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DIRECTIONAL EFFECTS ON COMBINED IN-PLANE AND OUT OF PLANE SEISMIC BEHAVIOR OF MASONRY INFILLS

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Keywords: Infilled RC Frames, nonlinear static analysis, masonry infills, in plane and out of plane interaction of infills.

Abstract. *Unreinforced masonry (URM) infill walls affect both the strength and the stiffness of reinforced concrete (RC) frame structures undergoing lateral loads. Despite being classified as non-structural elements and often neglected in design numerical models, URM infills have a relevant influence on the seismic behaviour of structures. The brittle nature of URM determines a swift degradation of stiffness, strength, and low energy dissipation capacity once the panels are damaged or fail in the one of the in-plane direction failure modes.*

The aim of this work is to adopt and calibrate a macro-model for masonry infill walls that considers simultaneous in-plane and out-of-plane actions, and apply it to the nonlinear pushover analysis of RC frame structures representative of traditionally and seismically designed buildings. To this scope, a recently proposed URM infill macro-model with in-plane out-of-plane interaction is calibrated with existing experimental data from quasi-static tests performed on two types of clay masonry infill walls that are commonly found both in Italy and other Mediterranean countries. The calibrated elements are included in planar numerical models of RC framed structures representative of the Italian building stock, considering both traditionally and newly designed frames. Nonlinear static pushover analyses are performed on the frames with simultaneous static forces acting on the walls elements in the out-of-plane direction. Results confirm that increasing the out-of-plane loads on the panels induces both cracking and failure of the walls at lower lateral drifts of the buildings. The global force-displacement curves of the frames are also affected.

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1 INTRODUCTION

Unreinforced masonry (URM) infill walls affect both the strength and the stiffness of reinforced concrete (RC) frame structures undergoing lateral loads. When an earthquake strikes, in particular, infill walls increase the global lateral stiffness and strength of the structure and they can contribute to the energy dissipation of the structure, if damage is limited to acceptable levels. However, in many cases masonry infill panels have also played a negative role on the seismic response of buildings; in fact, damage and failures to URM infill walls has been linked to heavy socio-economic consequences, including human casualties, unusable buildings and high repair costs. Several negative phenomena impact the seismic response of both old and newly constructed buildings. The interaction between infill walls and frame elements, as an example, can also be the source of localized damage to structural components, activating undesirable failure modes. Moreover, the brittle nature of URM determines a swift degradation of stiffness, strength, and low energy-dissipation capacity once the panels are damaged or they fail (El-Dakhakhni *et al.* 2003) [1].

In addition to in-plane (IP) failures modes, infill walls can also suffer the expulsion in the out-of-plane (OOP) direction, posing a serious hazard to human safety. Studies dedicated to the behaviour of URM infill walls in the out-of-plane direction have been historically less numerous, compared to those regarding the in-plane behaviour, and fewer studies have discussed the effects of a combination of in-plane and out-of-plane actions, which is the most realistic action on infill walls during an earthquake. URM infills are usually classified as non-structural elements and often neglected in design numerical models. Moreover, although a number of simple and more refined models for infill walls have been proposed in the past few decades, most of them consider only in-plane actions.

Several studies about macro-modelling of infilled frame structures have been proposed in recent years (Asteris et al. in 2011 [2], Jeselia et al. in 2013 [3] and Tarque et al. in 2015 [4]), in which different models have been analyzed, classifying macro-model in single diagonal strut models and more complex multi-strut models. Macro-models require less computational effort compared to micro-models, which instead involve non-linear finite element modelling of the RC frame, the infill panels and the interface between the frame and the wall. Therefore macro-models are more suitable to represent the global behavior of structures.

The representation of the masonry infill wall through an equivalent diagonal element was introduced in 1960s, who proposed a truss diagonal element characterized by the same material and thickness of the panel, but considering an "equivalent width". In the following years, Smith provided a more sophisticated formulation for the equivalent element width, which is a function of the ratio between the frame and panel stiffness.

Multiple-strut models were proposed with the aim of better simulating both the effect of the panel and the internal forces distribution on the frame members.

Since 1997 Crisafulli [5] carried out some studies to compare the performance of one, two and three-strut models. According to those studies, a single-strut model cannot properly represent the internal forces generated on the frame members, although its simplicity and ability to correctly represent the lateral stiffness of the infilled frame and the axial stresses induced from lateral forces; therefore, a 2-struts model at least should be used for a more appropriate modelling, considering also a 3-struts model to minimize the errors for the bending and shear stresses.

Regarding the IP/OOP interaction, in 2004 Calvi et al. [6] studied the resisting arch-mechanism of the masonry walls, depending on the slenderness (the ratio between height and thickness). In particular they referred to Flanagan & Bennett (1999) [7] and Angel-Abrams (1994) [8] studies. Flanagan & Bennett have demonstrated that the IP damage influence depends on the ratio of slenderness of the infill walls and not on the ultimate load capacity. Angel-Abrams have demonstrated experimentally that, for high levels of slenderness, the reduction of the OOP resistance due to the IP damage can be evaluated at about 50%. More recently, other authors who have been studied the influence of the IP damaging on the OOP behavior through a numerical model are Furtado and Rodrigues (2015) [9] and Najafgholipour et al. (2013) [10], while several studies and an experimental campaign on URM infill walls have been made by da Porto et al. [11], in particular considering thick panels. This study instead aims to consider the simultaneous combined IP/OOP action. In 2015 Mosalam & Gunay [12] proposed a macro-model (MG-model) to consider the IP/OOP interaction, calibrated according to the following expression:

$$\left(\frac{P_{il}}{P_{ic}}\right)^{3/2} + \left(\frac{P_{ol}}{P_{oc}}\right)^{3/2} = 1 \qquad (1)$$

where P_{il} and P_{ol} are respectively the in-plane and out-of-plane loads, instead P_{ic} and P_{oc} are the in-plane and out-of-plane capacities. This model (Figure 1) represents the infill by means of a diagonal element based on two bi-directional domains (Figure 2), which govern respectively the yielding and the removal criteria of the element itself. In particular, this element consists of two elastic beams with a plastic hinge in the contact point, where an inelastic fiber section with fibers spaced in the out-of-plane direction is defined: in this way, they withstand to axial force as well as to bending moment, combining the IP/OOP response; the fibers are defined through their area A_i, location z_i related to the central axes, yielding stress f_{vi} and yielding deformation ε_{vi}. Yielding condition is given by a IP-Axial Force/OOP-Bending Moment diagram (Figure 2a) derived from Eq. (1), and a similar domain is used to remove the element during the analysis when it is exceeded by the displacement of the central node. The model use a simple elastic-plastic constitutive law for the fibers, which means that, once the element yields, it maintains its capacity until the element removal occurs.

Starting from the MG-model, taken as reference, the paper proposes a more appropriate macro-model to consider simultaneous IP and OOP actions, calibrated on the basis of previous experimental campaings [6[11], with the aim to assess the influence of the seismic action directionality on the response of the infilled R.C. frame. For this purpose, a parametric non-linear pushover analysis was carried out in OpenSees, involving different direction of the load pattern, differrent configurations of R.C. frames, traditionally and seismically designed, and two types of infill, thin and thick, representative of the Italian building stock. Results are presented in terms of pushover curves, energy indexes and inter-storey drift profiles.

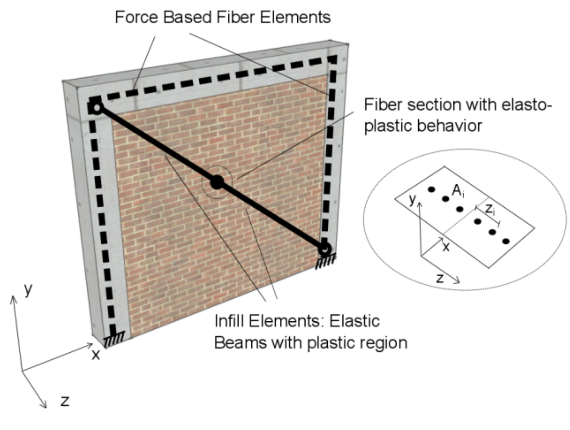
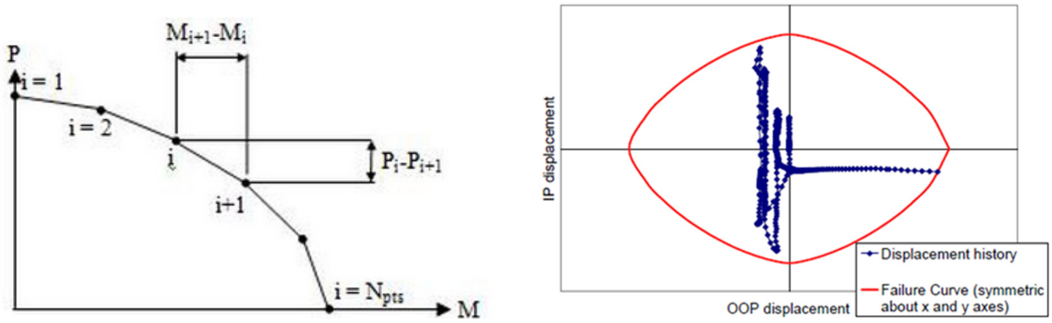


Figure 1. Infilled Frame Modelling according to Mosalam & Gunay [12]. Infills were modelled by using elastic beams with a plastic fiber region to simulate the In-Plane/Out-of-Plane interaction.



a) b)

Figure 2. a) IP-Force (P)/OOP-Moment (M) domain for the yielding condition of the fibers and (b) IP/OOP displacement domain for the element removal, from Mosalam & Gunay[12].

