# Investigation of Brick Masonry Behaviour Under Uniaxial Compression Test at Different Scales

**Tze Che Van, Tze Liang Lau and Fadzli Mohamed Nazri**

**Abstract** In the early era of performing physical studies on scaled masonry model, masonry was taken to be isotropic material, like concrete and its strength and stiffness remained unchanged under scaling. On the contrary, there were also studies suggesting that masonry was an anisotropic material and scaling affected its strength. This paper covers the experimental findings of scale effect on solid clay brick unit and masonry prism subjected to uniaxial compressive loading. The effect of scaling on constituent materials was assessed prior to the investigation of scale effect on masonry prism. Based on experimental results, compressive strength of half scale brick units is higher than full scale brick units. Similarly, compressive strength of half scale masonry prisms is also higher than full scale masonry prisms. Elastic modulus of half scale masonry prisms is smaller than full scale masonry prism. The ratio of mortar to brick unit strength of full scale masonry prisms is found to be governing the extent of increase in compressive strength of half scale masonry prisms. The reduction of scale effect on compressive strength of down-scaled masonry is possible with smaller ratio of mortar to brick unit strength.

**Keywords** Masonry behaviour · Brick wall · Scale effect · Prototype and model

## 1 Introduction

Masonry is a heterogenous structural material, comprises brick and mortar. And thus, its mechanical properties are highly dependent on the properties and interaction of its constituent materials. Over the decades, many physical studies have been conducted to assess the structural response of masonry, especially under complex loading conditions such as seismic load. Due to the limitation of space and capacity of loading equipment as well as substantial cost for fabrication and

T. C. Van · T. L. Lau (✉) · F. M. Nazri
School of Civil Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia
e-mail: celau@usm.my

 
F. Mohamed Nazri (ed.), *Proceedings of AICCE'19*, Lecture Notes in Civil Engineering 53, https://doi.org/10.1007/978-3-030-32816-0_10

disposal involving full scale structures, downscaled masonry assemblages were often opted for testing. However, masonry has anisotropic characteristic and its strength is inversely proportional to the scale, as suggested by Mohammed and Hughes [10] and Singhal and Rai [12].

In general, there are a few factors governing the strength under scale effect of quasi-brittle material like masonry [5]. One of the factors is random strength which accounts for random flaws distribution in heterogenous materials. Small-scaled specimen has larger surface to volume ratio than large-scaled specimen. This could affect the water suction of mortar bed by masonry units, curing and drying process which in turns, results in different strength development. Large weight in large masonry units exerts more load hence, speeding up compaction of mortar bed compare to small-scaled masonry units. Higher loading rate also leads to higher strength observed during a test. Smaller specimens have better capping accuracy and more evenly distributed stress, and thus, show higher strength.

The aim of this study is to investigate the effect of scale on properties of brick masonry under uniaxial compressive load test at two scales, that are full scale and half scale.

## 2 Experimental Design and Setup

### 2.1 Materials Used for Scale Effect

Solid clay bricks manufactured from local supplier with the general brick specification in compliance with Malaysia Standard MS76:1972 [11] and average dimension of 221 × 94 × 70 mm were used in this study. Manufacturing of bricks with half size of the full scale through burning is a complicated process yet can increase the strength of brick [4]. In contrast, cutting of full scale bricks to obtain desired downscaled bricks is easier and more time effective. Thus, half scale bricks in this study were produced by wet cutting one full scale bricks in length-wise, width-wise and height-wise direction as recommended by Hughes and Kitching [6]. As shown in Fig. 1, this method produced eight half scale bricks with the same orientation as per full scale bricks. With 2 cm thickness of cutter blade, the average size of half scale bricks produced were 109.5 × 46 × 34 mm. In this study, weak mortar mix with proportion of 1:6 (cement:sand) by volume were used. Standard Portland cement and river sand were used.

### 2.2 Compression Test for Brick Units and Mortar

Vertical compressive tests of both full scale and half scale bricks were conducted following BS EN772-1:2011 + A1:2015 [3]. Brick units were tested in a load-controlled testing machine at loading rate of 3.12 and 0.74 kN/s for full scale

**Fig. 1** Prototype and half scale bricks

and half scale specimens, respectively. A total of 10 brick units were tested for each scale. Compressive test on six mortar cubes were carried out after 28 days of curing following ASTM C109-07 [1]. The loading rate used in the test was 1.35 kN/s.

