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EVALUATING THE OUT-OF-PLANE RESPONSE OF MASONRY INFILL WALLS IN SEISMIC CONDITIONS: A PARAMETRIC ANALYTICAL MODEL

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Abstract

Masonry infill walls, often included within reinforced concrete (RC) frames, significantly impact the seismic response of these structures, even though they are typically classified as non-structural elements. During seismic events, these infill walls can interact with the surrounding RC frame in ways that alter the overall behaviour, sometimes leading to brittle failure mechanisms such as out-of-plane (OOP) collapse. This collapse is particularly concerning, as it can occur under lateral seismic loads, posing safety risks. This study addresses this challenge by presenting an analytical model developed to assess the OOP performance of masonry infill walls under seismic loads. We conduct a parametric analysis, evaluating key factors such as the geometry and mechanical properties of the masonry, the slenderness and aspect ratio of the infill to understand their influence on OOP behaviour.
The proposed model integrates vertical and horizontal arching mechanisms, considering the surrounding RC frame's flexibility, which can significantly affect the OOP response of the masonry. Validation against experimental data demonstrates the model's accuracy and reliability in predicting the OOP behaviour of masonry infill walls. This analytical model provides valuable insights for professionals designing safer RC structures, highlighting its potential applications in improving seismic performance and guiding future design for masonry infills.

Keywords: Masonry infill wall; Out-of-Plane (OoP) capacity; In-plane/Out-of-plane (IP/OoP); Parametric Study.

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1 INTRODUCTION

The incorporation of masonry infill walls within reinforced concrete (RC) frames is a widely adopted construction practice across the globe. Although these infill walls are often classified as non-structural elements in many design codes, their impact on the overall structural behaviour of buildings is considerable and cannot be disregarded. They influence the seismic response of RC frames by altering both strength and stiffness, while their fragility frequently results in damage that compromises building functionality and leads to significant economic losses, even during minor to moderate seismic events [1].

Over recent decades, extensive experimental research has been undertaken to enhance understanding of the in-plane (IP) and out-of-plane (OOP) behaviour of masonry infill walls [2–11]. However, the findings of these studies often vary due to multiple factors, including differences in test scales, the characteristics of the RC frames employed, 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 complicates the comprehensive interpretation of results and has hindered the development of universally accepted formulations for assessing the OOP capacity of different infill walls.

This study employs an analytical model, previously introduced and validated in earlier publications [12], to conduct a parametric analysis of the principal characteristics governing the behaviour of masonry infill walls. These characteristics encompass the mechanical and geometric properties of the masonry, as well as the slenderness and aspect ratio of the infill walls. The analytical model assesses the arching behaviour of the panel in both the vertical and horizontal directions, along with their combined plate effect, while also accounting for the deformability of the RC frame.

2 PRESENTATION OF THE ANALYTICAL MODEL

The analytical model is designed to assess the out-of-plane (OOP) capacity of masonry infill walls within reinforced concrete (RC) frames, considering both unreinforced and reinforced masonry configurations. It 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 plate-like behaviour and is evaluated through an 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 proposed by Vaculik and Griffith [13]—, the panel is divided into two or three rigid segments for both arching mechanisms.

Each segment undergoes rigid rotation around the frame supports (i.e., beams or columns), establishing a link between the displacement at the centre of the infill panel and a specific rotation angle, as shown in Figure 1. The model also accounts for the deformation of the elastic supports due to segment rotation, which influences the geometric configuration of the system and the internal forces (tension and compression) within the sections.