2 CALIBRATION OF THE F.E. MODELS THROUGH IP/OOP TEST RESULTS

2.1 Presentation of the reference tests

The available experimental results regard two different types of infill panel tested both in-plane and out-of-plane at the University of Padova (da Porto *et al.* 2013) [11] and Pavia (Calvi *et al*. 2004) [6]. These masonry panels have similar length and height but two different thicknesses, in order to assess the seismic behavior of both thick and thin infills. The walls tested by da Porto *et al.* [11] were full-scale panels made of clay units with vertical holes. Infills built with this thick units have become more common in recent years, because they can improve thermal insulation and are generally more robust, especially against earthquakes. However, thin walls made of clay units with horizontal holes have been the typical light enclosure system used since 1960s and are widespread in existing buildings. These infills were studied, still through full-scale tests, by Calvi et al. [6]. The characteristics of the experimental sets and the main results are shown respectively in Table 1 and Figure 3 and 4.

Looking at Figure 4, a progressive stiffness and strength degradation is observed in the OOP direction increasing the IP damage and the following points can be identified on the capacity curves:

- a *Damage Limit State* (DLS) corresponding to a first important variation of the slope;
- an *Ultimate Limit State* (ULS), corresponding to the peak strength;
- a *Collapse Point* (CP), which identifies the moment (determined also by test observations) of sudden strength degradation, which anticipates the out-of-plane collapse of the panel.

		Type Padova (PD)	*Type Pavia (PV)*
RC frame	Column section	300x300 mm	300x300 mm
	Beam section	250x500 mm	250x500 mm
	Frame height	3200 mm	3250 mm
	Frame length	4750 mm	4800 mm
	Concrete compressive strength	30 MPa	30 MPa
	Concrete elastic modulus	25000 MPa	25000 MPa
	Steel yield strength	450 MPa	560 MPa
	Steel elastic modulus	200000 MPa	195000 MPa
Masonry infill	Infill thickness	300 mm	115 mm
	Infill height	2650 mm	2750 mm
	Infill length	4150 mm	4200 mm
	Masonry compressive strength	6.0 MPa	4.5 MPa
	Masonry elastic modulus	6000 MPa	4500 MPa

Table 1. Geometrical and material properties for the two infilled RC frames tested.

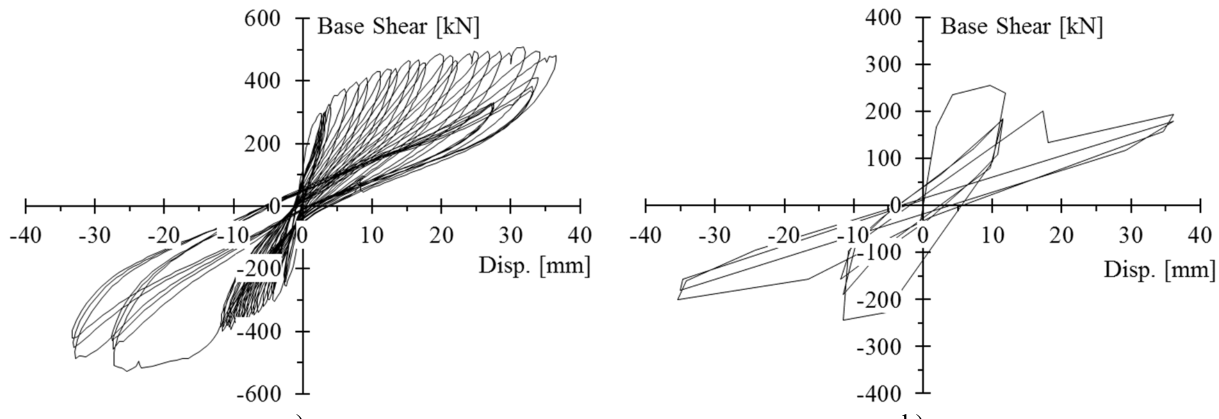


Figure 3. IP hysteretic cycles of infilled frames tested at the University of Padova (a) and Pavia (b).

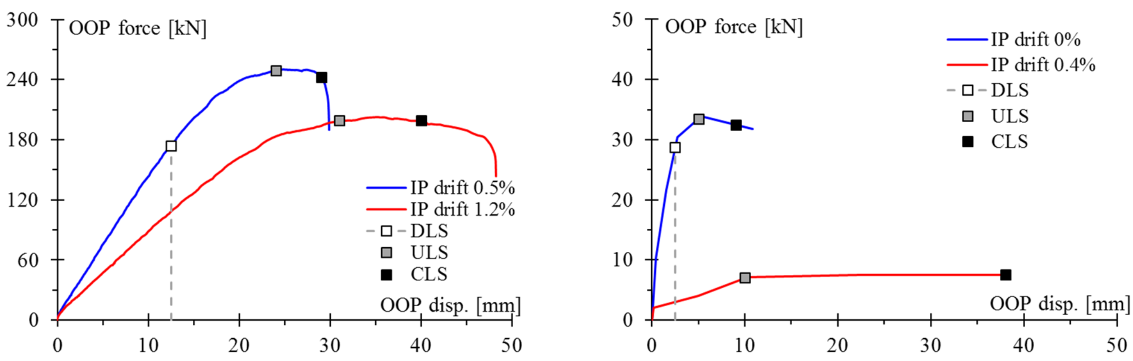


Figure 4. OOP test results starting from different IP damages: (a) thick panel (Padova), (b) thin panel (Pavia).

IP Limit States	*Thick panel (Padova)*	*Thin panel (Pavia)*
DLS	0.5 %	0.4 %
ULS	1.2 %	1.0 %
CLS	2.5 %	1.4 %

Table 2. IP limit drifts, associated to the principal limit states, for the two analyzed infill panels.

Finally, the IP limit states, directly derived from test observations, are reported in Table 2 (with the same meaning of those presented for the OOP direction).

2.2 Presentation of the F.E. model

In the proposed F.E model (see Figure 5), implemented in OpenSees, RC members were modelled using force based beam-column elements with non-linear fiber sections, using five integration points. The Kent-Scott-Park [13] constitutive law, with added linear tension softening, was considered for the concrete, while Mander's model was adopted to evaluate the confinement parameters for the core and cover concrete. For the steel bars, an elasto-plastic behaviour with strain hardening was used, as proposed by Menegotto & Pinto[14]. These material laws, calibrated through the previous test results, are shown in Figure 6a),b),c).

In order to confer a realistic OOP stiffness to the frame planar models, elastic springs with OOP stiffness were placed on the frame nodes which would be connected to the frames in the orthogonal direction. The stiffness values of these fictitious springs were iteratively calibrated for each model so as to obtain similar first periods of vibration in both OOP and IP directions.

The infill panels are modelled by means of two equivalent struts, each of them is defined similarly to the element of the MG-model [12], but with half IP/OOP resistance: the same fiber section, composed by 10 fibers symmetrically placed out-of-plane with respect to the strut axis, is used to consider the IP-OOP interaction, but a different hysteretic law is defined to represent the degradation of the masonry strength and stiffness. In particular, the "Hysteretic material" (from OpenSees material library) was used to simulates the infill experimental behavior and was calibrated, for each of the 5 different fibers, as shown in Figure 6d. The calibration of the "yielding point" (maximum strength) of the fibers was done in accord to MG model, with the only difference that the same "yield strain" (calculated as the medium yield stress of the fibers divided the masonry Young's modulus) was assumed for all the fibers, thus using different elastic moduli for the fibers (calculated as the yield stress of the specific fiber divided the yield strain), but such that their mean value is the elastic modulus of the masonry; considering a material with strength and stiffness degradation, this was necessary to increase the controllability of the model for the following calibrations.

The contact length, which define the distance between the struts, was appropriately calculated according to Stafford Smith (1966) [15].

The in-plane inertial masses include both the frame masses and the infill ones and they are represented as lumped masses at each beam-column joint. Instead, the out-of-plane mass is considered only for the masonry infill, because of the bi-dimensional model, and this is concentrated only in the central point of the two struts, equally subdivided between the struts. In the out-of-plane direction, the two central nodes of the struts are rigidly connected.

The calibrated hysteretic laws of Figure 6d) allow to better predict the real seismic behaviour of the masonry panels with respect to the MG model. Moreover, if for the MG model the removal domain is necessary to cut the capacity of the yielded panel, simulating the loss of the total IP and OOP strength of the panel after its collapse, in the proposed modified MG model (mMG) the same domain, corresponding to the Collapse Limit State (CLS) domain in Figure 7, is effectively used to describe only the real out-of-plane collapse of the panel, which corresponds to a sudden reduction of the infilled-frame IP resistance, equal to the residual IP strenght of the panel. Thus, the removal condition for the IP direction is not used, because the model already simulates the stiffness and strength degradation up to zero. The main differences between the MG model and that proposed are summarized in Table 3.

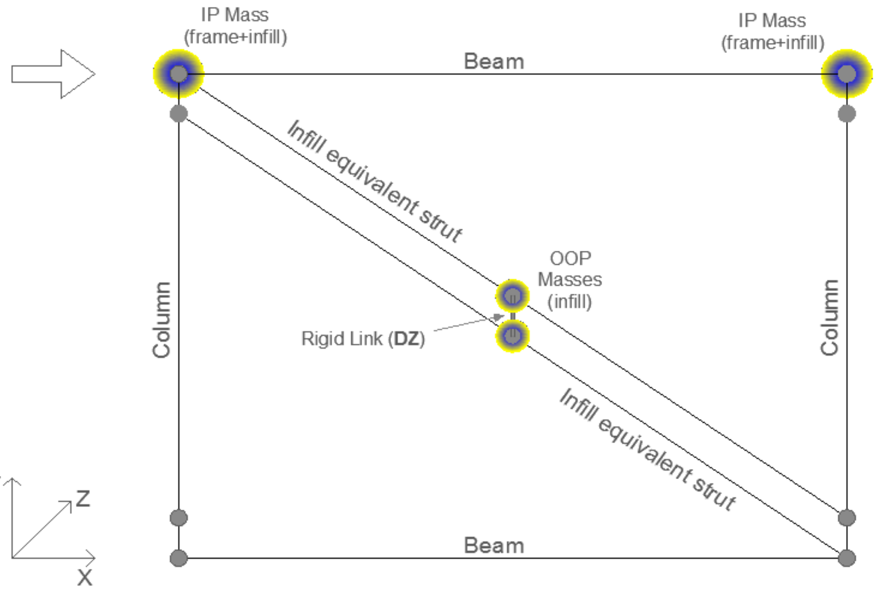


Figure 5. Model proposed by the authors, or modified Mosalam-Günay (mMG) model.

