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NUMERICAL EVALUATION OF MASONRY INFILL WALLS BEHAVIOUR UNDER OUT-OF-PLANE LOADS

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ABSTRACT

Observation of damage in seismic events has highlighted that collapse of infill walls in the out-of-plane direction may occur even for moderate intensity of ground motion. Different analytical models have been proposed in the last decades for the assessment of the out-of-plane response of infills and their applicability under different conditions has been checked also with experimental tests.
In this paper, a numerical solution is adopted by using a smeared crack approach, in which the masonry panel is modelled as a a non-linear continuum and contact surfaces are located only at the interface between masonry and frame elements; horizontal out-of-plane loads are applied monotonically as body forces.
Height/thickness ratio, height/length ratio, masonry compressive strength and stiffness of frame elements are varied to investigate their influence on the out-of-plane resistance. Results confirm previous experimental evidence, such as the inverse proportionality of the strength with respect to the span length, the strength reduction with varying height/length ratio slightly affected by masonry compressive strength and thickness.
Comparisons of the results with analytical models show that, in general, the latter give a conservative estimate of the strength, but the degree of approximation of the considered equations is strongly affected by the height/thickness of the infill, and, to a much lesser extent, by the infill height/length ratio, whereas it is not influenced by the masonry compressive strength. It is found that each equation is suitable in a different range of height/thickness ratios.

Keywords: Masonry infill; RC frame; Smeared-cracks method; Nonlinear analysis; Out-of-plane strength

1. INTRODUCTION

Masonry walls are widely used as infills in framed structures. The presence of regularly distributed infills is generally beneficial due to their contribution to withstand seismic actions, even if it depends, among other parameters, on relative stiffness and strength of the different elements and connections.
Apart from their influence on the overall behaviour of the structure (Liberatore and Decanini 2011), observation of damage due to seismic events has highlighted that the collapse of infill walls, especially in the out-of-plane direction, may occur even for moderate intensity of the ground motion, causing casualty risks and heavy socio-economic losses.
During the 2009 L'Aquila, Italy, earthquake (M=6.3), damage to reinforced concrete (RC) frames was

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often restricted to exterior infill walls and interior partitions, varying from small cracks to collapse (Braga et al. 2011, Decanini et al. 2012). Masonry infill panels failed primarily out-of-plane mostly due to the lack of connections between the two wythes of the masonry panels and between the infill and the surrounding frame. Similar conditions have been reported after the 2011 Simav, Turkey, earthquake (M=5.7) (Inel et al. 2013), which also highlighted the higher vulnerability of infill walls placed at the overhang portions of buildings due the effect of the vertical acceleration, which loosen the contact between the wall and the surrounding beams. At the same time, often, failure of infills takes place at the lower stories of buildings, due to the interaction between in-plane and out-of-plane loads; namely, damage produced by in-plane shear forces, which are larger at the bottom storeys, increases the out-of-plane vulnerability of the infills. This indicates that out-of-plane damage cannot be merely related to out-of-plane floor accelerations, which are generally higher at the upper stories.

Failures have also shown that a predominant role in the out-of-plane response is played by the type of connection between the masonry and the frame, as during the 1999 Athens, Greece, earthquake (M=5.9), when defective joints between the infill and the upper beam triggered the tilting of the panel (Decanini et al. 2005).

For these reasons, the interest in the out-of-plane behaviour of infill walls has been growing in the last years, as witnessed by many recent studies (e.g. Hak et al. 2014, Furtado et al. 2016, Shing et al. 2016, Asteris et al. 2017).

Experimental tests have been conducted by different researchers to asses strength and ductility of masonry walls loaded in the out-of-plane direction. The published literature reports monotonic, cyclic and dynamic tests on masonry panels. Such studies have investigated the influence of various factors, e.g. the height/thickness ratio, the panel thickness, the boundary conditions, the presence of prior in-plane damage. A review is presented in Liberatore and Pasca (2014). Test results have shown the importance of the boundary conditions on both the breaking mechanism and the strength of the masonry; furthermore, both the height/thickness of the panel and the presence of prior in-plane damage affect the out-of-plane stiffness and strength of the wall.

