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INELASTIC RESPONSE OF MASONRY INFILLED REINFORCED CONCRETE STRUCTURES

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Abstract. *It is well known that masonry infill walls, although non-engineered and considered as non-structural, may provide most of the earthquake resistance and prevent collapse of relatively flexible and weak RC structures. The objective of this study is to investigate the effect of masonry infill walls with openings on the performance of reinforced concrete frames under lateral loads. Specifically, this study is concerned with the evaluation of inelastic parameters of masonry infilled reinforced concrete buildings. Buildings with various heights are selected and designed according to EC8. Inelastic pushover analyses are performed and local and global strength and inelastic deformation characteristics are evaluated. The influence of various parameters, such as the number of storeys, the distribution of infill walls, their strength and their opening percentage on the seismic response of the buildings is thoroughly examined. The results from nonlinear pushover analyses indicate that the overstrength and ductility of RC buildings can be higher than the values considered in the design. The presence of infill walls increases considerably the stiffness of the structures and their global resistance to lateral loads. However, the irregular distribution of infills (soft storey – case of pilotis) significantly reduces the capacity of the structure.*

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1 INTRODUCTION

Reinforced concrete (RC) frames with unreinforced masonry infill walls are commonly used worldwide. Masonry infill walls are non-structural elements and are usually ignored in the design of the structures. However, the infill walls significantly influence the seismic response of a structure since they may interact with bounding frames when the structure is subjected to strong lateral loads induced by seismic load. In many cases infills may provide most of the earthquake resistance, improve the behaviour of the structure and prevent collapse of relatively flexible and weak RC structures. Nevertheless, an irregular distribution of infill walls may have negative effects on the structure's performance.

There is a complex interaction between primary structures and masonry infill panels and it is well known that in the presence of lateral actions masonry infills partially detach from the surrounding frame, remaining in contact with this only in correspondence of two opposite corners. A significant bracing action, affecting both the strength and stiffness, originates by this mechanism, as demonstrated by a large number of experimental investigations [1-13] and analytical-numerical studies [14-32]. However, despite several modelling strategies available in the literature, going from pinned equivalent struts macromodeling to FE micromodeling [33-38], masonry infills are generally not accounted for in models because of the large amount of uncertainties arising during their structural identification.

In this study, the effect of masonry infill walls with openings on the performance of reinforced concrete frames under lateral loads is investigated using inelastic pushover analyses. To this end, buildings with various heights and infill wall opening percentages are selected.

2 DESCRIPTION OF THE STRUCTURES

2.1 Building forms and infill walls parameters

In this study, the seismic response of masonry infilled reinforced concrete buildings is investigated. Buildings examined have 4, 6, 8 and 10 storeys. The storey height for all buildings is kept constant and equal to 3.0 m. All buildings have 4 spans with 6 m length. In the perpendicular direction the span length has been kept constant and equal to 5 m for all cases.

Both bare-frame structures as well as structures with fully or partially unreinforced masonry infilled frames with or without openings are analysed, in order to examine the influence of infill walls. Infill panels are 0.25 m thick, following the conventional construction double leaf walls with a masonry panel strength equal to 3.0 MPa, which represents a good clay masonry. Young's modulus E_w of masonry is 3.0 GPa. Four different cases for infill wall openings are studied. These are: fully infilled walls (0% openings), infill walls with small and large openings (25% and 50% openings) and bare frames (100% openings). Infill walls are uniformly distributed in all spans of the frame. Moreover, the case of an open storey at the ground floor (pilotis) is examined for each infilled frame.

In total, 28 different cases of infilled RC frames were analysed in order to investigate the influence of several parameters on the seismic response of infilled frame structures.

2.2 Design of structures

The frames are designed according to Eurocode standards using the software FESPA [39]. Modal response spectrum analysis was also performed. The frames were designed for seismic zone I with reference peak ground acceleration on type A ground, a_{gR} = 0.16 g, importance factor γ_I equal to 1.0, ground type B with soil factor S equal to 1.2, according to Eurocode 8, medium ductility class (DCM) and behaviour factor, q, equal to 3.45. Concrete strength class C25/30 was used for beams and columns, while steel grade B500c was used for the reinforcement steel bars. The dead load was 1.50 kN/m^2 plus 0.90 kN/m^2 to include interior partition walls in the mass of the building. Live load was 3.5 kN/m^2. Slabs were 150 mm thick for all cases. Beams were 250/600 mm for all frames. Square column sections were used for all frames. For the 10-storey frame, columns had dimensions ranging from 650x650 [mm] at the ground floor to 500x500 [mm] at the roof. For the 4-storey frame, column dimensions are 550x550 [mm] at the first three storeys and 500x500 [mm] at the roof. Column longitudinal reinforcement ratio was kept low and ranged between 1.0% and 1.5%, with most cases being under 1.15%.

