to-column friction connections. The results of preliminary numerical analysis showing its efficiency are also reported.

Keywords: Precast RC Structures, Friction Connections, Retrofitting, Nonlinear Analyses, Innovative Device.

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1 INTRODUCTION

Premature failure of structural joints is the main issue detected for the existing RC precast buildings during earthquakes. As demonstrated by recent seismic events in all Europe [1-7], this is caused by either the absence of a mechanical device, i.e., horizontal load transfer relying only on friction, or the inappropriate connection design, both resulting in inadequate seismic performance. Local collapse of structural joints often involves disastrous structural breakdown, due to the loads transfer inability and the loss of support phenomena. For this reason, together with retrofitting techniques at the structure and the element levels, some solutions aiming at improving connection seismic response are developed in last years. The simplest and most obvious intervention consists in the introduction of devices able to reproduce a hinged restrain at the joints level, thus reducing the deformation demand. However, a significant shortcoming for this solution is detected. Indeed, the stresses transmitted to the base of the columns are significantly higher than the ones recorded for the un-retrofitted structure, leading to a greater involvement of plastic hinges and, hence, a higher level of structural damage. Therefore, the state-of-the-art devices are able to both strengthen structural joints, limiting the relative displacement between the connected elements, and dissipate a portion of the seismic energy coming from the ground motion, avoiding high damage. Passive energy dissipation devices represent the easiest and most economical solution in the world of structural control systems, since they do not require any external energy power or electronic hardware and their functioning is simply activated by structural displacements. Martinelli and Mulas [8] investigated the potential application of a connection retrofitting device, already used for cast in situ reinforced concrete and steel buildings, to an RC precast industrial structure. The proposed system is able to both restrain the relative displacement between principal beams and columns and dissipate energy thanks to the friction developed during the rotation of an annular brass plate, inserted between steel components. Two UPN200 channel sections are connected to the beam and the column end respectively, creating the dissipative hinge at their intersection. The provided configuration allows a quick re-centering after the seismic event. Nonlinear dynamic analyses on a structural model are performed, comparing the seismic response of the bare building with the one equipped with rotational friction devices. Outcomes from this assessment show the good behavior of the analyzed retrofitting technique, able to enhance the damping of the structure reducing significantly the hysteretic energy ascribable to plastic hinges at the columns base, despite a moderate increase of the overall stiffness and, thus, of the seismic base shear. Pollini et al. 2018 [9] proposed an innovative connection retrofitting system, combining the deformability of steel with the high strength of composite materials. Carbon-wrapped steel tubes can be connected to the structural elements (beams and columns) thanks to a threated bar passing through circular holes on the tube basis. Each tube works in compression, dissipating seismic input energy and, thus, limiting the transmission of the stresses to the base; so, for each connection two devices have to be provided. Quasi-static monotonic and cyclic experimental tests were performed on the proposed system in order to assess the energy dissipation capacity, recording very stable hysteretic cycles. A numerical validation was also performed, even if considering a simple structural model, demonstrating the expected beneficial impact of the proposed device on the seismic structural response. Soydan et al. [10] dealt with a new lead extrusion damper (LED), usable in retrofitting interventions for precast structures joints. It is constituted by a cylinder full of lead, a shaft and a cap. Lead is a relatively flexible metallic material, able to dissipate a considerable amount of energy when it is forced to deform. In order to dissipate seismic energy, the cap and the shaft have to be connected to different structural elements (i.e., columns and beams), where relative displacements are expected. A numerical model of an existing RC precast structure is developed in SeismoStruct [11] and dynamic analyses are performed with ten historical ground motions. The outcomes from the seismic assessment of the bare structure are then compared with the response of the same structure retrofitted with lead extrusion dampers. Even if the recorded acceleration increases for the retrofitted structure, due to the increase in lateral stiffness, shear resistance in the columns is not exceeded and benefits from the application of the LEDs are clear: beam-column relative displacements are strongly reduced, as well as the bending moment at the base. In this way, the plasticization of the structure is limited and the damage level results to be lower.