At the same time, and in relation with the abovementioned experimental tests, several analytical models have been proposed, starting from the one-way spanning brickwork beams with rigid supports due to arching (McDowell et al. 1956). After that, based on empirical observations, the two-way arching action has been investigated by Dawe and Seah (1989) and Flanagan and Bennett (1999), who highlighted the circumstances that the support conditions influence noticeably the crack pattern and proposed similar expressions for the ultimate capacity, related to the masonry compressive strength, the panel thickness, length and height, and the bending and torsion stiffness of the columns and of the beams of the external frame.

Usually, the expressions suggested to estimate the out-of-plane capacity of infills are calibrated or verified through comparison with experimental results and are thus related to a specific type of frame (RC or steel) and of masonry (brick masonry, concrete block, etc.) and their use in different situations should be examined carefully. Models based on the arching behaviour may provide conservative or unconservative estimates of the capacity according to the model under consideration. Moreover, there are situations in which the arching behaviour does not develop even in the case of small height/thickness ratios.

A review of methods that have been proposed for the assessment of the out-of-plane response of infills is reported in Pasca et al. (2017), including those specified in current code provisions. In the same work, the authors have analysed the proposed analytical models suitability under different conditions, by applying some of these models to reproduce the out-of-plane strength measured in experimental tests.

Unfortunately, the use of predictive equations under conditions that differ from those used for their calibration turned out to be not always appropriate.

The great variability of the materials and the large number of parameters involved, makes it difficult the selection of a unique model for the assessment of the out-of-plane strength for the different real cases. And, even though different models take into account essential parameters, such as the height/thickness ratio and the boundary conditions of the panel, the strength of the masonry and the presence of cracks due to prior in-plane damage, the interaction among these factors is not straightforward and requires further investigation.

In this paper, the out-of-plane strength of infill walls is investigated by means of non-linear monotonic

(push-over) finite element analyses. Masonry is modelled by resorting to a smeared-crack approach, whereas contact surfaces are employed at the interface between masonry panel and surrounding structure. Frame elements are modelled by means of a linear elastic material.
With the aim of evaluating the influence of various features affecting the response, a parametric analysis is carried out. Different frame and panel characteristics are considered, such as the masonry panel dimensions, height/thickness ratio and compressive strength and the frame stiffness.
The results of the numerical analyses are discussed and compared with analytical expressions proposed by different authors. Being this study based on a parametric analysis, there is no comparison with experimental tests available in the literature, which has been performed and presented elsewhere (Pasca et al. 2017). Moreover, in a previous work (Liberatore et al. 2016), some experimental tests have been used to validate and calibrate the numerical model adopted herein for the parametric analysis.

2. NUMERICAL INVESTIGATION

To investigate the influence of the main parameters affecting the out-of-plane response, different models of one-bay one-storey RC infilled frames have been implemented varying the following features: height/length ratio (h/l = 0.6, 0.75, 1.0), height/thickness ratio (h/t = 8, 10, 12, 15, 20, 25), frame elements stiffness (two values are considered, one about double of the other), masonry compressive strength (f'_m = 1.5, 5, 10, 15 MPa). The height/length and height/thickness ratios are varied by changing the infill span and thickness, while the height remains constant and equal to 3 m.

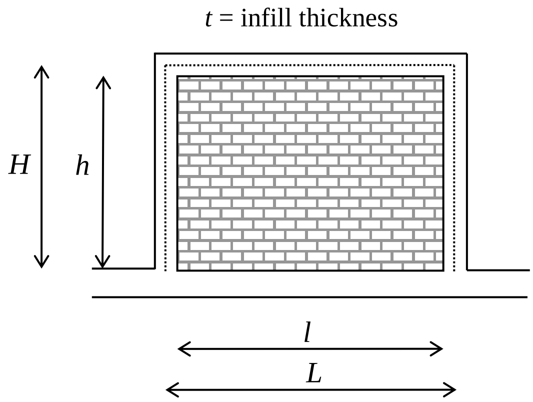

Figure 1. One-bay one-storey infilled frames.

