SAKARYA UNIVERSITY
INSTITUTE OF SCIENCE AND TECHNOLOGY

FINITE ELEMENT MODELING OF RETROFITTED MASONRY WALLS UNDER DIAGONAL LOADING

M.Sc. THESIS

Bawar Othman RASUL

Department	**:**	**CIVIL ENGINEERING**
Supervisor	**:**	**Assist. Prof. Dr. Zeynep YAMAN**

April 2022

SAKARYA UNIVERSITY
INSTITUTE OF SCIENCE AND TECHNOLOGY

FINITE ELEMENT MODELING OF RETROFITTED MASONRY WALLS UNDER DIAGONAL LOADING

M.Sc. THESIS

Bawar Othman RASUL

Department	**:**	**CIVIL ENGINEERING**
Supervisor	**:**	**Assist. Prof. Dr. Zeynep YAMAN**

This thesis has been accepted unanimously / with a majority of votes by the examination committee on 28.04.2022

Prof. Dr. Erkan ÇELEBI Head of Jury	**Assist. Prof. Dr. Yusuf SÜMER Jury Member**	**Assist. Prof. Dr. Zeynep YAMAN Jury Member**

DECLARATION

I declare that all the data in this thesis was obtained by myself by academic rules, all visual and written information and results were presented by academic and ethical rules, and there is no distortion in the presented data in case of utilizing other people's works they were refereed properly to scientific norms, the data presented in this thesis has not been used in any other thesis in this university or any other university.

Bawar OTHMAN

28.4.2022

ACKNOWLEDGMENTS

Above all, the almighty ***Allah***; the most merciful and the most gracious.

First of all, I would like to express my full thanks to my most generous supervisor Dr Zeynep YAMAN; without her help, this research was impossible. Her precision, professionalism, and guidance put me on the right path in my study.

It is the right time and the right place to thank most of the teachers of Sakarya University; during two semesters, they taught me the most basic material required for finishing and getting a master's degree with high quality. If I mention some of them: Dr. Erkan ÇELEBİ, Dr. Aydın DEMİR, Dr. Sedat SERT.

Also, I would like to thank these friends for their beings in my life and their amazing friendships; Aras Ahmed, Aras RASUL, Amina OSMAN, Mujahid ABDULRAHMAN, Bahoz ABDURAHMAN, and Asan JALAL.

Finally, my gratitude to the perfect parents (Othman and Habiba) ever in the world, who educated me and taught me the most basic morality for a good living life (i.e. Virtue). Also, my family; Omer and aunt Nyaz; and all brothers and sisters, especially Balen, Barham, Amina, and Sima.

TABLE OF CONTENTS

CHAPTER 1.

CHAPTER 2.

CHAPTER 3.

CHAPTER 4.

CHAPTER 5.

LIST OF SYMBOLS AND ABBREVIATIONS

Eb : Elasticity module of the brick
Em : Elasticity module of the morter
Fb : Compression strength of the brick
Fm : Compression strength of the mortar
FRM : Fiber Reinforce Morter
FRP : Fiber Reinforce Polymer
Gm : Shear elasticity module
MBW : Masonry Brick Wall
R : Reference Element
Vm : Poisson’s module of mortar

LIST OF FIGURES

LIST OF TABLES

SUMMARY

Keywords**:** Finite element analysis, Masonry units, Micro modelling, Wall window gap effect, ANSYS.

Masonry structures have long been popular in Iraq and around the world. Many masonry structures in our country are built in rural areas with no engineering services. The majority of the earthquake-related losses and demolitions were caused by insufficient masonry structures. As a result, determining the seismic behaviour of masonry structures is critical to preventing earthquake-related deaths and destructions. Because the structural system of these structures is made up of walls, it is necessary to anticipate the behaviour of the walls to comprehend the structural behaviour of such facilities. As a result, many experimental and numerical studies have been conducted to better understand the behaviour of walls. The finite element method is the most commonly used in numerical investigations. In this study, we have conducted a numerical study and used the experimental data for verification of the models. The experimental studies have been conducted previously in the Sakarya University Structural Mechanics Laboratory by Ahmadzai, E. (2020). In the experimental tests, diagonal compression tests were used to determine the behavior of wall units under the effect of diagonal load. Material information and fracture mechanics of the numerical model were taken from these experimental studies. The experimental mechanical behavior of the unreinforced and reinforced walls under diagonal load was investigated numerically by using the micro modelling technique. The force-displacement curves of the numerical and experimental results were obtained as approximately consistent with each other. After the verification study of the numerical models, a parametrical study was conducted. Wall window gap ratios in the masonry walls and expanded steel sheet thickness were investigated. According to the results, as the wall window gap increase, the strength of the wall decreases. In addition, the strength values increased with the increase in the thickness of the expanded steel sheet.

DÖNER YÜK ALTINDA YAĞ DUVARLARIN SONLU ELEMAN MODELLEMESİ

ÖZET

Anahtar Kelimeler: Sonlu elemanlar analizi, Yığma Duvar, Mikro Modelleme, Pencere boşluk etkisi, ANSYS.

Yığma yapılar Irak’ta ve dünyada uzun yıllardır tercih edilmektedir. Irak ta herhangi bir mühendislik hizmeti verilmeden kırsal alanlarda inşa edilmiş birçok yığma yapı bulunmaktadır. Depremlerden kaynaklanan kayıp ve yıkımların çoğu, bu tür yetersiz yığma yapılarda gerçekleşmiştir. Bu nedenle depremlerden kaynaklanan ölüm ve yıkımları önlemek için yığma yapıların sismik davranışlarının belirlenmesi gerekmektedir. Bu yapıların taşıyıcı sistemi duvar olduğundan, bu tür yapıların yapısal davranışını anlamak için duvarların davranışını öngörmek gerekir. Bu nedenle duvarların davranışını anlamak için birçok deneysel ve sayısal çalışma yapılmıştır. Sayısal araştırmalarda en yaygın olarak kullanılan yöntem sonlu elemanlar yöntemidir. Bu çalışmada modelleme ve sayısal çalışmalar yapılmış ve modellerin doğrulanması için deneysel veriler kullanılmıştır. Deneysel veriler Sakarya Üniversitesi Yapısal Mekanik Laboratuvarı'nda Ahmadzai, E.(2020) tarafından gerçekleştirilmiş olan diyagonal yük etkisi altındaki güçlendirilmiş ve güçlendirilmemiş duvar ünitelerinin davranışının incelendiği “Genişletilmiş çelik levhalarla güçlendirilmiş blok tuğla duvarlarda levha kalınlığının davranış üzerindeki etkisi” başlıklı tez çalışmasından alınmıştır. Sayısal modelin malzeme bilgisi ve kırılma mekaniği bu deneysel çalışmadan alınmıştır. Güçlendirilmiş ve güçlendirilmemiş duvarların diyagonal yük altındaki deneysel mekanik davranışı ANSYS programı ile mikro modelleme tekniği kullanılarak sayısal olarak incelenmiştir. Sayısal ve deneysel sonuçların kuvvet-yer değiştirme eğrileri birbirlerine yaklaşık olarak elde edilmiştir. Sayısal modellerin doğrulama çalışmasından sonra parametrik bir çalışma yapılmıştır. Bu aşamada yığma duvarlardaki pencere boşluk oranlarının duvar dayanım ve davranışına etkileri incelenmiştir. Pencere boşluk oranı arttıkça duvarın yük taşıma kapasitesinin azaldığı ve genişletilmiş çelik levhalar ile güçlendirmenin de bu düşüşü engellemediği görülmüştür. Boşluk oranındaki %10 luk artışın tüm duvar modellerinin diyagonal yük taşıma kapasitesinde ortalama %18 lik düşüş oluşturduğu gözlenmiştir.

CHAPTER 1. INTRODUCTION

Structures made of masonry It is constructed by fusing materials such as natural stone, brick, and aerated concrete with Mortar. Masonry structures have been around for a long time and will continue to do so. Many historical masonry structures, such as palaces, bridges, and mosques, are considered cultural heritage in our country (IRAQ), which has hosted many civilizations throughout history. Due to the uncertainty of strength, unknown earthquake behaviour, natural disasters, human factors, ground and environmental conditions, physical and chemical effects, and historical textures, important historic buildings like this one are in danger of being damaged or even destroyed [1]. In addition to important historical masonry structures, many masonry structures in Iraq were built in violation of engineering rules. When the structural systems of buildings are examined by the State Institute of Statistics' 2000 census, more than half of them appear to be masonry structures [2]. Many experimental and numerical studies have been conducted to better understand the structural behaviour of masonry structures and to strengthen existing masonry structures.

In this study, micro-modelling strategies on solid unreinforced masonry and reinforced masonry walls were numerically analyzed. For this, masonry walls reinforced with expanded steel plates as a strengthening technique were examined. For the modelling, the results of reinforced and unreinforced masonry walls experimentally examined by Ahmadzai [3] in the literature were taken into account. In Ahmadzai's study, the reinforcement technique of masonry brick walls with expanded steel sheet was used. The effect of using reinforced of different thicknesses on the strength and behaviour of masonry brick walls was investigated. The model in Ahmadzain's work is used to simulate the structural behaviour of walls using ANSYS software.

There are many experimental and numerical studies about understanding the structural behaviour of masonry structures and strengthening existing masonry structures. Some of the studies found as a result of the literature research are given below.

For accurately modelling the structural response of masonry walls, a numerical simulation is an appropriate tool. This method of calculation allows for the consideration of various boundary conditions, a wide range of materials, multiple geometries, and a variety of loading conditions. The main challenges when modelling a masonry structure with a finite element analysis are the material's orthotropic and nonlinear behaviour, which is characterized by brittle tensile failure; the nonlinear geometric response of slender elements (buckling or second-order bending); and the uncertainty, which is mostly related to material characterization. This ignorance is usually caused by the dispersion of the results of the few available experimental campaigns.

The increasing computational capacity has enabled the implementation of specific constitutive laws to describe the nonlinear response of all masonry and strengthening system components. However, due to the high computational effort required, this approach is not useful for analyzing full structures and is typically only used to model small portions of the material. These models are classified as micromodels because each component is modelled independently, and an interaction rule is defined between them. The blocks are considered separate parts. If the mortar joint is not represented as a separate part with its thickness, the model may be classified as a simplified micromodel. Otherwise, the micromodel is categorized as detailed. In both cases, contact elements govern the relationship between parts.

Page [4] presented one of the first micromodels used to simulate masonry, which is considered a bidimensional (2D) plane stress response and defined contact elements between the bricks. Later, the nonlinear response of the joints was considered in studies such as the one presented by Ali and Page [5]. However, the most well-known model for representing unreinforced masonry is that of Lourenço [6], who defined the interface cap model while also taking into account plastic strains. Later, threedimensional (3D) approaches, such as the one proposed by Martini [7], who studied the bidirectional out-of-plane response, were proposed. However, using 3D micro modelling approaches requires a significant increase in computational effort when compared to 2D ones, and they are unlikely to be considered for applications of this type. However, using 3D micro modelling approaches requires a significant increase in computational effort when compared to 2D approaches, and they are unlikely to be considered for practical applications.

Micro models were used to investigate the mechanical response of masonry as a composite material. Among the most important works in this field is the paper by Brencich and Gambarotta [8], who investigated the effect of eccentricity on the compressive strength of masonry. Similarly, Ordua [9] focused on analyzing the response of masonry brick wall joints using micromodels; in this case, the pieces were represented as rigid brick, and 3D simulations were performed to account for torsional effects. Recently, the periodic geometric definition of masonry has been considered for studying its response at a lower computational cost than common micromodels that do not take this hypothesis into account. One notable example of this trend is the work of Sacco [10], who examined the damage evolution in the mortar joint while accounting for the periodic definition of masonry.

Kömürcü et al [11]. In this study, unreinforced masonry walls were subjected to finite element analysis using micro and macro modelling techniques. Figure 1.1 depicts the geometry of the masonry wall and the masonry unit used at the wall. Loading the wall is done in two steps. The wall was loaded with a vertical pressure of 0.3 MPa to the top nodes of the wall in the first load step. The top nodes of the walls are given horizontal displacement in the second load step. The first load step is carried out by dividing it into ten equal sub-steps. The second load step is broken down into 40 sub-steps.

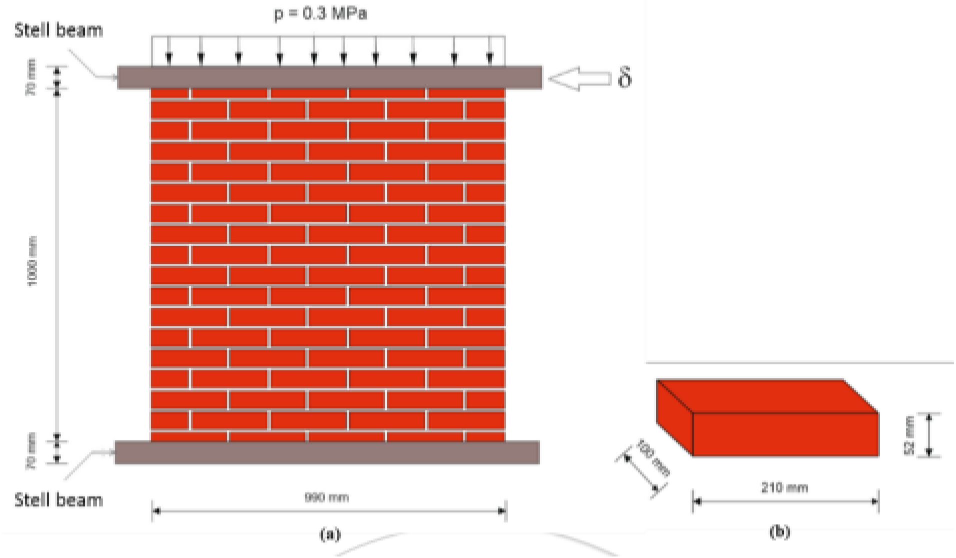


Figure 1.1. (a) Masonry wall geometry (b) masonry unit used in the wall [11]

The finite element analysis was performed using SOLID 65 finite elements in the ANSYS software. This element has 8 node points, each with three degrees of freedom in the x, y, and z directions. It can exhibit both tensile and compressive collapse mechanisms. Brittle materials such as rock, stone, brick, concrete, and so on can be modeled. This element is appropriate for modeling nonlinear behavior of structures, and cracks in the structure can be determined. Figure 1.2. depicts the structure of the SOLID 65 element.

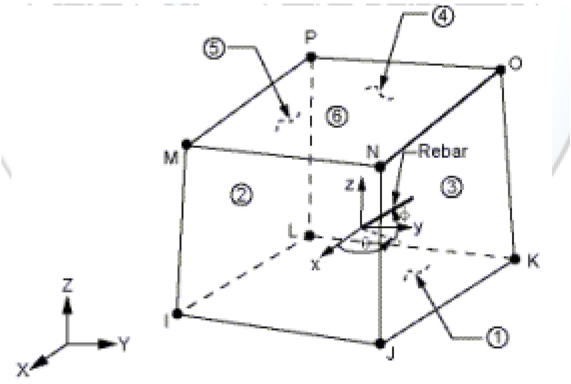


Figure 1.2. SOLID 65 element

Wall stresses and cracks spread under the influence of applied loads Examined. Cracks occur primarily in the upper left and lower right corners of the wall, cracks have been observed to spread from mortars to the walls. With the results of their analysis, the wall of the force-displacement curves of the test results in the literature has been observed to behave similarly. Micro in small-scale structures modeling technique, macro modeling technique in large-scale structures more accurate results.

Alyavuz ve ark. [12], low strength against non-plane lateral forces changing brick walls by pasting and strengthening CFRP strips in different ways experimental and numerically examined the behavior. One unemployed and reinforced wall by adhesive five CFRP strips in different layouts samples have been tested.

CFRP reinforced walls after experimental studies, ANSYS package Macro modeling using SOLID45 and SOLID46 financing elements in technique has been used and analyzed. Selecting the macro modeling technique purpose, reducing the total number of node points and the number of equations spent is stated that it is to reduce the time. Along with wall interfaces with CFRP strips "contact elements" are used. As a result of the analysis of the numerical model with the experiment, the resulting force-displacement graphs adapt to their peaks observed. The finite element model created is more rigid than the experiments and has less displacement.

1.1. Purpose and Scope Of The Study

In Iraq, especially in rural areas, using low-strength materials there are numerous masonry structures built without engineering service. As a result of the earthquakes, many of these inadequate masonry structures have been destroyed. residences and important historical buildings, because they are located in one of the earthquakes, are at risk. Therefore, inadequate masonry prevents the demolition of structures to pass on important historical structures to future generations without damage experimental and numerical studies are carried out.

Experimental studies since require time and skilled labor and are reserved for experimental studies in our country numerical studies have gained importance due to insufficient budgets. Masonry The main conveyor system of the structures consists of walls. Therefore, stacking to understand the structure behavior, it is necessary to predict the wall behavior. The main purpose of this study is to build a masonry wall under diagonal load for unreinforced and reinforced mesh masonry brick walls with different thickness mesh to understand the mechanical behavior of masonry a numerical model based on the finite element method corresponding to the experiments to improve.

CHAPTER 2. LITERATURE REVIEW

The masonry brick wall is described as a combination of bricks and Mortar. It is a complicated material. The ability to combine these elements with various quality and geometries gives brickwork mechanical and structural performance throughout the board options. It is commonly recognized that masonry brick wall performs well in resisting and transmitting compressive loads but poorly in resisting tensile forces. When exposed to high-demand loads, the component materials of masonry (brick and Mortar) have a nonlinear rigid structure reaction and, in most cases, an anisotropic behaviour. There's also the difficulty of defining the highly nonlinear mechanical behaviour of the brick-mortar contact zone. Furthermore, earthquake loads usually require a nonlinear reaction in structures and structural components. To better understand the structural behaviour of the wall, a brief overview of the characteristics and behaviour of some constituent elements and their failure modes is described below. A brief discussion of some of the requirements for various wall design codes concludes this section.

2.1. Constituents' Elements of Masonry Brick Wall

Masonry brick wall, as already mentioned (brick and mortar), is a complex material with variable properties depending on the geometric arrangement and quality of the components. In most cases, the properties of brick and mortar are determined by special experiments. These tests are widely described in literature and codes [13], [14]. Experiments are also carried out to determine the general qualities of the wall, taking into account the specific geometric composition and the quality of the materials. These tests are well documented in the literature and practice [15], [16].

2.1.1. Bricks and blocks

The properties of bricks vary greatly depending on the quality of the mortar (or concrete in the case of blocks) and the manufacturing method. Furthermore, Brick mechanical behavior is not always homogeneous and isotropic (especially for hollow or perforated bricks This means that the properties differ in various directions, as well as in tension and compression. Bricks' behavior is typically described as elastic-brittle.

Typically, a simple compression test is performed to explain the mechanical behavior made of bricks or blocks. Normally, these tests are performed in multiple directions to provide a complete characterization of bricks (the three orthogonal block directions (for example, parallel or perpendicular to holes). This examination yields the brick's curve of stress-strain, which is related to the applied load direction and measured deformation, as well as its characteristic compression strength. There are tests that can be used to determine the traction strength of bricks, such as the "uniaxial tensile strength test," "splitting tensile strength test," "flexural tensile strength," and "uniaxial tensile strength of bone-shaped specimens" (only for solid blocks). Some of these tests are depicted in Figures 2.1., 2.2., and 2.3. As already mentioned, these tests are widely and clearly described in literature [17], [18], [19], [20].

Figure 2.1. A brick specimen is subjected to a simple compression test [21]

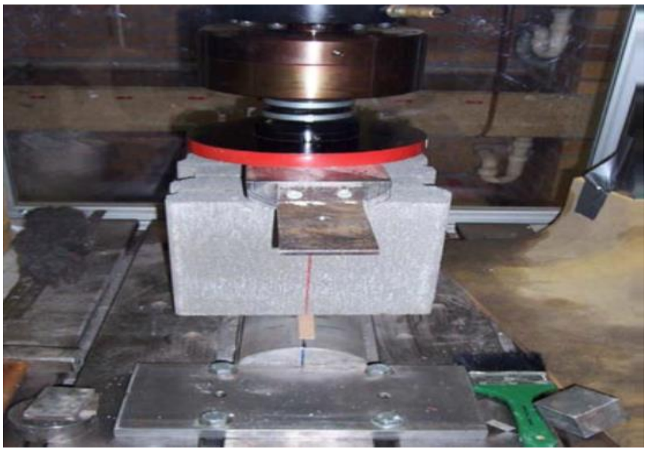


Figure 2.2. A brick specimen is split tensile tested [18].