The present work shows an innovative hysteretic device for the retrofitting of RC precast structural joints. The efficiency of the system is assessed evaluating the seismic response of an existing RC precast structure with beam-to-column friction connections, before and after the application of the hysteretic device. To reach this goal seven nonlinear dynamic analyses are performed, together with an energy balance estimation, demonstrating the ability of the proposed system in both preventing the relative displacements at the connection level and reducing the rotational demand at the base.

2 DESCRIPTION OF THE RETROFITTING SYSTEM

The proposed device represents an upgrading of an already patented system for the retrofitting of structural elements connections in precast buildings [12, 13], which consists of two hinged steel profiles, linked through horizontal dowels to the connected elements, i.e., beams and columns. A 2 mm rubber layer surrounds the dowels, since it is demonstrated [13] that this expedient is able to reduce the concrete cracking at the rods connection location, thus improving the device functioning. This arrangement allows turning the horizontal shear forces acting on the connection in axial forces in the rods, thanks to a three hinged-arch behavior. Therefore, it is able to significantly limit, or even prevent, relative displacement between beams and columns. It is possible to take advantage of the device in both existing buildings, often provided with friction connections, and current code-conforming buildings, as a valid alternative to the conventional dowel connection. In the herein presented version (Figure 1), the hysteretic properties are given by some special gadgets, moon sickle shaped, mounted on each profile, which yield under the axial load in the rods and dissipate seismic energy undergoing plastic deformations.

Figure 1: Metallic hysteretic device configuration

The device acts like a structural fuse, in which the seismic damage is concentrated, decreasing the ductility demand at the plastic hinges location. At the end of the ground motion striking the building, these gadgets can be easily replaced, without interrupting the productive activities. The force-displacement backbone (Figure 2) can be represented as an elastic-hardening curve, characterized by a yielding point (d_1,F_1) and a post yielding stiffness, defined thanks to the second point coordinates (d_2,F_2). In Table 1, standard mechanical properties for the rods are reported, provided by the manufacturing company. The proposed types underwent qualification tests according to the European code UNI EN 15129 [14], governing the seismic devices design. In the present study, rod type is chosen among the presented ones considering the shear associated to the yielding moment at the columns base, and applying a capacity design safety factor, so as to allow the plasticization of steel gadgets before the yielding of the plastic hinges. However, this is a preliminary study, conducted only to understand how the device works under seismic actions; a proper calibration should be performed, in order to maximize its performance.

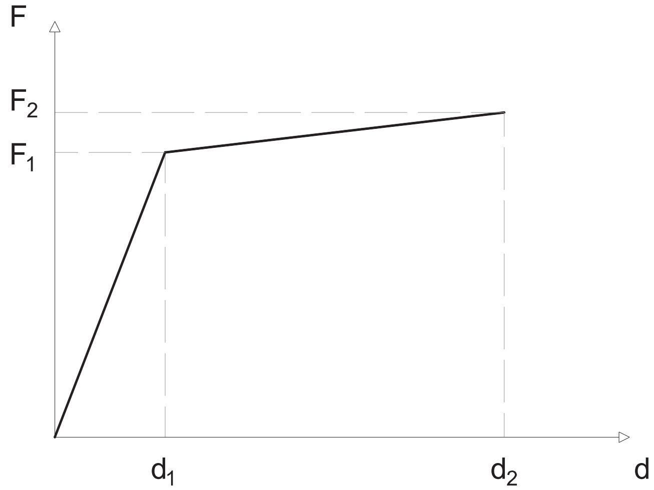


Figure 2: Monotonic force-displacement response

Type	d_1 [mm]	F_1 [kN]	d_2 [mm]	F_2 [kN]
1	3.9	34.5	20.0	40.0
2	3.7	43.5	20.0	50.0
3	3.0	52.0	15.0	60.0
4	2.8	75.0	15.0	86.0

