Height-to-Length Ratio Effect on the Response of Unreinforced Masonry Wall Subjected to Vertical Load Using Detailed-Micro Modeling Approach

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Abstract: ***This paper aimed to investigate the effect of the height-to-length ratio of unreinforced masonry (URM) walls when loaded by a vertical load. The finite element (FE) method was implemented for modeling and analysis of URM wall. In this paper, ABAQUS, FE software with implicit solver was used to model and analysis URM walls subjected to a vertical load. In order to ensure the validity of Detailed Micro Model (DMM) in predicting the behavior of URM walls under vertical load, the results of the proposed model are compared with experimental results. Load-displacement relationship of the proposed numerical model is found of a good agreement with that of the published experimental results. Evidence shows that load-displacement curve obtained from the FE model has almost the same trend of experimental one. A case study of URM walls was conducted to investigate the influence of the wall aspect ratio on its capacity and stress distribution due to a vertical load using DMM approach. In this paper, curves obtained that show a relationship between height level and generated compressive stress of walls with different aspects ratios and the strength of each URM wall and the DMM technique that has been utilized for numerical simulation.***

Keywords: URM walls, Concrete masonry units, Detailed Micro Modeling (DMM), Aspect ratio, Stress distribution

1. Introduction

Masonry as a material considered heterogeneous and composite that comprises of units and joints [2]. Due to its heterogeneous nature and nonlinear behavior, it is challenging to model and analyze masonry structures [11]. Although masonry material is ancient yet in today's buildings it has been frequently employed. In the last years, a new development in the masonry materials and applications happened but the assembling methods of masonry units are essentially the same as the methods used many decades ago. Masonry materials, procedures, and applications happened through time as expected, impacted by the capital and local culture, tools knowledge and availability and materials and architectural reasons. Simplicity is the greatest advantage of masonry construction. Laying on top of each other pieces of stone or brick, either with or without adhesive mortar, is a simple, nonetheless appropriate method that has been successful ever since centuries. Additional important features are the strength, durability, low maintenance, flexibility, sound absorption and fire protection. Examples where structural masonry still is used are load-bearing walls, infill panels to resist wind loads and seismic, low-rise buildings and pre-stressed masonry cores [1].

Nonetheless, advanced applications of structural masonry are far behind due to the fact that masonry design rules have not kept up with the developments of concrete and steel. The design rules development delay essentially because of lack of insight and lack of models that explain the complex behavior of units, mortar joints, and masonry as a composite. Procedures of calculation that are presently available are basically of empirical and traditional and the tools used for numerical analysis and/or design of masonry structures is impartially primary [1].

At the present time, more complex numerical tools have been presented, that are able to predict the behavior of structure from the linear stage, during the course of cracking and degradation up to complete failure. This goal can be reached only through accurate and robust constitutive model implementation using advanced solution methods of equations system, which results from the finite element method. Detailed Micro-Modelling (DMM) method is a finite element new technique that deals separately with masonry units and mortar. Lourenco in 1995 was initially adopted the DMM method where the representation of masonry units and mortar joints is by continuum solid elements while the representation of unit-mortar interface is by discontinuous contact elements [1]. All the failure mechanisms of masonry must be included in the micro model, and they are, joints cracking, sliding over one head or bed joint, units cracking and masonry crushing [6]. A comprehensive micro model has to include all the failure mechanisms of masonry, viz., joints cracking, sliding over one head or bed joint, units cracking and masonry crushing [6]. In addition, the computer hardware evolutions recently allowed sophisticated analysis methods to be implemented, which allow the structures detailed modeling and the following behavior simulation while subjected to distinctive actions. However, advanced methods usage requires, generally, also a complicated characterization of the model, including viz. a detailed representation of the geometry and a huge number of material parameters [10].

2. Modeling Strategy

Masonry material exhibits distinct directional properties because of the mortar joints [5], which act as planes of weakness [6]. Generally, the approach for numerical representation depends on the level of accuracy and the level of simplicity preferred. The consideration of micro modeling approach is to describe the individual components of masonry, namely, units and mortar. There are two types of micro modeling approach, simplified and detailed micro modeling [4].

The usage of detailed micro modeling (DMM) approach is to represent masonry units and mortar in the joints by solid continuum elements and unit-mortar interface by contact discontinuum elements. In this approach [4]:

Units and mortar consideration of both elastic properties (i.e. Young's modulus (E) and Poisson's ratio (ν)) and inelastic properties.

Interface representation as a potential crack/slip plane with initial dummy stiffness (slave elements) in order to avoid interpenetration of the continuum (master elements).

