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MECHANICAL BEHAVIOR OF BRICK MASONRY PANELS UNDER UNIAXIAL COMPRESSION

HACER BILIR ÖZHAN AND ISMAIL HAKKI CAGATAY

Structural design in masonry requires clear understanding of the behavior of the composite unit-mortar material under various loading conditions. The mechanical characteristics of brick masonry are influenced by the individual properties of the bricks and the mortar. The results of an experimental study focused on the properties of brick masonry using different combinations of bricks and mortars are presented in this paper. The strength and the elastic modulus of brick masonry under uniform concentric vertical loads have been investigated for strong mortar (M:1:3 cement-sand) and weak mortar (M:1:6 cement-sand) arrangements. The failure mechanisms of the infill walls with horizontal coring bricks have also been examined.

1. Introduction

Masonry walls are widely used in many types of buildings due to their low cost and good sound and heat insulation properties, as well as the availability of local material and skilled labor. Mathematical modeling of structures with masonry walls requires understanding of the material properties and the interaction of the masonry and its constituents. Masonry is typically nonelastic, nonhomogeneous and anisotropic material and is composed of two materials, stiffer bricks and relatively softer mortar. These two have quite different mechanical properties. However, under lateral loads, masonry does not behave elastically even in the range of small deformations. Masonry is very weak in tension since the bond between the brick and the mortar is frail. Therefore, the main expectation from masonry is its resistance against vertical (compressive) loading.

During compression of masonry panels constructed with stronger and stiffer bricks, mortar of the bed joint has a tendency to expand laterally more than the bricks because of lesser stiffness [Atkinson and Noland 1983]. However, mortar is confined laterally at the brick-mortar interface by the bricks because of the bond between them. Therefore, shear stresses at the brick-mortar interface result in an internal state of stress which consists of triaxial compression in mortar and bilateral tension coupled with axial compression in bricks [McNary and Abrams 1985]. This state of stress initiates vertical splitting cracks in bricks that lead to the failure of the panels [Drysdale et al. 1994].

Grenley [1969] studied the effect of various mortars on the flexural and compressive strength of masonry and on the tensile bond strength of crossed brick assembly. His test results showed that, in general, flexural and tensile bond strengths increased with the strength of brick and the strength of mortar. The masonry compressive strength also showed a similar trend. The correlation between bond adhesion and compressive strength of masonry seems to suggest the importance of brick-mortar bond on masonry compressive strength. However, the increase in bond strength is also accompanied by an

Keywords: brick, brick masonry, mortar, masonry compressive strength, modulus of elasticity.

increase in mortar compressive strength. Hence, the relative influence of the mortar-brick bond and mortar compressive strength on the masonry compressive strength is not clear. The compressive strength of masonry depends on several factors and the thickness of the mortar bed joint is one of the significant factors influencing masonry strength. Houston and Grimm [1972] showed that the compressive strength of brick masonry decreases with increase in mortar bed joint thickness for constant height of the brick. Venkatarama Reddy et al. [2009] investigated the influence of bed joint thickness and elastic properties of the soil-cement blocks, and the mortar on the strength and behavior of soil-cement block masonry prisms. The major conclusions of their work are:

(1) Masonry compressive strength is sensitive to the ratio of modulus of block to that of the mortar (E_b/E_m) and masonry compressive strength decreases as the mortar joint thickness is increased for the case where the ratio of block to mortar modulus is more than 1.
(2) The lateral tensile stresses developed in the masonry unit are sensitive to the E_b/E_m ratio and the Poisson's ratio of mortar and the masonry unit.
(3) Lateral stresses developed in the masonry unit are more sensitive to the Poisson's ratio of the mortar than the Poisson's ratio of the masonry unit.

Since masonry is an assemblage of bricks and mortar, it is generally believed that the strength and stiffness of masonry would lie somewhere between that of bricks and mortar. When one component of masonry, i.e., either bricks or mortar, is substantially weaker and softer, the other is stronger as suggested by Dayaratnam [1987] and Sarangapani et al. [2002]. Based on an experimental study by Sarangapani et al. [2002], the soft bricks' modulus of elasticity (500 MPa) was responsible for the development of triaxial compression in bricks and axial compression with lateral tension in mortar points of masonry prism. Sarangapani et al. [2005] conducted a series of tests on masonry prisms constructed with very soft bricks (modulus of elasticity $\sim$ 500 MPa) and a combination of different mortar grades. It was observed that for the soft brick-stiff mortar masonry, the compressive strength of masonry increases with the increase in bond strength. Using experimental data, Houston and Grimm [1972], Paulay and Priestley [1992], and Binda et al. [1988] suggested several analytical relations for estimation of strength and deformation characteristics of masonry, which depend upon the compressive and tensile strengths of bricks and mortar along with several other factors.