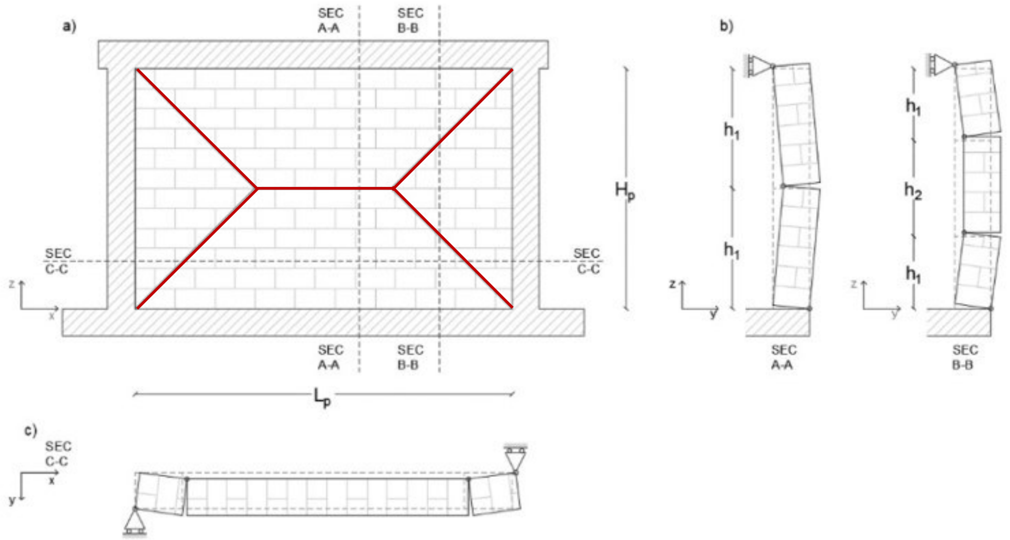

Figure 1: Front view of the infill wall (a); sections of the two-segment and three-segment (b) vertical arch mechanisms, and the three-segment horizontal arch mechanism (c).

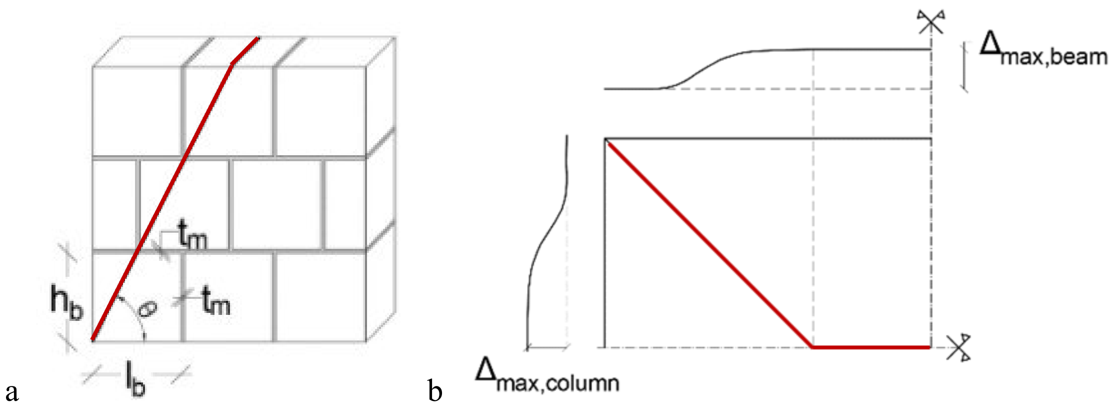

Figure 2: Failure angles θ and b) deformation of the perimeter constraints.

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. Maximum deformation occurs at mid-span sections, which comprise two segments, and decreases near the beam-column joint, where deformation is assumed to be zero.

The out-of-plane load can be modelled either as concentrated forces applied at one-third of the panel height (following 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 applied to the infill wall, is modelled as elastic with brittle fracture.

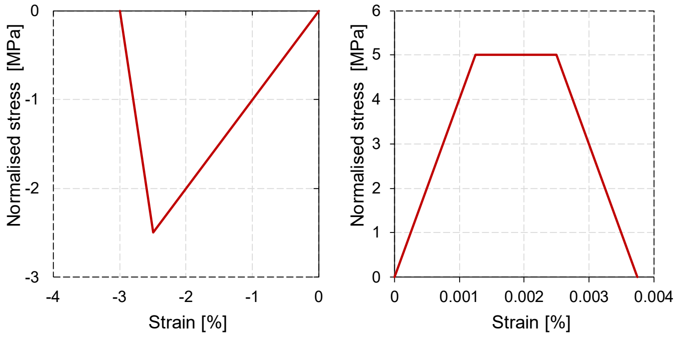

Figure 3: Stress-strain law of tensile reinforce (right), stress-strain law of masonry and plaster in compression (left).

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 begins by assigning an initial displacement and calculating the corresponding rigid rotation of the segments, along with the induced deformations of the bounding frame. The interaction between the masonry and confining elements is resolved iteratively by updating displacement and force equilibrium until convergence is achieved. Once the deformation state is established, stabilising moments are computed at cross-sections, followed by the external load required to impose the given 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, taking into account the specific mechanical properties governing each direction.

