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Behavior of Masonry Buildings Under Various Monotonic and Periodic Loadings; State-of-the-Art

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1- Introduction

The development of appropriate assessment, analysis, and retrofit methodologies for masonry buildings in seismic zones has sparked considerable attention due to its vulnerability to collapse during the earthquake. Unreinforced masonry structures represent a considerable percentage of existing structures all around the world, and in order to avoid life safety hazards and property damage, these structures must be assessed and strengthened by structural engineers.

The fracture of mortar joints, as well as the cracking and crushing of masonry units, play a substantial role in the failure of unreinforced masonry buildings subjected to lateral loads by **Kelly 2010**.

Many of these constructions are constructed in seismically active locations. However, in order to design, repair, and retrofit these structures. Which has been an engineering concern for many decades. It is necessary to be able to assess their lateral load-carrying capability and ductility by **Lotfi and Benson ASCE**. The large number and variety of these buildings as well as the nature of masonry and the way in which its assembly was done makes it even harder for researchers to deal with it.

The paper is divided into seven sections according to the collected studies and their objectives.

2- Studying the horizontal bending of unreinforced clay brick masonry:

2.1- C.R. Willis, M.C. Griffith and S.J. Lawrence (2004), studied the behavior of unreinforced brick masonry (URM) sections when subjected to horizontal bending. They developed a mathematical model to predict the first crack as well as ultimate and post-ultimate strengths. Firstly, they establish their models' accuracies by comparing them to the data from the conducted experiments. Their resulting expressions represented a major improvement over the current expressions for being dimensionally correct as well as explicitly accounting for unit strength, mortar and the contribution of shear strength from compressive stress and friction to bed joint. Additionally, they found that the perception gained into the overall behavior of the bed joints when undergo torsion also the flexural mechanisms of perpend joints as well as brick units may as well be used in the analysis of the walls that subjected to two-way bending, in which the same mechanisms, combined with perpend joint torsion and bed joint flexure, contribute to the overall behavior of the wall. With reference to fig. 2-2 they explained that in pure horizontal flexural actions, where the walls undergo a horizontal bending, two main failure scenarios are possible, that depends on the relative strengths of the constituents of the masonry assemblage.

Which is referred to as stepped and line failures as shown in fig.2-1. For those walls where the strength of the mortar bond is relatively stronger than the brick unit strength, vertical crack through the brick units and perpend joints will tend to occur which is referred to as line failure, as compared to stepped failure in which the propagation of a crack starts at perpend joint and then along half a bed joint.

in practice, and because of the material variability (brick units, mortar, and their bond) the mode of failure will be combination where all three mechanisms involved.

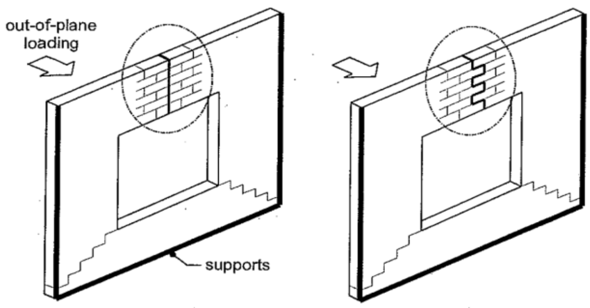

Figure 2-1: Crack patterns (a) Line crack (b) stepped crack [Willis et al., 2004]

They stated that when an unreinforced masonry section is subjected to an applied load P that induces horizontal bending, the generalized load-deflection behavior as shown in fig. 2 is linear-elastic until cracking begins in the perpend joints **Lawrence and Morgan 1975** and **Lawrence 1983** and **Lawrence 1995**.

P_1, the load at change of slope, is the load at which this cracking begins. Because the amount of torsional strain, and hence torsional stress, on each bed joint is minimal relative to its capacity for smaller load values, the level of deflection is small. As a result, the flexural strength of the perpend joints determines section cracking strength. Perpend joint cracking progresses as deflection exceeds the deflection at change of slope (Δ_1) by **Lawrence 1983** and **Lawrence 1995**, causing the load-deflection behavior to become progressively dictated by the torsional behavior of the bed joints. The load increases at a less steep rate until the section's ultimate strength, P_u, is attained at deflection (Δ_u). Due to torsional bed joint failure or fracture of the brick units, a full mechanism forms at this point, and the load is reduced to the residual capacity, P_t, at deflection (Δ_t). The residual capacity is proportional to the total compressive stress on the section and is related to the frictional resistance of the bed joints **Baker and Padhye 1980**. However, because no bed joints are involved in the mechanism, the residual capacity $P_t = 0$ for line failures.

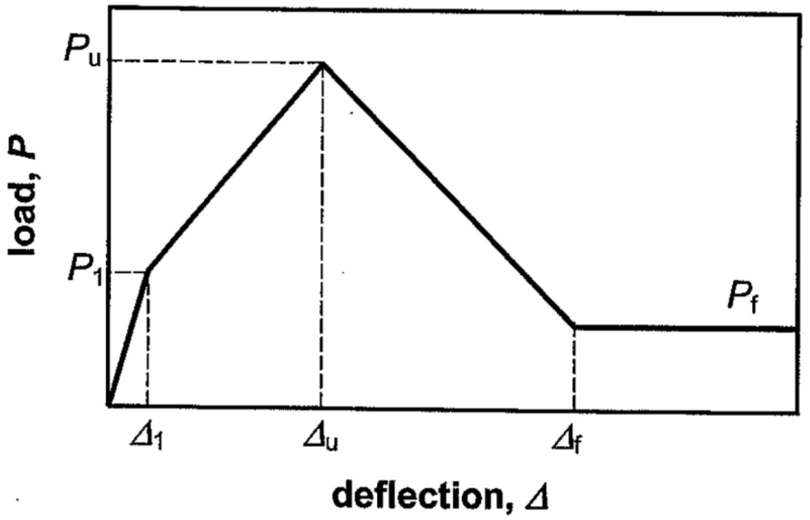

Fig. 2-2: Idealized one-way horizontal bending behavior **[Willis et al., 2004]**

