The masonry infill "downgrade" in the seismic strengthening of existing reinforced concrete buildings

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ABSTRACT
The efficiency of seismic retrofit of existing reinforced concrete (RC) buildings could be affected by the presence of masonry infill walls, typically characterized by a stiff-brittle in-plane response. In many cases, the resisting contribution of such masonry elements revealed as an important resource for the seismic resistance of buildings not adequately designed against the seismic actions. On the other hand, as demonstrated in many post-earthquake surveys, the interaction between masonry infills and RC frame can produce severe damage in the infill itself and/or in the surrounding frame, thus increasing the building vulnerability.
For the building seismic strengthening, different solutions consist in the introduction of additional seismic-resistant elements capable of resisting a share of or the whole design seismic action. Often such interventions cannot prevent the effects of the infill-frame interaction, therefore the efficiency of the seismic strengthening could be nullified by anticipated collapses (for very low inter-story drift values) related to local failures in the frame columns or in the infill.
In the present paper, the retrofit of a case study building is investigated, focusing on the efficiency of an "infill downgrade" intervention, aimed at limiting the infill-frame interaction, proposed in combination with the strengthening obtained with additional external shear walls connected to the existing structure.

1 INTRODUCTION

The relevant damages suffered by reinforced concrete (RC) buildings during the seismic events of the last decades underlined their high vulnerability to seismic actions and the need for strengthening in order to increase their safety and reduce their post-earthquake damage (Braga et al., 2011; Verderame et al., 2009). In detail, the most part of the RC buildings built after the second world war were not designed to withstand horizontal seismic actions and to develop ductile deformations in the structural elements to dissipate the seismic input energy. Such buildings are typically framed structures with rigid masonry infills, introduced for thermal and acoustic insulation purposes. The presence of the latter elements further jeopardized the safety of the structures, interacting with the in-plane response of the surrounding frame up to the activation of brittle collapse mechanisms in the frame columns. The effects of such negative interaction have been extensively investigated in the last decades both experimentally (Basha and Kaushik, 2016; Mehrabi Armin B. et al., 1996) and numerically (Bolis et al., 2017; Cavaleri and Di Trapani, 2015; Di Trapani and Malavisi, 2018).

Different strengthening solutions have been proposed in the last years to restore the structural safety of existing buildings against the design seismic actions (Di Ludovico et al., 2008; Gioiella et al., 2017; Metelli et al., 2017; Pampanin, 2012; Passoni, 2016; Riva et al., 2010). Such solutions are typically based on the increment of strength and deformation capacity of the existing structure or on the introduction of additional seismic-resistant elements coupled to the existing structures, designed to withstand a share of or the whole design seismic actions. However, the design of such interventions does not typically take into account the issues related to the infill-frame interaction above recalled, which could produce anticipated damages (or collapses) in the infill or in the structure itself, thus limiting (or nullifying) the efficiency of the seismic strengthening (Dolšek and Fajfar, 2008; Hak et al., 2012; Manfredi et al., 2012).

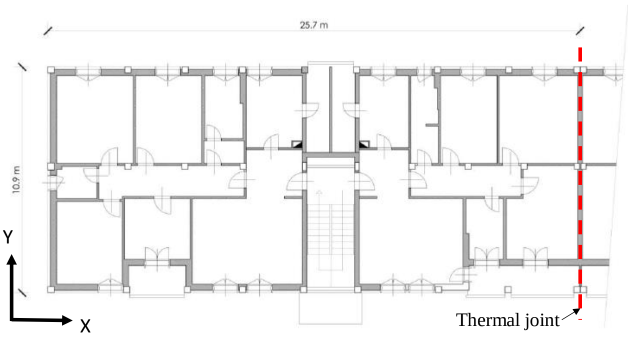
The present paper deals with the numerical assessment of the efficiency of a seismic strengthening intervention on a case study RC building. The strengthening is performed by means of the introduction of additional RC shear walls external to the building and connected to the latter at each floor level.

