

The impact of the variation in vertical load and the presence of openings on the mechanical response of masonry walls.

Chaimae Khanfri^{1*}, Ouadia Mouhat², Younes Elrhaffari², Fatima El Mennaouy¹ and Mohamed Rougui²

¹Civil Engineering and Environment Laboratory (LGCE), Mohammadia School of Engineers, Mohammed V University, Rabat, Morocco.

²Civil Engineering and Environment Laboratory (LGCE), Higher School of Technology, Mohammed V University, Rabat, Morocco.

Abstract. This article aims to analyse the mechanical response of masonry walls under cyclic loading using the finite element method with Abaqus software. The proposed model has been validated using available numerical and experimental results. This work provides an in-depth study of the cracking modes of masonry walls based on different vertical loads and the presence of openings. By using numerical simulations, it identifies the types of cracks that develop, their propagation, and their interaction with the structure. A parametric study will then be conducted to assess the influence of variations in vertical load and the effect of openings on the behaviour of the walls. Load-displacement curves and failure modes are presented and analysed. The results show that these parameters have a significant impact on wall behaviour. Specifically, an increase in vertical load improves the wall's resistance, while openings create weakness zones that promote degradation and reduce strength. A thorough understanding of the behaviour of unreinforced masonry structures is essential for making informed decisions regarding restoration methods.

Keywords: Masonry wall, mechanical response, openings, cyclic loading, vertical load, Abaqus.

1 Introduction

Masonry is one of the oldest materials used in the construction sector, composed of bricks and mortar [1]. It offers various advantages, such as its ability to withstand heat and provide sound insulation [2]. Masonry structures exhibit significant resistance to vertical compression but are highly vulnerable to lateral in-plane loads, such as earthquakes and strong winds [2]. During earthquakes, masonry structures suffer the most damage and are severely affected [3]. These constructions often follow traditional standards and methods established at the time of their construction, often without calculations or consideration of seismic constraints [4]. Therefore, it is imperative to conduct comprehensive studies to

* Khanfri Chaimae : chaimae.khanfri93@gmail.com

better understand the complex behavior of masonry structures subjected to lateral in-plane load [5]. This need is urgent, especially for evaluating the vulnerability of existing masonry structures, including historic buildings that represent cultural heritage and are located in various seismic regions worldwide [2]. Such studies contribute to identifying effective and sustainable solutions for strengthening and rehabilitating these structures [5]. There are various programs and methods for numerically studying the behaviour of masonry structures, the finite element method is commonly used in scientific research to simulate masonry constructions and analyze their structural response. Several researchers have made significant contributions to this field. Stavridis [6] successfully modeled masonry walls subjected to seismic loads using the finite element method. Feba S. Thomas and Bennet Kuriakose [7], also utilized the finite element method to study the response of unreinforced masonry walls, employing the ANSYS software for modeling. Additionally, Facchini and Betti [8] conducted seismic analysis of an irregular masonry tower using the finite element software ANSYS and Code-Aster. Bonisha Borah, Hemant B. Kaushik, and Vaibhav Singhal [9] used the ABAQUS program to model confined masonry walls and analyze their structural response under cyclic loading.

In this document, the finite element method was applied using a simplified micro-modeling approach to examine the mechanical response of a masonry wall, with and without openings, under cyclic load. The wall is modeled in 3D using ABAQUS software. The objective is to compare the results before and after creating the openings, while conducting a parametric study to evaluate the impact of the opening area ratio and variations in vertical load on the deformation modes and strength of the masonry wall. This study demonstrates that the location of openings is just as crucial as their size, revealing aspects that are often overlooked in the design of masonry structures.

2 Modelling condition

Several factors contribute to the complexity of masonry behaviour, such as anisotropy, unit dimensions, brick and mortar characteristics, construction method, assembly, and the width of head and bed joints [10]. Masonry structures can be modelled using one of three approaches: detailed micro-modelling, simplified micro-modelling, and macro-modelling [11], as illustrated in Fig. 1. In this article, the mechanical response of a masonry wall will be analysed in three dimensions using a micro-modelling approach based on the finite element method. This method produces accurate results in a relatively short computation time. The wall subjected to cyclic loading is modelled using Abaqus software. The brick units are enlarged in both directions of the mortar thickness and are modelled using continuous elements. The interaction characteristics between the bricks will be determined and represented as interfaces. The nonlinear behaviour of the mortar and brick finite elements is considered in this study. The bricks and mortar will be presented as continuous elements using the Drucker-Prager plasticity constitutive model available in Abaqus, the choice of this model is based on its ability to simulate frictional materials such as granular soils and rocks, whose elastic limit varies with pressure (material strength increases with increasing pressure), in order to analyse the behaviour of materials where compressive strength exceeds tensile strength, as is the case with masonry. The interaction between the bricks is modelled using normal and tangential behaviours of interactions available in the interaction module within ABAQUS, assuming that when two surfaces are in contact, they transmit shear forces and normal forces across their interface. Initially, the masonry wall is subjected to cyclic loading to observe its mechanical response. Subsequently, a parametric study will be conducted on the same wall by creating openings of various sizes and adjusting the vertical pre-compression force, in order to assess the influence of openings

and variations in vertical loading on the mechanical behaviour of the wall under cyclic loading.

