

**EFFECTS OF OPENING ON THE BEHAVIOUR OF AXIALLY LOADED  
FIREDCLAY SINGLE LEAF WALL**

**by**

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## LIST OF SYMBOLS AND ABBREVIATIONS

$\sigma_x$	Stress in X direction
$\sigma_y$	Stress in Y direction
$\sigma_z$	Stress in Z direction
ASTM	American Standards for Testing Material
OPC	Ordinary Portland Cement
$\tau$	Shear Stress
$\sigma$	Averaged Stress
$\varepsilon$	Averaged Strain
D	Stiffness Matrix
AS/NZS	Australian Standards and New Zealand Standards
$\sigma_n$	Normal Stress to the Crack Direction
$\sigma_p$	Parallel Stress to the Crack Direction
BS EN Standard BS	The European Standard EN has the Status of a British Standard BS
ADINA	Automatic Dynamic Incremental Nonlinear Analysis
FEM	Finite Element Method
PAM	Pro Analysis Methanol
$E_m$	Secant Modulus of Elasticity
h	Wall Height
t	Wall Thickness
w	Wall Length (Width)

aspect ratio	Height of the Wall Divided by Wall Length (h/w)
$\mu$	Poisson's ratio
$\mathcal{E}_{trans}$	Transverse Strain
$\mathcal{E}_{longitudinal}$	Longitudinal Strain
C.V	Coefficient of Variation
w/c	water cement ratio

# KESAN BUKAAN KEA TAS KELAKUAN DINDING BATA TANAH LIAT TERBEBAN PUGAK

## ABSTRAK

Kawasan di sekeliling bukaan seperti di pintu, tingkap dan untuk kemudahan mekanikal dan elektrik di dalam struktur panel masonry yang dikenakan bebanan paksi adalah terdedah kepada tekanan tumpuan yang tinggi. Terdapat kemungkinan wujudnya tekanan di sekeliling bukaan berdekatan dengan bucu. Tambahan pula, dengan kehadiran bukaan boleh mengganggu kekuatan muktamad panel masonry. Oleh itu, satu penyiasatan tentang ciri-ciri kegagalan dan agihan tekanan panel dinding masonry dengan bukaan di bawah pengaruh keadaan sokongan, lokasi dan saiz bukaan, susunatur bebanan dan geometri panel dibuat. Kajian ini dibahagikan kepada 3 peringkat. Pertama, penyiasatan makmal ke atas sifat-sifat bahan yang digunakan di dalam kajian ini. Kedua, ujian ke atas 33 skala penuh panel dengan bukaan dan tiada bukaan dijalankan dan ketiga, analisis berangka berdasarkan model elemen terhad dilaksanakan bertujuan untuk membuat perbandingan di antara ujikaji dan keputusan analisis. Hasil utama kajian ini termasuklah keadah inovatif untuk mengukur tekanan tinggi setempat di bucu bukaan panel masonry. Tekanan ini berkurangan apabila jarak dari sempadan bukaan bertambah di dalam arah kelebaran panel. Hubung kait yang baik telah diperolehi di antara ujikaji dan keputusan analisis. Kajian ini juga mewujudkan data asas dan bantuan kepada rekabentuk dan analisis panel masonry dengan bukaan yang dikenakan bebanan paksi.

## [EFFECTS OF OPENING ON THE BEHAVIOUR OF AXIALLY LOADED FIREDCLAY SINGLE LEAF WALL]

### ABSTRACT

The area around openings in the form of doors, windows, and for mechanical and electrical services in axially loaded structural masonry panels are subjected to high stress concentration. There is a possibility of tension developing around these openings near the corners. Furthermore, the presence of these openings could affect the ultimate strength of the masonry panel. Hence, an understanding of the failure behaviour and strain distribution of masonry wall panels with openings under the influence of support conditions, location and size of opening, loading arrangement and panel geometry were investigated. This research was divided in three stages. Firstly, laboratory investigations on the properties of materials used in this study was carried out. Secondly, testing of 33 full scale panels with and without opening was conducted and thirdly, numerical analysis based on finite element modeling was performed in order to make comparisons between experimental and the analytical results. The main outcome of this research works includes the innovative methodology to measure the high localized strain concentration at the corners of the opening in masonry panels. This strain reduces as the distance from the opening's boundary increases in the width direction of the panel. Good correlation has been obtained between experimental and analytical results. This research has also established a basic data and aid on the design and analysis of axially loaded masonry panel with opening.

## CHAPTER 1 INTRODUCTION

### 1.0 General introduction

Masonry is the oldest building material, which is still commonly used in the building industry. The placing of brick units on each other, bonded with mortar, has proved itself as a successful technique for thousands of years, which is mainly justified by its simplicity during the construction. In spite of the simplicity associated with building masonry, the analysis of the mechanical behavior of masonry structures remains a true challenge. When masonry wall is used as support to resist vertical compression, it is called the load bearing wall. If they are interior walls, this may be their singular structural function and they perform essentially like columns. There may be several openings in the load bearing wall, deployed at different locations on each floor to suit the function of the rooms. Engineer can not generally dictate this situation to suit structural convenience, so it is essential that the designers allow for openings in their design. The areas around the openings in the form of doors and windows in the axially loaded structural panels are locations of high stress concentration (Benayoune et al., 2003). Tension develops around the opening near the corners and the presence of the opening has an effect on the ultimate strength of the masonry panel (Pietruszczak and Ushaksaraei, 2003). Hence, an understanding of the mechanical behavior of masonry wall panels with openings under the influence of support condition, location and size of the opening, panel geometry, and loading arrangement is necessary to develop satisfactory design procedure.

