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Preliminary considerations on the selective weakening of RC columns through rocking systems

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Abstract

Most of the research on seismic retrofit approaches focuses on the development of innovative retrofit solutions with the aim to improve the seismic performance of existing buildings through either local or global strengthening. An effective alternative approach is controlling the seismic performance of existing buildings through the selective weakening of specific portions of the structure, particularly to reduce stiffness irregularities. The present research focuses on a possible weakening approach dealing with the transformation of the existing reinforced concrete (RC) columns of a given story, specifically at the ground level, into rocking columns. This solution will lead to a global behavior like the one of an isolated system. The advantages of such a solution are, among others: the reduction of the relative displacement demand at the stories above the rocking system (i.e., damage reduction at the upper stories), the reduction of damage in the RC columns through a confined rocking region, the lumping of the construction works at just one story, the possibility to couple the rocking columns with additional energy dissipation or recentering systems. The effectiveness of the proposed solution has been preliminarily evaluated through the application to a reference case study.

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1. Introduction

In the last years, different research works have focused on innovative retrofit solutions for the integrated renovation of the existing building stock with the aim to foster safety, sustainability, and resilience at the same time (Marini et al., 2017; Passoni et al., 2021; Manfredi and Masi, 2018; Smiroldo et al., 2021; Santansiero et al., 2021). As for the structural aspects, strengthening techniques have been developed with the aim of increasing strength, stiffness, and ductility of the existing building. Retrofit solutions carried out from outside were developed (Labò et al., 2020; Manfredi and Masi, 2018; Reggio et al., 2019; Santansiero et al., 2021; Smiroldo et al., 2021; Zanni et al., 2021) to tackle all the building deficiencies at the same time and to avoid the inhabitant's relocation, which is one of the major barriers to the renovation process. In this regard, the present work contributes to the development of suitable seismic retrofit systems by investigating the effectiveness of controlled selective weakening approaches applied to a specific floor of an existing building (Ireland, 2007; Kam and Pampanin, 2008; Ireland et al., 2006).

The proposed solution aims at improving the seismic performance of existing reinforced concrete frame buildings by reducing the stiffness of specific elements of the structural system while increasing their ductility. Specifically, such selective weakening is achieved by transforming the ground-level RC columns into rocking systems (Belleri et al., 2014; Kurama et al., 1999; Marriot et al., 2008; Restrepo et al., 2007; Mpampatsikos et al., 2020). The advantages of applying this technique to the ground floor are: 1) if the ground floor is not inhabited, the retrofit intervention can be carried out without relocating the inhabitants or interrupting the building activities; 2) in the case of an earthquake, the rocking mechanism provides the lateral displacement ductility demand; 3) the damage is limited in the upper stories for drift sensitive structural and non-structural systems; 4) the global response of the existing building is governed by the rocking behavior at the ground floor and, consequently, the system performance is more predictable.

Considering the paper, Section 2 provides some general considerations about the rocking behavior; Section 3 describes the proposed technological solution and the design and finite element (FE) modeling criteria. In Section 4, the solution is validated through the application to a reference building: an ordinary post-World War II RC building. Finally, Section 5 deals with a critical discussion of the main findings.

2. Selective weakening by means of rocking columns

Considering monolithic blocks with uniformly distributed mass (Makris, 2014), their rocking behavior under seismic actions allows horizontal displacements while limiting the damage and maintaining resistance against vertical loads (Fig. 1). The same behavior is associated with rocking columns, whose seismic behavior can be divided into three phases: 1) the pre-oscillation phase, in which the column exhibits an elastic, non-linear behavior; 2) the oscillation phase, in which the overturning moment due to the seismic action is balanced by the re-centering moment provided by gravity loads (in this phase, the column returns to its initial position when the lateral force is removed); 3) the overturning phase, in which the lever arm of gravity loads is beyond the rocking column footprint thus providing an overturning effect.

In general, allowing for a controlled horizontal displacement, the weakening has the effect of increasing the natural period of the reference building thus leading to a significant reduction in terms of spectral acceleration; on the other hand, such behavior involves an increase in terms of displacement demand which must be controlled and limited to avoid the overturning of the rocking columns and therefore the floor collapse.

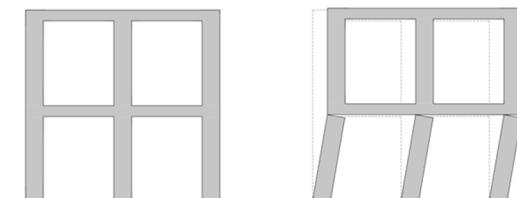


Fig. 1. Scheme of selective weakening through the rocking behavior of the ground-floor columns.

