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A Comprehensive Review on Unreinforced and Reinforced Masonry Structures Modeling Strategies

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ABSTRACT

Masonry structures were the oldest known construction system since the dawn of ancient civilizations and have a great width between all the structures; it was designed commonly for the past 100 years worldwide. As it was commonly effective to resist compressive stresses, despite its weak tensile strength. From a geometrical point of view masonry was generally able to withstand lateral loads such as wind, seismic, and blast loads. In the last decades, the scientific interest towards fiber-reinforced polymers (FRP) requirements for masonry reinforcement on one side, especially in highly diversified Italian architectural heritage. The reinforcing technique is dependent on a high-strength fiber-reinforced polymers (FRP) network embedded into inorganic matrices, which recently was promoted for seismic modifying of brickwork buildings. The modeling techniques for modeling masonry could be classified into three types: detailed micro-modeling, simplified micro-modeling, and macro-modeling. In this paper the authors have reviewed some unreinforced and reinforced masonry structure modeling strategies and methods, mechanical behavior, and the influencing factors, now available in the technical literature.

1. Introduction

Masonry was a structural composite material, and was usually described as bearing walls and infill walls [1]. Reinforced masonry was one of the oldest structure materials used by a human, as it was evident from the archeological remains of Egyptians and Greeks. This type of dense masonry material could resist large compressive forces and remains durable, despite its weak tensile strength [2]. Reinforced masonry was suggested in the 1920s in Japan, the USA, and India for reinforcing the tensile strength of materials. The first code was developed for reinforced masonry in the USA after the1933 as a result of the impact seismic on unreinforced Masonry [3, 4, 5].

Drysdale and Hamid [6] presented a study of the behavior of concrete masonry under axial compression, in which there were 146 samples of concrete masonry prisms. The results cleared that the grouted masonry strength was not largely influenced by the mortar joint. As it was observed that the lateral

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tensile strains in the grouted masonry similar to vertical compression strain levels in the grout by the way in which extensive micro cracking and greatly increased Poisson's ratios were bonded. Also, the results showed that the 3-course prism was better compared to the 2-course prism for representing the.

Tan and Patoary [7] Presented an experimental and analytical study on 13 models of masonry walls strengthened using three different fiber reinforced polymers (FRP) techniques. The FRP used in this study were (glass fiber reinforced polymers (GFRP), carbon fiber reinforced polymers (CFRP), and fiberglass woven with three different systems). The test results indicated that the strengthening of masonry led to an increase in the load-bearing capacity with an increase in the thickness of the FRP. Four different patterns of failure were (punching shear, flexural bond failure, flexural failure and FRP rupture) and were observed on all walls.

Maleki et al. [8] Presented an evaluation of the capability of layered finite element models using a method of smeared crack to capture the performance of fully grouted reinforced masonry shear walls subject to loading. The wall was fully grouted and distributed uniformly horizontally and vertically in both directions. The experimental results indicated that there was a significant similarity with the numerical results of failure patterns for its response pre-and post-peak.

Mohamed et al. [9] presented an experimental study on fully reinforced shear walls. In this study, the researchers conducted a comparison between glass fiber reinforced polymers and steel-reinforced shear walls, and this research aimed to define the behavior of masonry under seismic loads and methods of masonry modeling. All the specimens were reinforced with glass fiber reinforced polymers bars to resist flexure, shear, and sliding shear deformation. The test results indicated that the FRP-reinforced were higher than the steel-reinforced shear walls in terms of drift, deformability, and failure patterns of masonry.

Sandeep et al. [10] presented an analytical study on concrete masonry prisms with and without reinforcement under compressive strength. Concrete masonry prisms depend on some properties such as unit strength, mortar strength, and bonding strength. The 3D micro modeling system used ANSYS to estimate the strength failure and crack pattern of masonry was to predict the nonlinear studies. The test results indicated that ultimate failure of the compressive stress with and without reinforced masonry about 85% of experimental tests.

Saghafi et al. [11] Presented an analytical study on the unreinforced masonry and reinforced masonry by carbon fiber reinforced polymers sheets under the effect of vertical loads and in-plane shear using ANSYS. The test results showed that the numerical modeling curve was more rigidity than experimental curves and the bearing capacity showed 0.72 and 99.28 percentage error and precision, respectively because of calibration of the finite element model using ANSYS compared with experimental results.

Mohamed et al. [12] presented an experimental study on fully reinforced shear walls. All specimens were reinforced using glass fiber reinforced polymers bars and steel bars to investigate the strength and drift in requirements. In this study, the researchers conducted a comparison between glass fiber reinforced polymers shear walls and steel-reinforced shear walls. The test study consists of 4 samples of masonry shear wall prisms, only reinforced with steel bars and the others reinforced with glass fiber reinforced polymers bars under quasi-static reversed cyclic lateral loading. The test results showed that the recoverable and self-catering behavior reach to allowable drift before damage happens and could be achieving a maximum drift meeting most building codes. As it was observed that the energy dissipation levels by relatively small residual forces compared to the steel-reinforced wall were acceptable. It offers the promising results impetus for masonry shear walls reinforced with GFRP in lateral load systems.