## 1.1 Background

Many studies concerning the behavior of axially loaded masonry wall have been carried out. These studies include laboratory investigation and numerical analysis (Redmond and Allen, 1974; James et al., 1979; Shrive et al., 1979; Hatzinikolas et al., 1980; Pedreschi and Sinha, 1982; Ali and Page, 1989; Naraine and Sinha, 1989; Lourenco, 1992; Riddington and Naom, 1994; Alshebani and Sinha, 1999; and Ignatakis and Stylianides, 2004). Very limited and scarce research works, however, have been published on the behavior of the axially loaded masonry panels with openings under axial compressive loading. These published research works include numerical analysis only (Ganesan et al., 1990; Salerno et al., 2001; and Pietruszczak and Ushaksaraei, 2003). From the review of these literatures, stress concentration was found to occur near the corners of the opening. However, this numerical analysis has not been supported by experimental work in laboratory. Moreover, the effects of the opening size and position, the aspect ratio of the panel, the loading arrangement, and the boundary condition have not been verified. Therefore, there is a need for experimental program to be carried out on a full-scale wall panels to investigate the following parameters which may influence the behavior and the failure pattern of axially loaded masonry panel with opening:

- 1- Position of the opening.
- 2- Lateral supports along wall panel ends.
- 3- Size of the opening.
- 4- Aspect ratio (height to length) of the wall panel.
- 5- Loading arrangement applied to the wall panel.

## **1.2 Objectives of the research**

In order to investigate the effect of the opening on the behavior of masonry load bearing wall, experimental research work is needed. It is important that a research work is carried out to investigate and to establish the effect of the opening size and location, the boundary condition, the aspect ratio, and the loading arrangement. Therefore, the specific objectives of this research are:

- 1) To investigate experimentally the behavior of axially loaded single leaf masonry wall panel with opening under the influence of the following parameters:
  - a) Position of the opening.
  - b) Lateral supports applied to the wall panel ends.
  - c) Size of the opening.
  - d) Aspect ratio (height to length) of the wall panel.
  - e) Loading arrangement applied on the wall panel.
- 2) To investigate analytically using finite element technique the behavior of the experimentally tested wall panels.
- 3) To compare results obtained experimentally with that obtained analytically for wall panels.
- 4) To investigate experimentally the effect of opening on the compressive strength of axially loaded masonry panel.

## **1.3 Scope and outline of the thesis**

This study focused on the axially loaded fired-clay masonry panels with an opening. The behavior of masonry panels with opening under seismic load,

wind load, and lateral load (in plane and out of plane), which has been widely investigated in the past will not be included in this study. The experimental work has been carried using one type of fired-clay brick (SK30) and one type of mortar (ii) while the load applied on the wall was centrally static.

This thesis is divided into seven chapters. A literature review of previous work on factors affecting the compressive strength of axially loaded masonry wall panel is presented in Chapter 2. It includes an overview of modern numerical strategies applied to model the mechanical properties of masonry. This chapter also reviews the available literature on computational studies on the behavior of axially loaded masonry panels with opening.

Chapter 3 contains description of the material properties and experimental details. It describes the materials (brick unit, cement, lime, sand, and water) specifications in accordance with the British Standards and the American Society for Testing and Materials Standards and also presents results of the material laboratory tests. This chapter also describes the configurations of wall panels used in the laboratory investigation and construction details of these wall panels. Furthermore, this chapter describes test equipments employed to all specimens in the laboratory to acquire an accurate record of the response of each wall under axial load

In Chapter 4, results of a comprehensive experimental program are presented. This experimental program includes the laboratory tests of 33 wall panels to study the effect of the opening on the behaviour of masonry wall

panel. Tests are designed uniformly distributed axial compressive loading as well as for one loading point and two loading points of concentrated load. In addition, results of solid wall panels tested under uniformly distributed axial compressive loading are presented.

Results of numerical analysis of each experimentally tested panel are presented in Chapter 5. This chapter includes description of elastic parameters and the finite element model used in the analysis. Furthermore, results of parametric study, to verify the effect of size and position of the opening and the aspect ratio of the panel on the global displacement of the wall panel are given. The results of the sensitivity analysis, which is carried out to measure how sensitive the results of the finite element analysis are to the changing modulus of elasticity (E) are also given in Chapter 5.

The comparison of strain results between the experimental and the computationally predicted values for the 33 wall panels are presented in Chapter 6. The correlation between the experimental and analytical results is assessed by means of the correlation factor.

Chapter 7 contains the conclusions based on the analysis of the experimental and analytical results. Recommendations for future studies are also included.

## CHAPTER 2 LITERATURE REVIEW

### 2.0 Introduction

Masonry is the oldest building material that is still used in the building industry. The placing of brick unit on top of each other, bonded with mortar has proved itself as a successful technique used for thousands of years, which is mainly due to its simplicity during the construction (Massart, 2003). In spite of the simplicity associated with building in masonry, the analysis of the mechanical behavior of masonry construction remains a true challenge (Molnar, 2000). The area around the openings in the form of doors and windows in axially loaded structural panels are the location of high stress concentration (Ganesan et al., 1990; Benayoune et al., 2003). Due to the above reason, tensile stresses develop in the area around the opening, particularly at the corners (Pietruszczak and Ushaksaraei, 2003).

This chapter is organized into three sections comprising of sections 2.1, 2.2, and 2.3. Section 2.1 is the literature review describing the factors affecting the behavior of the full-scale axially loaded masonry walls. Section 2.2 touches on the literature review of masonry modeling using finite element technique, while section 2.3 describes the review on the computational studies on the behavior of the axially loaded masonry walls with opening and section 2.4 includes the overall concluding remark.

## **2.1 Factors affecting the compressive strength of the axially loaded masonry wall**

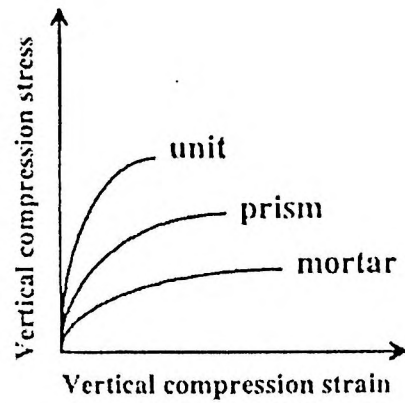
Load bearing masonry structures can be either for low-rise buildings typically in the industrial and commercial applications or for medium-rise to high-rise structures such as apartment buildings (Suter et al., 1980). Research work has shown that many factors are important in determining the compressive strength of the masonry panels, such as interaction of brick units and mortar, strength of mortar, joint thickness, water retentivity of mortar, suction rate of a unit, individual strength of a masonry unit, geometry of units, moisture content of the unit, loading rate, and workmanship. Some of these factors, such as the unit characteristics are determined in the manufacturing process, while others such as mortar properties are susceptible to variations in constituent materials, proportion, mixing and accuracy of construction. The following sections discuss their likely effects on the overall strength of masonry.