In the analysis of the structural seismic response, focus is made on the relevant role acted by the infill-frame interaction in limiting the deformation capacity of the existing structure due to the activation of anticipated collapses of the infills or of the structure itself. In order to limit such vulnerability, two alternative approaches are here considered: (i) on one side, the size of the strengthening walls is increased in order to control the deformation demand within values that can limit the damages; (ii) on the other side, the strengthening with external walls is coupled with a local "downgrade" of the masonry infills, obtained by means of the technique presented in (Preti et al., 2016; Preti and Bolis, 2017a). As demonstrated experimentally, this solution allows to significantly reduce the infill in-plane strength and stiffness, thus limiting the interaction with the surrounding frame, which can sustain higher deformation demands. Accordingly, also the size of the strengthening walls can be reduced, as a larger drift capacity is allowed by the "downgraded" infills.

2 CASE STUDY BUILDING AND STRENGTHENING INTERVENTION

The adopted case study frame structure is extracted from an existing three story RC framed building sited in Brescia and built in the 60's (Figure 1).

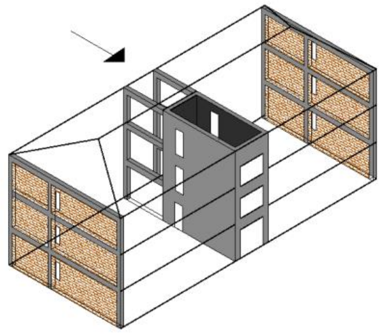
(a) picture



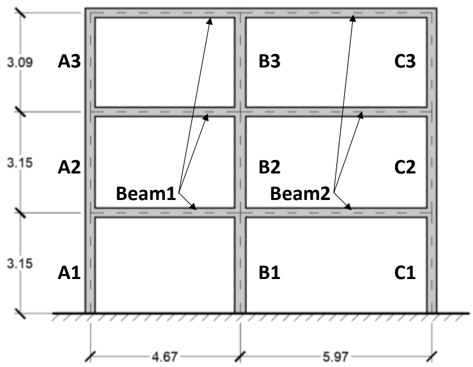
(b) plan view of the half portion

Figure 1. Case study building.

It is characterized by a rectangular plan with a central thermal expansion joint that split the building into two symmetric structures ((Figure 1b). Considering the transversal direction (Y), the resistance against seismic action is provided by a central RC staircase and by the two symmetric external frames, characterized, in first approximation, by solid infills (Figure 2a). The numerical study presented in this paper deals with the seismic response of one of the latter infilled frames, whose geometry is reported in Figure 2b and Table 1 and whose tributary story masses are assumed equal to ¼ of the total story masses.



(a) layout of the seismic-resisting system in the transversal direction



(b) geometry of the studied frame

Figure 2. Details of the 2D frame adopted for the analyses.

Table 1. Frame members' section geometry and reinforcement.

			A & C	B
Columns	Geometry		30x30cm	35x35cm
	Reinforcement	Level 1	4 Φ14	4 Φ16
		Level 2	4 Φ12	4 Φ14
		Level 3	4 Φ12	4 Φ12
Beams			Beam1	Beam2
	Geometry		24x50cm	24x50cm
	Reinforcement	Top	5 Φ12	3 Φ12
		Center	3 Φ8	3 Φ8
		Bottom	2 Φ12	4 Φ12

Focusing on the role of the role of the infills, a simplified 2-D analysis is performed limiting the study to the infilled frame without considering the specific effect of the stairways walls.

The infills consist in double-leaf hollow masonry walls with thickness 12+8cm and an interposed 5cm spacing.

2.1 *Seismic strengthening interventions*

The seismic response of the selected case study structure is obtained under five different configurations: the as-it-is case (Figure 3a “SI-unreinforced”), the strengthened case, obtained by adding an external shear wall to the existing structure (Figure 3b) and the case shown in Figure 3d, where the downgrade of the infill is introduced in addition to the strengthening with the shear wall. In the latter two cases the design of the shear wall is carried out to resist the design action according to the Italian building code (NTC, 2018), evaluated for the site of Brescia with a soil type C and a behavior factor equal to 2. Two additional cases are also considered in the analyses: an “over-strengthened” case (Figure 3c) to protect the solid infill from damage, and an “under-strengthened” case (Figure 3e) made possible by the increased deformation capacity provided to the infill by the infill “downgrade”. The former is obtained by designing the shear walls with a behavior factor equal to 1, while the latter by reducing the design actions to 60% of the design value for new buildings. In all cases the walls are meant to support the walls seismic action.