Ahmad et al. [13] Presented an experimental and analytical study on 30 models of cantilever shear wall specimens under reversed cyclic loading. Based on test results, the relationship between key design parameters and the nonlinear hysteretic response of the specimens was evaluated. The test results indicated the specimens exhibited flexural behavior, as intended. Increasing flexural capacity and initial stiffness led to an increase in the axial load and vertical reinforcement ratio, while increasing displacement ductility led to a decrease in the axial load. Aspect ratio led to an increase in displacement at failure up to 80% maximum loads. In addition, the strength of walls with lower aspect was suffered more than the walls with higher aspect ratios.

Singh and Munjal [14] presented an experimental study of the influence of flexural behavior of the response of masonry beams under four-point bending test, in which there were 12 samples of masonry beams of size (150 × 230 x 1300) mm. Eight specimens were reinforced using near surface mounted (NSM) Fiber Reinforced Polymer (FRP) bars to investigate the failure modes, load-deflection, and load-strain responses. In which four other specimens were not reinforced to act as a benchmark. In this study, clay burnt bricks were used in each beam; two layers of clay-burnt bricks were inserted having five brick units in each layer with four mortar joints. The test results indicated that the NSM FRP rebar led to an increase in the load-carrying capacity with an increase in the ductility of masonry beams. It was observed that the masonry beams showed ductile performance so could be used as structural beams.

Sandoval et al. [15] presented an experimental and analytical study on eight models of the masonry shear walls under reversed cyclic loading. All specimens were built using clay bricks and reinforced horizontally. The three parameters studied were aspect ratio, axial loads, and horizontal reinforcement ratio. The ductility results indicated an effect on the axial load more important than the effect on the aspect ratio, which value ranges between (2.5 to 5.5). The ultimate lateral force of the average drift for each wall of its value ranges between (0.2 to 0.62%).

Xu et al. [16] Presented an experimental and numerical study on five full-scale fully-grouted prefabricated reinforced masonry shear walls (PRMSWs) under a reversed lateral cyclic test and simulated by ABAQUS. The test results showed that compared to traditional reinforced masonry shear walls (RMSWs) under the same axial compression; the flexural capacity of precast walls has increased by 10%. Flexural failure pattern showed suitable deformation capacity, and displacement ductility was corresponding with degradation of force the value between (15 to 4.9%). Specimens with concentrated vertical rebar at the sides led to relatively higher load capacity and less ductility compared to the walls with evenly distributed rebar.

Abdellatif et al. [17] Presented an experimental and analytical study on fully-grouted strengthened masonry shear wall, as it types (rectangular, flanged or end-confined) to study their behavior under horizontal force. Thus, the seismic response factors were estimated on reinforced masonry: ductility capacity, energy dissipation, stiffness degradation and strength. The displacement ductility improved for flanged structures more than rectangular structures. End-confined masonry walls are more significant compared to adding flanged ones.

Koutras and Shing [18] Presented an analytical study on finite-element modeling for the analysis of reinforced concrete masonry walls under seismic loading. It was embedded with the smeared-crack shell elements with cohesive discrete-crack interface elements to capture crushing and tensile fracture of masonry. Simulating the bond-slip and dowel-action was highly influenced by the way in which the beam elements were bonded to the shell elements through interface elements. On the other hand, beam elements embedded geometric as well as material nonlinearity were used to capture the yielding, buckling, and fracture of the reinforcing bars. The test results showed that the quasi-static cyclic tests on reinforced masonry walls well with results from shake-table tests on reinforced masonry building systems the modeling scheme were validated. The material models and interface elements were modeled using finite element analysis programs, in which an element removal scheme was presented to enhance the robustness and accuracy of the numerical computation through these programs.

Cheng et al. [19] Presented an experimental study on two full-scale, single-stories, fully grouted for reinforced masonry wall specimens under quasi-static test. Two samples of masonry wall were built, the first specimen each specimen has two T-walls as the seismic force strength elements and a stiff roof diaphragm. The second specimen has six additional planar walls perpendicular to the direction of shaking. The test results were showing that the first specimen compared with the second specimen has a higher lateral load and had first cracks observed at a higher intensity ground motion. For T-walls it was shown initially flexural cracks with the yielding of the vertical reinforcement during earthquake motion and then diagonal shear cracks originated from each side of the wall. It was also observed specimens maximum roof drift ratios of 17% and 13%, without collapsing. Specimen second also exhibited a much lower drift ratio at comparable ground motion levels.

Cattari et al. [20] this search presented a comprehensive review of critical aspects of nonlinear modeling for evaluating the seismic response of masonry, in which it was concentrated on issues relevant to engineering practice. Numerical models were one of the sufficiently effective applied tools to support the seismic assessment of current masonry; however, it was not accurate in describing the behavior of masonry structures. In fact, these structures have highly complicated architectural designs, different masonry types, and various structural solutions, the available knowledge of numerical modeling was insufficient, and necessitating extra care was required in numerical modeling. Some researchers have shown that the significant scientific advancements obtained in the 1970s were the first applications of non-linear seismic analysis on masonry structures were considered.

