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MACRO-MODELLING OF COMBINED IN-PLANE AND OUT-OF-PLANE SEISMIC RESPONSE OF THIN STRENGTHENED MASONRY INFILLS

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Abstract

Some strengthening techniques, aimed to increase the infill Out-Of-Plane (OOP) resistance and its safety against OOP collapse, have been recently tested at the University of Padova. Based on this experimental work, a new infill macro-model consisting of two nonlinear fibre struts for each diagonal direction, able to predict the combined In-Plane/Out-Of-Plane (IP-OOP) seismic response of the panels, is proposed in this paper and calibrated on the above-mentioned experimental results for thin clay masonry panels strengthened by two external plaster layers, directly applied on the masonry surface, containing a biaxial basalt fibre grid. These macro-models were then used to carry-out parametric nonlinear static analyses on typical reinforced concrete infilled frames, designed both traditionally and seismically, with the aim of evaluating their lateral response both in the case of IP forces only (by assuming two force distributions applied to the frame) and in the case of IP-OOP combined forces (by applying OOP equivalent static forces to the panels). The main effects of the OOP forces are presented through pushover curves and drift profiles associated to the achievement of the various infill and frame limit states. Numerical results show the effectiveness of the infill strengthening in terms of improvement of the infills OOP performance and thus of the overall structural response.

Keywords: infilled RC frames; In-Plane and Out-Of-Plane interaction; masonry infill; strengthened masonry; macro-modelling; non-linear analysis.

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1 INTRODUCTION

Thin unreinforced masonry (TURM) infill, generally used as internal partition walls and classified as non-structural elements, are often neglected in the current design procedures. TURM 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. [1], 2004. These panels have a great influence on the seismic response of structures in terms of stiffness and strength, despite being their thickness low in the region of 10÷15 cm (Dolšek and Fajfar [2], 2008). Due to the brittle nature of masonry and to the limited thickness, a possible combined In-Plane/Out-Of-Plane (IP/OOP) seismic action can bring to a quickly collapse of the panel increasing the risk for human safety. As consequence, a first-storey mechanism can occur also in that buildings with a regular distribution of masonry infills (Dolšek and Fajfar [3], 2001). The recent seismic events have highlighted the high seismic vulnerability of weak traditional unreinforced masonry, above all related to the lack of a suitable and effective design procedure (Hak et al. [4], 2012). Braga et al. [5], (2011) studied the common damages on masonry infills to identify the causes of failure and linking them to the common construction rules.

Considering the intrinsic vulnerability of weak masonry infills, different strengthening techniques can be adopted to improve the seismic performances in terms, especially, of Out-Of-Plane resistance. This issue triggered great interest in the scientific world in the last decades. The first experimental campaigns focused on the application of external reinforcing layers applied directly on masonry infills: Fibber-Reinforced Plastic (FRP) layers (Tumialan et al. [6], 2003, Saatcioglu et al. [7], 2005) and strengthening meshes, embedded in one or more layers of plaster, were experimentally studied to increase the OOP capacity. In particular, the use of Textile Reinforced Mortars (TRM) on non-load bearing masonry panels has been studied by Calvi et al. [8], 2001, Papanico-lau et al. [9],2007, Valluzzi et al. [10], 2014, Minotto et al. [11], 2019. Furthermore, European standard EN 1998-1-1 [12] recommends adequate interventions on infill panels (slenderness > 15), proposing the use of light wire meshes.

The macro-modelling of masonry walls is a modelling strategy useful to investigate the overall response of the infill wall and the global behaviour of structure. In recent years, numerous studies concerning macro-modelling of infilled Reinforced Concrete (RC) frame structures have been proposed (Asteris et al. [13], 2011, Jeselia et al. [14], 2013 and Tarque et al. [15], 2015) studying different macro-models (single diagonal strut and more complex multi-strut models). The researchers have addressed their attention to the development of IP equivalent strut macro-models for the simultaneous prediction of the IP/OOP interaction effects on infill panels (Shing et al. [16], 2016, Ricci et al. [17], 2017). Mosalam & Gunay [18], (2015) proposed a macro-model (MG-model) based on a single diagonal element which consists of two elastic beams with a plastic hinge in the contact point, where an inelastic fibre section with fibres spaced in the OOP direction is defined. In this way, the fibres withstand to axial force as well as to bending moment, allowing to take into account the IP/OOP interaction. In this contest, a large numerical models state of art review is presented in Asteris et al. [19], (2017).

The aim of this work is to develop a new macro-model (derived from MG-model) for strengthened thin masonry infills based on two nonlinear fibre struts for each diagonal direction able to consider simultaneously the IP and OOP behaviour. The numerical model is calibrated on the experimental results obtained by combined IP/OOP tests (Minotto et al. [11], 2019) on strengthened masonry walls. In detail, three different types of strengthened thin clay masonry panel were numerically studied; the first strengthening type is characterized by the application of a bi-directional basalt mesh embedded in a special geo-polymeric plaster. The other two strengthening solutions consist of applying a fibre-reinforced lime-based plaster, and one of them is also provided with an additional bi-directional basalt mesh. Subsequent parametric nonlinear static analyses are performed on typical traditionally and seismically designed RC frame buildings with two In-Plane force distributions and simultaneous static forces acting on the panels in the OOP direction, defined according to the current Italian Standard [20] and [21].

2 MACRO-MODELLING OF REINFORCED MASONRY INFILLS

2.1 Description of the F.E. macro-model

The combined IP/OOP behaviour of thin reinforced masonry infills (TRM) was modelled through the macro-model (implemented in OpenSees) shown in Figure 1 and was derived from that proposed by Mosalam et al. [18], 2015. The macro-model was characterized by two equivalent struts for each diagonal direction in order to better evaluate the stress distribution on RC member (Crisafulli [22], 1997). The diagonal equivalent struts are connected to the RC frame (hinge connection) defining a contact length appropriately calculated according to Stafford Smith [23], 1966.