Several experimental and theoretical studies were also carried out on axially loaded masonry walls. Negro and Verzeletti [1996] conducted a series of tests on 1 to 1 scale reinforced concrete buildings with and without infill walls. They determined an increase of 1.5 times more load carrying capacity of infill walls over walls without any filling. Alshebani and Sinha [1999] tested brick wall panels under periodic axial loading. Different types of loadings vertical and parallel to the joints were applied until failure occurred. They concluded that the joint separation as well as the fractures in the bricks and in the joints was due to the applied vertical loading. Gumaste et al. [2007] investigated the mechanical properties such as the strength and the elasticity modulus of the walls having different brick-mortar combinations under axial loading.

The compressive strength and the elastic modulus of brick and mortar are the major factors, which influence the properties of brick masonry wall. Elasticity modulus of masonry wall, which affects the wall rigidity, is the dominant factor influencing the behavior of masonry wall on the frame systems. The behavior of brick masonry also depends on the other factors such as interfacial bond strength between

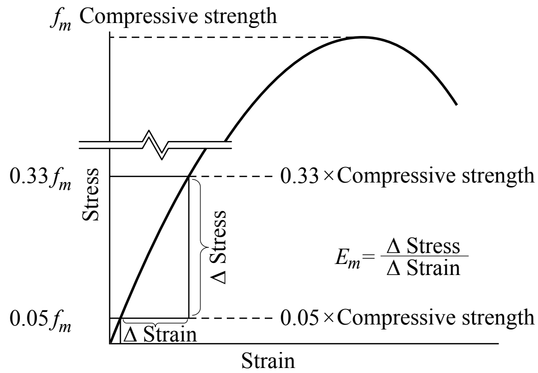

Figure 1. Stress-strain relationship of the infill walls based on the prism test.

brick and mortar, moisture in the brick at the time of laying, thickness of mortar joints, arrangement of bricks, workmanship. Modulus of elasticity changes with the direction (horizontal, vertical and diagonal) because of non-homogeneity of the wall. Elasticity modulus of masonry wall is also determined by the compressive strength of the material, the material height, the compressive strength of the mortar and the layer of the mortar line. The computation of modulus of elasticity for infill walls is given by

$$E_m = \frac{\sigma_{0.33} - \sigma_{0.05}}{\epsilon_{0.33} - \epsilon_{0.05}}, \tag{1}$$

where $\epsilon_{0.33}$ is the strain corresponding to the stress ($\sigma_{0.33}$), which is the compressive prism strength of 33% of masonry, and $\epsilon_{0.05}$ is the strain corresponding to the stress ($\sigma_{0.05}$), which is the compressive prism strength of 5% of masonry. A representation of this equation, following the American Concrete Institute [ACI 1999], is shown in Figure 1.

The elasticity modulus estimated in this study was compared and verified with the moduli available in the literature as presented in Table 1.

The aim of this study is to investigate the uniaxial monotonic compressive stress-strain behavior and other characteristics of bricks, (horizontal coring bricks), two types of mortar and unreinforced masonry panels (brick infill panel). In the comprehensive experimental study, tests were performed on 6 types of mortar cube specimens (with two different strength values as weak and strong), two different grades and 6 specimens of masonry panels (combination of one brick and two mortar types). Based on the experimental results and the observations, stress strain relationship curves were developed for mortars,

Source	Equation
[FEMA 1998]	$E = 550 f_m$
[Paulay and Priestley 1992]	$E = 700 f_m$
Canadian Standards Association [CSA 2004]	$E = 850 f_m$
American Concrete Institute [ACI 1999]	Equation (1), Figure 1
Turkish Earthquake Code [TEC 2007]	Average 1000 MPa

Table 1. Elasticity moduli from the literature.

horizontal coring bricks panels. Finally, as explained in the following section, elasticity moduli obtained from the experimental results were compared to the values reported in the literature.