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

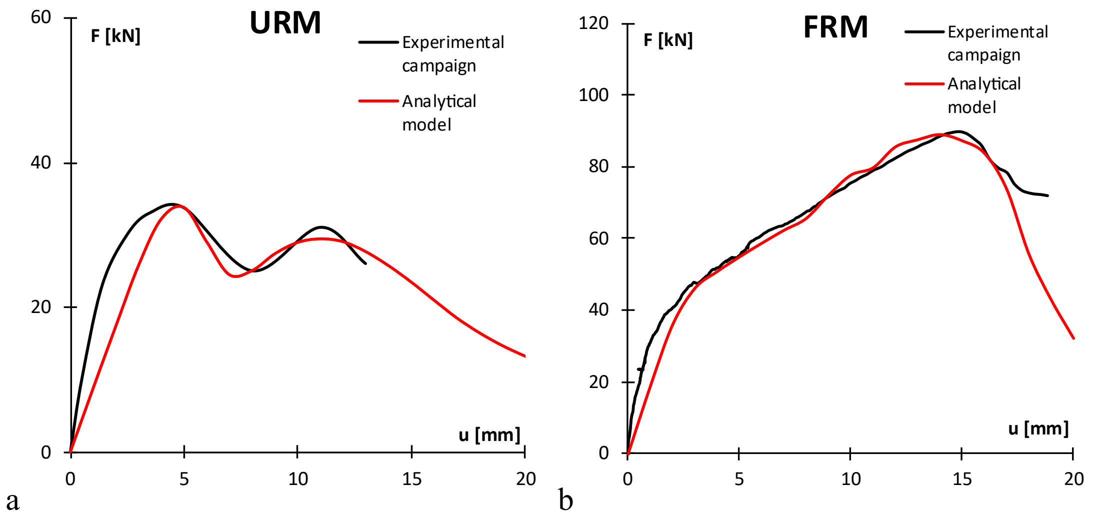

Figure 4: Comparison of the model's results with experimental campaign a) URM and b) FRM

3 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 examines the influence of the aspect ratio (L/H) and the compressive strength of the masonry (fm) on OOP resistance. The second explores the relationship between OOP resistance and the slenderness ratio (H/t) of the infill walls.

3.1 Effect of the aspect ratio

The analysis varied the aspect ratio while keeping the panel height constant at 2.65 m, a dimension selected to reflect typical RC frame construction. The panel width was incrementally increased, resulting in aspect ratios (L/H) ranging from 0.5 to 5. The compressive strength of the masonry (fm) was examined for three values—5.3, 4.1, and 3.3 N/mm²—measured along 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 strengths of 10 and 5 N/mm², as specified by the Italian building code [14]. Perpendicular to the perforations, the compressive strength was assumed to be one-quarter of that parallel to them.

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. Consistent with standard construction practices for slender masonry walls, the perforations in the clay blocks were oriented horizontally. In all cases analysed, the panel's failure angle (θ) was fixed at 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 measured 30×30 cm and contained longitudinal reinforcement equivalent to 3% of the cross-sectional area. Transverse reinforcement was provided by 10 mm diameter stirrups spaced at 50 cm in critical regions and 8 mm diameter stirrups spaced at 130 cm in non-critical sections. The beam had a 50×25 cm cross-section with 2% longitudinal reinforcement relative to its area, and transverse reinforcement consisting of 8 mm diameter stirrups spaced at 60 cm in critical regions and 130 cm elsewhere.

Figure 5 presents the results of the parametric analysis, illustrating the relationship between OOP resistance (Q) and the aspect ratio (L/H) for different masonry compressive strengths (fm). The findings indicate that walls with lower aspect ratios (L/H < 1) exhibit greater resistance, primarily due to the pronounced effect of the horizontal arching mechanism in this range. Additionally, because this mechanism develops in the direction parallel to the perforations—where masonry compressive strength is higher—the panel's resistance is further enhanced. For aspect ratios exceeding 1, the contribution of horizontal arching reaches a plateau, as the rotating segments resisting OOP loads no longer increase in size. Consequently, as L/H increases further, the panel's response stabilises and becomes primarily influenced by the vertical arching mechanism.

The impact of masonry compressive strength (fm) is also evident, with higher values consistently leading to greater OOP resistance across all aspect ratios. The trends observed align with the expected mechanical behaviour of infill walls, confirming that the analytical model effectively captures the governing parameters of OOP resistance.