Unit, mortar and unit-mortar interface combined action can be examined in this approach in more detailed manner.

The adopted modeling strategy used in this study is illustrated in **Error! Reference source not found.**.

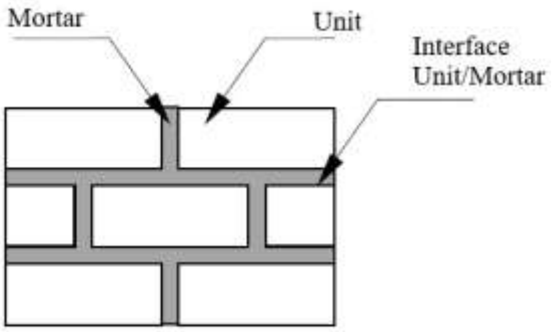


Figure 1: Modeling strategy adopted [4]

Interface elements allow discontinuities occurrence in the displacement field, their behavior is defined according to the relation between the tractions t and relative displacements Δu through the interface. The generalized stresses and strains can be written in a linear elastic relation in the standard form as in (1) [1].

$$\sigma = D\varepsilon \tag{1}$$

where, for a 2D configuration

$$\sigma = \{\sigma, \tau\}^T$$

$$D = diag\{k_n, k_s\}$$

$$\varepsilon = \{\Delta u_n, \Delta u_s\}^T$$

n and s = Normal and shear components, respectively.

The elastic stiffness matrix D capable to be found from the units and mortar properties which they are masonry components and the joint thickness as in (2) and (3) below [1].

$$k_n = \frac{E_u E_m}{h_m(E_u - E_m)} \tag{2}$$

$$k_s = \frac{G_u G_m}{h_m(G_u - G_m)} \tag{3}$$

Where,
E_u and E_m = The Young's moduli, respectively for unit and mortar.
G_u and G_m = The shear moduli, respectively for unit and mortar.
h_m = Joint thickness.

A multi-surface model, composite of yield functions can be used to define constitutive interface model, as in **Error! Reference source not found.**. This model composed of three separate yield functions associated with softening behavior for the three modes as in (3), (4) and (5) [2].

Tensile criterion:

$$f_t(\sigma, k_t) = \sigma - \overline{\sigma_t}(k_t) \tag{3}$$

Shear criterion:

$$f_s(\sigma, k_s) = |\tau| + \sigma \tan\phi - \overline{\sigma_s}(k_s) \tag{4}$$

Compressive criterion:

$$f_c(\sigma, k_c) = (\sigma^T P \sigma)^{1/2} - \overline{\sigma_c}(k_c) \tag{5}$$

Here,
ϕ = The friction angle
P = a projection diagonal matrix, based on material parameters.
$\overline{\sigma_t}, \overline{\sigma_s} and \overline{\sigma_c}$ = The isotropic effective stresses of each of the adopted yield functions.
k_t, k_s and k_c = scalar internal variables that affect the isotropic effective stresses.

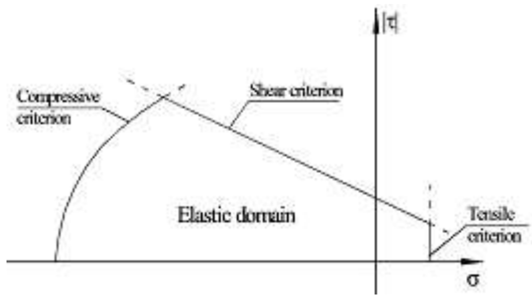


Figure 2: Multi surface constitutive interface model [6].

3. Numerical Simulation

The FE software, ABAQUS, was used in this study to develop an FE model of URM Walls. Generally, in FE models, the behavior of the real structure should be implemented with considering limitations of the applied model created. Thus, the following limitations applied in modeling URM wall [7]:

1) No cracking was allowed in masonry units with the increase of the applied loading. This consideration came from the uncertainty of cracking location in the unit. Therefore, all units were considered as full continuum units and mortar with no crack considered in their meshing.
2) The inelastic behavior of continuum part was modeled so that they can absorb some energy from the applied load that can be seen on their deformed shape.

The proposed strategy for modeling is that units and mortar joints are modeled with continuum elements while the unit-mortar interface represented by interaction properties [3]. The implicit solver in ABAQUS was used to model the URM walls. This method is a computationally efficient and capable to simulate linear static loading which was included in this study [8]. Masonry units, mortar and loading steel plates were modeled using Continuum 3 Dimensional 8 nodes Reduced Integration C3D8I element. The interface element (i.e. Interaction between Units and Mortar) modeled using tangential and normal behavior available in ABAQUS. The reason to select this model was to its ability to model frictional and cohesive materials, such as granular-like soils and rock [1]. Normal, tangential and cohesive behavior interactions available in interaction module in ABAQUS were used to model the interaction between the units and mortar [8]. When two surfaces are in contact, it is assumed that they usually transfer shear and normal forces along their interface [3]. The relationship between components of these two forces is generally recognized as friction between the contacting bodies. Data that were obtained from experimental tests by the researcher were used as an input data in the simulation process of verification.