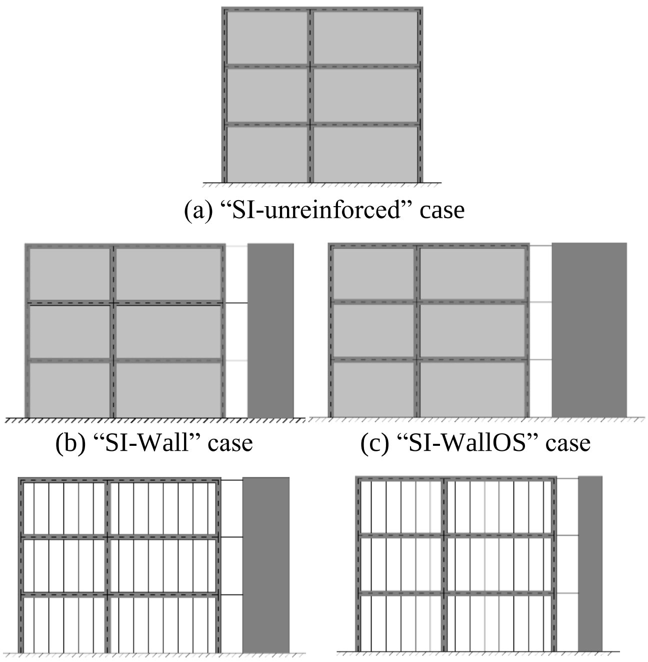


Figure 3. Schematic of the different configurations considered in the study.

2.2 *Infills “downgrade” intervention*

The here considered infill “downgrade” interventions aims at reducing the in-plane strength and stiffness of the masonry infill walls, ensuring its out-of-plane stability. The adopted technique was proposed and experimentally validated in (Preti and Bolis, 2017a) and consists in preforming vertical cuts into the masonry (with a 70-80 spacing), for the introduction of sliding joints connected to the frame beams. In addition, a horizontal cut is made between the wall and the top beam to create a 1-2cm gap, filled with deformable insulating material. As a result, the masonry walls is partitioned into several sub-panels capable of mutually sliding along the created vertical joints and activating a rocking mechanism around their base corners.

The obtained experimental results, reported in **Errore. L'origine riferimento non è stata trovata.**, show an in-plane response with low stiffness and negligible strength, if compared to the solid infill configuration. Thanks to the activated mechanism also the damage in the masonry is minimized, thus allowing a stable response at increasing applied inter-story drift (up to 2.5%), without strength degradation.

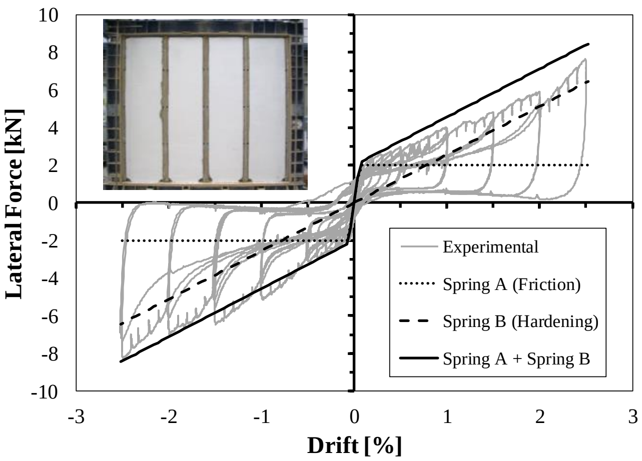


Figure 4. Infill “downgrade: experimental results obtained in (Preti and Bolis, 2017a) -vs.- equivalent double-strut model calibration.

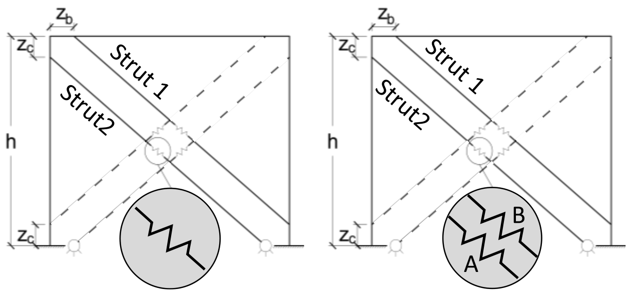
3 NUMERICAL MODEL DESCRIPTION

The seismic performances of the case study frame in the as-it-is configuration (“SI-unreinfroced”) and after the different proposed strengthening solutions are assessed by means of non-linear static and time-history analyses performed by means of the Opensees software (McKenna et al., 2000). The frame is modeled according to a lumped plasticity approach, with plastic hinges at the columns and beams ends, modelled with an bilinear *Hysteretic* stress-strain rule, calibrated on the members sectional properties. The shear failure of the frame members is not directly modelled, but the shear verification is carried out a-posteriori based on the Eurocode (EC8, 2005) formulations. The frame joints are modelled as elastic element and their verification is carried out a-posteriori based on the rotation capacity proposed by (Metelli et al., 2015).