2. Theory of structural masonry

2.1 Unreinforced masonry

Unreinforced masonry (URM) was usually found all over the world. Although it suffered from damage during seismic because of its high weight, low tensile strength, and confined ductility. There was also seismic damage in many countries that had a low possibility. For example, South Korea had a raised rate of 54.3% in the recent three years. Unreinforced masonry was designed commonly in the world before developing its guidelines to resist seismic loads. Thus, improving the load strength of unreinforced masonry by reinforcing the newly constructed buildings and retrofitting the existing damaged or undamaged buildings is of considerable significance. Thus, correct predictions of the unreinforced masonry nonlinear behavior were essential for investigating its seismic performance and its design [17, 21, 22]. The masonry of a structure exposed to horizontal loading commonly presented two types of failure. The first case was an out-of-plane failure in which cracks showed at length the horizontal mortar bed joints. The second case was an in-plane failure, generally characterized by a diagonal tension failure with crushing in compressive [23]. Unreinforced masonry was a composite material made of bricks with bed joints [24]. The principal mechanisms and failure modes of masonry were classified into three types: (a) Shear failure, in this situation, strength masonry deteriorated under seismic loads, leading to partially crushing of the masonry with complete loss of strength and was defined as ductile. On the other hand, shear failure occurs when the horizontal bars were not enough to transfer the tensile stresses with continually diagonal cracks which led to acceptable failure and was defined as a brittle [2]. Matsumura[25]; Okamoto et al [26] found that the masonry walls with low aspect ratios showed shear strengths at failure higher than those for a much slender masonry. As it was also observed that the shear strength played as important role of arching action in masonry walls with low aspect ratios, in which a large portion of the shear by compact zones which transferred large compression stresses and was defined as compression struts; (b) Sliding failure, in this situation, researchers found poor friction coefficient, poor quality mortar, seismic loads and the low vertical loads compared to the lateral loads that caused this type of failure. Thus, horizontal cracks were shown in the mortar joints in were sliding plane on the whole length of the masonry walls [27]; (c) Rocking failure and toe-crushing failure, in this situation, the shear resistance was improved which the toe crushing depend on the level of the applied normal force, as shown in Fig 1. Mechanics will be activated depending on the wall geometry (height/width ratio), quality of materials, the ratio of the compression shear stresses (σ/τ), and boundary restraints [23].

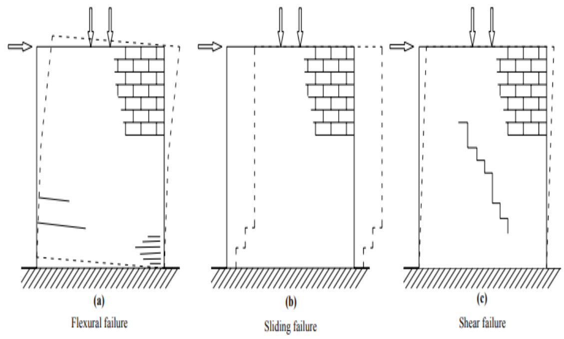


Fig.1.The failure modes of masonry wall [23].

2.2 Reinforced masonry

Reinforced masonry (RM) was a structural system consisting of several units that were filled with concrete or grout to anchor steel bars inside them. There were two major types of reinforced masonry: the first type was defined as the reinforced masonry horizontally in the cement mortar joint between units. In this state, the serviceability limit case of the masonry could be preserved. The second type which was defined as the reinforced masonry vertically, thus hollow units were used filled with concrete or grout to ensure the stress transfer between steel and masonry, as shown in Fig 2 [28, 29].

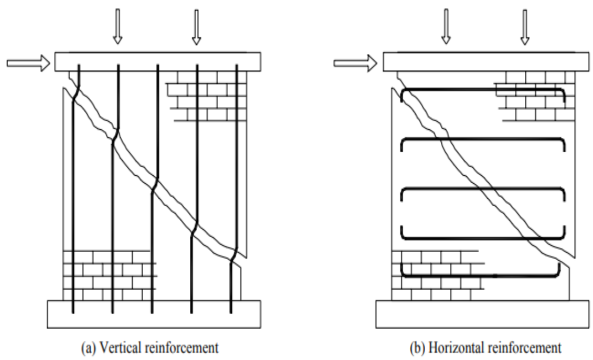


Fig.2. Role of reinforcement in resisting masonry shears Failure.