4. Verification of Numerical Model

FE model of URM solid walls was verified via comparing the load-displacement relationship of the masonry prism with the experimental results given by the researcher. The dimensions of prism were 500 mm high × 240 mm wide × 240 mm thick. The prism consists of 6 courses high and 1 unit across the thickness. Clay brick units of 240 mm ×115 mm × 75 mm and 10 mm thickened mortar were used to construct the prisms. The geometry of the clay masonry prism and testing setup can be seen in Figure 1. The prism was subjected to an increasing vertical load till it reaches failure. Figure 2 shows the numerical simulation for the FE model that has been implemented using ABAQUS.

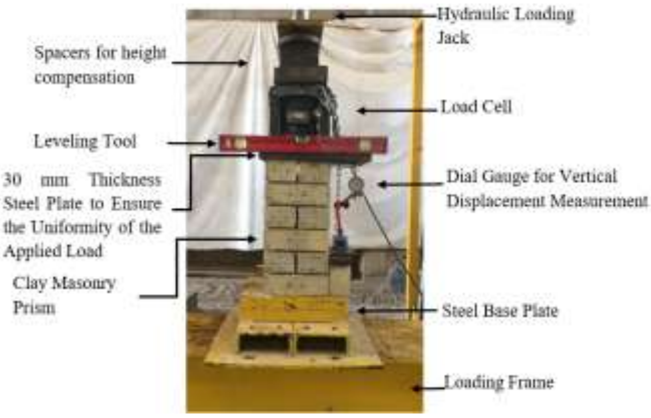


Figure 1: Clay masonry prism testing setup

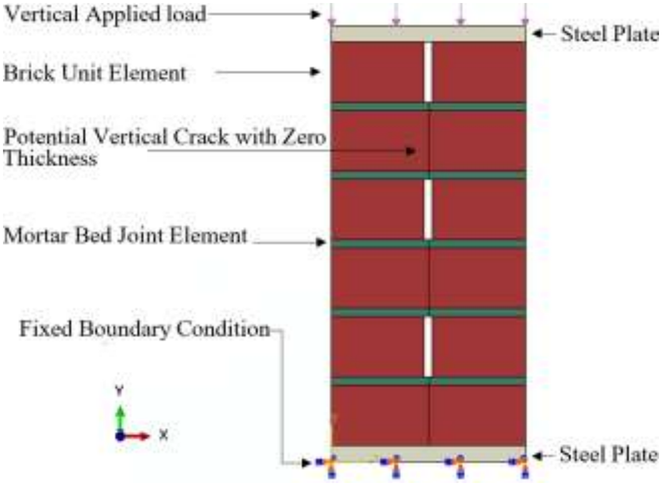


Figure 2: Numerical simulation for FE model of clay masonry prism

The trend of the load-displacement diagram of the numerical FE model shown in Figure 3 has almost the same shape of the load-displacement curve for the experimentally tested prism. It can be seen that at the beginning of load application there is a difference in the displacements between the experimental and the numerical model. When the load is increased to its maximum value, the displacements of both experimental and numerical models reach to almost equal values. 5.07 mm for numerical model and 4.63 for experimental one.

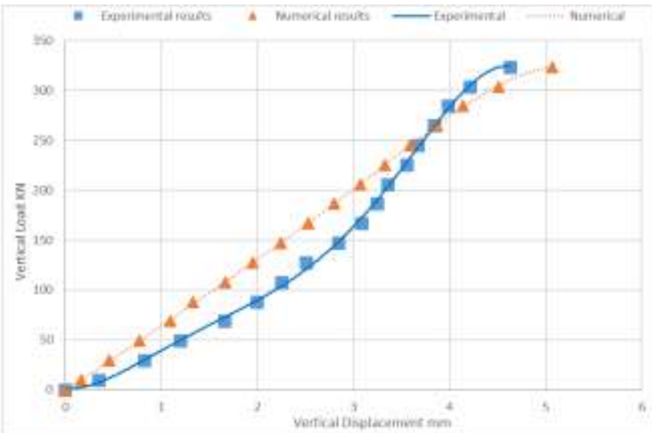


Figure 3 Comparison between load-displacement relationship of numerical and experimental model