3- Investigations of the diagonal bending of unreinforced clay brick masonry: -

3.1- The flexural behavior of unreinforced brick masonry (URM) walls undergoes a biaxial bending was examined by **M.C. Griffith, S.J. Lawrence and C.R. Willis (2005),** with a concentration on the flexural behavior along a diagonal crack line. In biaxial bending they devised a mathematical model to predict the diagonal bending moment capacity, M_d, which contributes to the ultimate strength of a wall. They first demonstrated the improved accuracy of their new M_d by comparing its predictions to those of current design code expressions using data from their diagonal bending studies on small wall specimens. They declaimed that the resulting diagonal bending expression was dimensionally correct and the beneficial effect of compressive stress was considered, regarding it a significant advance above current expressions. Using the virtual work approach, they proved that the modified expression offered excellent estimates of bending strength for 64 full-scale wall panels under biaxial bending.

In that work on masonry walls undergoing biaxial bending, it was found that when they were exposed to out-of-plane loads, such as that caused by wind and/or earthquake induced support motions, they were supported on three or four sides, resulting in biaxial bending situations. The failure mechanisms of two-way spanning walls were determined by panel dimensions and support conditions, as well as the relative strengths of brick units and mortar bond, and as shown in figure 2-3

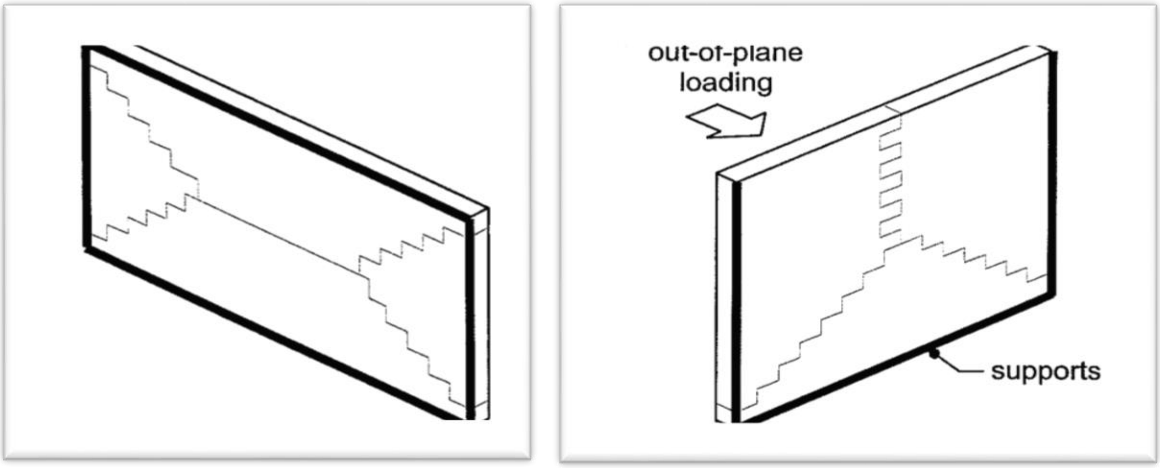

Fig. 2-3: Cracks on wall supported on: (1) four sides (2) three sides **[Griffth et al., 2005]**

The bending M_d capacity along diagonal crack lines was found to have a significant impact on strength. Accordingly, the failure mechanisms that could contribute to the moment capacity were:

1- perpend joints' flexural tensile strength (mechanism 1).
2- bed joints' torsional capacity (mechanism 2).
3- perpend joints' torsional capacity (mechanism 3).
4- bed joints' flexural tensile strength (mechanism 4).

They finally concluded that, prior to cracking, torsional and flexural mechanisms are both occurred simultaneously on each mortar joint due to two-way action, where the frictional capacity of the bed joints governed resistance after cracking. The usual load-deflection curve of a wall was observed in horizontal and two-way bending tests by **Willis 2004, Lawrence 1983, and Griffith 2000**, to show a steady loss of stiffness as the load approaches the wall's maximum strength. They concluded that the stiffness loss was caused by cracking in the perpendicular joints before they reach full strength **Lawrence 1983**. As a result, only the two bed joint mechanisms (torsion mechanism 2 and flexure mechanism 4) were assumed to be active at the point where maximum strength was obtained.

4- Observations of the behavior of unreinforced clay brick masonry at corners when subjected to lateral loads: -

4.1- Bansal, Nitin1 and Rai, Durgesh.C.2 (2017), used the finite element approach to investigate corner failure in masonry structures undergoing linearly increasing acceleration with diagonally acting motion along the corner. In the case of dry stack masonry, non-loadbearing and loadbearing failure patterns were observed. The out-of-plane component of the lateral load was found to be the cause of failure for non-loadbearing walls, while the in-plane component was found to be the cause of failure for loadbearing walls. They postulated failure mechanisms on the basis of those observed failure patterns, and limiting acceleration values were determined. Which matched finite element estimates quite well. By introducing an equal coefficient of friction, they took a new technique to simplify the micro-modeling of mortar bound masonry. This method was shown to be effective in determining the rate at which a fracture propagated through the masonry, and also the value of acceleration at which a piece of the corner walls accelerated.