3 MODELLING OF INFILL STRUCTURES

3.1 Modelling of infill walls

The response of composite infilled framed structures is modelled using diagonal compressive struts with appropriate geometrical and mechanical characteristics (Figure 1). As it is widely accepted, diagonal struts can adequately model the inelastic behaviour of infills with low computational cost. In Figure 1, w is the width of the diagonal strut, d is the diagonal length of the masonry panel, L is the distance between the centres of two columns, and z is the contact length of the diagonal strut to the column.

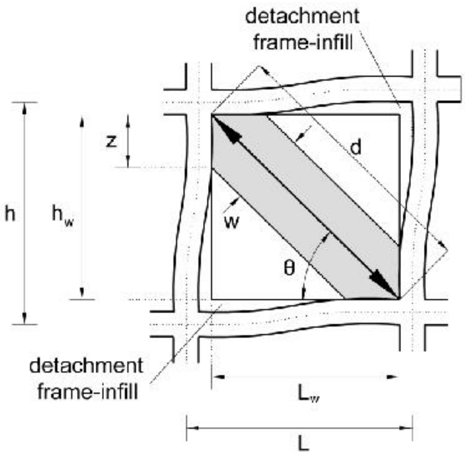


Figure 1: Masonry infill frame sub-assemblage.

Mainstone and Weeks [40] and Mainstone [41] based on experimental and analytical data, proposed the following empirical equation for the calculation of the equivalent strut width w, which was later included in FEMA-274 [42] for the analysis and rehabilitation of buildings as well as in FEMA-306 [43]:

$$\frac{w}{d} = 0.175\lambda_h^{-0.4} \tag{1}$$

where d is the diagonal length of the masonry panel and λ_h is given by the following equation,

$$\lambda_h = h\sqrt[4]{\frac{E_w t_w \sin 2\theta}{4EIh_w}} \tag{2}$$

where E_w is the modulus of elasticity of the masonry panel, EI is the flexural rigidity of the columns, t_w the thickness of the infill panel and equivalent strut, h the column height between centerlines of beams, h_w the height of infill panel, and θ the angle, whose tangent is the infill height-to-length aspect ratio, being equal to:

$$q = \tan^{-1}\left(\frac{h_w}{L_w}\right) \tag{3}$$

where L_w is the length of infill panel. All the above parameters are explained in Figure 1.

In case of openings in the infills, the infill wall stiffness can be multiplied with the following reduction factor λ, proposed by Asteris [44]:

$$\lambda = 1 - 2\alpha_w^{0.54} + \alpha_w^{1.14} \tag{4}$$

where α_w is the ratio of the area of opening to the area of infill wall. The above coefficient is used in the current study to find the equivalent width of a strut for the case of an infill with opening by multiplying the width obtained using Eq. (1) by the relevant reduction factor.

3.2 Modelling of RC structures

All buildings were modelled as plane frames using Seismostruct [45]. A plastic-hinge element has been adopted for beams and columns, with concentrated inelasticity within a fixed length at each member's end. The Mander et al. [46] model, later modified by Martinez-Rueda and Elnashai [47], has been assumed for the core and the unconfined concrete, while Menegotto-Pinto steel model has been adopted for the reinforcement steel [48]. Concrete compressive strength was equal to 25 MPa and the yield strength of the steel equal to 500 MPa. Mass was calculated using the seismic load combination, namely dead loads plus 30% of the live loads.

Masonry is modelled using the inelastic infill panel element. This is an equivalent strut nonlinear cyclic model proposed by Crisafulli [49] for the modelling of the nonlinear response of infill panels in framed structures. Each panel is represented by six strut members. Each diagonal direction features two parallel struts to carry axial loads across two opposite diagonal corners and a third one to carry the shear from the top to the bottom of the panel (Figure 2). The struts act only across the diagonal that is on compression, hence, its "activation" depends on the deformation of the panel. The axial load struts use the masonry strut hysteresis model, while the shear strut uses a dedicated bilinear hysteresis rule, as described by Crisafulli [49].