The additional shear walls are modeled as elastic elements with plastic hinge at the base calibrated on the different walls' sectional properties.

3.1 Equivalent strut model for infills

The modeling of the solid infills ("SI") recalls the strategy already presented and adopted in previous studies (Preti and Bolis, 2017b). Based on this approach, the in-plane response of the infill is modelled by means of two eccentric compression-only strut elements in each diagonal of the frame bay (Figure 5a), connected to the frame beams and columns at distance z_c and z_b from the joint (where z_c=1/10h and z_b=1/10L). Such a configuration is selected and calibrated to numerically reproduce the shear demand on the frame members, generated from the seismic infill-frame interaction. The nonlinear response of the infill associated to its progressive damage is assigned to the struts by adopting a *Concrete01* material, whose calibration parameters are reported in Table 2.



(a) (b)

Figure 5. Schematic of the simplified models for the solid infill ("SI") (a) and the "downgraded" infill ("VJ") (b).

Table 2. Calibration parameters of the Concrete01 material adopted for the two equivalent struts to model the in-plane behavior of the solid infill.

		Strut 1	Strut 2
L=4.67m	d_{max} [m]	0.004310	0.004310
	d_u [m]	0.00755	0.00755
	N_{max} [kN]	71.02	58.11
	N_u [kN]	16.84	13.77
L=5.97m	d_{max} [m]	0.005020	0.005020
	d_u [m]	0.00878	0.00878
	N_{max} [kN]	77.482	63.394
	N_u [kN]	15.3	12.52

It is worth noting that "Strut 1" and "Strut 2" are characterized by different calibration values based on the different shear demand on the windward and leeward columns during the lateral response, highlighted in several numerical and experimental studies (Bolis et al., 2017; Stavridis and Shing, 2010).

The model for the "downgraded" infills ("VJ") is built on the same layout of the model for the solid infills, by changing the calibration of the axial stress-strain law of the inclined struts. In this case, two parallel springs are adopted for each strut ("Spring A" with an *ElasticPP* and "Spring B" with an *ElasticPP_Gap* material), calibrated in order to reproduce the in-plane response of the experimental specimen tested in (Preti and Bolis, 2017a) (see Figure 4). In this case the calibration of the two struts is identical and their calibration parameters are reported in Table 3.

Table 3. Calibration parameters of the parallel springs adopted in each inclined strut to model the in-plane behaviour of the downgraded infill

		Spring A ("Friction")	Spring B ("Slip Bilinear")
L=4.67m	d_y [m]	0.002	9.09E-11
	d_u [m]	0.059	0.059
	N_y [kN]	1.353	6.76E-06
	N_u [kN]	1.353	4.364
L=5.97m	d_y [m]	0.002	9.54E-11
	d_u [m]	0.061	0.061
	N_y [kN]	1.289	6.45E-06
	N_u [kN]	1.289	4.159

4 RESULTS

4.1 Pushover analyses

Preliminary static non-linear analyses are carried out to obtain the capacity curves of the case study in the different configurations schematized in Figure 3. The analyses are performed by adopting a force distribution on the structure consistent with a linear distribution of the horizontal accelerations along the height and the results are reported in Figure 6. The introduction of the shear wall for the design seismic action (solid blue and red lines) allows an increase of the structure strength with respect to the unreinforced case (grey solid line). However a fundamental difference can be observed among the two reinforced cases in terms of damage mechanism: the "SI-wall" case experiences several early collapses in the frame columns (circles in the graph indicating column shear failures) and at the infill level (black lines), associated to the infill-frame interaction, which limit the deformation capacity of the structure. On the contrary, when adopting also the infill downgrade (case "VJ-wall") such collapses are avoided and the structure can develop all its design deformation capacity and satisfy the design seismic demand (black square in the graph) only activating the plastic hinge at the shear wall base.