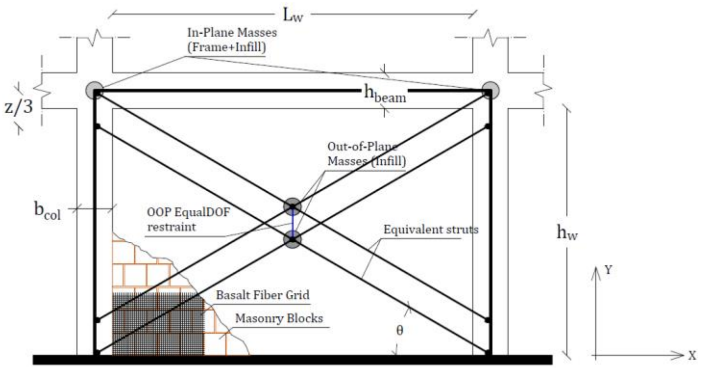
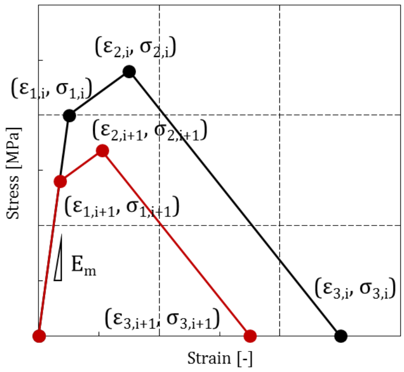


Figure 1. Macro-model proposed by the authors for thin reinforced masonry infills.

Each diagonal equivalent strut has a central fibre section composed of 120 fibres symmetrically placed Out-Of-Plane with respect to the strut axis. The fibres are defined through their area A_i, location z_i related to the central axes, yielding stress f_{yi} and yielding deformation ε_{yi}. Unlike the MG-model, the geometric position of the fibers and the yielding condition is given by an IP/OOP (Axial Force/Bending Moment) diagram based on the following domain:

$$\left(\frac{P_N}{P_{NO}}\right)^{3/2}+\left(\frac{M_N}{M_{NO}}\right)^{3/2}\leq 1 \tag{1}$$

where P_{N0} and M_{N0} are respectively the In-Plane and Out-Of-Plane capacities derived from experimental tests results. The calculation of the “yielding point” (maximum strength) of all fibres was done in accord to MG-model, considering the same masonry Young’s modulus. In order to represent the masonry strength and stiffness degradations, the “Hysteretic material” (*OpenSees* material library) was implemented to simulates the infill experimental behaviour. In particular, to take into account the contribution of the external reinforcement and calibrate the macro-model on OOP test results, the more external fibres present different material properties (but the same type of constitutive law) respect to the internal ones which represent the contribution of the masonry. This was necessary to increase the controllability of the model for the following calibrations. According to the negligible tensile behaviour of masonry, the constitutive laws of internal fibres are represented only by a compression envelope branch.



$$\sigma_{1,i} = -\sigma_{y,i}$$
$$\varepsilon_{1,i} = -\sigma_{y,i} / E_m$$
$$\varepsilon_{2,i} = \alpha\varepsilon_1$$
$$\Delta_{1,i} = \beta E_m$$
$$\sigma_{2,i} = \sigma_{1,i} + (\varepsilon_{2,i} - \varepsilon_{1,i})\Delta_{1,i}$$
$$\sigma_{3,i} = 0$$
$$\varepsilon_{3,i} = \gamma\varepsilon_{2,i}$$

Figure 2. Hysteretic constitutive laws of external and internal fibers.

According to the MG-model, a removal domain is necessary to describe the real Out-Of-Plane collapse of the infill wall at the Collapse Limit State (CLS). This corresponds to a sudden reduction of the infilled-frame IP resistance (residual IP strength of the panel). The constitutive laws of masonry fibers simulate the stiffness and strength degradation up to zero, thus the IP removal condition is not used. To assess the damage level reached by the masonry panels during the numerical analyses (for combined IP/OOP action), similar displacement domains were experimentally calibrated for Damage and Ultimate Limit States (DLS and ULS), also shown in Figure 4. Each IP-drift/OOP-displacement domain, is obtained by combined tests results interpolating the OOP displacements to achieve the specific LS, which are function of the in-plane damage (Figure 3), and limiting it to the maximum IP drift θ_{IP} of that Limit State LS (see Table 1).

The IP inertial masses include both the frame masses and the infill ones, and they are represented as lumped masses at each beam-column joint. 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 OOP direction, the two central nodes of the struts are rigidly connected.

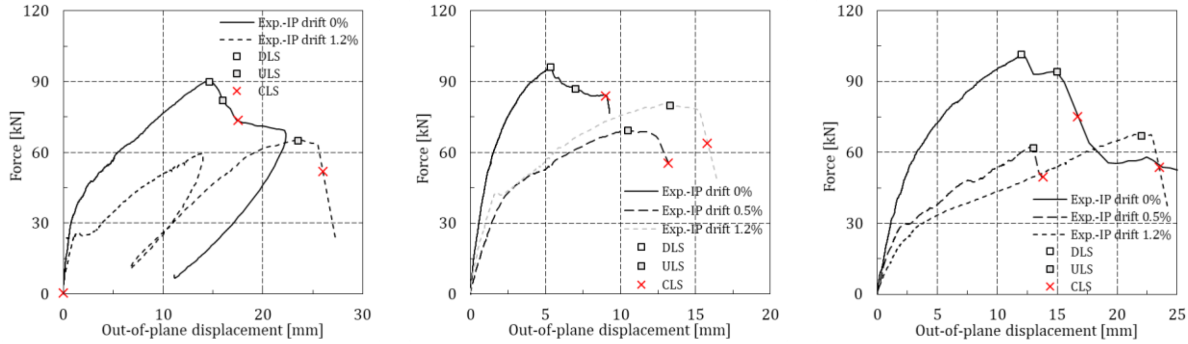
Furthermore, a more detailed RC frame model was developed to consider the effects of the different stirrups spacing between critical and not critical regions along beams and columns. All RC members were modelled using force-based beam-column elements with non-linear fiber sections. The concrete behaviour was modelled through the Kent-Scott-Park [24] constitutive law (Concrete02, linear tension softening) and the effects of the confinement given by reinforcing steel was taken into account thanks to the Mander's model [25]. Reinforcing steel bars were modelled with an elasto-plastic constitutive law with strain hardening (Steel02, Menegotto & Pinto [26]). Concrete and steel material laws were calibrated on the experimental test results conducted on bare frame (BF). The 2D RC frame model presents OOP elastic springs with OOP stiffness placed on the frame joints to confer a realistic OOP stiffness. 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.