### **2.1.1 Interaction of brick units and mortar**

Masonry is a composite anisotropic material. Therefore, when describing the load bearing behavior of masonry, the interaction of masonry units and mortar has to be taken into account (Walker, 1999). The bond helps to ensure that horizontal forces between units and mortar are transferred by means of adhesion and/or friction, and that vertical forces are transferred uniformly over the height of the component (Sutherland, 1981). The uniform distribution of the loads is also accommodated by the mortar in the bed joints because it compensates for deviations in the sizes of masonry units hence prevents stress concentrations (Hendry, 1987).

Initial suction of bricks influences the bonding between the units and the mortar (Sneck, 1982). The best bonding will be achieved when the initial suction is less than  $30\text{gm}/\text{min}/30\text{in}^2$  ( $1.55\text{kg}/\text{m}^2/\text{min}$ ) at the time of the laying of the bricks (Grimm, 1970). If the bricks' suction exceeds this value, then the bricks should be soaked for three to twenty-four hours prior to laying (West, 1974).

A masonry element loaded in compression perpendicular to the bed joints, compressive stresses build up in the direction of the load (Hilsdorf, 1969). As with the customary combinations of masonry units and mortar, the mortar exhibits a greater transverse deformability than the masonry units, and tries to deform more in the transverse direction than do the units (Hatzinikolas et al., 1980). This differential transverse deformation is hindered by the bond between masonry units and mortar, which sets up transverse tensile stresses in the masonry units and transverse compressive stresses in the mortar (Alexandropoulos, 1996). A triaxial stress condition arises in the units and in the mortar as shown in Figure 2.1. The different stress-strain relations for brick unit, prism, and mortar are also shown in Figure 2.1. A further increase in the vertical loads leads to the transverse tensile strength of the units being exceeded and the appearance of vertical cracks in the units. The increment of the load furthermore leads to failure of the masonry element (Alexandropoulos, 1996).



Stress strain relationship for prism and constituent materials

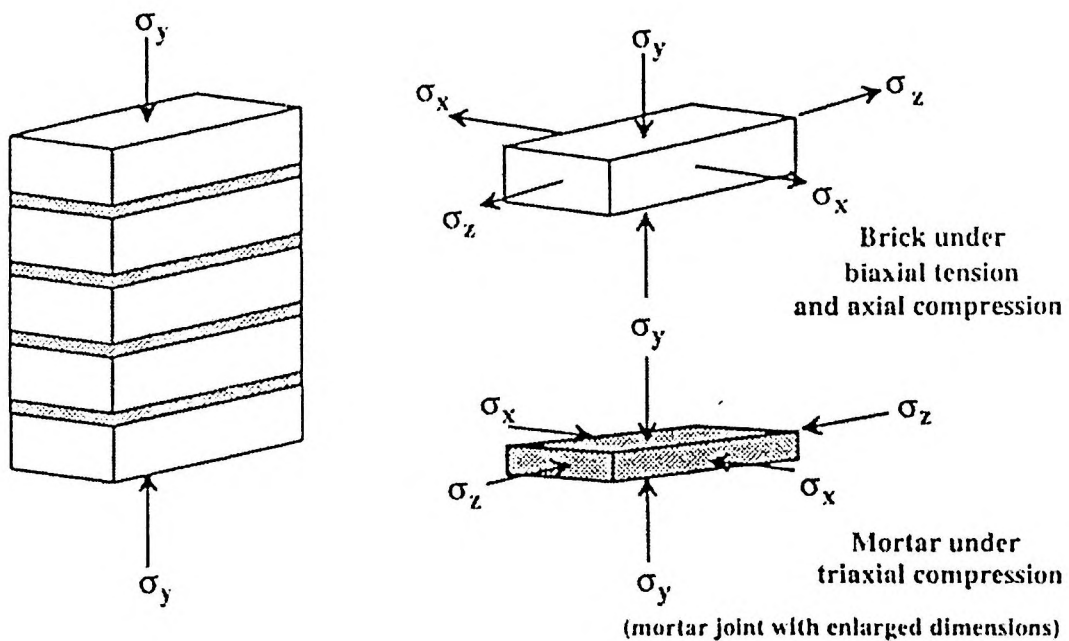


Figure 2.1: Brick and mortar stresses due to uniaxial compressive load (Alexandropoulos, 1996)

### 2.1.2 Strength of mortar

The compressive strength of masonry is significantly below the strength of the brick unit and higher than the strength of the mortar. This effect is due to the triaxial stress in the mortar within the bed joints (Hatzinikolas et al., 1980). The factors which affect the compressive strength of mortar are the cement content of the mix, the water to cement ratio, the proportion of the cement to

sand and the properties of the sand itself (Isberner, 1969). Macleod and Ndibaza (1987) carried out an experimental works to investigate the effect of low mortar strength on the strength of brickwork. It was found that the strength of brickwork increased with an increase of mortar strength as shown in Figure 2.2. This effect is due to transverse deformability of the mortar, where the mortar with the greatest compressive strength exhibits the lowest transverse deformability and vice versa.

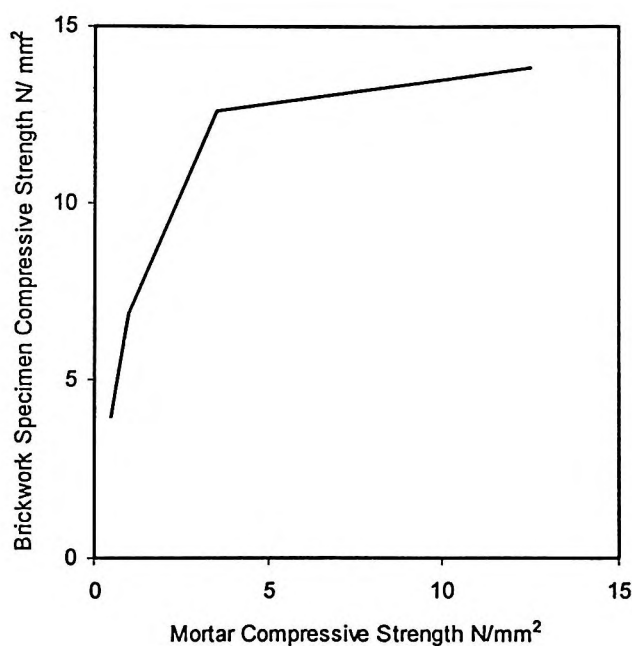


Figure 2.2: Brickwork strength against mortar strength (Macleod and Ndibaza, 1987)