The use of joint reinforcement reinforced the ability of walls to resist lateral loading [10]. The primary mechanism of shear failure worked when the masonry was reinforced vertically and horizontally .The reinforced masonry featured both in-plane and out-of-plane with shear and bending capacities. The reinforced masonry also affected the factor of safety of the building due to the ductility rate of steel bars

[30]. As it was cleared in experimental and analysis tests, the behavior of reinforced masonry was quite similar to reinforced concrete structural elements [31]. Two basic types of RM exist: (a) Bed-joint RM, in this situation, reinforcement was by two wires welded to a persistent curvy cross wire to form a lattice truss. There are many types of joint reinforcement involving welded wire fabric, deformed reinforcing wire, and ladder or truss type joint reinforcement, as shown in Fig 3. The method of bed joint reinforcement depends on the anchoring of steel bars within the mortar bed joints, which beforehand excavated for a few centimeters and then refilled by a repointing material. It was observed that bed-joint reinforcement controlled the dispersion and width of cracks at the serviceability [28, 32]; (b) Both-direction RM, in this situation, there were two main types of walls: single-leaf walls and multi-leaf walls. Firstly, single-leaf walls vertical bars were anchored within the cavity of the concrete or masonry blocks filled by grout, while the horizontal bars were within the mortar joints. Secondly, the two-leaf wall's two-directional reinforcement was within the two leaves of the wall cavity by grout. Horizontal reinforcement was located anchored in the bed joints or in the bond beam units, as shown in Fig 4. Reinforced masonry could be divided into the following classes: (a) reinforced cavity masonry, in this situation, two leaves of a cavity wall were tied with wall ties designed to endure horizontal loads due to seismic, masonry units must be placed in running or stacked bonds. This vertically stacked was not allowed in earthquake zones; (b) Reinforced solid masonry, in this situation, bonding single-leaf walls are mainly applied externally for land retaining buildings. It was possible to reinforce the brickwork using horizontal wires [28]; (c) Reinforced hollow unit masonry, in this situation, reinforced hollow unit brickwork featured for building in areas of high seismic due to the continuity development into the grout core and the ease of laying horizontal reinforcement bars the vertical or horizontal reinforcing bars were but to improve the tensile strength of masonry [28, 33]; (d) Reinforced grouted masonry, in this situation; the steel bars were tied to the masonry by grout as one system of strength loads. Composite walls contain two wythes of masonry with a solid grouted collar joint with or without steel bars; (e) Reinforced pocket masonry, in this situation, the bricks were placed the so called "quetta bond". The vertical bars or stirrups must be placed in the middle of the masonry and filled out with concrete or grout, while the horizontal bars were embedded within the bed joint. This type of reinforced masonry was similar to small columns joined together, as shown in Fig 5 [28].

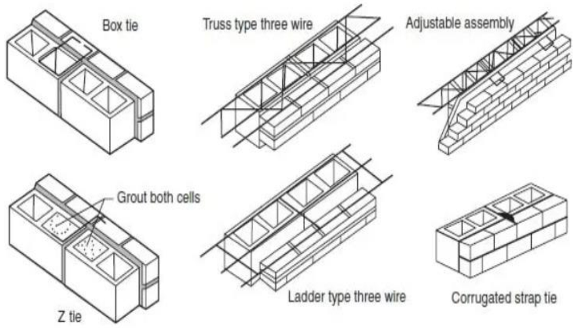


Fig.3. Joint Reinforcement Applications in Masonry

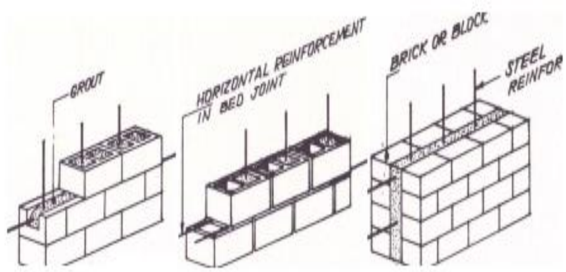


Fig.4. Placing of reinforcement in masonry

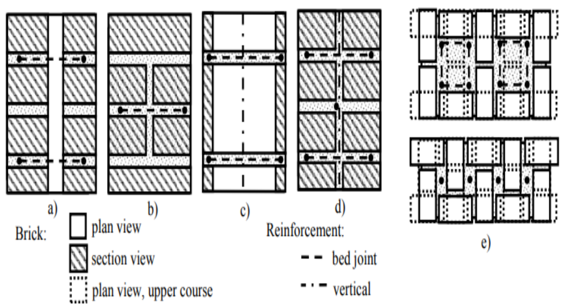


Fig.5. a) Reinforced cavity wall, b) Reinforced solid masonry, c) Reinforced hollow unit masonry, d) Reinforced grouted masonry, e) Reinforced pocket type wall.