2.2 Calibration on experimental results (IP/OOP tests)

A large experimental campaign was carried out at the Laboratory of the University of Padova concerning combined IP/OOP tests conducted full-scale, one-bay and one-story, RC frame specimen fully infilled by thin masonry walls made of clay units variously externally strengthened. The experimental campaign involves a total number of 8 specimens that were reinforced with three different strengthening solutions identified as F, FB and RBB. Specimen characteristics and tests results of the three tested strengthening solutions are available in Minotto et al. [11], 2019. The RC frame clear span and height were 4.15 m and 2.65 m respectively and the infill wall dimensions coincide with those values. All specimens were designed following the criteria described in da Porto et al. [27], 2013. A progressive stiffness and strength degradation is observed in the Out-Of-Plane direction increasing the IP damage (Figure 3) and the following Limit States can be identified on the capacity curves.

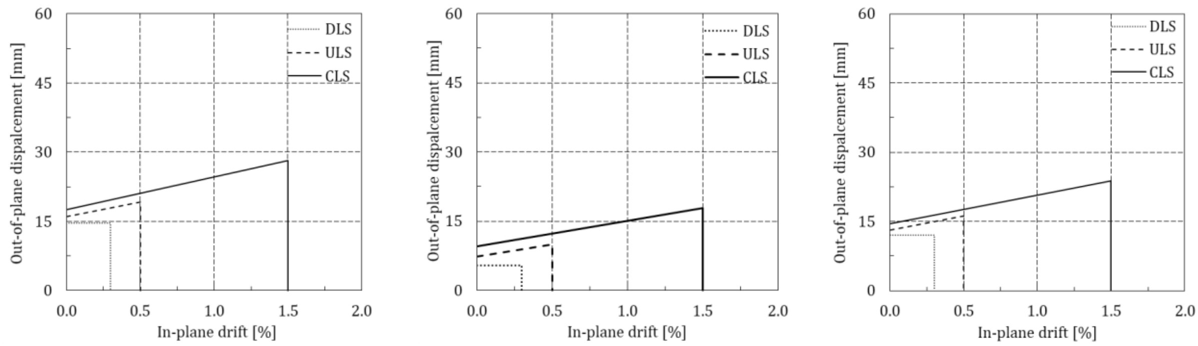
- a *Damage Limit State* (DLS) corresponding to the peak strength on the IP undamaged curve;
- an *Ultimate Limit State* (ULS), corresponding to the peak strength on the IP damaged curve;
- a *Collapse Limit State* (CLS), which identifies the moment (determined also by test observations) of sudden strength degradation, which anticipates the out-of-plane collapse of the panel.

The IP Limit States were derived by the experimental capacity curve of the only infill obtained by IP cyclic tests of infilled specimens less the contribution of the BF configuration. These values are reported in the following Table 1. Finally, Figure 4 shows the IP-drift/OOP-displacement domains used in the following parametrical analysis to identify the infill limit states (DLS, ULS and CLS). The results of the model calibration are reported from Figure 5 to Figure 7.



a) b) c)

Figure 3. Identification of the infill experimental OOP Limit States: a) reinforced panel type F, b) reinforced panel type FB, c) reinforced panel type RBB.

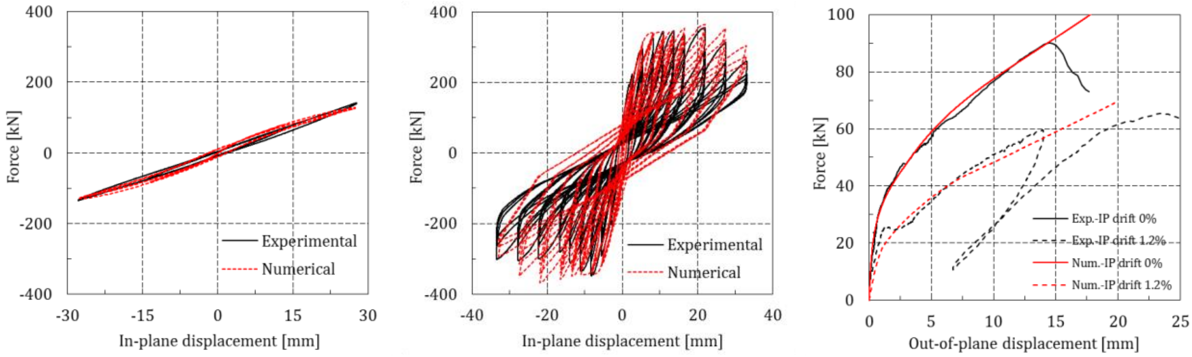


a) b) c)

Figure 4. IP-drift/OOP-displacement domains for all limit states: a) reinforced panel type F, b) reinforced panel type FB, c) reinforced panel type RBB.

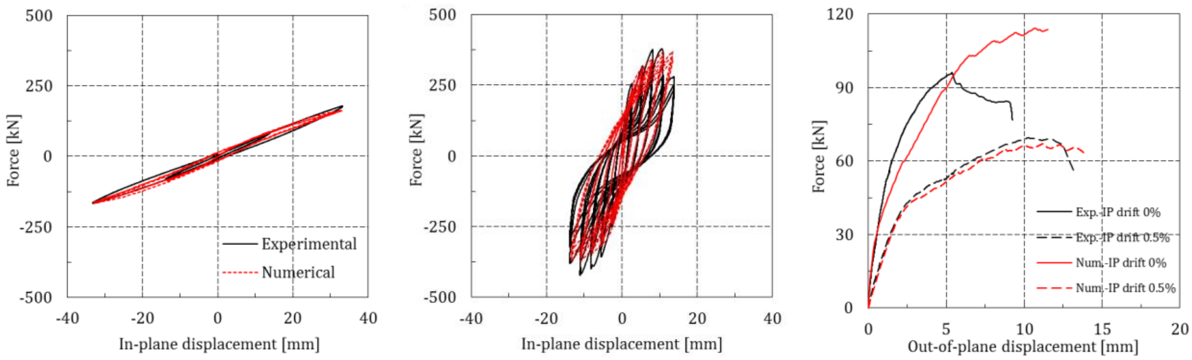
Limit State	F	FB	RBB
DLS	0.30%	0.30%	0.25%
ULS	0.50%	0.50%	0.50%
CLS	1.50%	1.50%	1.50%

Table 1: In-Plane limit drifts θ_{IP} at DLS, ULS and CLS.