2. Experimental program and discussions

In the present experimental study, several tests were carried out in order to evaluate the uniaxial compressive stress-strain relationship of masonry panels constructed with different combinations of mortar grades. Different types of mortar and bricks were utilized in the study. Masonry panels were subjected to monotonically incremental strain controlled axial loading. The load was applied vertically by a 550 kN load and ±10 mm displacement capacity hydraulic actuator in Hi-Tech Magnus loading frame (see Figure 2). Also, mortar cubes were tested in a 2,500 kN ELE Press testing machine under stress controlled loading. The specimens were built on 25 mm thick steel plates and cured under damp condition for 28 days and covered with wet jute sacks to maintain damp condition. The experimental study included total of 6 specimens of masonry panels with two different grades mortar.

2.1. ***Mortar testing.*** Masonry panels were tested with two different grades of mortar (cement/sand by volume) namely M:1:6 cement-sand mortar (weak), M:1:3 cement-sand mortar (strong). Since the mechanical properties of the mortar does influence the infill panel strength, mortar cubes of 150 mm size were tested after 28 days of casting to obtain their compressive stress-strain relationship. Determinations of compressive strength of mortar cubes, as as suggested by Turkish standards [TS 24 1985], are given in Table 2.

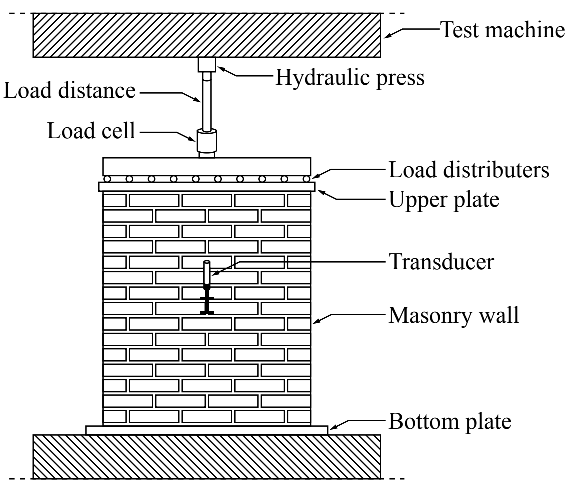

Figure 2. Test set-up and instrumentation.

mortar	compressive strength (MPa)	modulus of elasticity (MPa)	specimen dimensions (mm)
M:1:3	22.53	112.64	150 × 150 × 150
M:1:6	8.89	79.95	150 × 150 × 150

Table 2. Mechanical properties of mortars.

Figure 3. Appearance cracking of weak mortar cubes after loading (Failure modes of mortar cubes).

Figure 4. Appearance of failure modes of strong mortar cubes after the loading.

The appearances of fracturing of mortar cubes, after loading, for weak and strong samples are depicted in Figures 3 and 4, respectively.

The test results for the stress strain relationship are plotted in Figure 5. The dots in Figure 5 represent the test results. The best fitting curves obtained from statistical analyses are represented by the solid

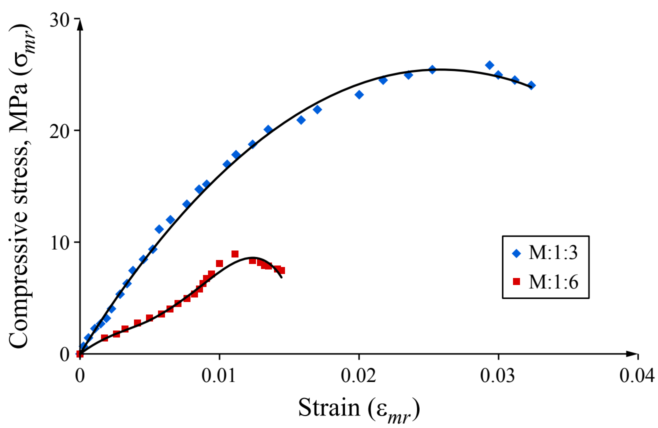

Figure 5. Comparison of compressive stress-strain curves for strong mortar cubes with weak mortar cubes.