3. Factors affecting masonry

Load-deformation response and failures of the masonry were affected by the following factors; (a) reinforcement, the ratio of reinforcement steel bars played an important role in the behavior of reinforced masonry. Alcocer and Meli [34] Found that the horizontal steel bars increase the shear capacity of brick walls up to 30% compared with the unreinforced walls. Fattal and Todd [35] Found that the quantity of horizontal reinforcement did not affect the primitive hardness of the wall despite the reinforced masonry walls resisting more forces than the unreinforced masonry walls. Xu et al. [16] Found that the horizontal and vertical reinforcement ratios for all walls were about 0.60%, 0.29%, respectively, and these ratios were considered the minimum reinforcement ratios of reinforced masonry. Sandoval et al. [15] Found the increase in horizontal reinforcement ratio led to a large increase in shear capacity and a slight increase in the lateral drift. Ghanern and Salarn [36] Found that the cracked deformations in addition to the final capacity of forced wall increased to 0.2% by increasing the horizontal reinforcement ratio; (b) Axial compressive, Fattal and Todd [35]; Ghanern and Salarn [36] Found that the increase in vertical load led to an increase in strength, ductility, and this increase improved the bond strength between mortar and masonry units. In addition, the large increase in axial compressive changed the failure wall from flexure to shear. Angelillo [37] Found that allowable code values for the axial compressive affected by remediating and age of properties of strength masonry; (c) Length to width ratio (H/L), Sandoval et al. [15] Found that increasing the aspect ratio led to the decrease of maximum lateral load. The aspect ratio of walls (H/L) played a significant role in the failure modes, as shown in Fig 6. For squat walls of (H/L=0.6), the shear that results from the flexural behavior mostly fails by diagonal cracking. For tall walls, a 45° crack happens in the bottom part of the walls showing flexural failure. Four square walls of (H/L=1), the diagonal crack square arises at the high corner of the wall and meets the base which the entire area by the compressive becomes effective in providing shear strength at the compression toe; (b) material properties, masonry properties were heavily depend on the characteristics of their constituents. For bricks, the basic units were composed of blocks manufactured by block factories that follow a unified modeling system subscribed to by the whole industry. There were some standardized forms and sizes used for various masonry units: concrete block, solid concrete, brick, clay block, solid or cored clay brick, clay tile, sand-lime units, and adobe units. The size of the large bricks reduces the number of mortar joints that were the weakest parts of the construction. The reduction in mortar bed joints will probably increase the strength and make the bricks economical. For mortar, all standard test samples were modeled into steel templates, thus the water absorption effect is neglected because it did not represent the composite mortar. The main aim of using mortar is to connect concrete masonry units to steel bars [38, 39].

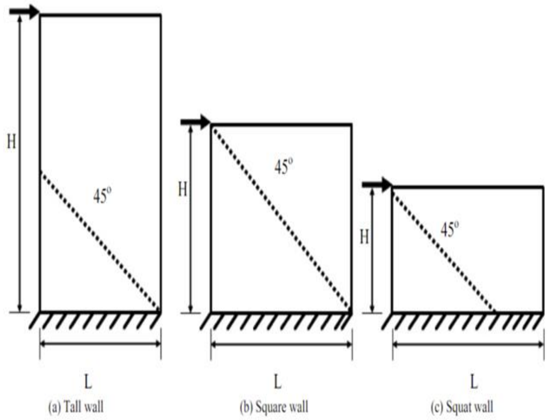


Fig.6. Direction of diagonal cracks in masonry shears walls [38].

4. Mechanical behavior of masonry

The masonry mechanical properties were depending on the properties consisting of elements of bricks and mortar [40]. The masonry composed of (brick and mortar) it was usually described by quasi-brittle tensile and compressive responses [41]. Characterized a very low tensile strength and this property was so important that it determined the shape of ancient structures [42]. The masonry mechanical behavior usually was determined for stiffness, strength, and ductility using two methods, namely variable scales, classically the scale of the material, and structural element. The studies developed in Italy have created a series of parameters that attempt to determine the level of construction bases by measuring the deviation of the geometric and mechanical properties of the walls. The masonry mechanical properties were defined as softening; it was a gradual loss of mechanical strength with a continuous increase in deformation forces.

For compressive failure, the softening was highly dependent on the crushing processes. Shear and tensile strength values were increased up to 175%, while the compressive strength was initially maintained. The mid-zone of the wall was resisting the lateral force for larger the result of increased shear bond strength, therefore of compressive failure predicted at corners. The masonry compressive strength was usually obtained from experimental work and impacted by mortar, units, and grout. Drysdale and Hamid [6] Found that the circular bars significantly enhanced the compressive strength of masonry by a small portion of 2%, while plate reinforcement structure continued to increase by 15% [31, 41, 43]. The masonry compressive strength was smaller than the uniaxial compressive strength of bricks due to the further tensile stresses equivalent to the mortar joint [28]. Shear failure was observed in the softening process, as it was related to the deterioration of the cohesive frictional [38]. Shear strength was defined as the masonry mechanical property and describes masonry strength as in-plane horizontal forces in the wall collapse in shear [44]. The shear behavior of strengthened masonry was also dependent on reinforced concrete masonry being wholly grouted and strengthened-e.g. strengthened masonry beams [37, 43]. For tensile strength, the masonry tensile strength plays a significant role in the failure of the masonry shear walls, so some researchers have investigated the tensile strength of unreinforced masonry [31]. Direct tensile stresses of masonry were observed as the result of in-plane loading impacts, as shown in Fig 7. These may be because of wind, gravity loads, and thermal or moisture movements. Flexural tensile strength of clay masonry in the force direction is ranged 2.0 to 0.8 N/mm^2. For direct tensile stresses, the strength depended on the properties of the adsorption bricks and the type of mortar used [45]. The code allowable absolute values for tensile stresses were 0.7 kg/cm^2 for tensile normal in the mortar joint and 1.4 kg/cm^2 for tensile parallel to the mortar joint running bond [28]. For modulus of elasticity (E_m), FRP modulus of elasticity will approximately one-third of the modulus of steel to one and a quarter times of steel [46]. Modulus of elasticity was calculated from the characteristic compressive strength of masonry (f_m).

