

Seismic Strengthening and Numerical Modeling of Masonry Walls Under Cyclic Loading

Fatima Ez-zahra KHOU^{1*}, and *Mustapha RGUIG*²

¹ERIC Research Team, Hassania Engineering School, Casablanca, Morocco

Abstract. The Moroccan medina is characterized by clay-brick masonry edifices, which can be structurally vulnerable because of their limited seismic resistance. Therefore, some kind of intervention is sought to improve the structural performance of these traditional buildings. This paper presents a numerical investigation of the behavior of masonry walls under gravitational, compressive, and cyclic lateral loads, using an explicit finite element model following the simplified micro-approach. The numerical results prove that the shear response can be impacted by stress redistribution despite the lateral loading being primarily in the vertical di-rection. Thus, this study is foundational for future studies on seismic vulnerability and retrofitting of masonry construction.

Keywords: Axial Compression · Masonry Walls · Seismic Performance · FRP Reinforcement · Numerical Modeling

1 Introduction

Many places in the world have traditional masonry buildings because they are a legacy of the past and are often less expensive. In Morocco, they make up a large part of the built morphology and represent the culture of the area. The Moroccan medina is full of clay brick masonry buildings, and since they often have very little seismic resistance due to limited modern reinforcement techniques, renovation is needed to improve the structural integrity of these historically important buildings. Earthquakes such as the devastating 1960 Agadir earthquake highlight the systematic need to retrofit unreinforced masonry (URM) buildings in Morocco [1] [2].

Globally, Many masonry structures around the globe were standing before seismic codes were even introduced, and this directly increased their susceptibility to seismic loading. Research has also shown that URM buildings are especially prone to failure [1], even in an earthquake when they have no means of resisting tensile strength and poor lateral stability systems, which provide non-destructive approaches and sensitivity of preserving heritage structures [3][4].

* Corresponding author: khoui.fatimaezzahra.cedoc@ehp.ac.ma

New innovations in strengthening methods also include advanced materials such as Fiber-Reinforced Polymers (FRPs) and Fabric-Reinforced Cementitious Matrix (FRCM), which are increasingly being employed in recognition of their efficient strengthening potential and preservation of the aesthetics of historic buildings [3] [5] [6] [7]. Additionally, experimental studies indicate that the application of steel plates can significantly enhance the resistance of earthen structures to seismic loads and, therefore, it is critical to consider the properties of clay-brick masonry in the retrofit-ting of earthen structures [8][2].

It is essential to understand the behaviour of clay-brick masonry subjected to different loads in order to develop sound retrofitting techniques. The use of sophisticated numerical modelling and analytical methods enables better predictions of the behaviour of masonry walls while taking into account the inherent variability of the masonry material [8][3]. By applying those techniques globally, accordingly, there is the potential to enhance the seismic performance of masonry constructions and at the same time preserve their cultural value.

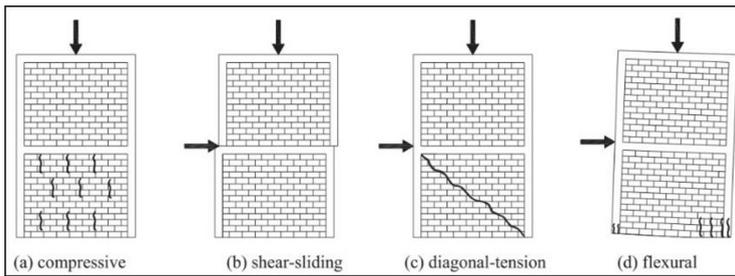


Fig. 1. failure modes of masonry wall under vertical and horizontal loads (based on [1])

2 Behavior of Masonry Structures Under Forces

Masonry structures have different responses to loads because of the physical proper-ties of the materials and the ways in which the structures have been built. The performance of masonry walls responding to seismic forces are based on their general shear capacity and the flexural capacity of the walls. Experimental studies show that unreinforced masonry (URM) walls cannot resist shear and typically fail because of low tensile capacity, whereas reinforced masonry structures can better carry lateral loads, if properly designed [9][1]. Overall, the incorporation of reinforcements has proven to be successful in improving the resiliency of masonry under vertical and lateral forces[3]. Understanding the behavior of masonry under various forces is important to ensure safe and durable structures. However, this becomes increasingly important in situations where risk exists of failure of masonry, such as with exposure to seismic loading. Accordingly, it is essential that reliable analysis and modernized and appropriate design codes are used to provide increased levels of safety when designing masonry.