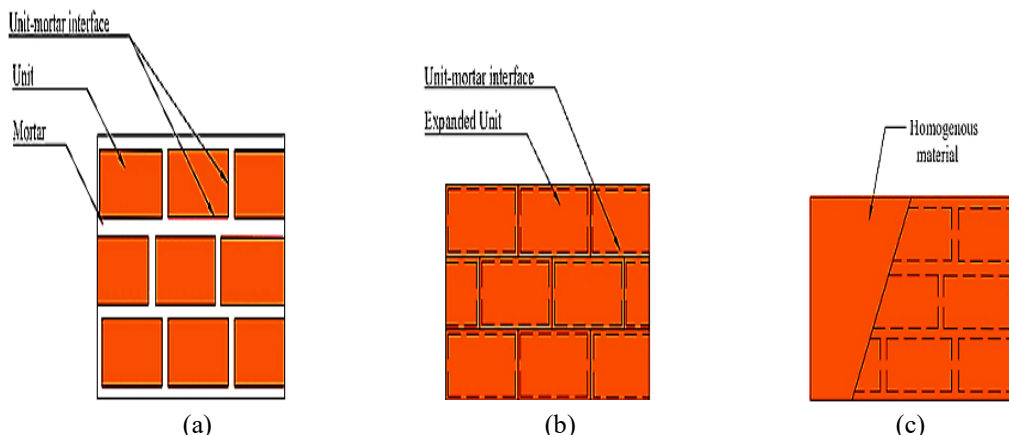


Fig. 1. Finite element methods: (a) micro-model in detail, (b) micro-model in simplified form, (c) macro-model.

3 Validation of FEM modelling

Model validation is an essential step to achieve an accurate numerical analysis of the mechanical response of unreinforced masonry. To this end, a vertical pressure of 0.3 MPa is applied to the proposed masonry wall, and a numerical analysis of its behaviour is performed using the ABAQUS software (Fig 2.b). The results obtained will then be compared to experimental and numerical results available in the literature [1-12]. The wall proposed for validation is an unreinforced masonry wall with the following dimensions: 1000 mm in length, 975 mm in height, and 110 mm in thickness. This wall is composed of fifteen rows of bricks, with each row being a continuous line consisting of a single construction unit. The bricks that make up the wall have dimensions of 250 mm in length, 65 mm in height, and 110 mm in thickness (Fig 2.a). The joint has a thickness of 10 mm, and its dimensions are adjusted using a simplified micro-modelling method (Fig 2.a).

3.1 Boundary conditions and loads

Rigid beams protected the lower and upper ends of the masonry wall. The lower beam was anchored to the ground, while the upper beam applied a vertical compression stress of 0.3 MPa to the wall to replicate the boundary conditions observed in experiments and other numerical models found in the literature [1-12]. The simulation was conducted using the ABAQUS software, employing a simplified micro-modelling approach based on the finite element theory. To analyse the nonlinear behaviour of masonry under compression, the Drucker-Prager plasticity model was applied (Table 1). Equation (22) [1] was used to calculate the adjusted elasticity modulus of the masonry elements, considering the original elasticity moduli of the mortar and masonry components, as well as the dimensions of the overall masonry structure. Table 2 presents the mechanical characteristics of the bricks and mortar. Rigid steel beams were used at the top and bottom of the wall for fixation, characterized by a high elasticity modulus of 210,000 MPa.