$$E_m = x\,f_m \tag{1}$$

Where:

'x' was a factor that varied from 500 to 1000 depending upon the type of mortar and bricks used in Masonry [31]. The stress-strain characteristics usually were treated as a linear elastic material, although tests suggest that the stress-strain relationship was maybe parabolic, and different formulas have been suggested to determine young's modulus. For estimating long-term deformations a reduced value of (E_m) should be used, in the region of one-half to one-third of that given by equation (2). Wilson and Varkey [23] Found that stainless steel confining plates in mortar beds results in a more gradual falling branch to the stress-strain curve.

$$E_m = 700\,\sigma_c' \tag{2}$$

Where:

'σ_c'' is the crushing strength of the masonry. This value will apply up to about 75% of the ultimate strength [44].

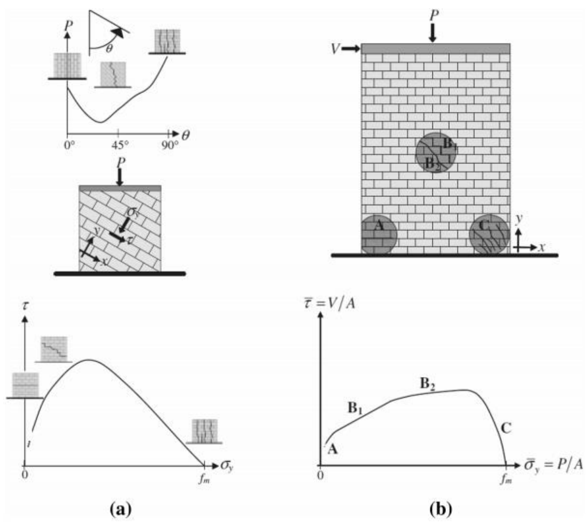


Fig.7. Failure modes and limit domains for masonry: a) Scale of the material; b) Scale of the pier from [41].

5. Finite element (FE) modeling strategies

5.1 FE modeling strategies for masonry

The modeling of masonry was used for determining its structural behavior or for understanding its material behavior [43]. Masonry was a composite material composed of two materials based on the characteristics of the masonry unit bricks and mortar [47]. Generally, some research concentrated on two numerical methods of masonry, namely micro-modeling as a separate material and macro-modeling as a composite material [48]. Evaluating masonry and design requires very stringent numerical models. During seismic the non-linear behavior of masonry was significantly dependent on modeling approaches, powerful numerical instruments, and masonry elements [49]. Final element models were developed to define the strength, deformation, and stress distribution for masonry walls. There were several modeling techniques for modeling walls constituting the masonry structures, as shown in Fig 8.

- *Detailed micro-modeling:*

In this situation, micro-modeling was suitable for analyzing the structural behavior used in small masonry, and it required a long central processing unit (CPU) time in models with a large number of elements [1]. Each element of masonry as units and mortar should be defined for this type of analysis. Thus, the mortar interfaces should include all the collapse mechanisms of masonry, namely crushing, sliding, and cracking of the mortar bed and units. Micro-modeling required more computational effort, but it gave us the best understanding of the local behavior of masonry [42]. Masonry units were defined as continuum elements, while mortar joints and unit-mortar interfaces as discontinuous elements [47].

- *Simplified micro-modeling:*

In this situation, reinforced masonry was defined as a set of elastic blocks connected with potential fracture/slip lines in the joints [42]. Expanded units were also defined as continuum elements, while mortar joints and unit-mortar interface as discontinuous elements [50].

- *Macro-modeling:*

In this situation, units and mortars together were modeled as continuum material. There was a massive effort to bond the micro and the macro modeling methods by homogenization techniques [50]. The macro-modeling was characterized with less computational effort compared to the micro-elements. Several massive masonry was used which showed the relationship between averages stresses and average strains, which it was accepted. Strategic categorization of masonry depends on how masonry structures are conceived and modeled. The principal modeling strategy categories of masonry were classified into three types [49]: (a) Block-based models, in this situation, masonry modeling was used of a block-by-block method taking into account the actual construction texture. Blocking behavior was defined as solid or deformable and could be represented mechanically with many suitable formulas; (b) Continuum models, masonry materials were modeled deformable continuum without distinction among both blocks and layers of mortar. Direct approaches and multi-scale homogenization procedures could describe the constituent law adopted for the material; (c) Geometry-based models, the masonry was modeling as a solid body. Therefore, masonry geometry provides the main inputs to modeling strategies. These methods usually implement some study-based solutions which could be depending on the static or dynamic theories [41].