3 Seismic Strengthening of Masonry Structures

3.1 Traditional Reinforcement Methods

This section presents traditional techniques of strengthening masonry structures.

- **Tying Elements.** This method connects walls and floors to improve structural integrity during earthquakes by distributing seismic loads to structural elements that form a box-like response to lateral loads. This method usually consists of connecting masonry walls and floors using ties in steel or reinforced concrete at the floor level [3][10].
- **Mortar Replacement (Repointing).** A traditional method fixing damaged mortar. Old mortar is taken out and replaced with stronger mortar. This technique is only effective on damage that is limited to joint areas [3].
- **Grout Injections.** A traditional effective method for stone masonry walls introduces grout into wall voids to create a cohesive structure that performs better under seismic loads [3].
- **Concrete Jacketing.** A classic method where reinforced concrete sleeves around masonry added around masonry to ameliorate strength and ductility (see fig.2)[3][11][12][13][4].

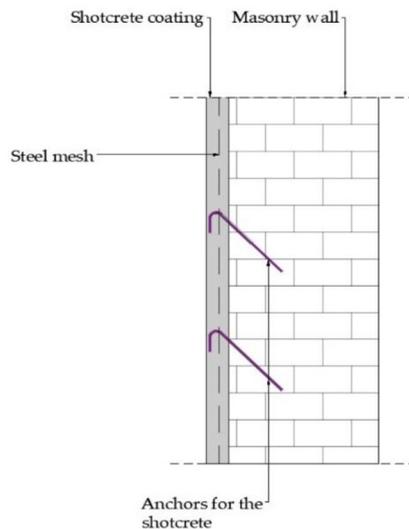


Fig. 2. Detail for single-sided concrete jacketing with Anchors (based on [3]).

- **Local Reconstruction:** Involves removing damaged bricks and mortar and replacing them with compatible materials to restore wall integrity [3][5][14].



Fig. 3. Before (left) and after (right) a local reconstruction.

- **Steel Reinforced Plaster (SRP):** An analytical approach to retrofitting masonry structures, where SRP is applied to enhance performance, addressing the configuration of connectors and material properties. It involves a plaster layer mixed with steel reinforcement, typically in the form of grids or meshes. The main components of SRP

include Cementitious Mortars or Concrete, Steel Reinforcement Grids/Meshes and Connectors [4].

3.2 Modern Reinforcement Methods

This section presents modern techniques of strengthening masonry structures.

- **Fabric-Reinforced Cementitious Matrix (FRCM):** This method uses composite materials for reinforcement (see fig.4), focusing on lightweight and high strength. The FRCM systems utilize an inorganic matrix instead of an organic one, which enhances performance in moist and high-temperature conditions. This method involves applying a mortar matrix reinforced with fibers, which are usually anchored to the masonry substrate with 4–6 anchors per square meter [3][5].

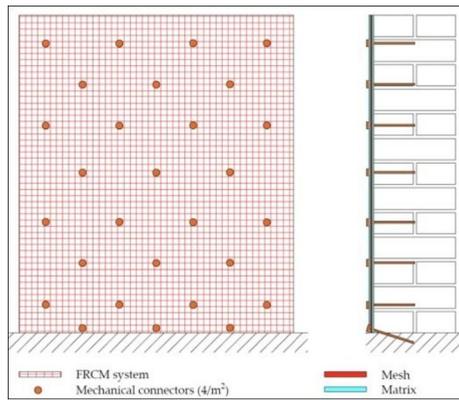


Fig. 4. FRCM system with the arrangement of mechanical connectors (front cross-section and side view) (based on[3])

- **Fiber-Reinforced Plastic (FRP) Systems:** Modern FRP methods are lightweight, quick to apply (see fig. 5), and combine different fiber types embedded in a polymeric matrix for efficient strengthening of masonry [5][7][15].

