EFFECT OF THE SLENDERNESS RATIO ON MASONRY WALL UNDER AXIAL COMPRESSIVE CYCLIC LOADING

by

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LIST OF ABBREVIATIONS

BS	British Standard
ASTM	American Society for Testing and Materials
UTM	Universal Testing Machine
MB	Mortar Batch
FEA/FEM	Finite Element Analysis/Finite Element Method

LIST OF SYMBOLS

c_{mr}	mortar cohesion
$\emptyset_{mr}$	mortar friction angle
f_{mr}	compressive strength of mortar
Ac_{mu}	masonry unit cohesion
$\emptyset_{mu}$	masonry unit friction angle
f_{mu}	compressive strength of masonry unit
$\emptyset_{i}$	initial internal friction angle
$\emptyset_{f}$	final internal friction angle
σ_{m}	mean stress
I_{1}	moment inertia
E_b	Modulus of elasticity of brick
Em	Modulus of elasticity of mortar
V	Poisson’s ratio

ABSTRAK

Nisbah kelangsingan sesuatu struktur merupakan faktor penting bagi struktur tersebut untuk berupaya menanggung beban mampatan. Struktur bata merupakan struktur yang mampu menampung beban mampatan namun nisbah beban hidup kepada beban mati yang besar boleh menggagalkan struktur bata kesan daripada mengalami beban dan tidak mengalami beban secara berulang. Apabila struktur bata terdedah kepada dua faktor utama ini, adalah menjadi keperluan untuk mengkaji kesan nisbah kelangsingan struktur terhadap struktur bata yang dikenakan beban mampatan berulang. Dalam kajian ini, dua belas binaan panel bata dengan ketinggian berbeza mewakili tiga nisbah kelangsingan diuji dengan mengenakan beban mampatan statik dan beban mampatan kitaran berulang. Daripada kajian ini didapati nisbah kelangsingan memberi kesan terhadap kekuatan panel bata sebagaimana yang dijangka di mana kekuatan panel bata berkurang apabila nisbah kelangsingan panel semakin tinggi dan paten beban kitaran berulang ini tidak memberi kesan terhadap kekuatan panel bata tersebut. Manakala kelengkungan tegasan dan keterikan spesimen yang dikenakan beban kitaran menepati kelengkungan tegasan dan keterikan spesimen yang diuji di bawah beban mampatan statik. Dalam kajian ini juga, kajian kesan nisbah kelangsingan ini dikaji dengan membuat analisis elemen terhingga di mana dari keputusan analisis yang diperolehi daripada Analisis Elemen Terhingga dapat mempersembahkan kajian secara eksperimen dengan baik walaupun kurang tepat. Panel bata mengalami pecahan pada muka panel bata dan keretakan sepanjang web bata manakala di bahagian tengah panel bata didapati berlaku kegagalan bagi panel yang paling langsing disebabkan kelengkokan.

ABSTRACT

Slenderness ratio is one of the factors affecting the capacity of masonry wall to resist compressive loading. Masonry wall structure is able to withstand compression load but having the large live to dead load ratio would impair the structure capability to withstand cycles of repeated loading and unloading condition. When the masonry structure is exposed to this combined factor, it is desirable to investigate the effect of the slenderness ratio on masonry wall subjected to cyclic compressive loading. In this study, twelve specimens of single leaf walls had been tested under monotonic and cyclic compressive loading with different height representing three different slenderness ratios. From this study the stress-strain curve of from the monotonic and cyclic load test was obtained and the relationship between the compressive strength and slenderness ratio of the masonry wall had been evaluated. It was observed that the masonry wall subjected to the cyclic compressive load behave as expected whereas the strength of the wall was decreased as the slenderness ratio increased and the cyclic loading pattern did not show significant effect. Meanwhile the stress-strain curves of cyclic test generally showed good agreement with the curves of the monotonically loaded specimens. This study also investigates the masonry wall strength subjected to compressive loading in relation to slenderness ratio effect using numerical modeling analysis. From the analysis, it was concluded that the analysis performed satisfactorily with poor accuracy and the vertically loaded wall under cyclic load test exhibited face-shell spalling and vertical cracking through the web and face shell and for the increasing the wall slenderness ratio, the wall chipping break about the middle of the wall due to buckling.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Masonry structures are the oldest structure that has been known as the ancient structure through the years. It has been used in many structures such as buildings, retaining wall, tunnel lining, bridge, etc. Masonry is an assemblage of the brick, block, stone, etc. that usually agreed as structural elements able to resist compression vertical loading and also act as elements that provide resistance against in-plane and out of plane lateral loading.

Masonry is a non-homogeneous, anisotropic composite material whereas the bricks or block as the building units and the mortar as the joining material, those are bonded together at an interface. The basic mechanical properties of the masonry are strongly influenced by the mechanical properties of these two constituent materials. The masonry compressive strength is widely used in masonry design and it can be calculated by testing masonry prisms, composed of two or more units, placed one over the other with mortar.

Type of masonry units has an important influence on the masonry compressive strength. Masonry units differ in the material (clay, concrete or other), in the size (bricks or blocks), and in the fabrication process (artisan or industrial). Therefore, prisms tests using local units need to be done, to determine correctly the value of compressive strength to be used in local design codes. The value of compressive strength depends on the slenderness of the wall and number of factors and research work by Sinha (1990) showed that the uniaxial compressive strength of brickwork in any direction depends on the brick strength, mortar grade, slenderness ratio and workmanship.

Masonry wall are commonly used in building constructions around the world for its low cost material and wide-ranging availability, and its sound isolation properties and energy proficiency. A part of that, with an applicable selection, masonry may be expected to remain serviceable for many decades with relatively low maintenance.

