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Preliminary considerations on coupled pin-supported walls as a strengthening solution for existing buildings

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Abstract

In the last years, attention to the seismic strengthening of existing buildings has increasingly grown, especially since a huge number of national incentives has been allocated for a deep renovation of the existing building stock. Various research has pushed toward new solutions suitable to account for the entire life cycle of the retrofit solution and that would overcome the main barriers to the renovation, which are, for example, the need to relocate the inhabitants. In this work, a strengthening system that involves the use of coupled pin-supported walls is proposed. The solution could be carried out from outside of the building thus not requiring the inhabitants' relocation. In particular, two pin-supported walls are coupled through horizontal beams connected to the walls by unbounded post-tensioning cables. The effectiveness of the proposed solution has been evaluated through the application to a reference case.

Keywords: Pin-supported walls; Rocking structures; Seismic strengthening

1. Introduction

Nowadays, the need for the existing building renovation has become a priority. A great share of the existing building stock was not designed for horizontal loads and the recent earthquakes that hit the Italian territory (L'Aquila, Amatrice, Central Italy) have highlighted the inadequacy of these buildings to withstand seismic loads. With reference to RC

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buildings, among the main collapse mechanisms, one of the most recurrent and destructive collapse mechanisms found in post-earthquake inspections was the soft-story floor mechanism. Such a mechanism is often linked to elevation irregularities. In the last years, various seismic retrofit techniques have been developed (Faiella et al., 2019; Labò et. al., 2020; Reggio et al., 2019; Zanni, et al., 2021; Smiroldo, et al., 2021; Santansiero et al., 2021; Sancin et al., 2021; Manfredi et al., 2021; Passoni et al., 2020), among these, pin-supported walls have been proposed (Belleri et al., 2016; Wada et al. 2011; Wada et al., 2018; MacRae et al., 2004; Casprini et al. 2022). Pin-supported wall aims to linearize the deformation along the building height thus avoiding soft-story mechanisms.

With the aim of minimizing structural seismic damage on RC existing buildings, the coupling of two post-tensioned pin-supported walls by horizontal beams connected through post-tensioned unbounded cables is proposed. The coupled pin-supported walls have the advantage of linearizing the building deflected shape while increasing the stiffness and the strength of the retrofitted building. Generally, the main advantages of the investigated solution are: 1) the linearization and the reduction of the seismic displacements and the prevention of a soft-floor mechanism; 2) the re-centring at the end of a seismic event and the consequence mitigation of residual displacements; 3) the damage localization in specific elements of the retrofitting system; 4) the mitigation of seismic demand for high intensity earthquakes considering the stiffness reduction after rocking has been triggered.

Given these premises, this paper investigates a simplified design methodology for double pin-supported walls moving from Casprini et al. (2022). **Section 2** reports some considerations on the investigated system, the design methodology is described in **Section 3** and then validated in **Section 4** through the application to a case study.

2. Coupled pin-supported walls: general considerations

The rocking behaviour and the re-centring capacity which characterizes the proposed retrofit system are based on the use of unbounded post-tensioning cables and coupling beams. It is worth noting that the coupling beams of the proposed system are conceived as rocking elements. The structural behaviour, the dissipated energy, and the stiffness of the proposed system are governed by different parameters such as the post-tension force, the geometry of the coupling beams and of the walls, and the presence of additional dissipative devices. Generally, the behaviour resembles that of a single rocking wall, i.e., a bilinear curve; the stiffness change is due to the activation of the rocking mechanism at the beam-wall interfaces (Fig. 1a). Instead, when additional dissipation devices are implemented, the combination of the re-centring mechanism provided by the unbounded post-tensioning cables and the energy dissipation ensures a flag-shap force-displacement hysteretic cycle (Mohd Asha and Nor Havati, 2020) (Fig. 1b). This paper investigates the case of pure rocking.

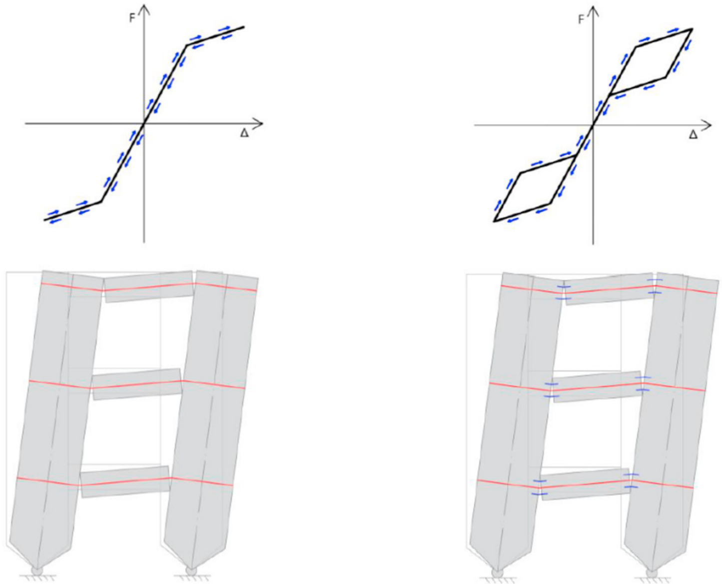

Fig. 1. Double pin-supported walls: (a) without energy dissipation; (b) with energy dissipation.