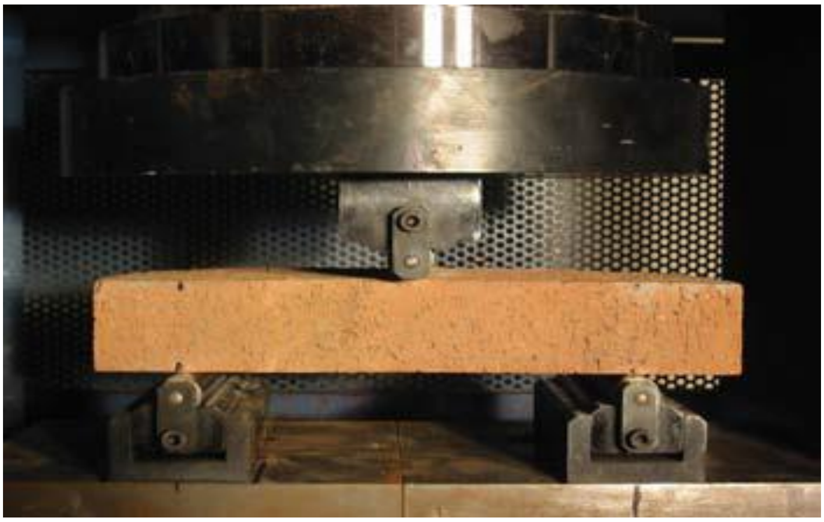


Figure 2.3. A brick specimen is subjected to a flexural tensile strength test [19]

The typical stress-strain curve of brick compression is shown in Figure 2.4.

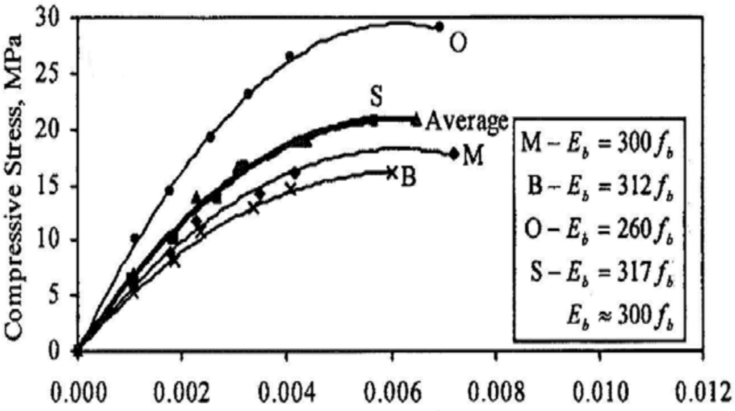


Figure 2.4. A brick specimen is subjected to a flexural tensile strength test [19]

This interaction is depicted visually in Figure 2.5.

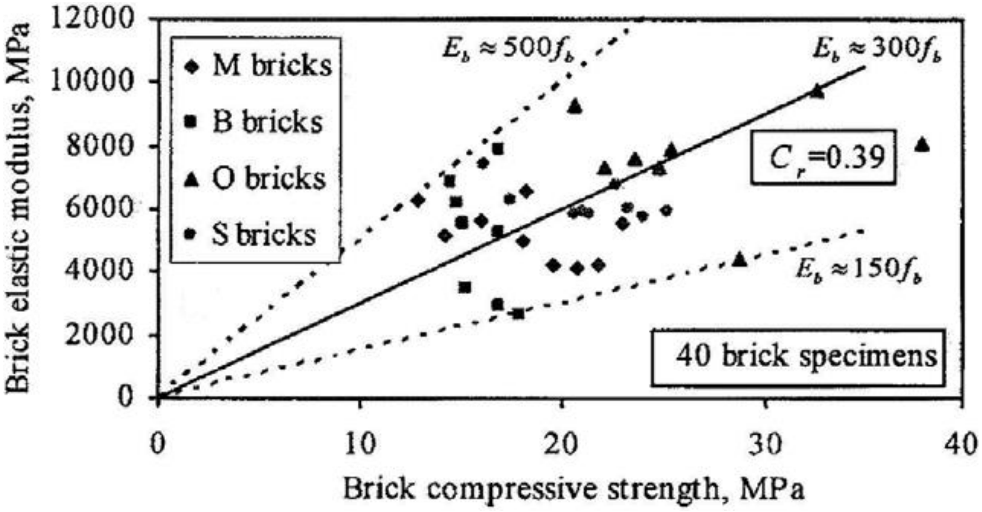


Figure 2.5. Relationship between compressive strength and modulus of elasticity for bricks [22].

2.1.1. **Mortar**

Mortar is similar to concrete in many ways, but the values of its constituents (cement, sand, lime, and gypsum) vary, which is important in determining its mechanical properties. In many cases, a good bond between mortar and brick is preferable to no mortar at all. Various tests can be used to explain the mechanical properties of the mortar. The basic pressure test is the first and most common and important test. This test can be carried out on either a cubic or a cylinder sample. This test generates a stress-strain curve for the mortar under normal pressure. Various tests can be performed to determine the strength of the various materials used in the mortar. The "uniaxial tensile strength test," "cleavage tensile strength test," and "flexural tensile strength test" are examples of such tests. Figures 2.6. and 2.7. demonstrate this. All of these tests are described clearly and concisely in the literature [17], [18], [19], [21].

Figure 2.6. Barraza [24] performed a simple compression test on a cubic mortar sample

Figure 2.7. A mortar specimen is subjected to a flexural tensile strength test [21]

Several types of mortar can be used depending on the type of brick: Standard mortar, thin-film mortar, or light mortar. Normal purpose mortar is a standard mortar that is only used for joints with dense aggregates that are 3.0 or 4.0 mm thick.

When the joints are 1 to 3 mm thick and must meet certain standards, a thin layer of mortar is usually used. Lightweight mortars are also made of lightweight materials and are designed to meet specific masonry requirements. [25]. The typical stress-strain curve of brick compression is shown in Figure 2.8.

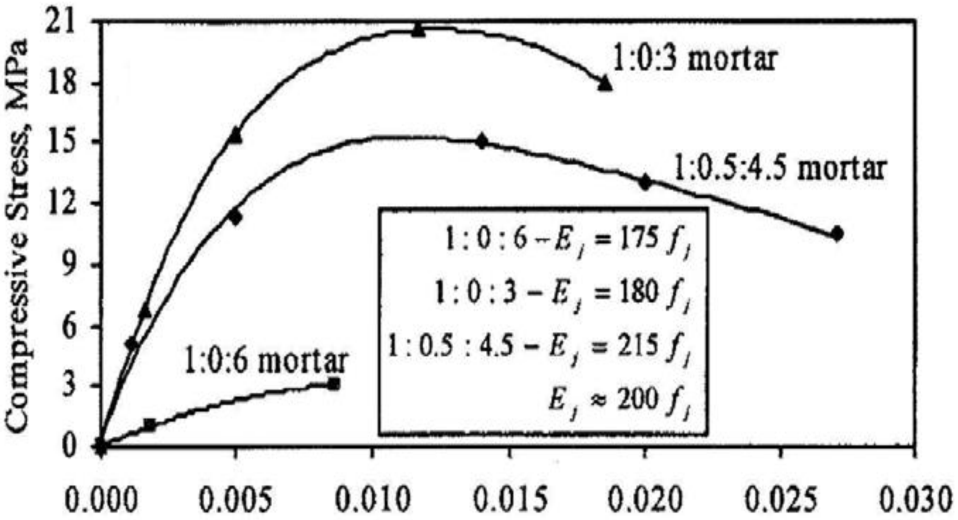


Figure 2.8. Shows a typical stress-strain curve for mortar compression [22].

To estimate the unit of elasticity (Em) for a mortar, [22] proposes a set of values based on the compressive strength of the mortar (FM). These values:

$$100\ \text{fm} \leq \text{Em} \leq 400\ \text{FM} \tag{2.1}$$

Figure 2.9. depicts this relationship graphically.

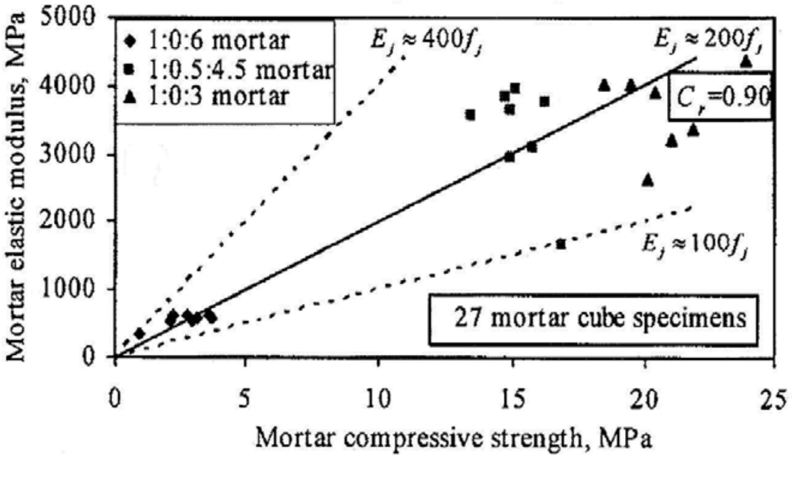


Figure 2.9. Depicts the relationship between mortar compressive strength and modulus of elasticity [22].

The shear elasticity module (Gm) is calculated using the elasticity theory.

$$G_m = \frac{E_m}{1+v_m} \tag{2.2}$$

Where "v_m" stands for Poisson's mortar module.

2.1.2. Contact (interface) between brick and mortar

Laboratory measurements can also be used to test the mechanical properties of contact with brick mortar. The Tensile Bond Test can be used to determine the rigidity of a concrete mortar connector (see Figure 2.10.). On the other hand (as shown in Figure 2.10.), the "shear bond test" is used to determine the shear-mortar contact characteristics of brick-and-mortar contact (See Fig. 2.11.) In this examination, failure of the visible connector or grout is possible. The main finding of both tests is greater strength (tensile or shear). Wholly of These examinations are well documented in the literature [17], [18], [19], and [21].

Figure 2.10. Tensile bond test for brick-mortar transition point [18]

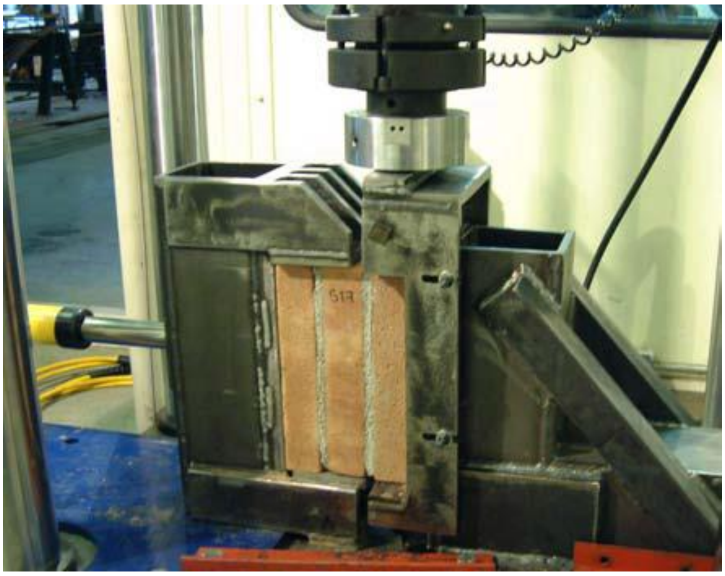


Figure 2.11. Shear bond test for brick-mortar interface [19]

2.1.3. **Masonry wall**

Sometimes it is necessary to analyze the general characteristics of the wall. In this case, it is important to consider the interaction between brick and mortar as well as the geometrical arrangement of the units. Various tests can be done in this situation. One such test is the stress test of Rilem specimens, where a stress-strain curve can be formed (see Figure 2.12.). Another way to assess wall structures is to perform diagonal stress tests on walls (see Figure 2.13.). Another stimulating aspect of this experiment is to examine how the outcomes differ when the load's direction changes for the load-bearing connection. By determining the effect of this parameter, a comprehensive study of these experiments can be found. [18], [19], [21],[26] [27].

Figure 2.12. A Rilem brickwork specimen is put through a compression test [18]

Figure 2.13. Diagonal compression test for a wall sample [24]

2.1.4. **Disposition of bricks or blocks**

Another significant reason to consider when determining the behavior of a wall is the arrangement of the bricks or type of bond. The way the bricks are laid can affect the interaction of the wall structure. The masonry wall is a common arrangement of bricks stuck in the mortar. An overview of a few of the most popular bond types is shown in Figure 2.14. In the case of direct joints that may or may not be filled with mortar, there is some difference in this type of binding.

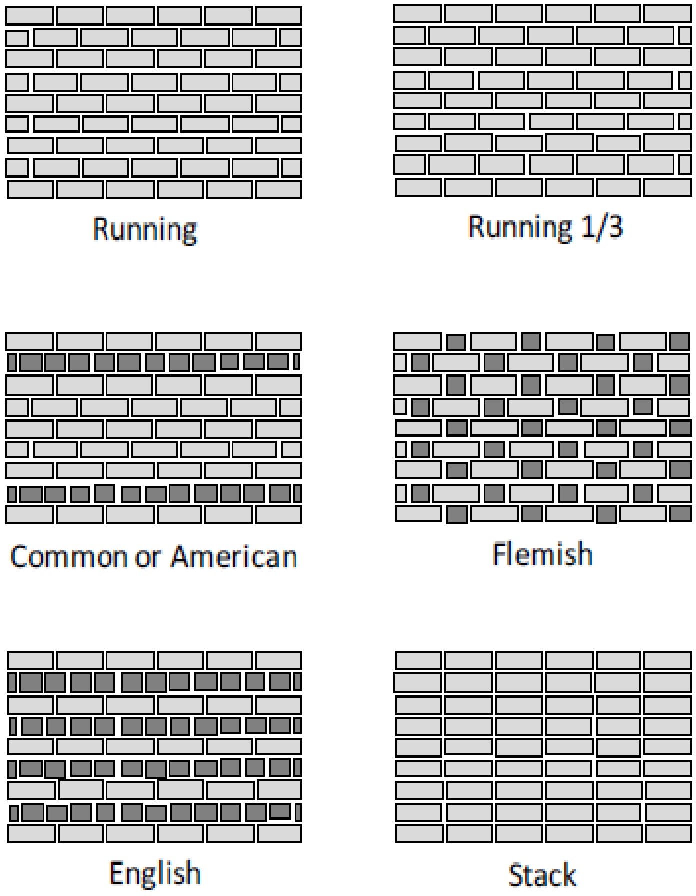


Figure 2.14. Types of bonds in a masonry wall

2.2. Recommended Reinforce Techniques in Standards and Codes

The masonry wall is usually defined by some basic structural criteria in technical rules. Modulus of elasticity, Poisson's modulus, compressive strength, shear strength, and other parameters are commonly used. To account for masonry wall non-linear behavior, the codes take into account a variety of parameters to depict the various difficulties in this circumstance. These elements are based on real-world experience and study.

The rules generally specify two design methods: the design of permissible pressures and the design of limited conditions. The stress from the applied loads should be less than or equal to the allowable pressures, which is the most important condition to be met in the event of an acceptable stress design. A key condition in the design of the situation is that the applied pressure is multiplied by the magnification factor less or equal to the normal pressures multiplied by the amplitude reduction factor.

2.2.1. **Codes of U.S.A.**

One of the best prominent masonry wall design codes in the United States is the MSJC code [28]. You can choose between designing for allowable stresses and designing for limited states with this code. Unreinforced, reinforced, and limited masonry wall designs are all covered by the code [29]. The code comprises classification tables and equations for calculating the basic properties of brick, mortar, masonry walls, and other reinforcements materials. Additional information for performing laboratory tests in line with other specified codes is also provided by the code.

Allowable stresses are calculated by dividing the damage stresses by a factor of safety that varies depending on the load and stress as well as material, shape, and other variables. Limit state design considers the type of load and stress as well as material, shape, and other factors. It's worth mentioning that this code's limit states design method for masonry walls is remarkably comparable to [30].

2.2.2. **European codes**

The European masonry wall code [31] and the German masonry wall code are similar. As in the German code, the choice design between allowable voltages and limit state design is based on analogous criteria and general conceptions for material quality and factor specification. The guideline also permits the adoption of a more basic or accurate masonry design process. To choose which method to use, you need to know the height of the wall structure, the distance between the support points of the slabs, and other details.

The code is part of a larger set (Eurocode 0 to 8), dedicated to the analysis and design of different types of structures. In this code, references [32] are very important.

Alternatively, the code group is considering installing national plugins to limit different parameters in a particular country.

2.3. Types of Masonry wall

The masonry wall has diverse configurations as a structural element depending on the locations of the world, as well as the country's construction traditions. Unreinforced masonry walls, reinforced masonry walls, and constrained masonry walls are all examples of these configurations. The type of masonry wall employed depends on the level of seismicity; for example, an unreinforced masonry wall is utilized in nations with very low seismic activity. On the other hand, reinforced or constrained masonry wall is used in countries with moderate to high seismic activity [33].

2.3.1. Unreinforced masonry wall

Unreinforced construction is the most common building structure in countries with little or no seismic requirements. The lack of steel reinforcement and the lack of reinforced concrete determine this. This type of construction is a popular approach to building low-rise housing, used almost everywhere in the world. As reinforced concrete became more common and available, improved forms of construction such as block and reinforced concrete masonry became increasingly common in low-rise homes. On the other hand, in many parts of Asia, traditional buildings with a load-bearing wall system not reinforced with burnt adobe are still under construction [24]. This form of construction is very susceptible to earthquakes. Many earthquake codes [34] consider this style of brickwork to be ineffective.

This type of brickwork can be done using general-purpose mortar or thin-film mortar. The recommended joint thickness for general-purpose mortar is approximately 1.0 or 1.5 cm to avoid structural difficulties. Solid blocks can be made with thin-bedded mortars (usually 1.0 or 2.0 mm thick). Figure 2.15. shows a simple unsupported construction diagram.

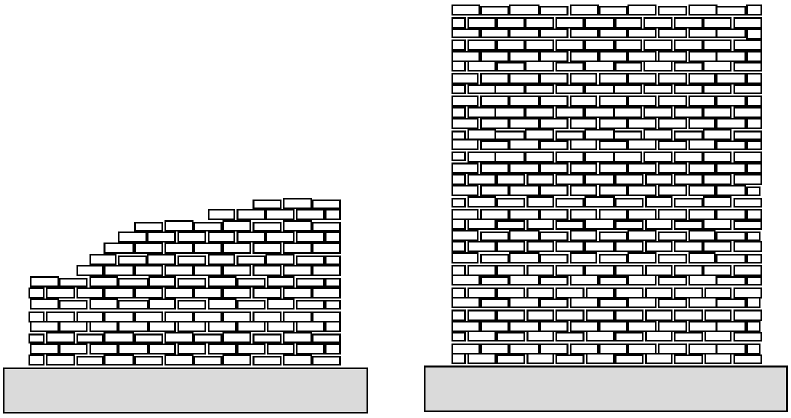


Figure 2.15. Unreinforced masonry wall

2.3.2. Reinforced masonry wall

Mortar-plated steel rods provide strength to this construction style. This reinforcement is applied to horizontal joints and/or brick holes before grouting. Horizontal reinforcement increases resistance to horizontal load (shear failure), while vertical reinforcement increases resistance to bending. This type of brick is often used and, in some cases, is needed in earthquake-prone areas. Unfortunately, this style of brick making is not well used in many developing countries, especially since the filling of concrete in straight bars has not been done sufficiently. There is a unique code in Chile that governs architecture considering this type of construction [35]. A typical diagram of a reinforced structure is shown in Figure 2.16.

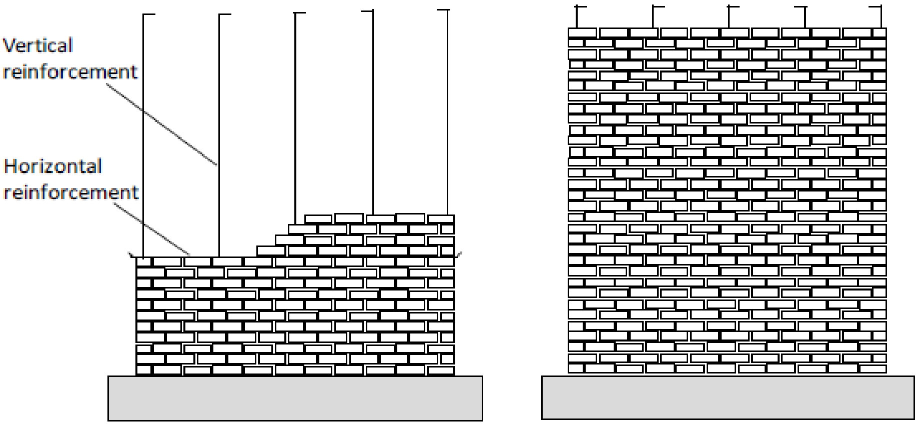


Figure 2.16. Reinforced masonry wall

2.3.3. **Confined masonry wall**

This is a type of construction that considers wall closures within a reinforced concrete frame. This constraint consists of a vertical tie-down column and a horizontal strapping beam. Most codes specify the maximum space that must be included for the build to work properly. This type of brick is frequently used in earthquake zones and is required in some cases. In this type of brickwork, the distribution of the fixture is critical at the joints between the connecting beams and the beams. It should also be noted that the type of wall used depends on the construction method of the wall. If a building plan is built before a reinforced concrete corpse, it is called a "closed masonry wall". If the construction is built behind a reinforced concrete body, the load system is known as a "full-frame". These differences can lead to different structural behaviors due to the "rough wall" found in the "bound building" [33]. In Chile, special legislation regulates the construction of buildings using such bricks [36]. Figure 2.17. shows a general constrained construction concept.

