The influence of infill walls in r.c. frame seismic response

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Abstract

A non linear finite element model for the seismic analysis of an infilled frame is proposed. Two no-tension struts to simulate the interaction between the r.c. frame and the infill wall, including windows and door openings, are calibrated on numerical evaluations. Results show that two different reduction factors have to be applied to stiffness and strength in order to consider the effects of openings compared to the full infill panel. The role of light infill walls - even with openings - is proved to be important.
Keywords: infilled r.c. frame, equivalent strut, seismic behaviour.

1 Introduction

Most studies on infill wall behaviour aim to understand their part in terms of strength in the assessment of the resistant capacity of existing buildings.

Whereas less attention is paid to infill wall - r.c. frame interaction modelling in order to evaluate their influence on r.c. frame response.

The famous case of the torsionally coupled building in Artegna, first damaged and then destroyed by the two earthquakes that struck Friuli in 1976, is sufficient to come to believe in the importance of infill panel contribution which is disregarded by Codes since considered too weak.

In the present paper a non linear finite element model for infilling walls also with openings is proposed and used to define a simple but efficient modified equivalent single strut model.

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2 Infill wall - r.c. frame interaction

Basic aspects to describe infill wall – r.c. frame interaction are:
- evaluation of equivalent single strut stiffness and identification of application zones of reactions;
- evaluation of equivalent single strut strength and of post-fracture behaviour;
- assessment of out of plan falling.

The evaluation of these aspects, at least with the approximation required in current practice, allows to master infill wall – r.c. frame interaction and to control global deformation in elevation and centre of instant rotation location of the building during infill walls progressive failure.

Infill wall collapse should precede structural yielding and develop so that the conditions for a torsionally uncoupled building continue to be satisfied (capacity design).

Optimal global deformation should have inter-storey drift decreasing from the top to the bottom so as to avoid soft storey mechanism at low levels.

In this case borne masonry significantly increase stiffness and strength of the building under small earthquakes (higher first damage limit state) and share in energy dissipation in case of more severe earthquakes.

3 Proposed model

In the present paper r.c. frame structure is modelled with current frame elements (likewise Badalà [1]) whereas infill wall with 125x125 mm^2 quadrangular finite elements (Figure 1). This dimension came the best to give right compromise between computational speed, result accuracy and real geometry of bricks (see Gambarotta and Lagomarsino [2], Dentamaro and Uva [3], Barsotti et al. [4]).
Interface element shear strength is assumed to be zero since analyses including that contribution do not lead to reliable results.

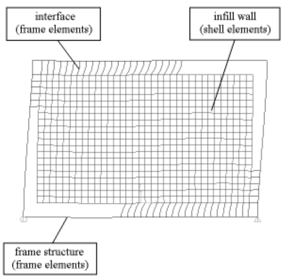

Figure 1. Proposed model scheme for infill wall.

Analysis goes on iteratively each time removing only the most tensile connection: at the end of the procedure only compressive interactions result which identify the extension of the contact zone between infill wall and r.c. elements (columns and beams). Suitable disconnections inside the wall are then introduced. They define cracks starting near the edge of possible openings and

diagonally developing until minimum stress is in compression or in negligible tension (<0,125 Nmm^{-2}).
Mechanical characteristics of bricks - $f_{m,ave}$($f_{t,ave}$)=average compressive(tensile) strength, $E_{m,ave}$(G)=average elastic (shear) modulus between 10 and 40% strength, $f_{v0,ave}$= average shear strength in absence of vertical load (cohesion) - (see Table 1) are deduced from experimental data of Calvi and Bolognini [5], relative to elements fitting current standards of production and building use, also accounting for general argumentations expressed by Dezi et al. [6].

Table 1: Mechanical characteristics of bricks.