1.2 Problem Statement

Compressive strength of masonry depends on the geometry and type of the units, unit strength, mortar grade, slenderness ratio, workmanship, etc. If possible to apply actual axial loading to walls then the type of failure which would occur would be reliant on the slenderness ratio which is the ratio of the effective height to the effective thickness. For short solid walls, where the slenderness ratio is slight, failure would result from compression of the material; meanwhile for long thin walls and high values of slenderness ratio, lateral instability would occur. It was observed that brickwork with lower slenderness ratio produced higher compressive strength. The prediction of the collapse load and mode of failure is greatly affected by the model used to analyze the masonry wall. In order to better understand the strength characteristic of the masonry wall, it is very important to study the constitutive laws of the components of masonry such as brick and mortar and their interaction. Nevertheless, a significant simplification is possible by assuming masonry to be a continuum medium. An average stress strain relationship between brick and mortar is then considered.

The vertical loads effectively pre-stress the masonry work and increase its resistance to cracking on the bed planes. The modern masonry wall constructions allow slenderness of the wall and the eccentricity of vertical loading by the application of a reduction factor to the masonry strength. However, slender masonry walls may be especially sensitive to the combined effects of vertical and dynamic loads because of the possibility of failure due to vertical instability.

The study on dynamic response, behavior of brick masonry under cyclic compressive loading are not been fully developed. There are numerous studies of masonry wall capacity and behavior subjected to cyclic loading but the finding was in connection to seismic design of buildings with no particular emphasis into cyclic deformation characteristics of the masonry assemblage. As mentioned in previous, compressive strength of masonry wall affecting by slenderness ratio by decreasing the compressive strength of the wall as the slenderness ratio increased and it was expected being vulnerable with combining effect of cyclic loading. The study on effect of slenderness ratio on masonry wall under axial compressive cyclic loading is crucial for the masonry structures that expose to the large live load to dead load ratio e.g. bridge, piers, tunnel, industrial building and etc. Therefore, it is desirable to adopt wall slenderness ratio as a criterion for dynamic assessment under compressive cyclic loading test with the developing model throughout the experimental to investigate the relation between the compressive strength of the masonry wall and the slenderness ratio. The idea on developing numerical analysis using finite element should be very useful to predict the behavior of the masonry with consuming less time and cost.

1.3 Objectives

The objectives of this research are:

i. To investigate the effect of the slenderness ratio on masonry single leaf wall subjected to compressive cyclic loading.
ii. To investigate the relation between the failure loads of the masonry wall and slenderness ratio subjected to compressive loading using numerical modeling analysis.
iii. To compare the experimental results on capacity of the wall and mode of failure obtained from numerical and experimental study.

1.4 Scope of Work

The materials used in this research are one type of common clay bricks from local manufacturer. Only type of mortar designation was used in this study which is mix proportions of 1: 1/2: 41/2 for cement, lime and sand respectively with mortar mix 1.1 of water/cement ratio. This research looks into the masonry wall compressive strength subjected to compressive cyclic loading being affected by different slenderness ratio of a single leaf masonry wall. The different ratio was taken appropriate to the wall specimens that built up with full scale masonry unit and not beyond the maximum slenderness ratio permitted according to BS 5628 (2005) which is 27. Generally, the limitations of the research works are described as follows:

i. Materials: One type of common clay bricks from local manufacturer.
ii. Equipments: Universal Testing Machine, Load Cell with Data Logger and Loading Frame and Flow Table apparatus.
iii. Parameters of study: Stress-Strain of the bricks, mortar and masonry wall, displacement under loading and failure mode of masonry wall specimen
iv. Specimens: Twelve Single Leaf Wall Specimens with 3 different slenderness ratios with approximately 10 mm mortar joint vertically and horizontally
v. Type of Mortar: M6
vi. Hinged-hinged support condition
vii. Loading Pattern: Monotonic and Cyclic loading

The research involved experimental works and numerical modeling and it was conducted in two stages. In the first stage, experimental tests were conducted to determine the mechanical properties of materials and conducted wall compressive tests subjected to monotonic and cyclic loading type. Second stage by using data from mechanical properties of materials, numerical modeling was simulated using finite element software LUSAS 14 for masonry wall under monotonic test loading type and validated by with experimental results. Next chapter is the literature review of the studies on the related field to appreciate the reference and gaps in what has been done.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a literature review of work published by previous researchers and authors subjected to related field of study which are described in flow on the behavior and strength of masonry wall, influence of slenderness ratio, masonry wall under cyclic loading, failure mechanism of masonry and the current numerical models used for the estimation of masonry wall under axial compressive cyclic loading.

2.2 Compressive Behavior of Masonry

Masonry is typically non-elastic, non-homogenous and anisotropic material composed of two materials of quite different properties which are stiffer bricks and relatively softer mortar. Masonry composed of two different materials disseminated at regular intervals and having the weak bond between them make the masonry is very weak in tension. Hence masonry is normally provided and expected to repel only the compressive forces.

This condition is very different from what happens in numerous cases where two materials have the other way round of different properties which are softer bricks and relatively stiffer mortar. It is useful to observe that the brick masonry in such situation has implications on the nature of stress in the brick and mortar where the brick has a modulus of elasticity that is much lower than the mortar. This characteristic of brick is often found in South India (Sarangapani et al., 2005). Sarangapani et al. (2005) in their studies observed that for strain compatibility, stiffer mortar pulling the bricks inwards that make the bricks having compression. The shear stress of the brick-mortar interface will lead to horizontal compression in the brick. Soft brick-stiff mortar masonry experience the failure mechanisms based on the shear bond strength of the brick mortar interface. The brick will develop a large horizontal compression with higher bond strength as long as the high shear stress in the brick-mortar interface is persistent.

