The influence of openings on the seismic behaviour of infilled framed structures

L.D. Decanini, L. Liberatore & F. Mollaioli
University of Rome "Sapienza", Department of Structural Engineering and Geotechnics

SUMMARY:
Framed structures are usually infilled with masonry walls. Since the infills included in the frame produce significant increase in both horizontal stiffness and strength their structural contribution should not be ignored, especially in regions of moderate and high seismicity. Simple models to take into account infill walls are available for solid walls, such as the diagonal no tension strut models, while infilled frames with openings have not been sufficiently investigated.
In the present study the effect of openings on the lateral stiffness and strength of infilled frames is studied by means of numerical and experimental analyses available in the literature and a simple model to take into account the presence of openings is presented.
The proposed model, which takes into account the presence and type of reinforcing elements around the openings, allows the evaluation of the reduction of stiffness and strength of the panel due to openings.

Keywords: Framed structure, infill wall, opening, stiffness, strength.

1. INTRODUCTION

Infill walls are usually adopted in steel and reinforced concrete (RC) framed structures in the form of exterior walls or interior partitions. It is recognized that framed structures benefit from the presence of uniformly distributed infills, which significantly contribute to withstand the seismic actions (Housner 1956, Fardis 1996, Negro and Verzelletti 1996, Kappos *et al.* 1998, Liberatore *et al.* 2004, Dolšek and Fajfar 2008) as also confirmed during earthquakes of moderate and strong intensity. In fact, infills significantly enhance both the stiffness and the strength of the structure, reducing the deformation demand and improving the energy dissipation capacity of the system. Conversely, irregular distribution of infills can produce negative effects, like for example unfavourable distribution of plastic hinges, high demand of inelastic deformations, with potential premature columns bending failure, and reduction of the global dissipation capacity. Irregularities can be due to architectural or functional reasons, but can also be the consequence of the collapse of some infill walls during the earthquake both for out of plane failure and for in plane collapse due to cyclic excursion in the non-linear range. Therefore, the structural contribution of infill walls should be taken into account, especially in earthquake prone regions. To this aim, simple model have been developed for solid infills walls, such as the diagonal no tension strut model. Concerning infilled frames with openings, different studies have been performed since the second half of the 1950s but there is not always accordance between them and, how highlighted by Smyrou (2006), there is a lack of recommendations to quantify the effect of the openings.

The presence of openings in the infills leads to significant uncertainty due to the variability of size and position of the openings. In general, the presence of openings results in a reduction of stiffness and strength of the panel and of the cracking force leading to the increase of the in the plane damage. The out-of plane component of the motion can accelerate the failure of a masonry wall once it is damaged in the plane. This is particularly true for a wall with an opening because the arching mechanism can not develop as in the case of a solid infill wall (Stavridis *et al.* 2011)

The presence of openings affects the crack patterns as well. Cracks may develop first at the corners of the opening and propagate towards the compressed corners. Anyway, in general, the crack pattern depends on the position and size of the opening (Fig. 1.1).

Figure 1.1. Crack pattern in infills wall with opening.

One of the first experimental studies on infilled frames with openings was carried out by Polyakov (1956), who tested eight infilled steel frames with openings of different sizes, estimating an ultimate strength reduction between 23% and 76% of the ultimate strength of the frame with a solid panel. Another early study was that performed by Benjamin and Williams (1958) on an infilled steel frame with a central opening with dimensions equal to 1/3 of the infill panel dimensions; the measured ultimate strength of the infilled frame with the opening was about 55% of the fully infilled frame. A number of experimental and numerical tests were carried out since 1960 as reported by Moghaddam and Dowling (1987) and Smyrou (2006). The experimental study performed by Stavridis *et al.* (2011) highlighted that walls with openings are much more vulnerable to collapse than solid walls. The research concerned a 2/3-scale, three-story, two-bay, RC frame infilled with unreinforced masonry walls tested on shaking table. The frame was infilled with solid masonry walls in one bay and infill walls with window openings in the other bay.

In the present study the effect of openings on the lateral stiffness and strength of infilled frames is studied by means of a number of numerical and experimental tests. A simplified model to take into account the presence of openings is also presented. The model proposed in the work is based on the use of a reduction factor to be applied to the simple strut model parameters. The reduction factor, which is function of both the opening size and the presence and type of reinforcing elements around the opening, allows to take into account the reduction of both lateral stiffness and strength of the frame-infill system due to the presence of openings.