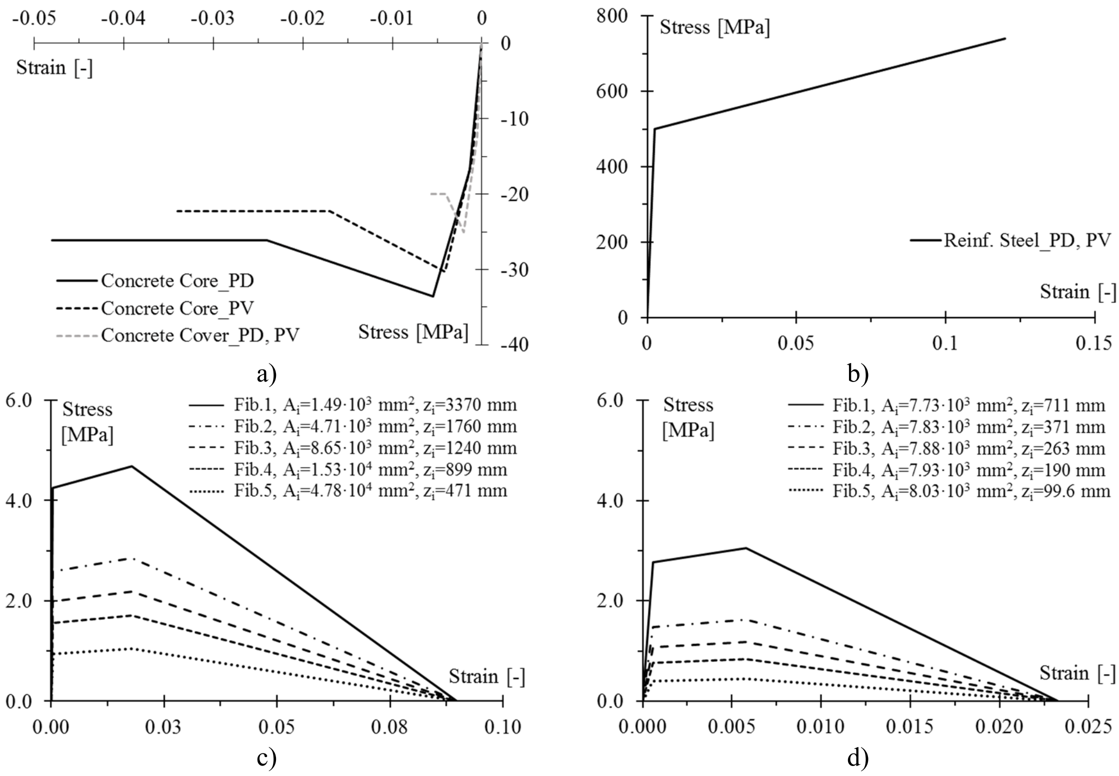


Figure 6. Constitutive laws, associated to the fibers, of the materials implemented in the F.E. analysis: a) concrete; b) reinforcing steel; c) infill type Padova; d) infill type Pavia.

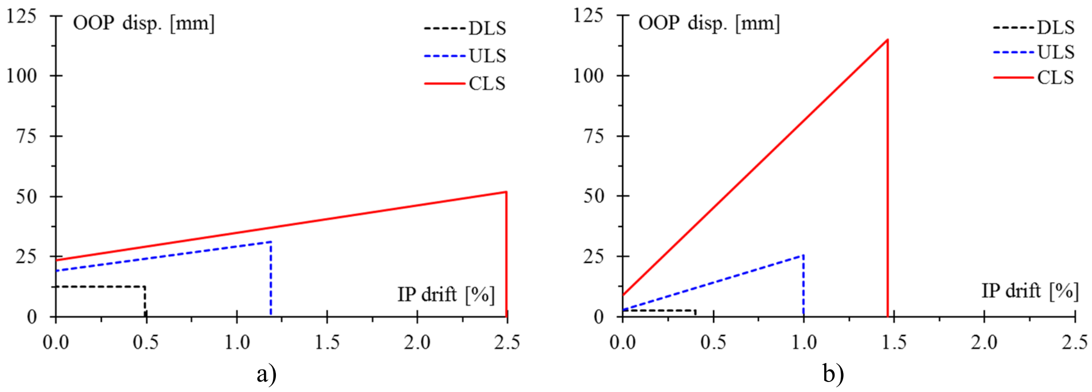


Figure 7. IP-drift/OOP-displacement domains for the principal limit states: a) thick panel; b) thin panel.

Differences	*Mosalam-Günay model (MG)*	*Proposed model (mMG)*
1	One diagonal strut	*Two diagonal struts*, to improve the evaluation of the infill effects on the frame, according to Crisafulli [5]
2	Elasto-plastic behaviour	*Hysteretic behaviour* with softening
3	IP-Force/OOP-Moment domain for the yielding criterion plus IP/OOP displacement domain for the infill removal according to a 3/2 power law	*OOP (only) displacement domain* for the infill removal, *calibrated* from test results

Table 3. Main differences between the original MG model and the modified one (mMG) proposed by authors.

Similar displacement domains, with the only purpose to assess the damage level reached by the infill panels during the IP/OOP numerical analyses, were calibrated for the Damage Limit State (DLS) and Ultimate Limit State (ULS), as shown in Figure 7. These domains, actually IP - drift/OOP - displacement domains, are obtained through a linear interpolation of

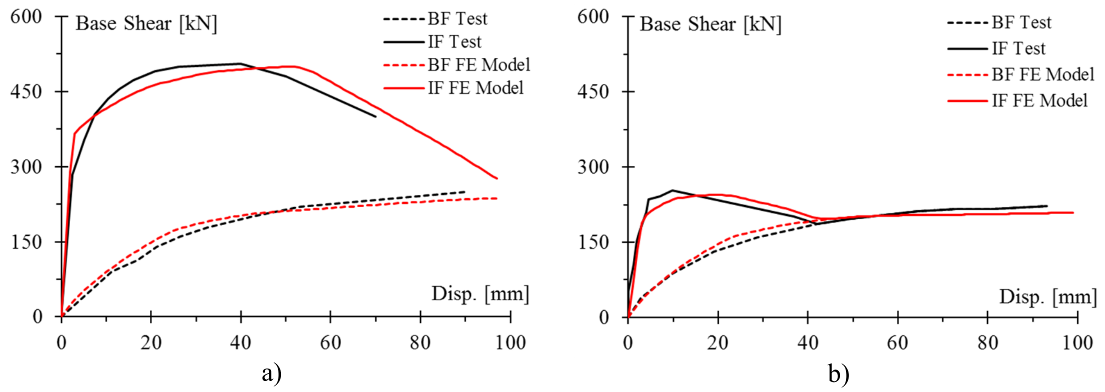


Figure 8. In-plane calibration results: a) thick panel (type Padova); b) thin panel (type Pavia).

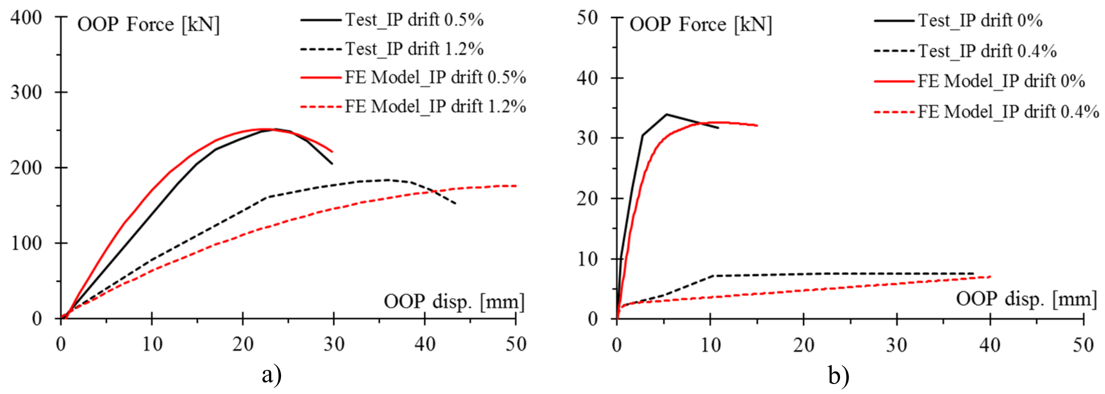


Figure 9. Out-of-plane calibration results for different levels of IP damage: a) thick panel; b) thin panel.

the OOP limit states, function of the in-plane damage, and the IP limit states presented in Figure 4 and Table 2 respectively, both deriving from experimental evidences.

The results of the model calibration, considering the tests related to both thick (Padova) and thin (Pavia) panels, are reported in Figure 8 and Figure 9, respectively for the IP behavior of the bare and infilled frames and for the OOP behavior of the infills at different IP damage.

3 PARAMETRIC ANALYSIS

A parametric non-linear static analysis was performed in OpenSees using the proposed model. Pushover analyses were initially carried out on the bare frame (BF) models, as reference, and then on the infilled frame (IF) models, considering both infill types previously calibrated, type Padova (PD) or thick and type Pavia (PV) or thin.

For the IP/OOP load pattern, the force distribution proportional to masses and heights was chosen, according to the Italian [16] and European codes [17], applying concentrated loads in each mass of the structural model. To consider various intensity ratios between OOP and IP forces acting on the panel, different inclination α of the seismic action were considered, specifically: 0°, 15°, 30°, 45°, 60°. In particular, the IP load pattern, applied to each beam-column node, is multiplied by $cos\alpha$, while the OOP load pattern, acting on the central nodes of the equivalent struts, is multiplied by $sin\alpha$.

The set of frames reported in Table 4, representing some of the most common Italian R.C. buildings, was analyzed in the parametric study, considering for each frame two different types of design: only for gravity loads, or traditional design (TD), and for both gravity and seismic forces, or seismic design (SD). The material characteristics and sections of these frames, with the longitudinal and transverse reinforcement, are reported in Table 5.