2.1. Technological aspects

To allow for a rocking behavior of existing RC columns, two solutions are preliminary investigated: a solution (Solution A) involving an additional RC casting, and a completely dry solution (Solution B).

In Solution A (Fig. 2a), a tubular confinement made by two half-circular steel plates welded or bolted on-site is placed at the ends of the existing RC column to allow for a confined region at the rocking interface. Such elements are infilled with high-performance concrete so that the spaces between the circular jacket and the rectangular column are filled, then the elements are connected to the existing floor and to the foundation to allow the transfer of the shear forces.

The construction phases of Solution A are:

- Partial cut at the top and at the base of the existing RC columns of the longitudinal reinforcements or of the concrete cover only. This operation allows for the development of a rocking interface at those regions. From a practical point of view, before carrying out this operation, the resistance of the weakened column cross-section must be checked and the ability to withstand the gravity loads must be guaranteed.
- Jacketing of the column base by means of two half-circular steel plates welded or bolted on-site, filled with high-performance concrete. The confinement aims at increasing the compressive strength at the rocking interface.
- Jacketing of the central part of the column. This step develops similarly to the previous one. A non-steel casing could be adopted. To maintain the discontinuity between the column base and the central part, a debonding agent should be applied on the surface before carrying out the additional casting.
- Jacketing of the column top. The casting operation is carried out under pressure to avoid air voids. As in the previous step, a debonding agent is applied before the casting.

Solution B (Fig. 2b) is a completely dry system; the construction phases are the same as in the previous solution, with the difference that, in this case, the concrete cast is not expected since metal jackets are implemented.

2.2. Finite element modelling strategies

The FE modeling choices described in this section apply to both Solution A and Solution B and refer to a two-dimensional RC frame resembling an ordinary post-World War II existing building, yet they could be extended and generalized to a 3D FE modelling. Beam and columns are modeled as *beam-like* elements. The column footprint at the rocking interface is modeled by means of two rigid elements with a length equal to half the size of the jacketed column placed in correspondence with the rocking interface (Fig. 3). In particular, the rocking motion is provided by vertical *compression-only* springs placed at the end of the rigid elements introduced to model the column width (Fig. 3c). For these preliminary analyses, only two compression-only springs have been adopted, although more springs can be used to better capture the rocking behavior, particularly in the case of 3D models. A horizontal spring is placed at the rocking interface to transfer shear forces.