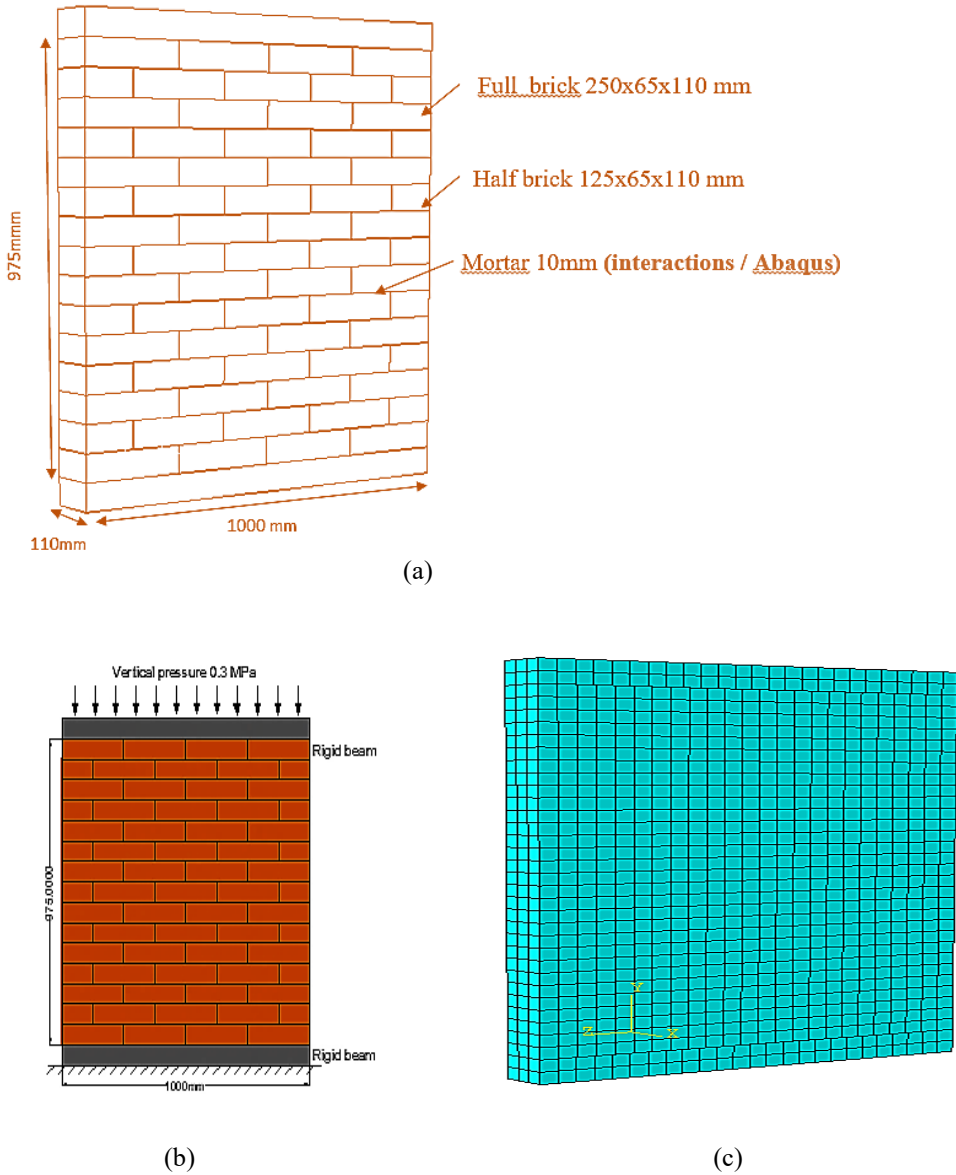


Fig 2. Proposed wall for validation (a) geometry of wall, (b) boundary conditions, (c) generated mesh of numerical models

A mesh size of 20 mm x 20 mm x 20 mm was used for the brick elements after conducting mesh convergence studies (Fig 2.c).

3.2 Material Properties

Table 2 presents the characteristics of the materials used in this study, specifically the parameters of the elastic and inelastic behaviour of brick and mortar units. In the simulation, the normal and tangential behaviours were determined using the interaction

module in the ABAQUS software to analyse the behaviour of the connections between the bricks.

Table 1. The parameters of the Drucker-Prager plasticity model.

Creep stress ratio (R)	1
Expansion angle (ψ)friction angle (β)	11.3°
Friction angle (β)	36°

Table 2. Material properties for bricks and mortar.

Parameter	Value
<i>Elastic properties :</i>	
-Elastic modulus of brick units E_u (MPa)	2880
-Density of brick units (g/mm ³)	2.6E-09
-Poisson ratio of brick units μ	0.3
-Elastic modulus of mortar E_m (MPa)	780
-Expanded units E_{adj} (MPa)	4993
<i>Interface Properties :</i>	
-Nominal Stress in Normal Direction K_{nn} (N/mm ³)	82
-Nominal Stress in Shear Direction –I K_{ss} (N/mm ³)	36
-Nominal Stress in Shear Direction –II K_{tt} (N/mm ³)	36
-Tangential behaviour frictional coefficient	0.7

The results of the proposed model for validation, obtained after numerical analysis under the pressure of a vertical load of 0.3 MPa, are compared to the numerical and experimental results obtained by other studies in the literature [1-12]. Fig. 3 shows a good agreement between the numerical results found and the results existing in the literature.