In particular, for SD frames a steel B450C and a concrete C30/35 were used according to

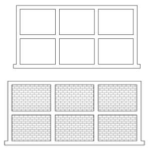
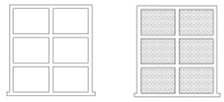
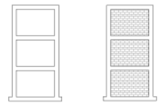
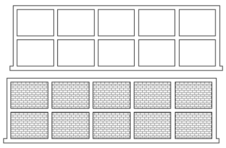
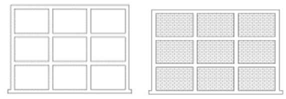
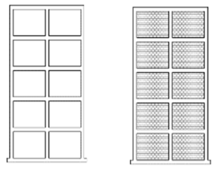
Squat	Regular	Slender
3x2	2x3	1x3
		
5x2	3x3	2x5
		
Frame for PD infill: bay length 4.55 m; storey height 2.85 m		
Frame for PV infill: bay length 4.60 m; storey height 2.95 m		

Table 4. Sample set considered in the parametric study, representative of the Italian R.C. frames.

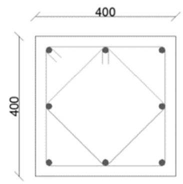
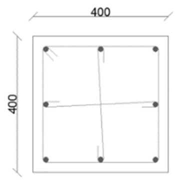
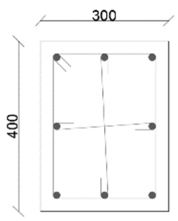
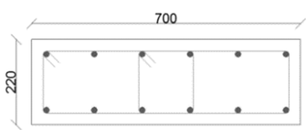
	Seismic Design (SD)	Traditional Design (TD)
Concrete	C30/35 $f_{ck} = -30\ MPa$ $E_c = 27386\ MPa$ $f_{ct} = 2.9\ MPa$ $E_{ct} = 1450\ MPa$	C20/25 $f_{ck} = -20\ MPa$ $E_c = 22361\ MPa$ $f_{ct} = 2.2\ MPa$ $E_{ct} = 1100\ MPa$
Steel	B450C $f_{yk} = 450\ MPa$ $f_{ym} = 500\ MPa$ $f_u = 620\ MPa$ $E_s = 205000\ MPa$	AQ50 $f_{yk} = 370\ MPa$ $f_{ym} = 410\ MPa$ $f_u = 550\ MPa$ $E_s = 195000\ MPa$
Column	 Long. reinforcement: 8 Φ18	 Long. reinforcement: 8 Φ16
Beam	 Long. reinforcement: 8 Φ16	 Long. reinforcement: 12 Φ16

Table 5. Materials, sections and reinforcement details of the R.C. elements of the frames analyzed.

NTC08 [16], while for TD frames a steel AQ50-60 and a concrete C20/25 were chosen following some common Italian design criteria of the 50-80s (Cristofaro *et al.* [18]).

For the evaluation of the structural damage level during the analysis, some Performance Levels (PLs) and Limit States were defined also for the R.C. frame. In particular, the PLs considered, which were verified step-by-step of the analysis, are:

• *colYM* (*column Yield bending Moment*), calculated from a paramtric moment-curvature analysis where the parameter is the vertical axial load N on the section; a function of the nominal yield curvature χ_y depending on N was derived and is reported in Figure 10;

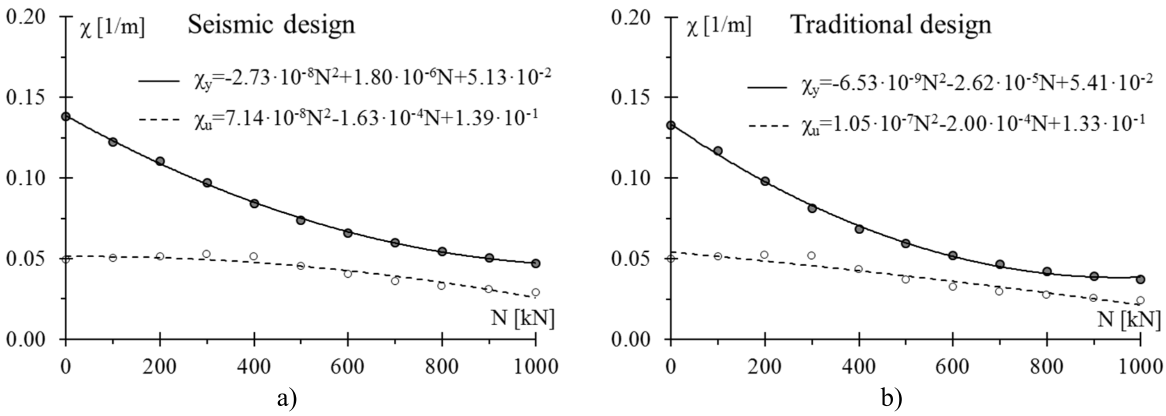


Figure 10. Nominal χ_y and ultimate χ_u curvature as function of axial load *N*, for both column sections of Table 5.

- *colUM* (*column Ultimate bending Moment*), calculated as *colYM;* a function of the ultimate curvature χ_u depending on *N* was derived and is shown in Figure 10;
- *colSF* (*column Shear Failure*), calculated according to the R.C. shear strength formulation of Sezen [19], which takes into account the section ductility;
- *colNF (column Nodal Failure*), obtained by the node rotation capacity defined in NTC08.

The Limit States (LS) of the frame (*fr*), yielding and ultimate LS, are therefore defined as:

$$\begin{gathered} frYield = colYM \\ frULS = \min\left\{colUM;\ colSF;\ colNF\right\} \end{gathered} \tag{2}$$

4 RESULTS

4.1 Pushover Curves

The pushover curves from Figure 11 to Figure 13 report the total in-plane shear force at the base versus the maximum displacement at the top of some frame configurations analysed. Each graph compares the pushover curves obtained for the bare frame (BF) and infilled frame in-plane (IP) to the ones obtained considering different directions of the load pattern, OOP15, OOP30, OOP45, OOP60 where the number is the inclination α of the seismic force. Furthermore, each curve reports the Performance Levels and Limit States reached by both frame and panel.

The principal outcomes from the pushover curves are briefly summarized below.

- The resistance of the bare frame (BF) is clearly different for the two designs, seismic (SD) or traditional (TD), resulting higher in the case of SD of about 1.2 to 1.4 times, depending on the frame type.
- For the infill type Padova, the maximum strength contribution of the panel to the infilled frame system in-plane (IP) (i.e. the maximum distance between the IP curve and the BF one) is between 1.5 and 2 times that provided by the infill type Pavia, depending on the frame type (for frame with the same number of floors, it increases with increasing number of bays).
- The infilled frames present a maximum strength much greater than that of the bare frames and, in the case of thick panel, this is about 1.8 times that of the related infilled frame with thin panel; this result is not inconsistent with the previous note, because the maximum strength of the infilled frame is reached at difference displacements for the two infill types.
- The pushover curves of the infilled frame with thick panel present a wide plastic branch, generally with strain hardening (at least for SD frames), while those relating to the thin panel present a softening branch.

- About the Performance Levels, it is possible to observe that their order of occurrence and position vary in function of infill type and design type of the frame. For example:

- in case of thick panel, its Ultimate Limit State occurs close or just after the frame yielding while, for the thin panel, all its limit states (also the collapse) anticipate the frame yielding;