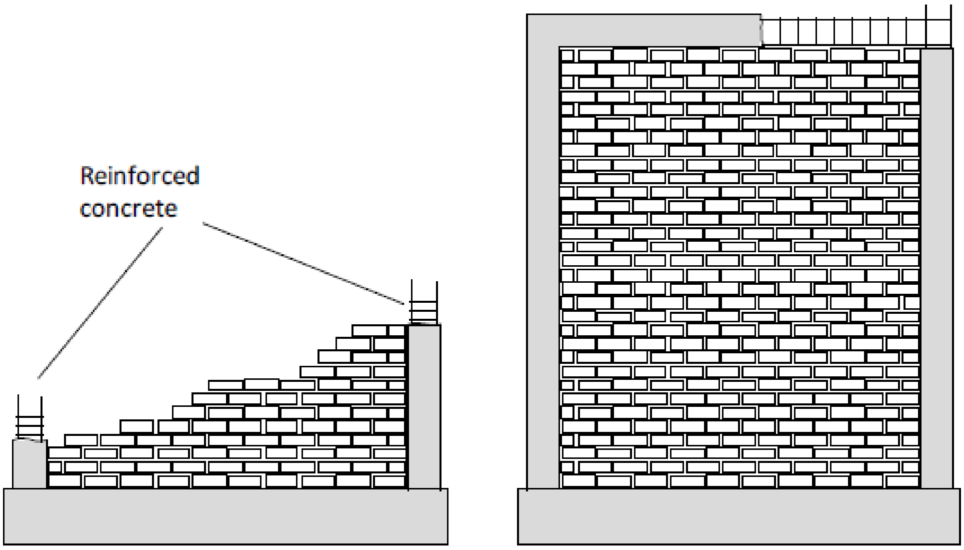


Figure 2.17. Confined masonry wall

2.4. Strengthening Techniques Used in Existing URM (unreinforced masonry Structures

Various retrofitting approaches have been developed and used throughout the construction history to overcome the shortcomings associated with the poor structural performance of URM structures under seismic procedures. The basic goal of strengthening procedures is to improve low masonry parameters like tensile and shear strength. When it comes to lateral loads, URM constructions are quite sensitive. As a result, this weakness will be addressed by strengthening approaches. These techniques are classified as traditional or modern depending on the method and materials employed.

2.4.1. **Traditional retrofitting techniques**

Traditional methods of modifying existing building structures include crack and void filling; ii) the use of metal or brick elements for grooving large cracks and weak areas; 3) post-tightening, external or internal, with a rigid ligament. iv) shotcrete casing; v) ferrocement, and 6) core core [37] [38].

Surface Treatment: It is a technique for covering the outer face of brickwork by altering the structure's architectural characteristics. It entails erecting a steel or polymer mesh around the perimeter of the structure, which is then covered with high-strength mortar. After cracking, this system limits the masonry and increases ultimate load resistance. The surface treatment increases out-of-plane resistance and minimizes "arching movement." However, the use of this technology has a significant impact on architectural qualities, and the absence of “breathing” in the wall may hasten its deterioration.

Ferrocement jacketing: This method involves the merging of fine gratings with a high-strength cement-slurry layer (15-30 MPa) with a thickness of 10-50 mm, a reinforcing ratio of 3 to 8 percent is used. The ratio of cement to sand in a regular mortar mixture is 1: (1.5-3) and the ratio of water to cement is 1: (1.5-3) 0.4 [39]. It causes a significant increase in hardness. The capacity and strength of previously damaged URM walls can be restored by strengthening them. Ferrocement's excellent flexural and shear strength allows the crack formation to be controlled.

Several studies have been conducted for both unreinforced and concrete constructions [40] [41] [42] [43]. According to Kochik et al. [44], ferritic cement has improved shaft crushing resistance [45], hardness, and ultimate load-carrying capacity as well as improved strength and ductility in both axial and eccentric loading situations [46].

Some of the benefits of iron cement, such as its low cost and ability to be completed by inexperienced people, make it a suitable solution for low-cost housing.

The mesh was discovered to help contain the block unit after crushing and increase the plane's elastic deformation capacity. The out-of-plane behavior (curvature motion and out-of-plane stability) increases as the iron cement wall height-to-thickness ratio increases [47] [48].

Reinforced Plaster: A thin layer of cement plaster is applied to the high-strength steel reinforcement. to achieve this approach (diagonal bars or horizontal grating). The in-plane resistance was found to rise by 1.25-3 times in radial tensile tests and static cycle tests [49].

Shotcrete: This is achieved by spraying coatings onto the surface of the masonry over a grid of reinforcement bars. The thickness of the shotcrete layer can be designed according to the seismic requirement.

Grout and epoxy injection: It is put to the wall by injecting grout into pre-drilled holes. The main goal is to restore the wall's original integrity and fill any voids or cracks that may exist. The injection is long-lasting and may be able to restore masonry's original strength. The effectiveness of this approach, however, is dependent on the mechanical properties of the grout mix being compatible with the physical and chemical properties of the retrofitted masonry wall.

- External Reinforcement: It is accomplished by adding steel plates or tubes to an existing URM structure as an exterior reinforcement.
- Confining using RC tie columns: The inclusion of tie columns and tie beams along the walls, which are connected at floor levels and constrain the URM walls at corners and wall junctions, constitutes this approach.
- Post-tensioning: It is accomplished by applying a compressive force to the masonry wall to counteract the lateral loads' tension stresses. It is primarily utilized for important structures like monuments.
- Center core technique: It entails drilling a vertical hole from the top to the basement of the existing URM wall, installing the reinforcement (50-125 mm), and pumping filler material from the Top to the bottom of the wall to create a reinforced grouted core inside the existing URM wall.

2.4.2. **Summary of traditional strengthening techniques**

Traditional strengthening techniques are a good way to improve the structural behavior of URM buildings, but they have some drawbacks, such as taking a long time to apply, reducing available space, causing disturbance to occupants, disrupting building operations, and impacting the old wall's beauty Furthermore, the extra bulk could increase earthquake-induced inertial forces, necessitating foundation reinforcement.

2.4.3. **Modern strengthening techniques**

The need to overcome the limitations of existing strengthening procedures prompted the development of novel materials and processes. Many of these drawbacks could be mitigated by employing current retrofitting techniques. Polymer reinforced polymers are a good choice because they improve masonry element performance under monotonic, seismic, and explosive loads. Furthermore, because the increased mass and stiffness are small, the reinforced structure's dynamic qualities will be unaffected.

2.4.3.1. Textile reinforced mortar

It is a technology that uses externally embedded textile grids in mortars to integrate the key features of both traditional and modern materials. The grid is constructed out of long fiber rovings (made of carbon, glass, or aramid) arranged in two orthogonal directions. Instead of polymer resins, cement or lime-based mortars are used. TRM achieves its composite effect by mechanically interlocking the grid structure with the mortar [50]. It improves ductility, stiffness, and shear strength.

The following are some of the benefits of using TRM instead of organic resins and replacing them with an inorganic binder:

- Poor thermal conductivity;
- Expensive cost;
- Vapor impermeability;
- Incompatibility with wall substrates;
- Irreversibility and irreversibility.

2.4.3.2. Fiber-reinforced mortar (FRM)

Microfiber includes metal, glass, synthetic fibers (acrylic, aramid, carbon, nylon, polyester, polyethylene, polypropylene), and natural fibers (grass, coconut, bamboo, etc.). Polypropylene fibers are non-chemical fibers with a large contact area that binds mechanically to the wall.

CHAPTER 3. NUMERICAL VERIFICATION STUDY

In this study, we have conducted a numerical study and used the experimental data for verification of the numerical models. Experimental tests have been conducted by Ahmadzai, E. (2020) [3]. By Ahmadzai; A total of five 1/1 scale stacking wall samples were tested under uniform diagonal load, one for reference, one for reinforced trial element and three for reinforced vertical perforated brick wall. Vertical loads create pressure stresses on the masonry walls. To create the reinforced test elements, extended steel sheets were applied to both sides of the wall. These steel plates are connected to the wall and each other with stretched steel bolts. The expanded steel plate thickness and bolt ranges are determined as variable parameters of the experimental study. Then 25 mm thick plaster was applied on steel sheets. Plaster was also applied on the plaster in order to observe the damages caused in the experiment and to obtain more realistic results. With the help of the results of the experiment; transportation capacity, ductless, rigidity and energy consumption evaluations were made. In addition, you can use the deformations on the front and back of the experimental elements were measured and unit elongations/shortenings occurred on the wall were evaluated.

In this study the last part, after verification of the numerical models, we have conducted a parametrical study. In this stage, the window gap in the walls with 10% and 20% per cent for 1.5mm, 2mm, and 3mm expanded steel sheets, respectively.

3.1. Experimental Campaign

This study has been carried out on the strengthening of brick walls constructed from vertically perforated load-bearing bricks with dimensions of 135×190×290 mm, which are used as load-bearing elements in masonry structures. The masonry brick wall samples to be examined experimentally were constructed as a unit panel with the dimensions of 1000×1000 mm and 1/1 scale. The explanation of the indices given to the test elements is given in Table 3.1. .and Figure 3.1.

Table 3.1. Features of experimental models [3]

Experiment No	Sample	Plaster (mm)	Sheet Thickness (mm)	Bolt Spacing (mm)	Bolt No
1	R	25	-	-	-
2	MBW 3-400	25	3	400	9
3	MBW 1.5-150	25	1.5	150	49
4	MBW 2-150	25	2	150	49
5	MBW 3-150	25	3	150	49

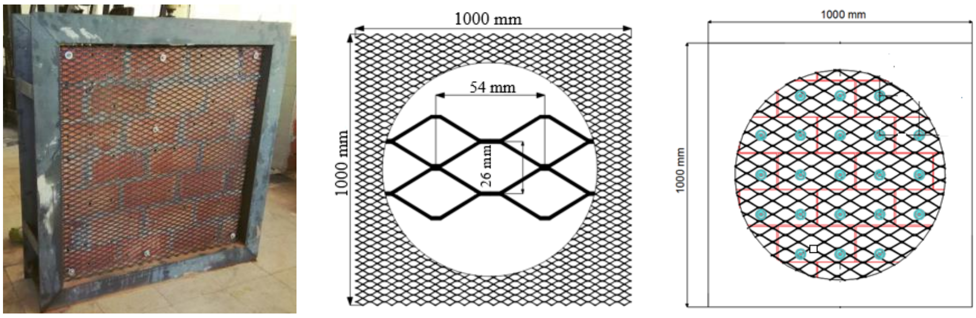


Figure 3.1. Sample of experimental test element [3]

3.1.1. Experimental models

The reference test model was built with hollow vertically perforated bricks, and a 25mm thick plaster was applied on both sides. No strengthening was used to the reference test model; it was simply tested under diagonal loads.

MBW 3.0-400 test model was prepared as a test model, with a thickness of 3.0 mm on a steel plate and a plaster thickness of 25 mm on a plate of 400 mm, the distance between the bolts fixing the steel plate to the wall.

MBW 1.5-150, 2.0-150, and 3.0-150 test models have a thickness of the steel plate is 1.5mm and 2mm and 3mm, and the distance between the bolts fixing the steel plate to the wall is 150 mm, and the plaster thickness is 25 mm.

3.1.2. **Loading System**

The steel frame with an internal scale of 1000×1000 mm, square, which they used to transfer the diagonal load to filler-walled models, was used in the experimental tests. A steel frame is prepared by combining four two U300 profiles to achieve a rigid plane. There are articulations in the four corners of this frame. Two of these joints have headgear. With the help of the heads, it ensured that the diagonal load was transferred directly to the models. Since there are articulates in the four corners of the frame, the steel frame does not resist the diagonal load applied to the wall, and the diagonal load is transferred directly to the wall [3]. A schematic view of the loading system is given in Figure 3.2.

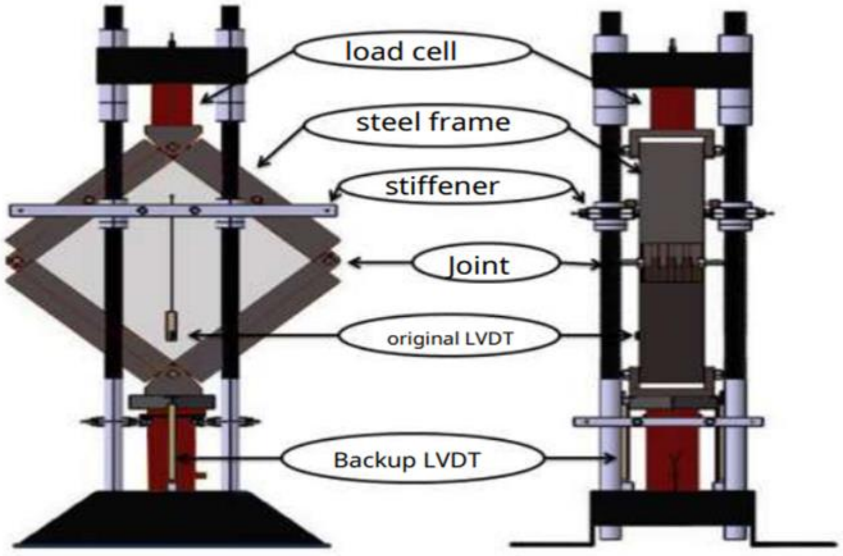


Figure 3.2. Loading system [3]

3.2. Numerical Study

Computer technology has improved in recent years. Thus, numerical modelling of structures and structural elements can be done easily. Especially among the numerical modelling techniques, the Finite Element (FE) method has started to be widely used. The finite element method divides complex models into simpler subunits of elements. In this way, determining the behaviour of the elements supplies grasping of system behaviour. [51]. When using this method, the geometry is divided into simple subunits called finite elements, and then each subunit behaviour determines the system behaviour that can be understood. The method in question accuracy depends on the accuracy of the data used, and the result should be predicted [51]. Many package programs, such as SAP2000, ANSYS, ABAQUS, ETABS, etc., are available using the finite element method. In this study, a strong finite element solver program called ANSYS was used. In the program in question, ready-made element-material modules that may be needed during modelling and analysis will make it easier to use.

The masonry structures are quite complex in numerical modelling. Therefore, need to accept some idealization of the numerical model.

To simulate experimental tests of the masonry walls, the finite element method was carried out. Three different modeling technics are used for masonry units. These are detailed micro modelling technic, simplified micro modelling technic, and homogeneous continuum modelling technic [52,53].

- In the detailed micro modeling technic, units and mortars are modeled separately. This technic presents real conditions more than other technics but needs more computational effort.
- In the simplified modeling technic, mortar doesn’t model, and its material properties are taken as interface elements.
- In the macro modeling technic, stone, mortar, and interfaces are modeled as a homogeneous continuum medium. This technic is a generalization technic that is used generally in complex models.

Representative shapes of these technics are given in Figure 3.2. In this study, a micro modeling technic was employed for modeling the walls.

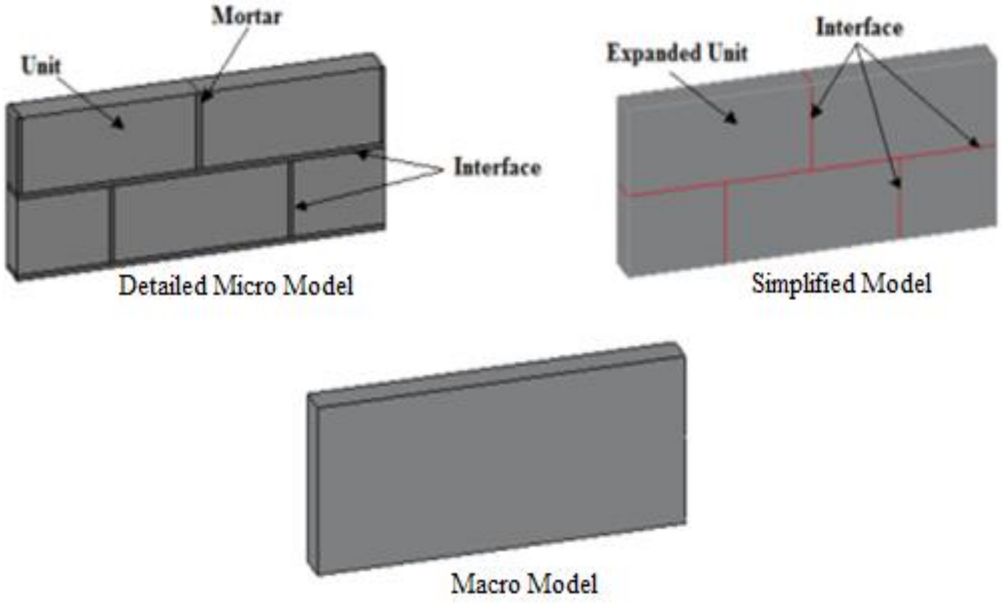


Figure 3.3. Masonry modeling techniques

3.2.1. **Finite Element Models of Masonry Walls**

Finite element (FE) models of the masonry wall models were created in the ANSYS Software [54]. The SOLID65 element type was used for modelling the brick, mortar, plaster, and steel loading system elements. This element type was created to represent the nonlinear behaviour of brittle materials such as concrete. This element has the capability of cracking (in three orthogonal directions), crushing, plastic deformation, and creep [54].

Reinforcement elements were modelled with the LINK180 element type. LINK180 element can be used to model trusses, sagging cables, links, springs, bars, etc. The element is a uniaxial tension-compression element and has three degrees of freedom at each node: translations in the nodal x, y, and z directions. As in a pin-jointed structure, no bending of the element is considered. Also, this element has plasticity, creep, rotation, large deflection, and large strain capabilities [54].

Contact conditions were simulated with TARGE170 and CONTA175 element types. The CONTA175 element type is used to represent Contact and sliding between two surfaces. TARGE170 is used to represent various 3-D target surfaces for the associated contact elements [54]. Schematic views of these elements are given in Figure 3.3.

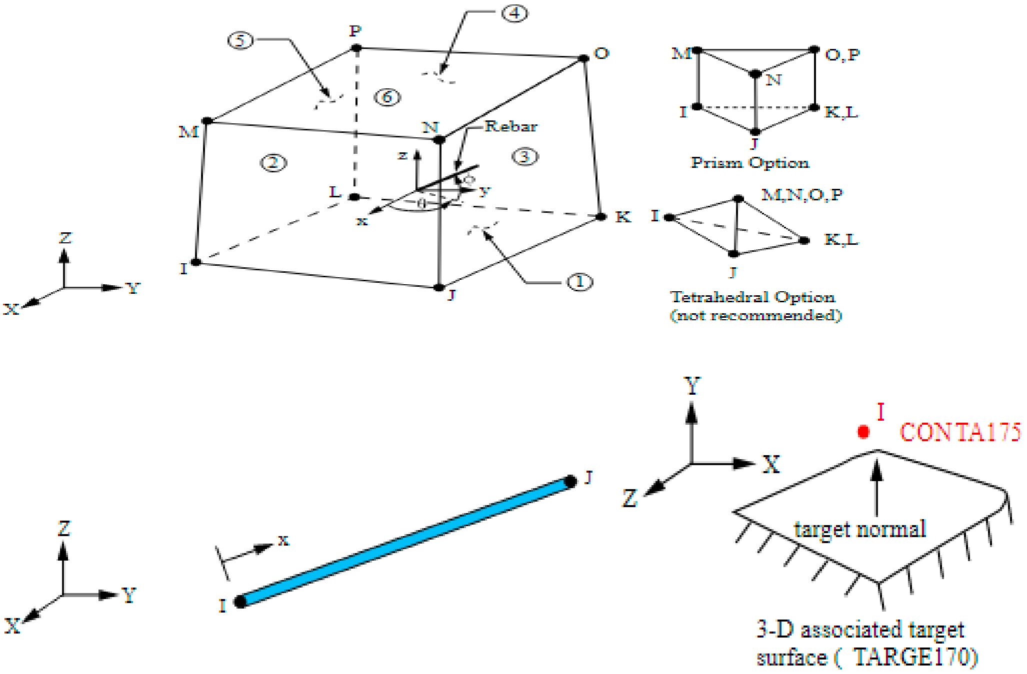


Figure 3.4. Schematic views of the SOLID65, LINK180, TARGE170, and CONTA175 element types [54]

3.2.2. Assigning of material properties

Some assumptions are made in the finite element models of masonry walls. It is assumed that the walls, plaster, and mortar are fully bonded with each other. Therefore, it is aimed that the damage will occur within the materials, not in the interfaces. The contact surface was defined between the expanded steel sheet and the plaster material. In addition, the contact surface was defined for the parts where the loading system touches the wall model. To represent the nonlinear behavior of the model, brick, mortar, plaster, and expanded steel sheet elements were modelled with nonlinear material models. The loading system and steel anchors, which are not expected to be damaged, are modelled as linear material. In the FE model, anchor materials were not modelled. To represent anchor elements, nodes were coupled at the application points.