5- Inspecting the in-plane-behavior of unreinforced clay brick masonry:

5.1- Zucchini a, P.B. Lourenço (2009), investigated the behavior of a brick wall under in-plane loads, up to collapse, and found that the suggested micro-mechanical homogenization model can describe this behavior. Their major goal was to demonstrate that the core of the homogenization model, namely the set of elastic micromechanical deformation mechanisms, was capable of reproducing overall cell behavior as anticipated by comprehensive finite element models. They designed the damage and plasticity models used in the homogenization process to be as similar as possible to those used in the interface model to avoid other potential causes of discrepancy. They demonstrated that numerical shear wall simulations using a homogenized material described by the micromechanical model and a coarse mesh provided global findings that were in good agreement with both a considerably more complex plastic finite element computation and experimental data. Their model included all of the critical components of the wall deformation up until the final collapse (tensile and compression cracks in the corners, diagonal crack, compression crushing). They said the method's implementation sounded promising in terms of reducing the computational effort required to analyze complex masonry structures, and that its integration into a standard finite element computer offers up new exploration possibilities.

5.2 Within the framework of seismic assessment of existing buildings, **G. MAGENES AND G. M. CALVI** examined the difficulties of evaluating the deformability, strength, and energy dissipation of unreinforced brick masonry walls. On the basis of numerical and experimental data, feasible solutions to simplified strength evaluation are examined, and formulae for assessment are offered. The importance of the shear ratio in shear failure mechanisms is demonstrated, and shear strength equations are suggested as a result. The most important deformability characteristics under cyclic stress are highlighted, and energy loss owing to hysteretic behavior is quantified for use in dynamic models. The findings of the experiments demonstrate that ultimate drift appears to be a parameter with a high degree of regularity for walls collapsing under shear. A feasible approach is suggested based on such a result.

6- Studies on the out-of-plane-behavior of URM: -

In the last three decades, studies have recognized the capacity of unreinforced masonry (URM) walls subjected to out-of-plane bending in a variety of locations around the world.

6.1- **Stephen Lawrence' and Ron Marshall (2000)**, invented an innovative approach to non-loadbearing wall design under lateral out-of-plane load based on knowledge of anticipated crack lines based on the material's simple tensile bond strength, the approach used virtual work principles to forecast wall resistance. They compared predictions to data collected from all across the world, and they covered both clay brick and concrete block masonry. Their approach was incorporated into the Australian Masonry (code AS 3700) revised version. They claimed that their method deals with support configurations not covered in prior regulations, and that it was the first to provide a reliable means of estimating the resistance of wall panels with door and window openings. They also stated that their method also eliminated the demand for an empirical factor to account for observed behavior differences between hollow-unit and solid-unit masonry walls.

They considered the fully cracked panel in each example and visualized a unit deflection of the panel and the corresponding rotations along the fracture lines to develop design equations. Because testing showed that this was how they behaved, the author assumed that the panels with all four sides supported break first into two sub-panels, each with support on three edges. They imposed the unit deflection to the center top for panels with three sides supported and the top right corner for panels with the bottom and one vertical edge supported. They computed incremental crack energy from the integral of the product of the resistive moment and the angle of rotation along all crack lines. They obtained the incremental work done by the summing of the product of load and deflection of each segment centroid over all panel segments. They adopted a traditional approach to virtual work based on combining the internal fracture energy and the work done to obtain an equation for the load resisted by the cracked panel.

Referring to fig. 2-4which shows a vertical supported on three sides and with the top being free, they proposed the following design equation:

$$W = \frac{2}{L_d^2}\left\{\frac{R_1 + R_2}{2} M_h + \frac{H_1}{H_d} M_h + \frac{H_1}{H_d}\left(1 + \frac{1}{G^2}\right) M_d\right\}\frac{1}{\left(1 - \frac{G.L_d}{3\,H_d}\right)}$$

Where:

G = slope of assumed crack line $=\frac{2(h_u+t_j)}{l_u+t_j}$

h_u = height of masonry unit

H_u = design height

H_1 = height of diagonal crack

H_v = height of vertical crack

L_u = length of masonry unit

L_d = design length $=\frac{L_{wall}}{2}$

L_{wall} = length of the wall

M_h = bending moment capacity per unit length of vertical crack line

M_d = bending moment capacity per unit length of diagonal crack line

R_1,R_2 = restraint factors for the supported vertical edges of the wall

t_j = mortar joint thickness

w = uniformly distributed load on the panel at failure

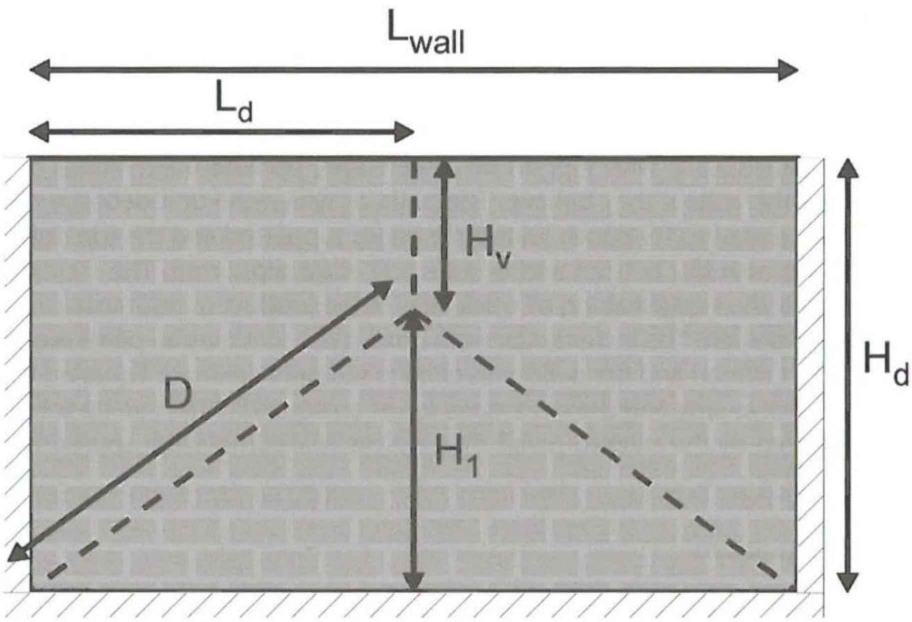

Fig. 2-4: Panel supported on three sides and with the top free **[Stephen Lawrence et al., 2000]**

6.2- **Lidia La Mendola, Matteo Accardi , Calogero Cucchiara, Vincenzo Licata c (2014)**, used experimental study and numerical finite element modeling to investigate the out-of-plane behavior of unreinforced and CFRP reinforced masonry walls by. Their analysis was based on a linear constitutive law for both brick units and mortar joints that make up masonry, and probable delamination lines were taken into consideration using a bi-linear interface element that reproduces the opening failure mode. When reinforcement was added, they used a bi-linear interface element to reproduce the sliding failure mode. They demonstrated their model's reliability is demonstrated through a comparison of numerical and experimental data. Furthermore, they performed a parametric analysis to explore the impact of the parameters that define the interface rules.