5. Parametric Study, Results and Discussion

Three URM walls with different height to length ratios subjected to vertical load were numerically analyzed to investigate the influence of the wall aspect ratios on the vertical stresses that generated at different levels of each wall. The three URM walls have aspect ratios of 0.5, 1, and 2 with a constant thickness of 200 mm of concrete masonry units (dimensions 400 × 200 × 200 mm) and 10 mm thick mortar, and loading steel plates placed at top and bottom of the wall to guarantee uniform distribution of the applied load. The first wall has dimensions of 4m length by 2m height, while the dimensions of the second wall were 2m for length and 2m for height. Finally, the third wall has of 1m length by 2m height dimensions. For numerical simulation, the type of mortar selected was M and the compressive strength of concrete masonry units was 13.1 MPa, hence of The compressive strength of masonry was 10.34 MPa [9]. **Error! Reference source not found.** and **Error! Reference source not found.** show the material properties that were used as an input data for the simulation process of the parametric study.

Table 1: Elastic properties of concrete masonry units and cement mortar

Properties	*Concrete Masonry Units*	Cement Mortar
Modulus of Elasticity MPa	7200	1500
Poisson's ratio	0.15	0.2

Table 2: Inelastic properties of mortar

Angle of friction φ	*Flow stress ratio k*	*Dilation angle ψ*
37º	0.8	20º

A vertical compression uniformly distributed force equals to 6 N/mm2 was applied along the length of the wall. **Error! Reference source not found.** illustrates the different wall's aspect ratios and the uniformly distributed applied load.

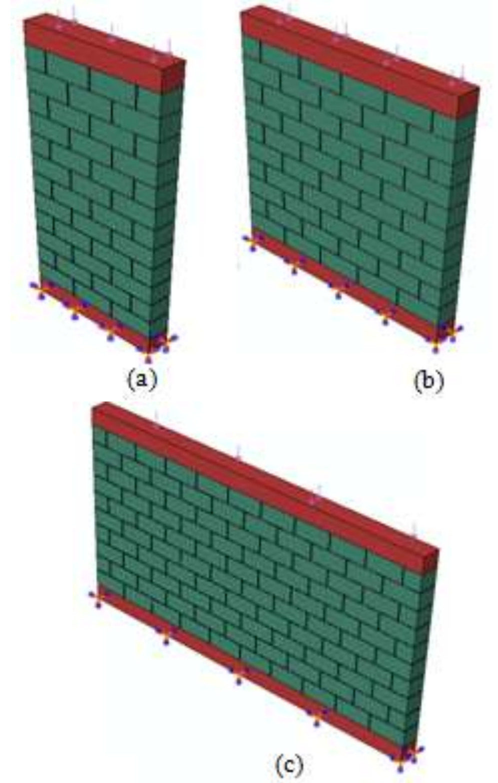
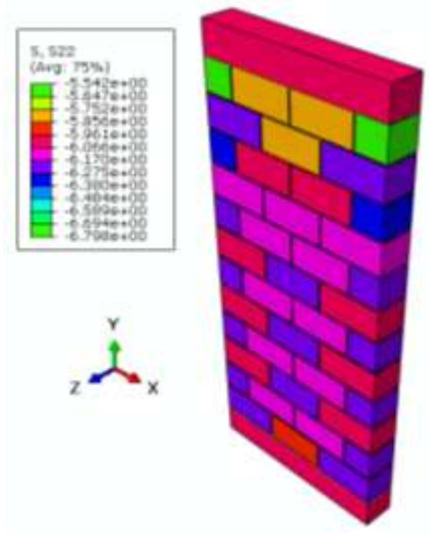


Figure 4: URM Walls with constant thickness of 200 mm for (a) Wall with aspect ratio 2 (b) Wall with aspect ratio 1 (c) Wall with aspect ratio 0.5

The generated stresses were detected at different levels of wall's height. Figure 5, Figure 6 and Figure 7 show an overview of the stress distribution on the wall as a whole, concrete units and mortar joints.