### 2.1.3 Joint thickness

The type of mortar joint affects the compressive strength of the masonry because the transverse deformability of mortar is the major influencing factor (Francis et al., 1970). A thicker joint leads to lower compressive strength for the masonry panel (Grimm and Halsell, 1970). This has been demonstrated by Francis et al. (1970), who carried out an extensive research to study the effects

of joint thickness on the compressive strength of four-brick prisms, using two types of brick units. Francis et al. classified the bed mortar joints according to their thickness into three types as follows: 1) thin (joint thickness 1mm-3mm), 2) medium (joint thickness 5mm-7mm), and 3) thick joint thickness (12mm), bed mortar. Francis et al. found that the compressive strength of the prism increases with the decrease in the mortar joint thickness as shown in Figure 2.3.

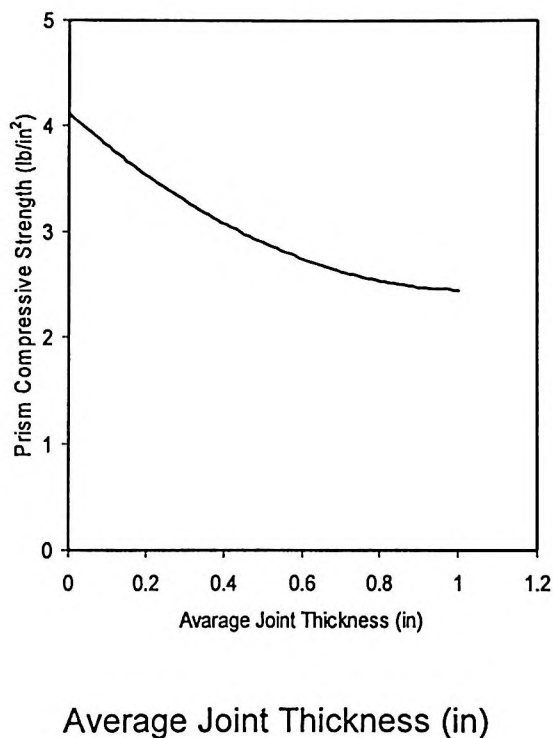


Figure 2.3: Effect of joint thickness on solid brickwork strength (Francis et al., 1970)

#### 2.1.4 Water retentivity of mortar

Portland cement requires a period of time in the presence of moisture to develop its full strength. Therefore, water retentivity of mortar is of considerable practical importance (Banfill, 1994). It is more serious if the mortar is to be applied on bricks with high water suction (Hendery, 1987; Grimm and Halsell, 1970). Hoath et al. (1970) has tested mortars made from seven different types of lime and standard sand in accordance with the requirements of the British

Standard 3502 (British Standard Institute, 1968 ) where the results are exhibited in Figure 2.4. It was found that the replacement of the cement with lime reduces strength but it improves water retentivity of the mortar.

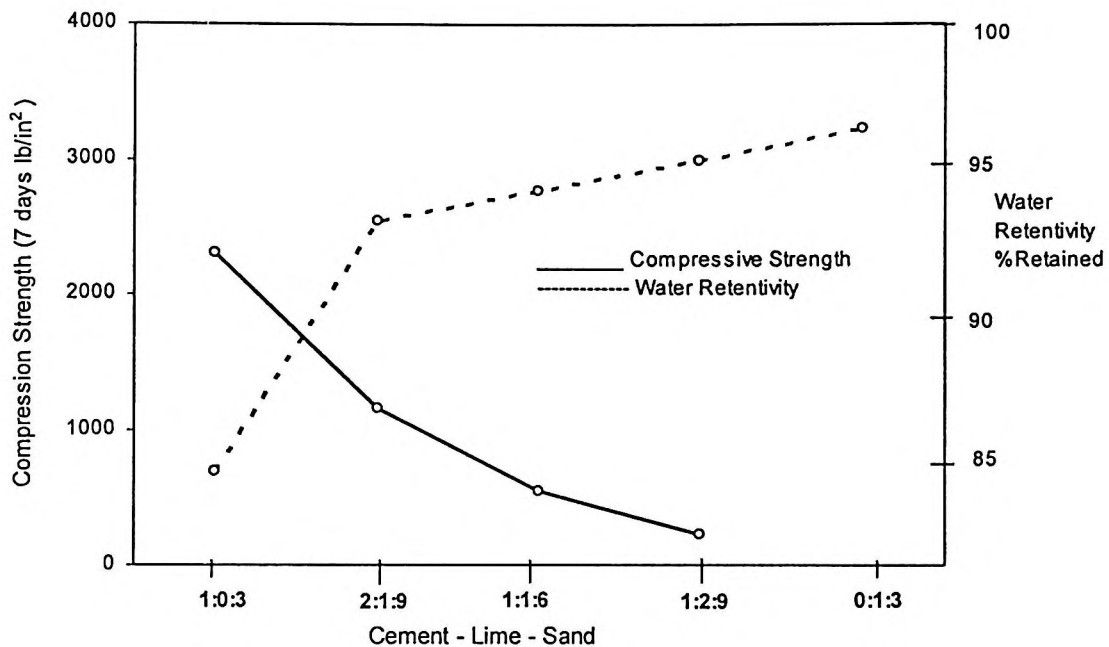


Figure 2.4: Relationship between mortar compositions, average compressive strength, and water retentivity for mortar made with different types of lime (Hoath et al., 1970)

### 2.1.5 Suction rate of masonry unit

A masonry unit with a high suction rate will absorb water from the freshly-laid mortar. This however could possibly deplete the water available for hydration of cements and consequently reduces the strength and causes poor bond between brick unit and mortar (Sneck, 1982). Such bricks should be soaked, i.e. placed in water for a short time before being laid (Grimm, 1970). Suction rate is determined by measuring the weight gain after immersing one

face of masonry unit in water for one minute (Hendry, 1987). Generally the suction rate is high for brick units with high porosity (Sneck, 1982). The porosity is given by the ratio of the volume of voids (pore water + air) to the total volume of the unit. The usual method of measuring porosity is through the boiling water test where the masonry unit is immersed in boiling water for 5 hours and the gain in weight is expressed as a weight per cent of the dry brick.