Thus, the mechanical properties of masonry as a composite material are the functions primarily of the mechanical properties of the individual masonry units, mortars and the bond characteristics between the units and mortar. The elastic modulus of masonry is controlled by the combined elastic modulus of masonry units and mortar (Hamid et al., 1987). Generally, it is believed that the strength and the stiffness of masonry lies somewhere between them since masonry is an assemblage of bricks and mortar. It may be true in cases when one component of masonry either bricks or mortar is significantly weaker and softer than the other (Kaushik, 2007).

It was easy to conduct compressive strength test and it gives a good indication of the general quality of material (Abdul Kudus, 2010). The Eurocode 6 (1995) used the compressive strength of the components to determine the strength of masonry even if a true indication of that value is not simple. Masonry unit and mortar joint under load could be subjected to a complex stress state that produces failure by reaching the tensile strength of the unit or even mortar crushing.

For real situation, unreinforced masonry construction results in an anisotropic material. However, for a simplified design approach, the elastic properties of masonry materials are usually considered as isotropic. These elastic properties are taken as those determined from tests on masonry prisms perpendicular to the bed joints. Drysdale and Hamid, (1980); Lee et al., (1984); and Khalaf, (1997) showed that the compressive strength of masonry parallel to the bed joint is less than the compressive strength of masonry normal to the bed joint. Figure 2.1 outlines the stress-strain relationship for both prisms with loading normal and parallel to the bed joint.

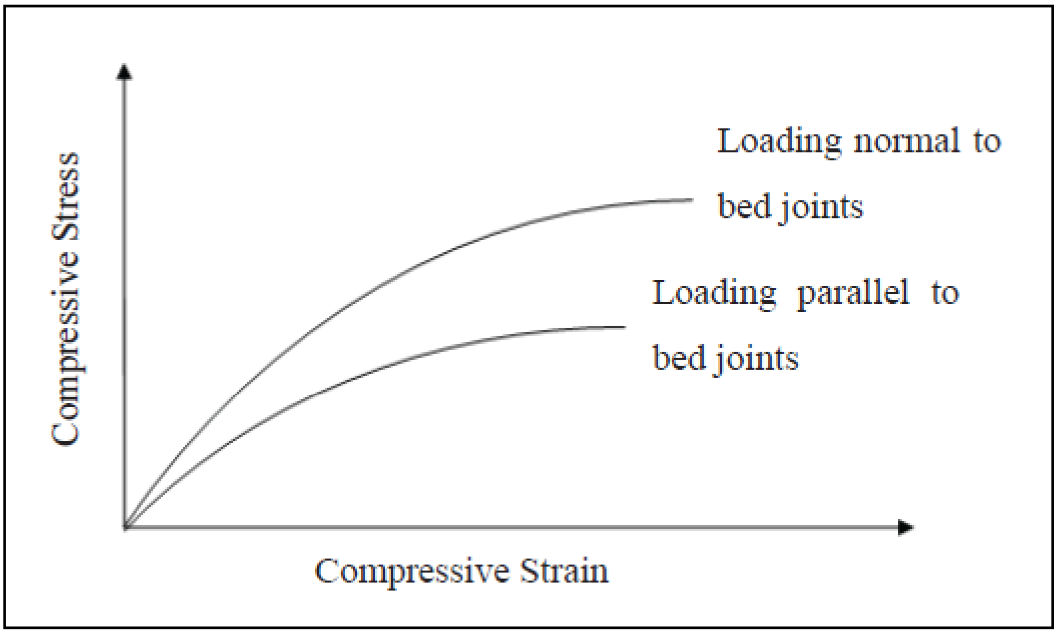

Figure 2.1: Schematic stress-strain relationships for masonry prisms subjected to loading parallel and normal to the bed joints (Tamara, 2013)

2.2.1 Stress-Strain Characteristics of Masonry

The stress-strain relationship is one of the parameters for structural masonry design that subjected to vertical and horizontal loading. It is important to understand that, the stress and strain mechanisms developed on masonry for design as the stress-strain curve reveal many properties of a material including data establish the modulus of elasticity, (E_b). The large scatter of experimental test, compressive strength of unit, shape of units (hollow or solid), compressive strength of mortar and state of stress developed during loading particularly influence mechanical property, E_b. Knowledge of the stress-strain relationship for brickwork is frequently required in structural design and to confirm a non-linear stress-strain relationship for brick masonry prisms tested in compression available is ample with experimental evidence (Naraine and Sinha, 1989).

Knutson (1993) evaluated the stress-strain curve for various masonry materials and showed that they can be cast in to a mathematical form. Complexity for masonry, the failure mechanisms depends on the difference of E_b between unit and mortar.

Khausik et al (2007) in their study on stress-strain characteristics of clay brick masonry under uniaxial compression observed that for the strong and stiff bricks and mortar of lesser but comparable strength and stiffness, the stress-strain curves of masonry do not necessarily fall in between those of bricks and mortar. In that experimental study, non-linear stress-strain curves have been obtained for bricks, mortar, and masonry and six “control points” have been identified on the stress-strain curves of masonry, which can also be used to define the performance limit states of the masonry material or member.

The stress-strain characteristic of brick masonry under uniaxial and biaxial compressive monotonic loading has been widely investigated over a long period of time and studies on the influence of the orientation of the bed joint on its deformation and failure characteristic also have been reported. The stress-strain relationship of brickwork is non-linear where deformation of resulting compressive strain depends on the type of the test prisms and significantly affected by the grade of mortar. The deformation increased with decreasing mortar strength or grade (Sarangapani et al., 2005).