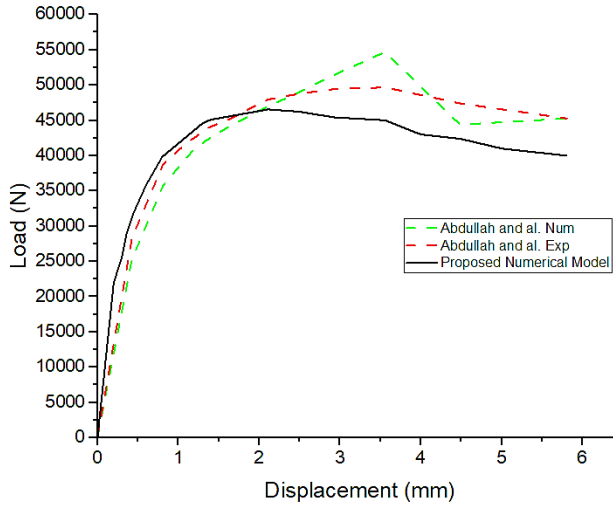


Fig. 3. Comparison of numerical results of the proposed model with experimental and numerical literature data under a vertical stress of 0.3 MPa

4 Numerical analysis

In this research, a simplified micro-modelling method is applied. The simulation is performed using an eight-node brick element (C3D8R). The bricks and mortar are modelled as a continuous element using the Drucker-Prager plasticity model available in ABAQUS. The interface is determined as a surface-based cohesive interface. In the interaction module of the Abaqus software, a general surface-to-surface contact is employed for the connection between adjacent bricks. The mesh size is chosen based on a mesh analysis study, with dimensions of 20 mm x 20 mm x 20 mm. The ABAQUS implicit solver was chosen to model the wall. The dimensions of the masonry wall and the brick units are identical to those used in the model validation part. Thus, a wall with fifteen rows is analysed under a cyclic load: once evaluating the impact of varying the pre-compression load, and another time studying the influence of the presence of openings on the response of the simulated wall.

4.1 The impact of varying the pre-compression load

In this step, the masonry wall is subjected to two types of loads. The first is a uniform vertical pre-compression load applied by the upper beam. The second is a cyclic load imposed at a reference point created in the upper beam by inducing horizontal displacements. The lower beam is fixed to the ground to prevent any movement or rotation. Fig.4 illustrates the load scheme applied to the wall. Two different values of pre-compression load, 1.20 MPa and 2.12 MPa, were applied to the wall to analyse their impacts on the failure mode and the wall's strength.

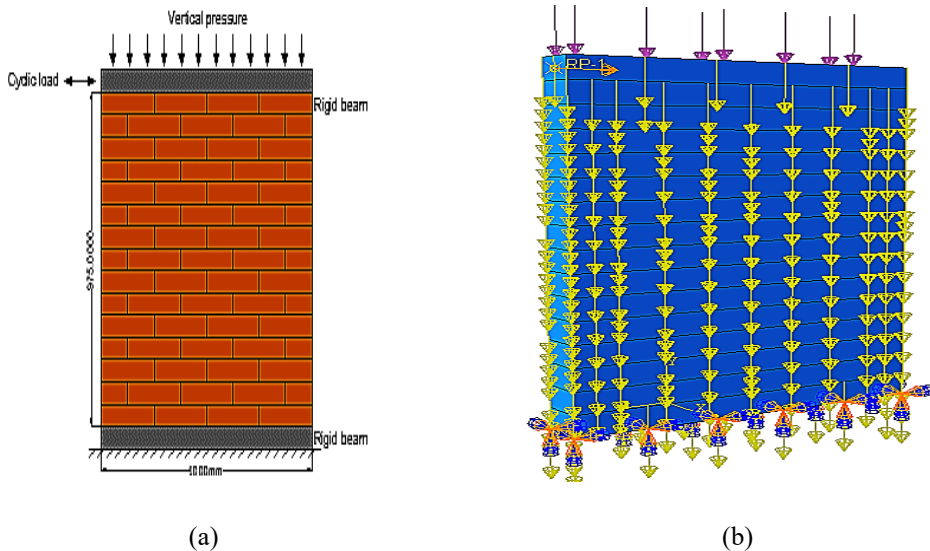


Fig. 4. Simulation example under cyclic load, (a) Geometry of wall, (b) boundary conditions-Abaqus