Thanks to the increased deformation capacity, for the case with downgraded infill the results show the possibility of reducing the shear wall design strength ("VJ-wallUS" - dotted blue line in Figure 6) without jeopardizing the safety of the structure: the demand is slightly increased, but remains lower than the large capacity achievable with strengthening+ infill downgrade.

On the opposite side, when applying the sole strengthening, the increase of the shear wall size (i.e. strength and stiffness) produces the reduction of the demand on the structure (see the "SI-wallOS" – dotted red line in Figure 6). However, the high vulnerability of the frame columns against the shear action produced by the infill-frame interaction, leads to anticipated collapses that does not allow the seismic verification of the structure.

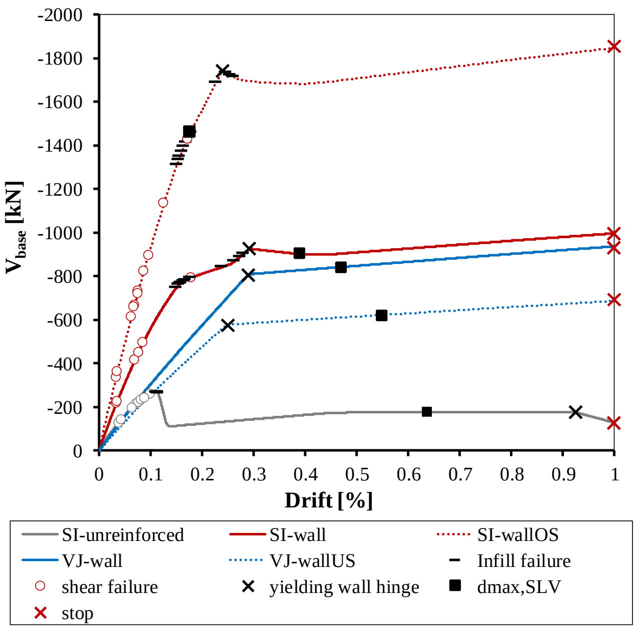


Figure 6. Results of the non-linear static analyses.

4.2 *Time-history analyses*

Dynamic non-linear analyses are carried out by means of seven ground motions selected to be spectrum-compatible with the design spectrum (Figure 7). The results for the different structure configurations are reported in terms of average values of story displacement (Figure 8), inter-story drift (Figure 9) and shear action on the column A (Figure 10), chosen as the most excited.

The introduction of the strengthening shear walls produces the modification of the deformed shape, passing from a drift distribution typical of a soft-story mechanism for the "SI-unreinforced" case, to that of all the strengthened cases, characterized by an almost linear distribution of the displacement along the height. Among the strengthened cases, the amplitude of the displacement is progressively reduced at the increase of the shear wall size, while the drift profile is slightly affected by the infill configuration (solid or with vertical joints).

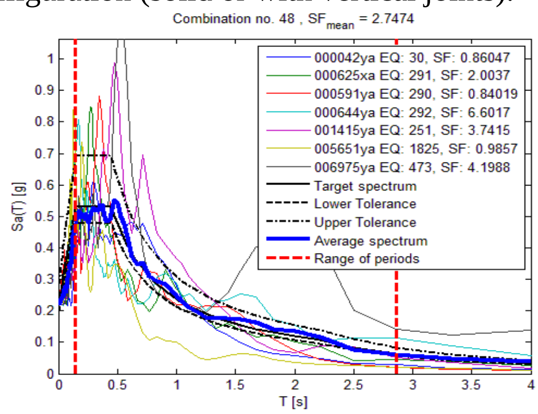


Figure 7. Selection of 7 spectrum-compatible ground motions for the time history analysis.

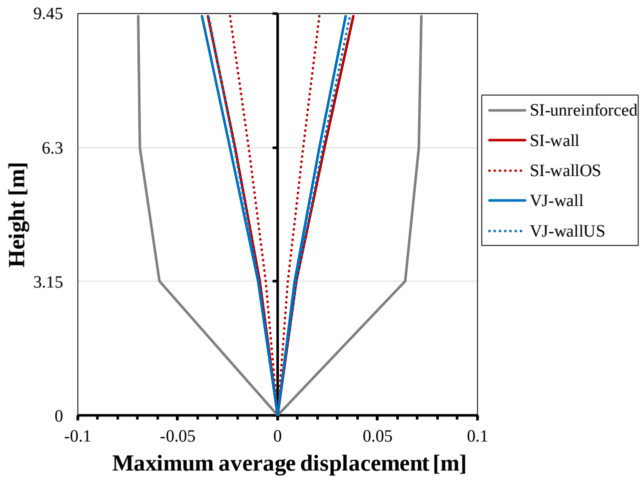


Figure 8. Results of the time-history analyses: maximum average displacement along the frame height.