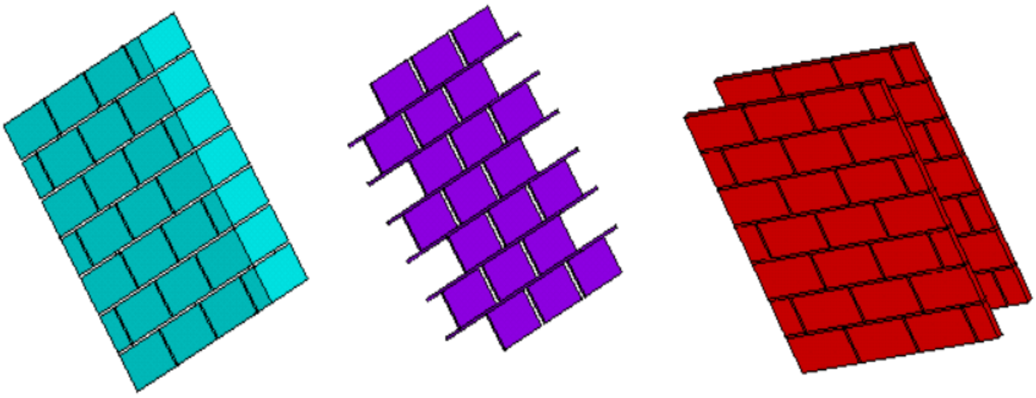
In the study, the nonlinear behavior of the brick, mortar, and plaster elements is defined by the Drucker-Prager (DP) criterion with the associated flow rule, and Willam-Warnke (WW) criterion was used as a failure surface. Cohesion (c) and internal friction angle (φ) are two constants that define the Drucker-Prager yield surface. The Willam-Warnke failure surface was defined by two material constants; the uniaxial compressive strength (Fc) and the uniaxial tensile strength (ft). Bilinear isotropic hardening plasticity (BISO) was used for the material model of the expanded steel sheet. Material properties of the FE models are given in Table 3.2.

Table 3.2. Material properties of the FE models [54]

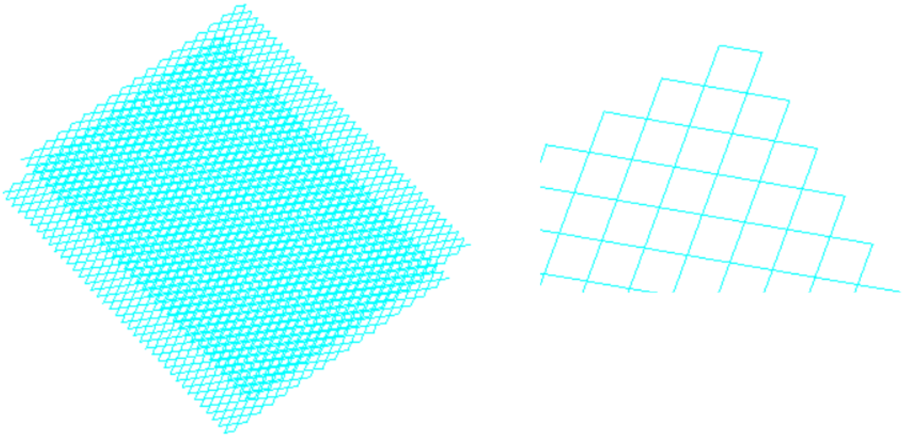
		Brick	Mortar	Plaster	Reinf. Mesh	Loading System Elements
Elastic Prop.	Young Modulus (Mpa)	2000	5000	5000	210000	210000
	s (-)	0.2	0.2	0.2	0.3	0.3
	Density (kg/m^3)	700	2000	2000	7850	7850
DP Criterion	Cohesion	0.09	0.12	0.12	-	-
	Dilatancy Angle	10	15	15	-	-
	Internal Friction Angle	45	38	38	-	-
WW Surface	Uniaxial compressive strength	3.3	10	10	-	-
	Uniaxial tensile strength	0.33	1.00	1.00	-	-
	Shear transfer coeff. Close cracks	0.75	0.75	0.75	-	-
	Shear transfer coeff. Open cracks	0.15	0.15	0.15	-	-
BISO	Yield stress (Mpa)	-	-		280	-

3.2.3. Parts of the FE model

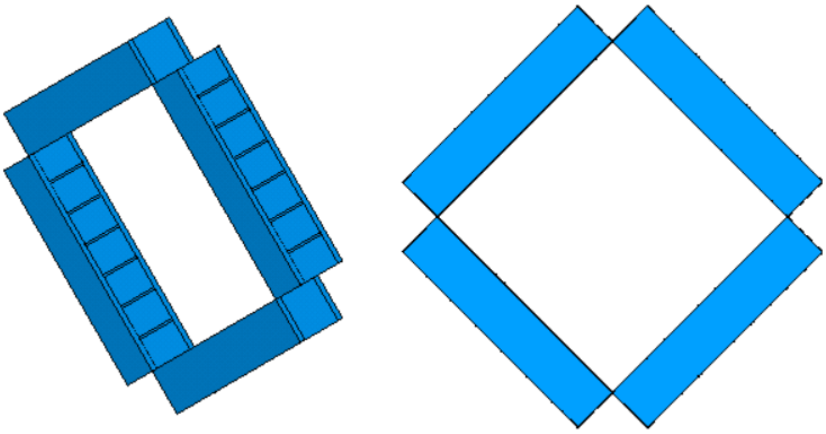
The elements of the FE models are given in Figure 3.4. In the finite element models of the walls, brick, mortar, plaster, expanded steel sheet, and loading profiles were modelled separately. In the reference model, there are no expanded steel sheetelements. Brick, mortar, plaster, and loading profiles were modelled as solid, and expanded steel sheet was created as lines. FE models of the masonry walls are given in Figure 3.5. Also, anchor points of the wall models are given in Figure 3.6. expanded steel sheet elements assumed as resist only tension stresses and ignore the compression stresses because of convergence problems.



Brick Mortar Plaster



expanded steel sheet



Loading profiles

Figure 3.5. Parts of the FE model

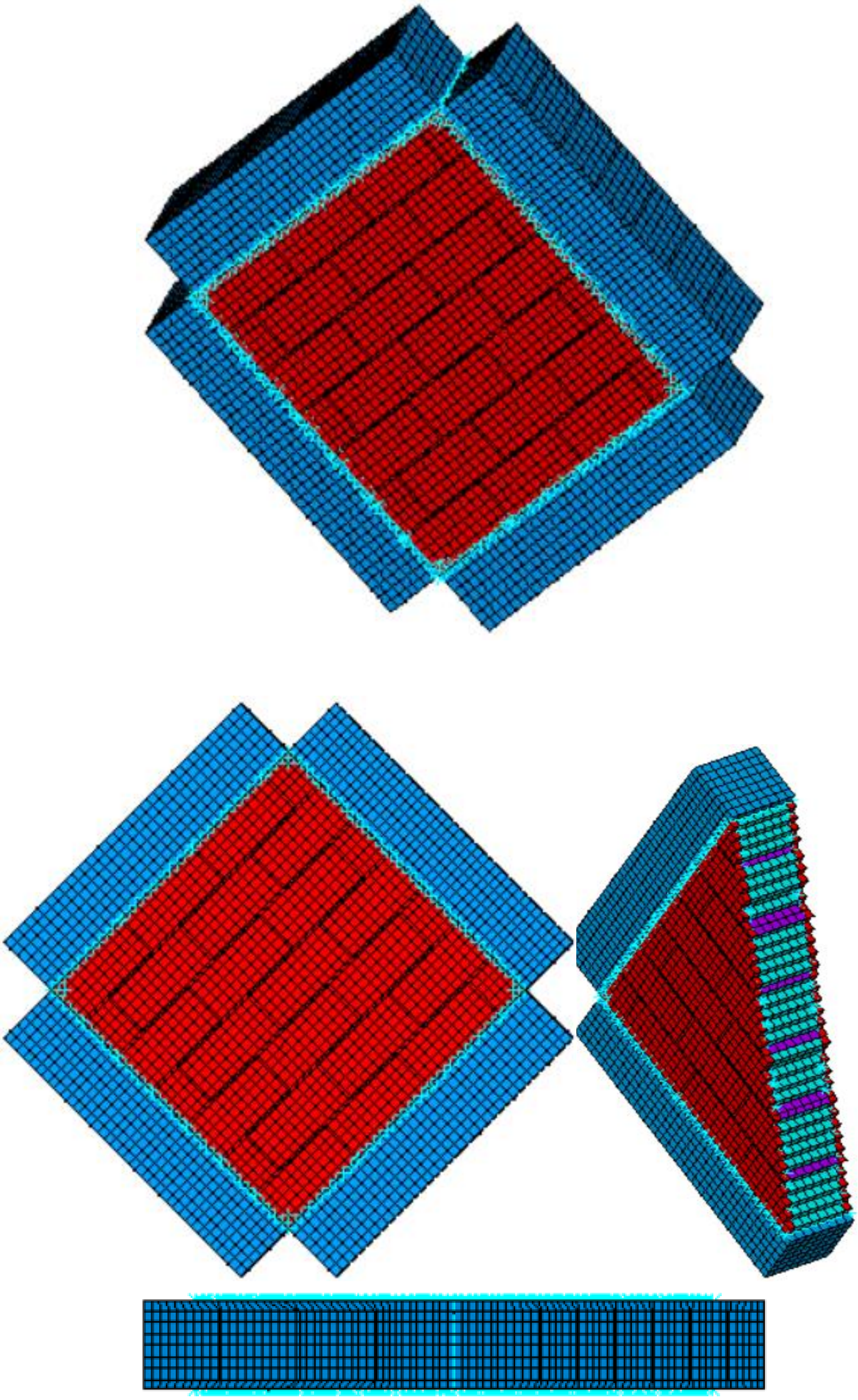


Figure 3.6. FE model of the masonry walls

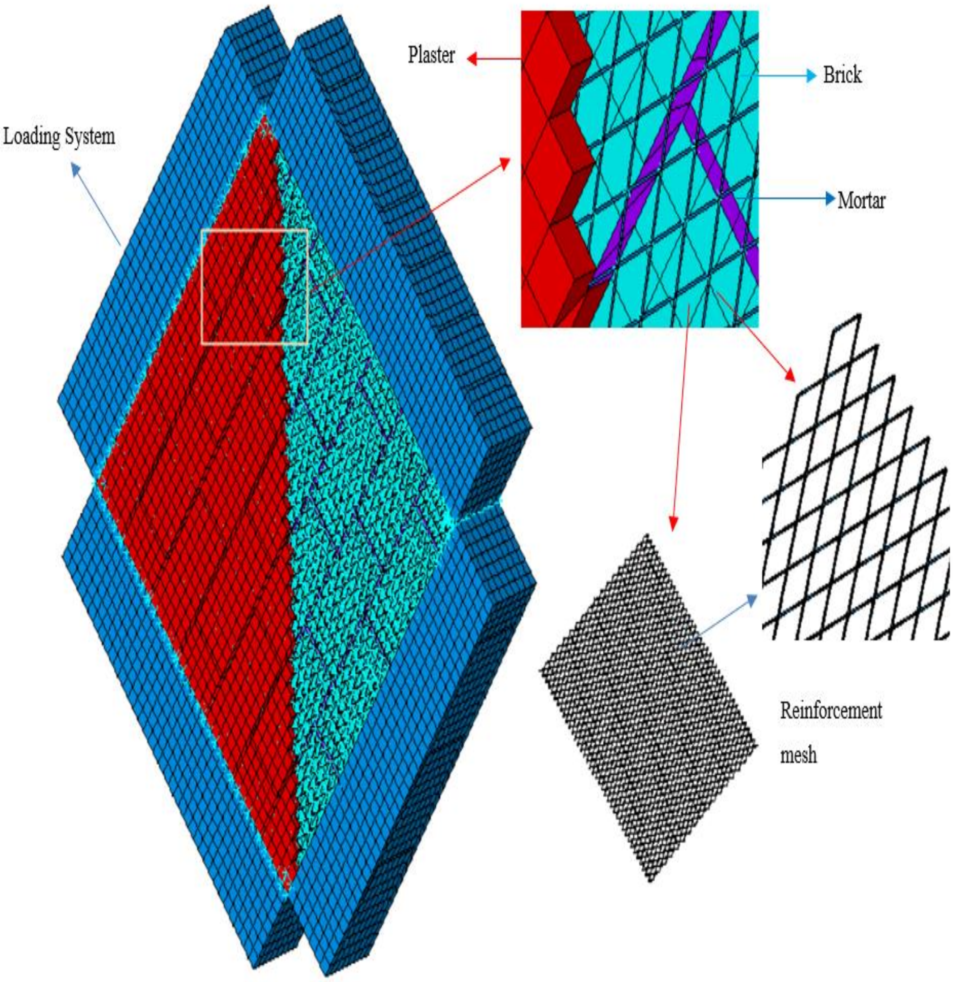
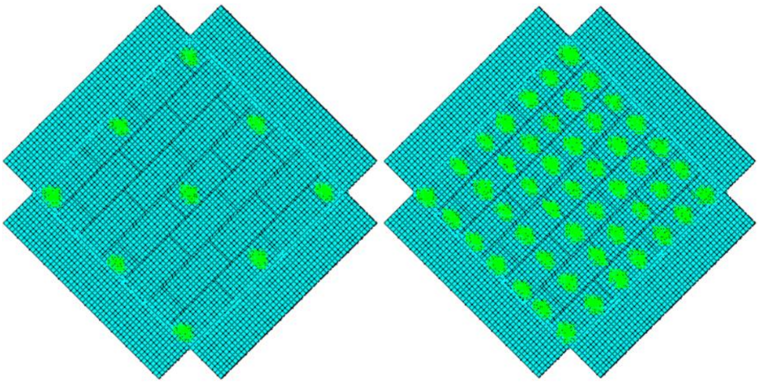


Figure 3.7. FE model of the masonry walls



MBW 3.0-400 MBW 1.5-150, 2.0-150, 3.0150

Figure 3.8. Location of the bulons (as coupling)

3.2.4. Finite element model brick walls

3.2.4.1. Reference brick wall

The reference brick wall was built with hollow vertically perforated bricks and a 25 mm thick plaster was applied on both sides. No strengthening process was applied to the reference test element, it was simply tested under diagonal loads (Figure 3.8.).

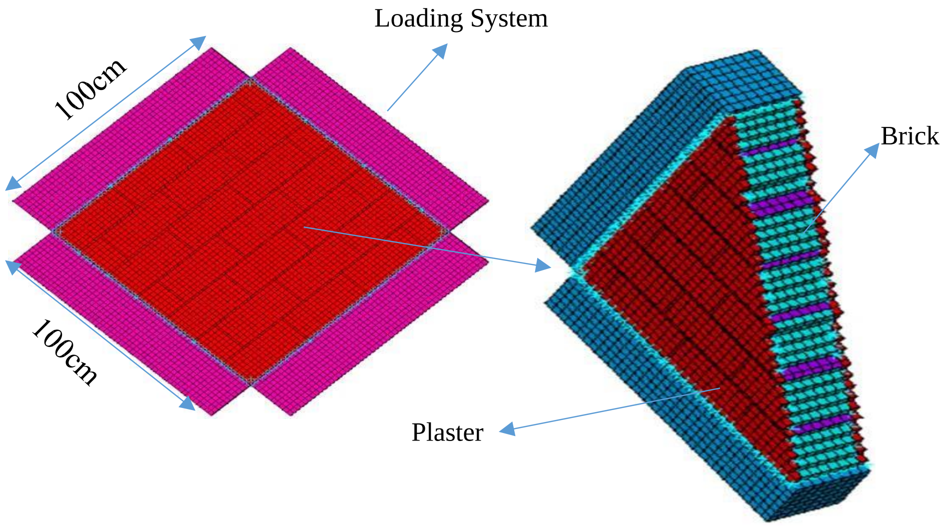


Figure 3.9. Dimensions of the reference of the numerical model [3]

3.2.4.2. MBW 3.0-400 brick wall

This brick wall was prepared as a test element, with a thickness of 3.0 mm on a steel plate and a plaster thickness of 25 mm on a plate of 400 mm, the distance between the bolts fixing the steel plate to the wall. The reinforcement details of this test element are shown in Figure 3.9.

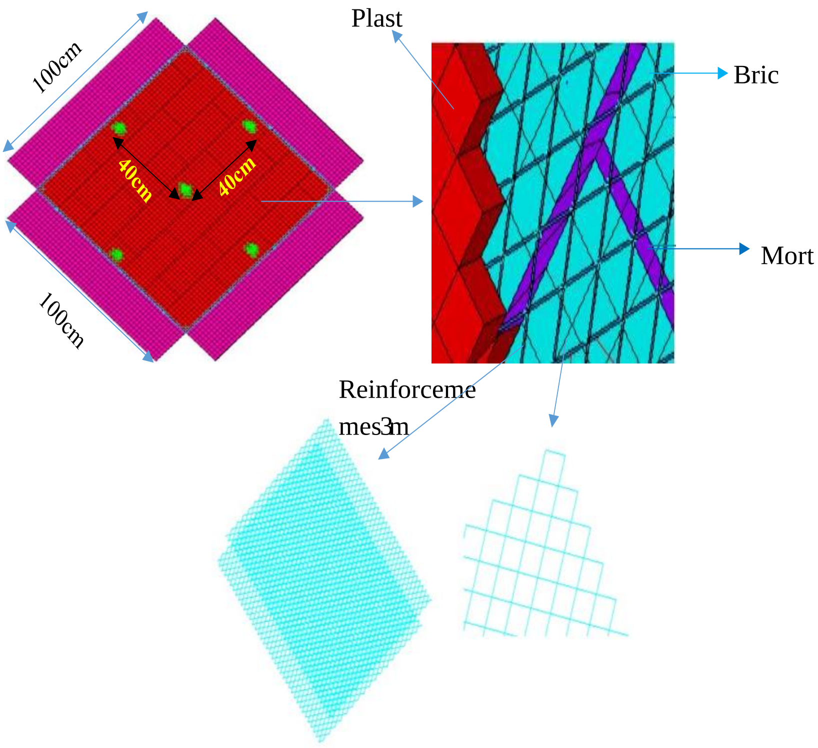


Figure 3.10. Dimensions of the MBW 3.0-400 the numerical model [3]

3.2.4.3. MBW 1.5-150, 2.0-150, 3.0-150 brick walls

The thickness of the steel plate is 1.5mm and 2mm and 3mm, the distance between the bolts fixing the steel plate to the wall is 150 mm, and the plaster thickness is 25 mm on the plate as a test element. The reinforcement details of this test element are shown in Figure 3.10.

