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Parametric Analysis of Out-of-Plane Seismic Behaviour of Unreinforced Masonry Infill Walls: An Analytical Study

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ABSTRACT

Masonry infill walls are a common technique in reinforced concrete (RC) frames. These elements, defined as non-structural, strongly influence the seismic performance of RC frames and can be responsible for brittle failure mechanisms, such as out-of-plane infill collapse.

This paper aims to present the application of an analytical model for evaluating out-of-plane (OOP) lateral behaviour in a comprehensive parametric analysis of the main parameters governing the OOP behaviour of masonry infills. The variation of the geometric and mechanical properties of the masonry, the slenderness and aspect ratio of the infill. The analytical model incorporates vertical and horizontal arch mechanisms, considering the flexibility of the RC frame elements surrounding the panel and considering potential external reinforcement solutions. The reliability of the proposed model was also demonstrated by comparison with experimental results.

KEYWORDS

Analytical model, arch mechanisms, Masonry infill wall, Out-of-Plane (OOP) capacity, Parametric Study.

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INTRODUCTION

The use of masonry infill walls within reinforced concrete (RC) frames is a widely adopted construction practice worldwide. While these infill walls are often classified as non-structural elements in many design codes, their influence on the overall structural behaviour of buildings is significant and cannot be overlooked. They can alter the seismic response of RC frames, affecting both strength and stiffness, and their fragility often leads to damage that compromises building functionality and incurs substantial economic losses, even during minor to moderate seismic events [1].

Over the past decades, extensive experimental campaigns have been conducted to understand better the In-plane (IP) and Out-of-Plane (OOP) behaviour of masonry infill walls [2-11]. However, the outcomes of these studies often differ due to a variety of factors, such as differences in test scales, the types of RC frames used, the mechanical properties and configuration of the masonry units (e.g., compressive strength and hole orientation), the slenderness and aspect ratio of the infill walls, and the nature of the applied loading. This variability makes it challenging to interpret the results comprehensively and has hindered the development of widely accepted formulations for evaluating the OOP capacity of different infill walls.

The present study applies an analytical model, previously introduced and validated in earlier publications [12], to perform a parametric analysis of the key characteristics governing the behaviour of masonry infill walls. These characteristics include the mechanical and geometric properties of the masonry, the slenderness, and the aspect ratio of the infill walls. The analytical model evaluates the arching behaviour of the panel in both vertical and horizontal directions, as well as their combined plate effect, while accounting for the deformability of the RC frame.

PRESENTATION OF THE ANALYTICAL MODEL

The analytical model is designed to evaluate the out-of-plane (OOP) capacity of masonry infill walls within reinforced concrete (RC) frames, accounting for both unreinforced and reinforced masonry configurations. The model has been developed and implemented in a MATLAB environment to facilitate the iterative resolution of equilibrium conditions.

The failure mechanism of the infill wall, illustrated in Figure 1, is based on a plate-like behaviour and can be assessed through the arching mechanism in both the vertical and horizontal directions. These mechanisms are analysed separately and then combined to determine the overall response. Depending on the section under analysis, the aspect ratio of the panel, and the failure angle—calculated as a function of the masonry unit geometry following the approach by Vaculik and Griffith [13]—, the panel is divided into two or three rigid segments for both arching mechanisms.

Each segment rotates rigidly around the frame supports (i.e., beams or columns), linking the displacement at the centre of the infill panel to a specific rotation angle, as shown in Figure 1. The model also considers the deformation of the elastic supports due to the rotation of the segments, which affects the geometric configuration of the system and the internal forces (tension and compression) within the sections.