Once the wall was analysed under cyclic loading, the cracking process initially manifests as horizontal flexural cracks, followed by diagonal cracks extending throughout the wall. Three essential stages characterize the mechanical response of this wall: flexural cracks form, then diagonal cracks develop from the center towards the sides of the wall, with the brick units cracking along the interface joints, creating stepped diagonal cracks, ultimately leading to the detachment of bricks along the two diagonals after several displacement cycles (Fig.5). Lateral displacement increased the size of the diagonal cracks. Fig. 5 illustrates the failure mode of the wall and demonstrates that variations in the applied vertical load significantly impact the behavior of masonry walls. Indeed, the wall subjected to a vertical load of 1.20 MPa (Fig. 5a) exhibits more pronounced damage, with greater detachment of brick units and larger joint sizes compared to the wall subjected to a vertical load of 2.12 MPa (Fig. 5b).

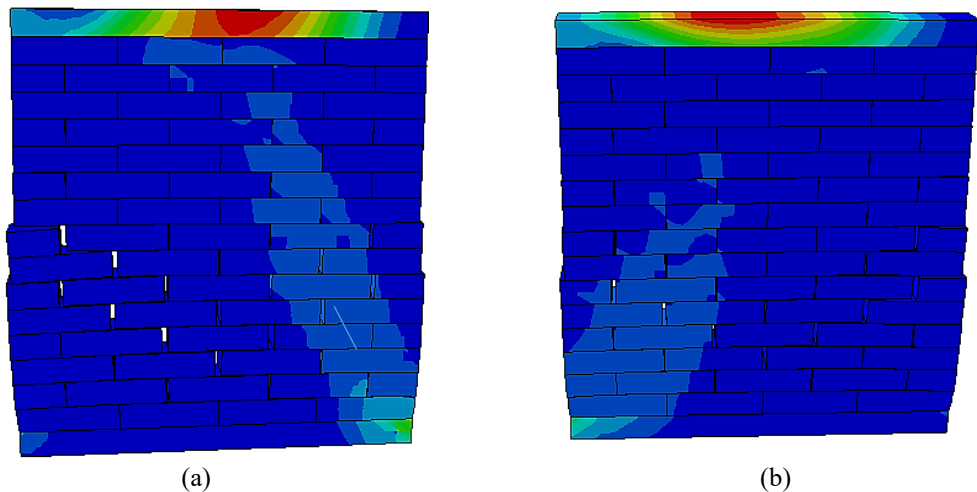


Fig. 5. Comparison of wall failure mechanisms: (a) wall with a vertical load of 1.20 MPa, (b) wall with a vertical load of 2.12 MPa

Fig. 6 presents the force-displacement curves obtained from the wall simulations under cyclic loading with two different vertical loads. It clearly shows that increasing the pre-compression load improves the wall's strength. The wall subjected to a vertical load of 2.12 MPa can dissipate a greater amount of energy, reaching up to 88 kN, while the wall under a pre-compression of 1.20 MPa does not exceed 58 kN. This highlights the high resistance of this type of structure under compressive loads.

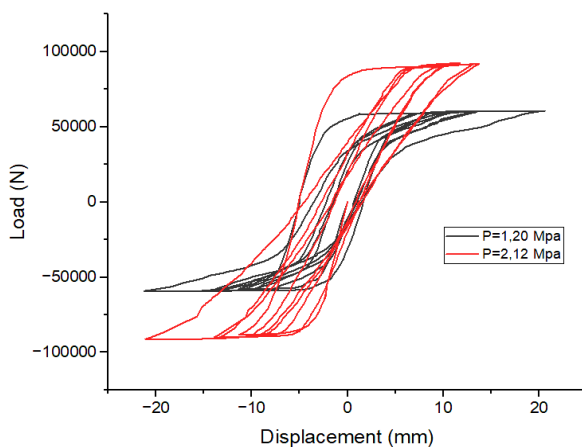


Fig. 6. Load-displacement curve for masonry wall with different pre-compression loads

4.2 The impact of openings

Unreinforced masonry structures are particularly vulnerable to horizontal loads, such as those induced by wind and earthquakes, due to their low tensile strength and the mortar bond between bricks [2]. Despite this vulnerability, masonry walls are still widely used around the world, especially as infill walls [2], and constitute a large part of historical architectural heritage. These structures often include openings for doors and windows. Hence, the focus of this study is to evaluate the influence of openings on the behaviour of walls subjected to cyclic loads. The model used in section (4.1) will be simulated using Abaqus software, maintaining the same vertical load of 0.7 MPa for all simulations. Initially, a masonry wall without openings will be analyzed, followed by the creation of new models by adjusting the parameter of the opening surface area (as per Table 3) to observe how the wall behaves with and without openings and to identify points of damage. For each configuration, the failure mode and the force-displacement curve will be presented and discussed.