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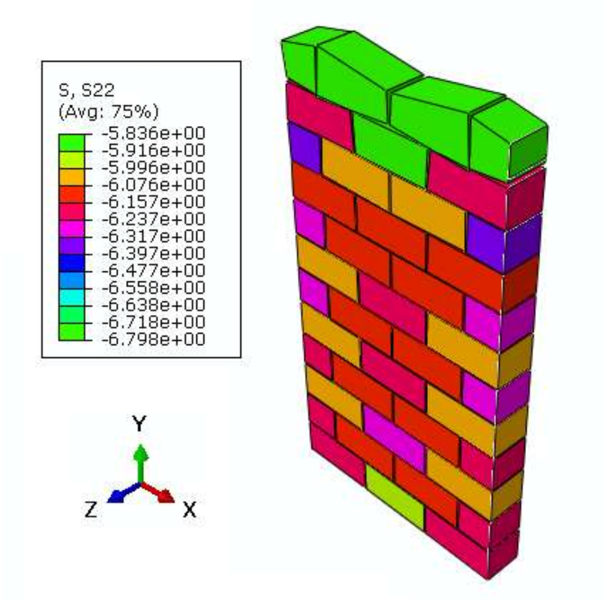

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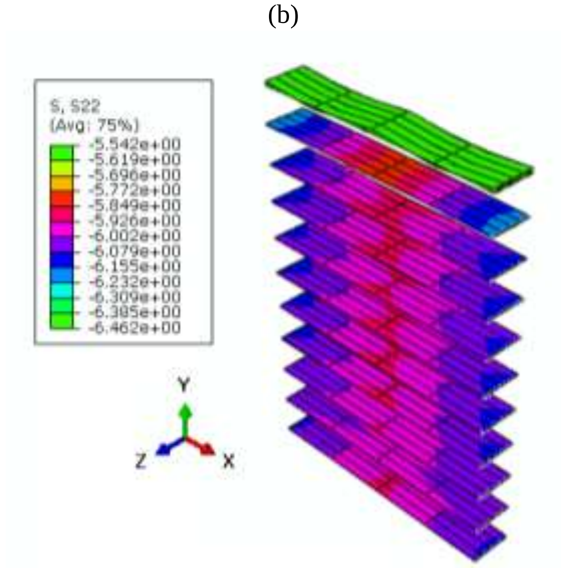

(c)

Figure 5: Stress distribution of URM wall with aspect ratio equals to 2: (a) Stress distribution for the undeformed wall (b) Stress distribution for the deformed concrete masonry units (c) Stress distribution for the deformed mortar

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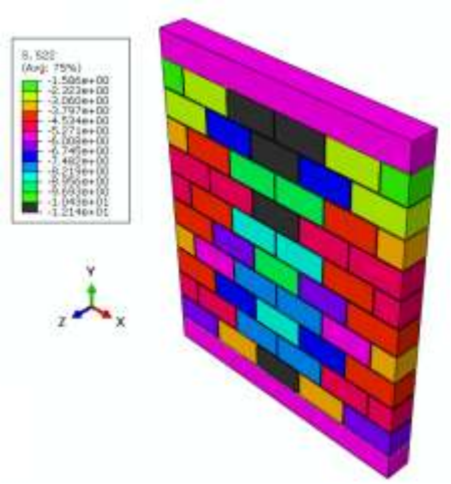

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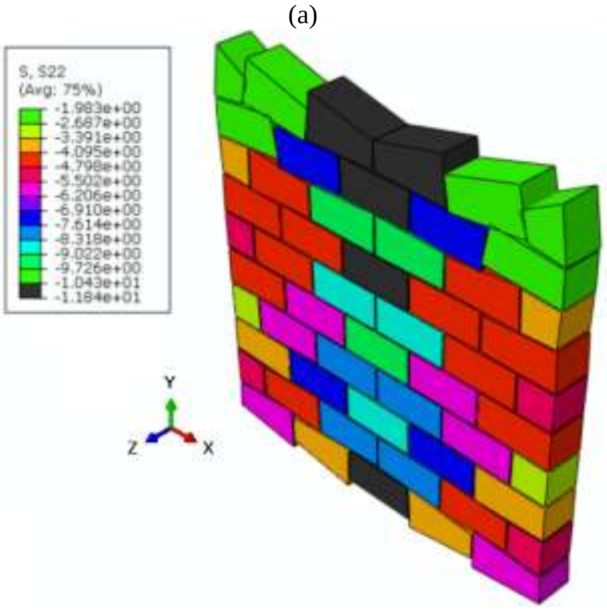