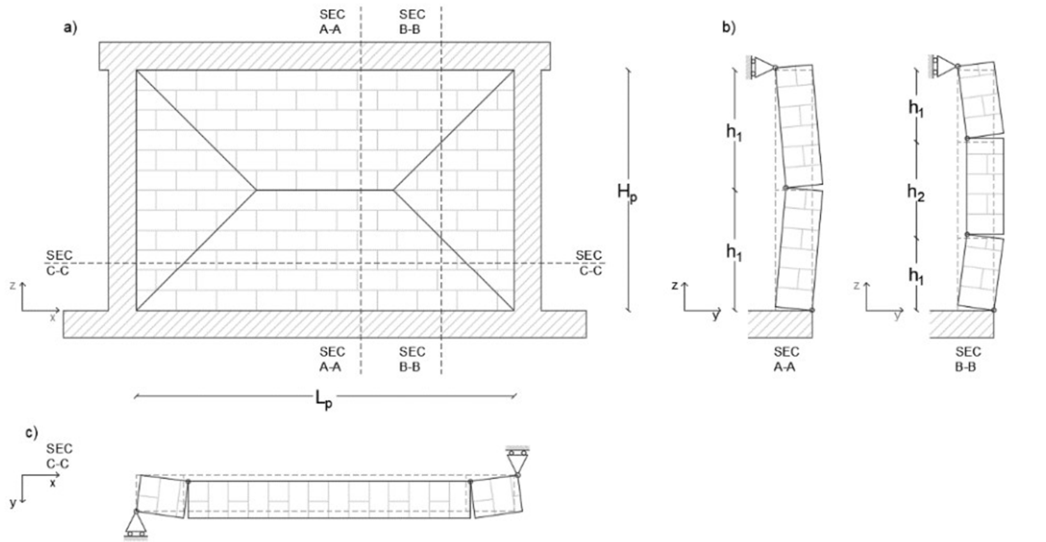
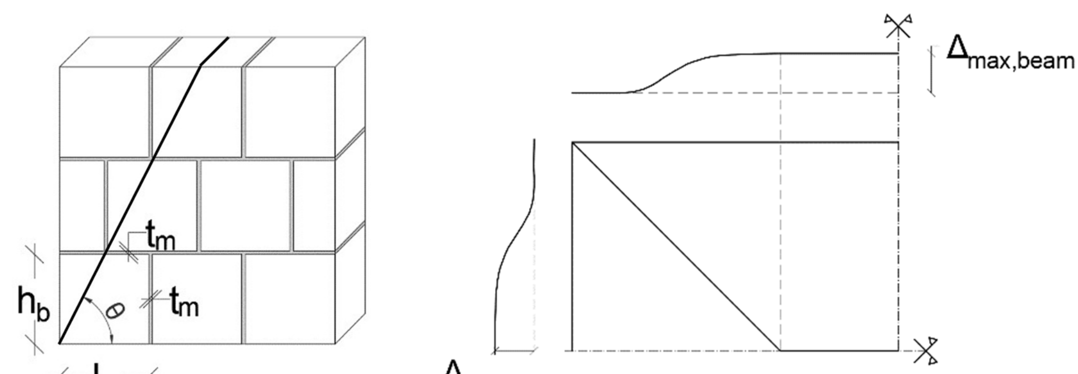


Figure 1: Front view of the infill wall (a); sections of the two-segment and three-segment (b) vertical arch mechanisms, and the three-segment horizontal arch mechanism (c).



a b

Figure 2: a) Failure angles θ and b) deformation of the perimeter constraints

The deformation of the perimeter constraints (Δbeam and Δcolumns) is defined as a function of their flexural stiffness in a double-clamped configuration, as illustrated in Figure 2b. The maximum deformation occurs at mid-span sections, characterized by two segments, and decreases near the beam-column joint, where the deformation is assumed to be zero.

The out-of-plane load can be modelled as concentrated forces applied at one-third of the panel height (according to Minotto et al. [3]) or as a uniformly distributed load (pressure) along the panel height.

The compressive behaviour of the masonry and plaster is represented using an elastoplastic stress-strain relationship with a softening branch (Figure 4), while the tensile behaviour of reinforcements, when these are applied to the infill wall, is modelled as elastic with brittle fracture.