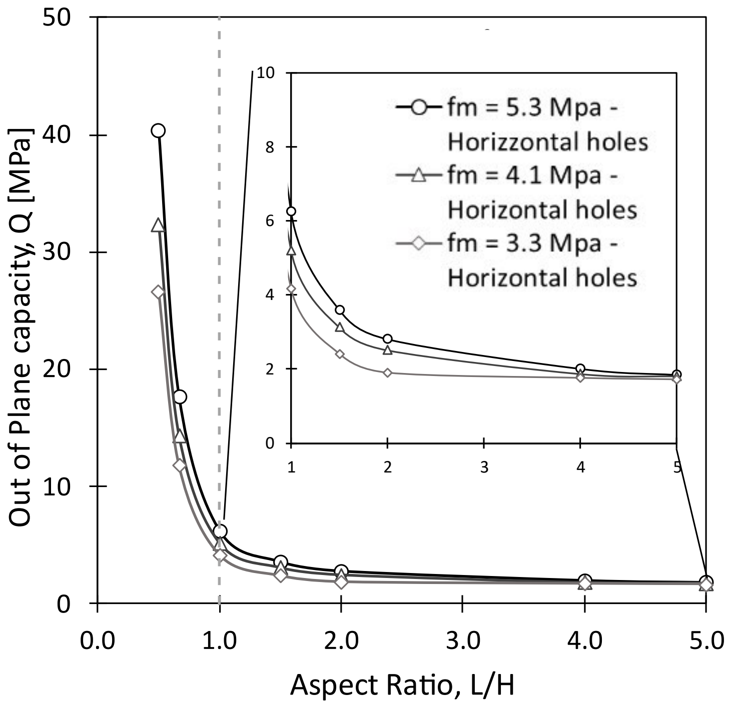

Figure 5: Out-of-plane capacity (Q) of the infill walls as a function of the aspect ratio (L/H) for different values of masonry compressive strength (fm)

3.2 Effect of the slenderness ratio

The second parametric analysis examined the effect of the slenderness ratio (H/t) of the infill walls, defined as the ratio between panel height (H) and thickness (t). Three aspect ratios (L/H) were considered: 0.67, 1, and 1.5, while the masonry compressive strength (fm) was fixed at 4.1 MPa. The out-of-plane capacity (Q) was assessed as a function of slenderness by varying the panel thickness (t) from 8 cm to 30 cm. In all cases, a 1 cm plaster layer was applied to both sides of the panel. The panel height remained constant at 2.65 m to reflect typical construction dimensions, while the failure angle (θ) and the frame characteristics were consistent with those used in the previous parametric study.

The results of this analysis are shown in Figure 6. The black line with circular markers represents the trend of OOP capacity for infill walls with vertical perforations, while the grey line with square markers corresponds to walls with horizontal perforations. The dashed line at H/t = 15 indicates the lower slenderness limit recommended by Eurocode 8 [15] for classifying masonry infill walls as slender. In line with standard construction practices for slender masonry walls, the perforations in the masonry units were oriented horizontally to improve mortar adhesion and bonding between blocks.

The orientation of the perforations, in combination with the aspect ratio (L/H), plays a crucial role in defining the out-of-plane (OOP) response of masonry infill walls. For L/H > 1, walls with vertical perforations exhibit significantly higher OOP capacities than those with horizontal perforations, demonstrating the dominant contribution of vertical arching mechanisms. This suggests that, in such configurations, a vertical perforation layout should be preferred to enhance structural performance. Conversely, for L/H = 1, the OOP capacities of both orientations are nearly identical, highlighting the aspect ratio as a key parameter in assessing the influence of perforation direction on panel behaviour.

Regardless of the aspect ratio, an increase in the slenderness ratio (H/t) leads to a significant reduction in OOP capacity. This effect becomes particularly pronounced when exceeding the Eurocode slenderness limit (H/t > 15), where the decrease in capacity is more abrupt, underlining the critical role of panel thickness in maintaining structural performance under out-of-plane loads.

To further verify these findings, a third parametric analysis was conducted, exploring the influence of aspect ratio while varying both L/H and the perforation orientation. The results, presented in Figure 7, maintain the same colour scheme and markers as the previous figure, with a dashed line indicating L/H = 1. This additional analysis reinforces the previous conclusions, emphasising the importance of aspect ratio and perforation orientation in determining OOP capacity.