3. System design and finite element modelling

3.1. Design procedure

The design method has been derived for planar systems and is developed in two steps: in the first step, the bending moment (M_w) which arises at the base of the coupled walls is derived; in the second step the pin-supported system proportioning is provided. The first step is based on the linear dynamic analysis of the existing structure. Given the design spectrum and an appropriate behaviour factor (e.g., 1.5 herein), the load demand can be derived. In the case the period of the retrofitted building is unknown, the plateau pseudo-acceleration could be initially used. Considering that the retrofitted building mass would be very similar to that of the existing building, the total base shear of the retrofitted building is directly taken as the product between the mass of the equivalent SDOF of the retrofitted building and the design acceleration. By linearly distributing the total shear along the building height, the seismic actions at each floor (F_i) are determined. Through these actions and knowing the inter-story height, the total overturning moment is obtained.

The overturning moment taken by the pin-supported structure (M_w) is taken as the difference between the calculated total overturning moment and the resisting moment that the existing building can develop. The latter is associated with a widespread plastic hinges distribution in the elements of the existing building; it is worth noting that despite the existing building could not have been conceived for seismic loads, the linear deflected shape introduced by the retrofit system provides the spreading of inelastic demand.

In the second step, based on (Priestley, 1996), the proportioning of the coupled pin-supported walls is provided. In particular, the bending moments at the ends of the coupling beams (M_i) are:

$$M_i = M_w/2n \quad (1)$$

where, n is the coupling beam number (Fig. 2a).

The base (b_b), height (h_b) and length (L'_b) of the coupling beam, and the width (L_w) of the pin-supported walls may be derived according to the existing building layout and to the indication provided in (Priestley, 1996) as a function of the existing building floor stiffness (Fig. 2b). The post-tension value to be applied to the coupling beam is derived by means of the iterative process reported below.

The beam stress block extension (a) is evaluated as

$$a = 0.1\, h_b \tag{2}$$

The level arm between the post-tension load and the compression load acting on the concrete at the interface (z) is

$$z = \frac{h_b}{2} - \frac{a}{2} \tag{3}$$

Then the first value of the post-tension to be applied to the coupling beam (F_p) is derived as

$$F_p = \frac{M_i}{z} \tag{4}$$

At this point, the iterative procedure starts by deriving the new extension of the stress block (a') and the associated post-tension force (F'_p) as

$$a' = \frac{F_p}{(f_{cd} * b_b)}; \quad F'_p = \frac{M_i}{\frac{h_b}{2} - \frac{a'}{2}} \tag{5}$$

Where, f_{cd} is the design cylinder compressive strength of the coupling beam concrete.