2.1 Modelling aspects

In order to reproduce the out-of-plane response of masonry infill walls, the LS-DYNA software package (LSTC 2013) has been employed here within an ANSYS environment. In a previous study, different modelling strategies were assessed by means of comparisons with experimental tests available in the literature (Liberatore et al. 2016). Specifically, the following approaches have been examined: i) finite-discrete method with an elastic material; ii) finite-discrete method with a non-linear material and iii) smeared-cracks method with a non-linear material. In the first two cases, units were modelled as isolated elements connected to one another and to the frame by means of contact interfaces; either an elastic material or a nonlinear material were used for the units; in the first case the non-linearity was thus concentrated along the contact surfaces. In the smeared crack approach, the masonry panel was modelled as a non-linear continuum; the contact interfaces were located only at the interface between masonry and frame elements. The latter approach, which was found both efficient and able to reproduce the experimental response, is used in the present study to perform the numerical analyses. Masonry is thus modelled as a smeared crack material. Eight-node solid elements with a single integration point are used. The major disadvantage of one-point integration is the need to

control the zero-energy modes that arise, called "hourglassing" modes, which might enlarge and destroy the solution; to overcome this flaw, a Flanagan-Belytschko stiffness-type stabilisation is used (Hallquist 2006).
Contact interfaces, which allow the transmission of both compressive and tensile forces, are used to model the interaction between the masonry and the surrounding frame. In compression, to avoid the penetration between nodes and contact surface, the standard penalty method is used. The method consists in placing normal springs between surfaces that are in contact. The interface stiffness depends on the stiffness of the materials that are in contact and on a scale factor, named penalty factor. For this parameter, a default value of 0.1 is recommended in the case of contact between similarly refined meshes of comparably stiff materials. However, a value of 0.05, which is expected to give more adequate results for masonry materials (Burnett et al. 2007), is used in this study.
To investigate the influence of specific parameters without introducing further sources of variability, the frame horizontal displacements are not permitted in the out-of-plane direction. At the bottom, the frame is fixed, whereas the masonry panel is connected to the ground by means of contact interfaces.
A linear elastic material is employed for the frame, whereas the Winfrith smeared-crack concrete material model (Broadhouse and Attwood 1993) is used for the masonry. The model is defined by the initial tangent modulus, the Poisson's ratio and the uniaxial compressive and tensile strengths. The default pressure versus volumetric strain curve is adopted.
Gravitational loads are first applied to the model. Static or quasi-static loads are simulated resorting to mass damping to eliminate dynamic oscillations. Moreover, to avoid high frequency oscillations during the application of the gravity loads, these are applied slowly from zero to gravity acceleration. Afterward, horizontal loads are applied monotonically in the out-of-plane direction as body forces, i.e. proportional to the mass.

3. RESULTS

Out-of-plane strength and stiffness are estimated from the numerical analyses. The pushover curves, i.e. the horizontal pressure versus horizontal displacement of the infill mid-point are plotted and analysed. An example is reported in Figure 2, where the pressure q is shown as a function of mid-point out-of-plane displacement. The curves show that the response is linear elastic until the cracking of the infill; afterward, an abrupt increment of the horizontal displacement is observed. Due to the fact that the analyses are force-controlled, ultimate displacements and ductility cannot be assessed. As expected, the effect of the panel height/thickness ratio on both horizontal stiffness and strength is significant.

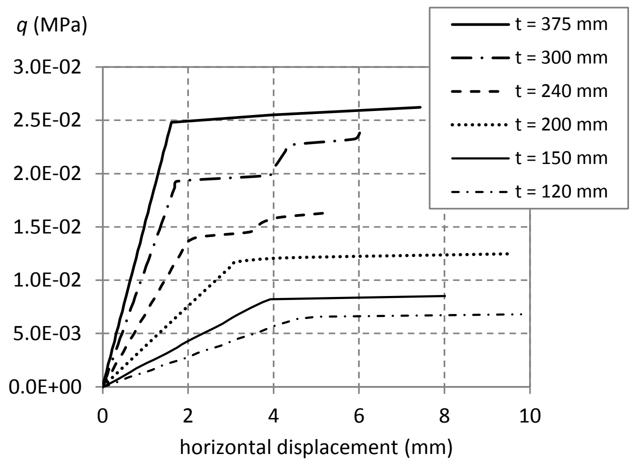

Figure 2. Out-of-plane pressure versus horizontal displacement with varying infill thickness, infill characteristics: h = 3 m, f'_m = 1.5 MPa.