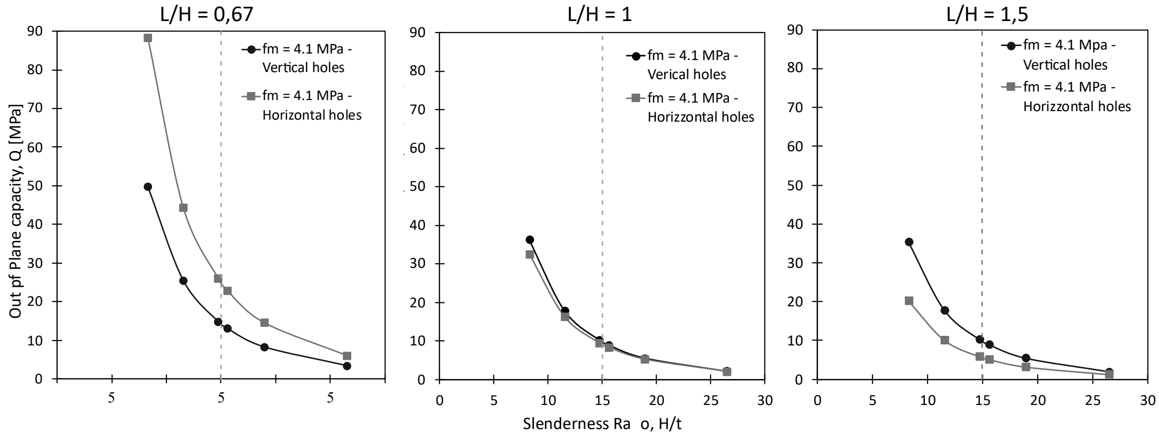

Figure 6: OOP capacity of infill walls depending upon the slenderness ratio (H/t) and aspect ratio (L/H)

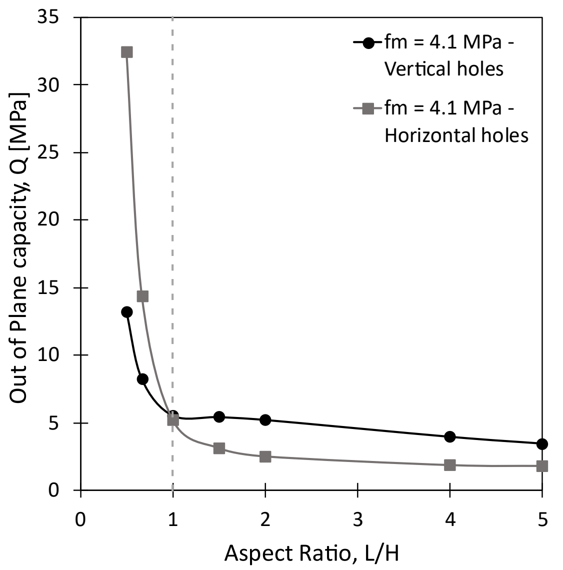

Figure 5: OOP capacity of infill walls depending upon aspect ratio (L/H) and perforation orientation

4 CONCLUSIONS

This study examined the out-of-plane (OOP) resistance of masonry infill walls via a parametric analysis that explored the effects of aspect ratio (L/H) and slenderness ratio (H/t). The findings provide crucial insights into the structural behaviour of these walls and underline the key factors that should guide design decisions.

The aspect ratio (L/H) was found to have a profound impact on OOP capacity. Infill walls with lower aspect ratios (L/H < 1) exhibited superior resistance when the perforations were oriented horizontally, whereas those with higher aspect ratios (L/H > 1) performed better when the perforations were vertical. When the aspect ratio was equal to 1 (L/H = 1), the OOP capacities of the two perforation orientations were almost identical. The analysis demonstrates that masonry walls with horizontally perforated units outperform those with vertical perforations only in configurations with very narrow frames (where the panel length is smaller than the height). However, such configurations are rare in practice. Therefore, it is recommended to use units with vertical perforations, especially for aspect ratios of 1 or higher, as this orientation enhances OOP resistance. These results underline the significant role that aspect ratio plays in determining the structural performance of masonry infill walls, as it directly influences the load transfer mechanisms and the development of arching behaviour.

The slenderness ratio (H/t) was another critical factor affecting OOP performance. Higher slenderness ratios were associated with a substantial decrease 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 finding emphasizes the importance of considering both the thickness and slenderness of masonry walls when designing for out-of-plane loads.

Further research is needed to explore the combined effects of aspect ratio, slenderness ratio, and perforation orientation on OOP resistance. Such investigations would offer practitioners more precise guidelines for design. By integrating experimental data, numerical modelling, and real-world applications, future studies could significantly improve the safety and effectiveness of masonry wall designs.

In conclusion, this study sheds light on the intricate relationship between geometric and material properties in determining the OOP behaviour of masonry infill walls. By incorporating these findings into design practices, engineers can create safer, more cost-efficient solutions for masonry construction that meet the evolving needs of modern buildings.