2.2.2 Factor Affecting Compressive Strength of Masonry Wall

The compressive strength is the most important mechanical property in design. Also, testing for the compressive strength of the component materials and prism is an essential quality control procedure used in construction. It has been established that the compressive strength of the masonry assemblage differs from the compressive strength of individual components of prism. Typical compressive strength of masonry units is relatively high but the compressive strength of mortar is low. It was observed that the resulted prism strength is found to be somewhere between the compressive strength of the masonry units and mortar.

Compressive strength of masonry wall depends on a number of factors. It was witnessed that the bond between brick and mortar is crucial for the composite behavior between two materials. It is useful to understand the correlation between bond and the compressive strength since the development of lateral tension and compression in the brick and mortar or the other way round is based on the assumption that there is no bond failure at the interface. Sarangapani et al. (2005) conducted a series of tests on masonry prisms with very soft bricks having modulus of elasticity of less than 500 MPa and combination of different mortar grades. For the soft brick-stiff mortar masonry, it was observed that the compressive strength of masonry prisms increases with the increase in bond strength, whereby the bond strength increases with the mortar strength and with other factors. The strength of masonry prism was observed to be more sensitive to brick-mortar bond strength than mortar compressive strength.

The compressive strength of masonry was also reported by Mckenzie (2001), where it is depending on numerous factors such as the mortar strength, unit strength, relative values of unit and mortar strength, aspect ratio of the units (ratio of height to least horizontal dimension), orientation of the units in relation to the direction of the applied load and the bed-joint thickness. The listed factors give an indication of the complexity of making an accurate assessment of the masonry strength.

Maisarah (2004) found that, the variation in mortar designations would also influence the compressive strength of brickwork. High strength mortar was discovered to be significant in improving brickwork prisms strength if low strength masonry units were used during construction of brickwork and vice versa. Masonry unit with lower strength will fail before the mortar. Other than that, it is also observed that, there is a direct relationship between the construction materials and the modulus of elasticity. The usage of high strength masonry unit and mortar designation will contribute to high modulus of elasticity. As the deformation rate is slow, higher failure load was obtained.

In addition to that, Bakhteri and Sambasivm (2003) showed experimentally for a brick of given height, brick strength is reduced as the joint thickness is increased and it was proven by Bakhteri et al. (2004) using finite element modeling. Apart from that it was reported that eccentricity of loading also influences the masonry strength. When load is applied away from the center of a uniformly loaded wall or prisms, there is often an apparent increase in compressive strength.

Water absorption behavior of masonry unit is one of the important factors affecting the fresh mortar, and consequently the properties of mortar joint and masonry strength. Masonry unit tends to absorb water from the fresh mortar when they are laid dry. If the rate of water absorption is high, the migration of water from fresh mortar to masonry unit will impair the hydration process and subsequently result in poor bonding interfacial between unit and mortar. Apart from affecting the hydration of mortar due to capillary action of the units, the possibility of reduction in strength increases. Initial Rate of Absorption (IRA) and Water Absorption (WA) tests are normally performed on brick units to get information about quality of bricks. Drysdale et al. (1994) observed such bricks may tend to flow on mortar, particularly if the bricks are damp if IRA is less than 0.25 kg/m^2/min, which is a case for low absorption or low-suction bricks. On the other hand, for highly porous and absorptive bricks (IRA>1.5 kg/m^2/min), thin mortar joints with less water-cement ratio results of poor brick-mortar bond because of water in mortar having rapid suction by bricks.

Research worked by Sinha (1990) showed that the uniaxial compressive strength of brickwork in any direction depends on the brick strength, mortar grade, slenderness ratio and workmanship. It was observed that brickwork with lower slenderness ratio produced higher compressive strength.

2.3 Relation between Compressive Stress and Slenderness Ratio of Masonry Wall

Failure will occur on masonry wall if it possible to apply pure axial loading and the type of failure which would occur would be dependent on the slenderness ratio, which is the ratio of the effective height to the effective thickness. If the slenderness ratio is low, failure would result from compression of the material, whereas for long thin walls and higher values of slenderness ratio, failure would occur from lateral instability (Hendry et al. 1997). A typical failure stress is shown in Figure 2.2.

The modern masonry wall constructions allow slenderness of the wall and the eccentricity of vertical loading by the application of a reduction factor to the masonry strength. In traditional construction usually the load bearing walls are relatively thick and if the ratio of height to thickness (h/t) is no more than about 10, the effect of slenderness will be negligible. Eurocode-6 (1995) and BS 5628 (2005) limits the slenderness ratio for masonry wall to 27. Within this constraint Hendry (1976) calculated maximum stresses due to eccentric loading by using conventional linear theory. The maximum compressive strength should not exceed the material strength divided by an appropriate safety factor whereas no tensile strength is assumed in this case.