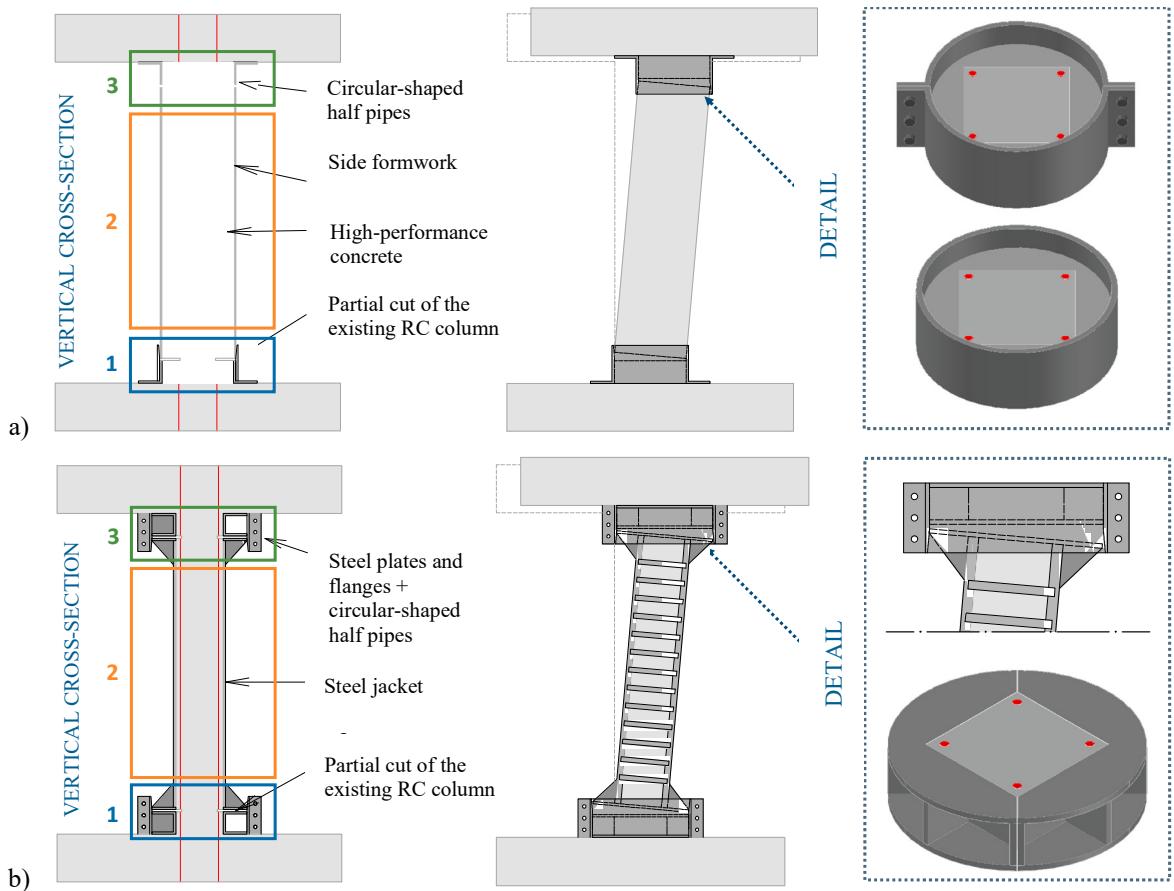


Fig. 2. Scheme and details of: (a) Solution A; (b) Solution B.

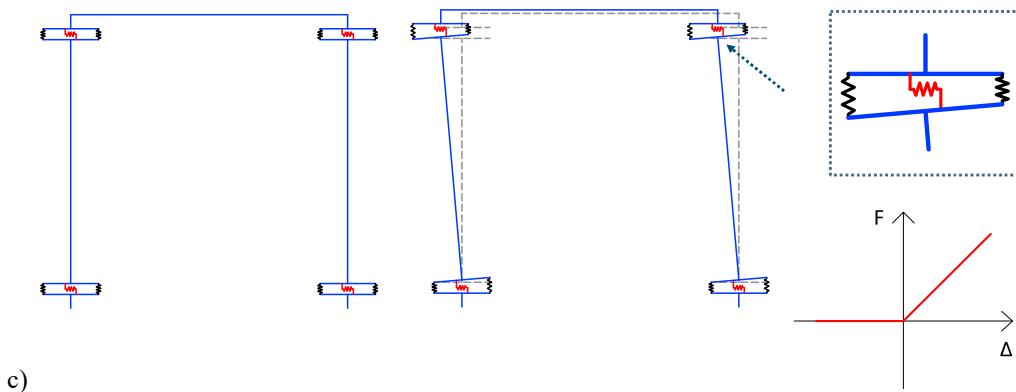


Fig. 3. FE modelling scheme for the rocking columns.

3. Application to a reference case study

To evaluate the potential benefits of the investigated retrofit scheme, both Solution A and Solution B were applied to a 2D reference frame (Fig. 4a) resembling a 1960s residential building located in the province of Brescia (Italy) with a RC frame bearing structure designed for gravity loads only: concrete C20/25 and steel Feb32k ($f_{yM}=315$ MPa, $f_{tk}=490$ MPa). The reference frame was modelled with the software MidasGen (2019). Beam elements were used to model the structural elements and lumped plastic hinges defined according to the formulations suggested in the European building code (EC8, CEN 2005) were implemented to account for their inelastic behavior. Columns were considered fixed at the base. The seismic performance of the reference frame was assessed through a nonlinear static analysis; the bilinear curve of the reference frame is plotted along with the acceleration-displacement response spectrum (ADRS) (Fig. 3b). As shown in Fig. 3b, the reference frame cannot satisfy the displacement demand both at the life safety limit state (LSLS) and at the collapse prevention limit state (CLS) since a soft-story mechanism arises at the ground floor due to the vertical irregularity of infill walls.