Load	$f_{m,ave}$ [Nmm^{-2}]	$E_{m,ave}$ [Nmm^{-2}]
parallel to holes, laying with vertical holes	3,970	5.646
Parallel to holes, laying with horizontal holes	1,110	991
perpendicular to holes	1,100	1.873

Load	$f_{t,ave}$ [Nmm^{-2}]	$f_{v0,ave}$ [Nmm^{-2}]	G [Nmm^{-2}]
average diagonal	0,150	0,090	1.039

Bricks laying with horizontal holes are considered. Investigations showed over 75% of infill panel are built in such a way and stiffness and strength in both vertical and horizontal direction are similar.
Actual wall thickness is 135 mm (115 mm bricks and 10 mm plaster on each side). Weight per unit volume is 5,00 kNm^{-3} (value conforming with that provided by manufacturers).
Wall is described as a homogeneous-orthotropic material, with Poisson's ratio equal to 0,25, whereas reinforced concrete as a homogeneous-isotropic material with modulus of elasticity and Poisson's ratio equal to 25.000 Nmm^{-2} and 0,15 respectively (according to Pagano [7]).
Proposed model results are in good agreement with experimental ones of Calvi and Bolognini [5] and with those of Badalà [1].
It is worth noticing that the model does not account for possible local recovery of the previously lost contact between panel and r.c. frame due to stress redistribution. This phenomenon has been demonstrated to have little influence: analyses performed adding further frame elements (without axial stiffness) at the interface, that activate in case of contact recovery, show differences about 1÷2%. Therefore the proposed model is considered to be effective in any case.

4 Equivalent strut model in presence of openings

Holed wall can be modelled as a whole one with reduced ultimate strength, (initial and secant) stiffness and first cracking load (Decanini et al. [8] e Papia e Cavalieri [9]). In conclusion equivalent strut width $w_{p,f}$ should be reduced with respect to the whole panel one $w_{p,p}$: $w_{p,f}=\rho w_{p,p}$.
Simplified models assume equal displacement at cracking in both whole and holed panel resulting in the same strength reduction as the stiffness one: $f_{p,f}=\rho f_{p,p}$.

In case of eccentric opening, mechanical characteristics of the two equivalent struts to be considered in the two load directions are different. Numerical analyses, summarised in chapter 6, let the equivalent struts stiffness and strength to be precisely defined as a function of those relative to the whole wall.
In particular, comparing the response of infill frame with and without openings, stiffness (ρ_s) and strength (ρ_r) reducing factors are defined varying opening dimensions and location and frame dimensions. It follows $\rho_s = w_{p,f} / w_{p,p}$.
Considering collapse mechanisms identified in Italian Codes ([10], [11]), it is assumed $\rho_r = \min(S^i_{p,f} / S^i_{p,p})$ being S^i the compressive, tensile or shear stress. It is an approximate assumption since ρ_r should be related to the stress causing failure.
Performed analyses also solve a question posed by some researchers about the effectiveness of macroscopic model: Braga and Liberatore [12] underline that equivalent single strut model, assuming a constant stress distribution, cannot get stress peaks at the edges of the panel thus overestimating its shear strength.

5 Numerical analyses

Numerical analyses have been performed on infilled frame with the aim of define geometrical and mechanical characteristics of the equivalent single strut as a function of the wall panel shape.
Two different frames are considered: a strong one (TYPE A) and a weak one (TYPE B) whose geometry is shown in Figure 2.

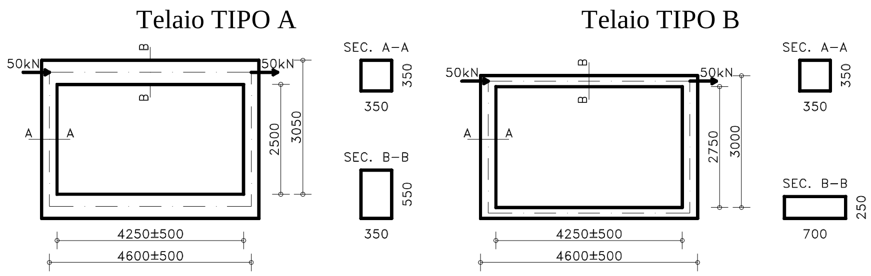

Figure 2. Frame geometry (mm).