On the contrary the infill layout plays a fundamental role in defining the shear action in the columns. As shown in Figure 10, significant shear demands are obtained for the cases with solid infill ("SI" cases), exceeding the shear capacity at the column ends, where the infill transfers its in-plane interaction force. In these cases, the collapse of the structure has to be considered. It is worth noting that the shear capacity of the columns ("*VRd*") is estimated according to Eurocode 8 (EC8, 2005), neglecting the effect of axial load variations during the dynamic response, that turned out in many cases to be detrimental being tension-side on the windward columns.

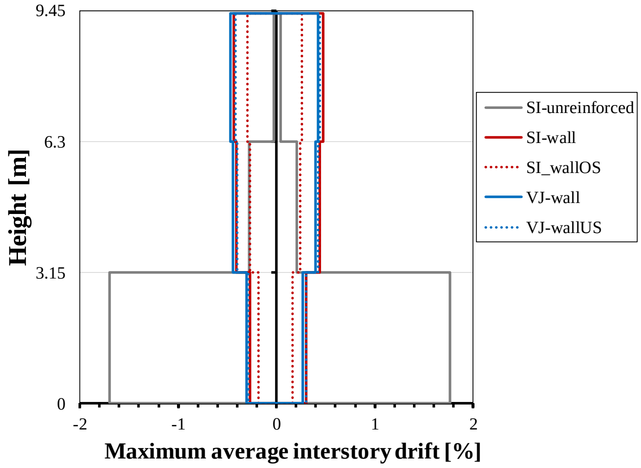


Figure 9. Results of the time-history analyses: maximum average inter-story drift along the frame height.

On the contrary, for the cases with downgraded infill, the shear demand increase due to the infill-frame interaction is negligible, thus avoiding unexpected shear collapses.

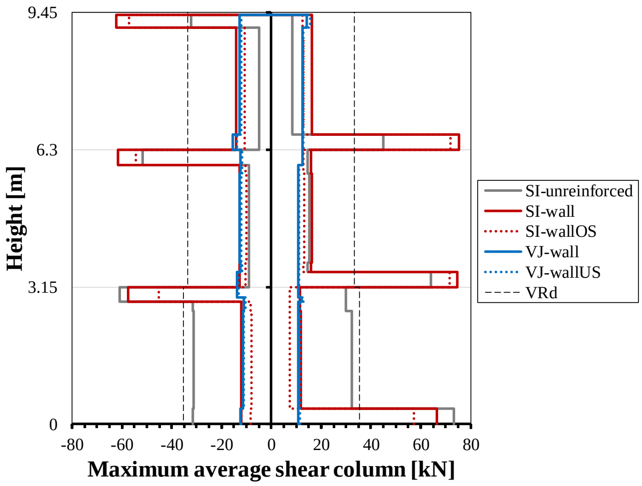


Figure 10. Results of the time-history analyses: maximum average shear demand in the column A.

5 CONCLUDING REMARKS

The paper focuses on the role acted by the masonry infills in jeopardizing the efficiency of seismic strengthening interventions on existing RC buildings. The presented numerical investigation on a simple infilled frame, selected as case study, emphasizes the risk of an anticipated collapses in both the infills and frame members caused by their mutual in-plane interaction. This phenomenon affects also the seismic response after the introduction of additional shear walls, designed to withstand the total design seismic action and connected to the existing structure at the storey levels.

In order to mitigate such a negative interaction, a downgrade intervention for the infills is considered, obtained by implementing a retrofit technique proposed in previous works. This solution consists in decomposing each solid infill panel into vertical sub-panels capable of activating a rocking mechanism around their base corners and mutually sliding. Thanks to this intervention the infill in-plane strength and stiffness are drastically reduced and its deformation capacity increased, thus preventing the brittle collapses characterizing the response of the solid infilled frame and ensuring the verification of the strengthened structure.

The obtained results provide a preliminary validation of the efficiency of the proposed downgrade technique, which can be further refined and improved in future works.

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