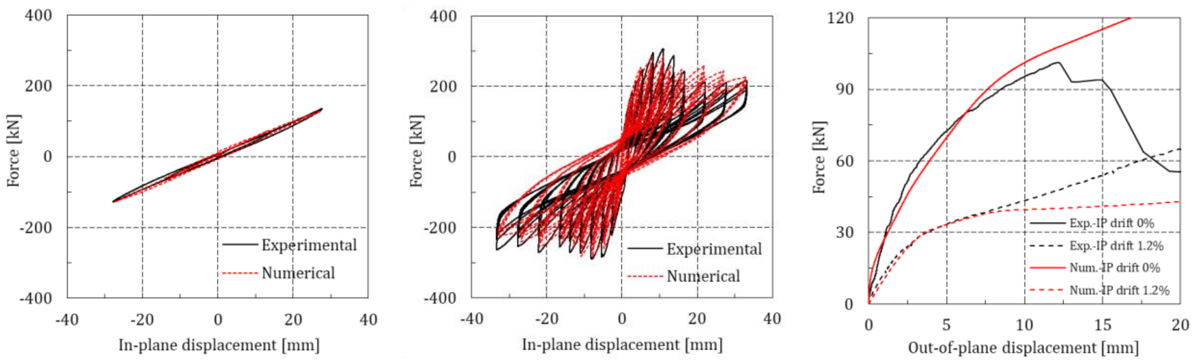
a) b) c)

Figure 5. Numerical calibration of specimen with panel type F: hysteresis loops of the BF, b) hysteresis loops of the infilled frame up to 1.2% IP drift, c) OOP capacity curve without and with IP damage.



a) b) c)

Figure 6. Numerical calibration of specimen with panel type FB: hysteresis loops of the BF, b) hysteresis loops of the infilled frame up to 1.2% IP drift, c) OOP capacity curve without and with IP damage.



a) b) c)

Figure 7. Numerical calibration of specimen with panel type RBB: hysteresis loops of the BF, b) hysteresis loops of the infilled frame up to 1.2% IP drift, c) OOP capacity curve without and with IP damage.

3 PARAMETRIC NON-LINEAR ANALYSIS

After the calibration of the proposed model for all strengthening solutions, a widespread parametric non-linear static analysis was performed in *OpenSees* in order to investigate the seismic response of RC infilled frames considering the combined IP/OOP response of infills. At this scope, several frame configurations (squat, regular and slender) were specifically designed. These frame configurations are named as “n x m” (n=number of bays, m=number of storeys). The following configurations have been studied: 4x2, 2x3, 1x3, 2x6. The bay length and the storey height are calculated considering the same geometry of the testes infills and considering the geometry of column and beam sections derived from the design procedure. The set of frames, representing some of the most common Italian R.C. buildings, was thought with 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 3. For SD frames a steel B450C and a concrete C30/37 were used according to Italian Code NTC18 [20]; 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. [28], 2011). The design of the RC frame was performed considering the variability of the column section every three columns.

Pushover analyses were initially carried out on the BF models, as reference, and then on the infilled frame (IF) configurations, considering both infill types previously calibrated. For the IP load pattern, two distributions of inertial forces were used (Gr1_a and Gr2_a) according to the Italian Standard NTC18 [20]. Distribution Gr1_a corresponds to a force distribution proportional to masses and heights while distribution Gr2_a corresponds to a uniform distribution of accelerations along the height of the building. In the OOP direction, all infills are characterized by the presence of a pattern of forces applied on the central nodes of the same. This distribution of forces is determined in accordance with the formulation of the seismic demand on non-structural elements (NTC18 [20] and [21]). In order to apply the formulation of the spectral acceleration S_a proposed in [21], a reduction of the masonry OOP infill period T_a was considered as function of the IP damage reached by the structure at each floor and at each analysis step. Three different values of PGA were chosen for the definition of the OOP pattern: 0,30g (SZ1), 0.20g (SZ2) and 0.10g (SZ3). Furthermore, the analysis with OOP distribution were conducted considering two different intensities of forces equal to 100% (IP+100%OOP) and 30% (IP+30%OOP) of the maximum PGA value.

During numerical analysis, step by step, the evaluation of the structural damage level was possible thanks to the definition of some Performance Levels (PLs) and Limit States defined also for the RC frame. In particular, the PLs considered are:

- *beamYM* (*beam Yield bending Moment*), calculated from a parametric 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;
- *beamUM* (*beam Ultimate bending Moment*), calculated as *beamYM;* a function of the ultimate curvature χ_u depending on *N* was derived;
- *colYM* (*column Yield bending Moment*), calculated as for beams;
- *colUM* (*column Ultimate bending Moment*), calculated as for beams;
- *colSF* (*column Shear Failure*), calculated according to the R.C. shear strength formulation of Sezen [29],2002, which takes into account the section ductility;
- *colNF (column Nodal Failure*), obtained by the node rotation capacity defined in NTC08 [21].

The Limit States of the frame (*fr*), Yielding and Ultimate, are therefore defined as:

$$\begin{aligned} frDLS &= \min\left\{colYM;\ \ ISDR = 0.5\%\right\} \\ frULS &= \min\left\{beamUM; colUM;\ \ colSF;\ \ colNF; ISDR = 2.0\%\right\} \end{aligned} \tag{2}$$

3.1 Capacity curves

The pushover curves (Figure 8-10) show the base total In-Plane shear force versus the maximum displacement reached at the top of some frame configurations analysed. Each graph plots the pushover curves of bare frame (BF) and infilled frame considering different load patterns: IP, IP+30%OOP and IP+100%OOP, where the number is the percentage of the reference PGA described before. Furthermore, each curve reports the Performance Levels and Limit States reached by both frame and masonry infills. The principal outcomes from the pushover curves are briefly summarized below.