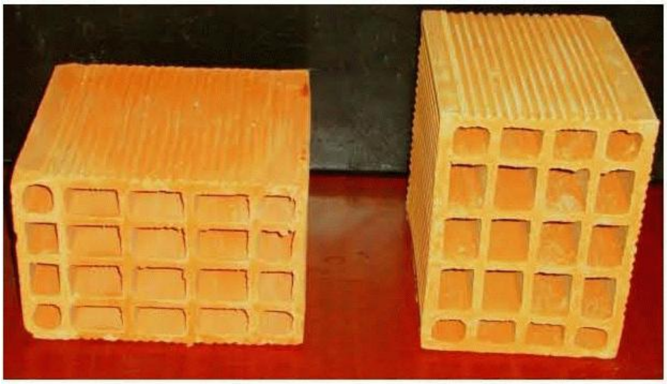

Figure 6. Horizontal coring brick.

lines. Table 2 lists the mechanical properties for each type as determined.

2.2. ***Infill wall testing.*** Horizontal coring bricks shown in Figure 6 were used in constructing masonry panels. Their average dimension (length × width × height) is 190 × 190 × 135 mm. Besides, bricks' average compressive strength was determined to be 5.2 MPa, through uniaxial compressive strength tests. Horizontal coring brick is used in experimental study because it is one of the widely used types in building masonry panels in the region.

The test set-up employed in the study is given in Figure 2. The load cell and the transducers were calibrated before they were used in the tests. The digital readings of uniaxial monotonic compressive load and corresponding vertical displacements were recorded through electronic data acquisition system during testing of each specimen.

The main focus of this study was to investigate the behavior of the brick infill wall, under vertical concentric uniform load, as well as to estimate the modulus of elasticity. The results are graphically illustrated in Figures 7 and 8.

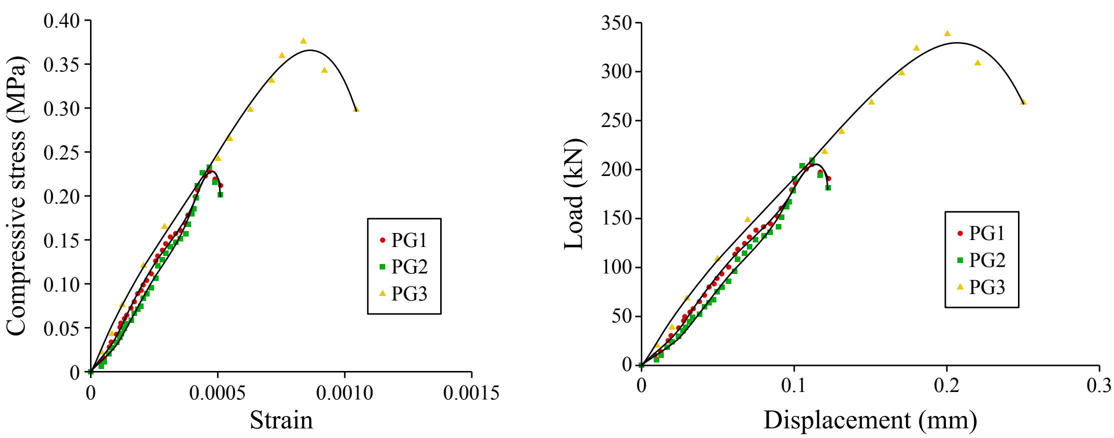

Figure 7. Compressive stress-strain curves (left) and load displacement curve (right) for brick masonry panel with M:1:3 (strong) mortar.