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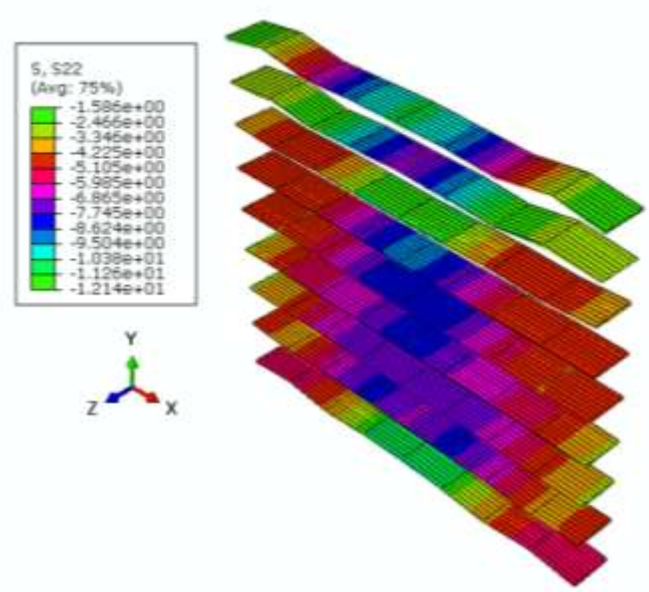
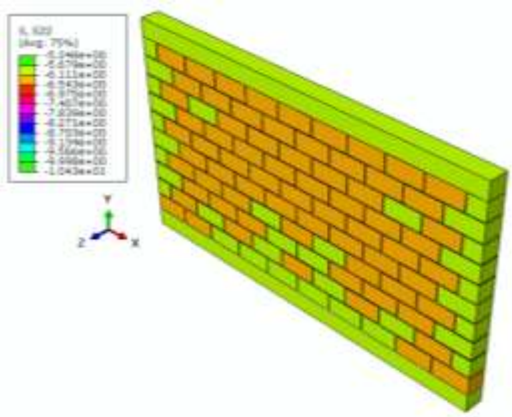


(c)

Figure 6: Stress distribution of URM wall with aspect ratio equals to 1: (a) Stress distribution for the undeformed wall (b) Stress distribution for the deformed concrete masonry units (c) Stress distribution for the deformed mortar



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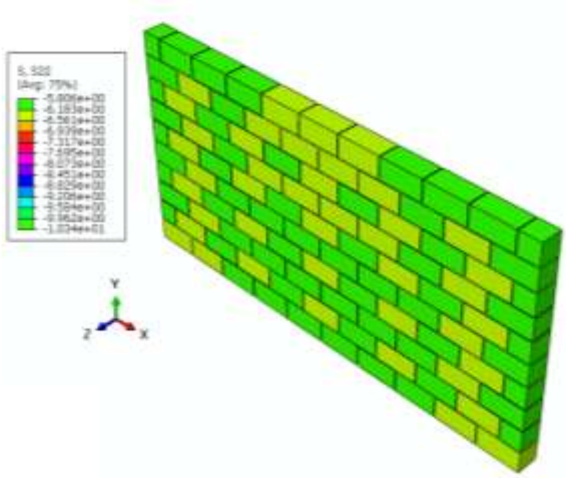

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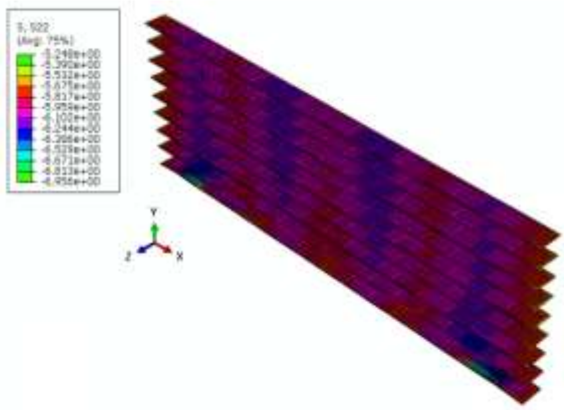


(c)

Figure 7: Stress distribution of URM wall with aspect ratio equals to 0.5: (a) Stress distribution for the undeformed wall (b) Stress distribution for the deformed concrete masonry units (c) Stress distribution for the deformed mortar

For each URM wall, the relationship between vertical compressive stresses generated in the walls due to the applied load across the length of the wall at different levels of height can be seen in Figure 8, Figure 9, and Figure 10.

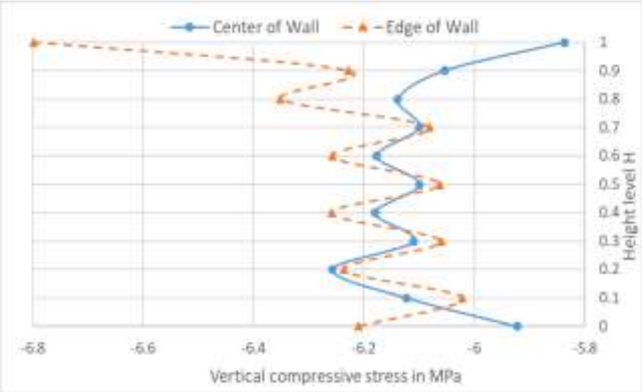


Figure 8: Relationship between height level and generated compressive stress of wall with aspect ratio equals to 2

