Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 2144-2154

ECCOMAS
Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

ANALYTICAL MODEL FOR PREDICTING OOP LATERAL BEHAVIOR OF MASONRY INFILL WALLS

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Abstract

The use of clay masonry infill walls in reinforced concrete (RC) frames is a common construction practice worldwide. These still represent a potentially critical problem for the overall seismic performance of buildings. This is because they are often overlooked in design procedures, being generally classified as nonstructural elements. However, their brittle behavior makes them easily damaged, resulting in a loss of building functionality and significant economic losses even at low to medium seismic intensities.
This paper aims to present a recently developed analytical model for estimating the lateral OOP response of various masonry infill walls; it implements the vertical and horizontal arch mechanisms, taking into account the plate effect, the deformability of the upper beam, and the presence or absence of external reinforcement. This analytical model was calibrated in this study for some types of thin infill walls, both unreinforced and reinforced. For illustrative purposes, a parametric analysis using this model is presented, which is useful for discussing the role of the main infill vulnerability parameters on OOP capacity.

Keywords: masonry infill walls; out-of-plane seismic response; in-plane/out-of-plane interaction, analytical model; arch mechanism.

Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10548.21206

1 INTRODUCTION

The use of clay masonry infill walls in reinforced concrete (RC) frames is a common construction practice worldwide. Although an extensive state of art on the seismic behavior of masonry infill walls is available, they still represent a potentially critical issue for the overall seismic performance of buildings. This is due to the fact that they are often neglected in design procedures, being generally classified as non-structural elements. However, their fragile behavior makes them easily damaged, with consequent loss of functionality of the building and significant economic losses even at low-to-medium seismic intensities, [1]. Despite the experimental knowledge acquired [2, 3, 4, 5, 6, 7, 8, 9], there are still no clear standard indications on the modelling/verification procedures of infill walls. Specifically, the Italian legislation [10, 11] does not currently provide a reliable method for calculating the out-of-plane capacity (OOP) of masonry infills, referring to other standards of proven validity (e.g., Eurocode 6 [12], which provides the arch mechanism). However, there is a lack of widely accepted formulations evaluating this OOP capacity for various types of infills (e.g., those strengthened), and in conditions of previous in-plane (IP) damage (which, as known, greatly reduces the OOP capacity), [2, 13, 14, 15, 16, 17, 18].

In this context, this paper intends to present an analytical model developed for the estimation of the OOP lateral response of various masonry infill walls; it implements the vertical and horizontal arch mechanisms, considering the plate effect, the deformability of the upper beam, the presence or absence of an external reinforcement and the degradation of the materials according to the IP damage of the panel. This analytical model is calibrated in this study for some types of thin infill walls, both unreinforced [4] and strengthened using textile or fiber-reinforced mortar solutions (TRM, FRM), [3]. Thin walls made of clay units with horizontal holes have been the typical lightweight envelope system used since the 1960s and are very common in existing buildings.

With this model, it is possible to investigate the influence of the main geometrical (e.g., slenderness, aspect ratio) and mechanical parameters (e.g., compressive strength and elastic modulus of masonry) on the OOP response of the panels, as well as the effects of various external strengthening solutions. For example, purposes, a parametric analysis using this model is presented, which is useful in discussing the role of the main infill vulnerability parameters on the OOP capacity.

2 PRESENTATION OF THE ANALYTICAL MODEL

The proposed analytical model is developed to assess the out-of-plane (OOP) capacity of reinforced concrete frame infill walls made of simple or reinforced masonry.

Given the low tensile strength of masonry, in particular, after their cracking, many of the models in the literature show that the out-of-plane response of infill walls and the calculation of their out-of-plane strength are based on the development of an arching mechanism (or compressed strut), while the contribution offered by the masonry's flexural strength would be minimal. An example that confirms this assumption can be found in EN 1996-1-1 [7], where simple masonry is analysed with a simplified formula based on the arching mechanism.

In this work, the analytical model developed is based on both the formation of an arch collapse mechanism in the wall thickness (a combination of a vertical and a horizontal arch mechanism) and the resulting deformation of the upper restraint beam.

Referring to this second aspect, in the analytical model the vertical deformation of the beam is considered by relating it to its flexural stiffness. To determine the flexural stiffness of the beam, it is sufficient to know the geometric characteristics of the cross-section and the mechanical characteristics of the materials used. Furthermore, to schematize the stresses generated by the infill wall on the beam as a load uniformly distributed along the length of the beam itself, it is possible to compare the confinement action generated by the frame to that of a perfectly elastic constraint.