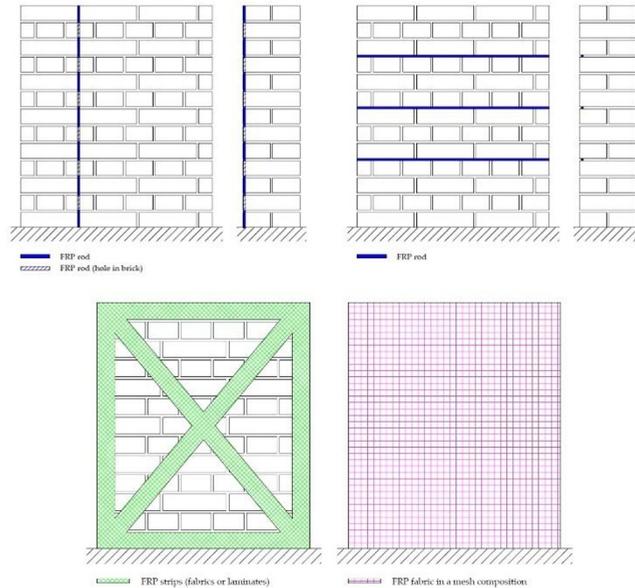


Fig. 5. Systems of FRP reinforcement applied on masonry walls.

- **Centercore Technique:** This innovative method involves introducing a reinforced grouted core into existing walls, significantly enhancing their stiffness and strength without compromising the structure's historical integrity [16][17].

4 Choice of Reinforcing Method

Although there are various methods for the strengthening of masonry structures, challenges remain, particularly with respect of existing building codes and standards, which may not adequately address the unique properties of masonry [8]. Additionally, retrofitting existing structures without compromising their historical value continues to be a major concern among engineers and architects.

Thus, the choice of the most appropriate retrofitting method should account for structural requirements, the architectural significance of a structure, environmental factors, and economic considerations. Advances in material technology and structural modeling are leading to opportunities for better and less invasive solutions to extend durability and the resilience of masonry to seismic events [18][4].

5 Numerical Simulation of Masonry Structures

There are multiple modeling techniques available, each focusing on different aspects of the complex, heterogeneous properties of masonry (see fig.6). One important approach is detailed micromodeling (DMM), in which individual masonry units and mortar are modeled as continuum elements with its unique constitutive laws, connected through interface elements. This technique has proven effective in estimating the in-plane and out-of-plane response of masonry [19][20][21][22]. Instead, simplified micromodeling (SMM) offers a more computationally efficient method in which one can average behaviours over larger scales, and is useful for larger assemblies as highlighted in [23]. Macromodeling is yet another technique, which is a simplification of masonry representation focusing on whole

structural response rather than detailed individual component or level of interaction as discussed in [18] [24]. Moreover, the combination of these methods, such as micromodeling with multiscale techniques, has shown some potential to enhance accuracy while remaining efficient, and there-fore has become a common approach in the current literature as noted in [22]. The variety of modeling techniques highlights the progress in numerical simulation of masonry, which aids in understanding masonry behavior in extreme conditions and helps improve design and retrofitting possibilities.

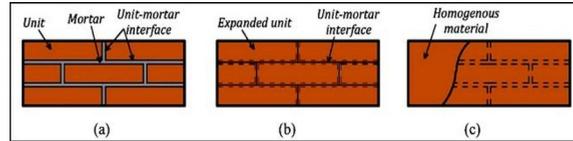


Fig. 6. (a) detailed Micro-model; (b) simplified Micro-model; (c) Macro-model (based on [23])

6 Simplified Micromodeling of Masonry Wall Behavior

This paper focuses on modeling a masonry wall that consists of 13 rows of solid clay bricks with the following dimensions: 230 mm (length) * 76 mm (width) * 110 mm (depth). There is a mortar thickness of 10 mm that uses a mix of 1:1:6 cement:lime:sand, which permits practical interaction between masonry units. A rein-forced concrete beam (1200 mm (length) * 86 mm (width) * 110 mm (depth)) is at the top of the wall, which serves an important structural function. (see fig.8).

