External steel exoskeleton for a life-cycle upgrading approach for seismic retrofit of existing RC framed structures

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Abstract In many regions of the world with medium or high seismic hazard the majority of existing buildings does not comply with prescriptions of current seismic codes or were even designed considering gravity loads only. Hence, existing RC buildings are often seismically deficient. In addition, they may present excessive energy consumption. In this framework, this study investigates a new retrofit technique for buildings with RC framed structure. The intervention requires the addition to the building of a vertical external steel exoskeleton. This research aims at sounding the impact of the proposed retrofit solution by nonlinear dynamic analysis in terms of lateral strength and story drift ratio, in order to quantify the expected impact of the proposed retrofit intervention.

Keywords Seismic retrofit, Steel exoskeleton, Hysteretic dampers

1 Introduction

Since most of the existing RC buildings were constructed between the middle and the end of the XX century, when seismic codes were not in force yet or seismic zonation was still under evolution, they are affected by different levels of seismic deficiencies. Unfortunately, recent earthquakes showed the high vulnerability of such structures, which require to be seismically upgraded. In this framework, this paper proposes a retrofit technique, named e-EXOS, which aims to avoid the formation of the story drift mechanism, by preventing drift concentration. This condition allows e-EXOS to reduce the drift demand caused by earthquake and to enhance the seismic dissipation capacity of the structure. Furthermore, the e-

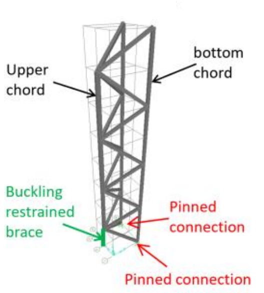
EXOS system is designed to allow a quick and easy external installation that minimizes disturbance to the occupants. Finally, the e-EXOS system is conceived to be combined with energy-efficient solutions, in view of an integrated (seismic and energy) approach to the building renovation and its geometry may be customized to pursue also the architectural renovation of the building.

To investigate the effectiveness of the proposed technique, a case study frame was designed for gravity loads only, so that it could reproduce seismic shortcomings common in the building stock spread in the Mediterranean territory. A finite element numerical model was developed and the seismic response of the case study structure was assessed by nonlinear dynamic analysis and compared to the seismic response of the structure enhanced by e-EXOS.

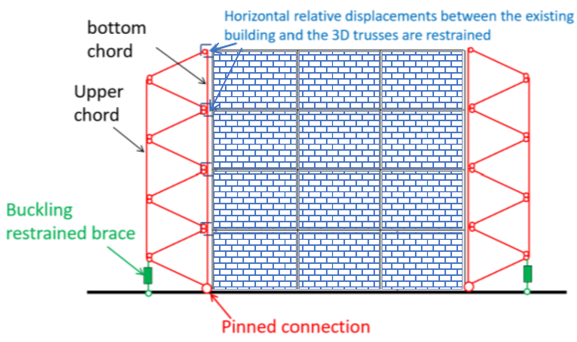
2 Description of the structural rehabilitation system

The e-EXOS system consists of a set of 3D steel trusses (Figure 1(a)) applied to the building façade, as showed in Figure 1(b) as an example. Each truss is pinned at the base to the foundation. The nodes of the bottom chords of the truss are linked to the building decks, so that all nodes belonging to the same floor have the same horizontal displacement. The connection between truss and deck allows the steel truss to transmit to the RC building horizontal forces, but not vertical forces.