2. MODELLING OF INFILLS

A number of analytical models have been proposed to reproduce the behaviour of infilled frames. The models can be roughly grouped in two categories according to whether they are based on a macro-model approach (strut model) or on a micro-model approach (finite element).

The equivalent diagonal strut model was initially based on the observation that the compressive path in the masonry panel, due to horizontal loads, develops mainly along its diagonal (Stafford Smith 1963, Mainstone 1974). The width of the strut (Fig. 2.1) depends on different features, such as the extension of the region of interaction between masonry and frame. The ultimate horizontal strength of the infills depends also on the failure mechanism (diagonal tension, slipping in mortar bed, corner compression or diagonal compression failures). The prediction of the failure mode is rather difficult since it is influenced by the material properties, the dimensions of the system and the stress level in the panel. Keeping in mind that the masonry is a heterogeneous material, the strut model can be regarded as a method to reproduce only the global behaviour and its suitability depends on the appropriate calibration of the parameters involved.

The application of the strut model to the infills with openings can follow two different ways. One is based on the use of several diagonal struts around the opening (Thiruvengadam 1985, Hamburger and Chakradeo 1993). The multi-strut configuration takes into account the presence of openings but the evaluation of the characteristics of the struts (position, width, etc.) is somewhat complicated. The second way is to modify the width of the diagonal strut by means of a factor to account for the stiffness and strength reduction (Fig. 2.2). The proposals formulated by Sachanski (1960), Polyakov (1956), Imai (1989), Durrani and Luo (1994), Al-Chaar (2002), Asteris (2003) and Mondal and Jain (2008) belong to this procedure. Considering that when the opening is relatively small the transfer of shear is still possible with a diagonal strut while when the opening is larger the diagonal compression strut mechanism cannot develop (Durrani and Luo 1994), the reduced diagonal strut cannot represent the actual stress distribution in the panel but only a way to take into account the role of the infill panel with openings in the global behaviour of the fame-infill system.

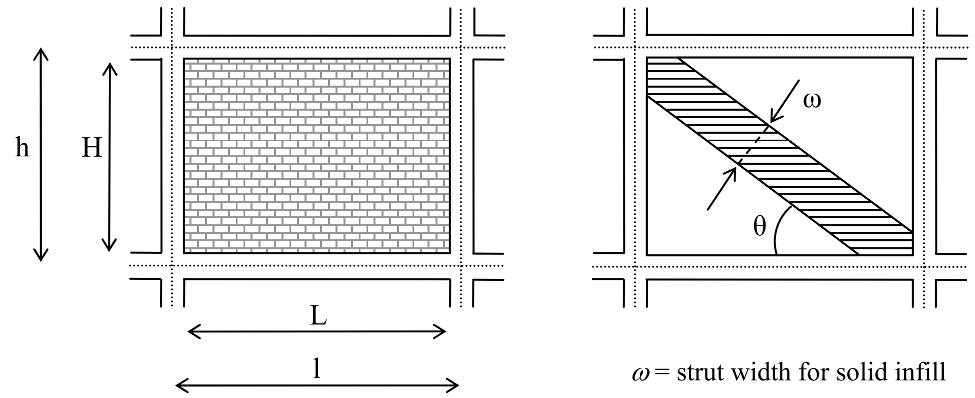

Figure 2.1. Diagonal strut model.

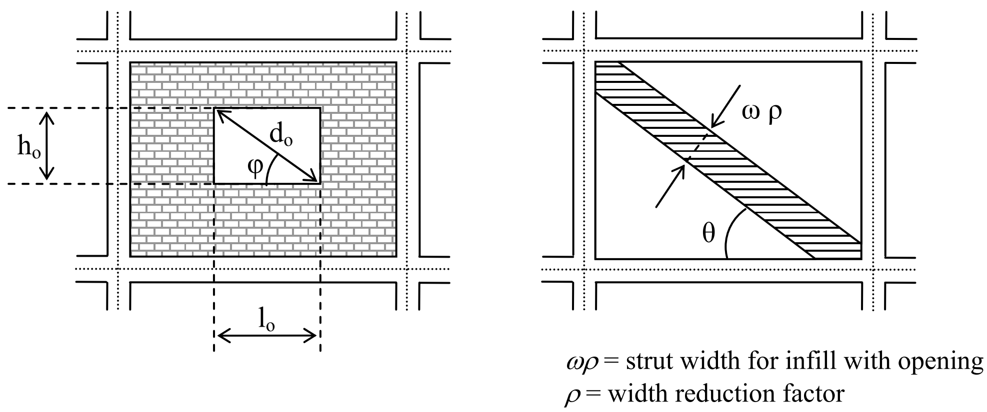

Figure 2.2. Diagonal strut model for infill with opening.