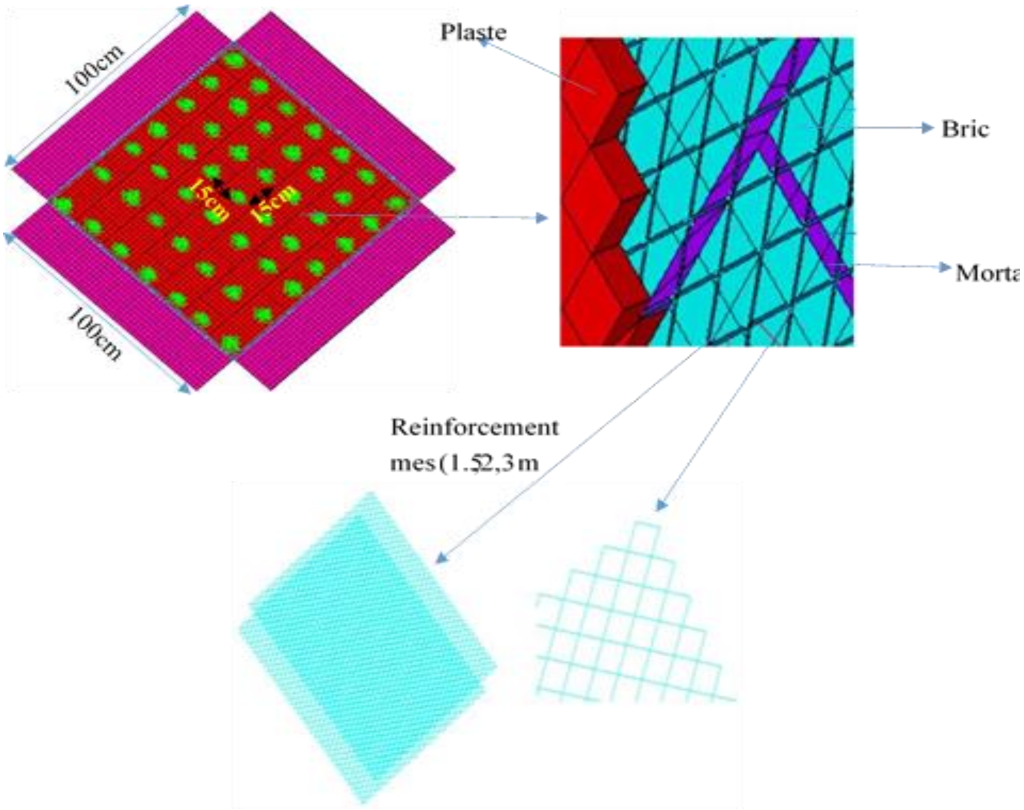


Figure 3.11. Dimensions of the MBW 1.5-150, 2.0-150, 3.0-150 the numerical model [3]

3.2.5. Results of the masonry walls and comparison with experimental results

3.2.5.1. Reference wall

The load-displacement curve and crack situation of the reference wall is given in Figure 3.10. According to the results of the reference wall, which is unreinforced, the maximum load was obtained as 100kN, as seen in Figure 3.10. In the analysis, the first cracks occurred earlier when compared experimental test explained by Ahmadzai, E. (2020) [4]. First damage was obtained at 15mm displacement. Unknown differences between the loading system and reference model boundary conditions such as unknown gaps can lead to this situation. The analysis didn't converge at the displacement value of 35mm. This range (0-35mm) may be acceptable and sufficient when comparing the experimental result that reached the peak at the displacement of 30mm

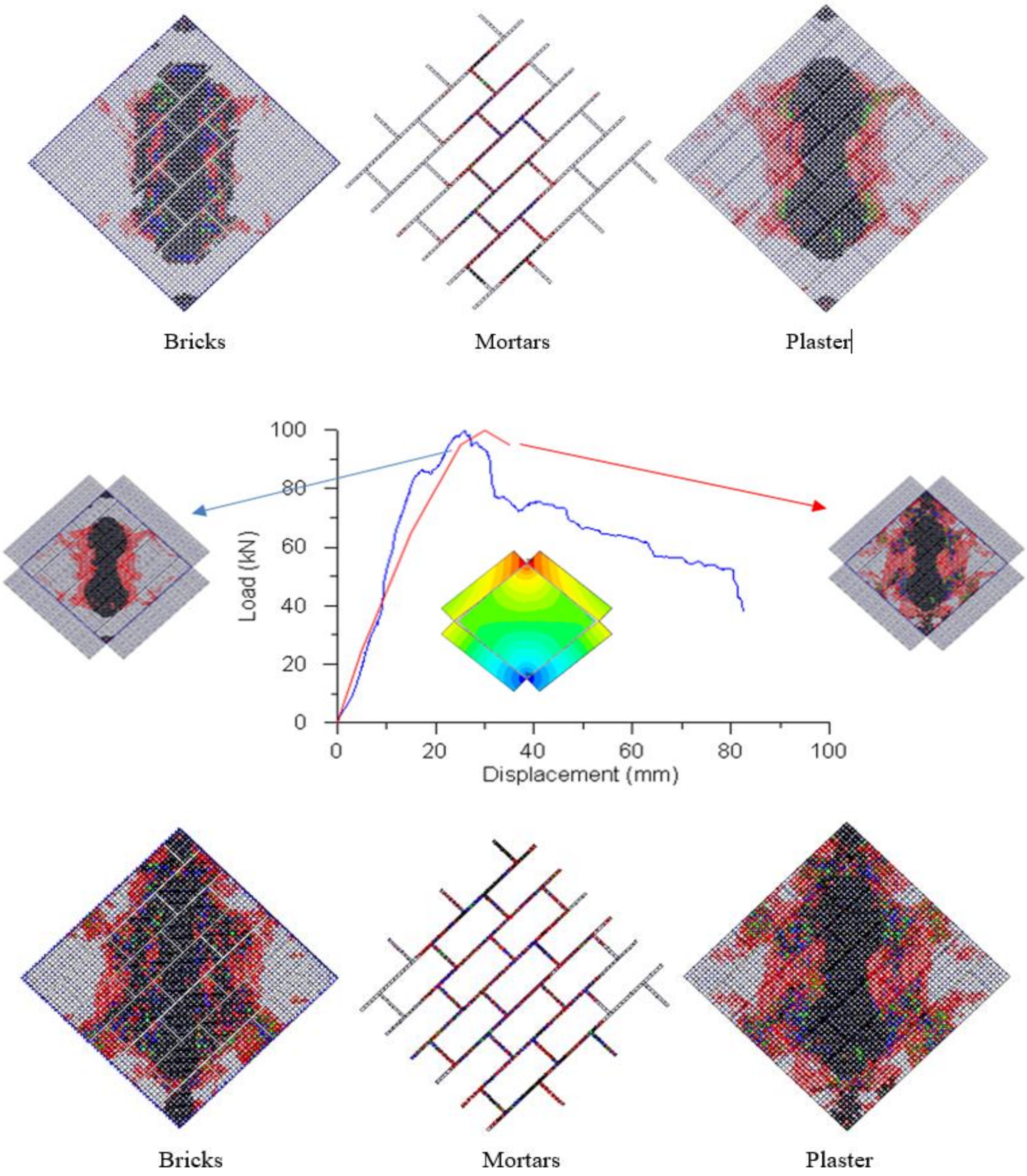


Figure 3.12. Load-displacement curve, deformation shape, and crack pattern of the reference model

3.2.5.2. MBW 3.0-400 Wall

The load-displacement curve and crack situations of the MBW 3.0-400 wall are given in Figure 3.11. The analysis didn't converge at the displacement value of 30mm. Due to high nonlinearity situations such as material and Contact, softening behaviour of the model was not simulated. To grasp softening behaviour of the model needs more computational effort and high hardware capacity. According to the results of the MBW 3.0-400 wall, which is reinforced with a expanded steel sheet, the maximum load was obtained as 158kN, as seen in Figure 3.11. This value is a bit more than the experimental result. First damage was obtained at 16mm displacement. Crushing damage occurred on the wall in the direction of loading direction. Especially brick elements are damaged more than others because of the very low compressive strength. Also, the tensile stress diagram of the expanded steel sheet is given in Figure 3.12. As seen from the figure expanded steel sheet resists the tensile stresses at the region side part of the wall. In the figure, red and grey parts show the yielding elements..

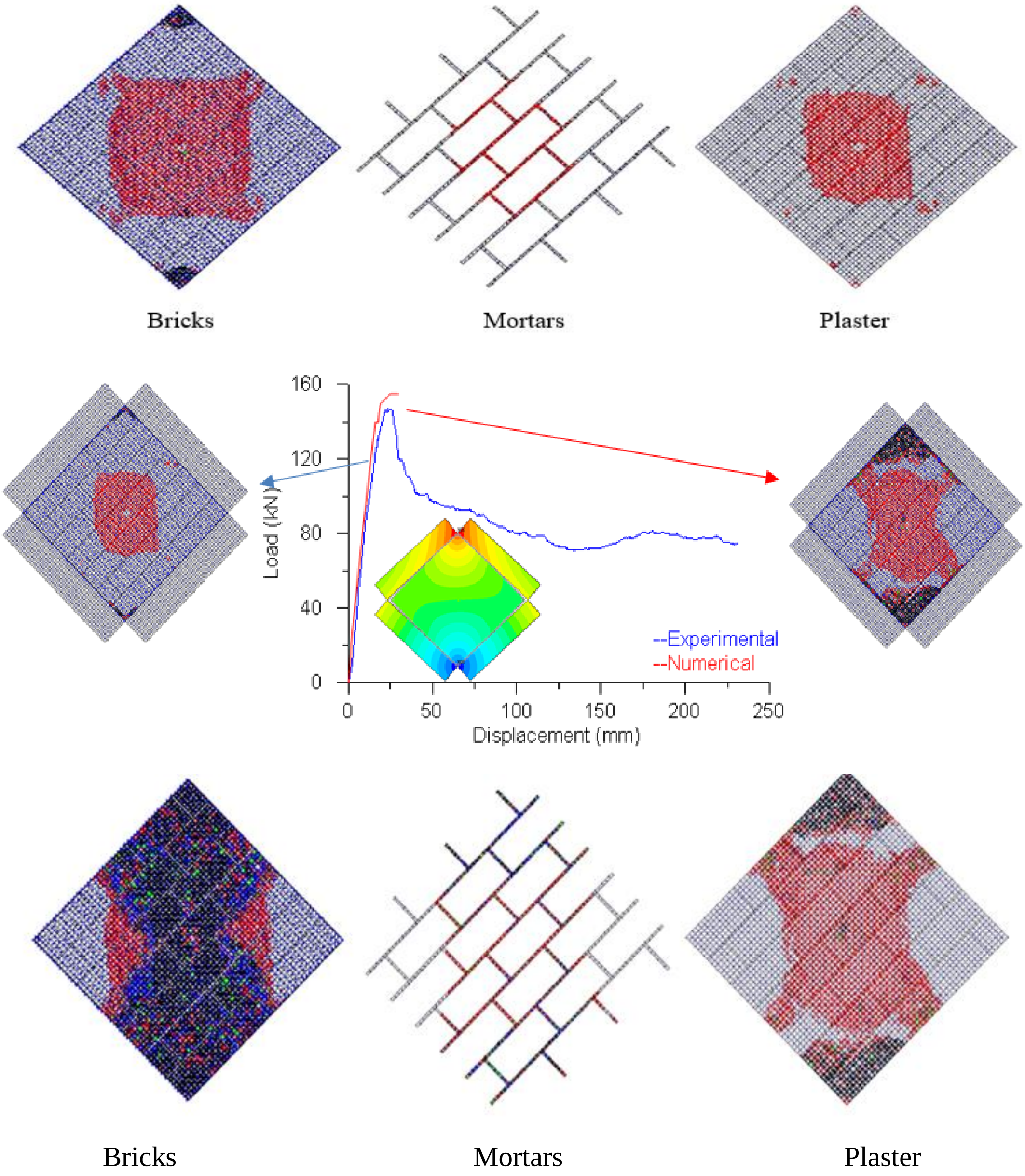


Figure 3.13. Load-displacement curve, deformation shape, and crack pattern of MBW 3.0-400 model

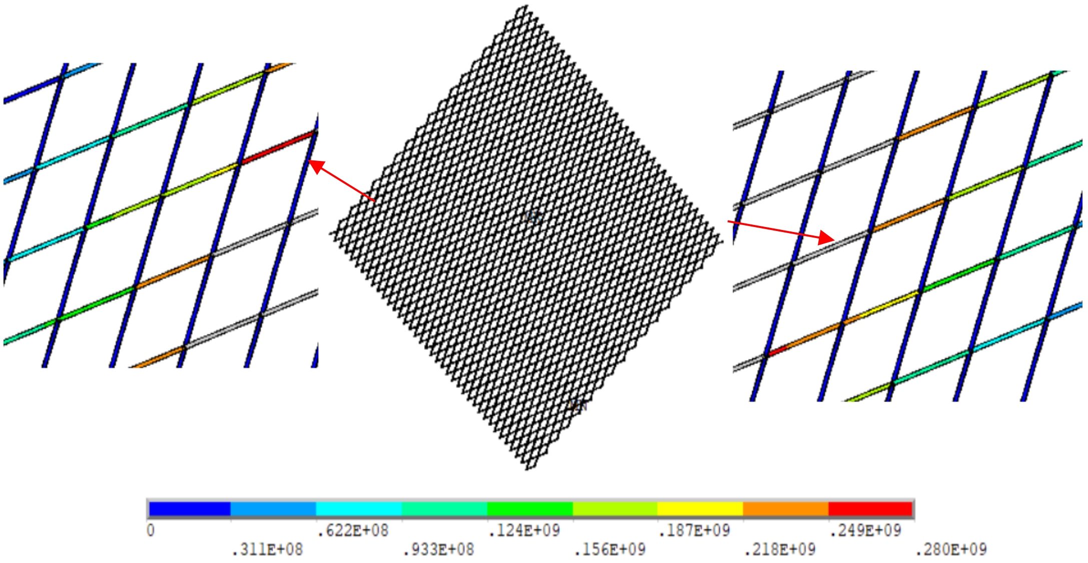


Figure 3.14. Tensile stress diagram of the expanded steel sheet (Pa)

3.2.5.3. MBW 1.5-150 Wall

The load-displacement curve and crack situations of the MBW 1.5-150 wall are given in Figure 3.13. The analysis didn't converge at the displacement value of 38mm. According to the results of the MBW 1.5-150 wall, which is reinforced with expanded steel sheet, the maximum load was obtained as 185kN, as seen in Figure 3.13. This value is higher than the experimental result. First damage was obtained at 15mm displacement. Also, the tensile stress diagram of the expanded steel sheet is given in Figure 3.14. As seen from the figure expanded steel sheet resist the tensile stresses at the region side part of the wall. In the figure, the red and grey parts show the yielding elements.

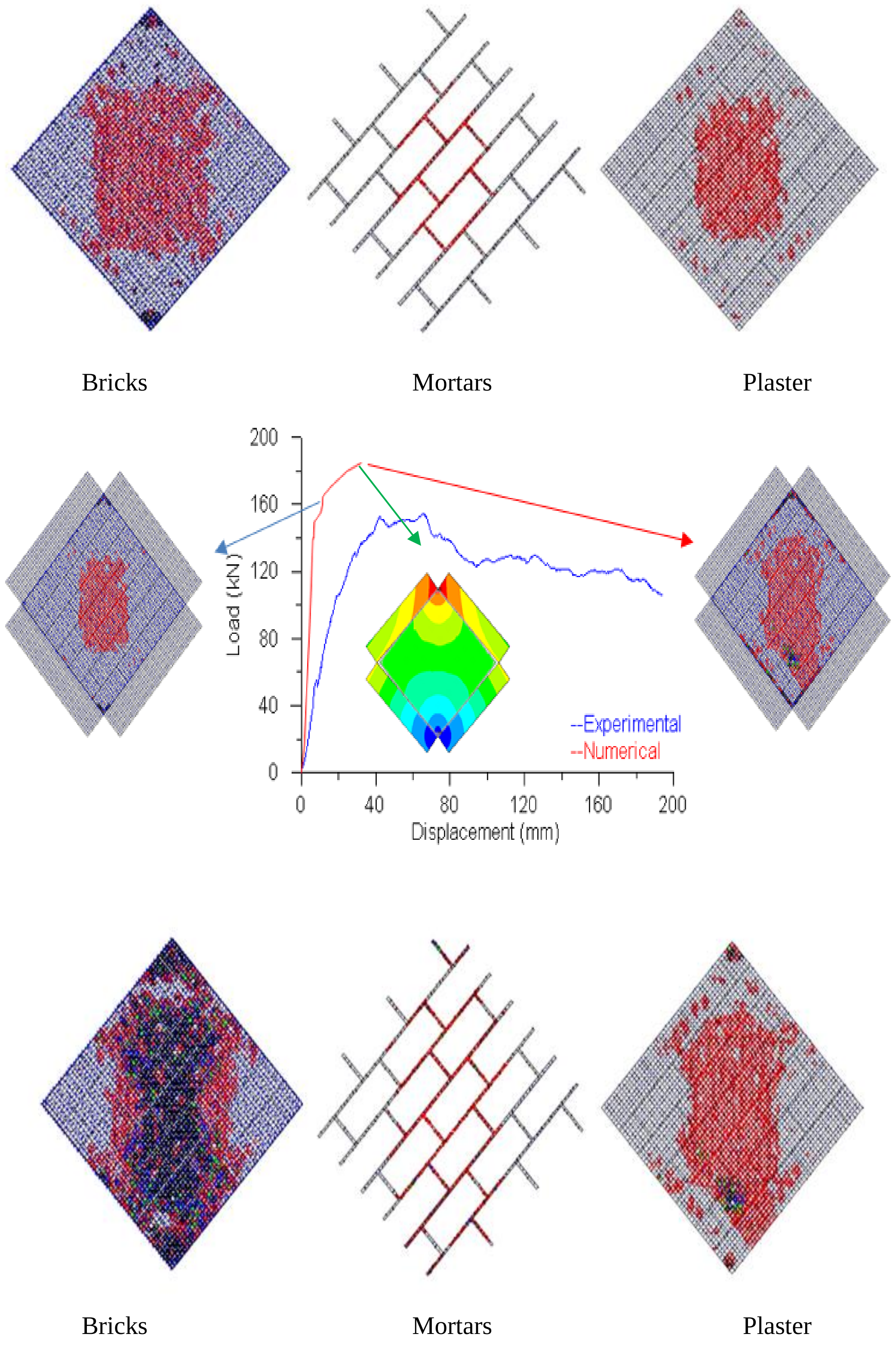


Figure 3.15. Load-displacement curve, deformation shape, and crack pattern of MBW 1.5-150 model

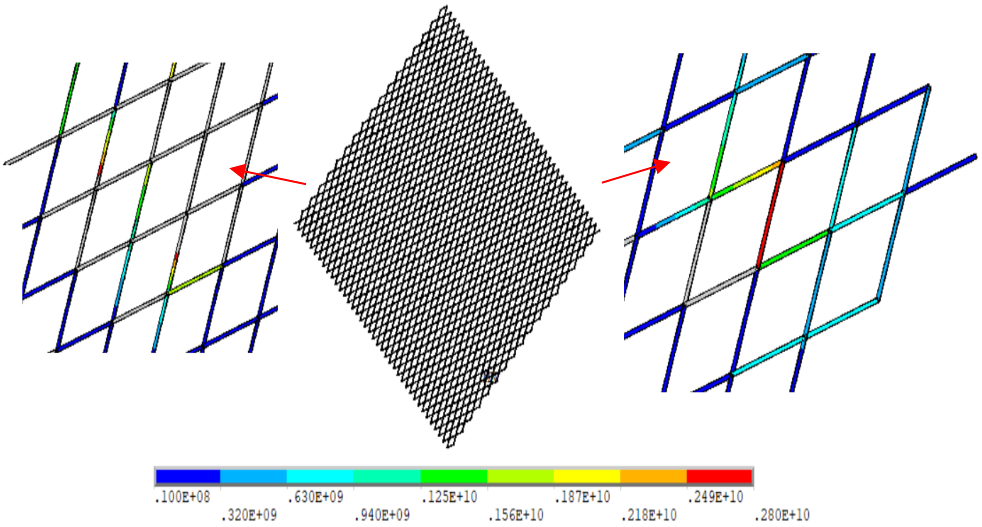
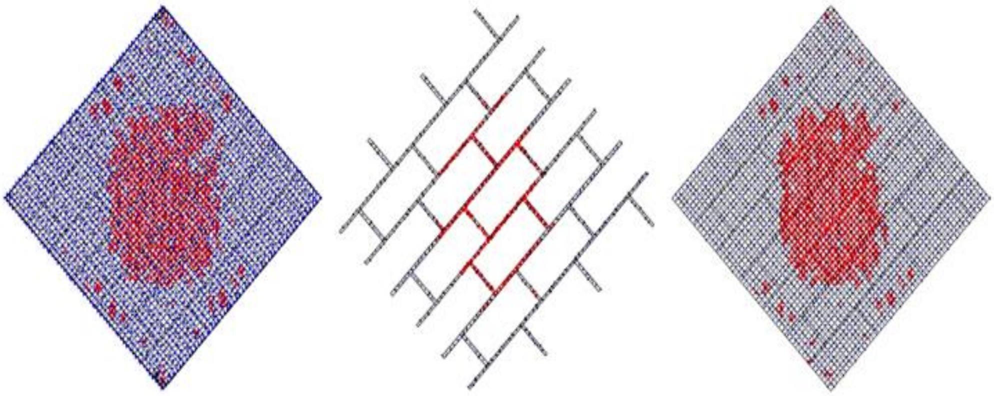