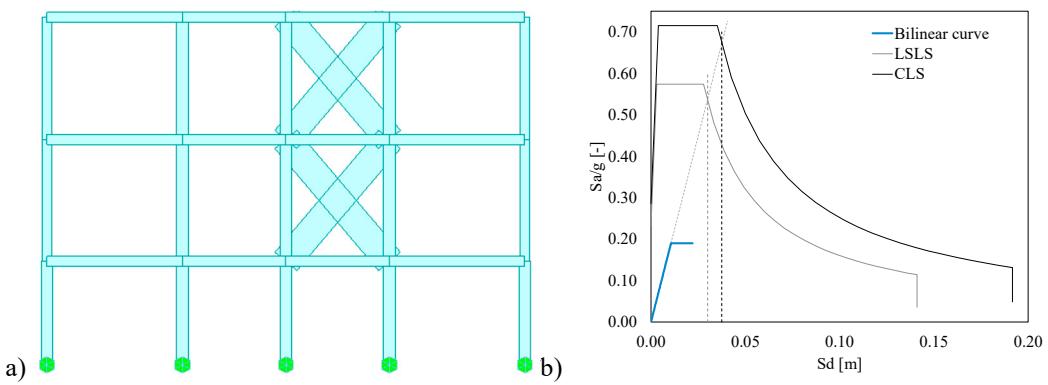


Fig. 4. a) reference frame; b) Bilinear curve of the reference frame in ADRS terms.

In the retrofit case with circular rocking columns (Solution A), the existing columns of the ground floor (30cmx30cm cross-section) were supposed weakened at the new rocking interface; the tubular circular-shaped jacket had 50 cm diameter. S235 steel was adopted for the top and bottom plates. A high-performance concrete was considered for the new casting (C45/55). As for Solution B, a steel jacket system was implemented considering a battened configuration; S235 L-shaped angles (5 mm thick, and 5 cm width per side) and steel battens (5 mm thick, 8 cm height, 20 cm length) were arranged along the central portion of the existing columns with the aim of stiffening and confining such sections. Also in this case, the column ends were weakened to allow the rocking behavior.

Nonlinear static analyses were carried out to assess the effectiveness of the retrofit solutions. The bilinear curves of the retrofitted frame are plotted along with the acceleration-displacement response spectrum (Fig. 5). It is worth noting that second-order effects were not accounted for in this preliminary study. From the pushover analyses (Fig. 5), it appears that, in both cases, the displacement capacity is greater than the demand required by the design earthquake at the LSLS, however, Solution B still does not satisfy CLS.

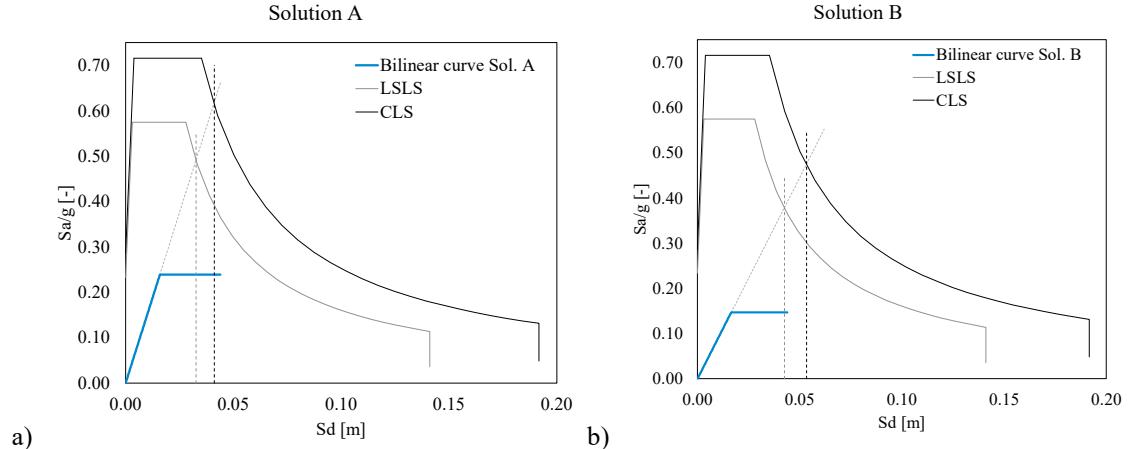


Fig. 5. Seismic vulnerability assessment (ADRS) of the retrofitted system: (a) Solution A; (b) Solution B.

To better control the lateral displacements and to reduce the displacement demand, especially for Solution B, a hysteretic or fluid-viscous dissipation system could be added to the retrofitted system (Fig. 6). In this work, a fluid viscous damper was supposed implemented: a final system damping ratio equal to 15% was considered in the ADRS definition to account for the fluid-viscous device introduction. Thanks to such a reduction, the displacement capacity is higher than the displacement demand at the LSLS and CLS for both solutions (Fig. 7).