A further hypothesis in the analytical model is the assumption of the plate behaviour of the infill panel. In fact, after the formation of an initial crack, the wall is subdivided into three segments near the perimeter constraints (frame beams and columns) and into two segments in the central strips of the infill. Each segment rotates rigidly concerning two supports, so it is possible to associate a certain rigid rotation of the segments with each imposed displacement of the center of the infill, Figure 1. Furthermore, the rigid rotation of the segments causes a displacement of the elastic supports, generating reaction forces that oppose the rotation of the segments. Thus, the axial tensile and compressive forces acting on the segments cause deformation, which consequently changes the initial geometric configuration of the system.

In addition, the tensile-strain constitutive laws of the material implemented in the model are of type:

- Elastic with a brittle fracture about the reinforcement layers subject to tension (whereas the tensile strength of masonry was assumed to be zero).
- Elasto-plastic with softening branch, for masonry and reinforcement layers subject to compression.

To calculate the out-of-plane resistance of the infill walls, an iterative procedure is used to determine the rotational equilibrium of the masonry segments subject to both the external out-of-plane loads and the reaction forces generated by the confinement frame. Consequently, it follows that the collapse of infill walls can occur:

- Due to failure of the constituent elements, in the case where the confining frame is very rigid.
- Due to loss of equilibrium following excessive out-of-plane deformation, in the case where the confining frame is less rigid.

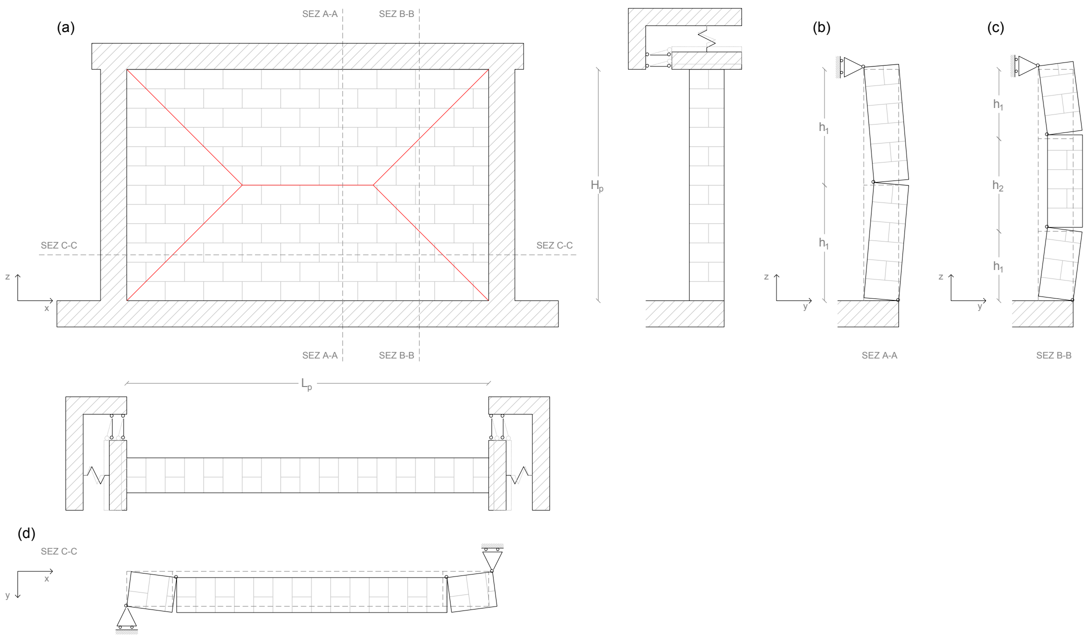


Figure 1: Frontal view of the infill wall (a); sections where the two-segment (b) and three-segment (c) vertical arch mechanism is developed; section where the three-segment horizontal arch mechanism is developed (d)