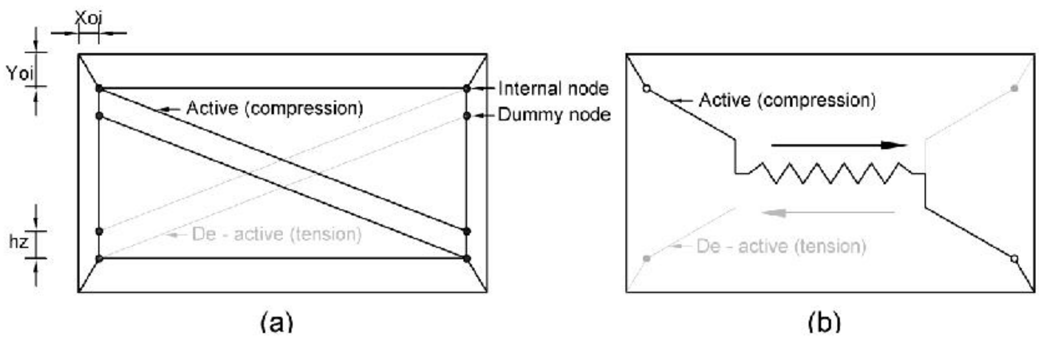


Figure 2: Infill panel element proposed by Crisafulli [49]. a) Compression/Tension Struts, b) Shear Strut.

3.3 Performance criteria

Local or global failure definition criteria are adopted, in order, to estimate the limiting lateral deformation capacity and corresponding limit resistance, global deformability and ductility of the infilled RC structures. In the present study, it is assumed that local failure occurs only when a column fails, thereby, assuming that beam failure cannot cause a brittle catastrophic type of failure of the entire structure, due to the expected redistribution of loads that takes place in this case. The following criteria are evaluated for every structure:

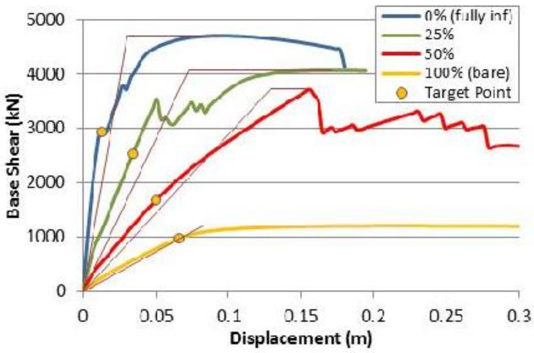
a) local inelastic rotation capacities at the end critical regions of beams and columns according to EC8-3,
b) local shear force capacity of the individual members according to EC8-3 and
c) failure of the compression struts of the infill masonry walls for the infilled frames

3.4 Target Point

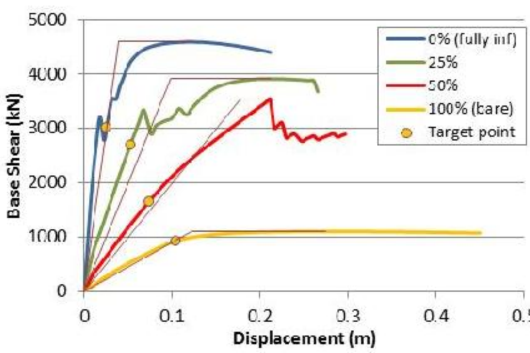
Target displacement is evaluated according to EC8 procedure for three performance levels. The idealized elasto-perfectly plastic force displacement relationship is determined in such a way that the areas under the actual and the idea1ized force deformation curves are equal and the yield force of the idealized system is equal to the base shear force at the formation of the plastic mechanism.

4 INELASTIC ANALYSES

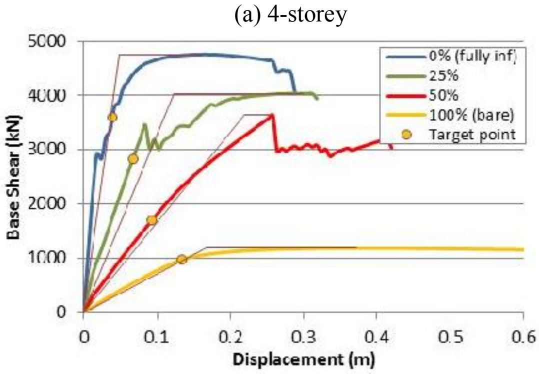
Pushover analyses with two distributions of lateral loads (uniform and triangular) were performed for all the frames. The predicted base shear – roof displacement characteristics are shown in Figures 3 to 6. On each capacity curve, the bilinear approximation and the target point for limit state of significant damage (SD) are also shown. In this study, failure is considered when at least one of the performance criteria described above is reached.