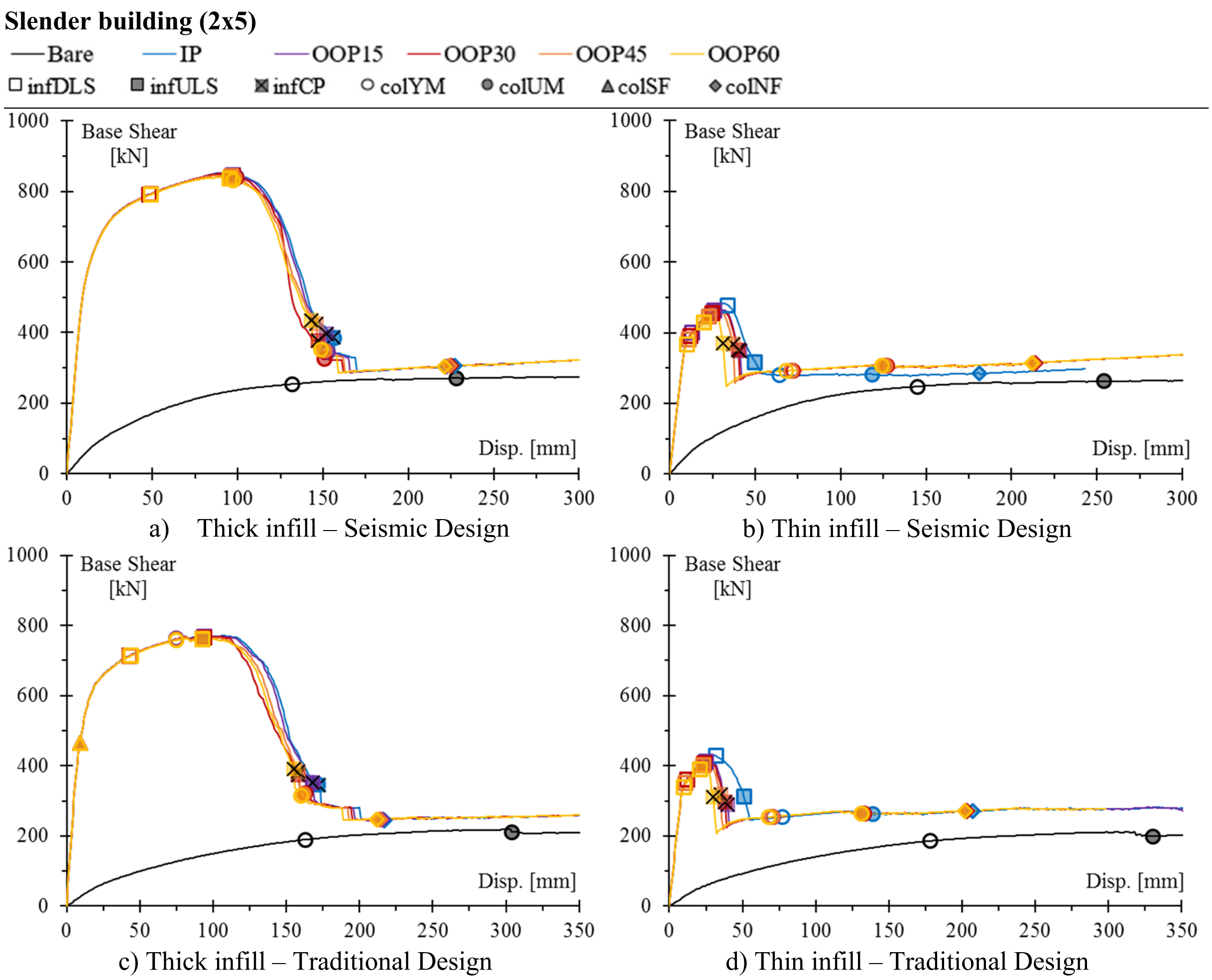
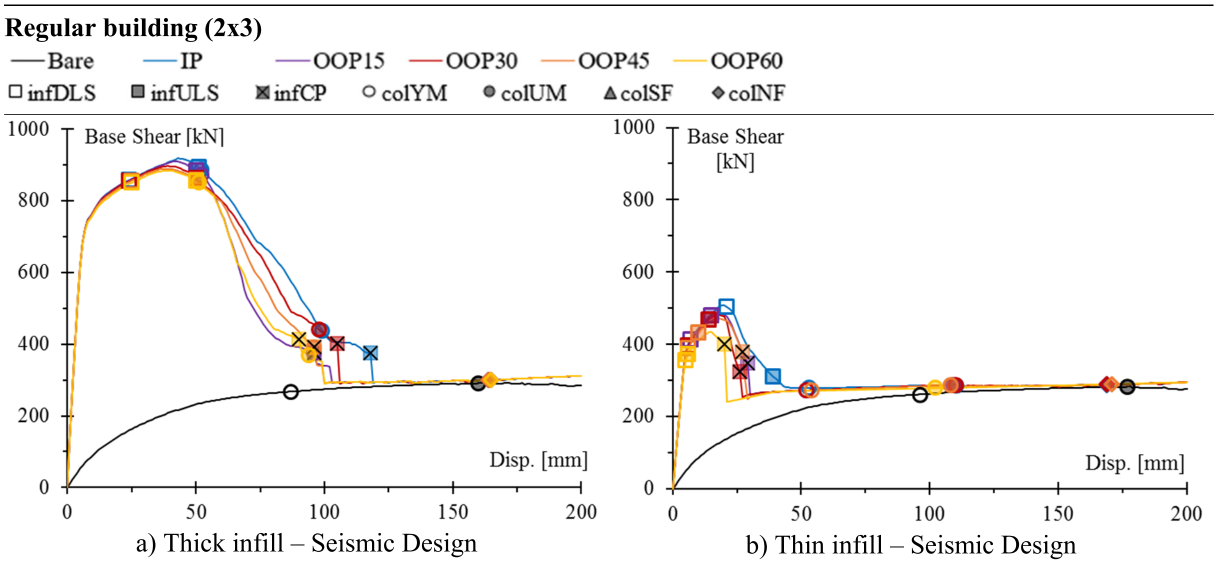
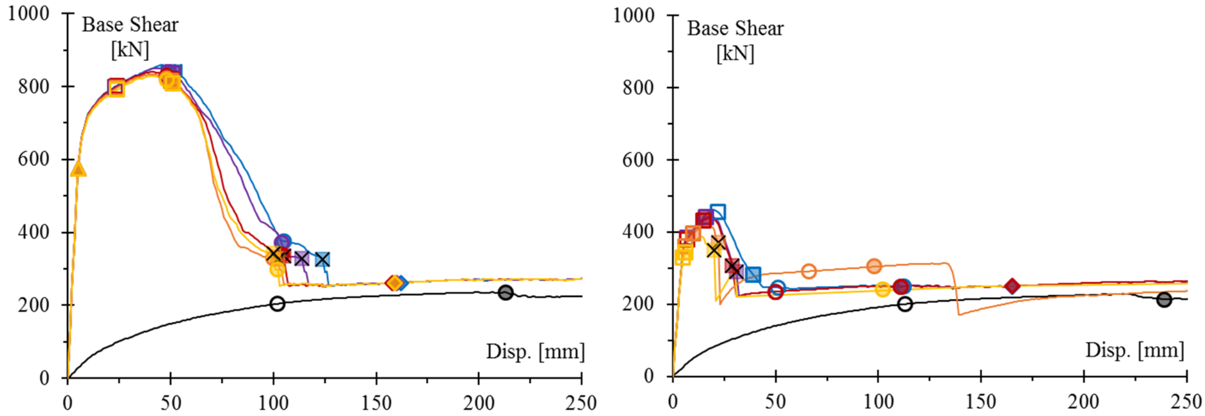


Figure 11. Pushover curves of bare (BF) and infilled frame (IP, OOP at 15°, 30°, 45°, 60°): slender frame (2x5).

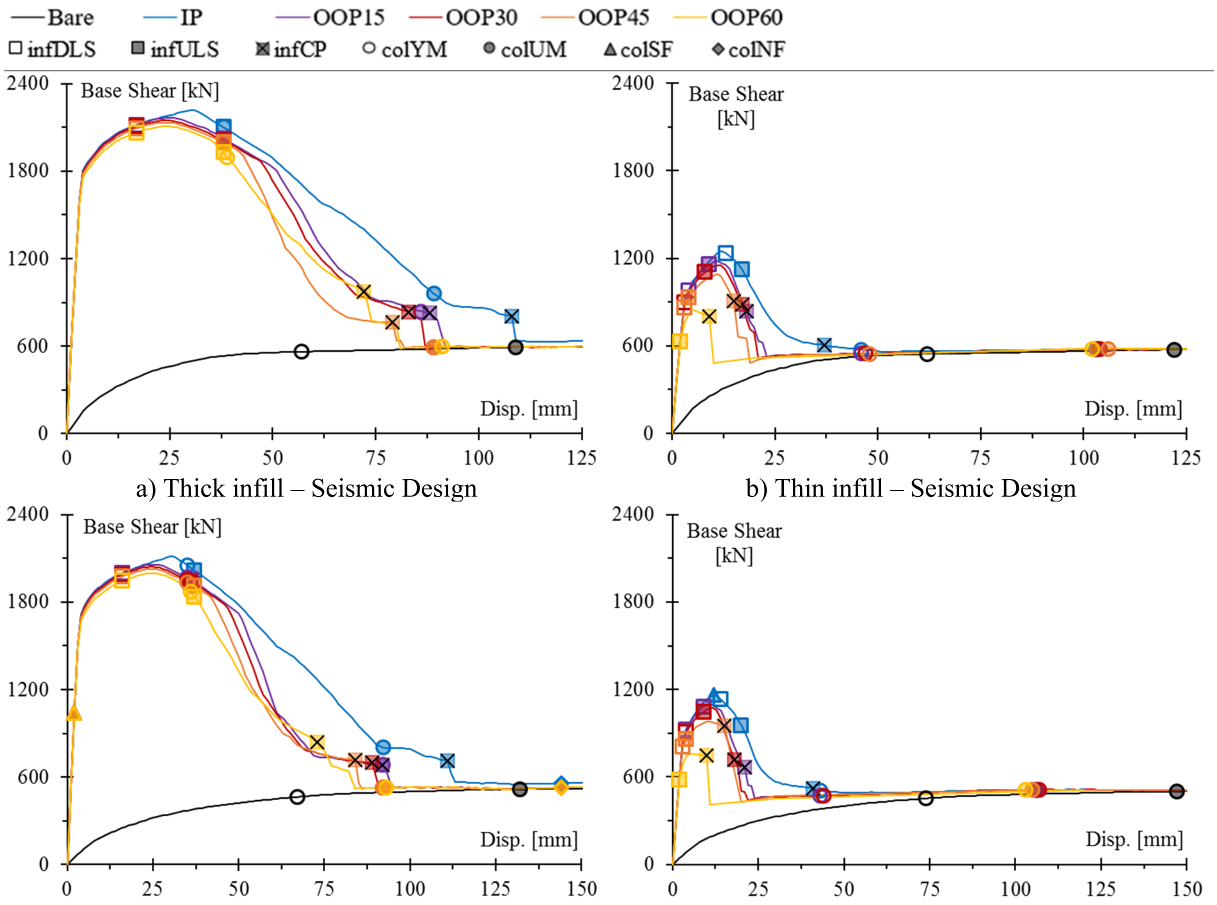




c) Thick infill – Traditional Design d) Thin infill – Traditional Design

Figure 12. Pushover curves of bare (BF) and infilled frame (IP, OOP at 15°, 30°, 45°, 60°): regular frame (2x3).

Squat building (5x2)



c) Thick infill – Traditional Design d) Thin infill – Traditional Design

Figure 13. Pushover curves of bare (BF) and infilled frame (IP, OOP at 15°, 30°, 45°, 60°): squat frame (5x2).

- the performance levels of the frame are generally anticipated in case of traditional design and thick panel, in fact, a thicker panel increases the bracing effect leading to smaller displacements but higher stresses on the frame; in these cases, furthermore, columns experience the shear failure and thus the ULS is suddenly reached in the elastic branch of the pushover curve.

- Increasing the ratio OOP/IP of the load pattern, through an increment of the inclination α of the seismic action, the collapse of the panels is generally anticipated, with a consequent reduction of the overall in-plane resistance (capacity curve) of the infilled frame. But while for the case of thick panel the OOP effects only slightly affect the width of the plastic branch of the pushover curve and the softening phase, negligibly influencing the limit states, for the case of thin panel it can be observed, increasing the OOP action, a significant reduction of the maximum resistance as well as an anticipation of the infill limit states.