In the finite element approach the frame, the infill and their interface are modelled by means of finite element with given constitutive laws. Smeared crack models have been often used to model both the frame and the infills; these models cannot capture different aspects, such as the shear sliding of masonry mortar. The use of interface elements within an infill to model mortar joints allows taking into account this effect. To this aim several plasticity-based continuous interface models have been developed (Shing and Mehrabi 2002 *and references therein*). With the finite element method, the presence of openings can be directly allowed for.

In general, if the finite element method is properly developed enables the accurate modelling of the behaviour of the frame-infill system under horizontal loads while inadequate use of such models may produce unconservative results (Shing and Mehrabi 2002). Moreover, the application of finite element models is quite complex due to the large amount of information demanded. Conversely, the macro-models, even though do not capture the local phenomena occurring between the infill panel and the surrounding frame, are characterized by an advantageous simplicity. Often, the finite element analyses of infilled frames were aimed to the calibration of the parameter for the constitutive laws of simpler models, like the equivalent strut model.

3. INFILLS WITH OPENING

Within the equivalent strut method, the stiffness and strength reduction due to openings can be obtained decreasing the effective width of the strut. In this work the assessment of the reduction factor is made through the results of many experimental and numerical tests. By means of all the available data, the main parameters affecting the response of infills with opening are identified and the influence of these factors on the strength and stiffness of the infills is evaluated. First of all, the strength reduction and the stiffness reduction are compared with the aim of verifying if a unique factor is suitable to represent both the stiffness and strength decrease. Afterwards, a function for the reduction factor, which takes into account the main parameters involved, is calibrated.

3.1. Data set and main parameters involved

The whole data set consists of 80 experimental tests and 63 numerical tests. The data base includes different type of frame-infill systems. Both RC frames and steel frames are considered and the type of infills and the boundary conditions between frame and infill include a large set of situations, reflecting the great variability in the materials and in the construction techniques adopted in different countries. Moreover, the type of tests and the related results are not uniform. Some analyses are conducted in the linear range and therefore only the initial stiffness or the level of stress due to a given horizontal load is assessed. In other cases the ultimate strength is evaluated as well; in this case, the investigations are conducted mainly by means of monotonic analyses, while the number of cyclic analyses is small.

As already mentioned, the most important factors affecting the structural response of infilled frames with openings are: the opening size, the strengthening conditions around opening and the opening position within the panel. In this work the influence of the opening position is not taken into account.

The opening size is taken into consideration by means of the following ratios:

$$\alpha_a = \frac{l_o h_o}{LH}\,100 \qquad \alpha_l = \frac{l_o}{L}\,100 \qquad \alpha_h = \frac{h_o}{H}\,100 \tag{3.1}$$

where L, H, l_o and h_o are indicated in Fig. 2.1 and 2.2.

The distribution of the data according to the ratios α_a and α_l is shown in Fig. 3.1. In 87% of the examined cases the area ratio, α_a, is in the range 0.02-0.25. In 97% cases the ratio between the opening width and the infill width, α_l, is in the range 0.02-0.40. The distribution according to the opening height to the infill height ratio, α_l, is somewhat regular.