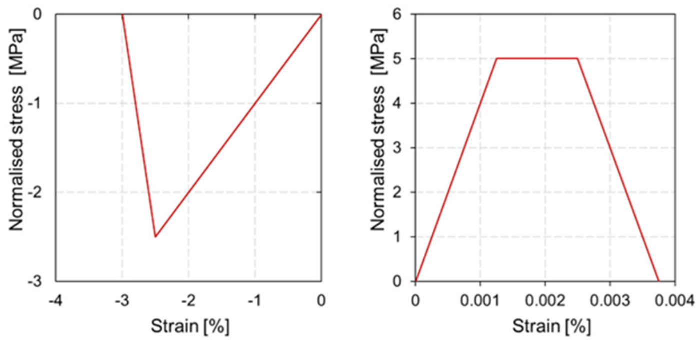


Figure 3: Stress-strain law of tensile reinforce (right), stress-strain law of masonry and plaster in compression (left)

The OOP resistance of the infill walls is determined through an iterative computational process that establishes the rotational equilibrium of the masonry segments under external OOP loads and the reaction forces from the confining frame. The algorithm starts by assigning an initial displacement and computing the corresponding rigid rotation of the segments, along with the induced deformations of the bounding frame. The interaction between masonry and confining elements is resolved iteratively by updating displacement and force equilibrium until convergence is reached. Once the deformation state is determined, stabilizing moments are computed at cross-sections, and finally the external load responsible for the imposed OOP displacement. The process continues iteratively until the post-peak resistance drops to 60% of the maximum capacity or a predefined displacement threshold is reached. This approach is applied separately to both vertical and horizontal arching mechanisms, considering the specific mechanical properties governing each direction.

For further details on the functioning of the analytical model, readers are referred to the work of Gaspari et al. [12], where its validation is also presented through different experimental campaigns conducted on various infill walls. Additionally, Figure 4 provides an excerpt of this validation, comparing the model's results (red line) with two experimental campaigns (black line): one on an unreinforced masonry (URM) panel [4] and another on a panel strengthened with a fiber-reinforced mortars (FRM) solution [3].

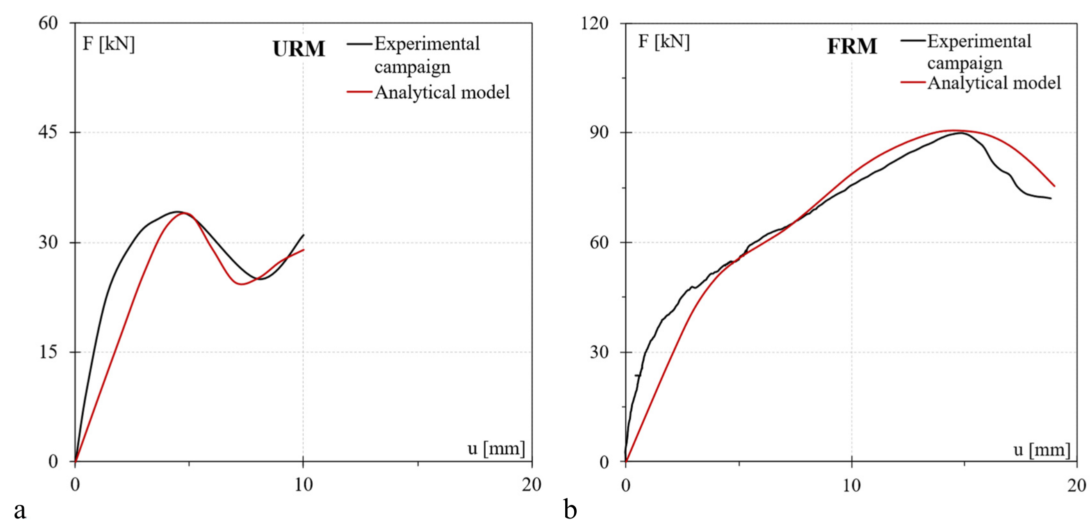


Figure 4: Comparison of the model's results with experimental campaign a) URM and b) FRM

PRESENTATION OF THE PARAMETRIC ANALYSIS AND DISCUSSION OF THE RESULTS

This study presents a parametric analysis aimed at evaluating the Out-of-Plane (*OOP*) resistance of unreinforced clay unit masonry infill walls. The resistance, expressed as a uniform pressure on the panel (in MPa), is analysed through two distinct parametric investigations. The first analysis examines the influence of the aspect ratio (*L/H*) and the compressive strength of the masonry (f_m) on the OOP resistance. The second analysis explores the relationship between the OOP resistance and the slenderness ratio (*H/t*) of the infill walls.