If the moisture from the mortar is too rapidly absorbed by the masonry unit then the lime will be separated from the mixture and crumble, whereby the bricks will not be able to maintain cohesion with the mortar and consequently the compressive strength of the brickwork will be reduced (Sneck, 1982). Masonry wall built with saturated masonry units develops poor adhesion between brick and mortar (Lovewell, 1974). Plamer & Parsons (1934) examined the effects of brick unit suction on the bond strength between mortar and masonry unit for three types of mortar mix (1:3, 1:1:6, & 1:3:12), as shown in Figure 2.5. It can be concluded that the value of  $20\text{gm}/30\text{in}^2/\text{min}$  ( $1\text{kg}/\text{m}^2/\text{min}$ ) is an optimum value for bond strength. This value is in agreement with ASTM specifications for clay brick C62-97a (The American Society for Testing and Material, 1998).

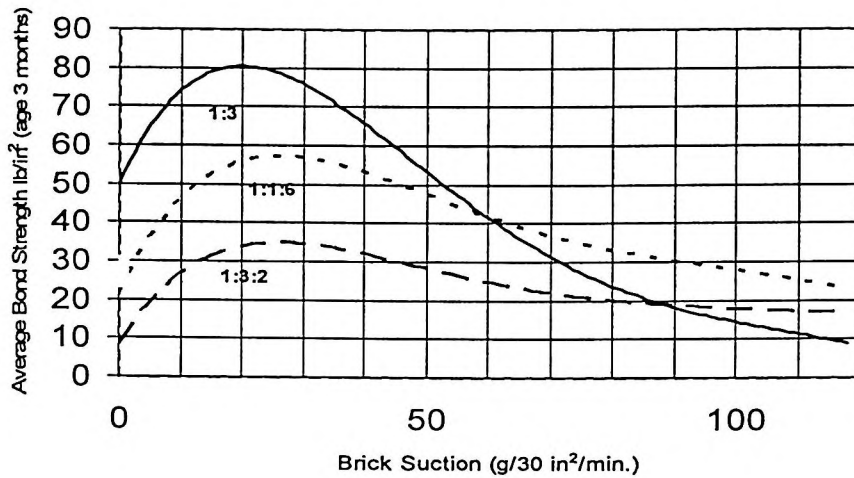


Figure 2.5: Effect of brick suction and water-retention capacity of mortars on bond strength (Plamer & Parsons, 1934)

### 2.1.6 Strength of masonry unit

The strength of masonry unit is given by the nominal stress at failure, i.e. the external force at failure divided by the gross cross-sectional area of the unit. The presence of pores reduces the cross-sectional area of the unit so that the actual average stress is higher than the nominal stress (Brooks, 2005). An even greater factor is the shape of the pores which can increase local internal stresses to two or three times. However, it is not the limiting internal compressive stress that is actually responsible for the failure but the limiting tensile stress, which is generated at right angles to the local compressive stress at the edge of the pores as shown in Figure 2.6 (Brooks, 2005).

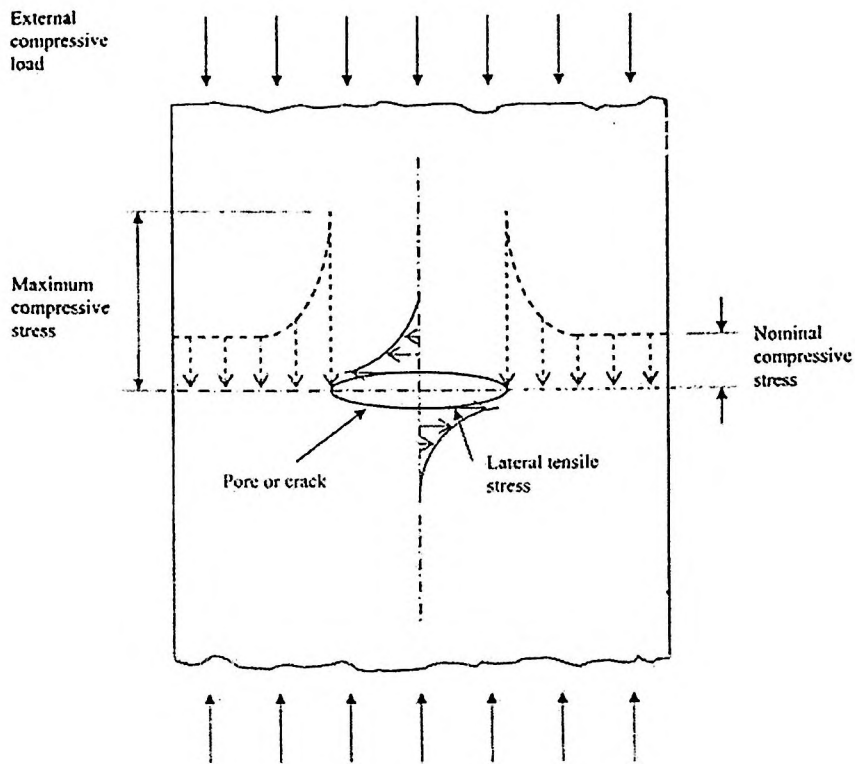


Figure 2.6: Generation of internal tensile stress at the edge of a pore or crack in a masonry unit under external compression (Brooks, 2005)

Another factor that determines the failure strength is the restraint of the steel platen of the testing machine, which prevents lateral movement of the brick unit due to friction. The compressive test of a masonry unit is critically dependent on the aspect ratio, i.e. height of the specimen relative to the cross-sectional area (Brooks, 2005). As the aspect ratio decreases, the observed compressive strength of the masonry unit increases due to confining effect of the platens on the testing machine. Therefore, the aspect ratio factor (height to thickness ratio) should be applied to the compressive test results to provide the value of characteristic unconfined compressive strength, which can be applied in design considerations (Australia / New Zealand Standards, 1997). The unconfined compressive strength enables all masonry units to be treated on an equal basis, which represents their true performance in a wall (Sneck, 1982).