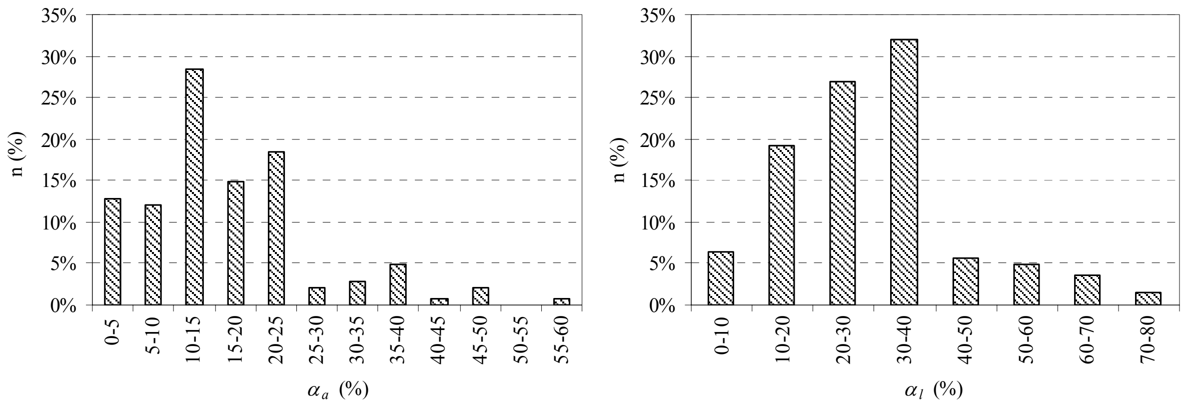

Figure 3.1. Distribution of tests according to the opening dimensions.

The presence of strengthening elements around the openings affects noticeably the strength and stiffness reduction and the crack pattern in the wall (Decanini *et al.* 1994). The reinforcement types can not be traced back to a strict classification due to their great variability. Anyway, taking into account the most frequent situations, the following classification is herein adopted:

- Not Strengthened opening (NS): the opening is not confined by lintel bands or steel reinforcement.
- Partially Strengthened opening (PS): at least the upper edge of the opening is strengthened by a lintel band.
- Strengthened opening (S): at least two opposite edges of the opening is strengthened by two lintel bands or by a lintel band and a steel bar, if the wall is reinforced the opening is considered strengthened.

Examples of partially and fully strengthened opening are schematically depicted in Fig. 3.2. Considering the whole data set, the openings are not strengthened in 68 tests, are partially strengthened in 25 tests and strengthened in the remaining 50 cases.

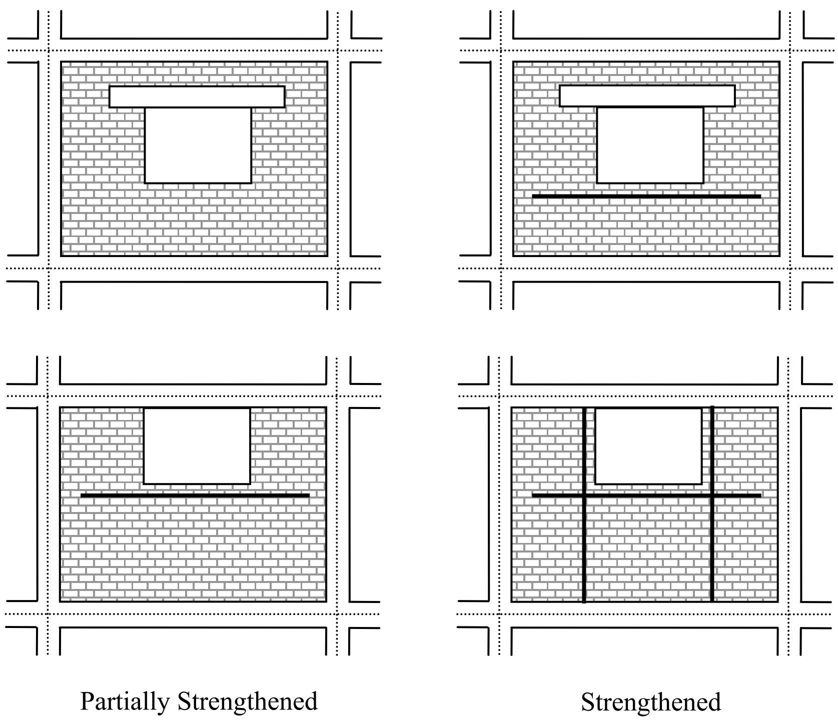

Figure 3.2. Examples of strengthening around opening

3.2. Stiffness and strength reduction

As already mentioned, the extension of the model to infills with openings requires a modification of both the cracked stiffness and the ultimate strength. The model proposed by Decanini *et al.* (Decanini and Fantin, 1987, Bertoldi *et al.* 1993, Decanini *et al.* 2005) for infills without openings supplies the ultimate horizontal strength, H_{mm}, and the stiffness corresponding to a state of steady cracking, K_{mm}, of the infill (Fig. 3.3):

$$H_{mm} = \left(\sigma_{br}\right)_{\min} e\omega\cos\theta \tag{3.2}$$

$$K_{mm} = \frac{E_m e\omega}{d}\cos^2\theta \tag{3.3}$$

where E_m and e are the Young's modulus and the thickness of the infill, ω is the effective width of the strut, θ and d are the slope and the length of the strut, respectively, and $(\sigma_{br})_{min}$ is the minimum ultimate stress among that corresponding to different modes of infill failure.