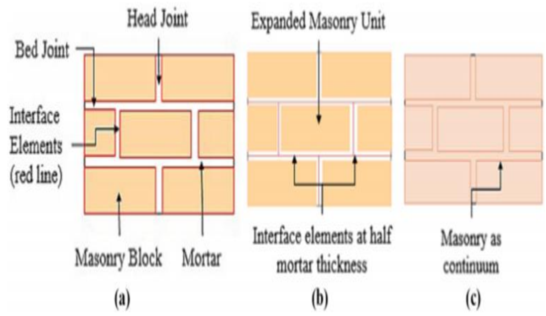


Fig.8. Modeling strategies of masonry structures: a) detailed micro-modeling; b) simplified micro-modeling; and c) macro-modeling [51].

5.2 FE modeling of interfaces between bricks and mortars

Masonry structures were divided into interior elements of bricks in which these elements represented the mortar interfaces or internal brick. The mortar thickness and the brick–mortar interfaces were lumped into zero-thickness plane elements of 16 nodes and 4 gauss points while the dimensions of the brick units were expanded to keep the geometry of a masonry structure unchanged. These elements were inserted between two adjacent units in the horizontal or the vertical direction. These elements were so designed that all three failure modes can be captured, [24, 48]. Several modeling of mortar and interface approaches were discussed in this section, as shown in Fig 9.

- *Crack modeling approaches:*

In this situation, constitutive simulations were developed using the smeared crack method as one of the methods used to model the cracking of mortar in the finite element program. Therefore, the cracking was analyzed together in a connected medium and two significant ideas of decomposed strain and total strain. Although, the smeared crack approaches his several difficulties as the geometric mesh size, diagonal shear failure, directional distractions, and stress [48].

- *Plasticity-based discrete constitutive models:*

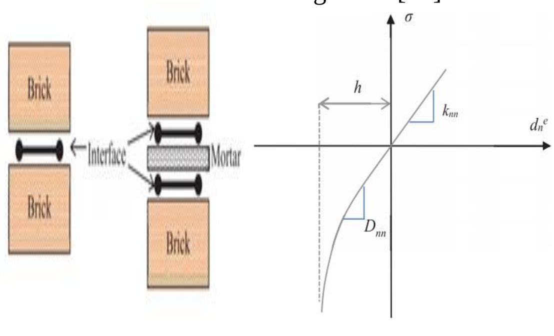
In this situation, the surface models were classified mathematically into two types: single-yield and multi-yield. Single-yield and multi-yield were explained clearly in this reference. Some researchers have analyzed plasticity-based discrete models and displacement between the upper face and the down face for elasticity and plasticity [48].

- *Fracture mechanics-based joint constitutive models:*

In this situation, some researchers Cervenka [52] have developed a joint model for fracture mechanics: a hyperbolic function and two variables that describe a yielding surface. Also, the plastic displacement of the same researchers was determined by the plastic displacement rates. The models based on crack mechanics resulting from the were modified and combined with friction models to discuss cyclic loading to develop zero-thickness interfaces by Puntel et al. [53] Models for nonlinear fracture mechanics, fictitious crack models, and cracking energy were proposed through two material parameters to control tensile strength and cohesion by Carol et al. [54].

- *Damage-based constitutive models:*

In this situation, some researchers Gambarotta and Lagomarsino [55] described the mortar model using frictional and rigidity failure below compressive stresses and brittle performance below tensile stresses. As a result, the horizontal stress with horizontal relative displacement curves was symmetrical to the test results. Stretching and the effect of shearing on axial displacement and volumetric strains have been neglected [48].



(a) **(b)**

Fig.9. Elastic tensile and compressive was developed for masonry behavior: a) interface unit's model; b) zero-thickness element for modeling.

6. Finite element modeling methods

It was shown that the continuum simulation technique became poor due to finite element methods and the non-linear materials. In addition, it was overburdened with the extra level of contact nonlinearity. The finite element method was usually used modeling masonry and some other engineering difficulties. The finite element methods of structural analysis could be classified into the continuum method and the discrete element method: (a) Continuum method, in this situation, could be classified into the finite element methods and boundary element methods. For the boundary element methods, the researchers were not interested, and the non-linear masonry behavior was known as cracking and crushing failure models. Either for the finite element methods of masonry analysis, it was computationally easy; (b) Discrete element methods, in this situation, different numerical methods depend on the discrete element computational were established, for example, discontinuous deformation analysis, combined discrete-finite elements, rigid bodies spring method, non-smooth contact dynamics, modified distinct element method, and applied element method. All classifications depend on experimental material assumptions and during the first category were included with continuum materials. Considered the old masonry unreinforced or traditionally reinforced was very complicated with the 3D arrangements. So there was a difference between the old masonry modeling and the modern masonry modeling because modern masonry was easy and regular with and without reinforcing steel [56]. So the geometrical simulation was used by various elements as trusses, beams, solid, membrane, plate, shell elements, columns, arches and vaults [48]. The simulation depends on the non-linear performance for joints and vertical potential resulting from centerline units. In addition, computational effort of local studies and small models was highly influenced. The construction was improved and studied into triple or quadruple elements; it was the best method to analyze finite elements by average constitutive reckonings [51], as shown in Fig 10.