The effect of the height/thickness ratio and of the masonry compressive strength on the out-of-plane resistance is highlighted in Figure 3 for three different height/length ratios: h/l = 1, 0.75 and 0.6. A strength reduction is noted with decreasing height/length ratio. This outcome is consistent with the

formation of a two-way arching action that can fully develop when the height/thickness ratio is close to 1; on the contrary, when one dimension is significantly larger than the other, the arching action tends to develop mainly along the shorter direction.
The strength reduction with varying height/length ratio is slightly affected by the masonry compressive strength and by the infill thickness. The ratio between the strength estimated for height/length ratios lower than 1 and the strength obtained for the square infill (height/length ratio = 1) is almost constant with the variation of the other two parameters; the mean values of this ratio and the corresponding standard deviations and coefficient of variations are reported in Table 1. For height/length ratios equal to 0.75 and 0.60 the strength is, on average, about 0.73 and 0.58 of that for h/l = 1.00, respectively. These values confirm experimental evidence according to which the strength is inversely proportional to the span length (Pasca et al. 2017). The coefficient of variation of the above ratio is about 0.11 in both cases, indicating a very low dispersion of the data.
In Figure 3, trend-lines are also reported for different values of the masonry compressive strength. The strength is accurately reproduced as a function of the height/thickness ratio by a power law with exponent comprised between –1.17 and –1.37, such as:

$$q = c\left(\frac{h}{t}\right)^{-1.17 \div -1.37} \quad (1)$$

where c is a coefficient dependent on the masonry compressive strength and, to a lesser extent, on the panel height/length ratio. As expected, the out-of-plane capacity decreases with decreasing masonry compressive strength. However, this reduction is more evident for the thicker infills (lower height/thickness ratio in Figure 3).