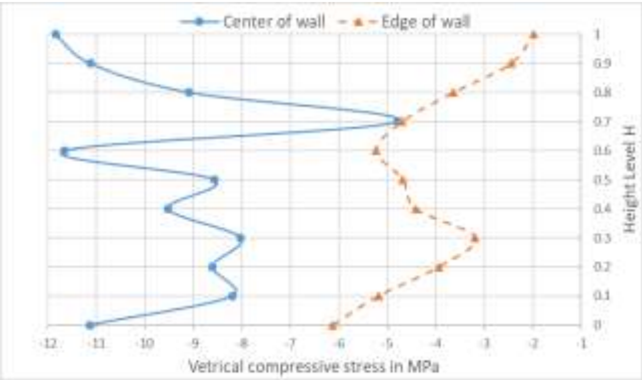


Figure 9: Relationship between height level and generated compressive stress of wall with aspect ratio equals to 1

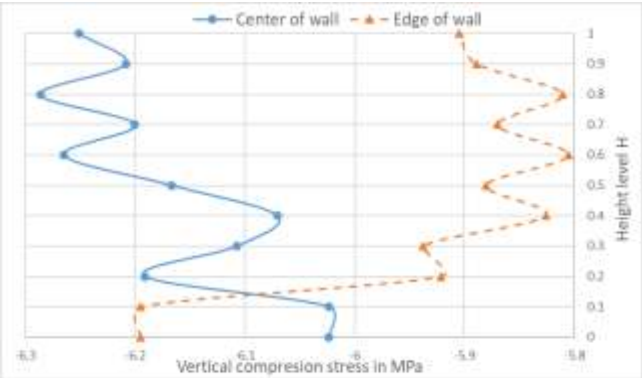


Figure 10: Relationship between height level and generated compressive stress of wall with aspect ratio equals to 0.5

Figure 11 illustrates the generated compressive stress distribution at the center of URM walls at different levels of height. It can be seen that the variation ranges of the wall with an aspect ratio of 2 from -5.8 to -6.4 MPa, whereas for the wall with an aspect ratio of 1 from -4 to -12 MPa, and for the wall with an aspect ratio of 0.5 varies from -6 to -6.3 MPa. Figure 12 shows the generated compressive stress distribution at the edge of URM walls at different levels of height. For a wall with aspect ratio equals to 2 the generated stresses range from -6 to -6.8 MPa, while the stresses range from -2 to -6 MPa for the wall with an aspect ratio of 1, and from -5.8 to -6.2 MPa for the aspect ratio of 0.5.

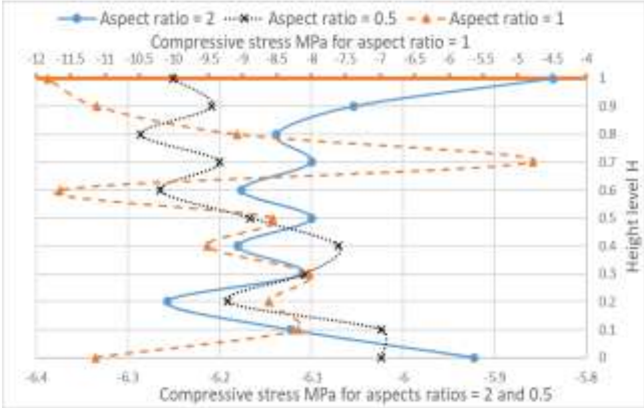


Figure 11: Relationship between height level and generated compressive stress at center of wall

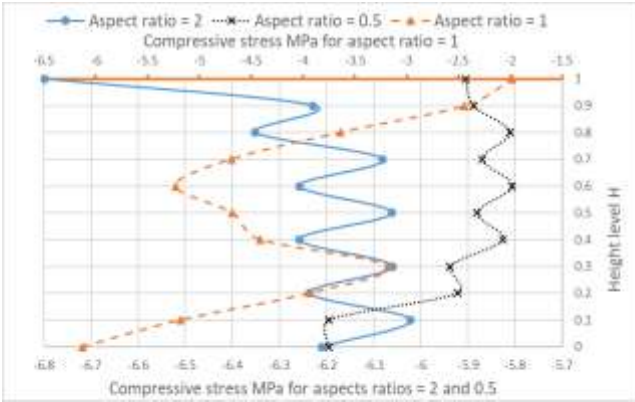


Figure 12: Relationship between height level and generated compressive stress at edge of wall

The compressive strengths of URM walls with aspects ratios equal to 2, 1 and 0.5 are 10 MPa, 8 MPa, and 10 MPa respectively as it is shown in Figure 13. The failure locations for wall with aspect ratio equals to 2 were at the edges of the wall, while the failure occurred for wall with aspect ratio equals to 1 at the center of the wall, for the wall with aspect ratio equals to 0.5, the failure locations were at the center and edges of the wall as can be seen in Figure 14 below.