1. The type of frame design, seismic (SD) or traditional (TD), significantly influences both its ultimate strength and the position of Performance Levels. In the case of traditional design, the yield of the RC vertical resistant elements occurs very quickly and for lower strength values, depending on the configuration, from 2.5 to 5 times compared to the same seismically designed configurations. In case of SD frames, the strength corresponding to the frame Ultimate Limit State (*frULS*) is 2-2.5 times higher than in the traditional case. In conclusion, the yield and the last displacement of the bare frame are anticipated in the case of traditional design, whose pushover curve has a more sudden passage from the elastic to the plastic branch with respect to the seismic case.
2. 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 not very affected by the number of bays, but becomes greater as the number of bays increase (squat configurations);
   - is greater in the case of a seismic frames (SD) than in the traditional ones (TD), with the same panel, with a ratio between ~ 1.0 and 1.2. This last observation is justified by the fact that the SD frame guarantees a better distribution of the seismic action between the various floors of the building, taking into account the resistance of the upper floor panels. In relation to this behaviour, it is possible to observe on the capacity curves of the buffered frames a "residual" contribution of resistance of the panels for high displacements, compared to the naked frame, which is greater for the slenderer (globally more deformable) frame configurations.
3. The extension of the pushover branch given by the resistance contribution of the panels (excluding the subsequent "residual" contribution to large displacements) is greater in the case of distribution Gr1_a type, while it is reduced with distribution Gr2_a due to the greater concentration of IP forces at the ground floor level which leads to a more rapidly collapse of the infill.
4. Concerning the Performance Levels of the RC frame, the presence of the infill anticipates both *colYM* columns and the frame Ultimate Limit State (*frULS*). Traditional frames show the columns brittle failure, therefore the SLU of the frame is reached for limited displacements on the elastic branch of the capacity curve.
5. The OOP actions acting on infill walls with an external reinforcement solution does not induce any effect in terms of anticipated collapse and, therefore, no reduction in the maximum resistance. The FB type infill shows an anomalous behavior different from what has just been described with a reduction in the capacity curve linked to the OOP action (although much more contained than in the case of an unreinforced panel). As already observed, in fact, the FB-type reinforcement solution is characterized by a high experimental stiffness with peak strength values comparable with the other strengthening solution (see Figure 3), with a subsequent anticipation of the collapse due to the IP/OOP interaction. Finally, the OOP action does not produce relevant effects of variation in the position of the

Limit States of the panels along the capacity curves except for FB-type reinforcement solution for the reasons explained above.

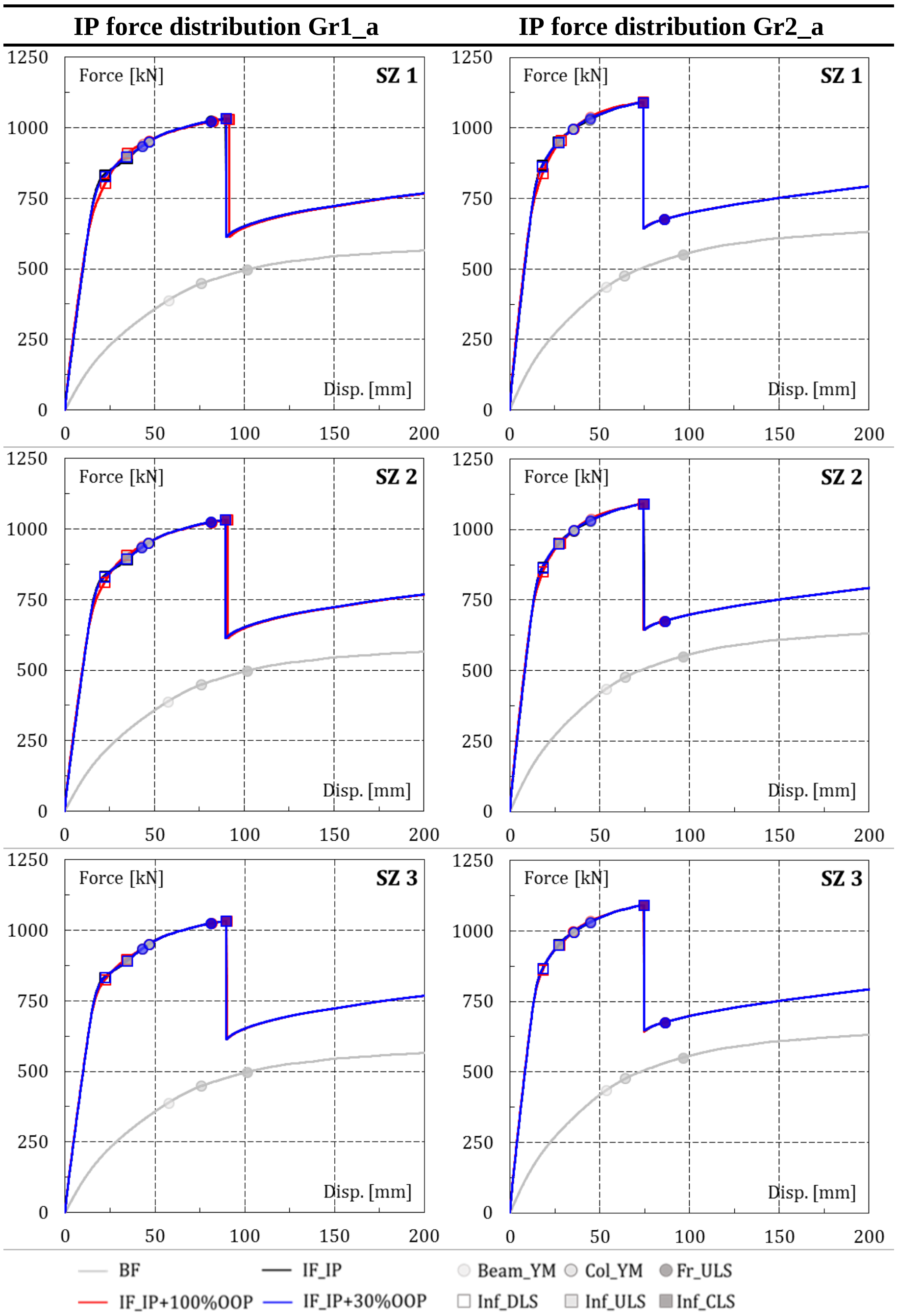


Figure 8. Capacity curve of 2x3 configuration, seismic design (SD) and infill type F.