Table 1: Rods standard mechanical properties

3 CASE STUDY

An existing single-story RC precast structure, dated back to the Seventies, is considered in order to assess the effect of the proposed retrofitting device. The construction is configured with a single bay, 15 m long, in x direction and four bays, each of them 6 m long, in z direction. Columns' total height is equal to 9 m; furthermore, since this kind of buildings are usually intended for industrial activities, design procedure and modeling take into account the presence of a crane and the relative brackets supporting the crane, placed at 7.5 m from the columns' base. Structural layout is presented in Figure 3. A design simulating the elements dimensioning process is performed taking into account codes and regulations of the Seventies, i.e. DM 3/05/1974 [15] and CNR 10012/1967 [16]. The building is located in Catania, an Italian city with a high seismic hazard; nevertheless, at the time of construction, it was not considered as a seismic-prone area, so the design procedure ignored seismic actions. Roof covering consists of prestressed double T elements, with equivalent section of 0.40 x 1.60 m, placed one near the other on the top of the principal beams and linked together by a 5 cm thick concrete slab. The slope of the covering is assumed to be 10%. The presence of the topping slab involves a rigid diaphragm behavior, i.e. a rigid behavior of the floor in its own plane.

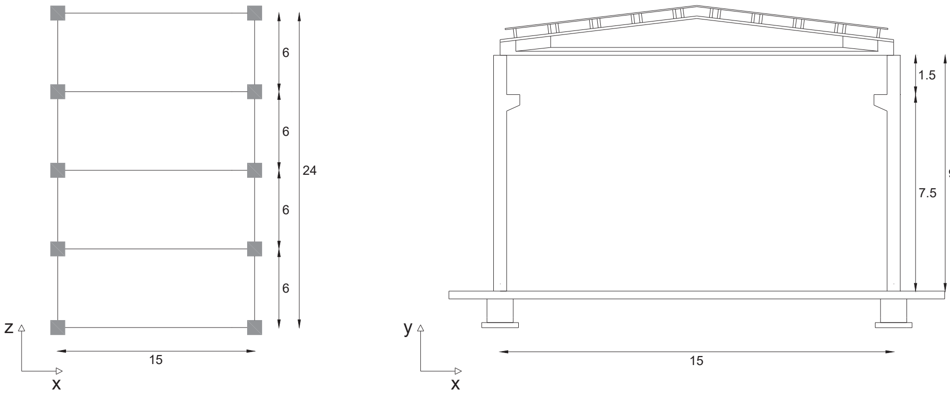


Figure 3: Structural configuration: plan view and transversal view

Roof elements are jointed to the principal beams through steel plates and bolts, ensuring in this way a hinge constrain. Principal beams in transversal direction (x direction) present a variable height and a variable section (T-shaped at the extremities and, after a tapering zone, I-shaped in the middle). However, an equivalent rectangular area (0.17x1.14 m) is assumed, since beams section shape does not affect the results. In z direction, instead, secondary beams are provided in order to both collect rainwater and connect structural frames in longitudinal direction. They usually have a U section, but an equivalent rectangular one is considered, with dimensions 30x50 cm. Unlike roof elements and beams, which are dimensioned only for vertical loads (permanent and variable actions), columns are also designed for horizontal (wind) forces acting on the structure. They consist in precast monolithic elements with a square section, whose dimensions and reinforcement are shown in Figure 4a. The presence of socket foundations allows considering the columns fixed at their base. Principal beams are simply supported on columns' head through a neoprene pad, with dimensions 0.25x0.25x0.01 meters, generating a friction connection; secondary beams are hinged to the columns' head through steel angles and bolts. Indeed, according to the design practice of the time, the higher value of axial load provided by principal beams on the top of the columns was deemed sufficient to ensure a proper strength to the friction connection. From this assumption follows the most important weakness detected for existing RC precast structures.