In specific they used the finite element software **Lusas Release 2015**, to perform a two-dimensional nonlinear analysis. The calcarenite and mortar were modelled using the QPM8 plane stress element (an eight-node regular quadrilateral element with a Gauss 3 3 integration scheme and quadratic interpolation). For modeling the connections between ashlars and joints, they used the discrete element IPN6, which in a 2D configuration, was an interface element between two lines with quadratic interpolation. They found that this type of element, which is situated along the lines of probable delamination, as particularly well suited to modeling interlaminar failure as well as crack initiation and propagation. It was a six-node element with zero thickness that describes the relationship between stresses and displacements of the nodes connecting the two sides.

The author utilized those interface elements, of a bi-linear law as shown in Figure 2-5, to form the Delamination Damage Model, which was characterized by two failure modes: Opening and Sliding **Thomas 1999**.

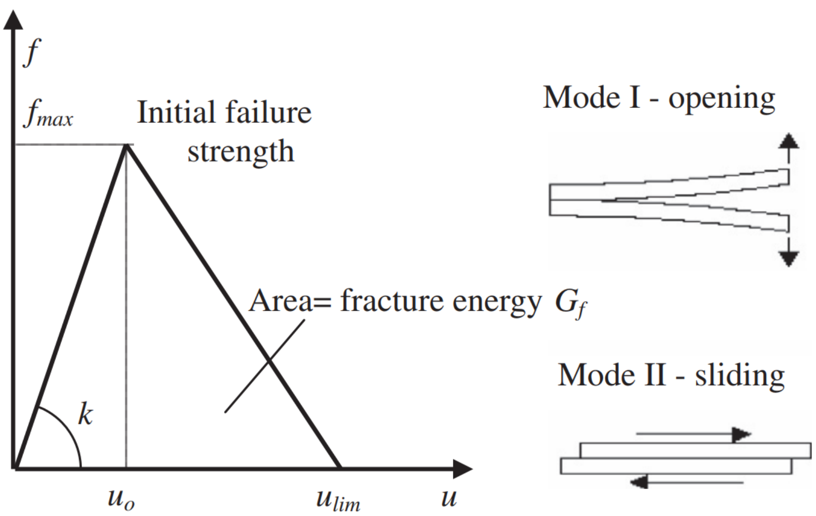

Fig. 2-5: Interface law **[Mendola et al., 2014]**

6.3- Chris Meisl 1, Dominic Mattman1, Kenneth Elwood2, Tim White3, and Carlos Ventura4 (2005) studied the sensitivity of the rocking behavior to the type of ground motion and investigated the quality of the wall construction. According to a parametric study employing a nonlinear-elastic single-degree-of-freedom model they found that buildings on solid ground are less prone to undergo out-of-plane wall collapse than those on soft soil sites. They carried out a shake table tests on two full-scale three-wythe unreinforced masonry walls with good collar joints and poor collar joints and reported their results from which they recognized that when the input ground motion was scaled above the uniform hazard spectrum from the proposed 2005 National Building Code of Canada (NBCC), both walls showed stable rocking behavior.

6.4- M.C. Griffith and Jaroslav Vaculik (2007) performed a study that described static airbag tests performed on eight unreinforced brick masonry walls as shown in figures 2-6and 2-7. Six of the eight walls had full moment connections along both vertical sides, and six of them featured a window opening, their experiments showed that face-loaded masonry walls had some ductility and significant displacement capacities beyond the cracking and displacement points when their peak strengths were first reached. They observed that the cracking patterns in the walls at the end of the static tests all matched the expected cracking patterns quite well, with the striking exception that essentially no cracking ever developed along the vertical edges, despite achieving the walls' maximum strengths. Furthermore, they noticed that the deflected shapes for all of the walls were reasonably consistent with the idealized shapes corresponding to the virtual work method's assumptions.

Fig. 2-6: Overview of Wall Test Set-Ups [Griffith et al., 2007]

Importantly, they demonstrated that the virtual work methodology may be used to predict the static strength of brick walls in two-way bending. However, they stated that where the vertical edges of walls had full moment connections to the rest of the structure, these expressions should be utilized with caution. According to their findings, only 50% of the horizontal bending capacity was active along the vertical margins of the walls when they reached their maximal strength. Furthermore, they realized that walls with higher horizontal span-to-height ratios would be less affected by vertical edge boundary constraints and, as a result, would be weaker. Nonetheless, the displacement capacity of long walls, where vertical bending governed the reaction in the limit, was often equal to the wall thickness.