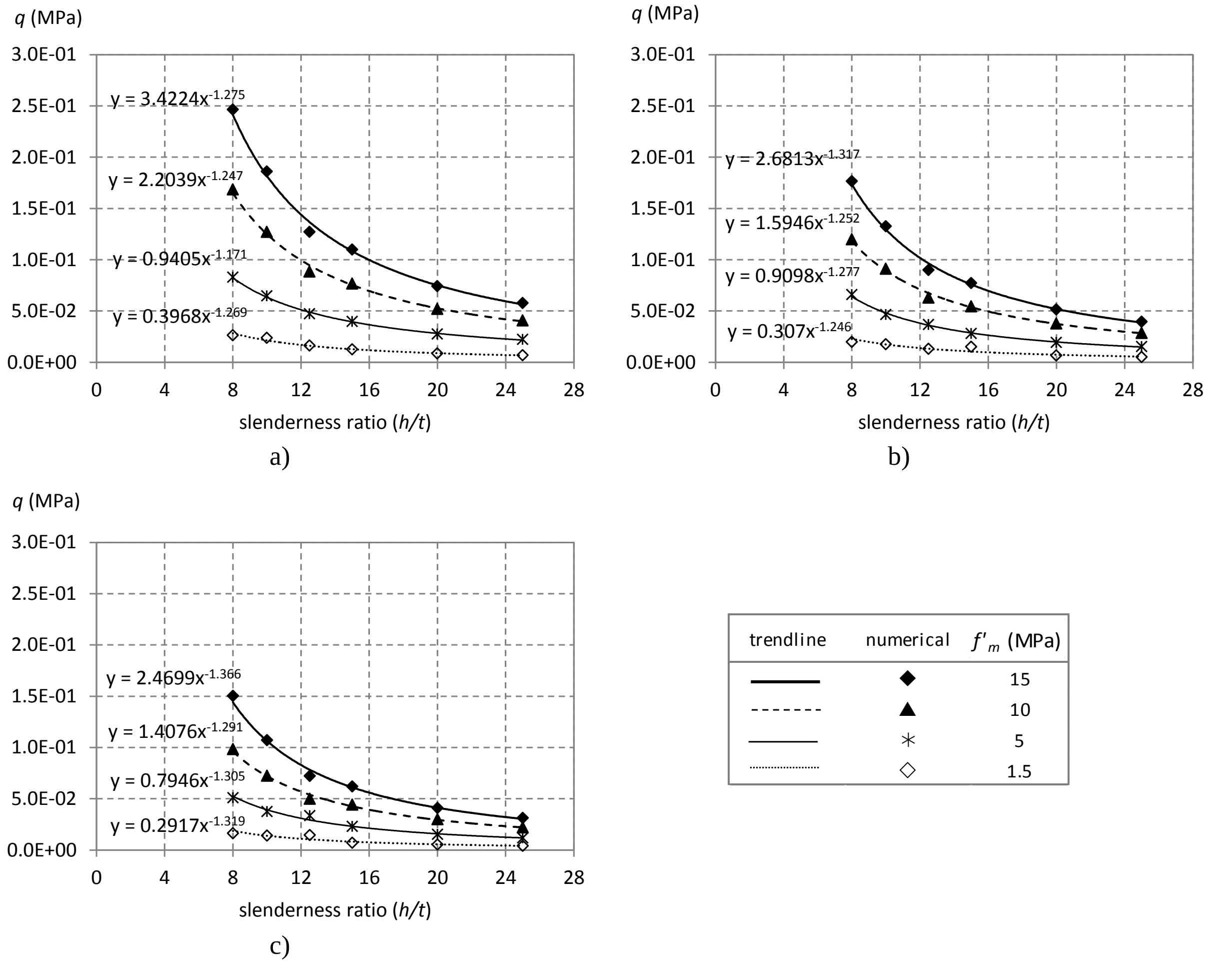

Figure 3. Out-of-plane strength: a) h/l = 1 (panel 3×3 m^2); b) h/l = 0.75 (3×4 m^2); c) h/l = 0.6 (3×5 m^2). Trend-lines are also reported, where y represents the strength per unit area, q, and x is the height/thickness ratio, h/t.

Table 1. Ratio between the strength estimated for infills having h/l = 0.75 (3×4 m^2) and h/l = 0.6 (3×5 m^2) and the strength obtained for the square infill (h/l = 1, 3×3 m^2).

	$q_{3\times4}/q_{3\times3}$	$q_{3\times5}/q_{3\times3}$
mean	0.731	0.584
standard deviation	0.081	0.061
coefficient of variation	0.111	0.105

As far as the frame stiffness is concerned, the performed analyses do not show significant differences for the two frames considered. However, the increase of the frame member stiffness should result in an improvement of the infill out-of-plane capacity. This aspect deserves further investigation.

3.1 Comparison with analytical models

For the considered infilled frames, the ultimate load has been calculated according to different formulas available in the literature. Specifically, the equations listed in Table 2 have been applied. They are based on the arching theory (one-way arching or two-way arching), according to which an arching effect develops in the panel, if properly constrained, when subjected to out-of-plane loads. In general, this effect depends on the capacity of the frame members of resisting the thrust and on the infill height/thickness and height/length ratios.

Table 2. Analytical model considered for comparison.

Ref.	**Equation**	
Dawe and Seah (1989)	$q = 4.5(f'_m)^{0.75} t^2 (\alpha/l^{2.5} + \beta/h^{2.5})$	(2)
Angel et al. (1994) and Abrams et al. (1996)	$q = \dfrac{2f'_m}{(h/t)} \lambda R_1 R_2$	(3)
Bashandy et al. (1995)	$Q = 8\,\dfrac{M_{yv}}{h}(l-h) + 8\,M_{yv} ln(2) + 8\,\dfrac{M_{yh}}{h}\left(\dfrac{x_{yv}}{x_{yh}}\right) ln\left(\dfrac{l}{l-h/2}\right) l$	(4)
Eurocode 6 (2005)	$q_d = f_d \left(\dfrac{t}{l_a}\right)^2$	(5)

h = panel height; l = panel length; t = panel thickness; f'_m = masonry compressive strength; q = uniform pressure which causes the out-of-plane collapse; α and β = parameters which depend on the bending and torsional stiffness of columns and beams; λ = parameter depending on the height/thickness ratio; R_1 = reduction factor that accounts for the magnitude of prior in-plane damage;
R_2 = reduction factor that accounts for the flexibility of the confining frame; Q = out-of-plane force resistance; x_{yv} and x_{yh} are functions of the mechanical and geometrical characteristics of the infill;
M_{yv} and M_{yh} are functions of x_{yv} and x_{yh} and of the masonry compressive strength; q_d = design lateral strength; f_d = design compressive strength of the masonry in the direction of the arch thrust and l_a = length or height of the wall between supports capable of resisting the arch thrust.