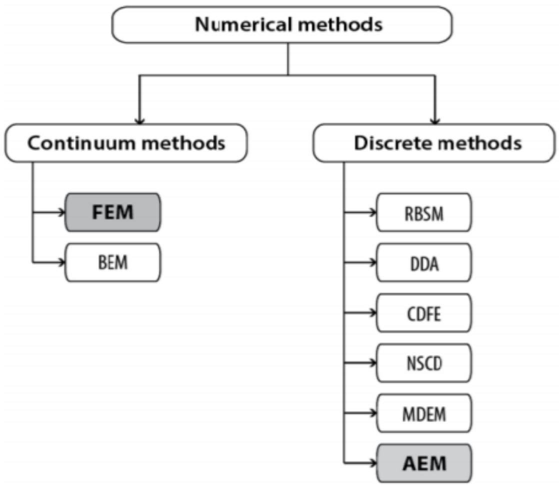


Fig.10. Numerical analyzed methods for masonry structures [56].

7. Conclusions

In this paper the authors have reviewed some unreinforced and reinforced masonry structure modeling strategies and methods, mechanical behavior, and the influencing factors, now available in the technical literature. From a geometrical point of view masonry was generally able to withstand lateral loads such as wind, seismic, and blast loads. The main objective of the reinforcement is to enhance the seismic resistance of masonry structural elements, in order to avoid failure modes that manifest in brittle and unforeseen manner. The main conclusions of the some researches were summarized as follows:

- It was observed that unreinforced masonry walls deteriorated under seismic loads, leading to partially crushing of the masonry with complete loss of strength and was defined as ductile. On the other hand, sudden brittle failure occurs when the horizontal bars were not enough to transfer the tensile stresses with continually diagonal cracks which led to acceptable failure.
- Reinforced masonry with concentrated vertical rebar at the sides led to relatively higher load capacity and less ductility compared to the walls with evenly distributed rebar; it was also observed that a horizontal rebar is essential to obtain reliable results on to improve the tensile strength of walls.
- It was cleared in experimental and analysis tests; the behavior of reinforced masonry was quite similar to reinforced concrete structural elements.
- It was observed that load-deformation response and failures of the masonry were affected by some factors such as reinforcement, axial compressive, and length to width ratio (H/L). Reinforcement ratio on masonry led to an increase in the shear capacity while axial compressive led to change the failure wall from flexure to shear.
- It was also observed that the aspect ratio had a clear effect on the coupling between the inelastic flexural and shears deformation.
- Increasing flexural capacity and initial stiffness led to an increase in the axial load and vertical reinforcement ratio, while increasing displacement ductility led to a decrease in the axial load for different failure modes.
- Shear failure was observed in the softening process, as it was related to the deterioration of the cohesive frictional for masonry mechanical properties. Masonry mechanical behavior is widely used for the stiffness, strength, and ductility using two methods, namely variable scales, classically the scale of the material.
- Direct tensile stresses of masonry were observed as the result of in-plane loading impacts; these may be because of wind, gravity loads, and thermal or moisture movements.
- It was observed that an accurate description of tensile cracking and opening of mortar joints, by means of an appropriate interface element, is essential to obtain reliable results on the buckling failure of walls.
- Some research concentrated on two numerical methods of masonry, namely micro-modeling as a separate material; such models require more computational effort, but it gave us the best understanding of the local behavior of masonry and macro-modeling as a composite material; such models require special failure surface for masonry under biaxial stress state. Modeling; such models require a special failure surface for masonry under biaxial stress state.
- Constitutive simulations were developed using the smeared crack method as one of the methods used to model the cracking of mortar in the finite element program, and is commonly adopted as it is economical.
- Models for nonlinear fracture mechanics, fictitious crack models, and cracking energy were proposed through two material parameters to control tensile strength and cohesion.
- Some researchers described the damage-based constitutive models using frictional and rigidity failure below compressive stresses and brittle performance below tensile stresses. As a result, the horizontal stress with horizontal relative displacement curves was symmetrical to the test results.
- Continuum element method (CEM) and discrete element method (DEM) are emerging powerful methods in modeling masonry as these methods largely rely on the interface contact formula between large blocks that may be rigid or deformable.
- Continuum models represent widely used solutions for the structural analysis of masonry buildings.

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