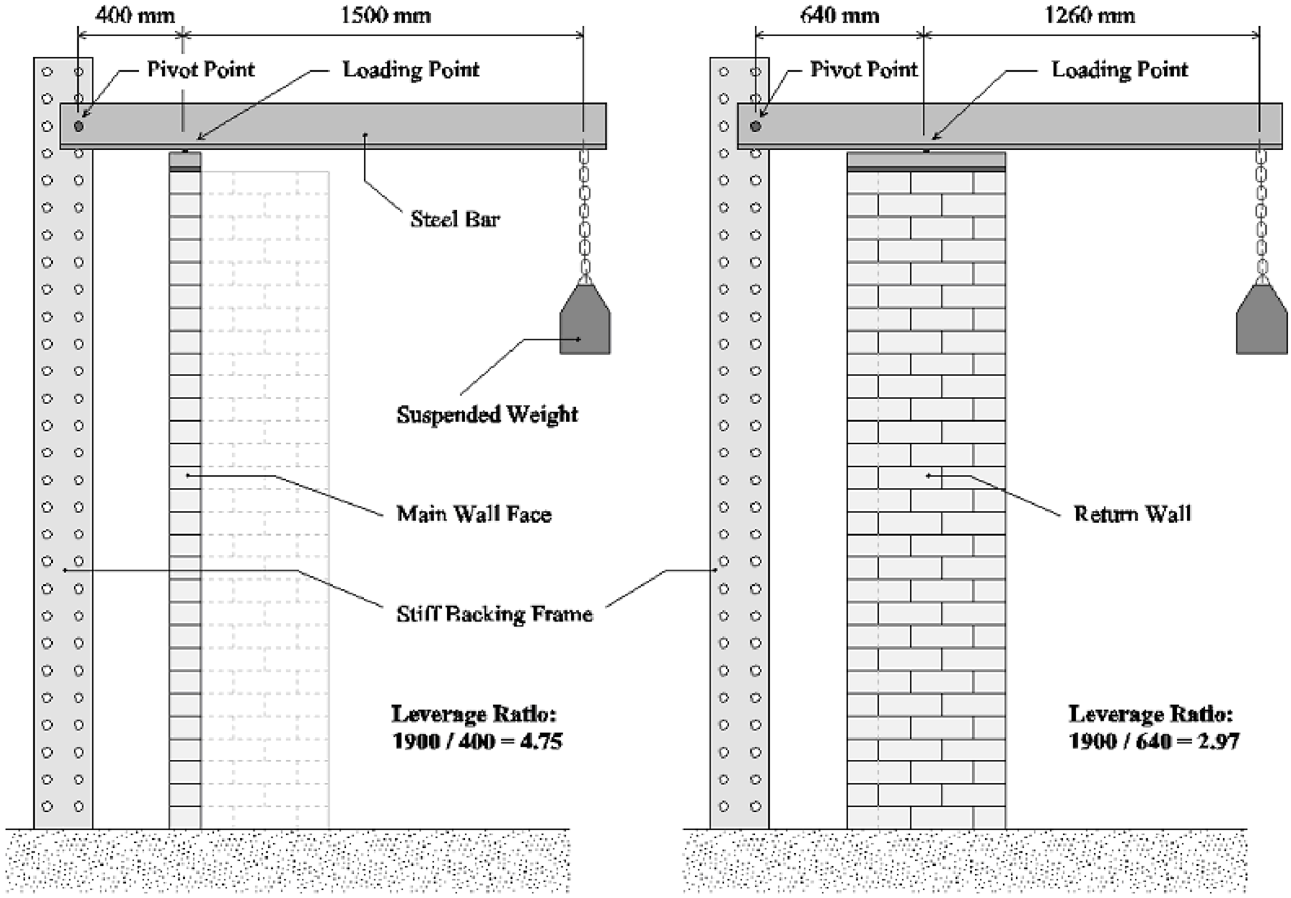

Fig. 2-7: Vertical Pre-Compression Loading Scheme (25.4 mm = 1 in.) [Griffith et al., 2007]

6.5- **Gabriele Milani, Paulo Lourenço, and Antonio Tralli (1663**), examined the brickwork which subjected to out-of-plane loading, using a simplified homogenization method. The anisotropic failure surface is combined with finite element triangle elements for the upper and lower bound limit analyses, which is based on the definition of a polynomial approximation of the stress tensor components in a finite number of subdomains. The findings of the limit analysis had given some rules to determine the pattern of internal forces at critical points, as well as the collapse mechanisms and failure loads. In every example, excellent results are obtained, suggesting that the proposed basic technique is sufficient for assessing the safety of out-of-plane loaded brickwork panels. We can define a small interval for the true collapse load by combining top and bottom bound techniques and their associated simplifications.

7- Pursuing the interaction between in-plane and out-of-plane behaviors of unreinforced clay brick masonry: -

During any seismic event, simultaneous in-plane and out-of-plane demands on load-bearing masonry walls are imposed. Most of the studies dealing with unreinforced masonry (URM) wall structural elements have focused on either the in-plane or the out-of-plane behavior, and clearly oversimplifying the bidirectional behavior of these structural elements.

By using finite element analysis, **Kiarash.M. DOLATSHAHI1, Amjad AREF2, and Mohammad YEKRANGNIA3 (2014)** examined the multi-directional behavior of a typical unreinforced masonry wall under different loading directions. They reported the results of a set of 13 monotonic loading analyses in terms of failure modes and force-displacement diagrams. Which clearly illustrated that the in-plane and out-of-plane behavior of unreinforced masonry walls were highly dependent, resulting in significant capacity reduction in both directions.

8- Studies on the behavior of unreinforced clay brick masonry when subjected to stress (uniaxial and biaxial): -

8.1- **Łukasz Kowalewskia and Marcin Gajewski (2015)** investigated the ability of predicting suitable failure processes for different biaxial stress modes using heterogeneous FEM models of brick walls. They used the application of cohesive elements to characterize the mortar joint zone in micro-modeling of masonry buildings. They simulated the conventional biaxial tests for the boundary value problems modeling different brick patterns. They made a comparison of numerical test solutions with laboratory experiment findings on masonry panels in biaxial stress states in one scenario (the most common pattern). From a qualitative comparison of numerical and real-life trials they demonstrated the utility of using Abaqus FEA's built-in constitutive material models to assess masonry behavior under biaxial stresses. Finally, they claimed that such models -when correctly validated- can be used as virtual experimental testing for determining parameters for macroscopic continuum elasto-plastic models.