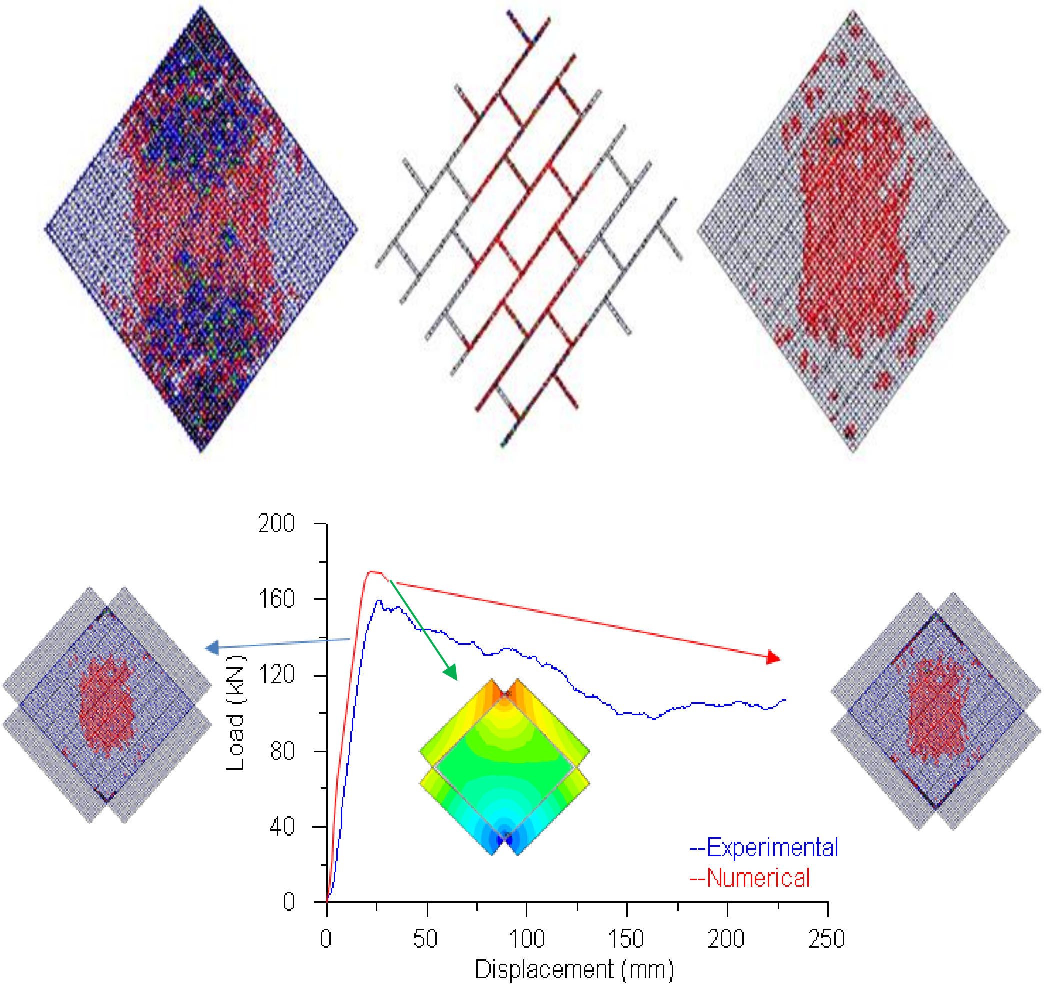
Figure 3.16. Tensile stress diagram of the expanded steel sheet (Pa)

3.2.5.4. MBW 2.0-150 Wall

The load-displacement curve and crack situations of the MBW 2.0-150 wall are given in Figure 3.15. The analysis didn't converge at the displacement value of 38mm. According to the results of the MBW 2.0-150 wall, which is reinforced with expanded steel sheet, the maximum load was obtained as 177kN, as seen in Figure 3.15. This value is higher than the experimental result. First damage was obtained at 19mm displacement. Also, the tensile stress diagram of the expanded steel sheetis given in Figure 3.16. As seen from the figure expanded steel sheet resists the tensile stresses at the region side part of the wall. In the figure, red and grey parts show the yielding elements.



Bricks Mortars Plaster



Bricks Mortars Plaster

Figure 3.17. Load-displacement curve, deformation shape, and crack pattern of MBW 2.0-150 model

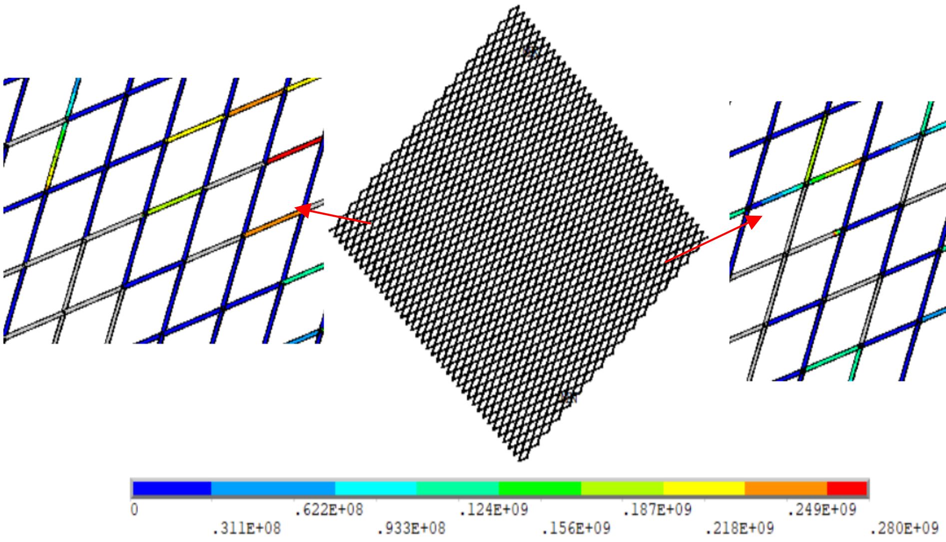
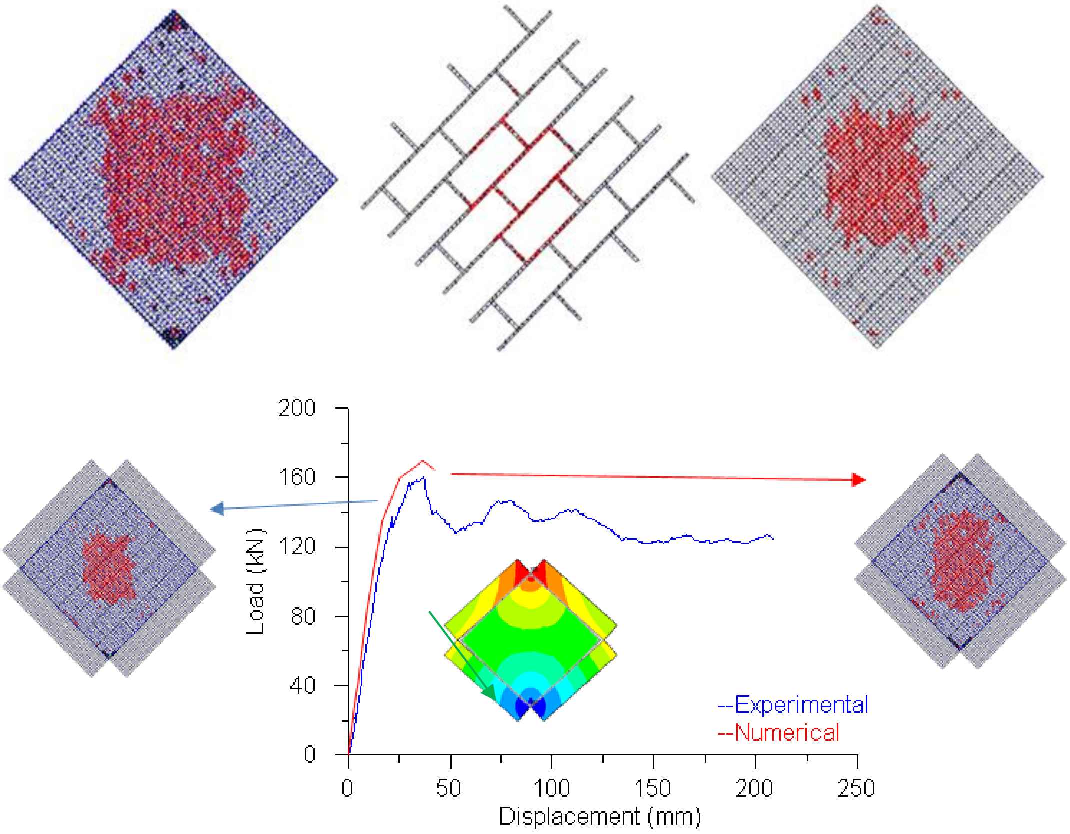


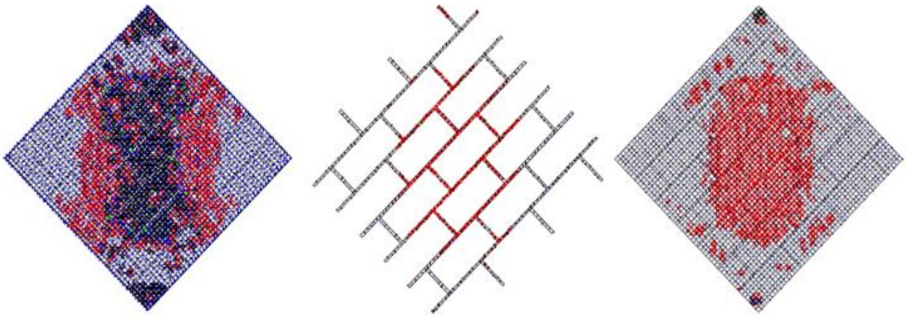
Figure 3.18. Tensile stress diagram of the expanded steel sheet (Pa)

3.2.5.5. MBW 3.0-150 Wall

The load-displacement curve and crack situations of the MBW 3.0-150 wall are given in Figure 3.17. The analysis didn't converge at the displacement value of 45mm. According to the results of the MBW 3.0-150 wall, the maximum load was obtained as 170kN as seen in Figure 3.17. This value is higher than the experimental result. First damage was obtained at 22mm displacement. Also, the tensile stress diagram of the expanded steel sheet is given in Figure 3.18. As seen from the figure expanded steel sheet resists the tensile stresses at the region side part of the wall. In the figure, red and grey parts show the yielding elements.



Bricks Mortars Plaster



Bricks Mortars Plaster

Figure 3.19. Load-displacement curve, deformation shape, and crack pattern of MBW 3.0-150 model

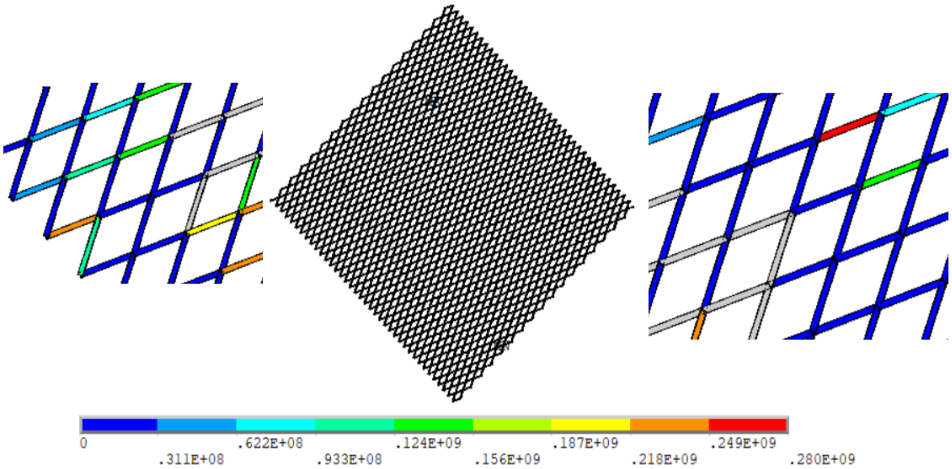


Figure 3.20. Tensile stress diagram of the expanded steel sheet (Pa)

3.2.5.6. Comparison of Experimental and Numerical Results

A comparison of experimental and numerical results is given in Table 3.3. The experimental test results were compared to the FE results, and the behavior was observed. For the reference wall, the results are good in terms of max. Force and per cent of error is 0.15% but quite faulty in terms of displacements, and per cent of error is 15.8%. Maybe the model is not able to represent this type of failure properly in unreinforced walls, or the decisive mechanical properties of the materials for this case were not well estimated.

On the other hand, better results were obtained in the model for Wall MBW 3.0-400. The results are good in terms of max. Force and displacements at the peak load and the difference are 7.46% and 2.7% for both maxes. Load and displacement, respectively.

For Wall MBW 1.5-150, the results are quite faulty in terms of max. Force and displacement and difference are 19.6% and -41.9% for both maxes. Load and displacement, respectively. Unknown differences between the loading system and MBW 1.5-150 FE model boundary conditions such as unknown gaps can lead to this situation.

The results for Wall MBW 2.0-150 and MBW 3-150 are acceptable in terms of maximum force and displacement. The difference ratios are about 10 per cent.

Table 3.3. Comparison between experimental and FE results

Test series	Max. Load FEM(kN)	*Dif (%) Max. Load*	Max. Load EXP(kN)	Disp FEM	*Dif (%) Max. Load*	Disp EXP
Wall Reference	100	*0.15*	99.85	30	*15.8*	25.9
Wall MBW 3.0-400	158	*7.46*	147.02	26	*2.7*	25.3
Wall MBW 1.5-150	185	*19.6*	154.65	38	*41.9*	65.4
Wall MBW 2.0-150	177	*9.9*	161	30	*11.76*	34.0
Wall MBW 3-150	170	*5.91*	160.5	37	*0.1*	36.7

CHAPTER 4. EXAMINING OF OPENING EFFECT

At this stage of the study, the effects of the window gap in the masonry walls on strength were investigated. In this context, analyzes were carried out by removing 10% and 20% of the wall surface area from the middle of the wall. In addition, analyzes were carried out using 1.5mm, 2.0mm, and 3.0mm thick expanded steel sheets for two different window gap conditions. 10 cm displacement was applied to all models to compare the window gap ratios more understandably. In the analyses, material properties were taken as similar to the previous chapter. However, failure surface parameters didn't consider in the analyses. Dimensions and details of the FE models are explained in Figures 4.1.-4.6.