Infill wall built with bricks having holes percentages (60÷70%) well higher than those prescribed by Italian Code for structural wall panel (≤45%) are considered to match the most widespread real applications.
Besides studying frame with whole wall panels, infilled frames with window and door openings having various dimensions (Table 2) and horizontal positions are analysed to evaluate the influence of such geometrical singularities on the whole panel behaviour.
An opening spread through the whole height of the panel was considered too but analysis results pointed out that in such case the share in stiffness given by the panel is nearly negligible.

Furthermore wall thickness influence on frame behaviour was studied resulting almost negligible on stiffness but considerable on strength since varying wall stiffness may change collapse mechanism.

Table 2: Openings geometrical characteristics

distance between window-sill and lower beam [mm]	875
window ($a \times b$) [mm^2]	(1250±250)×1375
door ($a \times b$) [mm^2]	(1250±250)×2250

6 Results of numerical analysis

For the sake of brevity only some of the results of performed analyses are shown. Compressive stress distribution inside the panel of the frame TYPE A (a=1250 mm) in case of window and door opening respectively is shown in Figure 3. White lines stand for cracking inside the panel.

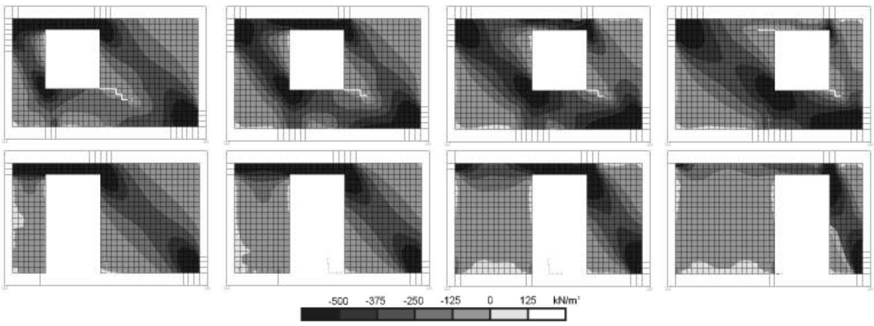

Figure 3. Frame TYPE A with window and door opening – stress distribution.

It came out that in the presence of openings the number of possible collapse mechanisms increases since further failures may arise due to compressive crushing, slipping or excessive diagonal tension in an edge or near the opening.
Fall in strength observed in wall panels with door opening is due to those mechanisms; this effect is less important in case of window opening since stress flows pass mainly under the hole leaving the upper edge nearly unloaded.
ρ_s and ρ_r trend, varying position x and width a of window and door opening in frame TYPE A and TYPE B respectively (keeping wall panel dimensions $l \times h$ and hole height b constant), is shown in Figure 4 and Figure 5.
ρ_s and ρ_r trend varying window and door opening position x and wall panel length l in frame TYPE A and TYPE B respectively (keeping $a \times b$ and h constant) is shown in Figure 6 and Figure 7.
With reference to a hole in the middle, ρ_s and ρ_r trend varying window and door opening width a in frame TYPE A and TYPE B (keeping b and $l \times h$ constant) is shown in Figure 8.