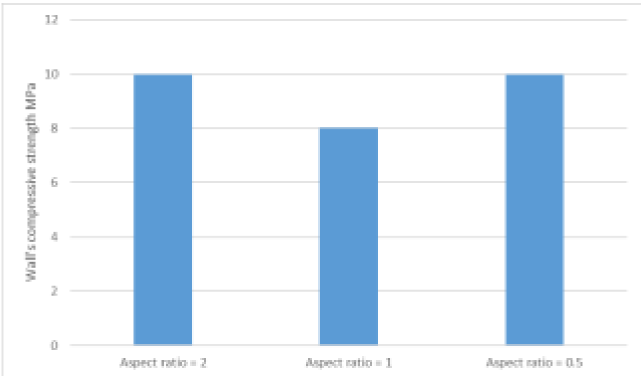
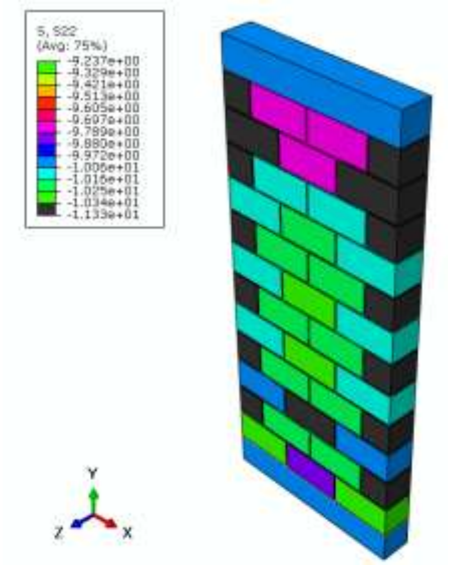


Figure 13: Strength of each URM wall MPa



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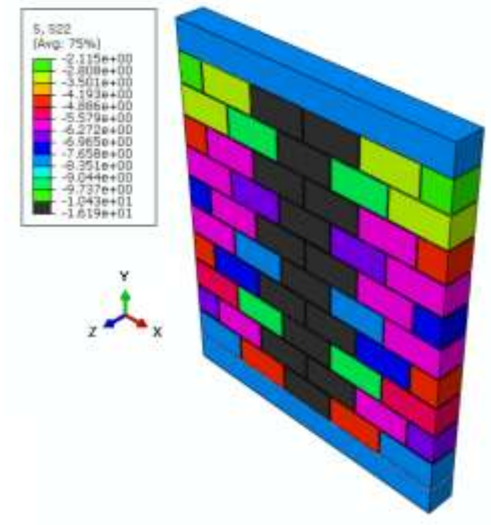

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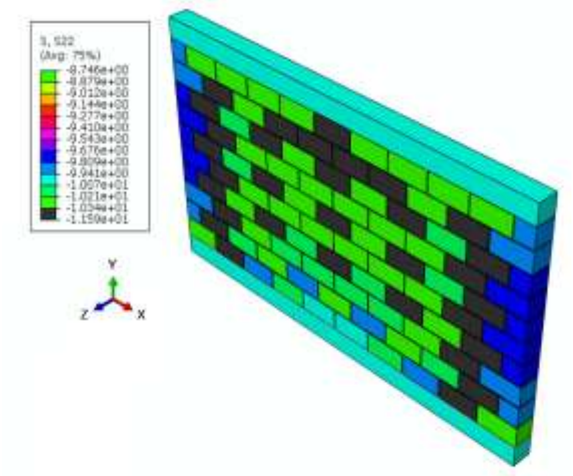

(c)

Figure 14: Location of the failure of walls with aspects ratios equal to (a) 2 (b) 1 (c) 0.5

6. Conclusion

Three URM walls with aspects ratios equal to 2, 1 and 0.5 were subjected to a uniformly distributed vertical compression applied load equals to 6 MPa to examine the effect of the aspects ratios on the generated stresses along the wall. It was found that the wall with aspect ratio equals to 2 exhibited a failure at load 10 MPa and the failure occurred at the edges of the wall. While the wall with aspect ratio equals to 1, the failure load was 8 MPa and the location of the failure was at the center of the wall. And for the wall with the aspect ratio equals to 0.5, 10 MPa was the load that caused failure and the failure located at the center and edges of the wall.

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