Equations 2 and 4 take into consideration the two-way arching effect, which develops when the infill is restrained at four edges. In Bashandy et al. (1995), the infill is divided into vertical and horizontal strip segments, the maximum out-of-plane deflection is governed by the crushing of masonry in the central strips, and, in Equation 4, the first term is the force resisted by the central vertical strips, the second term is the force resisted by the lateral vertical strips and the third term is the force resisted by

the horizontal strips. Equations 3 and 5 take into account the arching action only in one direction (vertical or horizontal), the former considers also the effect of in-plane damage on the out-of-plane resistance and the effect of the flexibility of the confining elements. Equation 5 gives a design lateral strength and is valid for height/thickness ratios not exceeding 20; in this paper, with the aim of comparison, this equation is applied considering the mean compressive strength of masonry in lieu of the design strength.
The mean, standard deviation and coefficient of variation of the predicted/numerical strength ratios are reported in Table 3. The predicted values are those calculated with the equations listed in Table 2, whereas the numerical values are those estimated through the numerical analyses. On average the considered analytical models give a conservative estimate of the numerical strength, with the exception of the Bashandy et al.'s one. However, the degree of approximation of the considered equations is strongly affected by the height/thickness ratio of the infill, and, albeit to a much lesser extent, by the infill height/length ratio, as shown in Figure 5, where data are grouped according to height/thickness ratio, height/length ratio and masonry compressive strength.