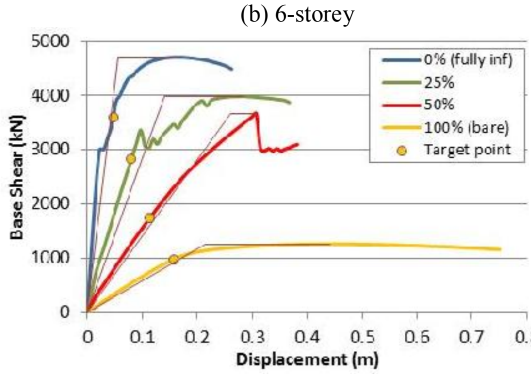
(a) 4-storey



(b) 6-storey



(c) 8-storey



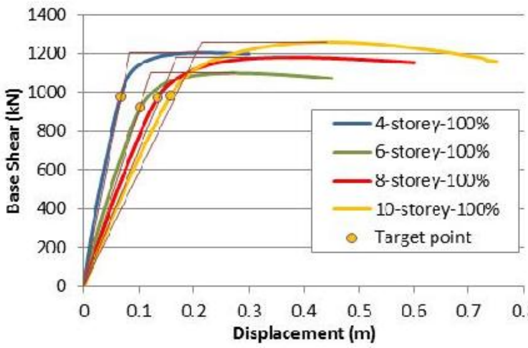
(d) 10-storey

Figure 3: Capacity curves of examined frames.

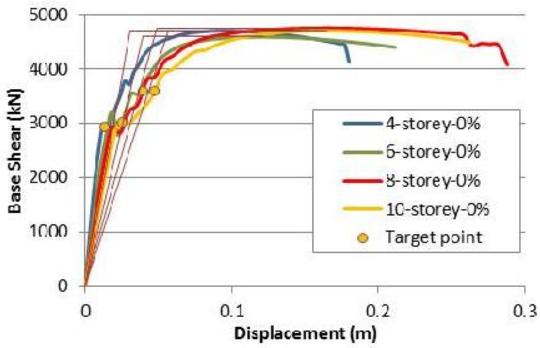
In Figure 3 the capacity curves of frames with 4, 6, 8 and 10 storeys are shown, for the fully infilled frame (0% openings), the frames with 25% and 50% infill opening ratios and the bare frame (100% openings). As expected, masonry infills significantly influence the seismic response of the frames. For fully-infilled frames, the stiffness of the frame increases considerably compared to the bare frame. This increase is smaller for frames with 25% and 50% opening ratio. As also shown in previous studies [50-51] for opening ratios above 80% the influence is insignificant.

Total displacement and interstorey drifts of the infilled frames decrease compared to bare frames. Target displacement also decreases. Consequently, both ductility capacity and demand decrease with the presence of infill walls. On the contrary, overstrength significantly increases with the presence of infill walls. The capacity strength of the examined fully-infilled frames increased by 374% to 417% compared to the strength of the bare frames. However, after the failure of the infills the strength reduces.

The capacity curves of the bare frames and the fully-infilled frames with different number of storeys are shown in Figure 4. It can be seen, that higher frames have smaller initial stiffness and higher target displacement for both bare and infilled frames. The predicted base shear – roof displacement characteristics with uniform and triangular lateral loads are compared in Figure 5 for the 6-storey bare and fully-infilled frame. The maximum strength from pushover with uniform lateral loads is higher, while the target displacement is smaller, compared to the capacity curve with triangular distribution of lateral loads.



(a) Bare frame



(b) Fully infilled

Figure 4: Capacity curves of 4, 6, 8 and 10-storey (a) bare and (b) fully-infilled frames.