If the story drift caused by earthquake excitation is constant along the height, the steel trusses do not transmit forces to the building and do not provide the frame with additional lateral stiffness/strength. In this situation, each truss rigidly rotates about the base without experiencing internal forces. However, if the damage and the related drift tend to localize in one or few stories, the uneven distribution of drift induces internal forces in the truss that reacts transmitting forces to the existing building. Hence, the truss avoids the formation of the story drift mechanism, forcing a uniform distribution of story drifts. Preventing drift



(a)



(b)

Figure 1: Application of e-EXOS: (a) steel truss, (b) upgraded building

concentration allows e-EXOS to enhance the seismic capacity of the structure in two ways. First, since after the yielding of the weakest structural members other members are forced by the steel trusses to participate to the resisting mechanism, the RC structure upgraded by e-EXOS exhibits a lateral strength larger than that of the original existing building. Furthermore, the spreading of the damage in the whole structure increases the dissipation capacity of the structure.

If these enhancements do not allow the achievement of the target seismic performance yet, steel trusses can be equipped with Buckling Restrained Brace (BRB) at the base. The cyclic rotation of the truss about its base induced by the seismic excitation causes the yielding in tension and compression of the BRBs, that act as replaceable fuses and dissipate part of the input seismic energy by the plastic deformation of their steel core.

3 Design of the case study frames

The case study frame is a 5-story high RC framed building, with interstory height of 3.2 m and rectangular plan layout (Fig. 2). The unidirectional RC slab is characterized by steel reinforcement orientated along the Y-direction and it is 4 cm thick. Seismic resistant members are located so that the distribution of stiffness and strength is symmetric with respect to the geometric center of the plan layout. Dead and live loads resting on structural elements are determined based on nominal values provided in [1]. The decks are supported by four seven bay frames orientated along the X-direction (Fig. 4), instead four frames are disposed along the Y-direction. Due to the fact that the majority of beams is aligned along the X-direction and almost all columns have their strong axis along the X-direction, the case study building is characterized by a larger lateral stiffness and strength along the X-direction compared to the Y-direction. To design the building, the internal forces were determined considering gravity loads only. The areas of cross sections and reinforcement bars of columns and beams were sized according to the allowable stress method prescribed by the Italian code in force in the 1970s [2].

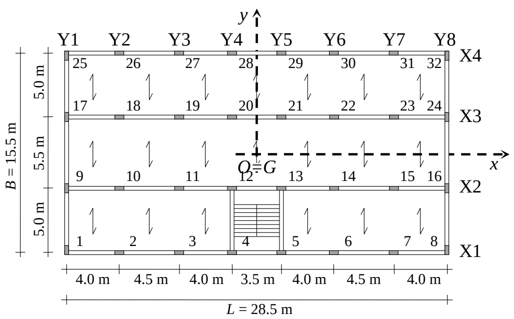


Figure 2: Plan layout of the case study frame

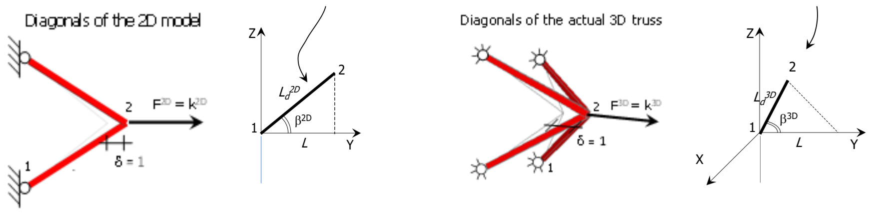
The materials, C20/25 for concrete and steel grade Feb38K for reinforcement, are consistent with those used in the seventies. Internal forces of beams are determined considering the scheme of continuous beams and the boundary schemes of single span beams fixed at their ends. It is assumed that columns sustain axial force only.

The e-EXOS solution is implemented by eight steel trusses applied to the building façade, two trusses for each façade. Steel trusses are not equipped with BRBs. The depth of the steel truss is 2.0 m and the distance between its two bottom chords is 2.0 m. All the members of the truss are made with steel tubes made of steel grade S235. In particular, sections 190x10 mm and 245x12 mm are used for bottom and upper chords, respectively and sections 170x7 mm for diagonal members.