Table 3. Type of openings.

Opening Type	percentage of occupancy versus wall
Opening 1	5 %
Opening 2	10 %
Opening 3	15%

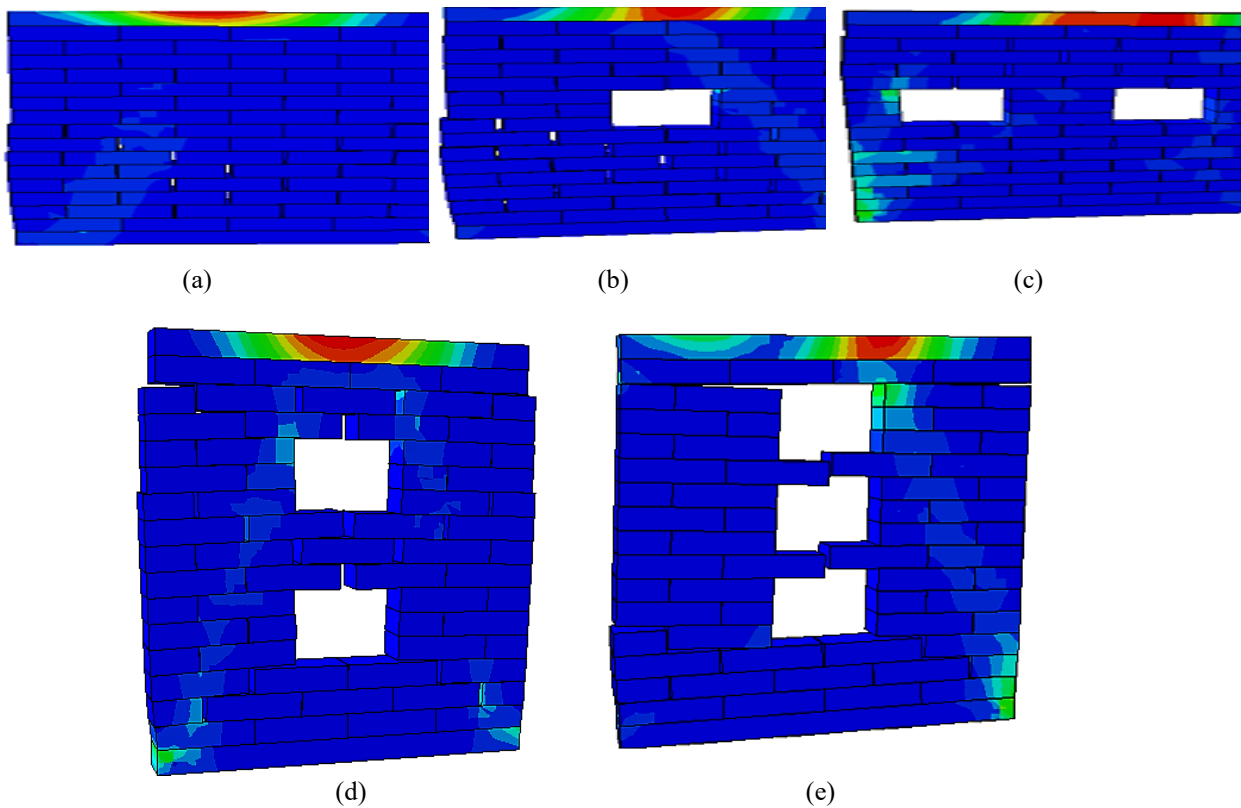


Fig. 7. Comparison of wall failure mechanisms: (a) wall without openings, (b) wall with opening 1, (c) wall with opening 2- Horizontal, (d) wall with opening 2-Vertical, (e) wall with opening 3

Fig. 7 illustrates the failure process of walls with and without openings, each case presenting a specific cracking mode after the simulation. For the wall without openings, diagonal cracks in a staircase pattern appear in the lower half, leading to the detachment of bricks in this area (Fig. 7a). The wall with a centered opening occupying 5% of the total surface area (Fig. 7b) shows pronounced cracks in the lower part, as well as new cracks in the upper part and around the opening. Figures 7c and 7d present walls with an opening occupying 10% of the surface area, but positioned differently. This indicates that the position of the opening can also influence the wall's resistance and failure mode. Indeed, the wall with a vertical opening (Fig. 7c) experiences more significant brick detachments than the wall with a horizontal opening (Fig. 7d). These openings represent points of weakness, promoting the formation of large diagonal cracking areas and the sliding of brick blocks around the openings. In the last case (Fig. 7e), the opening, which occupies 15% of the surface area of the wall, concentrates the propagation of cracks in the upper and lower parts, as well as around the openings. With displacement cycles, these cracks extend significantly, ultimately leading to the wall's collapse. These results demonstrate that the size and position of the openings strongly influence the response of masonry walls: the larger the opening, the lower the resistance; similarly, the closer the opening is to the

corners of the wall, especially at the bottom, the more pronounced the cracks become. In comparison, the wall with a centered opening exhibits fewer cracks (Fig. 7b).