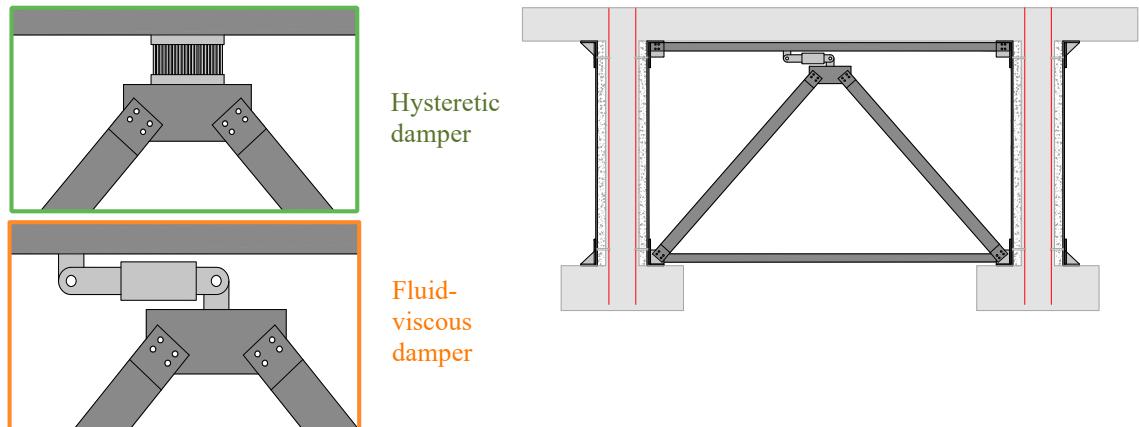


Fig. 6. Introduction of energy dissipation devices in the retrofit scheme.

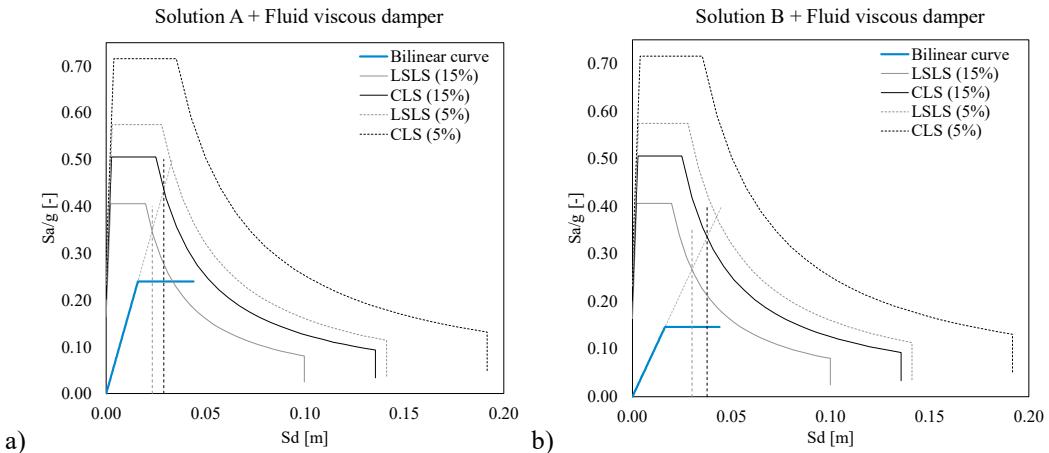


Fig. 7. ADRS plot after the introduction of a fluid-viscous system for: (a) Solution A; (b) Solution B.

4. Conclusion

This paper preliminary investigated the effectiveness of a weakening technique as seismic retrofit system; in particular, a weakening approach that exploits the rocking column mechanism at the ground floor was investigated. Two solutions were proposed: in Solution A, a tubular jacketing made by two circular shaped-half pipes welded or bolted on-site was placed at the existing RC column ends and then high-performance concrete was cast to fill the spaces between the circular jacket and the existing column. In Solution B, a completely dry system was proposed in which steel jackets were placed around the existing RC columns in a battened configuration. The technological and construction aspects were preliminarily addressed, and a finite element modeling strategy was defined. To evaluate the effectiveness of the retrofit solutions, an existing reinforced concrete frame resembling a post-World War II building was considered. Nonlinear static analyses were carried out on the retrofitted system showing the potential benefits of the investigated solutions. Finally, a fluid-viscous device was combined with the two solutions to further reduce the displacement demand.

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