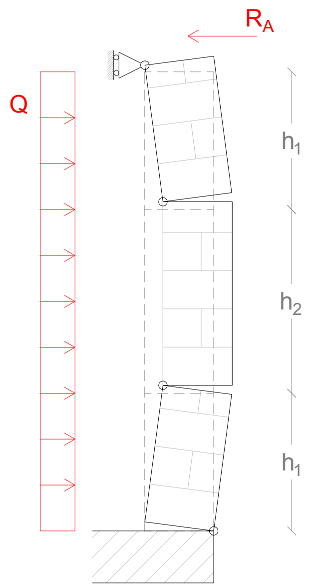


Figure 2: External load Q distributed along the infill panel

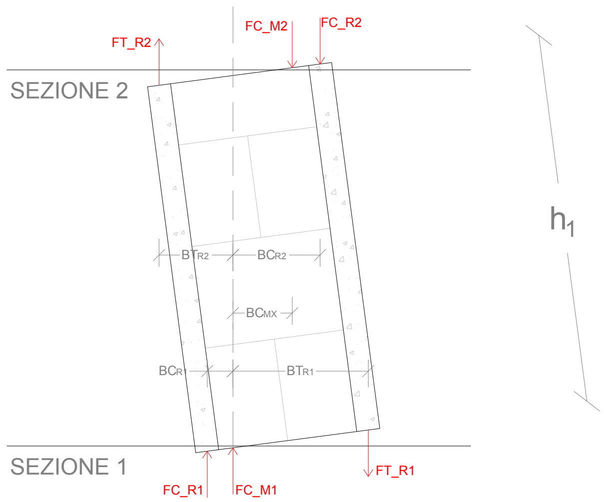


Figure 3: Internal reaction forces generated in each segment and related arms required for the calculation of rotational equilibrium

The analytical model consists of the following calculation steps:

1. The dimensions of the panel, the mechanical characteristics of the masonry and any reinforcement used, and the characteristics of the frame surrounding the panel are established; the position of the fracture lines that may develop in the panel is determined geometrically.
2. An initial out-of-plane displacement is assumed at the centreline of the panel; this displacement is then gradually increased for trials after the first.
3. Their rigid rotation is calculated from the segments' geometry.
4. The displacement of the beam capable of allowing the rigid rotation of the segments is calculated geometrically.
5. The reaction force generated by the beam is calculated from the displacement calculated in the previous step.

6. The deformations that develop in the segments due to the confinement forces exerted by the beam are determined.
7. The depth of the cross-section neutral axis is calculated to obtain the compressed section size at the points of rotation of the segments and the corresponding stress distribution is obtained by assuming a material behaviour that follows an elastoplastic stress-strain law with softening branch.
8. The deformations in the compressed sections (for both masonry and reinforcement) and the associated stresses are determined geometrically; the reaction forces are then derived from stresses.
9. The vertical masonry displacement generated by the deformation of the segments is determined.
10. The vertical displacement calculated in step 4 is updated accordingly with the masonry deformation induced by the beam reaction forces. Steps 4 to 10 are repeated iteratively until the calculated displacements of the beam and infill are considered equal.
11. The reaction force arms in the cross-sections considered and the stabilising moment generated are calculated.
12. Considering the assumed load distribution, the external force that balances the internal moment is calculated, in Figure 2.
13. The procedure is restarted from step 1 by increasing the displacement of the center point; this procedure is repeated iteratively until the set post-peak load limits are achieved (corresponding to 80% of the maximum out-of-plane load).
14. Steps 1 to 13 are developed for forming the vertical arch and then repeated for the horizontal arch considering the mechanical properties relative to the horizontal direction for both masonry and reinforcement.