Effect of the aspect ratio

The analysis varied the aspect ratio by maintaining a constant panel height of 2.65 m, selected to reflect realistic dimensions commonly used in RC frames, while incrementally increasing the panel width. The aspect ratio (L/H) ranged from 0.5 to 5. The compressive strength of the masonry (f_m) was analyzed for three values: 5.3, 4.1, and 3.3 N/mm², in the direction of the perforations in the masonry units. These values correspond to clay blocks with characteristic compressive strengths of 10, 7.5, and 5 N/mm², respectively, combined with mortar of 10 and 5 N/mm², as prescribed by the Italian building code [14]. In the direction perpendicular to the perforations, the compressive strength was assumed to be 1/4 of the strength parallel to the perforations.

The wall thickness was fixed at 120 mm, including two 10 mm layers of plaster on both sides. This configuration resulted in a slenderness ratio (H/t) of 18.92, classifying the panel as a slender masonry wall according to Eurocode 8 recommendations. In accordance with typical construction practices for slender masonry walls, the perforation in the masonry units were oriented horizontally. For all the analyses performed, the failure angle (θ) of the panel was set to 45°.

The RC frame was defined with a rectangular cross-section for both the columns and the top beam, adopting dimensions and reinforcement details representative of construction practices in seismic zones. The columns had a cross-section of 30×30cm, with 3% longitudinal reinforcement relative to the cross-sectional area. The transverse reinforcement consisted of 10 mm diameter stirrups spaced at 50 cm in the critical zones and 8 mm diameter stirrups spaced at 130 cm in the central zones. The beam had a cross-section of 50×25cm, with 2% longitudinal reinforcement relative to the cross-sectional area. Its transverse reinforcement included 8 mm diameter stirrups spaced at 60 cm in the critical zones and 8 mm diameter stirrups spaced at 130 cm in the central zones.

The results of this parametric analysis are illustrated in Figure 5, which shows the OOP resistance (*Q*) of the infill walls as a function of the aspect ratio (*L/H*) for varying values of masonry compressive strength (f_m). The graph highlights that infill walls with low aspect ratios (*L/H<1*) exhibit higher resistance values. This is because the contribution of the horizontal arching mechanism increases significantly in this range. Additionally, since the horizontal arch acts along the direction parallel to the perforation of the clay blocks, where the compressive strength is higher, this further enhances the resistance of the panel. Beyond an aspect ratio of 1, the contribution of the horizontal arching mechanism stabilizes, as the size of the rotating segments resisting the OOP load no longer increases. Consequently, as *L/H* increases further, the behaviour of the panel stabilizes and transitions toward being dominated by the vertical arching mechanism.

The influence of masonry compressive strength (f_m) is also evident in the graph, with higher f_m values consistently leading to greater resistance across all aspect ratios. The trends observed align with the expected mechanical behaviour of infill walls, confirming the analytical model's ability to capture the key parameters governing OOP resistance.

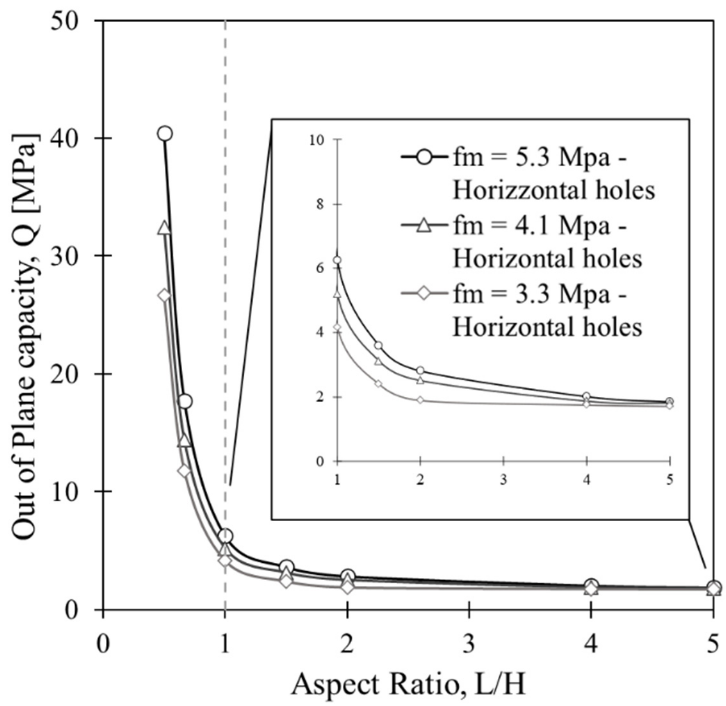


Figure 5: Out-of-plane capacity (Q) of the infill walls as a function of the aspect ratio (L/H) for different values of masonry compressive strength (fm)