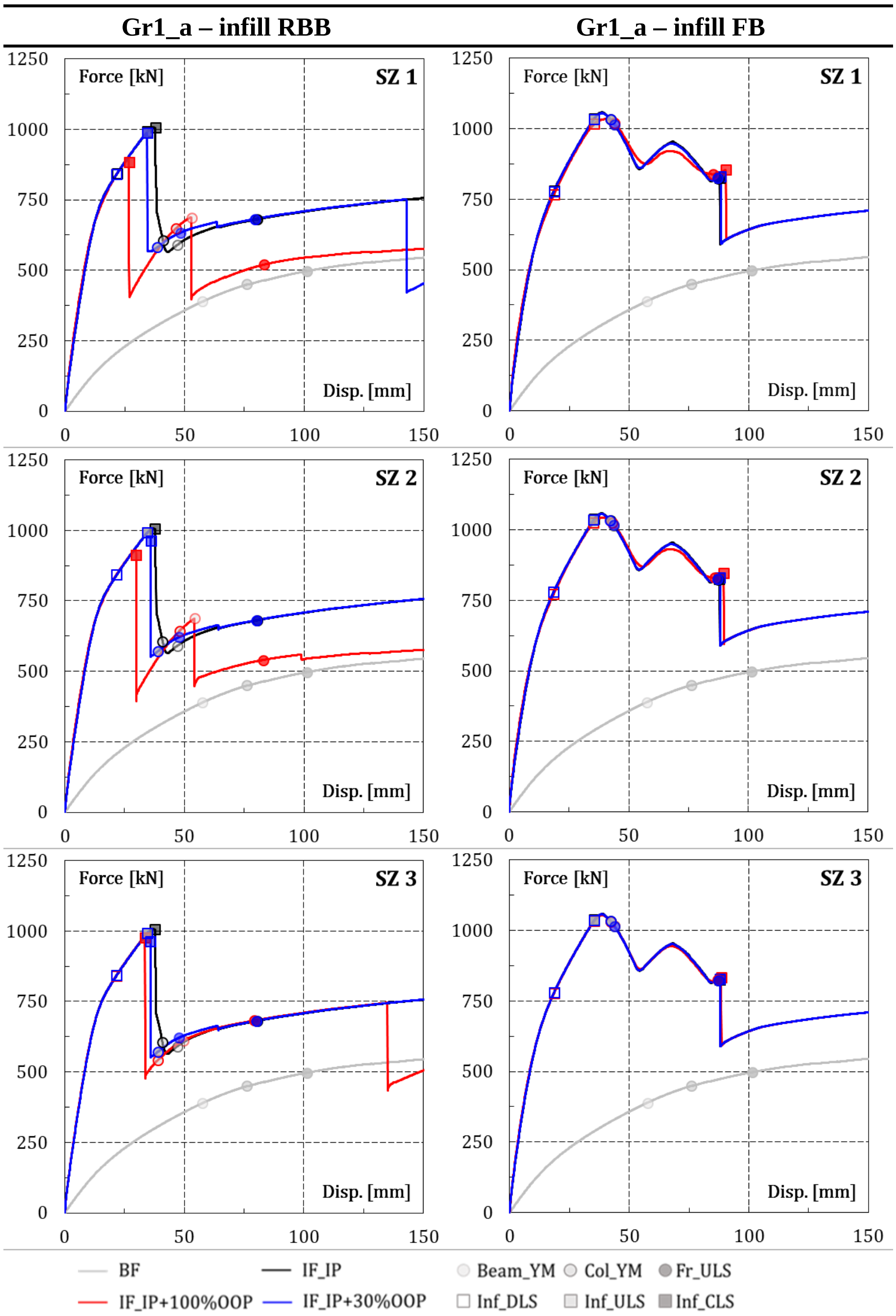


Figure 9. Capacity curve of 2x3 configuration, seismic design (SD) and infill type FB and FB (Gr1_a).