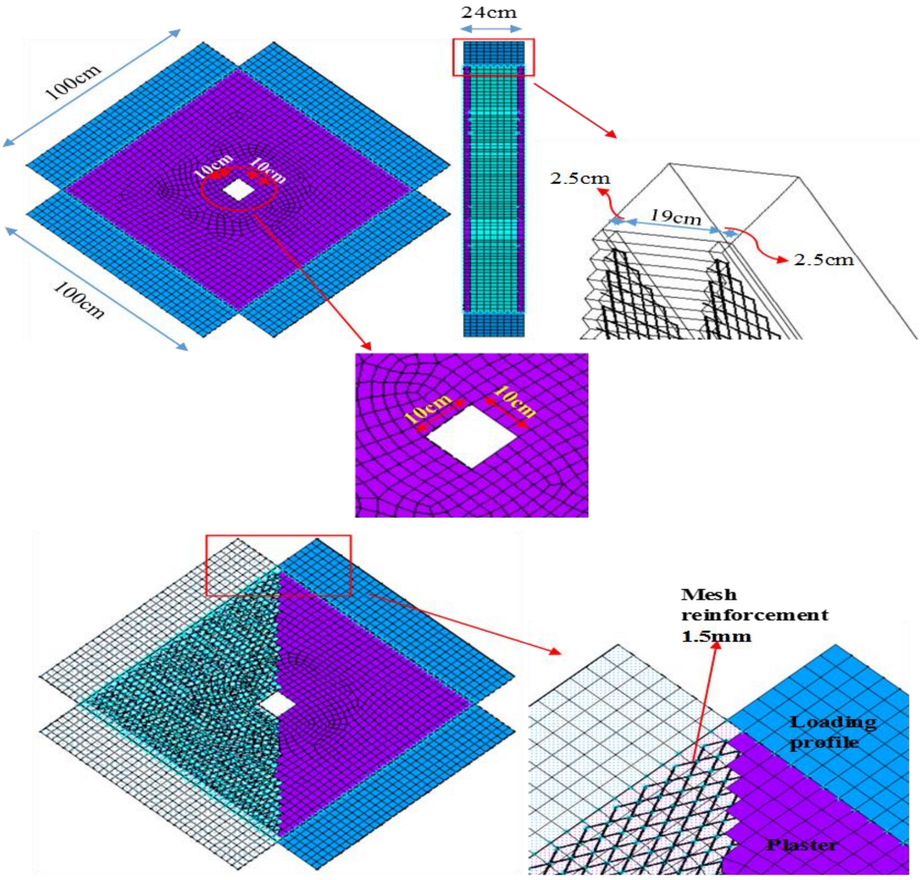


Figure 4.1. 10% opening ratio of the masonry wall model-1.5mm mesh reinforcement

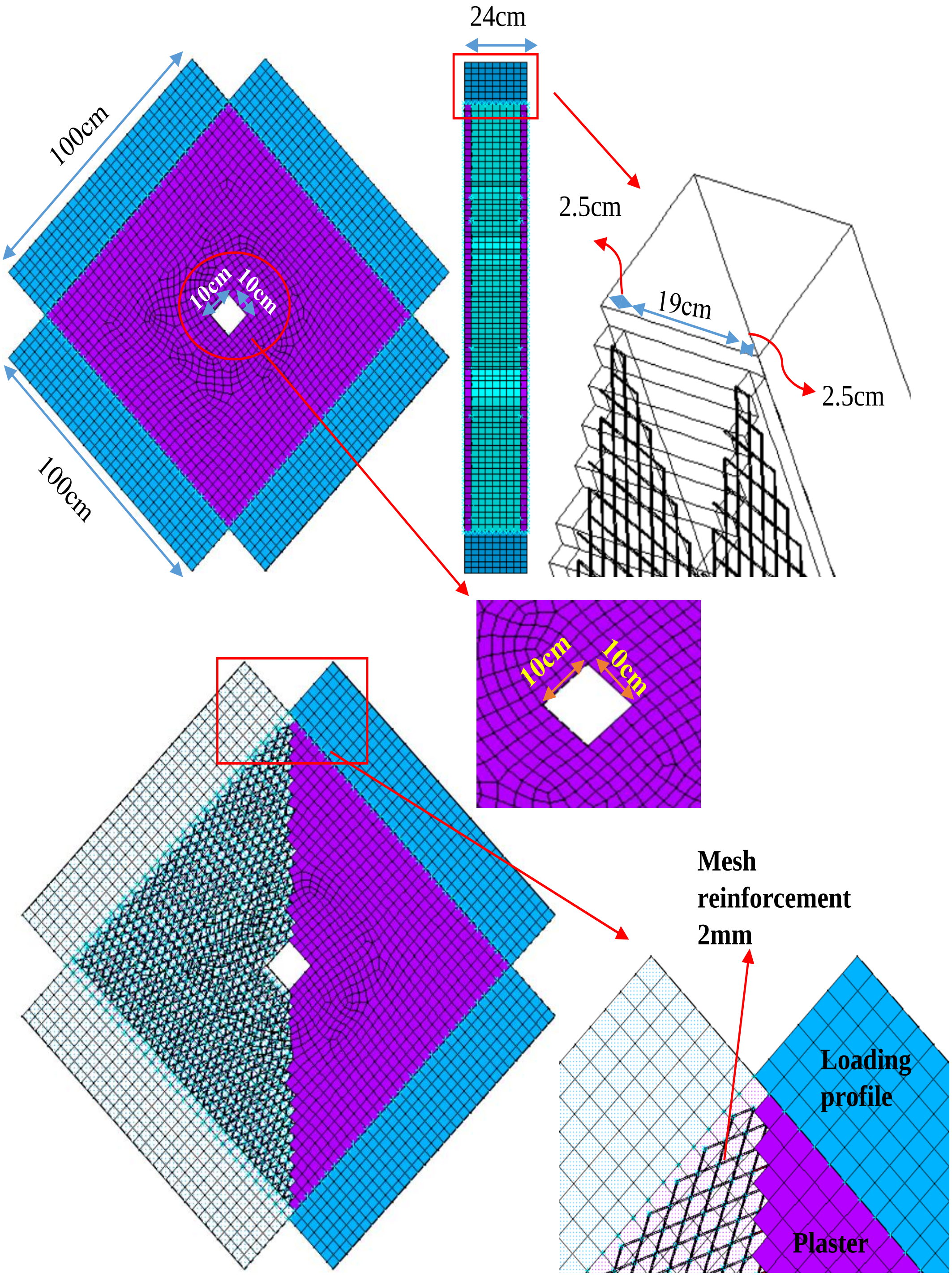


Figure 4.2. 10% opening ratio of the masonry wall model-2.0mm mesh reinforcement

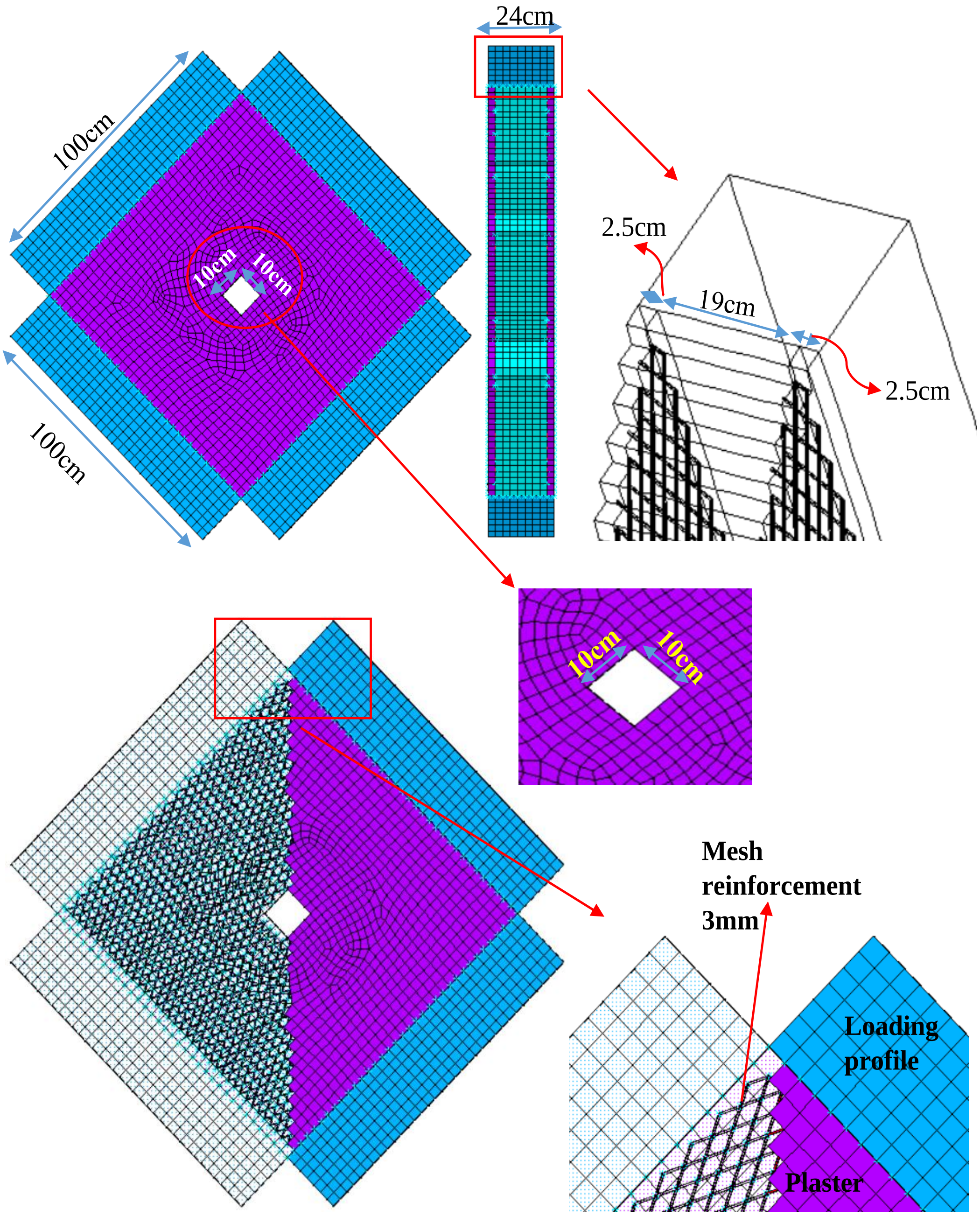


Figure 4.3. 10% opening ratio of the masonry wall model-3.0mm mesh reinforcement

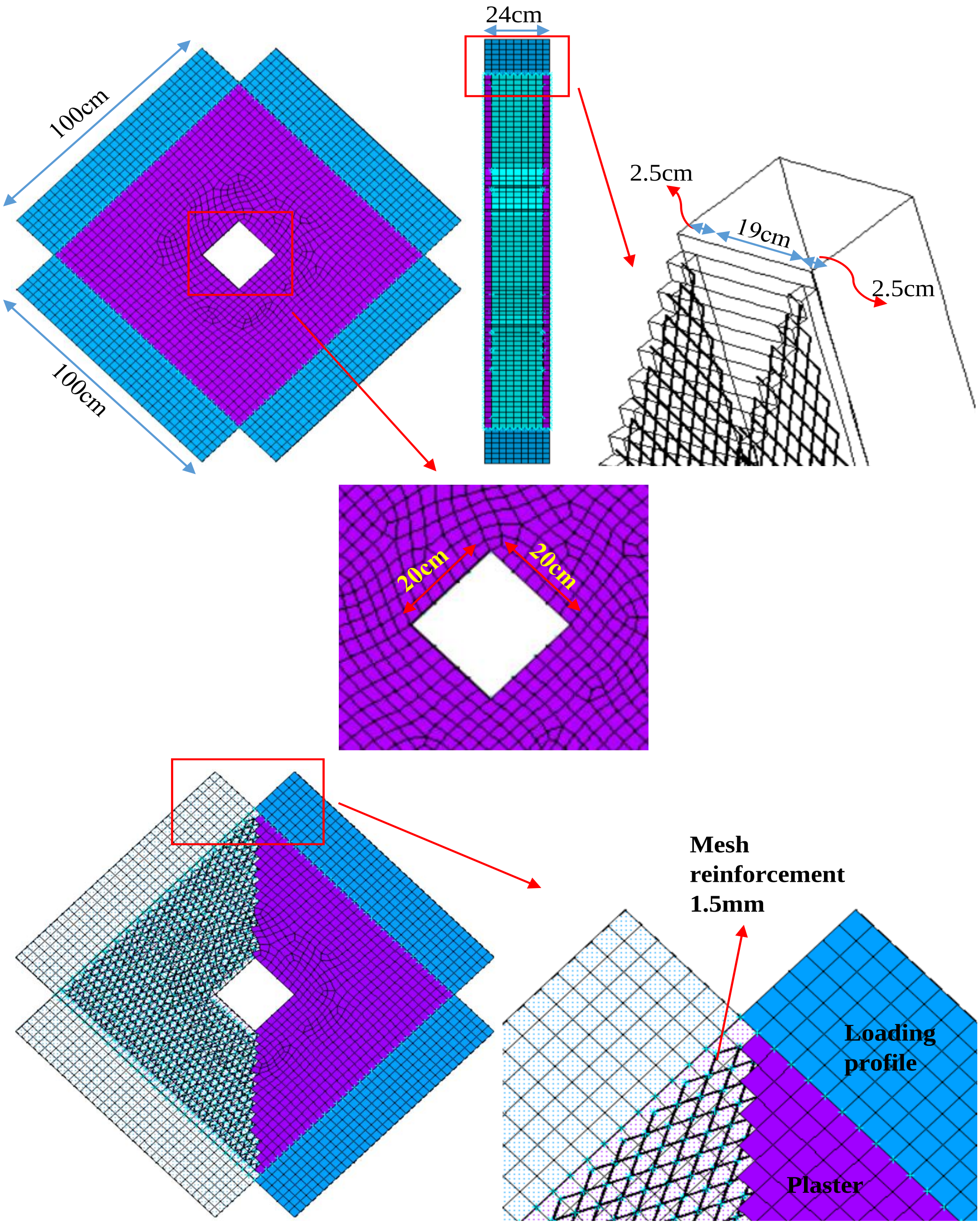


Figure 4.4. 20% opening ratio of the masonry wall model-1.5mm mesh reinforcement

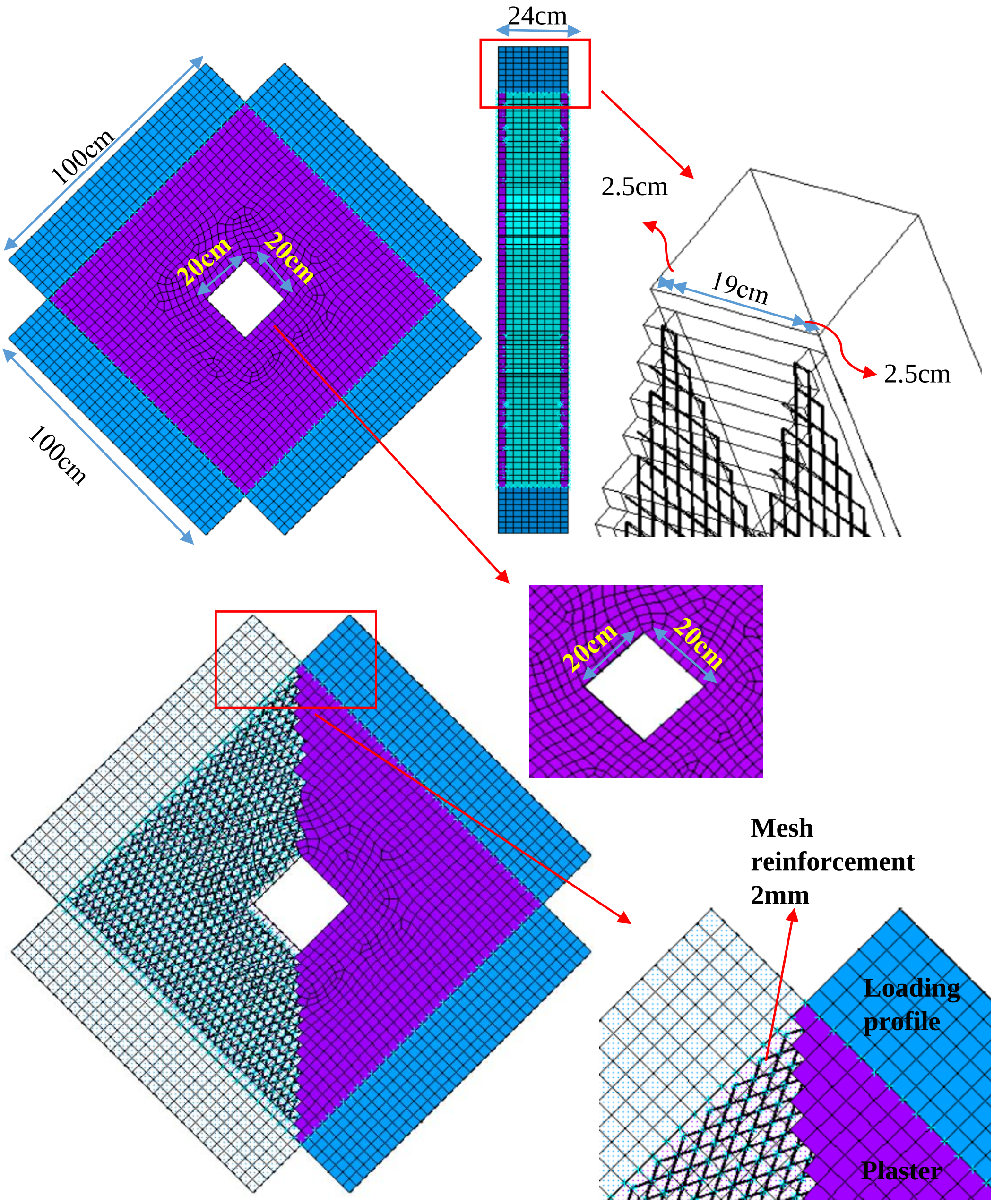


Figure 4.5. 20% opening ratio of the masonry wall model-2.0mm mesh reinforcement

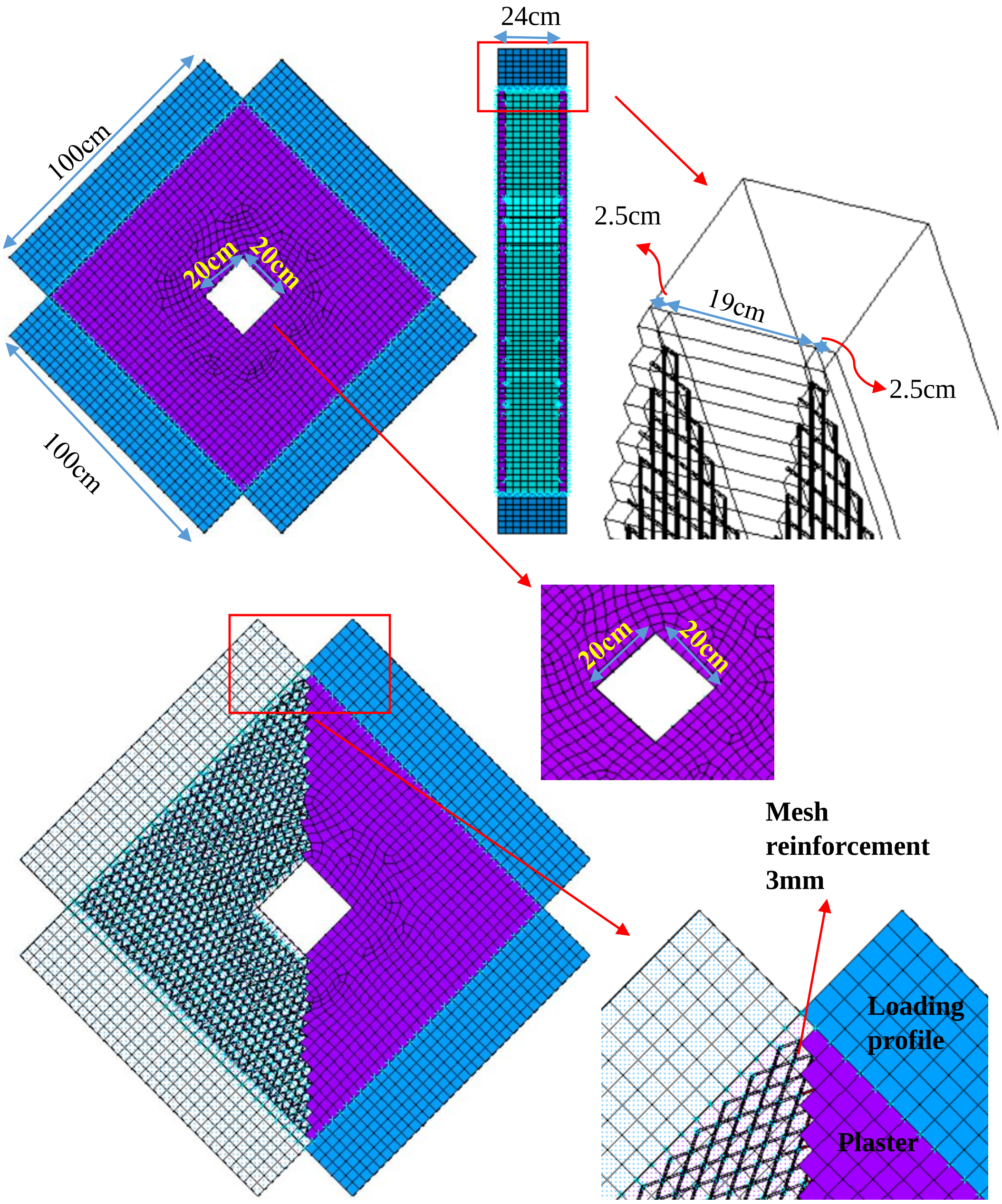


Figure 4.6. 20% opening ratio of the masonry wall model-3mm mesh reinforcement

The load-displacement curves, deformation shape, and total mechanical strain diagram at the last point of the analysis are given in Figures 4.7.-4.12. Also, a comparative chart of the results is given in Figure 4.13.

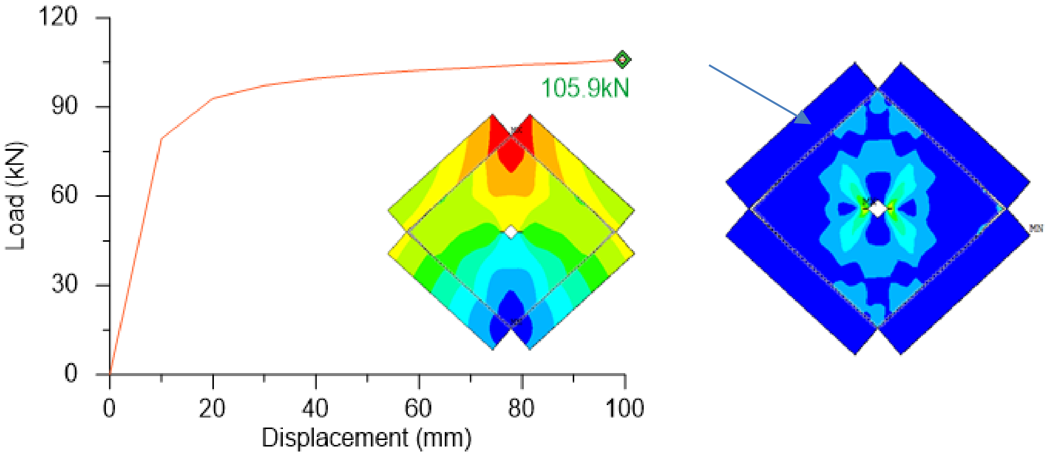


Figure 4.7. Load-Displacement curve, deformation shape, and total mechanical strain diagram of the wall with 10% opening (thickness of steel mesh 1.5mm)

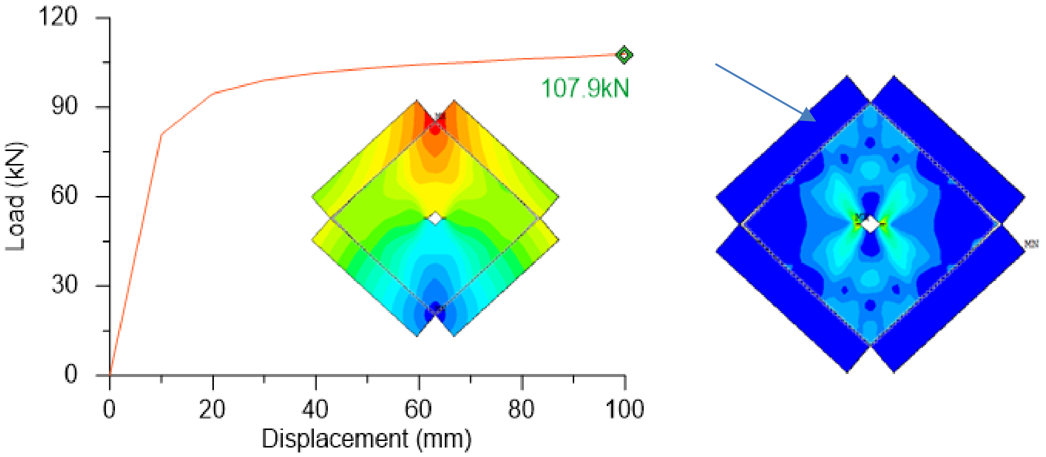


Figure 4.8. Load-Displacement curve, deformation shape, and total mechanical strain diagram of the wall with 10% opening (thickness of steel mesh 2.0mm)

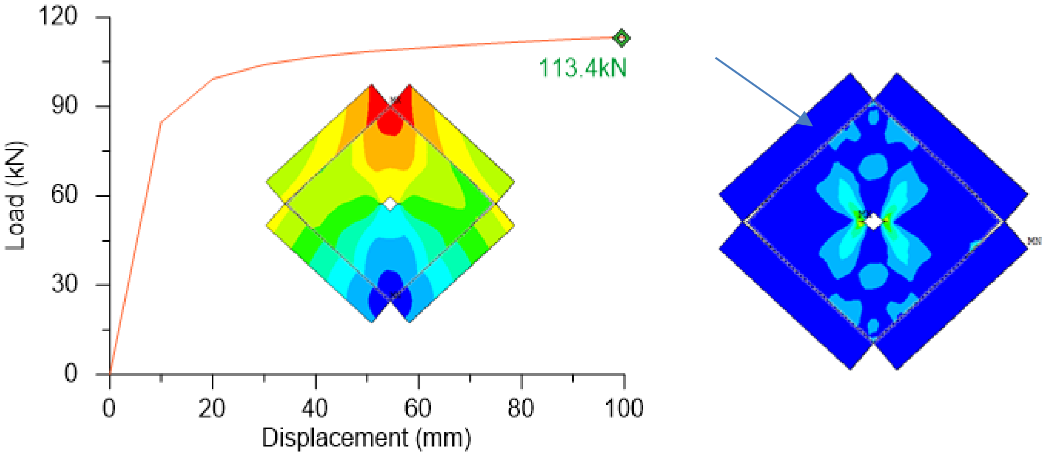


Figure 4.9. Load-Displacement curve, deformation shape, and total mechanical strain diagram of the wall with 10% opening (thickness of steel mesh 3.0mm)