8.2- **Hemant B. Kaushik, Durgesh C. Rai, and Sudhir K. Jain, M.ASCE3 (2007)** conducted several laboratory tests to investigate the uniaxial monotonic compressive stress-strain behavior of unreinforced masonry and its constituents, notably solid clay bricks and mortar, and other characteristics of unreinforced masonry and its constituents Based on the findings and observations of the thorough experimental study, they created nonlinear stress-strain curves for bricks, mortar, and masonry. They then identified six "control points" on masonry stress-strain curves, which can also be used to determine the masonry material or member's performance limit states. They proposed a simple analytical model for calculating stress-strain curves for brickwork, which can be employed in analysis and design operations utilizing linear regression analysis. The model just needed the compressive strengths of bricks and mortar as input data, which could be easily obtained experimentally and were also often available in codes, and the modulus of elasticity of bricks, mortar, and masonry could be derived using simple relationships. They claimed that for strong and stiff bricks and mortar of smaller but comparable strength and stiffness, the stress-strain curves of masonry do not always fall in between those of bricks and mortar.

8.3-Stress inhomogeneous and masonry walls subjected to vertical loads were examined by **B. STAFFORD SMITH and C. CARTER**. They analyzed the detailed stress pattern in walls of various height/length ratios and with various brick/mortar modular ratios using the finite element method. They demonstrated the horizontal tensile stresses caused by the spreading, or Poisson's effect, to be substantially stronger in the brickwork walls, particularly in the vertical mortar joints, than in the homogeneous walls at equivalent points. They found that the peak tensile stress values in a wall are found to increase with the wall's height/length ratio and the brick/mortar elastic modular ratio.

They summarized their findings as follows:

8.3.1. When a vertical load was imposed to a brickwork wall with a mortar that was less stiff than the brick, horizontal tensile stresses were created in the bricklayers, with peak values in the vertical mortar joints, promoting vertical cracking through the joints.
8.3.2. The greater the height-to-length ratio of a wall, the higher the horizontal tensile stresses in the vertical joints, and therefore the wall's resistance to vertical splitting under load.

8.3.3. In a brickwork wall, the higher the ratio of brick to mortar elastic moduli, the greater were the horizontal tensile stresses caused in the vertical mortar joints by a vertical load. Consequently, the weaker the mortar for a particular type of brick in a brickwork wall, the greater the horizontal tensile stresses and the weaker the wall against vertical load splitting.

8.3.4-Assuming that the tensile strength of the brick was larger than tensile strength of the mortar or even of that in the brick-mortar bond, when the elastic modulus of the mortar equals that of the brick, splitting would occur under the vertical load.

9- Other publication in field: -

9.1-**Alaa Hussein Al-Zuhairi (2019)** studied the impact of crack incidence in the two-dimensional numerical model of the bonding mortar and masonry units on the behavior of unreinforced masonry walls that supports loaded reinforced concrete slab as shown in fig. 2-9. For the modeling and analysis of unreinforced masonry walls, by the finite element approach. he used the FE software system ABAQUS, including an implicit solver, to simulate and assess vertically loaded unreinforced masonry walls. The technique of detailed micro-modeling was utilized. Separately, the masonry units, mortar, and unit-mortar contact were all modelled. He discovered that taking into account the possibility of pure tensional cracks vertically located in the middle of the mortar and units, a 10% improvement in masonry strength over the estimated strength was achieved using the Masonry Society Joint Committee's suggested procedure in the building code.

With reference to figure 2-9 Al-zuhairi simulated the shown three URM walls supporting an RC slab in a two-dimensional model. Pure tensional potential cracks in the midst of the mortar and units were used to represent the three URM walls. The model's failure pressure was 1.327 MPa in simulation. Before comparing the results to the masonry code, the failure pressure, representing the ultimate condition, must be divided by a safety factor. He decided to use a safety factor of 1.5. as 0.885 MPa was the maximum allowed load determined by the numerical analysis. The compressive stress that was allowed on the gross cross-sectional area was 0.807 MPa, according to Table 5.4.2 in the code (1). He concluded that, even though cracks in masonry units and mortar joints were simulated, the code was conservative by around 10% when compared to the simulated model.

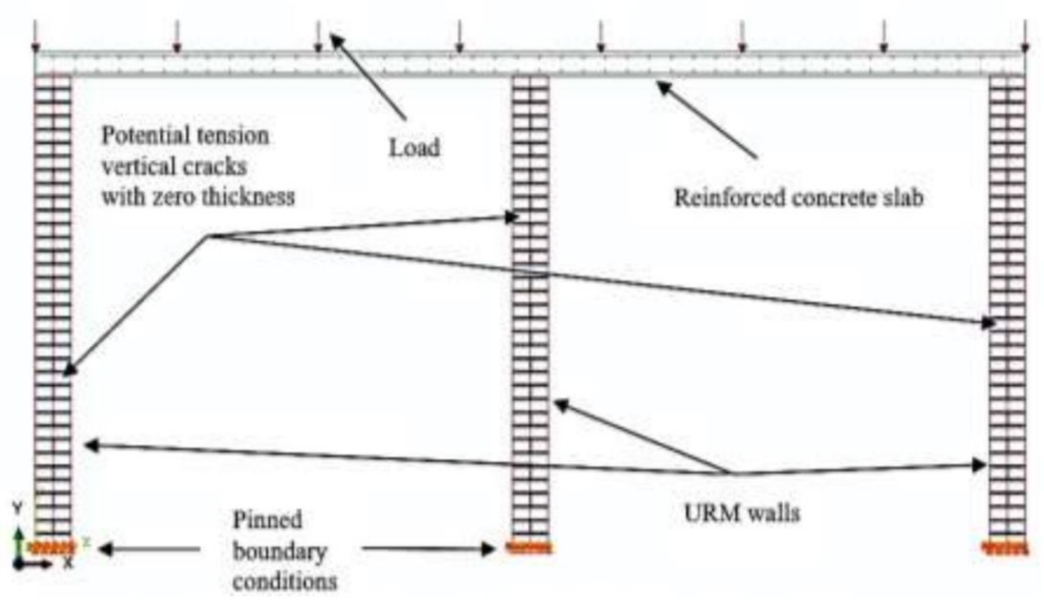

Fig. 2-8: Modeling of reinforced concrete slab supported by three URM walls. [Al-Zuhairi, 2019]