4 Description of the numerical model

A 2D numerical model has been developed in Opensees to assess the seismic response of the case study frame by nonlinear dynamic analysis. In particular, the numerical model of the RC frame is first developed and then expanded introducing the finite elements that replicate the members of the e-EXOS system.
A member-by-member modelling is adopted for the analyzed frame. The concrete slab at each story of the RC frame is assumed to be rigid in its own plane. To take into account the P-Δ effect, a leaning column is added to the numerical model. The gravity loads assigned to beams and columns are those specified in EuroCode 8 (EC8) for the seismic design situation. The floor masses are equal to 220.4 t and are concentrated at the floor levels. Columns and beams are modelled as "beamWithHinges" with fiber cross section assigned to the plastic hinges. The Kent-Scott-Park ("Concrete01" uniaxial material) is the constitutive law for concrete, while the Giuffrè-Menegotto-Pinto ("Steel 02" uniaxial material) is the constitutive law for steel. A "zeroLength" element is added at one end of each beam. This element connects the end of the beam to the corresponding node restrained by the rigid deck and is characterized by a large axial deformability, large shear and flexural stiffnesses to transfer shear force and bending moment from the beam to the frame node [3]. Infill panels are included in the numerical model by means of a pair of diagonal trusses without tension resistance. The force-displacement relationship of the diagonal truss consists of four branches [4-5]: a linear elastic behaviour up to the first cracking, a first reduction of stiffness up to the maximum resistance, an abrupt reduction of lateral resistance and a low residual resistance.

With regards to e-EXOS members, since members of the steel trusses should be designed to remain elastic, they are modelled by elastic finite elements. Specifically, elastic "truss" elements are used to model diagonal members, while bottom and upper chords of the steel truss are modelled by "elastic beam-column" elements. It is notable that the 3D steel truss is simulated by a 2D numerical



(a) (b)

Figure 3: Stiffness of diagonals of the (a) 2D model and (b) 3D truss

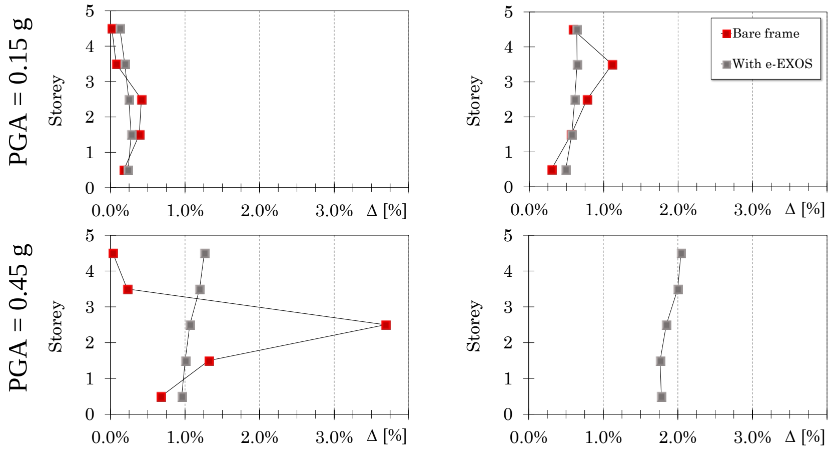
model. Hence, an equivalent cross section area is assigned to the elements of the numerical model to account for the difference between number, orientation and length of the members of the real 3D truss and the relevant finite elements of 2D numerical model. The equivalent area of the diagonal truss of the 2D numerical model A^{2D} is determined based on the assumption that the stiffness k^{2D} of the generic pair of diagonals, determined as shown in Figure 3a, is equal to the stiffness k^{3D} of the corresponding set of 4 diagonals of the actual 3D steel truss (Fig. 3b).

The connection between truss and decks of the building is modelled by constraining the horizontal displacement of each node of the upper chord to that of the adjacent deck by means of “equalDOF” constrains. Finally, in order to simulate the presence of the deck, the nodes of the same floor are constrained to have the same horizontal displacement.