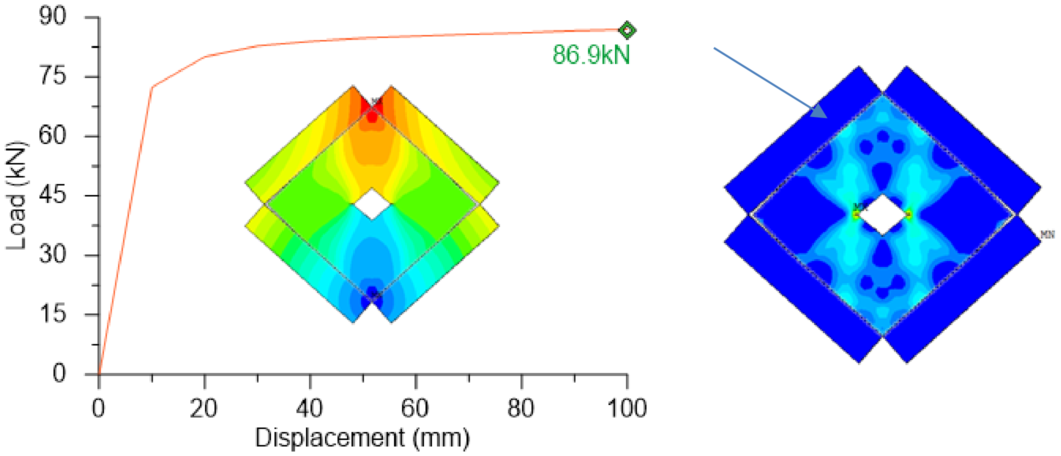


Figure 4.10. Load-Displacement curve, deformation shape, and total mechanical strain diagram of the wall with 20% opening (thickness of steel mesh 1.5mm)

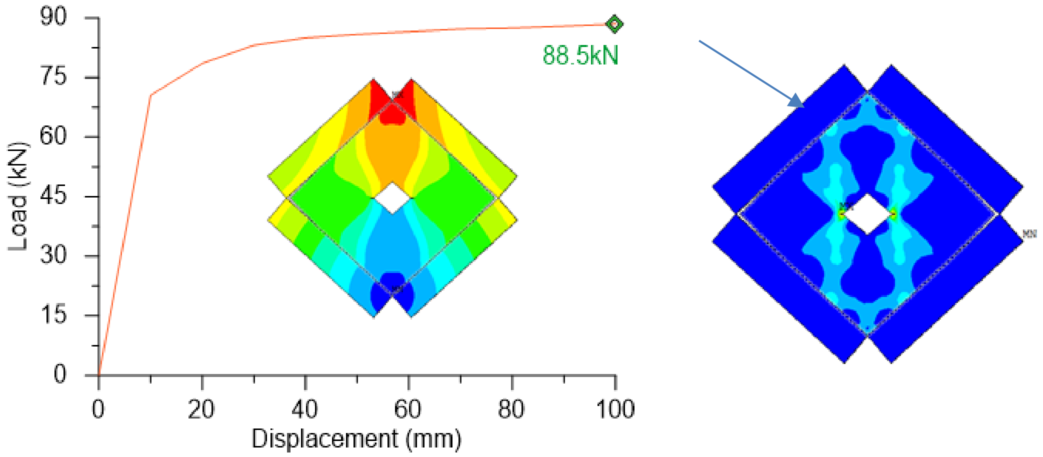


Figure 4.11. Load-Displacement curve, deformation shape, and total mechanical strain diagram of the wall with 20% opening (thickness of steel mesh 2.0mm)

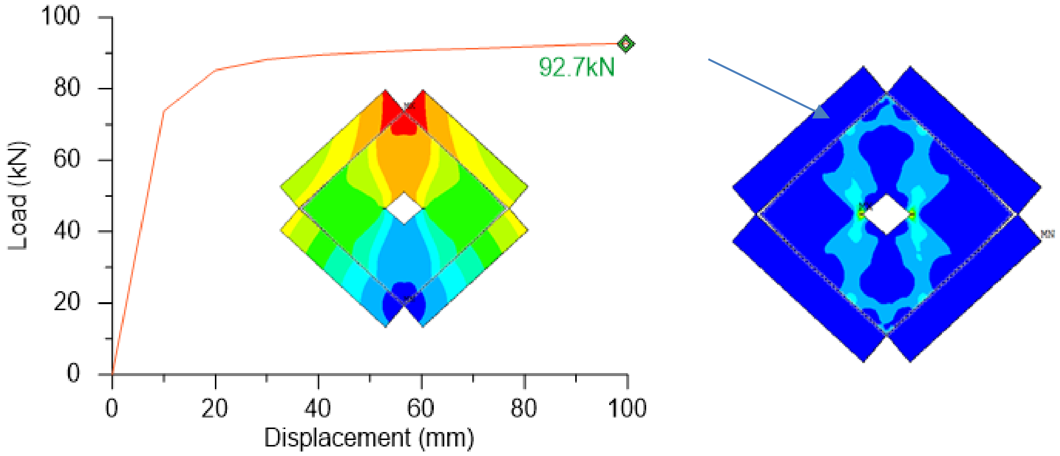


Figure 4.12. Load-Displacement curve, deformation shape, and total mechanical strain diagram of the wall with 20% opening (thickness of steel mesh 3.0mm)

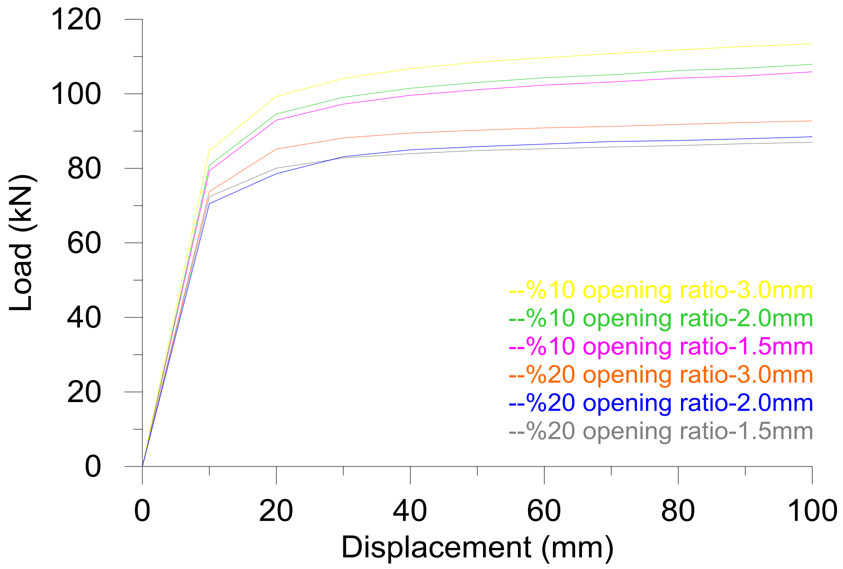


Figure 4.13. Comparative charts of load-displacement curves of walls

According to the results, as the wall window gap increases, the strength of the wall decreases, and the strains are concentrated at the opening corner points. In addition, it was observed that the strength values increased with the increase in the thickness of the expanded steel sheet. Maximum load values and differences between opening ratios are given in Table 4.1. As seen from the table, about an 18% difference occurred between the maximum loads of opening ratios. When comparing the reinforced mesh thickness, about a 2% difference was obtained between 1.5mm and 2.0mm mesh thickness reinforced situations. Also, about a 5% difference was obtained between 1.5mm and 2.0mm mesh thickness reinforced situations. These situations were obtained similarly for 10% and 20% of opening situations.

Table 4.1. Comparison between experimental and FE results

Diff (%)	**10% opening**	***Diff(%)***	**20% opening**	***Diff (%)***
	(1.5mm) 105.9 kN	*17.9*	**(1.5mm)** 86.9 kN	
1.9				*1.8*
	(2.0mm) 107.9 kN	*18.0*	**(2.0mm)** 88.5 kN	
5.1				*4.7*
	(3.0mm) 113.4 kN	*18.2*	**(3.0mm)** 92.7 kN	

CHAPTER 5. CONCLUSIONS

Rational, economic, and innovative applications of masonry imply advanced and continuous research. To this belongs the development and use of reliable numerical models. In particular, the models are of special interest to describe the post-failure behaviour of masonry structures to assess their safety. Reliable models consist of accurate material descriptions in combination with robust solution strategies. In this study, an attempt has been made to provide such a set of models for the analysis of unreinforced and reinforced masonry structures under diagonal loading. Besides, Wall window gap effects on the masonry walls were investigated.

According to the study's findings, existing commercial software may be utilized to efficiently model complex masonry wall use. Within a short time, complex structure analysis can be performed by numerical analysis, which takes a longer time experimentally. The numerical simulations and calculations employed in this study contributed to a better understanding of the structural behaviour of unreinforced and reinforced masonry walls under diagonal compressive load. The following conclusions can be drawn from numerical simulation results:

- Maximum experimental load capacity values of the Reference, MBW 3.0-400, MBW 2.0-150, MBW 3-150 walls were approximately grasped by numerical models.
- Displacement values at the peak load of the MBW 3.0-400 and MBW 3-150 walls were approximately grasped by numerical models.
- Maximum load and displacement couldn’t verify for the Wall MBW 1.5-150.
- The crack pattern of the experimental masonry walls was approximately identified by the numerical models.

- The differences between the experimental and numerical results occur due to the accepted numerical material model, some unknowns, and gaps in the experimental system.

In the last part of the study, the effects of the openings on the strength values of the masonry walls were investigated. Analyses were carried out by removing 10% and 20% of the wall surface area from the middle of the wall. In addition, analyzes were carried out using 1.5mm, 2.0mm, and 3.0mm thick expanded steel sheets for two different opening conditions. The following conclusions can be drawn:

- According to the results, as the wall opening increases, the strength of the wall decreases, and the strains are concentrated at the opening corner points.
- The strength values increased with the increase in the thickness of the expanded steel sheet.
- About 18% difference occurred between the maximum loads of opening ratios of 10% and 20%.
- When comparing the reinforced mesh thickness, about a 2% difference was obtained between 1.5mm and 2.0mm mesh thickness reinforced situations. Also, about a 5% difference was obtained between 1.5mm and 2.0mm mesh thickness reinforced situations. These situations were obtained similarly for 10% and 20% of opening situations.

As a result, calibrated numerical models successfully represent real loading and failure conditions. For this, correct material models are needed. In further studies, different material models can be used to represent the stress-strain graph and the failure mechanism. In addition, in further research, the dynamic behavior of the masonry walls investigated under static loading in this study can be calibrated numerically.

REFERENCES

[1] Mahrebel, H., A., Tarihi yapılarda taşıyıcı sistem özellikleri, hasarlar, onarım ve güçlendirme teknikleri. İstanbul Teknik Üniversitesi, Fen Bilimleri Enstitüsü, İnşaat Mühendisliği Bölümü, Istanbul, Turkey Yüksek Lisans Tezi, 2006.

[2] Budak, A., Uysal, H., Aydın, A., C., Kırsal yapıların deprem karşısındaki davranışı/earthquake behaviour of rural buildings. Atatürk Üniversitesi Ziraat Fakültesi Dergisi., 35(3-4): 209-219, 2004.

[3] Ahmadzai, E., The effect of extended steel sheet thickness used on vertical hole block brick walls under diagonal loads on wall behavior. Sakarya:Sakarya Üniversity, Institute of Science, Master Degree, Sakarya, Turkey, 2020.

[4] Page, A.W., Finite Element Model For Masonry, ASCE J Struct Div. 104: 1267–1285, 1978.

[5] Ali, S, Page, A. W., Concentrated Loads On Solid Masonry Walls-A Parametric Study And Design Recommendations., Proc. Inst. Civ. Eng. 85: 271–289, 1988.

[6] Lourenço, P.B., Rots, J.G., Blaauwendraad, J., March Implementation of an interface cap model for the analysis of masonry structures. In Proc. Euro-C Conf. on Computational Modelling of Concrete Structures (Eds. H. Mang, N. Bicanic and R. de Borst), Innsbruck, Austria, Pineridge Press, UK, 123-134, 1994.

[7] Martini, K., Finite element studies in the two-way out-of-plane failure of unreinforced masonry, in Earthquake Engineering Research Institute (Ed.), Proc. 6th Natl. Conf. Earthq. Eng., Seattle, pp. 1–12, 1998.

[8] A. Brencich, L. Gambarotta, Mechanical response of solid clay brickwork under eccentric loading. Part I: Unreinforced masonry, Mater. Struct. 38: 257–266, 2005.

[9] A. Orduña, Seismic assessment of ancient masonry structures by rigid blocks limit analysis, Ph.D. Thesis, University of Minho, Portugal, 2003.

[10] E. Sacco, A nonlinear homogenization procedure for periodic masonry, Eur. J. Mech. - A/Solids. 28: 209–222, 2009.

[11] Kömürcü, S., Gedikli, A., macro and micro modeling of the unreinforced masonry shear walls. III. International Conference on Engineering and Natural Science., pp. 790-797, 2017.

[12] Alyavuz, B., Anıl, Ö., Bulut, N., Nonlinear finite element analysis of masonry wall strengthened with CFRP strips. Advanced Composite Materials., 25(2): 159-175, 2016.

[13] D.I.N., DIN EN 772 Prüfverfahren für Mauersteine. Deutsche Norm: Deutsches Institut für Normung, Germany, 2011.

[14] D.I.N., DIN EN 1015 Prüfverfahren für Mörtel für Mauerwerk. Deutsches Norm . Germany, 2007..

[15] D.I.N., DIN EN 1052 Prüfverfahren für Mauerwerk. Deutsche Norm, Deutsches Institut für Normung., Germany, 1998.

[16] D.I.N., DIN 1053 Mauerwerk. Deutschland: Deutsches Institut für Normung, Germany, 1996.

[17] Lourenço, P.B., Analysis of masonry structures with interface elements. Theory and applications, Delft University of Technology, Faculty of Civil Engineering, Delft, Netherlands,1994.

[18] Grabowski, S., ESECMaSE - Material properties for the test in WP 7 and 8 and the verification of the design model of WP 4. Munich, Ger ESECMaSETechnische Universität München, 2005.

[19] Charry, J. A., Estudio experimental del comportamiento de paredes de obra de fábrica de ladrillo ante la acción de cargas laterales. Barcelona, España: Universitat Politècnica de Catalunya, 2010.

[20] Barbosa, C.S., Hanai, J.B., Strength, and deformability of hollow concrete blocks: correlation of block and cylindrical sample test results. Revista IBRACON de Estruturas e Materiais, 2(1): 85-99, 2009.

[21] Bergami, A. V., Implementation and experimental verification of models for nonlinear analysis of masonry infilled R.C. frames. PhD Thesis, Università degli Studi Roma Tre, Roma, Italia, 2007.

[22] Kaushik, H.B., Rai, D.C., Jain, S.K., Stress-strain characteristics of clay brick masonry under uniaxial compression. Journal of Materials in Civil Engineering, 19(9): 728-739, 2007.

[23] Irmschler, J., Schubert, P., Jäger, W., Mauerwerk Kalender, Ernst & Sohn, Germany, 2004.

[24] Campbell Barraza, J.A., Numerical model for nonlinear analysis of masonry walls, Ph.D. Thesis, Aachen University: Mainz, Germany, 2012.

[25] Tomazevic, M., Earthquake-Resistant Design of Masonry Buildings. Imperial College Press London, England, 1999.

[26] Page, A., The biaxial compressive strength of brick masonry. Proceedings of Institution of Civil Engineers, London, England: Institution of Civil Engineers,71(3): 893-906, 1981.

[27] Anthoine, A, In-plane behavior of masonry: A literature review. Commission of the European Communities, Luxemburg, 1992.

[28] Masonry Society., Masonry designer's guide-Fourth edition, based on building code requirements for masonry structures. The Masonry Society, Colorado, U.S.A, 2003.

[29] Klingner, R., Especificación, Diseño y Cálculo de Mampostería. Simposio sobre Diseño en Mampostería. Instituto Chileno del Cemento y del Hormigón, Santiago, Chile, 2003.

[30] ACI., 318-08 Building code requirements for structural concrete and commentary. American Concrete Institute., USA, 2008.

[31] CEN., Eurocode 6 - Design of Masonry Structures. European Committee for Standardization, Brussels, Belgium, 2005.

[32] CEN., Eurocode 0 - Basis of Structural Design. European Committee for Standardization, Brussels, Belgium, 2005.

[33] Blondet, M., Construction and maintenance of masonry houses. Pontificia Universidad Católica de Perú, Lima, Perú, 2005.

[34] D.I.N., Eurocode 6: Bemessung und Konstruktion von Mauerwerksbauten. Deutsches Insitut für Normung, Germany, 2006.

[35] I.N.N., NCh2123.Of97 Albañilería Armada-Requisitos de Diseño Estructural. Chile: Instituto Nacional de Normalización, Chile, 1997.

[36] I.N.N., NCh1928.Of93 Albañilería Reforzada-Requisitos de Diseño Estructural. Norma Chilena Oficial . Chile: Instituto Nacional de Normalización, Chile, 1993.

[37] Kalali A., Kabir M. Z., Experimental response of double-wythe masonry panels strengthened with glass fiber reinforced polymers subjected to diagonal compression tests, Engineering Structures, 39: 24-37, 2012.

[38] Triantafillou, T.C., Strengthening of masonry structures using epoxy-bonded FRP laminates, ASCE Journal of Composites for Construction, 2: 96- 104, 1998.

[39] Montes, P. F. A., Behaviour of a hemispherical dome subjected to wind loading, Journal of Wind Engineering and Industrial Aerodynamics, 89: 911-924, 2001.

[40] Rosenthal, I., Precast ferrocement columns, Journal of Ferrocement, 16: 273-284, 1986.

[41] Winokur, A., Rosenthal, I., Ferrocement in centrally loaded compression elements, Journal of Ferrocement, 12: 357-364, 1982.

[42] Razvi S., Saatcioglu, M., Confinement of reinforced concrete columns with welded wire fabric, ACI Structural Journal, 86: 615-623, 1989.

[43] Mourad S. M., Shannag, M. J., Repair and strengthening of reinforced concrete square columns using ferrocement jackets, Cement & Concrete Composites, 34: 288-294, 2012.

[44] Kaushik, S., Prakash A., Singh, A., Inelastic buckling of ferrocement encased columns, in 5th International Symposium on Ferrocement, London, UK, 1990.

[45] Ahmed, T., Ali, S., Choudhury, J., Experimental study of ferrocement as a retrofit material for masonry columns, In 5th International Symposium on Ferrocement, London, UK, 1990.

[46] Nedwell, P., Ramesh, M., Tabhanaki, R. S., Investigation into the repair of short square columns using ferrocement, In 5th International Symposium on Ferrocement, London, UK, 1990.

[47] Mustafaraj, E., Yardım, Y., Usage of ferrocement jacketing for strengthening of damaged unreinforced masonry (URM) walls, 3rd International Balkans Conference on Challenges of Civil Engineering, 3-BCCCE, 19-21 May 2016, Epoka University, Tirana, Albania, p. 153-163, 2016.

[48] ACI., State-of-the-art Report on Fiber Reinforced, Concrete American Concrete Institute, Farmington Hill, USA, 2002.

[49] Jabarov, M., Kozharinov, S., Lunyov, A., Strengthening of damaged masonry by reinforced mortar layers, In 7th WCEE, Istanbul, Turkey, 1980.

[50] Papanicolaou, C., Triantafillou, T., Lekka, M., Externally bonded grids as strengthening and seismic retrofitting materials for masonry panels, Construction Building Materials, 25(2): 504-514, 2001.

[51] Jafarov, O., Lifli polimerle güçlendirilmiş yığma duvarların modellenmesi. Yıldız Teknik Üniversitesi, Fen Bilimleri Enstitüsü, İnşaat Mühendisliği Bölümü, Doktora Tezi, 2012.

[52] Lourenco PB. Computational strategies for masonry structures//Ph. D. Thesis. Delft University of Technology. Delft. The Netherlands, 1996.1

[53] Lourenço PB. Computations on historic masonry structures. Progress in Structural Engineering and Materials. 2002 Jul;4(3):301-19.2

[54] ANSYS Inc. Swanson analysis system. Pennsylvania, U.S.A.3

[55] Othman, B., Yaman, Z., Numerical analysis of Masonry brick walls under diagonal compression load by Ansys. Academician Globe: Inderscience Research, 2(08): 20-29, 2021.

[56] Othman, B., Yaman, Z., Finite element analysis of masonry walls reinforced with expanded steel plates. International Research Journal of Advanced Science, 2(2): 27-32, 2021.

RESUME

Name Surname: Bawar Othman RASUL

EDUCATION

Degree	School	Graduation Year
Master	T.C. Sakarya University/ Department of Civil Engineering	Continue
Degree	University of Sulaimaniyah/ Department of Civil Engineering	2018
High School	Harem High School	2013

JOB EXPERIENCE

Year	Place	Position
2021-Still	IRAQ	Engineer
2018-2019	Betwin City	Ass.Engineer

FOREIGN LANGUAGE

English, Turkish

PRODUCTS (articles, papers, projects, etc.)

1. Othman, B., Yaman, Z., Numerical analysis of Masonry brick walls under diagonal compression load by Ansys. Academician Globe: Inderscience Research, 2(08): 20-29, 2021.

2. Othman, B., Yaman, Z., Finite element analysis of masonry walls reinforced with expanded steel plates. International Research Journal of Advanced Science, 2(2): 27-32, 2021.

HOBBIES

Reading, Writing, Physical Exercises (Fitness and MMA).