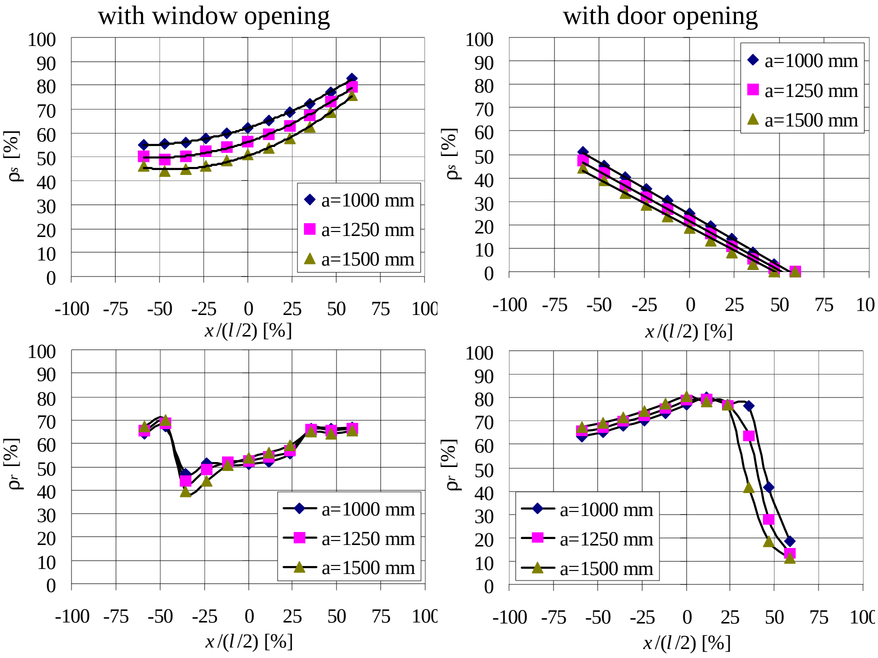

Figure 4. Frame TYPE A with window and door opening $-\rho_s$ and ρ_r trend.

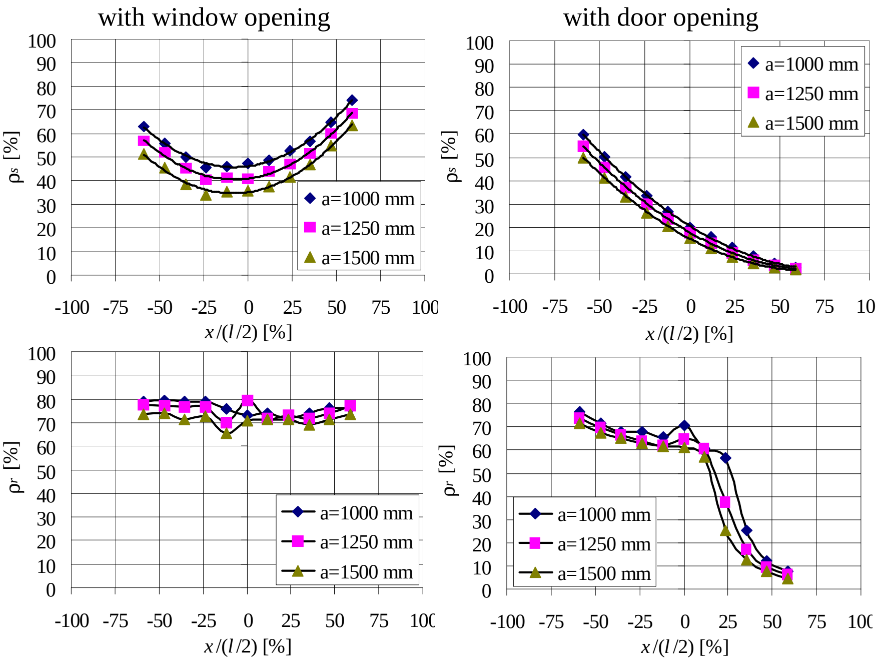

Figure 5. Frame TYPE B with window and door opening $-\rho_s$ and ρ_r trend.