Due to the aforementioned reason, the standard compressive strength test gives a measure of quality rather than a true strength. It is determined normal to the bed face of wet bricks with holes filled with hardened mortar (Zsembery et al., 1982). At least ten clay brick units to be tested between plywood platens and the strength of all units must be greater than 80% of the mean (Brooks, 2005).

The strength of masonry unit also depends on the moisture content of the unit at the time of testing. The higher the moisture content the lesser the strength is. In practice, moisture content of masonry unit in air-dry condition should be considered to estimate the design strength. Units to be tested should be conditioned by immersing in water or by oven drying; only then should the obtained compressive strength be converted to an air-dry condition. BS EN 772-1 (British Standard Institute, 2000) states that the conversion factors are as follows: 1.2 for units conditioned by immersing in water and 0.8 for the units conditioned by oven drying method.

Due to the reason that testing machines used in testing of brick unit with compressive strength above 70 MPa are scarce and expensive, Zsembery et al. (1982) examined the test of the whole brick unit as opposed to half or other portions of the brick unit. As shown in Figure 2.7, it was found that the pressed brick must always be tested as a whole unit (Zsembery et al., 1982). The AS/NZS 4455 (Australia / New Zealand Standards, 1997) requires brick manufactures to make available information about the characteristic unconfined compressive strength of masonry unit.

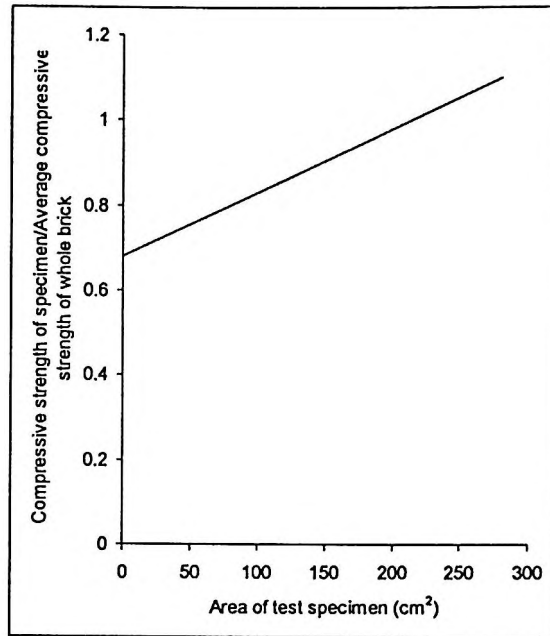


Figure 2.7: Pressed brick compressive strength against area of test specimen (Zsembery et. al, 1982)

### 2.1.7 Geometry of brick unit

The geometry of masonry unit varies and depends upon the type of product and also the purpose of application. The compressive strength of each unit is also very much influenced by the geometry of the unit (Dymiotis and Gutleiderer, 2002). It is not sufficient to define the compressive strength of unit by one figure but also by the dimension of the units (Dymiotis and Gutleiderer, 2002). In order to overcome the different strength of units with different dimensions of the exact same materials, shape factor has been adopted by British Standard 772-1 (British Standard Institute, 2000) as shown in Table 2.1.

Table 2.1: Shape factor to allow for different dimensions of brick unit (British Standard Institute, 2000)

Width (mm) \ Height (mm)	50	100	150	200	≥250
40	0.80	0.70	-	-	-
50	0.85	0.75	0.7	-	-
65	0.95	0.85	0.75	0.70	0.65
100	1.15	1.00	0.90	0.80	0.75
150	1.30	1.20	1.10	1.00	0.95
200	1.45	1.35	1.25	1.15	1.10
≥250	1.55	1.45	1.35	1.25	1.15
Interpolation is permitted					

### 2.1.8 Loading rate

Loading rate is the magnitude of load per minute applied on the masonry test specimen to determine the compressive strength. The loading rates (in terms of stress) used by Maurenbrecher (1980) to investigate the effect of loading rate on prisms compressive strength ranged from 9.5 MPa/min for extruded brick prisms to approximately 0.3 MPa/min for the running bond prisms made from pressed brick. As shown in Table 2.2, the slower rate of loading could reduce the compressive strength of brick prism as compared to standard rate of loading (Maurenbrecher, 1980).

Table 2.2: Compressive strength test results for brickwork prism utilizing slow and standard loading rate (Maurenbrecher, 1980)

Load rate	Pressed Brick		Extruded Brick	
	X (MPa)	V (%)	X (MPa)	V (%)
slow	15.9	12	35.3	4
Standard	17.1	16	36.7	8
ratio	0.93		0.96	

### 2.1.9 Workmanship

Workmanship is an important factor in the construction of masonry structures, which is significant in developing a specified strength (Hendry, 1987). The most common workmanship defects are as follow:

- i- Incorrect proportioning and mixing of mortar: the reduction in compressive strength of mortar cube from 14 to 7 N/mm<sup>2</sup> could reduce the compressive strength of brickwork built with brick units of strength of about 35 N/mm<sup>2</sup> from 16 to 14 N/mm<sup>2</sup> (Grimm, 1970).
- ii- Incorrect adjustment of suction rate: the absorption of water from mortar bed causes the mortar to be shaped as pillow at the edge of the masonry as shown in Figure 2.8. Therefore, when the load is applied, it tends to close the gap producing high elastic strain (Abu Bakar, 1998). This mechanism causes the strength of wall to be reduced greatly especially under eccentric loading or for slender wall built with relatively low strength bricks (Hendry, 1987).