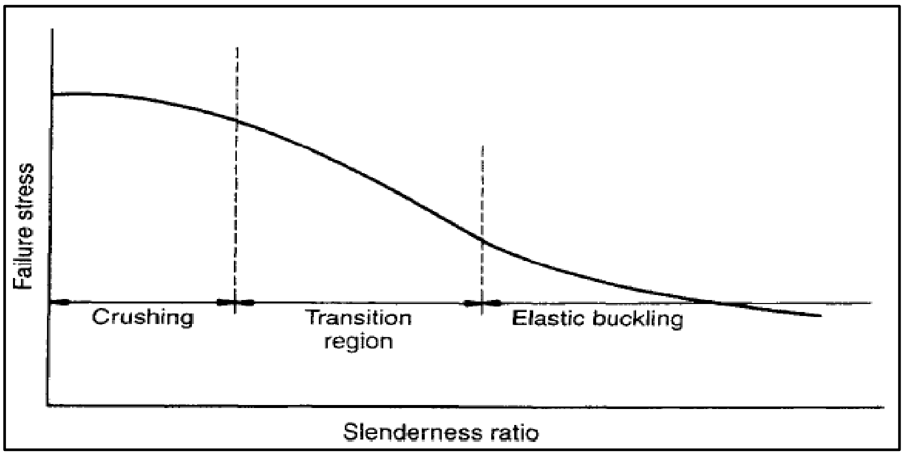

Figure 2.2: Failure stress plotted against slenderness ratio (Henry et al., 1997)

Primary variables in the calculation of the compressive strength of a masonry wall, in addition to the unit strength, include the eccentricity of loading and the slenderness ratio (Hendry, 2001). Both of these are difficult to assess on a theoretical basis depending as they do on interaction between wall and floors and the presence of interconnected walls. Allowance for eccentricity and slenderness in design requires in turn the viability of a capacity reduction factor and a variety of theories on which to base this have been developed. High slenderness ratio and low reduction factors indicate general buckling when low slenderness ratio and high reduction factors produce Euler buckling.

Kirtschig and Anstotz (1991) have developed the relation between the compressive stress and slenderness ratio in their study on the influence of slenderness ratio and eccentricity of the load on the load bearing capacity of the masonry subjected to different practice in various codes. The main objective of the experimental tests developed by Kirtschig and Anstotz (1991) was to verify the overestimation by comparing load bearing capacity values with theoretically derived results. The relation between compressive stress and slenderness ratio developed by Kirtschig and Anstotz (1991) is shown in Figure 2.3. The relation clearly showed the slenderness ratio affected the strength of the wall. The strength masonry wall decreased with increasing the slenderness ratio and buckling failure greatly affecting by the eccentricity of loading applied.

In that test, the masonry units considered for the test were calcium silicate and lightweight aggregate concrete with average compressive strength of the units 20.9 MPa and 4.1 MPa respectively. For the specimens, mortar with a compressive strength of about 5 MPa was used. The length of the walls was about 1 m and a thickness of 11.5 cm. In this study, the authors introduced the study with different slenderness ratio; walls were made of different heights. These heights were 63.5 cm, 125 cm, 212 cm and 312 cm, which translates into approximately slenderness ratio (calculated as ratio between height and thickness) of 5.6, 11.1, 18.8 and 27.7. A total of 64 walls were tested (32 for each type of wall).

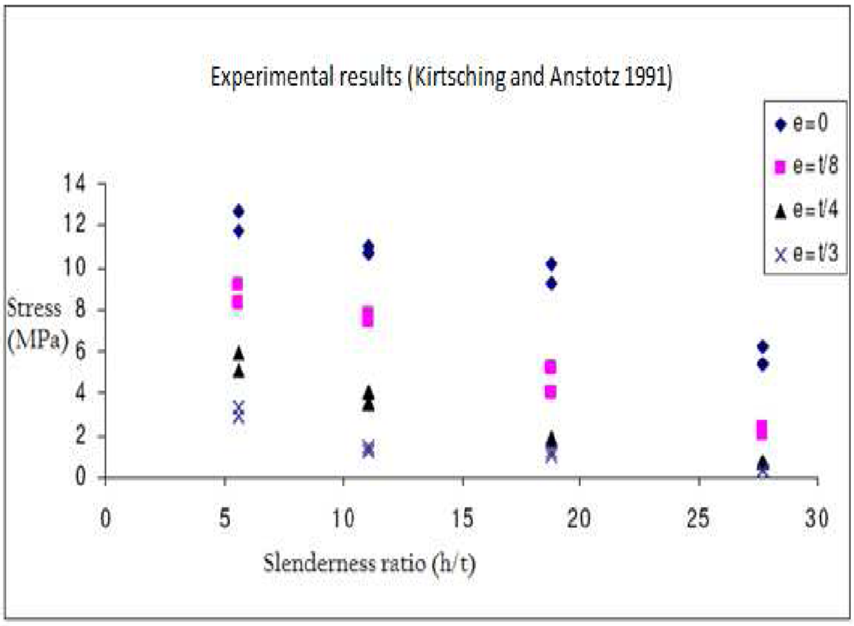

Figure 2.3: Relation between compressive stress and slenderness ratio in case of calcium silicate units (Kirtschig and Anstotz, 1991)

Meanwhile, the effect of slenderness ratio and eccentricity on the compressive strength of walls was investigated by Hasan and Hendry (1976), to determine whether the reduction factors prescribed in various codes are conservatives. One third scale model has been tested with axial and eccentric loading and with various end conditions. The results were compared with various national codes. Twenty five specimens were tested in different end conditions such as flat ended, reinforced concrete slab and hinged with different load eccentricity. The walls were constructed by using stretcher course and English bond. The results found in this test showed decreased in strength of walls of flat ended with the increase in slenderness ratio except for wall with slenderness ratio of 12. The relation between compressive stress and slenderness ratio in this study had been developed as shown in Figure 2.4.