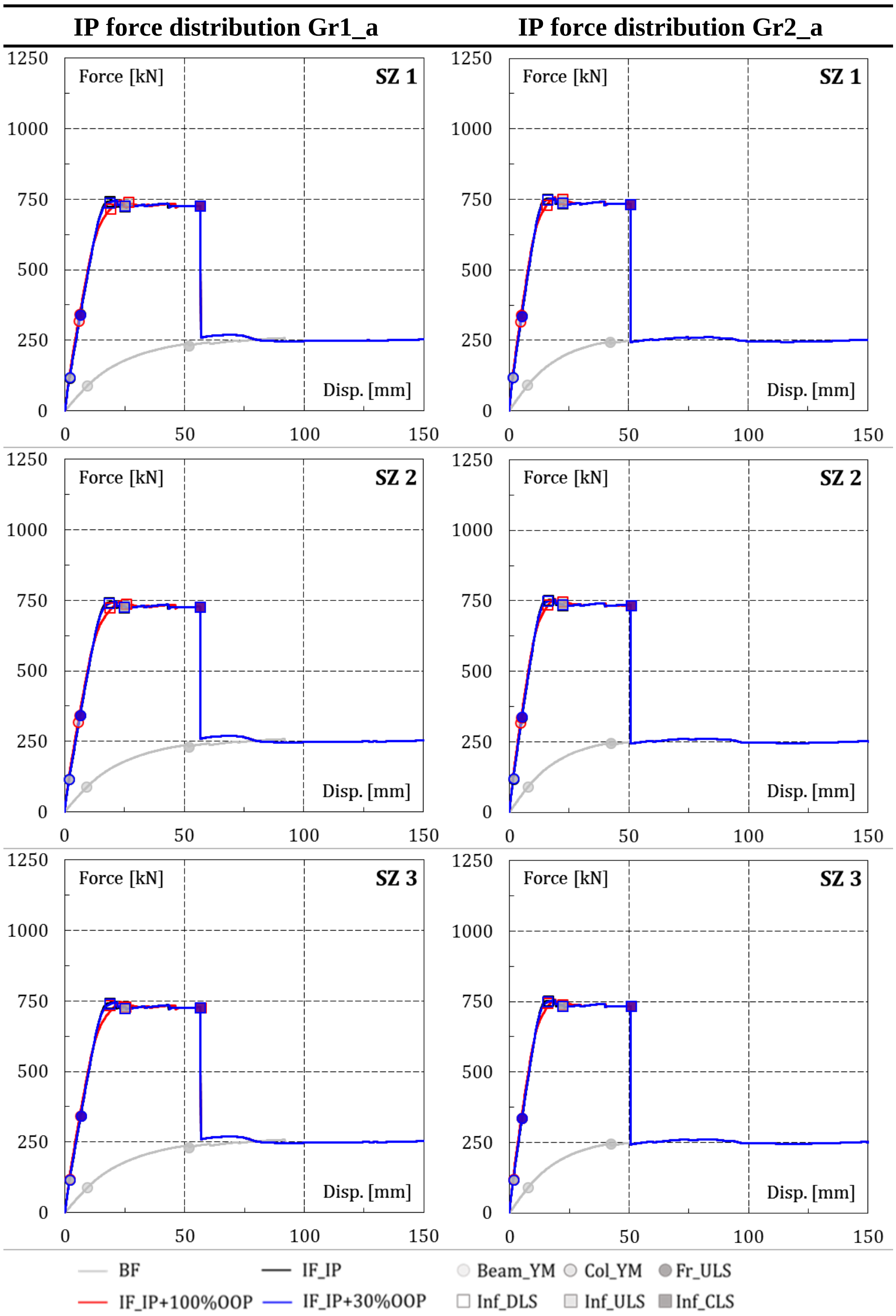


Figure 10. Capacity curve of 2x3 configuration, traditional design (TD) and infill type F.

3.2 Inter-storey profiles

In the following Figure 11 and 12 are shown the IP 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*) and ultimate limit states of the frame (*frULS*). These profiles are calculated as an envelope of the profiles corresponding to the two distributions Gr1_a and Gr2_a considering at each floor the most relevant drift. In the case of reinforced panels (RBB, FB and F), the OOP action has almost negligible effects. In fact, the reinforcement solution avoids an anticipation of the damage and expulsion of the panel ensuring that the response is linked to the IP behaviour of the infill. As consequence, all structural configurations, both seismic and traditional, equipped with reinforced panels, the drift profiles are not affected by OOP actions.

The OOP action does not affect the frame Limit States. At this regard, it is interesting to observe that in case of slender configurations (2x6) the drift profile due to IP actions shows a concentration of deformation at the second level and increasing the OOP seismic actions the behaviour remains the same. In case of BF configuration, it is underlined also a great deformation at the 4th floor associated to the reduction of column section, as explained before. In case of traditional frame (TD), the drift profile at the *frULS* Limit State, is very squashed towards the ordinate axis due to the breaking of the columns.

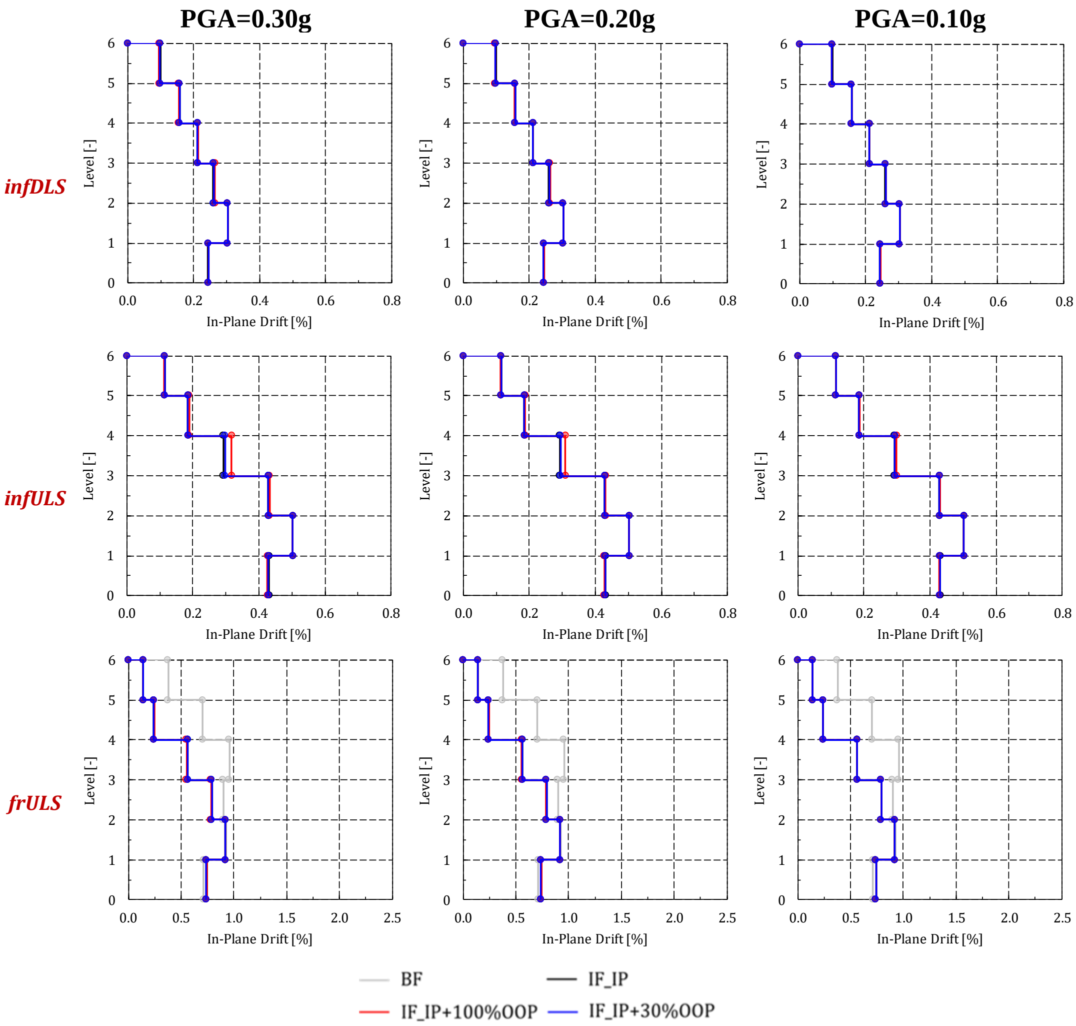


Figure 11. Inter-storey drift profiles: 2x6 configuration, seismic design (SD) and infill type F.