3 EXPERIMENTAL CALIBRATION

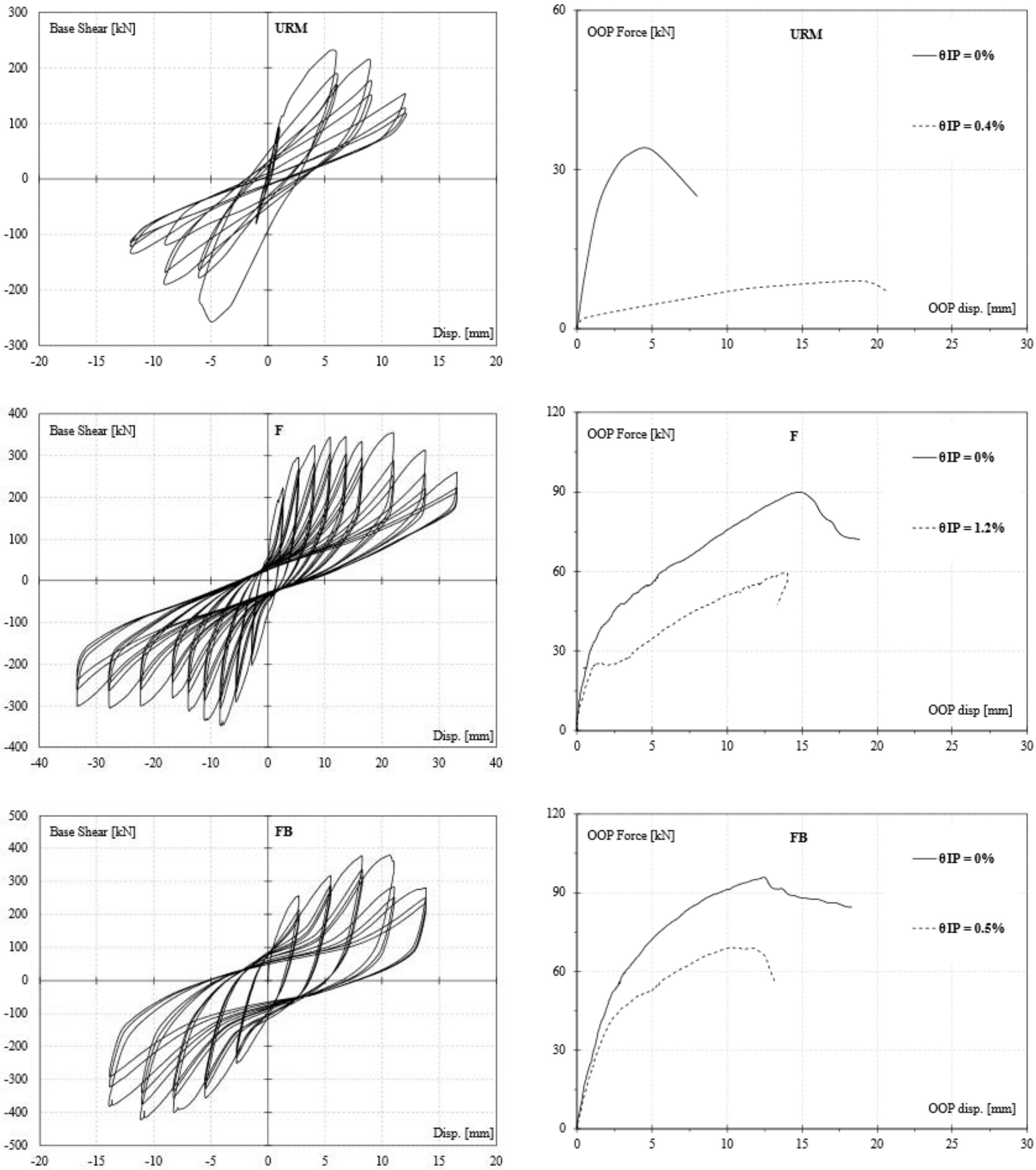
3.1 Presentation of the reference tests

The proposed analytical model was calibrated on the experimental results of some IP/OOP tests performed on thin unreinforced (URM) or solution-reinforced thin infill walls based on textile and fiber-reinforced mortar (TRM/FRM). Regarding the URM infill panel, the result of the test performed on full-scale one-span RC infilled frames by Calvi and Bolognini [4] at the University of Pavia (UniPV) was taken as a reference. About the FRM/TRM infill panels, reference was made to the results of the experimental campaign (Minotto et al. [3]) conducted at the University of Padua (UniPD).

Both experimental campaigns use wall panels with similar lengths, heights, and thicknesses. Both experimental tests consisted of quasi-static cyclic IP displacements, with incremental drift and monotonic loading of the OOP at zero panel damage and after reaching an IP drift of 0.4%, for UniPV experimental campaign [4] or 0.5% and 1.2% for the UniPD campaign [3]. Three different reinforcement solutions were studied in the UniPD experimental test [3]. The first, F (Fiber plaster), is characterized by a 15-mm layer of fiber-reinforced based plaster made of hydraulic lime and reinforced with glass fibers. The second solution, FB (Fiber plaster and Basalt grid) adds a bidirectional basalt grid, embedded in the plaster, to the first solution. The last solution, RBB (Render, Basalt grid, and helicoidal Bars), designed to be applied directly to an existing curtain wall, consists of a bidirectional basalt grid placed between a 10-mm layer of plaster and a 5-mm layer of high-quality, high-strength plaster. The characteristics of the experimental sets and the main results are shown in Table 1, and Figure 4, respectively.