4 NONLINEAR MODEL

A nonlinear numerical model is created in OpenSees [17] in order to perform a seismic assessment of the un-retrofitted and the retrofitted structure. Columns and beams are represented as elastic elements through their longitudinal axis; the eccentricities generated at the connection level, typical of precast structures, are modelled thanks to rigid brackets. Roof elements are taken into account only as vertical load and mass, but they are not explicitly modelled since they do not affect the seismic response. Cladding panels are not modelled, only their mass contribution is considered. Even if the cladding affects the seismic behavior of the building, making it stiffer, it should be noted that, in existing structures, panels connections were not provided with earthquake resistance, so panels collapse at very low seismic intensities, i.e., in the early stages of a ground motion, leaving the structure bare. Therefore, the assumption of neglecting cladding panels in the modelling is reasonable. A lumped plasticity approach is followed, concentrating the nonlinear behaviour at the columns base. Moment-rotation curves are detected performing a fiber analysis of the columns cross section and applying Fardis formulations [18] for the yielding and the ultimate chord rotations. Different backbones are obtained for the two horizontal directions and for corner and lateral columns. These differences are due to the different longitudinal reinforcement provided in the two orthogonal sides of the columns cross-section and to the different value of axial loads on the top of the columns. Figure 4b illustrates the moment-rotation curves. Each column and the corresponding plastic hinge constitute a system working in series, so their stiffness are calibrated in order to return the overall nonlinear stiffness.

Particular attention is paid to the friction connection modelling, since the great impact of its seismic response on the structural global collapse condition. A zero-length element is inserted at the principal beam-to-column intersection, and proper materials are assigned for each degree of freedom. The horizontal translations in x and in z directions (Figure 3) are characterized by a frictional behavior, with an elastic perfectly plastic response; the elastic branch is defined by the lateral stiffness of the neoprene pad, whilst the flat branch is attained in correspondence of the friction force. In the vertical direction an elastic material, identified by the axial stiffness of the pad, is considered as acting only in compression, given that the pad does not react in tension. Rotation around the z axis (in the xy plan) is left free, whereas rotations around x and y axes are constrained.

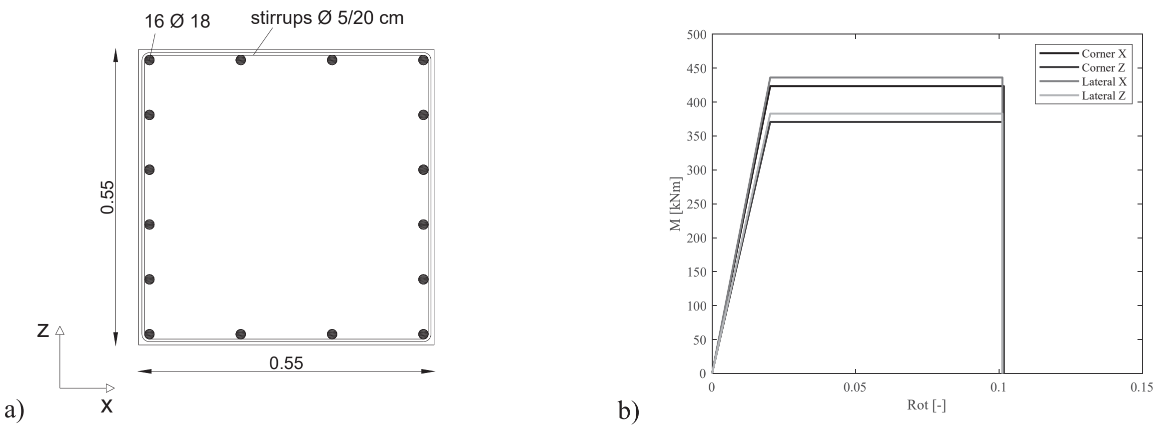


Figure 4: a) Column cross section and b) Moment-rotation backbones at the column plastic hinge

Finally, steel profiles constituting the retrofitting device are modelled thanks to truss elements, i.e., elements absorbing only axial loads. To define the constitutive law, the assigned material is a series of an elastic perfectly plastic gap material, in order to simulate the rubber layer around the dowels, and a hardening material, considering a kinematic hardening response. Parameters to be assigned are calibrated in order to reproduce a Type 1 rod response, according to the design procedure illustrated in Section 2. Following the recommendations provided by the manufacturer company, the device configuration is chosen so as to maintain a difference in the rods length equal to 0.4 m. Rigid brackets are inserted in the model in order to connect the rods to the beam and the column, representing the distance between the longitudinal axis of the structural elements and the connection provided by the device. Retrofitting is performed only in the transverse (x) direction. Figure 5 shows the schematic representation of a typical frame of the retrofitted structure in the x direction.