Effect of the slenderness ratio

The second parametric analysis focused on the slenderness ratio (*H/t*) of the infill walls, defined as the ratio between the panel height (*H*) and its thickness (*t*). In this analysis, three aspect ratios (*L/H*) were investigated: 0.67, 1, and 1.5, while the masonry compressive strength (f_m) was fixed at 4.1 MPa. The out-of-plane capacity (*Q*) was evaluated as a function of the slenderness ratio by varying the panel thickness (*t*) from a minimum of 8 cm to a maximum of 30 cm. A 1 cm plaster layer was applied on each side of the panel for all configurations. The panel height was kept constant at 2.65 m to reflect realistic dimensions. The failure angle (θ) of the panel and the frame characteristics were the same as those used in the previous parametric analysis.

The results of this parametric analysis are illustrated in Figure 6. The black line with circular markers represents the OOP capacity trend for infill walls with vertical perforation, while the grey line with square markers corresponds to infill walls with horizontal perforation. The dashed line at H/t = 15 represents the lower slenderness limit recommended by Eurocode 8 [15] to classify a masonry infill walls as slender. In accordance with typical construction practices for slender masonry walls, the perforations in the masonry units are oriented horizontally to ensure adequate mortar adhesion and bond between blocks.

The relationship between perforation orientation and aspect ratio (L/H) plays a critical role in determining the out-of-plane (OOP) behaviour of masonry infill walls. For L/H > 1, infill walls with vertical perforation exhibit significantly higher OOP capacities compared to those with horizontal perforation, highlighting the dominant contribution of vertical arching mechanisms. This suggests that vertical perforation orientation should be preferred over horizontal orientation in such configurations to enhance structural performance. Conversely, for L/H = 1, the OOP capacities of both orientations are nearly identical, indicating that aspect ratio serves as a pivotal parameter in assessing the influence of perforations orientation on panel behaviour.

Regardless of the aspect ratio, increasing the slenderness ratio (H/t) leads to a marked reduction in OOP capacity. This effect becomes especially pronounced beyond the Eurocode slenderness limit (H/t > 15), where the decline is sharper, underscoring the importance of panel thickness in ensuring structural performance under out-of-plane loads.

To further validate the described observations, a third parametric analysis was conducted, focusing on aspect ratio while varying both the aspect ratio (L/H) and the direction of perforations. The results of this analysis are presented in Figure 7. The colour scheme and markers are consistent with those of the previous figure, and the dashed line highlights the condition where L/H = 1. This additional parametric study further confirms the conclusions outlined above, reinforcing the significance of aspect ratio and perforations orientation in influencing OOP capacity.