		UniPV [4]	*UniPD* [3]		
		URM	*F*	*FB*	*RBB*
Masonry infill	Length L_w [mm]	4200	4150		
	Height h_w [mm]	2750	2650		
	Thickens t_w [mm]	115 (+ 20 mm plaster)	120 (+30 mm plaster)		
	Masonry units [mm]	245 x 245 x 115	250 x 250 x 120		
	Compressive strength f_m [MPa]	1.1	2.8	2.8	2.9
	Elastic modulus E_m [MPa]	1873	4752	4752	4777

Table 1: Geometry and material properties for the infilled RC frames tested



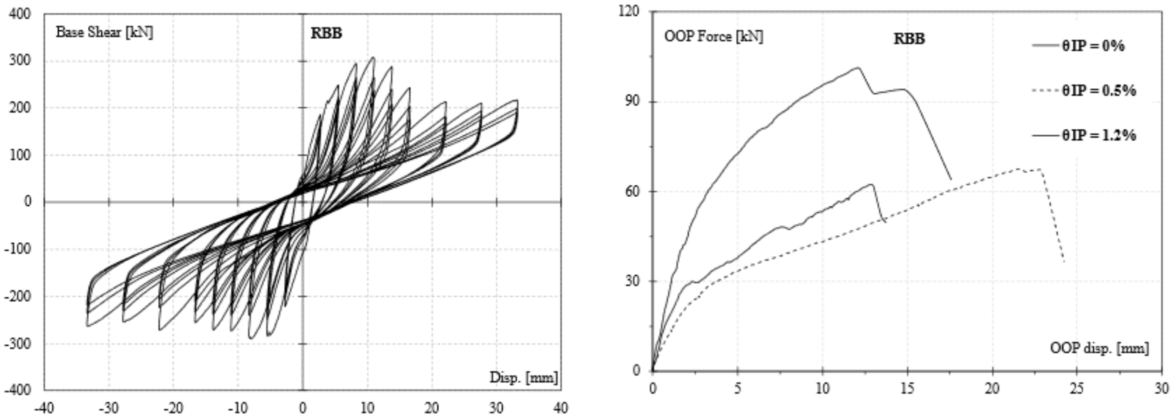


Figure 4: Experimental results: cyclin IP (left) and monotonic OOP (right) response

3.2 Presentation of the calibration analytical model

Calibration of the proposed model was done by changing the compressive strength (f_m) and elastic modulus (E_m) of masonry and compressive reinforcement from what is stated in the bibliography. The calibrated values are given in Table 2.

The results of the model calibration, for all experimental campaigns, are reported in Table 3 and Figure 5, for the comparison between the analytical model and the experimental campaign.

			Vertical arch		*Horizontal arch*		*Plaster/Reinforcement*	
			Calibration	*Test*	*Calibration*	*Test*	*Calibration*	*Test*
UniPV	*UR*	*Fm [Mpa]*	1.10	1.10	4.00	3.97	2.70	-
[4]	*M*	*Em [-]*	1873	1873	5646	5646	10000	-
	F	*Fm [Mpa]*	0.80	-	3.00	-	6.00	8.60
		Em [-]	3000	-	5000	-	6000	7400
UniPD	*FB*	*Fm [Mpa]*	0.80	-	3.00	-	6.50	8.60
[3]		*Em [-]*	3000	-	5000	-	7900	7400
	RB	*Fm [Mpa]*	0.80	-	3.00	-	7.30	-
	B	*Em [-]*	3000	-	5000	-	8300	-

Table 2: Result of the calibration of Compressive strength (fm) and Elastic modulus (Em)

			Analytical model	*Test*	*Δ*
UniPV	*UR*	*Fmax [kN]*	34.25	33.7	0,55
[4]	*M*	*Umax [mm]*	5.00	5.00	-
	F	*Fmax [kN]*	89.47	90.05	0,58
		Umax [mm]	15.00	14.88	0.12
UniPD	*FB*	*Fmax [kN]*	96.48	96.01	0.47
[3]		*Umax [mm]*	13.00	12.41	0.59
	RBB	*Fmax [kN]*	101.52	101.31	0.20
		Umax [mm]	12.00	12.10	0.10