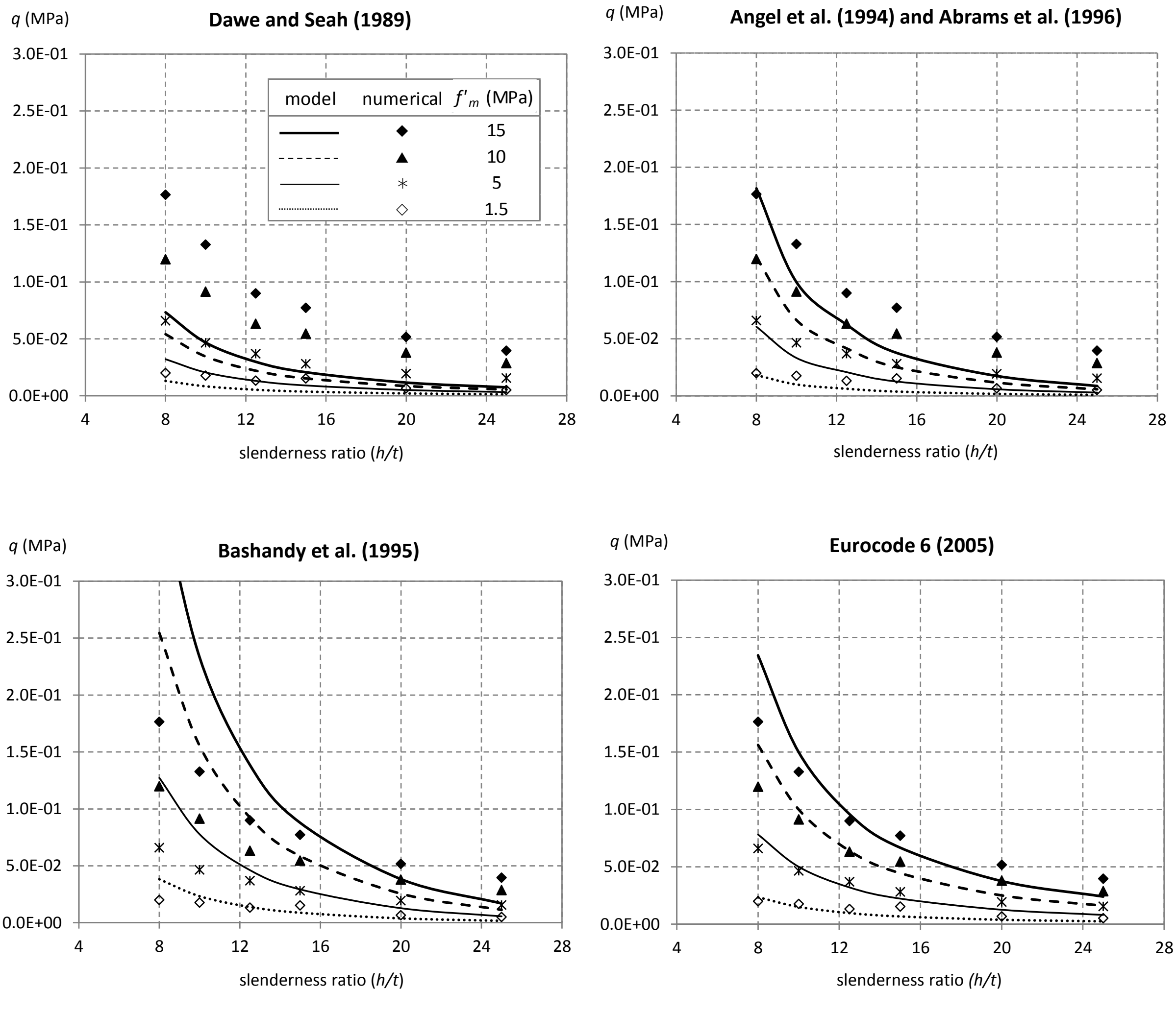

Figure 4. Out-of-plane strength, panel dimensions 3×4 m^2, comparison between numerical values (present study) and analytical models (Table 2).

Figures 4 and 5 highlight that:

- the Dawe and Seah's equation underestimates the numerical strength, the mean values of the predicted/numerical ratio being always smaller than 0.6. The degree of approximation is almost independent of the height/length ratio and of the masonry compressive strength, whereas it depends on the height/thickness ratio: the higher is the height/thickness ratio, the worst is the prediction;

- concerning the Angel et al.'s model and the Eurocode 6 equation, the prediction/numerical ratio decreases, on average, with increasing height/thickness and height/length ratios, while the influence of the masonry compressive strength is not evident;
- the Bashandy et al.'s equation overestimates the numerical strength for height/thickness ratios lower than 15, whereas it underestimates the strength for higher height/thickness ratios. The mean predicted/numerical strength ratio is not affected by height/length ratio, indicating that the equation is able to capture the two-way arching effect, which depend on both height and length of the infill wall, and it is slightly affected by the masonry compressive strength, being the mean ratios comprised between about 1.06 and 1.34.

Table 3. Ratio between the strength predicted by analytical models (Table 2) and estimated by the numerical analyses.

	predicted/numerical strength			
	Dawe and Seah (1989)	Angel et al. (1994) Abrams et al. (1996)	Bashandy et al. (1995)	Eurocode 6 (2005)
mean	0.3868	0.6532	1.2280	0.8525
standard deviation	0.1362	0.3885	0.5953	0.3167
coefficient of variation	0.3520	0.5948	0.4848	0.3715