4.2 Energy indexes

The graphs reported in Figure 14 show the values of the energy index E (or area under the pushover curve) for the in-plane deflection of the infilled frame, up to reach the ULS of both

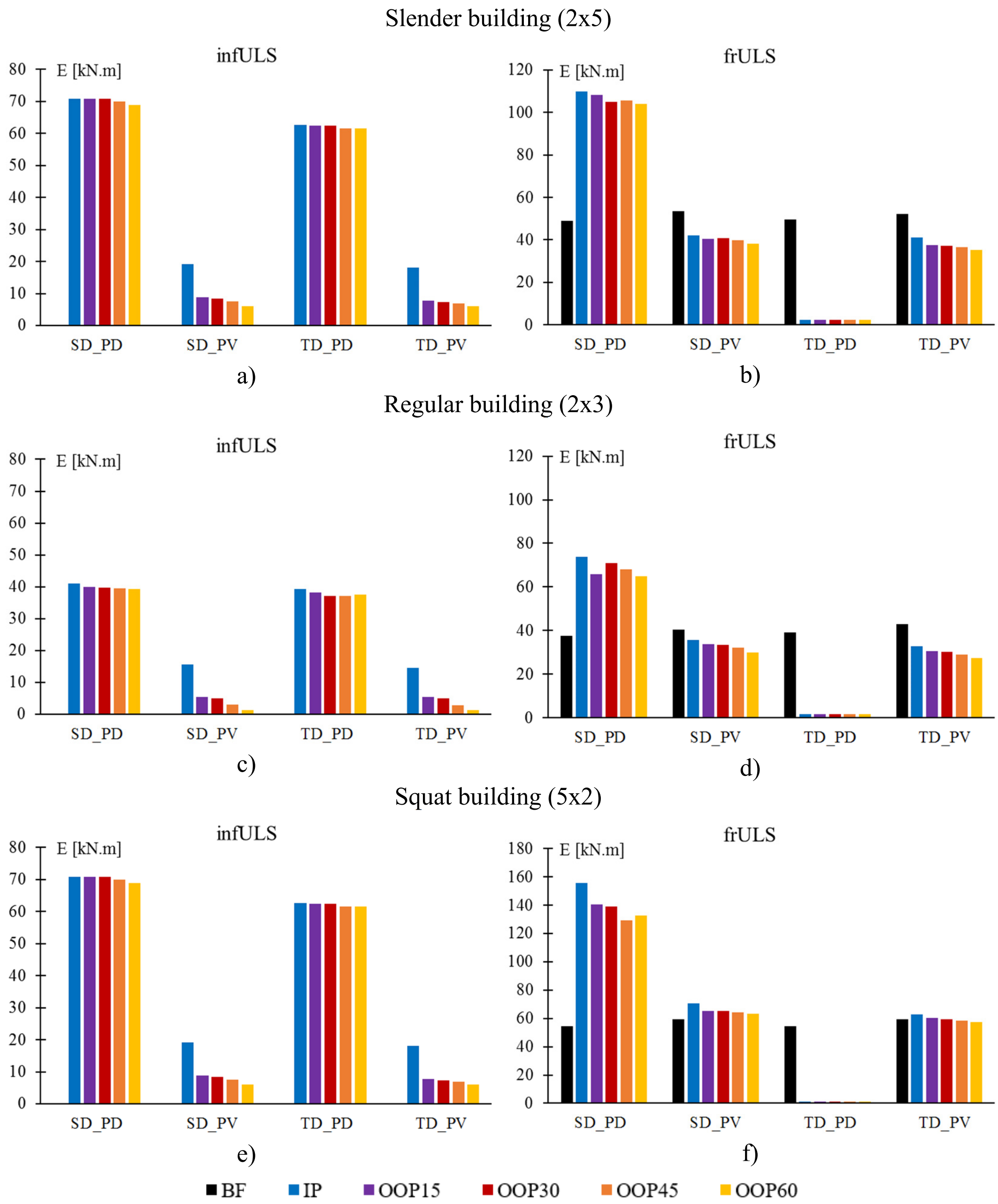


Figure 14. Energy index or area under the pushover curve, related to the ULS of the infill (a, c, e) and frame (b, d, f), for different inclinations (OOP) of the seismic action.

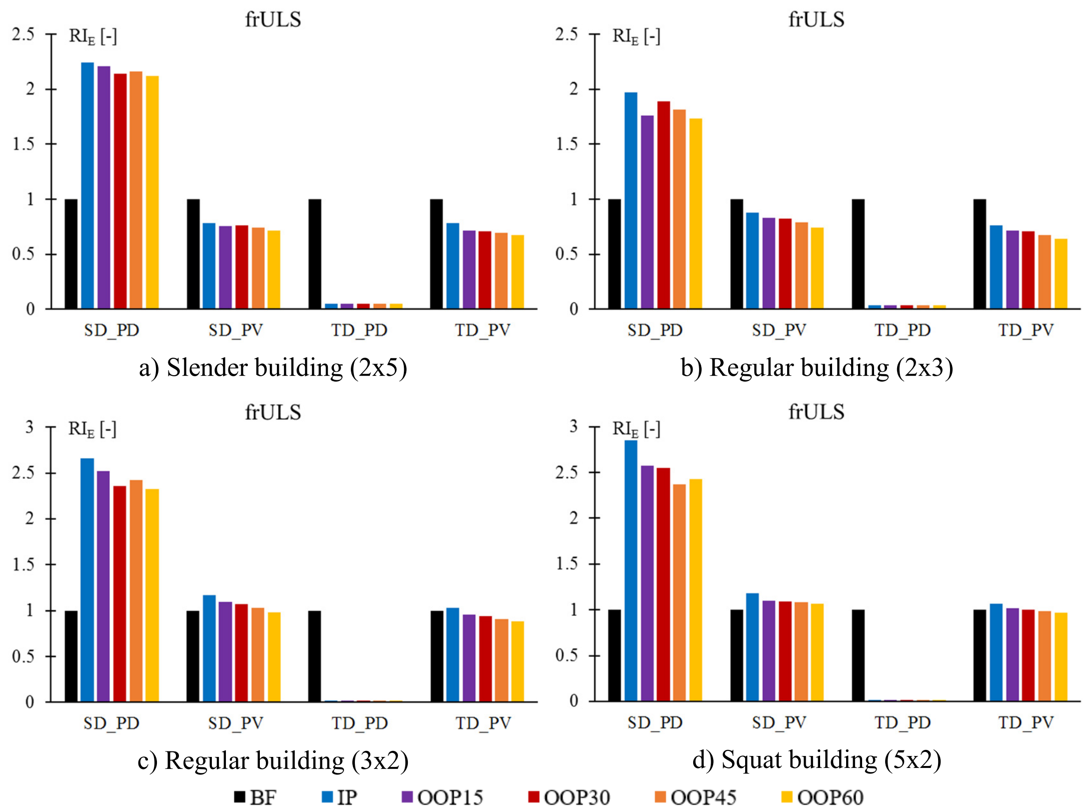


Figure 15. Energy robustness index related to the frame ULS, for different inclinations of the seismic action.

infill and frame. Figure 15, instead, shows the energy robustness index RI_E, calculated as the ratio between the energy dissipated by the infilled frame and that dissipated by the associated bare frame (BF): from this definition, it is clear that RI_E, which do not exist for the infill ULS but only for that of the frame, quantifies in terms of energy the beneficial contribution of the infill relatively to the BF.

The principal results from Figure 14 and Figure 15 are summarized hereinafter.

- The values of the energy index (E) associated to the infill ULS are strongly affected by the OOP actions only in the case of thin panel: in this case, respect to the thick panel, E is much smaller and decreases rapidly with increasing load pattern inclination.
- About the ULS of the frame, it is possible to do the following considerations:
  - the use of a thick panel greatly increases the energy dissipated by the building in case of seismic design of the frame while, in case of traditional design, because of the possibility of a brittle collapse, this index shows minimum values;
  - using a thin panel, instead, the infill effects on the energy dissipation of the building are slightly advantageous only in the case of squat frames, since in the other cases (slender and regular) the small energy contribution of this type of infill is not able to compensate the reduction of energy due to the anticipation of the ULS respect to the bare frame.
- Finally, using thin panel, the energy dissipated at the ULS by the seismically designed frame is slightly higher than that dissipated by the traditional frame.
- The energy robustness index (RI_E), which is 1 (by definition) for the bare frame, explicitly shows the beneficial or not effects of the infills in increasing the energy dissipated by the infilled frame to reach the ULS of the frame. The previous remarks about the energy index are still valid for the energy robustness index.

4.3 Inter-storey drift

Figure 16 to Figure 19 show the in-plane inter-storey drift profiles along the building height, for different case studies, at the following limit states: damage and ultimate limit states of the infill (infDLS and infULS respectively) and yielding and ultimate limit states of the frame (frYield and frULS respectively). The principal remarks are listed hereinafter.

- Regarding the case with thick panel, the inter-storey drift profiles at the infill limit states are not affected by the OOP actions, as well as the ones at the frame yielding, which generally occurs very close to the infill ULS. The profiles at the frame ULS, also, are only slightly influenced by the OOP actions, in particular at the first floor. The presence of a thick panel, regarding the frame limit states and with respect to the bare frame, tends to reduce drift values of the upper floor and to concentrate the deformation at the first level where, for the slendernest buildings, the drift value becomes higher than that of the bare frame.
- In case of thin panel, instead, the drift profiles at the infill DLS and ULS greatly depend on the inclination of the load pattern and the drift values from the IP-OOP analyses are very smaller than those obtained by the IP only analysis. At the frame limit states, instead, similar conclusions to those for the thick panel can be done for squat configuration while, for regular (2x3 TD) and slender (2x5) frame configurations it is possible to observe an interesting phenomeno: starting from a drift profile due to IP actions that concentrates the deformation at the first level, increasing the OOP effects on the infills, the soft storey moves from the first to the second floor.