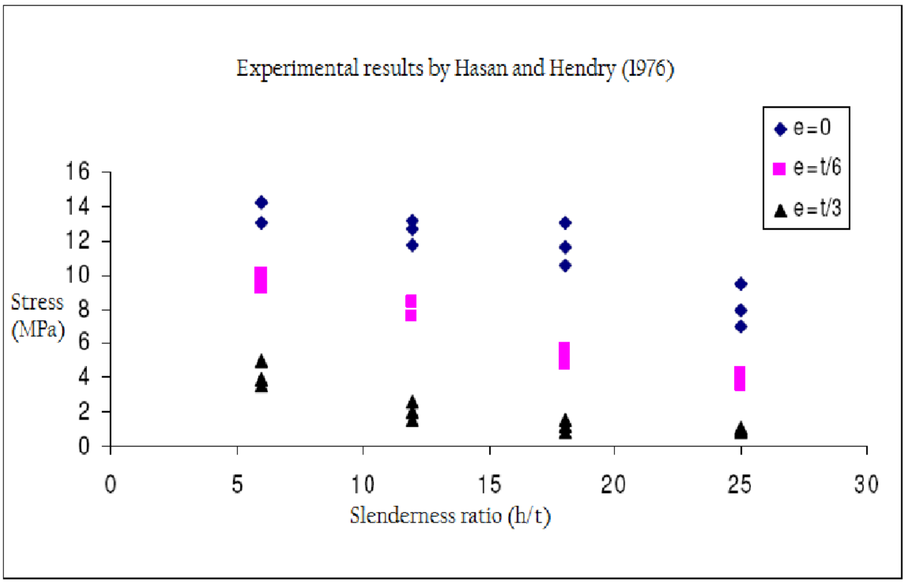

Figure 2.4: Relation between compressive stress and slenderness ratio (Hasan and Hendry, 1976)

Besides of type of masonry units, the masonry compressive strength also depends on the slenderness ratio. ASTM C1314 (2003) uses a nominal slenderness ratio of 2 for masonry prisms in determination of masonry compressive strength. For other slenderness ratio, a set of correction factor is given. Bartolome and Quiun (2007) had been reviewed different masonry design codes or standards to compare the way the slenderness ratio is considered to determine the masonry compressive strength. The revision included documents from USA, Mexico, Chile, Columbia and Peru. They concluded that the Masonry Codes differ in the correction factors, the normalized slenderness ratio and the minimum number of layers of each prism and the tests for evaluation of slenderness correction factor for masonry prisms was carried out. From the investigation that had been done the experimental results demonstrated that data was very sensitive to slenderness ratio below 3. Therefore, for the normalized slenderness, it was suggested to use a ratio larger than 2 as reference to ASTM code practice. Also, the prisms should be composed of at least 3 layers to avoid test problems in smaller specimens.

In addition, study of behavior and strength of masonry prisms loaded in compression by Tamara (2013) noticed that prisms height does not seem to have a pronounced effect on the compressive strength of prisms. This is different from some previous studies where an increase in the height to thickness ratio was shown to lead to a reduction in the prism compressive strength. This discrepancy is believed by using the small size of the scaled block. The effect of the height was possibly outweighed by the inherent scatter in the test results.

Tu et al. (2011) in the other hand studied about slender confined masonry panels under monotonic and cyclic loading. Position of tie column, the number of panels and the loading pattern is the main variables in this experiment. Monotonic loading was applied to test the three specimens including two single wing-walls with tie column placed at the tensile and compressive side respectively and one twin wing-wall with the tie column place at the middle. Another test was cyclic test on single wing-wall and twin wing-wall specimens. Common factor in the three types of the wall is slenderness, and the main difference between them is the condition of the vertical boundaries. All fives specimens were tested with in-plane lateral load and also being subjected to a vertical compression force. The test result indicated that the loading pattern did not significantly affect the behavior of the specimens but the failure of the wall was severely affected by the position of tie column.

Abdul Kudus (2010) in his study on numerical simulation on buckling failure of the masonry load bearing walls involved the diverse combinations of slenderness ratio and load eccentricity used in the experimental program which provided the means for comprehensive numerical analysis of the masonry wall. In this research a set of experimental tests on the buckling failure of masonry wall has been numerically simulated by means of simplified micro-modeling approach. The parametric analysis shows that the end condition has great influence on ultimate capacity and buckling behavior of the masonry wall.

Study on effect of unreinforced masonry wall slenderness ratio on out of plane post cracking dynamic stability had been made by Derakhshan et al. (2010). They found that wall slenderness ratio governed the wall behavior although ground motion records were different in nature and the results confirmed that wall evaluation method based on wall slenderness ratio is viable option for predicting the out of plane stability of cracked wall.

2.3.1 Mode of Failure Affected by Slenderness Ratio

Failure mode of masonry in compression is usually one in which a tensile crack propagates through the units and the mortar in the direction of the applied load (Mckenzie, 2001). Figure 2.5 shows the failure mode of masonry in compression as a result of tensile stresses resulting from restrained deformation of the mortar in the bed joints of the brickwork. The tensile stresses inducing the crack are developed at the mortar-unit interfaces and are due to the restrained deformation of the mortar. In most cases, masonry strength is considerably less than the strength of the individual units. It can however be considerably higher than the mortar strength. The apparent enhancement in the strength of the mortar is due to the biaxial or triaxial state of stress imposed on the mortar when it is acting compositely with the units. The compressive strength of brickwork varies, roughly, as the square root of the nominal brick crushing strength, and as the third or fourth root of the mortar cube strength.