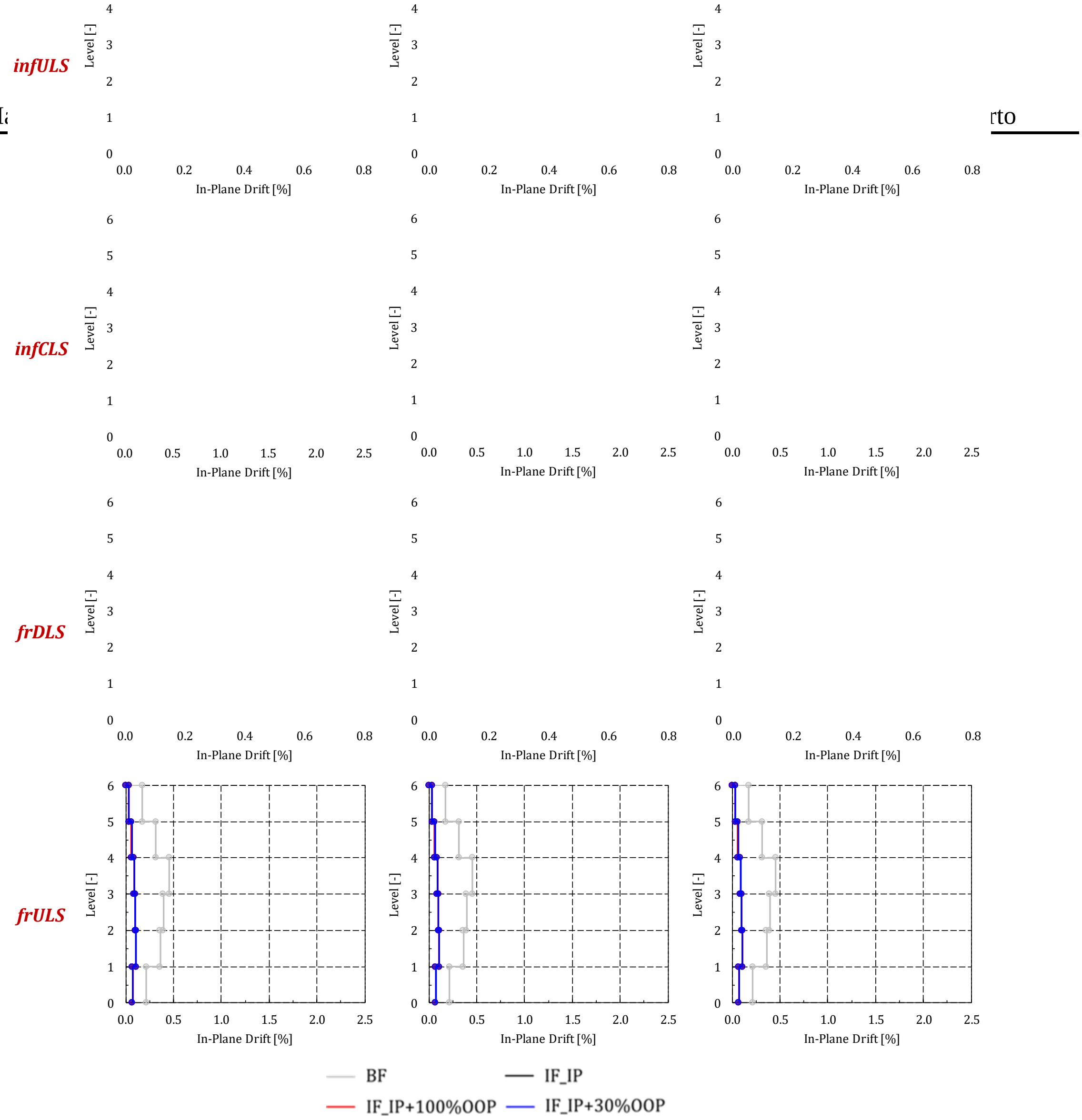


Figure 11. Inter-storey drift profiles: 2x6 configuration, traditional design (TD) and infill type F.

4 CONCLUSIONS AND OBSERVATIONS

The paper discusses about a new F.E. macro-model developed to simulate the interaction between the In-Plane and Out-Of-Plane behaviour of strengthened thin masonry infills in RC frames. The aim of the work is to evaluate the performances of the mentioned solutions starting from the calibration of the macro-model on combined test results obtained from previous experimental campaigns on real scale infilled frame. To investigate the seismic response of RC infilled frames, the model has been implemented in a parametric pushover analysis (*OpenSees*). Four frame configurations (squat, regular and slender) and, for each of these, two types of design (for gravitational loads only and for seismic actions) were specially designed and implemented in the analysis. The analyses were conducted applying wo different IP force distributions (Gr1_a and Gr2_a) and an OOP force pattern associated to three different PGAs (PGA=0.30g, 0.20g and 0.10g). The main influences of the OOP forces are presented through the capacity curves (indicating the principal performance levels and limit states), and the inter-storey drifts. The principal outcomes are listed below.

- The infill contribution on the global capacity of the infilled frame is much greater and extended in case of SD squat frames and for solutions F and RBB.
- Traditional frames, bare and infilled, reach their yielding and ULS before than the seismic frames and a brittle shear failure of the columns may occur.
- The OOP action, also in case of high values of PGA, does not induce effects of early collapse of the panels and, therefore, no reduction in the maximum resistance.

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