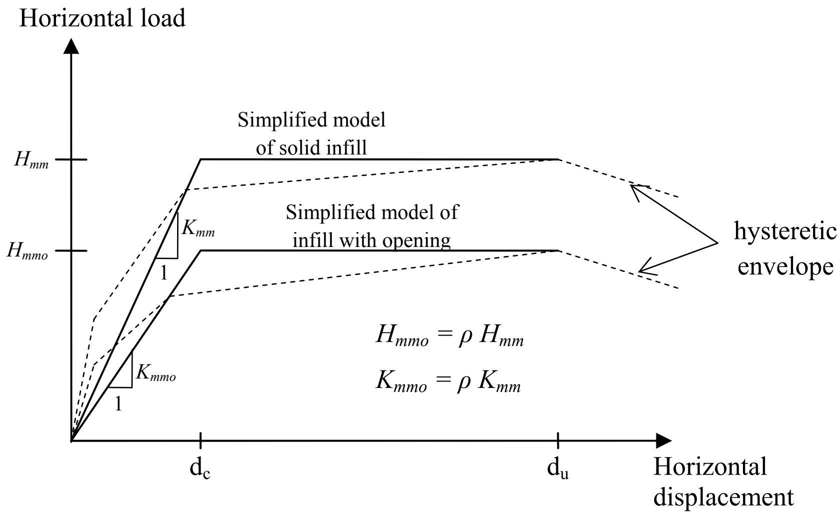

Figure 3.3. Example of strengthening around opening

A reduction of both stiffness and strength can be obtained decreasing the effective width of the strut. To asses if a unique factor is suitable to model both the strength reduction and the stiffness reduction the relation between them is analysed. In 59 of the considered tests both the stiffness (initial and/or secant) and the ultimate strength have been evaluated. For these tests, the relation between the stiffness reduction and the strength reduction due to the openings is analysed by means of the following ratio:

$$R = \frac{\rho_{stiffness}}{\rho_{strength}} \tag{3.4}$$

where $\rho_{stiffness}$ is the stiffness reduction factor, and $\rho_{strength}$ is the strength reduction factor due to openings.

A clear trend of R is not traceable. The average of the ratio R, evaluated for each group of tests, ranges between 0.60 and 1.46 and from 0.59 and 1.28 for steel frames and for RC frames, respectively. Considering the whole data base, the mean values of the ratio between the stiffness reduction and the strength reduction are equal to 0.94 and 0.93 when considering the secant stiffness and the initial stiffness, respectively. Moreover, the ratio R is not significantly affected by the opening size.

From what observed, it seems acceptable the use of a unique reduction factor for the evaluation of both the stiffness and the strength of the frame-infill systems with openings, i.e. the extension of the equivalent strut model can be realised simply modifying the strut width by means of a reduction factor ρ (Fig. 3.3). Anyway it must be underlined that this assumption derives from the approximation of an average trend and it is not always satisfied. In fact it would involve that the deformation at the attainment of the ultimate strength is the same in the panels with and without openings but this condition is not always achieved in the experimental tests.

The reduction factor (ρ) determined from the analyses is shown in Fig. 3.4 as a function of α_a. The reduction factor tends to decrease when the opening area increase. The influence of the opening length on the reduction factor is still present but less marked while the influence of the opening height is negligible. In any case the dispersion of the data is noticeable. The dispersion decreases if the samples are grouped according to the strengthening conditions of the opening, as shown in Fig. 3.4. Therefore, the whole data set has been divided according to the opening strengthening conditions: not strengthened (NS), partially strengthened (PS) and strengthened (S).