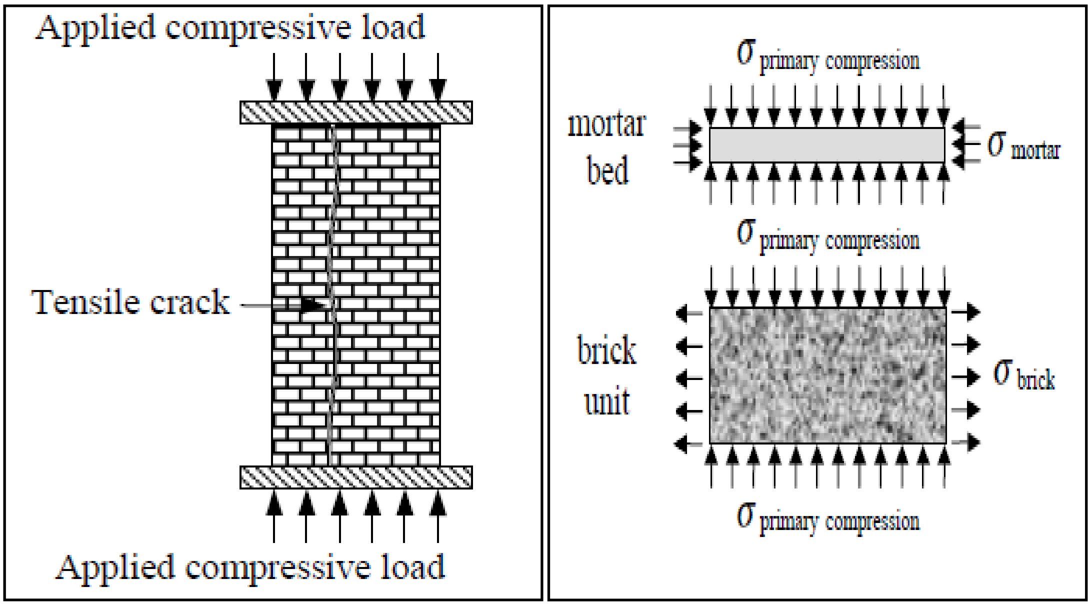

Figure 2.5: The failure mode of masonry in compression (Mckenzie, 2001)

In addition, Gihad et al. (2012) reported that the failure mechanism of masonry caused by initiation and propagation of cracks, which starts from mortar that exhibits high porosity and different sizes of voids with a possible initial decrease in volume caused by closing of flaws and voids.

In the case of ungrouted prisms, when the stresses are applied parallel to the bed joints, Drysdale and Hamid (1980) and Lee et al. (1984) found that ungrouted prisms exhibited vertical splitting across the central webs due to tensile stresses that are developed within the blocks. While Drysdale and Hamid (1980) reported that grouted prisms displayed a similar failure mode as ungrouted prisms, Lee et al. (1984) observed otherwise. Lee et al. (1984) noted that for ungrouted prisms failure was sudden and horizontal cracks were developed in the flanges of the units near the loaded surface, these cracks diminished towards the mid-height of the prism. For grouted prisms, the mortar joint failed at an early stage and the prisms experienced severe cracking of the bed joints and cracking or crushing of the head joints.

Any compression member usually fails both due to the buckling and material overstressing. The more slender the member the greater the possibility to buckling failure; the more squat the member the greater propensity to material overstressing. The combination of buckling failure mode with the mode of ultimate material failure is shown in Figure 2.6. The figure shows that with the increasing of both slenderness ratio and reduction factor the possibility of buckling failure increases. The material failure occurs in the case of low slenderness ratio with high reduction factor. In addition, buckling failure connect with material failure where the members may fail due to combination of both mechanisms.

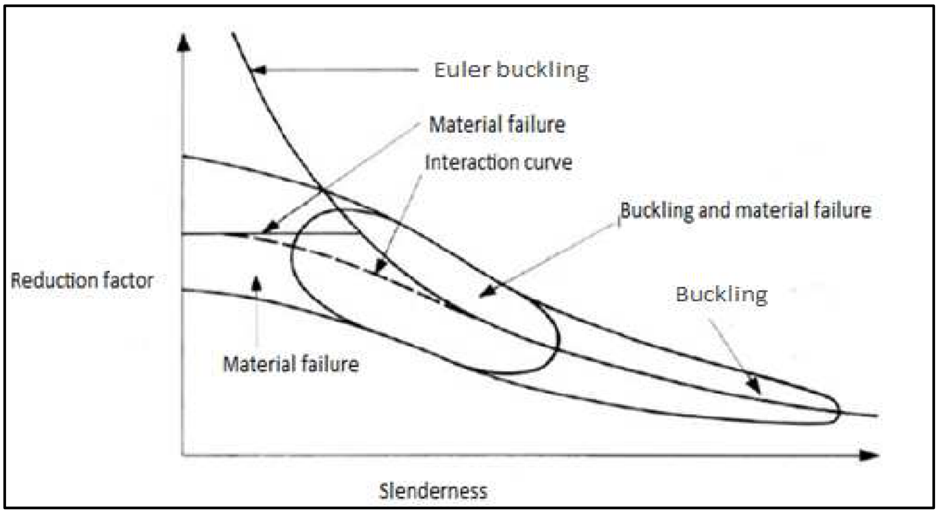

Figure 2.6: Buckling and material overstressing interaction curve (Morton, 1990)

Hasan and Hendry (1976) studied whether reduction factors prescribed in various codes are conservatives, all walls specimens were tested for various slenderness ratio 6, 12, 18 and 25 with different end conditions of flat ended and reinforced concrete slab and load eccentricity of 0, t/6 and t/3 where t is for wall thickness, showed the first hairline crack appeared between 50% to 60% of failure load and enlarged with further increase of load. The general mode of failure of the walls was vertical splitting accompanied by crushing and splitting of various courses of bricks. However, in walls with slenderness ratio of 25 and all walls of vertical load eccentricity t/3 group failure occurred at mortar brick interface due to breakdown of bond between the mortar and the brick at the time of maximum deflection.