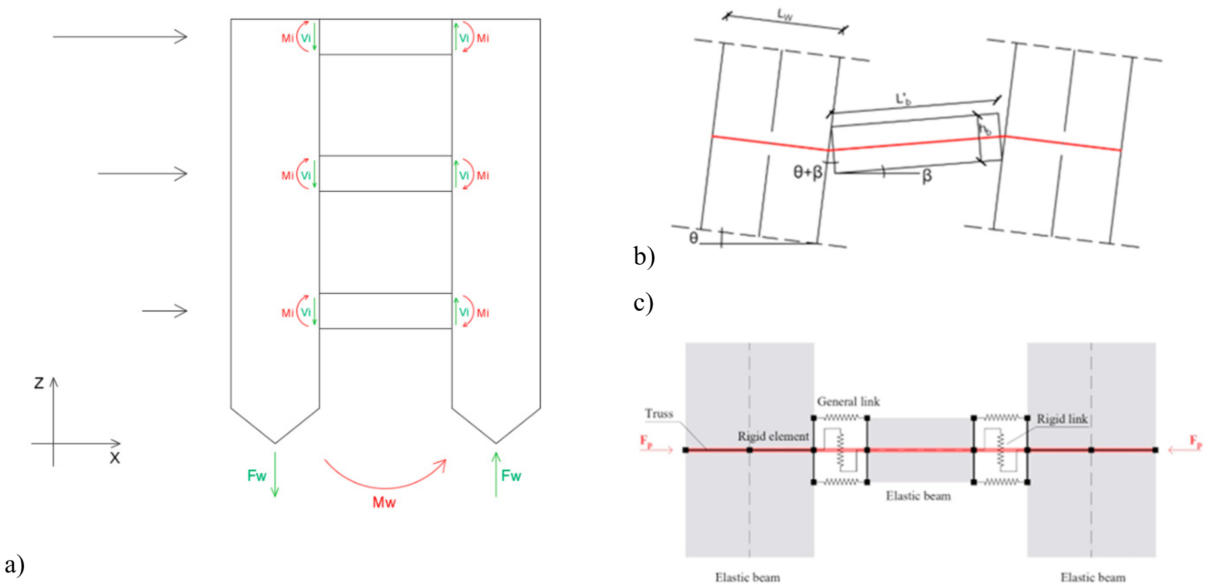

Fig. 2. (a) double pin-supported walls internal actions; (b) beam to pin-wall interaction; (c) finite element modelling scheme.

Once the compressive post-tension force is derived, the rotation (α) of the beam ends with respect to the wall is derived as the sum of the rotation θ and β (Fig. 2b).

$$\alpha = \vartheta + \beta = \frac{\vartheta}{1 - L_w/L_b} \tag{6}$$

θ can be set as a design parameter since it represents the maximum drift allowed to the existing structure after the retrofitting intervention. The compression region extension in the coupling beam (η) is

$$\eta = \frac{\alpha/\beta_1}{h_b} \tag{7}$$

where β is the stress-block coefficient, herein set equal to 0.8.
Neglecting the concrete deformation, the stress increases due to the post-tension cable elongation is

$$\Delta fp^{\infty} = 0.5E_p \, \alpha \frac{h_b}{L_{pu}} \tag{8}$$

where L_{pu} and E_p are the cable extension and elastic modulus, respectively. Consequently, a more accurate estimation of the post-tension load increase is

$$\Delta fp = \Delta fp^{\infty} \, (1 - 2\eta_d) \tag{9}$$

The post-tension cable design stress ($f_{p,des}$) must be at most equal to the yielding stress at the design rotation θ and lower than the initial admissible stress (f_{pi}) when θ is equal to zero (initial conditions). Therefore,

$$f_{p0} = f_{py} - \Delta f_p$$

If $\quad f_{p0} \geq f_{pi}$ then: $\quad f_{p,des} = f_{p0} + \Delta f_p$

Else $\quad f_{p,des} = f_{py}$ (10)

The minimum cross-section area of the cable is:

$$A_P = F_P / f_{p,des} \tag{11}$$

The design post-tension force is

$$F_{p0} = f_{p0} * A_P \tag{12}$$

3.2. Finite element modelling strategy

As regards the finite element (FE) modelling of the proposed system, beam-like elements are used to model the pin-supported walls and the coupling beams; the post-tension cables are modelled by means of a truss-type elements to which the post-tensioning load is applied. The pin-supported walls are hinged at the base. At the floors, horizontal rigid elements are introduced to represent the pin-supported wall width (Fig. 2c). The same approach is adopted for the coupling beams to capture the pivot point of the rocking mechanism. In this regard, general links (compression-only springs) are placed between such vertical rigid elements (Belleri et al. 2013, Mpampatsikos et al. 2020).

A simplified modelling strategy is also possible based on the numerical results obtained from the double pin-supported walls modelled as previously described: the coupled pin-supported walls can be substituted by a single element with a rotational spring at the base whose nonlinear characteristics are calibrated to obtain a response equivalent to the response of the complete model. The single wall element stiffness should also be equivalent to that of the coupled system. The spring at the base, defined as a general link, is obtained directly from the moment-rotation diagram of the coupled system.

4. Application to a case study

The effectiveness of the proposed system and design approach was assessed through the application to a reference case. For this purpose, a single planar frame of an existing building was considered. The reference case is a 1960s residential building located in the province of Brescia (Italy) and designed for gravity loads only. The bearing structure is made of RC frames with concrete C20/25 and steel Feb32k (f_{ym}=315 MPa, f_{tk}=490 MPa). The reference frame was modelled with the software MidasGEN (2019). The structural elements were modelled as beam elements and their inelastic behaviour was accounted for through lumped plastic hinges. The strength and deformation capacity of beams and columns were defined according to the formulations suggested in the European building code (EC8, CEN 2005). Columns were considered fixed at the base.

The seismic behaviour 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 to evaluate its seismic vulnerability (Fig. 3a). Fig. 3b shows the collapse mechanism exhibited in the AS-IS condition. The seismic vulnerability assessment highlights that the reference frame cannot satisfy the seismic demand since a soft-story collapse mechanism develops. The displacement demand is 0.037 m (0.048 m) while the capacity is 0.027 m (0.035 m.) at the life safety limit state (collapse prevention limit state).