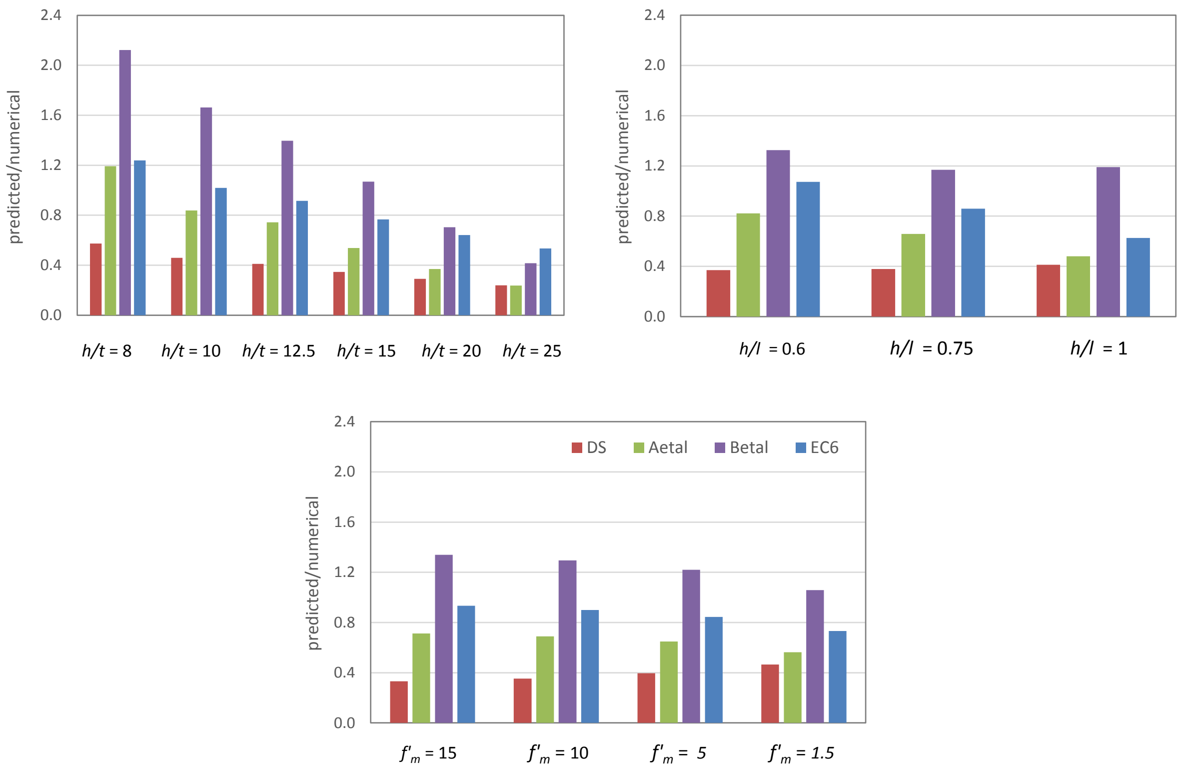

Figure 5. Mean ratio between the predicted and numerical strength. Data are grouped according to slenderness ratio (*h/t*), height/length ratio (*h/l*) and masonry compressive strength (f'_m). DS = Dawe and Seah (1989), Aetal = Angel et al. (1994) and Abrams et al. (1996), Betal = Bashandy et al. (1995), EC6 = Eurocode 6 (2005).

4. CONCLUSIONS

Numerical analyses were performed to assess the out-of-plane response of masonry infills. Masonry is modelled by resorting to a smeared crack approach and contact surfaces are placed at the interface between masonry and frame elements. Horizontal out-of-plane loads are applied monotonically as body forces, therefore the degradation of stiffness and strength after the peak load and the ultimate displacement are not assessed. The out-of-plane resistance has been investigated considering the following parameters: height/thickness ratio, height/length ratio, masonry compressive strength and stiffness of frame elements. A comparison of the results with analytical models proposed by different authors is finally performed. The main inferences of the study can be summarised as follows.

- For height/length ratios equal to 0.75 and 0.60, the strength is, on average, about 0.73 and 0.58 of that for a square infill, respectively. This trend confirms experimental evidence according to which the strength is inversely proportional to the span length.
- The strength reduction with varying height/length ratio is slightly affected by the masonry compressive strength and by the infill thickness.
- The strength is accurately reproduced as a function of the height/thickness ratio by a power law with exponent comprised between –1.17 and –1.37.
- The reduction of the out-of-plane capacity with decreasing masonry compressive strength is more evident for thicker infills and less for more slender panels.
- Concerning the surrounding frame, it was expected that an increase of the member stiffness, which implies a larger capacity to resist thrusts from arching actions, would result in an increase of the infill out-of-plane capacity. Such effect was not observed but this aspect requires further investigations.
- In general, the considered analytical models give a conservative estimate of the strength, with the exception of the Bashandy et al.'s one. However, the degree of approximation of the considered equations is strongly affected by the height/thickness ratio of the infill, and, to a much lesser extent, by the infill height/length ratio, whereas it is not influenced by the masonry compressive strength. This indicates that each of the considered equations is suitable in a different range of height/thickness ratios.

Other aspects that require further investigations and are not dealt with in this study are the presence of previous in-plane damage and the presence of openings in the infill. Several authors have investigated the former, whereas the effect of openings has not been adequately studied until now. However, it is possible to assert that both the in-plane damage and the openings have a negative effect on the out-of-plane stiffness and strength of an infill wall.

5. ACKNOWLEDGMENTS

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