2.4 Cyclic Compressive Loading-unloading Curves of Brick Masonry

For many years, monotonic loading was the standard method for testing masonry wall because it provided a good indication of the performance under one-directional loading, or wind loading. Many studies also have evaluated and predicted the performance of masonry walls subjected to monotonic loading. Many studies also have been reported for many past years and current on the static compressive strength of brick masonry and related elastic properties. A number of investigations have been conducted on different aspects of masonry including effect of slenderness ratio under static compressive loading.

Very little research has been reported on the behavior of brick masonry under cyclic compressive loading. The structure having a large live to dead load ratio, the ability to predict the behavior or response under cyclic compressive loading is needed. This understanding is very desired for designing of structure being expose to the huge vibration and the effects of repeated compressive loading are particularly applicable to brick masonry structures having large live to dead load ratio for example brick masonry industrial building, arches and piers of railway bridges. However, numerous researchers (e.g. Tu et al., 2011; Timothy, 2010; Chen et al., 1978 and Macchi, 1985) have been studied on cyclic loading test but the findings were in connection to seismic design of building with no particular emphasis on cyclic deformation characteristics of the masonry assemblage. Thus the type of cyclic loading was not available because cyclic tests had been performed to understand how walls behaved under earthquake loads.

Test on masonry under cyclic loading to simulate loading and unloading conditions are vital for information related to material ductility, stiffness degradation and energy dissipation (Alshebani and Sinha, 2000). Effects of monotonic loading versus cyclic loading on shear wall stiffness and strength need to be considered as well as the contribution of dissimilar materials to stiffness and strength (Rose 1998).

In an early investigation into cyclic loading, Naraine and Sinha (1989) reported that cyclic compressive tests of brick masonry prisms subjected to varying amounts of sustained and alternating stress levels indicate reduction in compressive strengths as large as 30% of the static compressive strength. Meanwhile the laboratory tests on solid clay brick masonry subjected to uniaxial cyclic compressive loading have been reported only in the last decade.

La Mandola and Papia (2002) mentioned in their study that cyclic models to simulate stress-strain behavior of concrete have been previously reported by Sinha et al. (1964), Karsan and Jirsa (1969), Yenkelevsky and Reinhardt (1987), and Bahn and Hsu, (1998). More recently, Bahn and Hsu (1998) have proposed a general cyclic model to describe the behavior of random cycles on concrete. They have expressed the unloading curve as a parabola and reloading curve as a straight line. The behavior of brick masonry in general depends on its load history. The path of unloading for any cycle depends primarily on the plastic strain accumulated in that cycle, and reloading path depends on the previous unloading path.

The extensive studies have been made on this type of loading test in order to establish the stress-strain relation. Thus, La Mandola and Papia (2002) had proposed the constitutive law of experimental deducible by means of uniaxial cyclic compressive tests on material having softening post-peak behavior in compression and negligible tensile strength using analytical forms with very good approximation. The proposed model adequately approach by characterizing the envelope, unloading and reloading curves structural responses corresponding to different levels of nonlinearity and ductility, not requiring very high number of parameters to be calibrated experimentally. By comparing the results the reliability of the model showed that it is able to provide deduced reference model analytically.

2.5 Cyclic Test Program

This section describes the cyclic compressive testing programs that had been developed by previous researcher. As mentioned previously, testing under loading and unloading condition to simulate the cyclic compressive loading tests are not numerous. However the early studies on this loading pattern exist but established procedure on that is still lacking and uncertain.

Alshebani and Sinha (2000) had carried out the cyclic test program on sand plast brick masonry panels of dimension 360 mm x 360 mm x 115 mm constructed from sand plast half brick units each measuring 110 mm x 55 mm x 35 mm. The average compressive strength of the brick unit was 23.4 N/mm^2 and the average compressive cube strength of the mortar used for the joints at 28 days was 10.2 N/mm^2. X-Y plotters have been used to monitor the displacements and the applied load through LVDTs and a load cell respectively. The loading and unloading was controlled by a Universal Testing Machine (UTM).

The laboratory experiments consist of three types of tests. The first test was a monotonic one in which load is steadily increased until failure. This test establishes the monotonic stress-strain curve. The second test was a cyclic test in which loading originates at zero stress level and terminates at the envelope stress-strain curve. Unloading, then, commences from the envelope curve and terminates at zero stress level for each cycle. The stress-strain hysteresis so obtained possesses a locus of common points. A common point is defined as the intersection point of the reloading curve of any cycle with the unloading curve of the previous cycle.

The reloading curve is terminated when its peak approximately coincides with envelope curve. This is done by monitoring the incremental increase of axial strain in the ascending branch of the envelope curve. In the descending branch of the envelope curve, the load was released when the reloading curve tends to descend. The third test was also a cyclic test in which for each cycle reloading and unloading are repeated when reloading curve intersects the original unloading curve of that cycle. The process forms locus of common points in descending order until it stabilizes at lower locus. The locus of the lower bound points termed as the stability point curve.

The envelope stress-strain curve is established by superimposing the stress-strain peaks of the second and third cyclic tests on the monotonic stress-strain curve. The envelope curve was found to follow an exponential formula developed by the Alshebani and Sinha (1999). The parameters of this formula depend on the direction of loading being normal or parallel to the bed joint.

Similar test type also had been taken by Nazar and Sinha (2006) in study of influence of the bed joint orientation of interlocking grouted stabilized mud-flyash brick masonry under cyclic compressive loading except distinct of loading direction