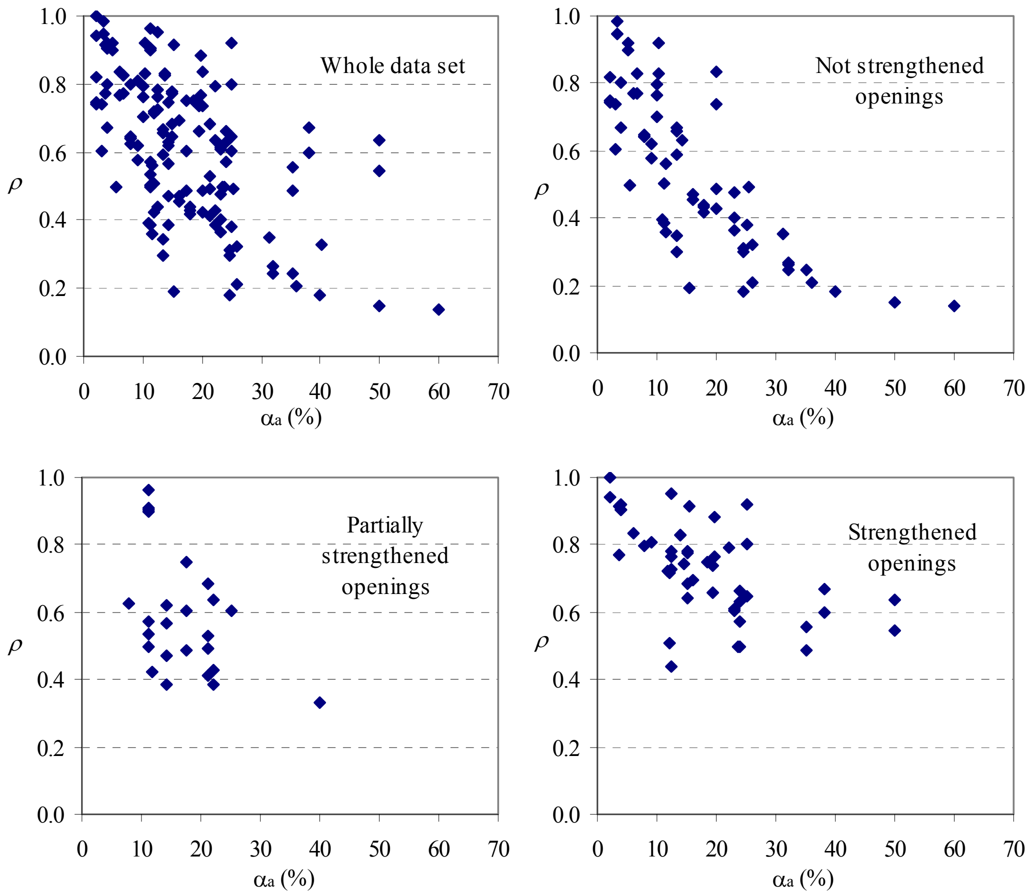

Figure 3.4. Reduction factor evaluated from experimental and numerical analyses

For each group of data, different equations have been taken into consideration (linear, polynomial, exponential and logarithmic) to express the reduction factor as function of the opening area and of the opening length ratios. Among the above functions the exponential one was found to be the most suitable to fit the observed data. Specifically, the reduction factor can be adequately expressed by the following equations, given by the sum of two exponential functions:

$$\rho = 0.55\exp(-0.035\alpha_a) + 0.44\exp(-0.025\alpha_l) \quad \text{For not strengthened opening} \quad (3.5)$$

$$\rho = 0.58\exp(-0.030\alpha_a) + 0.42\exp(-0.020\alpha_l) \quad \text{For partially strengthened opening} \quad (3.6)$$

$$\rho = 0.63\exp(-0.020\alpha_a) + 0.40\exp(-0.010\alpha_l) \quad \text{For strengthened opening} \quad (3.7)$$

The parameters of these functions have been evaluated by means of regression analyses.

The mean, the standard deviation and the coefficient of variation of the ratio between the prediction and the actual value, are reported in Tab. 3.1. In the same table the standard error is indicated. These values indicate that the proposed equations fit the observed data reasonably well in the average. The standard deviations and the coefficient of variation are acceptable for engineer problems.

Table 3.1. Comparison between predicted and actual reduction factor, statistical parameter

Strengthening conditions	Number of tests	Mean	SD	COV	SE
NS	68	1.083	0.288	0.266	0.136
PS	25	1.045	0.223	0.213	0.156
S	50	1.001	0.150	0.149	0.106

The reduction factor functions are plotted in Fig. 3.5 as a function of α_a for α_l = 20%, 40% and 60%. Each curve is depicted in its range of validity; for example the curves with α_l = 20% are shown only for 2% ≤ α_a ≤ 20% because values smaller than 2% would imply an opening height unrealistically small while values of α_a greater than 20% would entail α_h being greater than 100% (opening height greater than wall height).