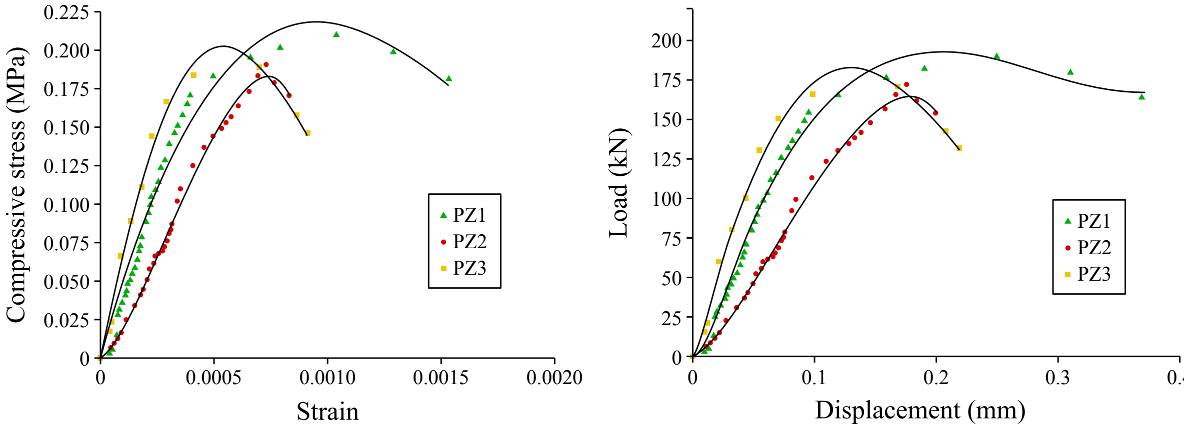

Figure 8. Compressive stress-strain curves (left) and load displacement curve (right) for brick masonry panel with M:1:6 (weak) mortar.

The results show that there are no substantial differences between PG1, PG2 and PG3 panels. It was observed that while PG1 and PG2 samples endured similar loading capacities, PG3 attained higher loading levels and failed after corresponding greater displacement values. The differences in cracking styles among these samples which were made up of similar strong mortars were believed to be because of the fracturing mechanisms involved (Figure 9). The M:1:3 cement-sand mortar panels generally showed better strength which was greater than the M:1:6 cement-sand mortar panels. When the mortar became considerably stronger as in the case of M:1:3, the improvement in strength of brick masonry panel was clearly achieved. The strength of masonry values ranged from 0.18 MPa to 0.38 MPa. Once again the best fitting curves obtained from statistical analyses are plotted in Figures 7 and 8.

Various failure patterns were observed in the test conducted on brick masonry walls. The first sample was a 1 m × 1 m panel (PG1) made up of horizontal coring bricks. The mortar rate employed was 1:3. As a result, in parallel with the load applied, symmetrical cracks on the center and on the corners of the panel were observed. These cracks, for all the panels tested, are shown in Figure 9. In the case of masonry walls, mortar in the vertical joint can cause splitting failure in the brick below, since the stress in the mortar is much higher because of its greater stiffness, the masonry wall is likely to split vertically in the middle of the thickness. The cracks initiated at the loading level of approximately 10 t on the PG1, PG2 and PG3 infill wall panels made up of strong mortar. The ultimate fracturing occurred around 20 t to 30 t. Similarly initial fracturing in PZ1, PZ2 and PZ3 infill wall panels began in the mid sections in the form of tiny cracks at 6 to 6.5 tons loading levels. As a result of this mechanism, which is thought to be due to the lower mortar strengths in comparison to the other panels, bending cracks on the face of the panels (around the mid sections) as shown in Figure 9 were observed. Test results showed that, in general, flexural and tensile bond strengths increased with the strength of brick and the strength of mortar. That's why, the masonry compressive strength also showed a similar trend.

It was observed that the flexural cracks started to appear in a direction perpendicular to the infill wall panel axis at a loading level of about 50% of the maximum load on the tensile side of the specimens. The existing cracks propagated and new cracks were observed along the tensile side of the panel specimens with the increase of loading level. Beyond the maximum load, major cracks appeared on the tensile side

Sample	Masonry panel with strong mortar	Sample	Masonry panel with weak mortar
PG1		PZ1	
PG2		PZ2	
PG3		PZ3	

Figure 9. Cracks on the brick masonry panel with M:1.3 (strong) and M:1:6 (weak) mortars after loading.

and the masonry infill wall crushed on the compression side at or close to mid-height of the masonry infill wall panel. Also, significant drop was measured in the loading resistance. Failure occurred in the most heavily compressed region for all the masonry infill wall panels. Cracking mechanisms depicted in Figure 9 are not quite inconsistent. They are assumed to be due to varying loading durations, which aimed to better observe the cracking behaviors, and due to the combined effects of several other factors such as non-homogeneity of the panels.