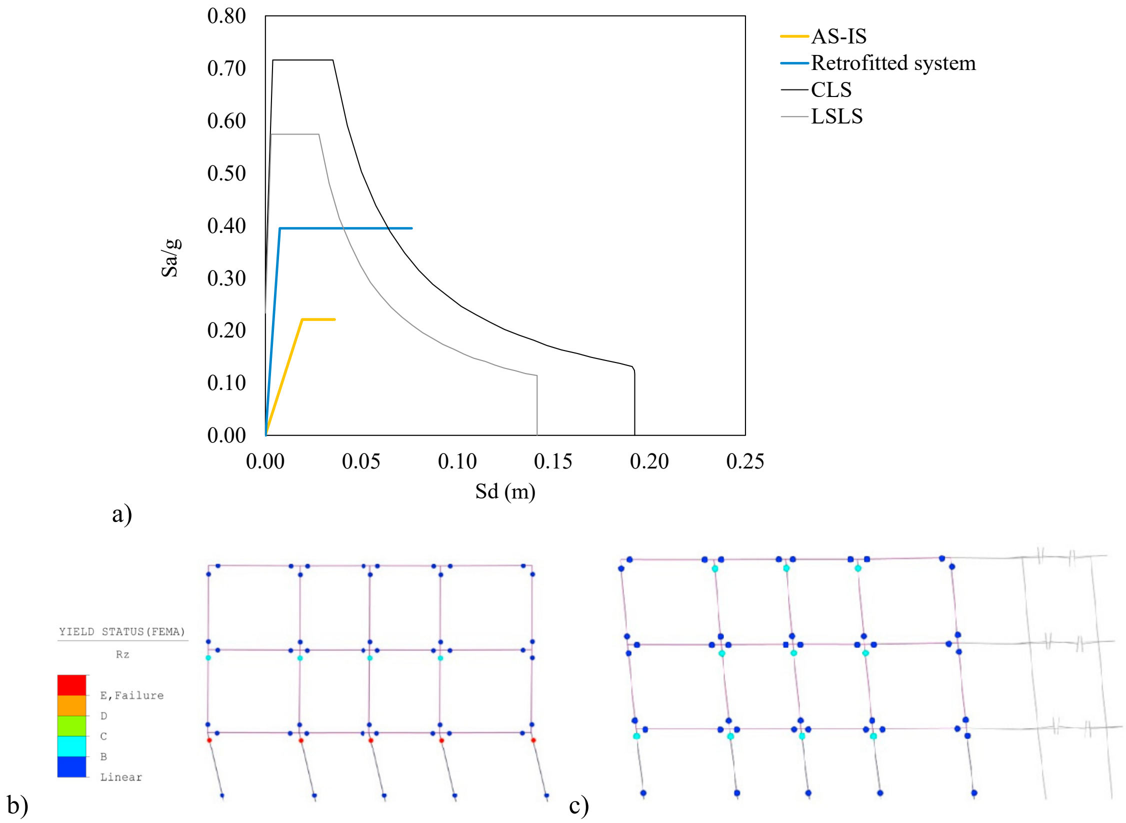

Fig. 3. (a) bilinear curve of the reference frame in the AS-IS condition and after retrofit; (b) collapse mechanism of the frame in the AS-IS condition; (c) collapse mechanism of the frame after retrofit. In grey, the retrofitting system.

For representation clarity, the coupled pin-supported walls system was positioned to the side of the existing frame (Fig. 3c); in practice, it could be positioned in adherence to the frame itself. The retrofit system was designed following the procedure described in the previous section and its effectiveness was evaluated through a nonlinear static analysis.

The coupled pin-supported wall was tied to the existing frame through truss-type elements which allow transferring the axial actions without being subjected to bending moments.
The retrofitted system shows a higher capacity both in terms of forces and displacements compared to the existing system. In particular, 1) the deformation of the frame is linearized, and the soft story mechanism is avoided; 2) the rocking mechanism is established at the beam-wall interfaces (Fig. 3c).
From Fig. 3a it is possible to see how the considered RC frame experiences a substantial improvement both in terms of strength and deformation capacities and it satisfies the seismic demand.

5. Conclusion

The potential of coupled pin-supported walls as a seismic retrofit solution for post-World War II RC buildings was investigated. Compared to a single pin-supported wall, a coupled pin-supported wall allows for a significant increase in stiffness and strength of the retrofitted system thanks to the development of flexural stiffness provided by the walls coupling. In this paper, a simplified design method was proposed, and a finite element modelling strategy was described. The effectiveness of the system and of the design method was assessed through the application to a reference case. The results of nonlinear static analyses showed how the retrofit system provides a higher lateral stiffness and lateral capacity to the building compared to the existing conditions.
Possible future developments concern the development of a design procedure based on the Direct Displacement Based Design (DDBD) method which allows setting a target displacement as design target. In addition, the system technological aspects may be investigated such as, for example, the structural details to be developed to guarantee a complete re-centring of the coupled systems or the introduction of dissipative devices.

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