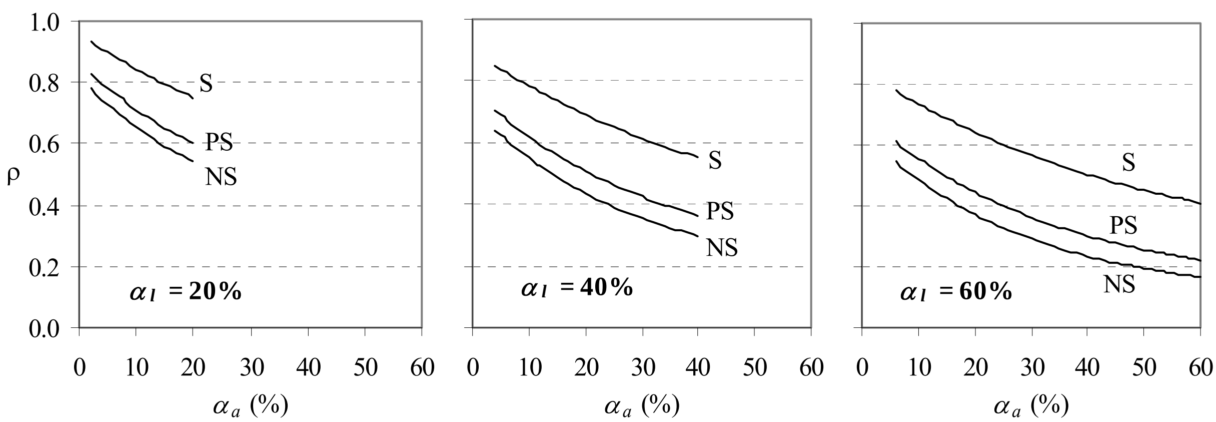

Figure 3.5. Proposed equations of the opening reduction factor

The proposed equations reflect several aspects, which have been experimentally observed:

- the reduction factor increases due to the presence of strengthening elements around the opening especially when a complete strengthening is provided (S curves);
- the influence of α_a and α_l decreases when the level of opening strengthening increases;
- when a non strengthened opening (NS curves) with an area greater than 40% of the infill area is present, then the contribution of the infill is negligible while if the opening is completely strengthened (S curves) the reduction factor is always greater than 0.4.

4. SUMMARY AND CONCLUSIONS

In framed structures the infill walls play an important structural role. Therefore their presence should be taken into account in the design and assessment procedures, particularly in regions of moderate and high seismicity. To this aim, simple model are available for solid infills walls, such as the diagonal no tension strut (or multi-strut) model while infills with openings have not been adequately investigated, even though different studies have been performed since the second half of the 1950s.

The presence of opening in infill panels represents a significant uncertainty in the evaluation of the seismic behaviour of infilled frames due to the great variability of opening sizes, opening position within the panel and presence of strengthening elements around the opening.

In the present study the effect of openings on the lateral stiffness and strength of infilled frames is studied by means of 143 numerical and experimental tests available in the literature. The study highlighted that the area and the depth of the opening and the strengthening conditions around the opening, like for example the presence of lintel bands or steel reinforcements, affect significantly the reduction of stiffness and strength of the panel. The position of the opening within the panel has not been specifically analysed in the present work, however, it is worthwhile to point out that opening located in a corner of the panel may produce unfavourable effects, like the formation of short columns in the frame. In seismic area openings in the corners should be avoided.

A simplified model to take into account the presence of openings in the infills is proposed. To this aim an extension of the strut model for solid infills to infills with openings is herein developed. This extension involves a modification of both the stiffness and the ultimate strength of the panel; this is obtained decreasing the effective width of the strut by means of a reduction factor. The reduction factor is function of: i) the ratio between the opening area and the panel area; ii) the ratio between the opening depth and the panel depth; iii) the presence of reinforcing elements around the openings.

The equations proposed for the reduction factor reflect different aspects experimentally observed: the strength and stiffness reduction decrease when strengthening elements are present around the opening; the influence of the opening size diminishes when the opening is strengthened; when a non strengthened opening with an area greater than 40% of the infill area is present, then the contribution of the infill is small while if the opening is strengthened the reduction factor is always greater than 0.4.

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