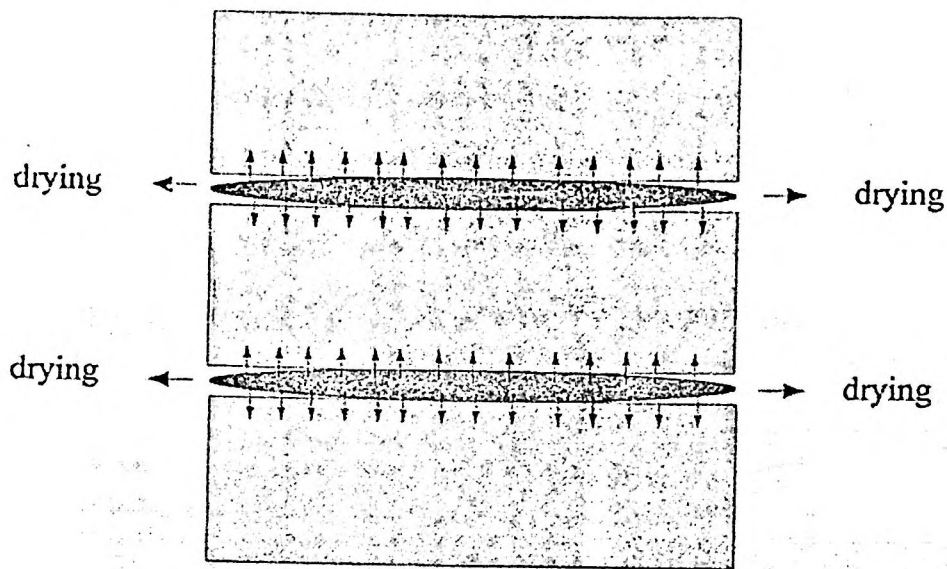


Figure 2.8: Effect of moisture absorption from mortar bed (Abu Bakar, 1998)

- iii- Incorrect joining procedure: incomplete bed joint causes high stress concentration which can lead to failure of the masonry under relatively low load (Grimm, 1970). Incomplete filling and deeply furrowed bed joint can also lead to a reduction of wall strength by as much as 33% (Hendry, 1987).
- iv- Failure to build wall plumb and true to line and level: this type of defect can cause rise to concentric loading in a wall under compression and thus reduces the strength. Walls built with alignment errors or out of plumb by about 18 mm may be 12-20% weaker than these built correctly (Hendry, 2001).
- v- Failure to protect work from weather: walls built in ambient temperatures between 25.6 to 37.8 °C and cured under the hot sun for five or six days showed reduction in strength of about 10% as

compared with walls cured in the shade under polythene sheets (Grimm and Hasell, 1970).

### **2.1.10 Concluding remark**

From the review of the research works shown above, it can be seen that considerable research works have already been done on the factors affecting the compressive strength of the axially loaded masonry wall. The findings of those researches are utilized in the planning of the experimental works done in this research study.

## **2.2 Modeling masonry- a literature review**

### **2.2.1 Introduction**

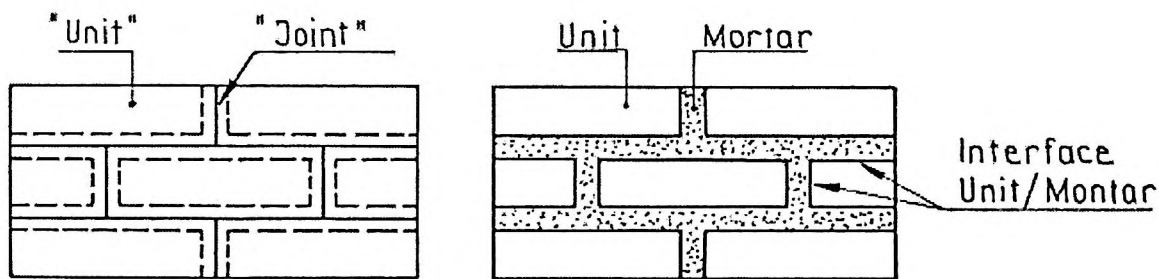
This section presents a short literature review of modern numerical strategies applied to model the mechanical properties of masonry. Masonry is a composite material consisting of units and mortar jointed in a regular pattern. There is a considerable range of possible material combination, all of which result in masonry with different mechanical properties (Molnar, 2000). Whether masonry should be treated as homogeneous continuum or as a system consisting of discrete constituents depends on the behavior to be modeled, stress state and desired level of refinement (Massart, 2003).

Studying a real structure by discretization of its components can be unwieldy due to large number of elements in the model (Molnar, 2000). It can be convenient to treat masonry as a homogeneous material and establish a

constitutive relation between the average stress and strain. The following sections survey the three basic approaches to model the behavior of jointed masonry, which have been proposed (Molnar, 2000):

### 2.2.2 Micro – level

In this approach, the brick units are mostly presented by continuum elements and the mortar material between the brick units is presented by either continuum or interface elements as shown in Figure 2.9, modelling phenomena resulting from different elastic properties of brick units and mortar (Massart, 2003; Molnar, 2000; Lourenco, 1996; and Rots, 1991).



a) Simplified micro – modeling      b) Detailed micro- modeling

Figure 2.9: Modeling masonry at micro-level (Lourenco, 1996)

Ali and Page (1988) presented a micro-level finite element model for brick masonry subjected to in-plane concentrated loads. Non linear phenomena such as tension bond failure, cracking and crushing were accounted for. Both bricks and joints have non linear constitutive relations, determined from tests as shown in Figure 2.10. The properties of the bricks were obtained from compression tests on masonry wallets. The technique of smeared crack modeling is applied in order to account for the effect of cracking. It was

concluded that better agreement with experiments achieved, when realistic strain softening parameters are used instead of the initially assumed elastic-brittle behavior.