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REFERENCES

[1] C. Del Gaudio, G. De Martino, M. Di Ludovico, G. Manfredi, A. Prota, P. Ricci, Empirical fragility curves from damage data on RC buildings after the 9 L'Aquila earthquake. *Bull. Earthq. Eng.* 15(4):1425–1450, 2016. https://doi.org/10.1007/s10518-016-0026-1

[2] F. da Porto, M. Donà, N. Verlato, G. Guidi, Experimental Testing and Numeri-cal Modeling of Robust Unreinforced and Reinforced Clay Masonry Infill Walls, With and Without Openings. *Front. Built Environ*., 6, 591985, 2020. https://doi.org/10.3389/fbuil.2020.591985

[3] M. Minotto, N. Verlato, M. Donà, F. da Porto, Strengthening of In-Plane and Out-of-Plane Capacity of Thin Clay Masonry Infills Using Textile and Fiber-Reinforced Mortar. *J. Compos. Constr.,* 24, 04020059, 2020. https://doi.org/10.1061/(ASCE)CC.1943-5614.0001067

[4] G. M. Calvi, D. Bolognini, Seismic response of reinforced concrete frames in-filled with weakly reinforced masonry panels. *Journal of Earthquake Engineering*, 5, 153–185, 2001. https://doi.org/10.1080/13632460109350390

[5] M. T. De Risi, C. Del Gaudio, P. Ricci, G. M. Verderame, In-plane behaviour and damage assessment of masonry infills with hollow clay bricks in RC frames. *Engineering Structures*, 168, 257–275, 2018. https://doi.org/10.1016/j.engstruct.2018.04.065.

[6] A. Furtado, H. Rodrigues, A. Arêde, H. Varum, Out-of-plane behavior of ma-sonry infilled RC frames based on the experimental tests available: A systematic re-view. *Construction and Building Materials*, 168, 831–848, 2018. https://doi.org/10.1016/j.conbuildmat.2018.02.129.

[7] R. R. Milanesi, P. Morandi, S. Hak, G. Magenes, Experiment-based out-of-plane resistance of strong masonry infills for codified applications. *Engineering Structures*, 242, 112525, 2021. https://doi.org/10.1016/j.engstruct.2021.112525.

[8] P. Ricci, M. Di Domenico, G. M. Verderame, Experimental assessment of the in-plane/out-of-plane interaction in unreinforced masonry infill walls. *Engineering Structures*, 173, 960–978, 2018. https://doi.org/10.1016/j.engstruct.2018.07.033.

[9] C. Butenweg, M. Marinković, R. Salatic, Experimental results of reinforced concrete frames with masonry infills under combined quasi-static in-plane and out-of-plane seismic loading. *Bulletin of Earthquake Engineering*, 17, 2017. https://doi.org/10.1007/s10518-019-00602-7.

[10] P. Morandi, S. Hak, R.R. Milanesi, G. Magenes G, In-plane/out-of-plane interaction of strong masonry infills: From cyclic tests to out-of-plane verifications. *Earthquake Eng. Struct Dyn*., 51: 648–672, 2022. https://doi.org/10.1002/eqe.3584

[11] X. Xinyao, G. Zi-Xiong, S. H. Basha, Out-of-Plane behavior of clay brick masonry infills contained within RC frames using 3D-Digital image correlation technique. *Construction and Building Materials, 0950*-0618, 2023. https://doi.org/10.1016/j.conbuildmat.2023.131061.

[12] M. Gaspari, M. Donà, F. da Porto, Analytical Model for Estimating the Out-of-Plane Behaviour of Masonry." *18th International Brick and Block Masonry Conference. IB2MaC 2024. Lecture Notes in Civil Engineering*. https://doi.org/10.1007/978-3-031-73314-7_10

[13] J. Vaculik, M.C. Griffith, Out-of-plane load–displacement model for two-way spanning masonry walls." *Engineering Structures*, 141, 328–343, 2017. https://doi.org/10.1016/j.engstruct.2017.03.024

[14] NTC2018-D.M (8) . " 7 / / 8 : Aggiornamento delle Norme tecniche per le costruzioni" (in Italian)

[15] CEN (4) (European Committee for Standardization) "EN 998 Eurocode 8-1: design of structures for earthquake resistance part 1: general rules, seismic actions and rules for buildings." https://doi.org/10.1680/cien.144.6.55.40618.