Finally, for the various configuration analysed, Figure 20 reports the IP inter-storey drifts, related to the achievement of the infill limit states, versus the inclination of the seismic action. This figure clearly shows what already seen previously, namely that the OOP actions, in the

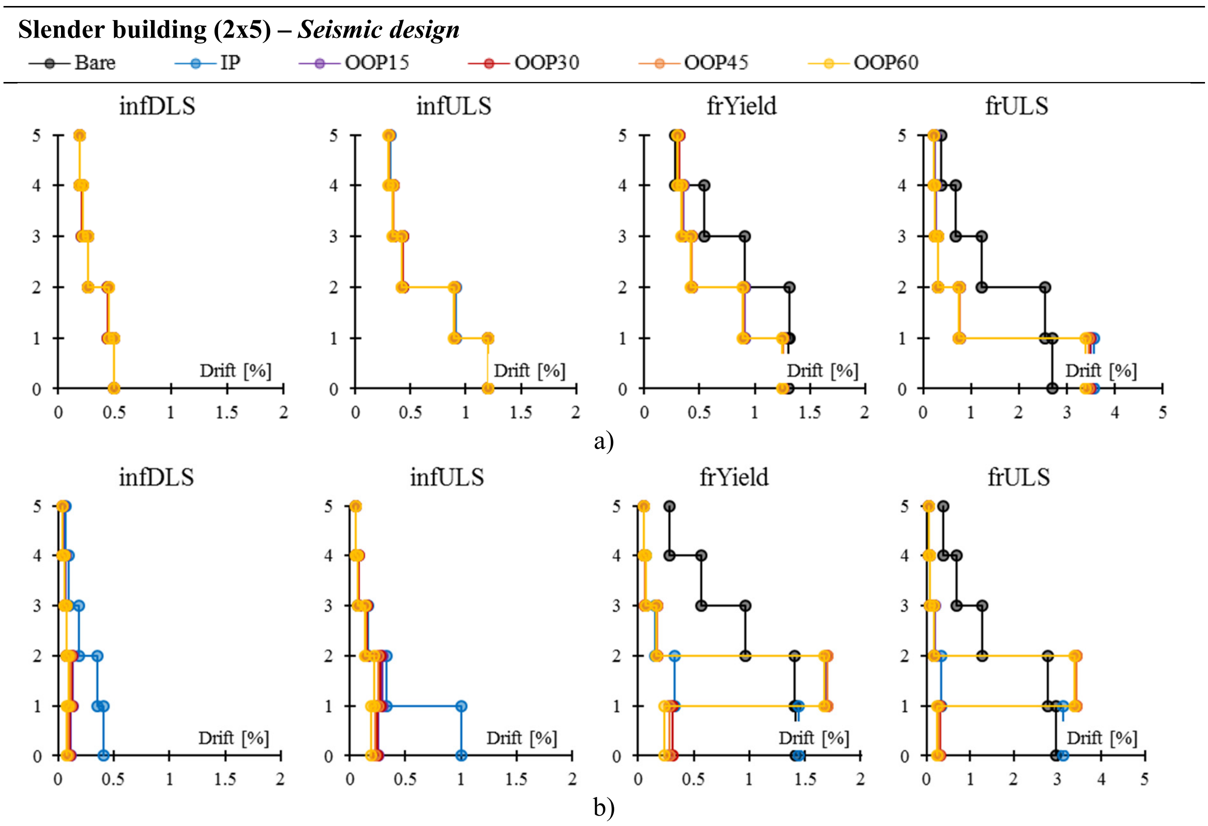


Figure 16. Inter-storey drift profiles for the SD frame (2x5), for different inclinations of the seismic action and at the various limit states of infill and frame: a) thick panel (type Padova); b) thin panel (type Pavia).

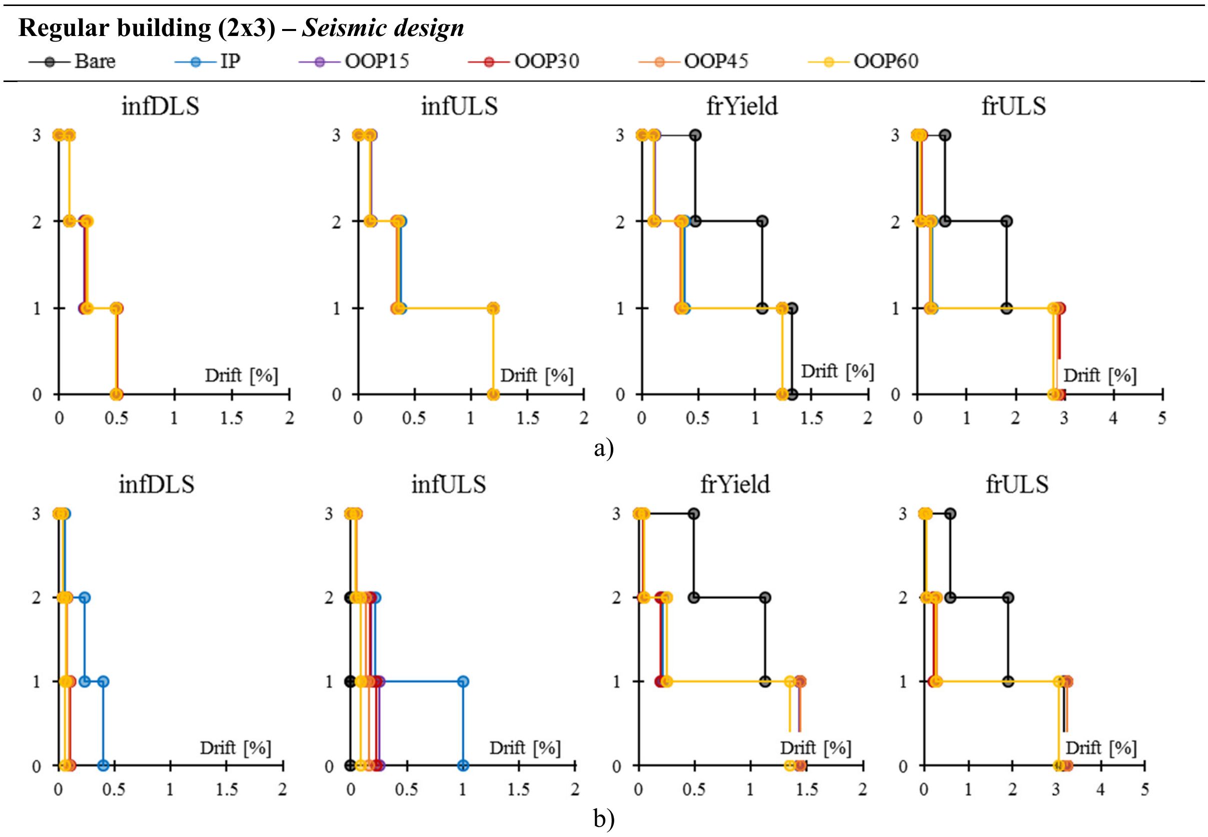


Figure 17. Inter-storey drift profiles for the SD frame (2x3), for different inclinations of the seismic action and at the various limit states of infill and frame: a) thick panel (type Padova); b) thin panel (type Pavia).

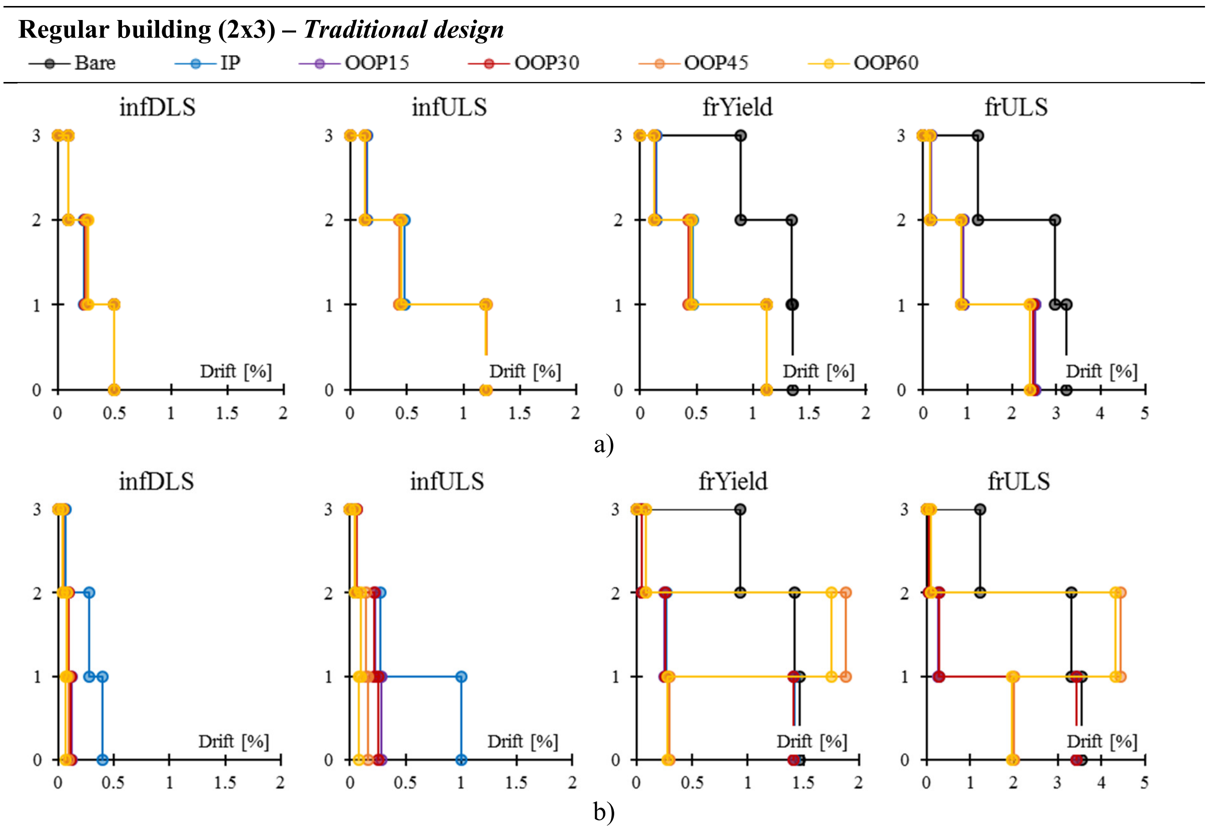


Figure 18. Inter-storey drift profiles for the TD frame (2x3), for different inclinations of the seismic action and at the various limit states of infill and frame: a) thick panel (type Padova); b) thin panel (type Pavia).