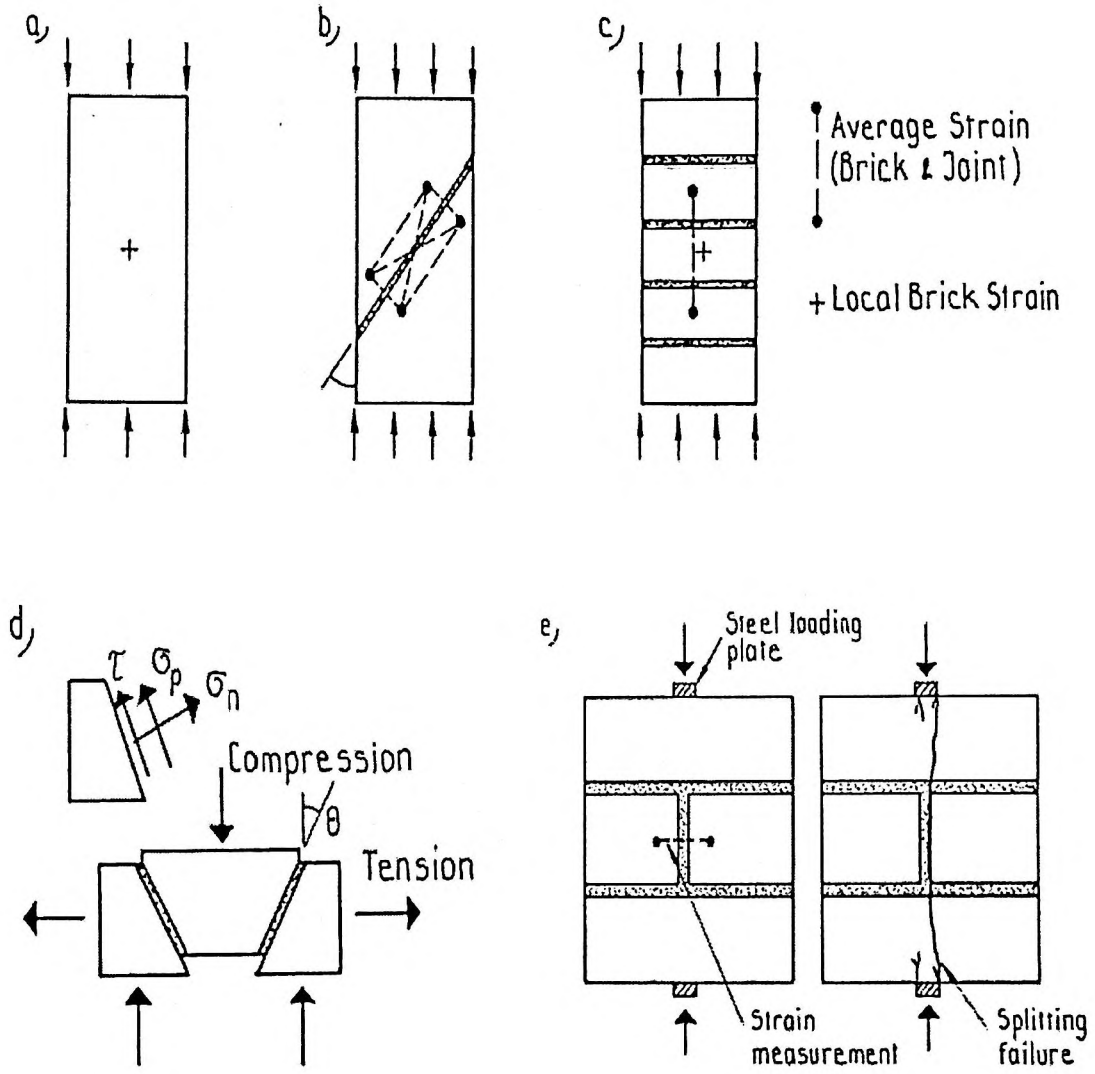


Figure 2.10: Tests performed in order to obtain material properties and failure criteria for modeling masonry subjected to concentrated loads: (a) compression on bricks; (b) and (c) compression on prism and couplets; (d) triplet tests; (e) splitting tests (Ali and Page, 1988)

2.2.3 Macro level

Macro level models treat masonry as a homogeneous anisotropic material (Lourenco, 1996). This is a major advantage, because relatively large

wall panel can be modeled with low computational efforts (Molnar, 2000). Constitutive relations are established in terms of average stresses and strains. Yield criterion and hardening rules are applied to the composite material. As a practical consequence, the anisotropic plasticity approach requires the properties of masonry to be deduced from experiments on relatively large specimens, under various loading conditions. Figure 2.11 presents the tests required to calibrate an anisotropic plasticity model proposed by Lourenco (1996). Performing all the proposed tests, in particular those where wallets are tested in uniaxial and biaxial tension, seems time consuming and costly. Besides the high costs, macro level models are only able to describe the behavior of the tested material combinations.

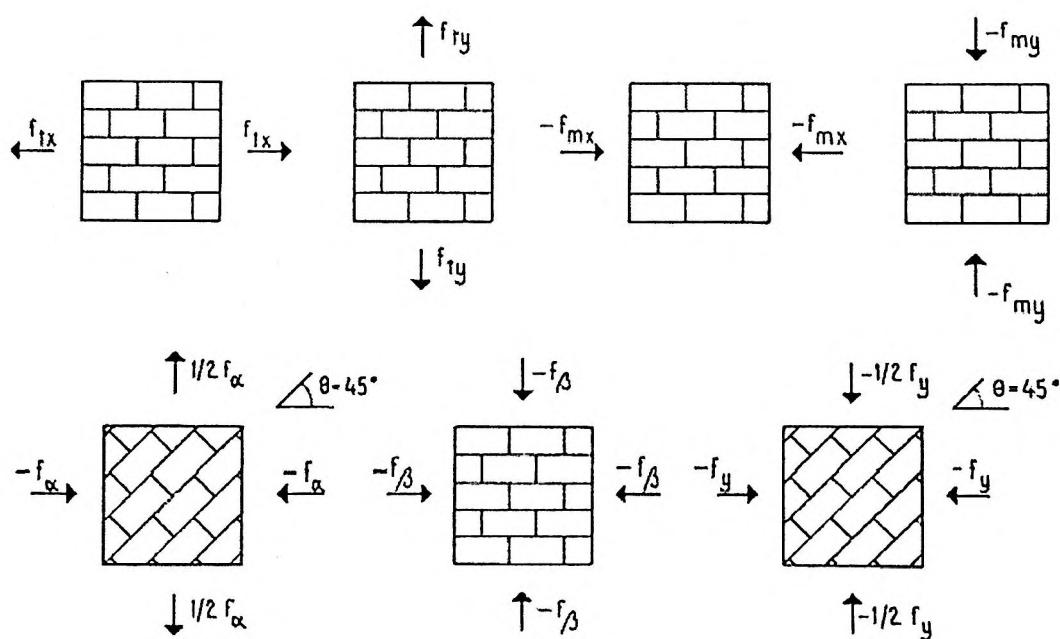


Figure 2.11: Plasticity model (Lourenco, 1996)

## 2.2.4 Homogenization

The technique of homogenization is aimed to solve the problem of modeling the mechanical behavior of large masonry structure, by treating