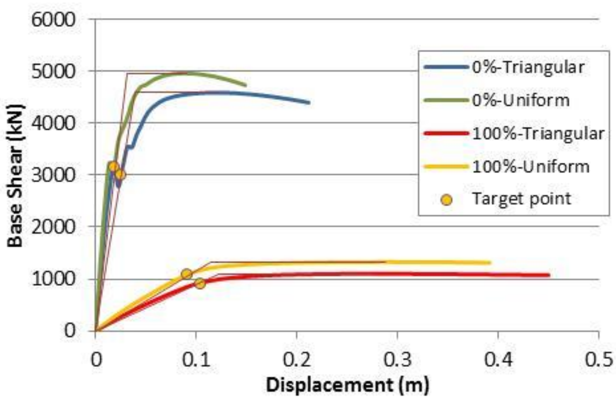
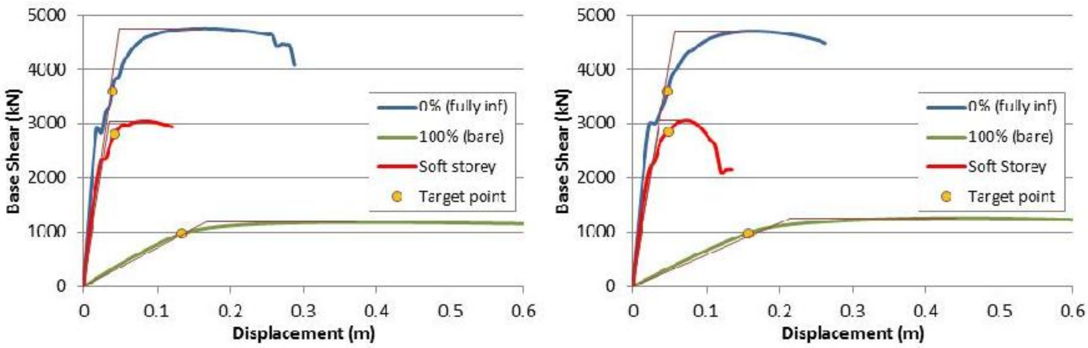


Figure 5: Capacity curves of 6-storey bare and fully-infilled frame with uniform and triangular lateral loads.

Capacity curves for bare, fully infilled frames and frames with soft storey are compared in Figure 6 for the 8 and 10-storey frames. The deformed shape of these frames is shown in Figure 7. In the same figure, the performance criteria are shown for the members of the frames.

Yield is indicated in green, flexural failure in red and shear failure of the members in blue. In the structures with a soft storey at the first floor, infills do not reach their strength degrading branch since inelastic energy absorption concentrates to the columns of the open storey. On the contrary, infills in the lower part of the fully infilled frames do reach their maximum resistance. Fully-infilled frames having regularly distributed infills, exhibit reduced local deformation demands and therefore behave in a desirable manner.



(a) 8-storey (b) 10-storey

Figure 6: Capacity curves of the 8 and 10-storey bare, soft storey and fully-infilled frame.

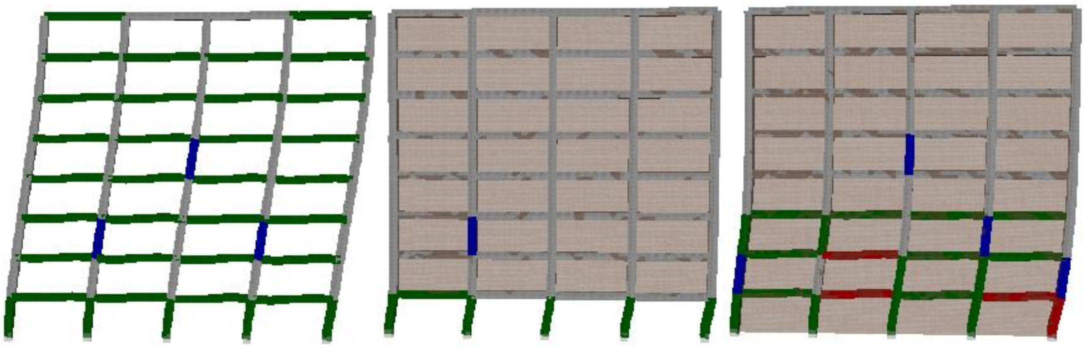


Figure 7: Deformed shape and performance criteria of the 8-storey bare, soft storey and fully-infilled frame (green: yield, red: flexural failure, blue: shear failure).

5 CONCLUSIONS

The influence of the masonry infill walls on the seismic performance of reinforced concrete frames is investigated in this study. Buildings with four to ten storeys are initially designed according to EC8. Static pushover analyses are subsequently performed for bare and infilled frames with various opening ratios. Based on the results of these analyses, the following are concluded:

- Results from static pushover analyses confirm the significant influence of the infills on the seismic response of the structures. Thus, infill walls should be included in the model.
- Infill walls increase the stiffness and overstrength of the structure but reduce its deformability and thus its ductility.
- A non-uniform distribution of infills, like an open first storey, results in a concentration of damage at this storey, creating a soft-storey response mechanism. The irregular distribution of infills significantly reduces the capacity of the structure which necessitates their inclusion

in the structural model. On the other hand, regularly distributed infills significantly reduce the deformation and ductility demand in structural elements, with the frames exhibiting an improved performance.

- As the opening percentage of the infills increases, the stiffness and overstrength decreases and the behaviour of the frame approaches that of the bare frame. For opening ratios above 75% the influence of the infills is insignificant.

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