6.1 Cohesive Elements

The joints between the blocks and the mortar are modeled using cohesive elements with zero thickness (see fig.8). This approach greatly reduces the cost of computation. Thus, it meets the criteria for frequently being used in numerical studies [16].

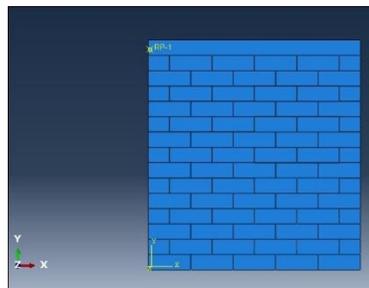


Fig. 7. Masonry wall simplified micro-model.

6.2 Material Properties

The definition of material properties is one of the most critical components in representing the behavior of the wall of the material which experiences various forms of loading. This study establishes the elastic modulus, Poisson's ratio, crushing strengths of both brick (the clay bricks) and mortar based on [23] which are aligned with experimental results in the literature.

6.3 Loads Application

In this study, two sequential loading steps were considered:

- **Step 1:** Involves applying gravity loads to represent the self-weight of the masonry wall and reinforced concrete beam, in addition to considering an axial vertical load that would characterize an external axial load.
- **Step 2:** Introduces horizontal cyclic loading, which represents dynamic effects such as those induced by seismic activity or repeated service loads.

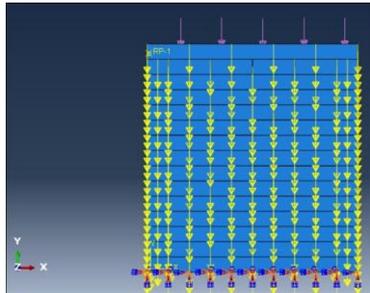


Fig. 8. Masonry wall under applied loads.

6.4 Results and Discussions

The numerical results provide a detailed understanding of the behavior of the masonry wall under sequential loading conditions.

- **Von Mises Stress:** As illustrated in fig.9, the stress distribution reveals critical areas of the initiation of failure phenomenon. In the first step of loading, the highest stress concentrations appear at the lower corners and along the mortar joints. This observation agrees with the findings of [23], where stress localization in masonry structures was observed because of joint discontinuities and material heterogeneity. In the second cyclic loading step, stress redistributions occur, with increased concentrations along diagonal parts and potential crack paths. This behavior is similar to previous studies on cyclically loaded masonry walls, where repeated loading generates progression of damage, and leads to stiffness degradation [23] [25].

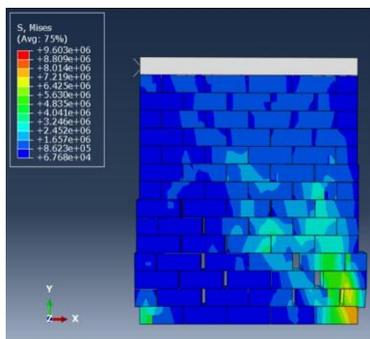


Fig. 9. Distribution of the Von Mises stresses during the loading history

- **Displacement and Crack Propagation:** Fig. 10 illustrates the displacement of the structure. It shows a significant accumulation of deformations in the lower left region. The propagation of large displacements in these areas is accompanied by potential cracking and localized masonry unit detachment, as observed in experimental cyclic loading tests [26]. In [27], the diagonal cracking pattern induced by cyclic loading is consistent with the stress distribution. Stress redistribution results show that the shear response can be affected by stress redistribution under cyclic loading in the horizontal direction. The effect of cyclic loading in shear joint separation and subsequent failure is progressive in nature.