Table 3: Comparison between the analytical model and the experimental campaign

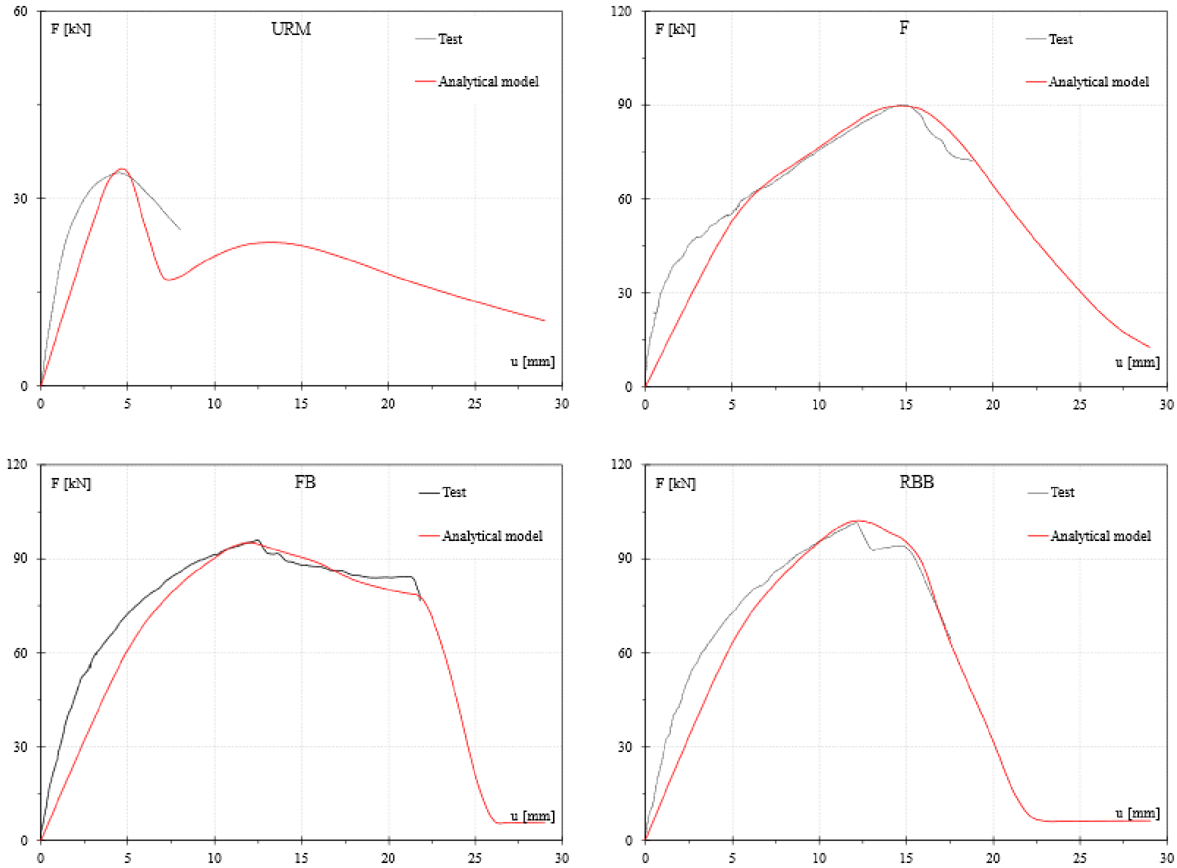


Figure 5: Comparison between the analytical model and the experimental campaign

4 PARAMETRIC ANALYSIS OF THE OOP BEHAVIOR

An initial parametric analysis was performed to see the potential of the proposed model. Specifically, various geometric ratios (*L/H*) were analyzed for the same panel of thickness t_w of 300 mm, with vertical hole masonry, with compressive strength (f_m) and elastic modulus (E_m) of 5.3 MPA and 5300, respectively, and without the presence of strengthening. The proposed model allows us to evaluate the Out-of-Plan resistance provided by arcs separately and their final combination of the two. Table 4 and Figure 6 show the results of the parametric analysis.