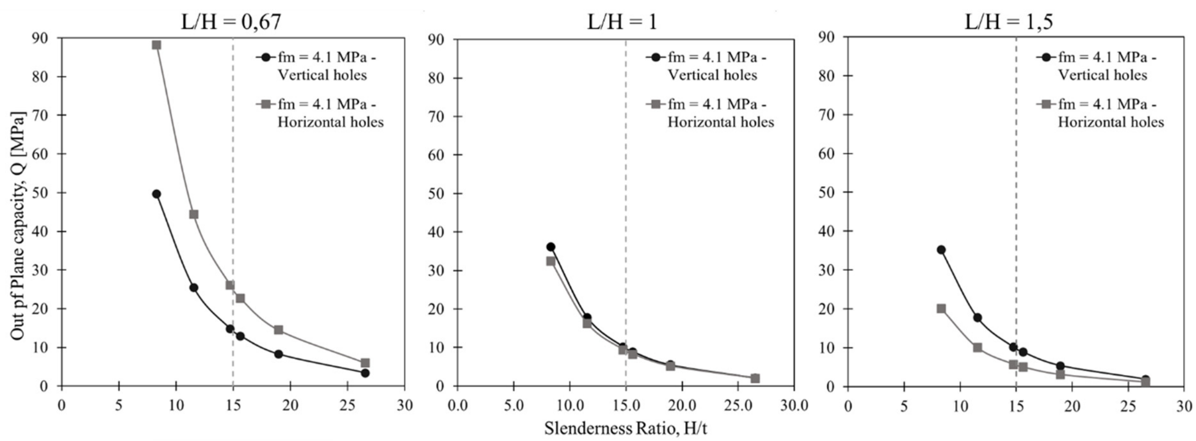


Figure 6: OOP capacity of infill walls depending upon the slenderness ratio (H/t) and aspect ratio (L/H)

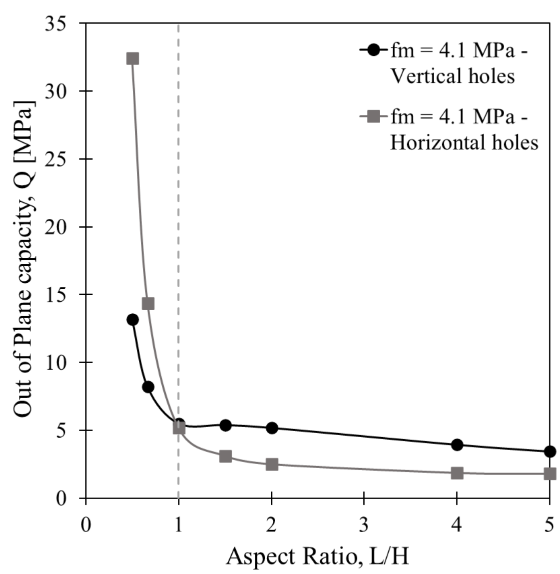


Figure 7: OOP capacity of infill walls depending upon aspect ratio (L/H) and perforation orientation

CONCLUSION

This study investigated the out-of-plane (OOP) resistance of masonry infill walls through a parametric analysis focusing on the influence of aspect ratio (*L/H*) and slenderness ratio (*H/t*). The results provide valuable insights into the structural behaviour of masonry infill walls and highlight critical factors that should inform design practices.

The aspect ratio (L/H) was found to significantly affect the OOP capacity of masonry infill walls. Infill walls with lower aspect ratios (L/H < 1) exhibited higher capacities when perforations were oriented horizontally, while infill walls with higher aspect ratios (L/H > 1) performed better with vertically oriented perforations. For infill walls with L/H = 1, the OOP capacities of both perforation orientations were nearly identical. The results of the parametric analysis clearly show that masonry with horizontally perforated units outperforms vertically perforated units only in the case of very narrow frames (i.e., when the panel length is smaller than its height). However, such configurations are rarely encountered in practice. Therefore, the preferred solution should be the use of vertically perforated units, particularly for aspect ratios greater than or equal to 1, as this orientation enhances OOP performance. These findings emphasize the importance of the aspect ratio in determining the structural performance of masonry infill walls, as it directly influences the load transfer mechanisms and the development of arching behaviour within the panel.

The slenderness ratio (*H/t*) also played a critical role in the OOP response, with higher slenderness ratios leading to a significant reduction in resistance. The Eurocode 8 [15] effectively recommends *H/t* = 15 as the lower slenderness limit to classify a masonry infill walls as slender. Beyond this threshold, thinner infill walls exhibited a marked decrease in performance. This observation underscores the importance of properly considering panel thickness and slenderness in the design of masonry walls.

Future research should further investigate the combined effects of aspect ratio, slenderness ratio, and perforation orientation on OOP resistance to provide practitioners with more refined design guidelines. By bridging the gap between experimental results, numerical analyses, and real-world applications, these studies could significantly enhance the safety and efficiency of masonry wall designs.

In conclusion, this study highlights the complex interplay between geometric and material properties in determining the OOP performance of masonry infill walls. By incorporating these findings into design practices, engineers can develop safer and more cost-effective solutions for masonry construction, tailored to the specific demands of modern building requirements.

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