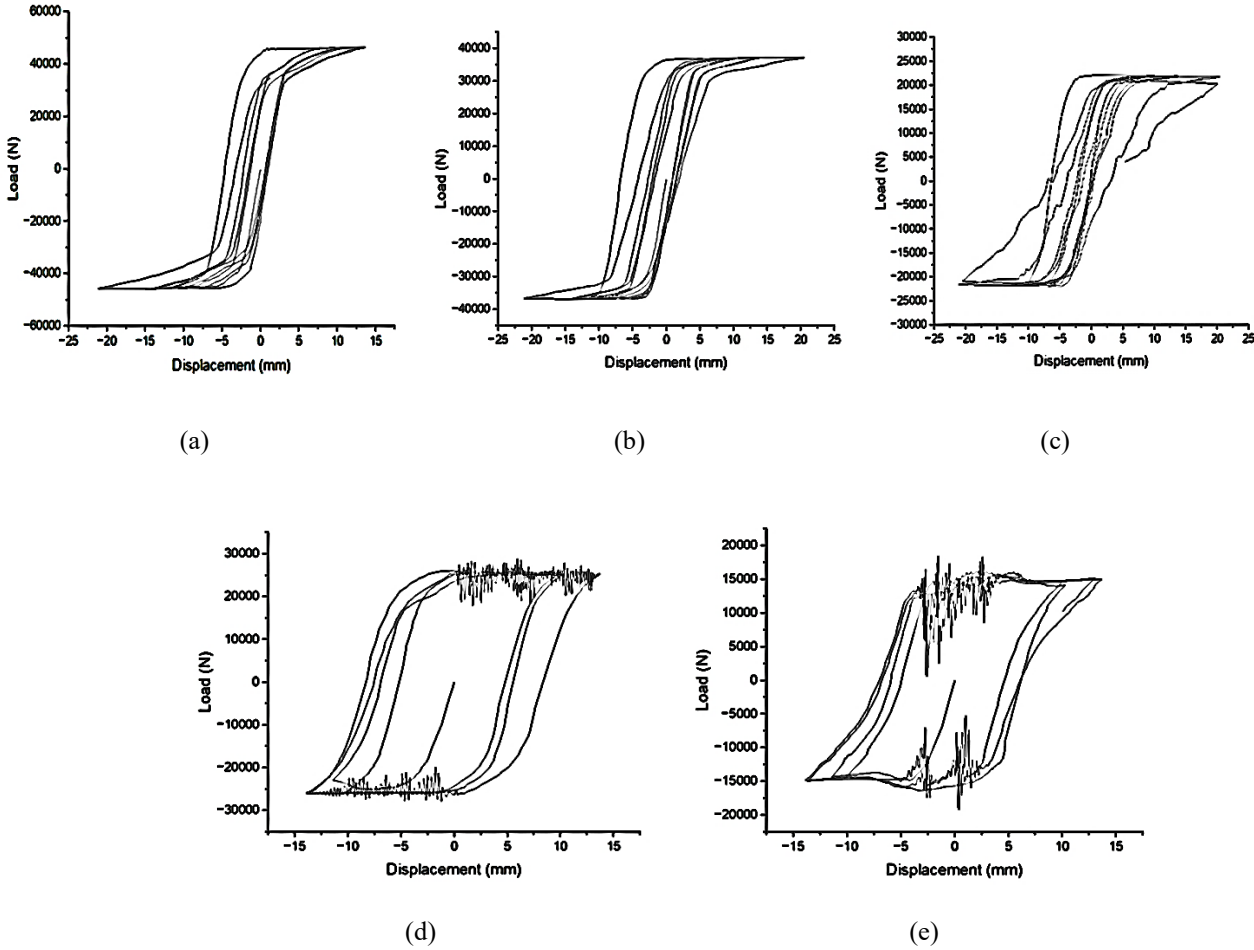


Fig. 8. Load-displacement curve: (a) wall without openings, (b) wall with opening 1, (c) wall with opening 2- Horizontal, (d) wall with opening 2-Vertical, (e) wall with opening 3