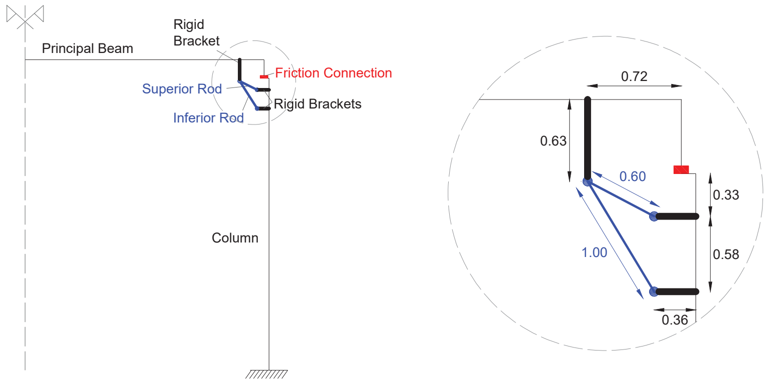


Figure 5: Retrofitted frame layout

5 ANALYSES OUTCOMES

In order to demonstrate the functioning of the proposed system, seven ground motions (GM) are selected and applied, first, to the un-retrofitted structure and, then, to the retrofitted one. For the records selection, Conditional Spectrum Method [19, 20] is implemented, according to [21]. All the spectrum coordinates are conditioned to the one corresponding to the fundamental structural period. A soil type C is considered to determine the elastic spectrum. The chosen intensity level refers to a return period, T_R, equal to 2500 years, i.e., a 2% in 50-years exceedance rate. Seismic records, taken from database of the Italian accelerometric archive (Itaca) [22] and from the database NGwest [23], are properly scaled in order to match the obtained target spectrum. As concern the un-retrofitted structure, outcomes show that the friction connections activate in the very first stages of the ground motions and significant relative displacement between principal beams and columns are recorded. Since, as expected, the sliding begins before the activation of the plastic hinges at the columns base, the structure shows an elastic response until the collapse, due to the loss of support of the beams. Applying the retrofitting device to the structure at each connection location (Figure 5), the first detected benefit is the strong reduction in beam-to-column relative displacements. In Figure 6, the recorded deformations of a friction connection element, corresponding to the relative displacements of the jointed members, is reported in both the case of the un-retrofitted and the retrofitted structure for a single ground motion.

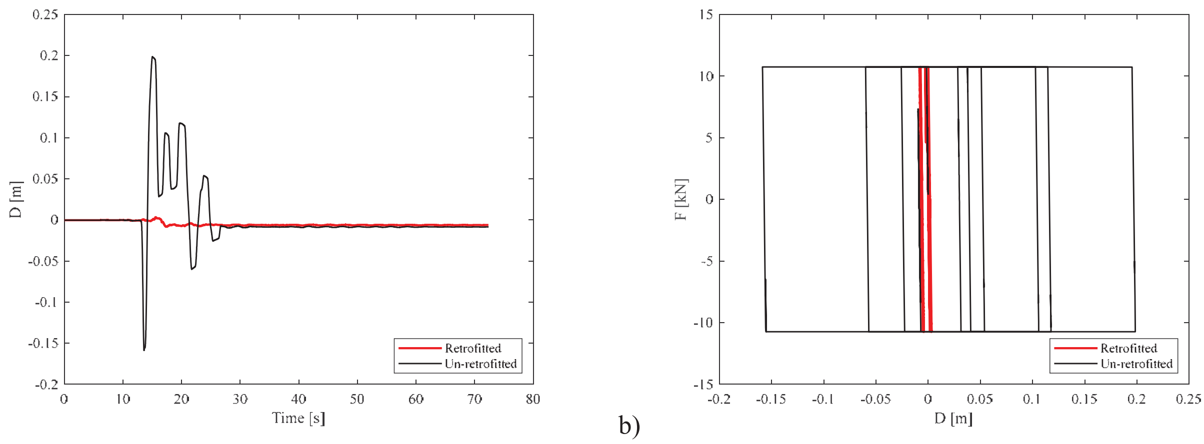


Figure 6: a) Comparison between the relative beam-to-column displacement for the un-retrofitted and the retrofitted structure for GM1, b) comparison between the force-displacement response for the un-retrofitted and the retrofitted structure for GM1

For the same connection and the same seismic input, force-displacement response of the retrofitting device, i.e. of the pair of rods, is reported in Figure 7, confirming the correspondence to the assigned behavior.