9.2-**Amjad J. Aref and Kiarash M. Dolatshahi (2013)** proposed a 3D cyclic constitutive material model, which can be utilized to predict massive deformation behavior of brick walls. They applied that material model inside an explicit analysis approach. They also suggested and validated a rigorous constitutive material model is suggested and validated using accessible experimental data from prior studies, as well as a number of new experimental tests undertaken for qualities for which experimental data was not easily available. The author used ABAQUS to compile the material model, which was implemented in a user-defined function (VUMAT). To analyze the behavior of the material model, then they tested the subroutine using multiple numerical instances on a single element under cyclic normal and transverse deformations. Furthermore, the numerical findings are compared with experimental data to test the resilience and prediction capacities of the proposed material model and numerical solution algorithm.

At both the element and structure levels, multiple simulations were run to assess the accuracy and robustness of the developed material model and its implementation, and the numerical results were compared to several well-documented experimental results acquired by the authors and others.

They summarized their conclusions in the following points:

1. Exponential softening was well-suited to represent cohesion or tensile strength deterioration because it closely matched the behavior of the mortar during tensile or transverse displacements.
2. When utilizing a relatively weak mortar with a strong brick, the mortar would not fail under compression due to the high confinement of the thin mortar layer between neighboring bricks; thus, no cap regime for the yield surface of the mortar should be defined.
3. After failure of the wall in the in-plane direction, the wall continued to withstand loading by frictional forces (considering its aspect ratio); however, in the out-of-plane direction, the out-of-plane strength after reaching a peak value rapidly diminished to zero due to the low aspect ratio of the tested walls that were governed by the dominance of the rocking behavior.
4. By comparing numerical simulations to theoretical results in out-of-plane loads, numerical simulations were able to anticipate the collapse of the wall and accurately traced the theoretical results.
5. While various academics commented on the convergence and stability concerns with implicit models used to simulate masonry structures, the created material model and its implementation in the user-defined subroutine in ABAQUS addressed these issues. Furthermore, the modeling technique was efficient and had a low computing requirement. However, more effort was required to improve the computational efficiency of the numerical modeling technique.

9.3- The fracture is not treated as a single discontinuity that propagates continuously in this numerical technique for crack growth. Instead, a series of overlapping coherent parts is used to illustrate the fracture. That method was used by **J. J. C. Remmers, R. de Borst and A. Needleman (2003)** used a partition-of-unity property of shape functions was used to insert these cohesive pieces into finite elements as discontinuities in the displacement field. They stated that the cohesive segments could be used in any place and orientation, and they were not restricted to any mesh direction. They guided the progression of segment decohesion by a cohesive law, and concluded a characteristic length which was included into the formulation as a result of the independent specification of bulk and cohesive constitutive relations. Crack nucleation and discontinuous crack growth may both be modeled using this formula.

9.4- The nonlinear behavior of masonry structures when subjected to static stress and/or dynamic excitations was predicted using a three-dimensional microscopic finite element model **by A.D. Tzamtzis~ and P.G. Asteris 2 (2003).** They separated their study into two parts due of its length. The first section summarized their work and many approaches and finite element models created for static and dynamic analysis of masonry structures. Then, they detailed the creation of the proposed microscopic model in the second section of their study, which also demonstrated the model's accuracy and promise. Finally, they verified the findings obtained from the application of the suggested finite element model using analytical and experimental solutions, demonstrating that it was capable of a high degree of accuracy.

9.5-**Bahman Ghiassi1, Masoud Soltani1, Abbas Ali Tasnimi** applied the macro-modeling method for estimating the nonlinear behavior of masonry walls with all feasible failure modes, with choosing the appropriate constitutive models and biaxial failure criteria, and assuming the brickwork to be orthotropic. They simplified the effects of shear and flexural deformations, which were significant in the overall response of the walls. Modeling the nonlinear behavior of a masonry element and extending it to the masonry wall yields shear deformations. For modeling shear failure in masonry elements, the contact density model developed at the University of Tokyo was updated and employed. They announced that their proposed computational methodology can be used to anticipate the nonlinear behavior of brick walls with various geometry and material qualities. Then, the compared the analytical and experimental findings to determine the correctness of the adopted approach.

They demonstrated that the predicted results were satisfactory in terms of accuracy, while the analysis time was much less than that of finite element methods. Furthermore, shear and flexural deformations played a role in the overall behavior of the reference specimens.

9.6- **D.V. Oliveira , P.B. Lourenco (2004),** studied a new constitutive model based fully on the incremental theory of plasticity and capable of describing the cyclic loading of interface parts. In an existing monotonic model, additional yield surfaces were introduced, with each unloading surface only being able to move inside the admissible stress space and towards a similar monotonic yield surface. A mixed hardening law governs their movement. The normal stress component is thus stated in a non-linear manner, while elastic unloading is solely considered for the shear component

The comparison of uniaxial experimental and numerical findings reveals that the model captures the most important characteristics seen in experiments. These findings demonstrate the importance of taking non-linear material behavior into account when calculating the normal stress component during unloading.

Three brick walls were used to verify the efficiency of the established constitutive model. The numerical findings reveal that the model can mimic the key characteristics of cyclic behavior, such as stiffness degradation, energy dissipation, and distorted patterns, allowing it to be used to analyze masonry structures subjected to cyclic stress.