Fig. 8 presents the force-displacement curves obtained after analysing the different cases. This figure highlights the inverse relationship between the strength of masonry walls and the presence of openings. As the percentage of openings increases, the wall's ability to resist loads decreases. Indeed, the wall without openings is capable of withstanding a load of 45 kN due to its continuous and homogeneous structure, which promotes optimal force distribution. In contrast, the wall with a 5% opening can withstand 38 kN. The addition of an opening, even a minimal one, disrupts the continuity of the structure and diminishes its load-bearing capacity, although the wall remains relatively solid. The wall with a 10% opening can support 23 kN; at this point, the increase in the open area leads to a more pronounced decrease in strength. Cracks may begin to form around the opening, and the ability to dissipate applied forces is reduced. Finally, the wall with a 15% opening can withstand only 17 kN. The larger opening creates significant weak areas, making the wall

much more susceptible to failure. The structure becomes less stable, resulting in a much lower resistance. These results demonstrate that openings, by altering the structure of the wall, affect its ability to withstand loads, emphasizing the importance of the design and placement of openings in masonry walls, as well as the need to reinforce these areas if they are compromised.

5 Conclusion

This article primarily aims to analyse the behaviour of unreinforced masonry walls under cyclic loads, based on a parametric study divided into two parts. The first part evaluates the impact of varying vertical loads on the wall's resistance, while the second part examines the effect of openings on the wall's behaviour. Such studies contribute to a better understanding of these structures, thereby enabling effective interventions to reinforce them and, most importantly, reduce their vulnerability to seismic effects. The results of this study highlight the following points.

- The variation in the applied vertical load significantly affects the behavior and strength of masonry walls. Indeed, the wall subjected to a vertical load of 1.20 MPa experienced significant degradation and wider cracks compared to the wall subjected to a vertical load of 2.12 MPa. Moreover, the results of the force-displacement curves show that increasing the value of the pre-compression load leads to an increase in the wall's strength.
- The size of the openings influences the failure process of masonry walls and reduces their strength. Diagonal cracks, which become wider in the presence of openings, are the predominant type of crack. These openings represent points of weakness in the wall, accelerating its degradation. The larger the opening, the greater the deformations. The results show that the wall with an opening occupying 5% of the total surface can withstand 38 kN, while the wall with an opening occupying 15% of the total surface can only withstand 17 kN.

This research deepens the understanding of the behavior of masonry walls and provides valuable insights that may promote the development of targeted reinforcement techniques for masonry walls with openings, thereby enhancing their resilience to future loads and reducing the risk of failure.

6 References

- [1] Kurdo F. Abdulla a, Lee S. Cunningham a, Martin Gillie b. Simulating masonry wall behaviour using a simplified micro-model Approach. (2017).
- [2] Meillita Finite element modelling of unreinforced masonry (URM) wall with openings: studies in Australia. The Proceedings of 2nd Annual International Conference Syiah Kuala University (2012).
- [3] Danna Darmayadi, Muhamad Rusli. Element modeling of masonry wall with opening under lateral force (2018).
- [4] Éric BOLDIREFF. Characterization of the mechanical properties of traditional stone masonry with massive walls. Ph.D. thesis graduate school of technology, Université du Québec. (2018)

- [5] Marie Bisoffi-Sauve. Study of stone masonry works by the discrete elements method: characterization and modelling of cohesive behaviour of joints. Ph.D. Thesis University of Bordeaux (2016).
- [6] Stavridis A, Shing PB. Finite-element modeling of the nonlinear behavior of masonry infilled RC frames. (2010)
- [7] Feba S. Thomas, and Bennet Kuriakose. Nonlinear finite element analysis of unreinforced masonry walls. (2016)
- [8] L. Facchini, M. Betti, Simplified seismic analysis of disordered masonry towers, ASCEASME. (2016)
- [9] Bonisha Borah, Hemant B Kaushik and Vaibhav Singhal. Finite element modelling of confined masonry wall under in-plane cyclic load. International Conference on Materials, Mechanics and Structures 2020 (ICMMS2020)
- [10] P.B. Lorenço, Computational strategies for masonry structures, PhD thesis, Delft University of Technology, The Netherlands. (1996).
- [11] Nonlinear Finite Element Analysis of Unreinforced Masonry Walls. Geeta University and Bennet Kuriakose. (2017)
- [12] Pranoy Debnath a, Sekhar Chandra Dutta a,* , Parthasarathi Mandal b. Lateral behaviour of masonry walls with different types of brick bonds, aspect ratio and strengthening measures by polypropylene bands and wire mesh (2023)