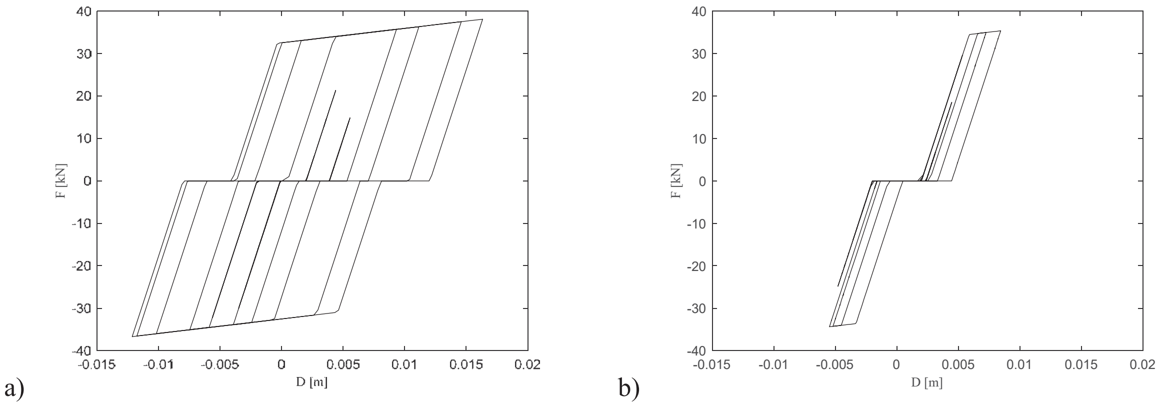
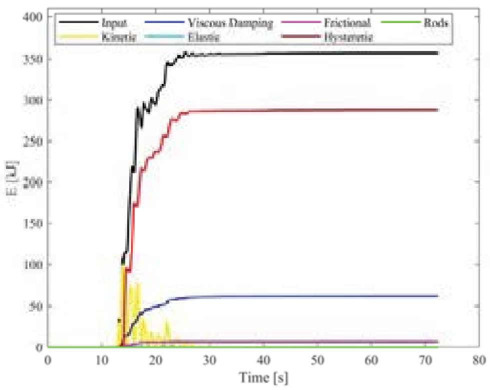
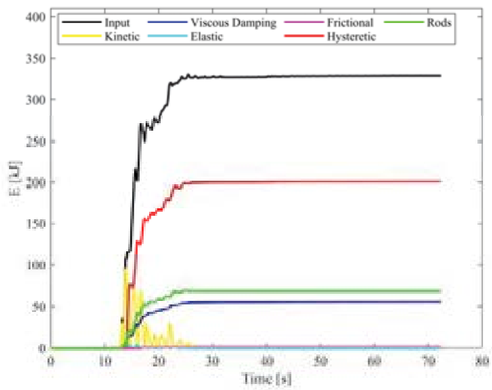


Figure 7: Force-displacement response of a pair of rods, in particular for a) an inferior profile and for b) a superior profile.