Between both the three shear-walls studied, significant differences in structural behavior, failure mode, and wasted energy were discovered.

REFERENCES

1- TREVOR E. KELLY. EARTHQUAKE RESISTANCE OF UNREINFORCED MASONRY BUILDINGS. New Zealand.
2- Interface Model Applied to Fracture of Masonry Structures By Hamid R. Lotfi1 and P. Benson Shing,2 Members, ASCE)
3- LAWRENCE, S.J., MORGAN, J.W. (1975a), "Investigations of the Properties of Small Brickwork Panels in Lateral Bending". Technical Record TR52/75/418, Department of Housing and Construction, Experimental Building Station, North Ryde, Australia, January 1975, 29 p.
4- LAWRENCE, S.J. (1983), Behavior of Brick Masonry Walls under Lateral Loading. Thesis (Ph.D.), The University of New South Wales, November 1983.
5- LAWRENCE, S.J. (1995), "The Behavior of Masonry in Horizontal Flexure". Proceedings of the J1h Canadian Masonry Symposium, Canada, June 1995, pp. 525-536.
6- BAKER, LR., PADHYE, P.Y., SCHULZE, P.N. (1980), "Torsional Resistance from Friction Between Overlapping Masonry Units". International Journal of Masonry Construction, 1, (2), 1980, pp.62-66
7- Willis, c r (2004) design of unreinforced masonry walls for out-of- plane loading “Ph.D. thesis. School of civil and environmental engineering. The university of Adelaide. November 2004, 333p117
8- GRIFFITH, M (2000), “experimental study of the flexural strength of URM (brick) walls”. The university of Adelaide, research report No. R 169, August 2000, 21 p
9- -MSJC, (2011). Specification for Masonry Structures TMS 602-11/ ACI 530.1- 11 / ASCE 6-11.
10- Lourenço PB. Experimental and numerical issues in the modelling of the mechanical behaviour of masonry. Struct Anal Hist Constructions Ii 1998:57–91.
11- Łukasz Kowalewskia and Marcin Gajewski (2015),
12- LUSAS. User Manual, FEA Ltd., Kingston-upon-Thames, UK, 1999.
13- Pandey BH, Meguro K. Simulation of Brick masonry wall behavior under in plane lateral loading using applied element method. In: 13th World conference on earthquake engineering, Vancouver, BC, Canada; August. 2004.
14- Qiu Y, Crisfield MA, Alfano G. An interface element formulation for the simulation of delamination with buckling. Eng Fract Mech 2001;68(16):1755– 76.

15- Roca P, Cervera M, Gariup G. Structural analysis of masonry historical constructions. Classical and advanced approaches. Arch Comput Methods Eng 2010;17(3):299–325.
16- Zucchini, A. and Lourenço, P.B., 2009. A micro-mechanical homogenisation model for masonry: Application to shear walls. *International Journal of Solids and Structures*, *46*(3-4), pp.871-886.
17- Tena-Colunga, A., Juarez-Angeles, A. and Salinas-Vallejo, V.H., 2009. Cyclic behavior of combined and confined masonry walls. *Engineering Structures*, *31*(1), pp.240-259.
18- La Mendola, L., Accardi, M., Cucchiara, C. and Licata, V., 2014. Nonlinear FE analysis of out-of-plane behaviour of masonry walls with and without CFRP reinforcement. *Construction and Building Materials*, *54*, pp.190-196.
19- Turek, M., Ventura, C.E. and Kuan, S., 2007. In-plane shake-table testing of GFRP-strengthened concrete masonry walls. *Earthquake Spectra*, *23*(1), pp.223-237.
20- Griffith, M.C., Vaculik, J., Lam, N.T.K., Wilson, J. and Lumantarna, E., 2007. Cyclic testing of unreinforced masonry walls in two-way bending. *Earthquake Engineering & Structural Dynamics*, *36*(6), pp.801-821.
21- Lourenço, P.B. and Milani, G., 2014. Homogenization and seismic assessment: review and recent trends. *Mechanics of masonry structures*, pp.293-341.
22- Kaushik, H.B., Rai, D.C. and Jain, S.K., 2009. Effectiveness of some strengthening options for masonry-infilled RC frames with open first story. *Journal of structural engineering*, *135*(8), pp.925-937.
23- Stafford Smith, B. and Carter, C., 1969. A method of analysis for infilled frames. *Proceedings of the institution of civil engineers*, *44*(1), pp.31-48.
24- Ahmed, A.R. and Al-Zuhairi, A.H., 2018. Finite Element Analysis for The Response of URM Walls Supporting RC Slab. *International Journal of Engineering & Technology*, *7*(4.20), pp.259-265.
25- Aref, A.J. and Dolatshahi, K.M., 2013. A three-dimensional cyclic meso-scale numerical procedure for simulation of unreinforced masonry structures. *Computers & Structures*, *120*, pp.9-23.
26- Remmers, J.J., Borst, R.D. and Needleman, A., 2003. A cohesive segments method for the simulation of crack growth. *Computational mechanics*, *31*(1), pp.69-77.
27- Asteris, P.G. and Tzamtzis, A.D., 2003. On the use of a regular yield surface for the analysis of unreinforced masonry walls. *Electronic Journal of Structural Engineering*, *3*, pp.23-42.
28- approach for the limit analysis of out-of-plane loaded masonry walls. *Journal of structural engineering*, *132*(10), pp.1650-1663.
29- Oliveira, D.V. and Lourenço, P.B., 2004. Implementation and validation of a constitutive model for the cyclic behaviour of interface elements. *Computers & structures*, *82*(17-19), pp.1451-1461.
30- Magenes, G. and Calvi, G.M., 1997. In-plane seismic response of brick masonry walls. *Earthquake engineering & structural dynamics*, *26*(11), pp.1091-1112.