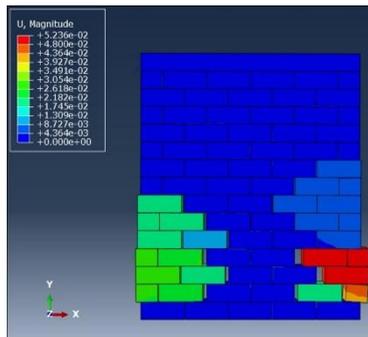


Fig. 10. Distribution of the displacements during the loading history

7 Conclusions

This study is a numerical investigation of the behavior of a masonry wall under gravity, compressive, and cyclic loadings using an explicit finite element model with cohesive elements. The key findings conducted are summarized as follows:

- The lower corners and vertical regions displayed stress localization indicating an evident progressive degradation mechanism from cyclic loading, analogous to experimental observations in [26].
- Cyclic loading significantly directed the pattern of internal stress redistribution, which ultimately resulted in progressive degradation in stiffness and more rapid crack extension, coinciding with previous observations in [28].
- Displacement results indicated the early manifestation of cracking and specific unit separation, which coincided with damage profiles in previous studies on cyclically loaded masonry walls [1].
- The cyclic loading produced stress concentrations in diagonal areas, close to the lower edges and along mortar joints, leading to a progressive degradation mechanism rather than a direct shear failure. Displacement results confirm an accumulation of deformation over time, which can lead to joint separation and local instabilities, as found in [1].
- The study highlights the need to investigate long-term effects of cyclic loadings, as well as reinforcement strategies to prevent progressive masonry damage.

Given the limitations of the current model, future works should focus on studying reinforcement techniques such as FRP strengthening to improve masonry shear resistance [29].

References

1. R. Marques and P. B. Lourenço, "Structural behaviour and design rules of confined masonry walls: Review and proposals," *Construction and Building Materials*, vol. 217, pp. 137–155, Aug. 2019.
2. J. C. Reyes, R. Rincon, L. E. Yamin, J. F. Correal, J. G. Martinez, J. D.Sandoval, C. D. Gonzalez, and C. C. Angel, "Seismic retrofitting of existing earthen structures using steel plates," *Construction and Building Materials*, vol. 230, p. 117039, Jan. 2020.
3. I. Hafner, T. Kišic`ek, and M. Gams, "Review of Methods for Seismic Strengthening of Masonry Piers and Walls," *Buildings*, vol. 13, no. 6, p. 1524, Jun. 2023.
4. M. Scamardo, S. Cattaneo, P. Crespi, and L. Biolzi, "Design method for masonry structures retrofitted with steel reinforced plaster," *Journal of Building Engineering*, vol. 79, p. 107828, Nov. 2023.
5. P. Zampieri, N. Simoncello, C. D. Tetougueni, and C. Pellegrino, "A review of methods for strengthening of masonry arches with composite materials," *Engineering Structures*, vol. 171, pp. 154–169, Sep. 2018.
6. A. Cascardi, R. Dell'Anna, F. Micelli, F. Lionetto, M. A. Aiello, and A. Maffezzoli, "Reversible techniques for FRP-confinement of masonry columns," *Construction and Building Materials*, vol. 225, pp. 415–428, Nov. 2019.
7. P. K. Mallick, *Fiber-Reinforced Composites: Materials, Manufacturing, and Design*, Third Edition, 3rd ed. Boca Raton: CRC Press, Nov. 2007.
8. A. Nour, A. Benanane, and H. Varum, "Seismic behavior of reinforced concrete buildings using chained masonry walls randomly located," *Revista Facultad de Ingeniería Universidad de Antioquia*, no. 107, pp.102–112, 2023.
9. F. Yavartanoo and T. H. K. Kang, "Retrofitting of unreinforced masonry structures and considerations for heritage-sensitive constructions," *Journal of Building Engineering*, vol. 49, p. 103993, May 2022.
10. A. S. Arya, "Earthquake Resistant Design of Masonry Buildings," in *Advances in Indian Earthquake Engineering and Seismology: Contributions in Honour of Jai Krishna*, M. L. Sharma, M. Shrikhande, and H. R. Wason, Eds. Cham: Springer International Publishing, 2018, pp.259–271.
11. M. ElGawady, P. Lestuzzi, and M. Badoux, *Seismic Behavior of URM Walls Retrofitted Using Shotcrete*, Mar. 2006.
12. C. D'Ambra, G. P. Lignola, and A. Prota, "Simple method to evaluate FRCM strengthening effects on in-plane shear capacity of masonry walls," *Construction and Building Materials*, vol. 268, p. 121125, Jan.2021.
13. S. W. Chuang and Y. and Zhuge, "Seismic Retrofitting of Unreinforced Masonry Buildings – A Literature Review," *Australian Journal of Structural Engineering*, vol. 6, no. 1, pp. 25–36, Jan. 2005.
14. S. A. Babatunde, "Review of strengthening techniques for masonry using fiber reinforced polymers," *Composite Structures*, vol. 161, pp. 246–255, Feb. 2017.
15. E. J.Barbero, "Introduction to Composite Materials Design – Third Edition," <https://barbero.cadec-online.com/icmd/index.html>.
16. E. M. Farahani, M. Yekrangnia, M. Rezaie, and R. Bento, "Seismic behavior of masonry walls retrofitted by centercore technique: A numerical study," *Construction and Building Materials*, vol. 267, p. 120382, Jan.2021.