4. Nonlinear dynamic analysis of case study frame with e-EXOS

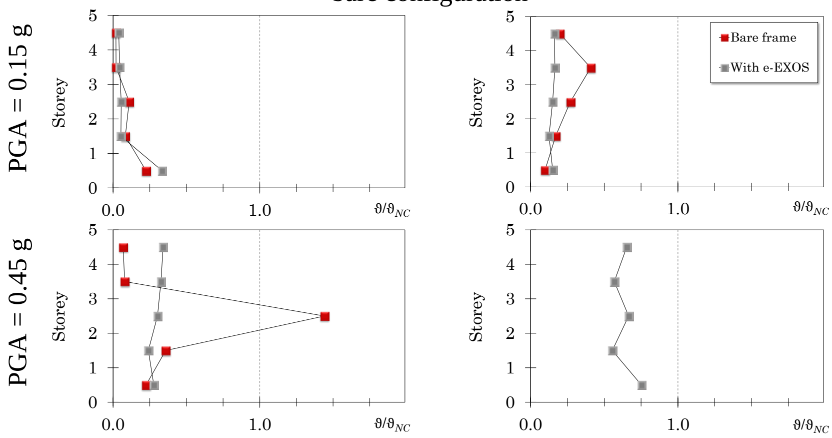
The nonlinear dynamic analysis is performed twice, considering the numerical model with and without infills. Both framed structures are analyzed in the original configuration and in that enhanced by e-EXOS. The seismic excitation is applied in X-direction and three values of PGAs are considered: 0.15, 0.35 and 0.45 g. A suite of 10 artificial ground motions, compatible with the EC8 elastic spectrum for soil type C and characterized by 5% damping ratio. Each ground motion is characterized by a total duration of 30.5 s [6].

The seismic performance of the analyzed RC frames is evaluated in terms of story drift demand Δ and chord rotation demand to capacity ratio of columns, (ϑ/ϑ_{NC}). The chord rotation capacity of columns ϑ_{NC} is assumed equal to the ultimate value of chord rotation calculated according to the equation provided by EC8 [7] for the Near Collapse (NC) limit state. For a given seismic excitation level, the maximum values of the response parameters are evaluated for each ground motion and then averaged over the ten inputs.



(a) (b)

Figure 4: Story drift of the frame with and without e-EXOS in the (a) infilled and (b) bare configuration



(a) (b)

Figure 5: Chord rotation demand to capacity ratio of columns of the frame with and without e-EXOS in the (a) infilled and (b) bare configuration

Figure 4 compares the heightwise distribution of the story drift angle demand of the case study building in the original configuration and in that enhanced by e-EXOS, for the case study building with and without infill panels. For the sake of brevity, only figures referred to the minimum (0.15 g) and the maximum (0.45 g) PGA are considered. The results show that bare infilled frame in the original configuration exhibits a story collapse mechanism at third story for PGAs larger than 0.35 g. Because of this concentration of damage, the maximum story drift ratio reaches a value about 4% when the PGA = 0.45 g is applied, which suggests a low seismic performance. It is noteworthy that, in the case of the PGA equal to 0.45 g, all the 10 dynamic analyses concluded prematurely, which can be