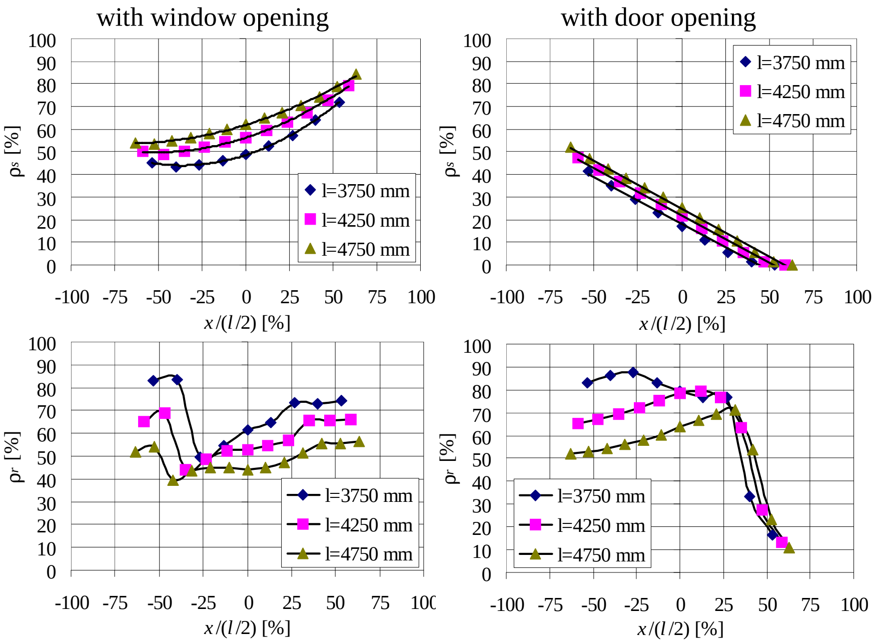

Figure 6. Frame TYPE A with window and door opening $-\rho_s$ and ρ_r trend.

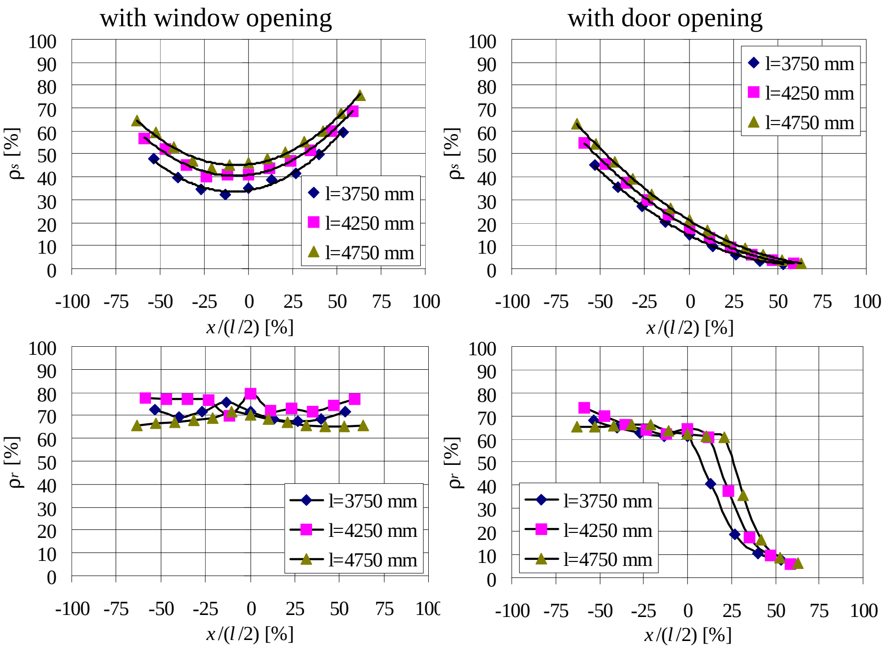

Figure 7. Frame TYPE B with window and door opening $-\rho_s$ and ρ_r trend.