Table 3 tabulates the values of elastic moduli of all panels with M:1:6 and M:1:3 mortars. From the comparison of the values obtained for panels using horizontal coring bricks, it was observed that the

Methods	Panels: PG1	PG2	PG3	PZ1	PZ2	PZ3
Experiment Result	490	499.52	453.33	202.05	190.76	268.24
TEC	1000	1000	1000	1000	1000	1000
Fema	126	128.21	207.78	115.77	115.77	104
Paulay and Priestly	160	163.18	264.44	147.33	133.53	132
ACI	490	499.52	453.33	202.05	190.76	268.24
CSA	194	198.14	321.11	179	162.14	161

Table 3. Modulus of elasticity, E (Mpa) results of all panels. For the abbreviations TEC, ACI and CSA, see Table 1.

elastic moduli of PG1, PG2 and PG3 panels (with M:1:3) were in a very close range. The moduli of elasticity of PZ1, PZ2 and PZ3 panels are much lower than the others, PGs.

In order to see the effect of mortar type on the infill wall strength, three wall panels, having the same dimensions and properties, for each type were prepared and tested. The tested panels did have compatible results within each category. Strong infill panels, in parallel to the increase in mortar strength, attained higher loading and deformation values. Whereas the weaker ones, with decrease in mortar strength, could achieve lower loading and deformation values. Although the mortar strength is not the single parameter governing the panel strength, its influence cannot be ignored. The results obtained showed perfect correlation with similar studies reported in the literature by Grenley [1969], Dayaratnam [1987], Sarangapani et al. [2002], Gumaste et al. [2007] and Venkatarama Reddy et al. [2009].

The moduli of elasticity obtained, as shown in Table 3, were exactly same as the value proposed by the American Concrete Institute, whereas the other standard values from the literature were below the experimental results obtained.

3. Conclusions

In this research, tests were performed on 6 types of mortar cube specimens (with two different strength values as weak and strong), two different grades mortar and 6 specimens of masonry panels (combination of one brick and two mortar types). Based on the experimental results, modulus of elasticity of masonry was found to vary between 190 MPa and 500 MPa. This variation, as expected, clearly shows that the mechanical behavior of masonry infill panels depends on its constituents, mainly mortar type. Besides, the compressive strength of masonry was observed to be increasing with the compressive strength of the bricks and the mortar. Specimens with 1:6 cement-sand mortar failed due to the loss of the bond between the brick and the mortar. The results show that there are no substantial differences between PG1, PG2 and PG3 panels. The moduli of elasticity of PZ1, PZ2 and PZ3 panels are much lower than the others, PGs. The M:1:3 cement-sand mortar panels generally showed better strength which was greater than the M:1:6 cement-sand mortar panels. Samples showed failure due to splitting of the bricks. The first crack formation occurred to PGs when the loading level reached 10 tons during the tests. Further experimental verification may be required for the extension of these results for different kind of bricks and mortar of different grades. It was observed that the flexural cracks started to appear in a direction perpendicular to the infill wall panel axis at a loading level of about 50% of the maximum load on the tensile side of the specimens. The existing cracks propagated and new cracks were observed along the tensile side of the panel specimens with the increase of loading level. Beyond the maximum load, major cracks appeared on the tensile side and the masonry infill wall crushed on the compression side at or close to mid-height of the masonry infill wall panel. Stress-strain curves of masonry constructed with bricks and mortar of comparable strengths and stiffness was observed to lie below the stress-strain curves of both bricks and mortar, which is not in accordance with the generally accepted compressive behaviour of masonry. Therefore, more experimental study is required with different combinations of brick types and mortar grades to develop a generalized model for compressive behavior and elastic moduli of masonry.

4. Notation

The following symbols are used in this paper:

PG1	Infill wall panels 1 made up of strong mortar (1:3)
PG2	Infill wall panels 2 made up of strong mortar (1:3)
PG3	Infill wall panels 3 made up of strong mortar (1:3)
PZ1	Infill wall panels 1 made up of weak mortar (1:6)
PZ2	Infill wall panels 2 made up of weak mortar (1:6)
PZ3	Infill wall panels 3 made up of weak mortar (1:6)
σ	Compressive stress
ϵ	Strain
σ_{mr}	Compressive stress for strong mortar cubes
ϵ_{mr}	The strain for strong mortar cubes
f_m	Compressive prism strength of masonry
E_m	modulus of elasticity of masonry in compression

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