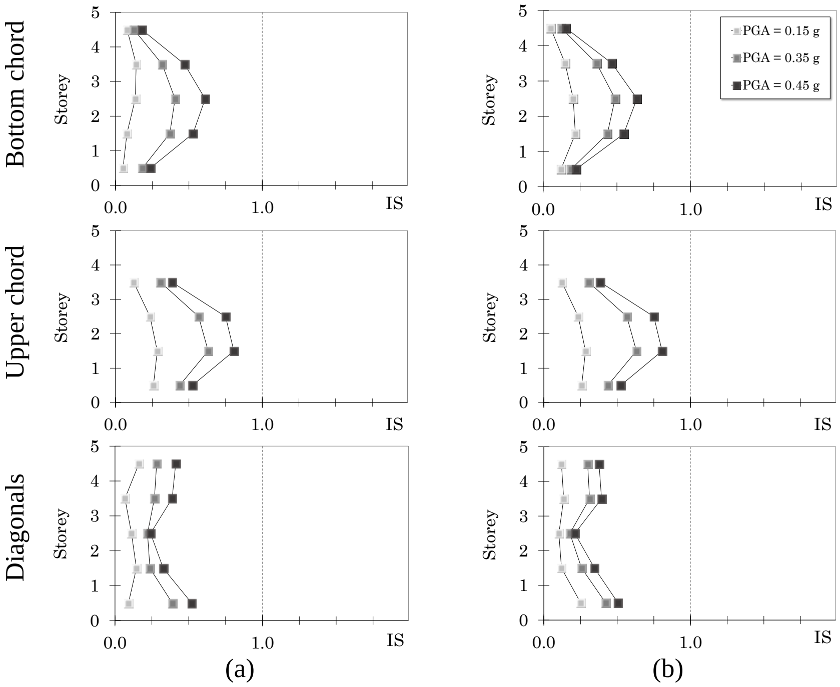


Figure 6: Index of Stability of the bottom chord, upper chord and diagonal of the e-EXOS systems applied to the RC frame in the (a) infilled and (b) bare configuration

identified as collapse of the bare RC frame in occurrence of the related accelerograms. The formation of a story collapse mechanism at third story is observed also in the building without infills. In this case, the recorded story drifts are generally larger than those of the infilled frame and the story drift of 3% is exceeded for PGA = 0.35 g. The application of e-EXOS, for PGA = 0.45 g, leads to maximum story drifts of 1.3% and 2.1%, for the infilled and the bare RC frame, respectively.

The demand to capacity ratio in terms of chord rotation of the columns of the RC frame is plotted in Figure 5. The verification of the NC limit state is fulfilled when the demand to capacity ratio is lower than 1. It is evident that the RC frame in the original configuration largely exceeds the NC limit state for PGA equal to 0.35 g or larger. In particular, the chord rotation demand to capacity ratio exceeds unity in the columns of the third story. Instead, the RC frame retrofitted by e-EXOS, regardless of the presence of infill panels, exhibits values of chord rotation demand to capacity ratio smaller than unity at every story even for the strongest seismic excitation.

The attainment of instability and yielding of chords and diagonal of the steel exoskeleton is checked according to the resistance criteria stipulated by Eurocode 3 [8] and its outcome is represented by the Index of Stability (IS) or the Index of plastic Resistance (IR). Member instability or yielding of columns occurs when the IS or IR exceeds unity. Figure 6 plots IS of the bottom chord, upper chord and diagonals of the e-EXOS system. Each plot shows three curves related to the three considered values of PGA. Even for the largest value of PGA, IS is smaller than 1 and none of the members of the steel truss experience instability. The results in terms of plastic resistance are not shown in any figure for brevity. However, IR is always smaller than IS and, therefore, than 1. Hence, none of the members of the steel truss yield during the ground motion.

5 Conclusions

The effectiveness of the proposed intervention retrofit technique for buildings with RC framed structure, named e-EXOS, is investigated in this paper by nonlinear dynamic analysis. The results of the numerical investigation, performed with three different values of PGA on a case study building designed for gravity loads and analyzed (1) with and without infills and (2) with and without retrofit intervention, provide to the following conclusions:

1. the structure in the original configuration suffered from a concentration of story drift that leads to the exceeding of the NC limit state for PGA lower than 0.35g;
2. e-EXOS inhibited the formation of the story collapse mechanism and consequently led to a uniform distribution of the drift along the height of the building;
3. the retrofit by e-EXOS allowed the fulfillment of the verification of columns in terms of chord rotation even for the largest seismic input considered (0.45 g);
4. None of the members of e-EXOS experienced yielding or instability.

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