	Q [kN/m²]		
L/H	*Vertical Arch*	*Horizontal Arch*	*Plate behaviour*
0.5	117.46	43.35	44.30
0.8	72.62	21.36	36.83
1	57.72	16.88	37.30
1.5	47.82	10.81	36.01
2	42.45	7.80	35.23
4	32.02	3.49	30.25
5	29.15	2.69	28.06

Table 4: OOP resistance for differnte geomtric ratios

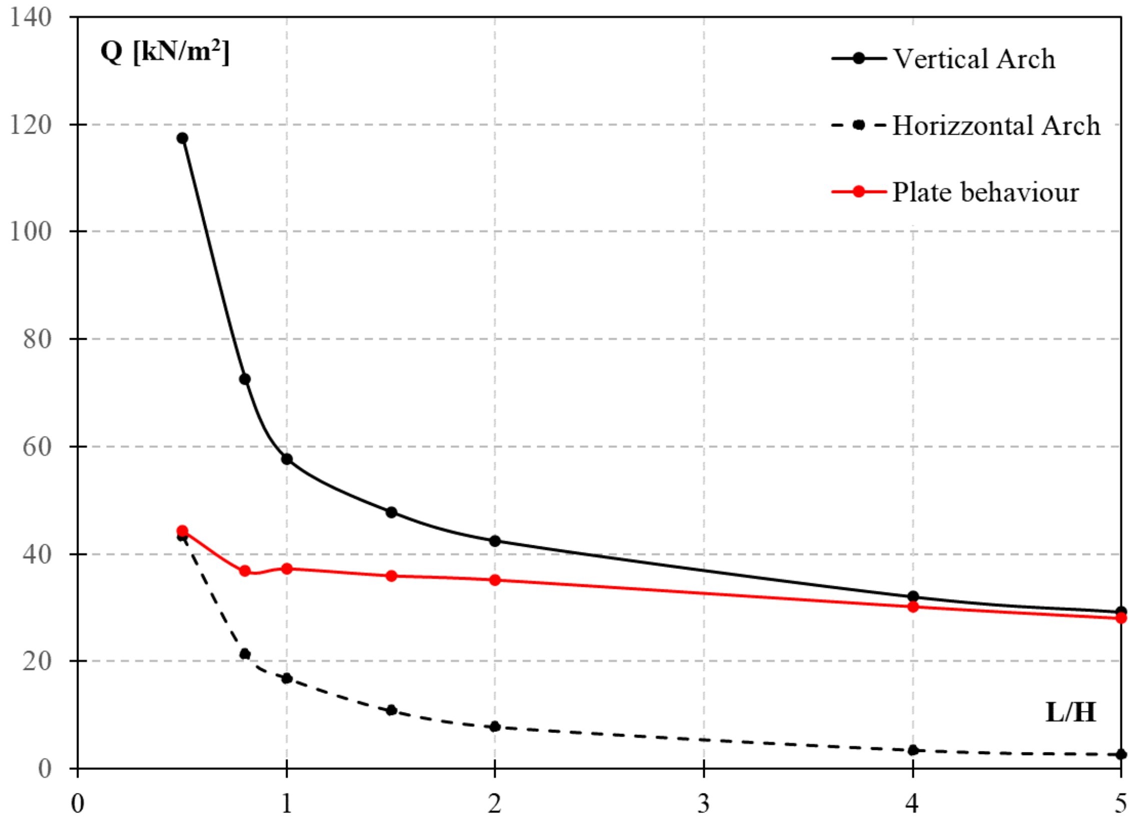


Figure 6: OOP resistance for different geometric ratios

5 CONCLUSIONS

This paper presents an analytical model able to reproduce the Out-of-Plane behavior of masonry infill panels of different thicknesses. The model is based on the formation of two arch mechanisms, vertical and horizontal, and considers the stiffness of the constraints (deformation of the upper confinement beam). The model was calibrated on the results of two different experimental campaigns for thin, reinforced, and unreinforced infill panels. To demonstrate the potential of the model, a parametric analysis was, in addition, performed by varying different geometric ratios.

The calibration results show that the proposed model is a useful tool to predict the out-of-plane behavior of various types of masonry infills, and therefore, to evaluate OOP based on their main structural parameters, such as slenderness, and shape ratio of the panel, dimensions, arrangement, strength, and elastic modulus of masonry blocks.

Further development of the model will take into account the in the plane damage of the panels, with the final aim of proposing useful verification/design guidelines for professionals.

ACKNOWLEDGMENTS

Special thanks are due to the Italian Department of Civil Protection and ReLUIS, which funded this study in the framework of the ReLUIS-DPC Project 2022-2024 – Work Package 10 Task 1.2: "Non-structural masonry".

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