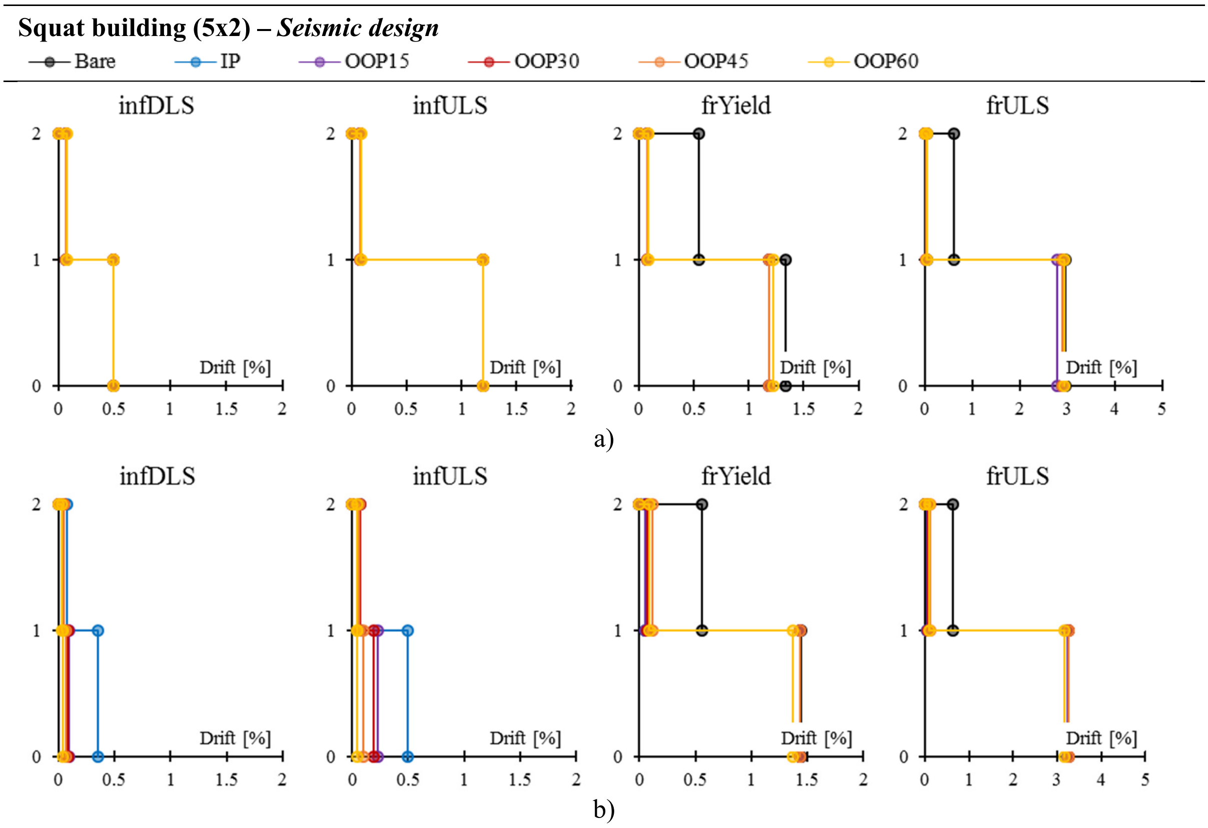


Figure 19. Inter-storey drift profiles for the SD frame (5x2), for different inclinations of the seismic action and at the various limit states of infill and frame: a) thick panel (type Padova); b) thin panel (type Pavia).

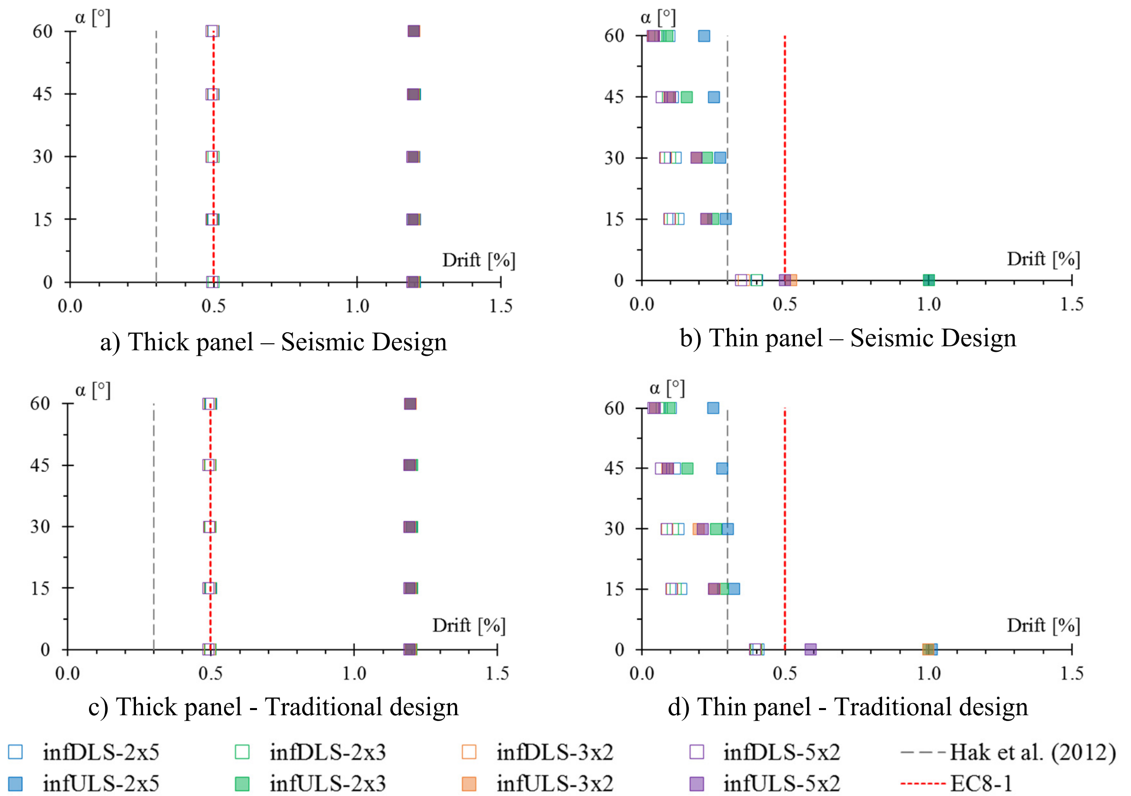


Figure 20. IP inter-storey drift values, at the infill DLS and ULS, versus the seismic action inclination (α), for the different case studies analysed; indication of the EC8 drift limit and of a suggested value by Hak et al.[20].

case of thin panel, strongly affect the value of the IP inter-story drift at which the DLS or ULS of the panel is reached, while are unimportant for the case of thick panel. For this reason, the EC8 [17] drift limit of 0.5% (in case of non-structural components not specifically designed to withstand seismic forces) can be considered appropriate only if a thick panel (type Padova) is used; the same limit was already shown to be not conservative in case of thin masonry panel, type Pavia, by Hak et al.[20], who suggested a more conservative limit of 0.3%. However, considering the IP/OOP interaction effects, also this drift value becomes not appropriate at all for the thin panels, which can reach the DLS at drift values (measured in plane) also much smaller. Finally, a similar dependence of the trend of the drift values on the inclination of the seismic force can be observed for both DLS and ULS of the same infill type.

5 CONCLUSIONS

- The paper presented a new FE macromodel to simulate the interaction between the in-plane (IP) and out-of-plane (OOP) behaviour of masonry infills in R.C. frames. The model was calibrated for two different types of masonry infill, thick and thin, through test results obtained from previous experimental campaigns on real scale infilled frame.
- The model was implemented in a parametric pushover analysis in OpenSees, with the aim to assess the influence of the directionality of the seismic action on the lateral response of different R.C. infilled frames. In particular, six frame configurations (squat, regular and slender) and, for each of these, two types of design (for gravitational loads only and for seismic actions) were considered in the analysis, studing the cases of bare frame, infilled frame with thick panel and infilled frame with thin panel.
- The main influences of the OOP forces on the infilled frame seismic behaviour are presented through pushover curves (with the indication of the principal performance levels and limit states) and energy indexes, drift profiles and drift values related to the achivement of the various limit states (for both infill and frame).
- Some of the principal conclusions from this numerical study are:
  - IP/OOP interaction of the infill considerably affects the structural response of the infilled frame in case of thin panel (type Pavia), reducing the global resistance and anticipating the infill limit states;
  - the peak resistance, higher in case of thick panel and seismic design of the frame, reduces increasing the inclination of the seismic action;
  - infilled frames with thick panels present pushover curves with a wide plastic branch, generally with strain hardening, while those related to infilled frames with thin infills show a softening branch (so the firsts present a more ductile behaviour);
  - the infill ULS is achieved close to the frame yielding in case of thick panel; for the thin panel, instead, all the limit states (including the collapse) are reached before;
  - considering the regular frame configurations analysed in this study, if the in-plane seismic action generally leads the soft storey to be localized at the first level of the infilled frame, for both infill panels, the out-of-plane effects, in case of thin panel, move this soft storey to the second floor;
  - thin panels are greatly influenced by the OOP forces: the inter-storey drifts of the infilled frame, registered in-plane, required to reach the infill limit states, strongly decrease with increasing inclination of the seismic action; for this reason, the current drift limit proposed by EC8, i.e. 0.5% (in case of non-structural components not specifically designed to withstand seismic forces), can be considered appropriate only if the panel is thick (type Padova), which is negligibly influenced by the IP/OOP interaction effects.

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