The inferior rod shows always a higher engagement, with larger and more numerous hysteretic cycles. It is worth to remember that each rod is provided with a 2 mm gap, simulating the rubber layer around the dowel: it is partially visible only in the superior rod response, represented by the flat branch at force equal to zero. In order to highlight the beneficial effect of the dissipative device on the hysteretic seismic response of the structure, the same set of ground motions is applied to the same structure retrofitted with an identical device but indefinitely elastic. For both the retrofitted systems, the elastic and the hysteretic one, the limitation of the displacements at the connection level is achieved, but in the first case the only source of hysteretic dissipation is provided by the plastic hinges at the columns base. From the comparison between these two solutions, it is possible to understand how much the proposed hysteretic device is able to reduce the plastic rotational demand at the base and, therefore, the structural damage. An energy balance analysis is performed on both the structures, allowing a rapid and synthetic evaluation. The input energy, transferred to the structure by the ground motion, is absorbed and dissipated thanks to energy contributions related to the structural response. In particular: kinetic energy, that is originated by the motion of the building; elastic strain energy, which depends on the level of strain recorded for the structural elements; hysteretic energy, given by the moment-rotation cycles of the plastic hinges at the base, i.e., by the nonlinear response of the structure; frictional energy, provided by the force-displacement cycles generated by the friction connection; viscous damping energy representing the contribution of the damping of the structure (Rayleigh damping is considered). Finally, there is the contribution of the retrofitting devices, which is recoverable for the elastic system and unrecoverable for the hysteretic device, thanks to its dissipative properties. Figure 8 shows the outcomes of the energy balance analysis for both the structures for a single ground motion.



a)



b)

Figure 8: Energy balance for GM1 for a) the structure with an elastic retrofitting device and b) a structure with a hysteretic retrofitting device.

The beneficial effect of the hysteretic device in reducing the dissipated energy of the plastic hinges at the base is evident. The other energetic contributions seem not to be affected by the dissipative behavior of the device. This trend is observed for each of the considered seven ground motions, even if not to the same extent. In Figure 9 the plastic hinges hysteretic energy for both the systems is charted, expressed as a percentage of the total input energy. For some earthquakes, the proposed device slightly reduces the plastic involvement of the structure, and, in any case, it is not able to prevent the yielding of the hinges at the columns base. As already observed, a proper calibration is needed for the hysteretic device and a sensitivity analysis on the parameters conditioning its response should be performed.

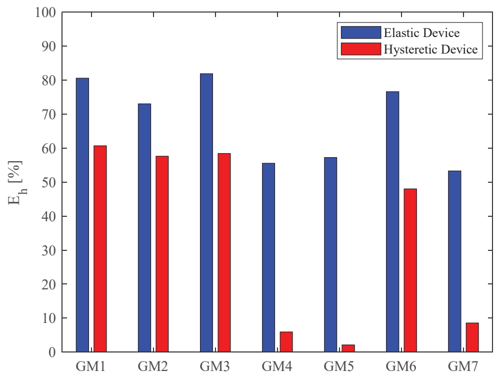


Figure 9: Plastic hinges hysteretic energy in the case of an elastic retrofitting device and a hysteretic retrofitting device for all the ground motions.

6 CONCLUSIONS

This paper presents a novel metallic hysteretic device, intended for the seismic retrofitting of beam-to-column connections in RC precast buildings. The proposed system, applied at the joint level, is designed to both restrain the relative displacement between the connected elements, working as a three-hinged arch, and dissipate the ground motion input energy, thanks to special gadgets with hysteretic response. A nonlinear model of a RC precast industrial structure with friction connections is implemented in OpenSees [17], and seven nonlinear dynamic analyses are performed, highlighting the weakness of the structural joints. Indeed, the detected global collapse is due to the beams loss of support, when the structure is still in the elastic field. Then, hysteretic devices are inserted in the structural model, at the connection levels along the transversal direction, and the same seismic inputs are applied on the retrofitted building. The comparison between the response of the un-retrofitted and the retrofitted structure leads to the following findings.

i) The proposed device is able to strongly limit the relative displacements between beams and columns, avoiding structural collapse due to loss of support phenomena.
ii) The seismic demand at the base increases when the device is inserted, resulting in the yielding of the plastic hinges. However, it is demonstrated that the recorded level of damage is lower than the one corresponding to the application of a traditional device, with an elastic behavior.
iii) The hysteretic properties showed by the metallic device are not sufficient to reduce significantly the plastic deformations at the columns base for all the applied ground motions; indeed, in all the cases, yielding is never prevented. A proper calibration is needed to optimize the retrofitting performance.

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