17. G. Mohamad, P. B. Lourenço, and H. R. Roman, "Mechanics of hollow concrete block masonry prisms under compression: Review and prospects," *Cement and Concrete Composites*, vol. 29, no. 3, pp. 181–192, Mar. 2007.
18. P. Lourenco, "Computational Strategy for Masonry Structures," Jan.1996.
19. A. M. D'Altri, S. de Miranda, G. Castellazzi, and V. Sarhosis, "A 3D detailed micro-model for the in-plane and out-of-plane numerical analysis of masonry panels," *Computers & Structures*, vol. 206, pp. 18–30, Aug. 2018.
20. C. Sandoval and O. Arnau, "Experimental characterization and detailed micro-modeling of multi-perforated clay brick masonry structural re- sponse," *Materials and Structures*, vol. 50, no. 1, p. 34, Aug. 2016.
21. A. Drougkas, P. Roca, and C. Molins, "Numerical prediction of the be- havior, strength and elasticity of masonry in compression," *Engineering Structures*, vol. 90, pp. 15–28, May 2015.
22. "Detailed Micromodeling and Multiscale Modeling of Masonry under Confined Shear and Compressive Loading | Practice Periodical on Structural Design and Construction | Vol26, No 1," <https://ascelibrary.org/doi/10.1061/%28ASCE%29SC.1943-5576.0000538>.
23. K. F. Abdulla, L. S. Cunningham, and M. Gillie, "Simulating masonry wall behaviour using a simplified micro-model approach," *Engineering Structures*, vol. 151, pp. 349–365, Nov. 2017.
24. P. B. Lourenço and J. G. Rots, "Multisurface Interface Model for Analysis of Masonry Structures," *Journal of Engineering Mechanics*, vol. 123, no. 7, pp. 660–668, Jul. 1997.
25. R. Xin and P. Ma, "Experimental investigation on the in-plane seismic performance of damaged masonry walls repaired with grout-injected ferrocement overlay," *Construction and Building Materials*, vol. 282, p. 122565, May 2021.
26. V. Singhal and D. C. Rai, "Behavior of Confined Masonry Walls with Openings under In-Plane and Out-of-Plane Loads," *Earthquake Spectra*, vol. 34, no. 2, pp. 817–841, May 2018.
27. N. Gattesco, E. Rizzi, I. Boem, L. Facconi, F. Minelli, A. Dudine, and M. Gams, "Full-scale cyclic tests on a stone masonry building to investigate the effectiveness of a one-side application of the composite reinforced mortar system," *Engineering Structures*, vol. 296, p. 116967, Dec. 2023.
28. B. R. Robazza, T. Y. Yang, S. Brzev, K. J. Elwood, D. L. Anderson, and W. McEwen, "Response of slender reinforced masonry shear walls with flanged boundary elements under in-plane lateral loading: An experimental study," *Engineering Structures*, vol. 190, pp. 389–409, Jul.2019.
29. M. A. ElGawady, P. Lestuzzi, and M. Badoux, "Aseismic retrofitting of unreinforced masonry walls using FRP," *Composites Part B: Engineer- ing*, vol. 37, no. 2-3, pp. 148–162, 2005.