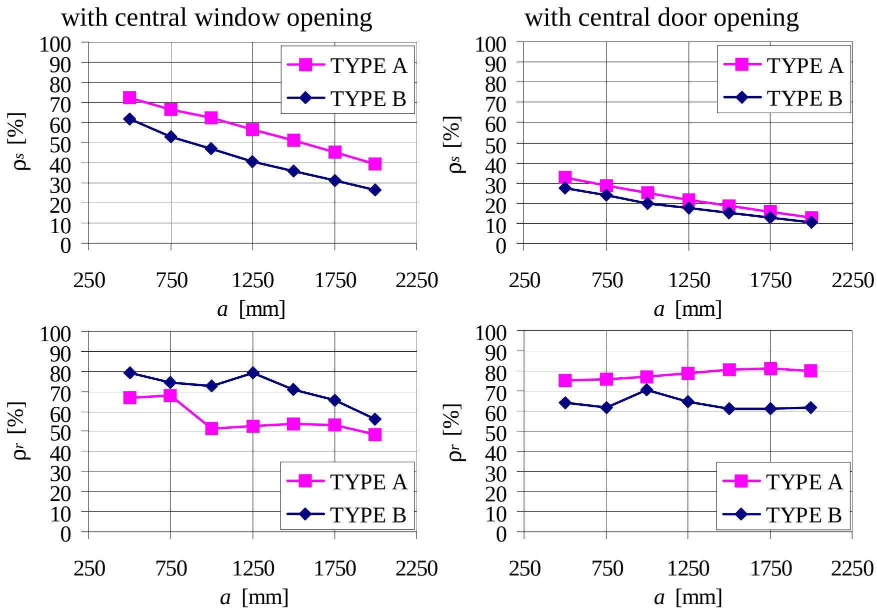

Figure 8. Frame TYPE A and B with central opening $-\rho_s$ and ρ_r trend.

For both frames ρ_s linearly decreases as window or door opening width increases: $\Delta\rho_s\cong$-22 Δa in presence of window and $\Delta\rho_s\cong$-12 Δa in presence of door. In presence of window in frame TYPE A the more eccentric the opening is the more different the stiffnesses of the two struts are with ρ_s decreasing until 50% for one and increasing until 80% for the other with respect to the value 55% in case of a central opening. In frame TYPE B stiffnesses of the two struts are nearly the same with ρ_s varying within 40% (in case of a central opening) and 60%. A sort of localized anomaly due to a different attitude of the opening to let the stress path pass is observed: mainly under (right way) or above (left way) the hole. In presence of door differences between the two frames are less evident. In both cases the more eccentric the opening is the more different the stiffnesses of the two struts are with ρ_s increasing until 50% for one and decreasing until a negligible value for the other with respect to the value 20% in case of a central opening. For both frames ρ_r linearly decreases as window opening width increases while remains nearly constant, 80% for TYPE A and 60% for TYPE B, in case of door. Wall panel length significantly influences ρ_r only in frame TYPE A. In particular the shorter the wall panel is the more different the strengths of the two struts are depending on shear failure increasing importance. In presence of window the two struts have similar strength in both frames with ρ_r varying within 50% (eccentricity <25% of wall panel half-length) and 65% for frame TYPE A and with ρ_r remaining nearly constant, 75% for TYPE B. In presence of door the strengths of the two struts become considerably different as the opening eccentricity goes over 25% (15%) of wall panel half-length for frame TYPE A

(B) with ρ_r varying within 65÷75% for one and decreasing until 10% for the other. The abrupt strength fall depends on slip and traction phenomena causing the rupture of the part of the panel included within opening upper edge and the near frame corner.
Showed results were found applying no load on the beams of the frames. Studying distributed load influence it follows that ρ_s remains constant and then independent on the applied load while ρ_r decreases as the applied load increases.

7 Equivalent strut effective length

Performed analyses pointed out the possibility to relate (even if with approximations) the stiffness reduction factor ρ_s with a geometric parameter expressing the interference produced by opening in diagonal strut resistant mechanism formation. Considering the stretch of the diagonal strut (with length l_{diag}) crossed by the opening (for the length l_{infl}) (Figure 9) the effective length of the equivalent strut l_{eff} is defined as follows: $l_{eff}=(l_{diag}-l_{infl})/l_{diag}$.
In the considered cases a direct proportional relationship exists between l_{eff} and ρ_s. This interesting aspect worth further investigations to assess its usefulness in current practice.

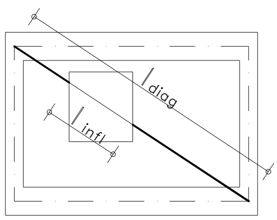

Figure 9. Equivalent strut effective length.

8 Conclusions

A non linear finite element model that accounts for cracking development at the interface between wall panel and r.c. frame and inside the panel is proposed.
Numerical analyses performed with the proposed model prove the two no-tension struts of great effective to simulate infill wall influence also in presence of windows and door openings.
Results show that the effects of windows and door openings including their position can be accounted for by simply introducing two reduction factors which apply to stiffness and strength of the current equivalent strut defined for a whole wall panel. These factors have different trends especially as a result of openings position.
To an accurate description of infilled frame behaviour, stiffness of light also holed walls, usually neglected by Code in capacity assessment, have to be considered.

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