## *2.3 Compression Test for Masonry Prism*

Compression strength and elastic modulus were assessed through vertical compression test of five-course stack bond prisms as per ASTM C1314-14 [2]. Three full scale masonry prisms and three half scale masonry prisms were constructed. The thickness of mortar is 10 mm for former prisms and 5 mm for later prisms. Hence, the dimension of prototype masonry prisms is 221 × 94 × 390 mm and 109.5 × 46 × 190 mm for half size masonry prisms. Bricks were prewetted prior to construction to ensure good bond strength is achieved between brick units and mortar. All prisms were tested after 28 days from construction.

Compression tests were carried out by subjecting all prisms under compressive load using servo-controlled compression testing machine. Loading rate of 1 and 0.5 mm/min were adopted for full scale masonry prisms and half scale masonry prisms, respectively. Demec gauge with gauge length of 150 and 50 mm were used for the determination of elastic modulus of full scale masonry prisms and half scale masonry prisms, respectively. Utilization of Demec gauge requires loading to be held still when readings are taken. Thus, prior to testing of the six masonry prisms, one extra sacrifice model for each scale of prisms were constructed and subjected to compression test up to failure in order to obtain an estimation of elastic state for the determination of elastic modulus. When testing full scale prisms, loading was hold still at every 5 kN interval up to 40 kN in order to measure displacement. After that, loading was continued to be applied until a drop of 20% after maximum stress is achieved. Displacement for half scale prisms were obtained at every 2 kN interval up to 12 kN. Vertical displacement across three brick units for full scale prisms and two brick units for half scale prisms were taken. Horizontal displacement of middle brick unit were also recorded.

# 3 Results and Discussion

## *3.1 Compressive Strength Test for Brick Units and Mortar*

The compressive strength of brick units is shown in Table 1. Based on the result, the mean compressive strength of half scale brick units is 37% higher than full scale brick units. This observation is unexceptional as it obeys scale effect rule, stating the increase of strength in smaller scale specimen due to lesser flaws compare to larger scale specimens according to Griffith theory of brittle fracture. Variance of former brick units was larger than later, indicating larger dispersion of strength observed. From Table 2, the mean compressive strength of mortar is 8.1 MPa with coefficient of variation (COV) of 0.1. According to ASTM C270, the strength of mortar used in this study falls in between strength of mortar Type N and S, which are for general purpose with good bonding capabilities and workability.

**Table 1** Brick units compressive test result

| Specimen | Brick compressive strength, $f_b$ (MPa) | |
|---|---|---|
| | Full scale | Half scale |
| S1 | 17.0 | 24.8 |
| S2 | 17.3 | 23.1 |
| S3 | 20.0 | 26.0 |
| S4 | 22.2 | 28.9 |
| S5 | 16.6 | 32.5 |
| S6 | 18.6 | 27.5 |
| S7 | 18.9 | 31.4 |
| S8 | 21.2 | 24.3 |
| S9 | 19.8 | 22.0 |
| S10 | 18.7 | 20.5 |
| Mean | 19.0 | 26.1 |
| Standard deviation | 1.8 | 4.0 |
| Coefficient of variation (COV) | 0.1 | 0.2 |

**Table 2** Mortar compressive test result

| Specimen | Mortar compressive strength, $f_j$ (MPa) |
|---|---|
| S1 | 7.8 |
| S2 | 9.0 |
| S3 | 8.3 |
| S4 | 7.6 |
| S5 | 7.6 |
| S6 | 8.6 |
| Mean | 8.1 |
| Standard deviation | 0.6 |
| Coefficient of variation (COV) | 0.1 |

## *3.2 Compressive Strength Test for Masonry Prism*

### 3.2.1 Failure Mechanism

Figure 2 shows the typical failure mode of full scale and half scale masonry prisms. All full scale and half scale masonry prisms showed vertical tensile splitting cracks under vertical compressive test. This phenomenon was caused by the confinement of Poisson effect in mortar due to bond and friction between brick unit and mortar, which in turn, leads to a state of lateral tension in the unit and triaxial compression in the mortar as explained by Mohammed [9]. The evidence showing occurrence of lateral tension in brick unit in this study is presented and discussed in next sub-section. Vertical cracks are more prominent on sides with shorter length.

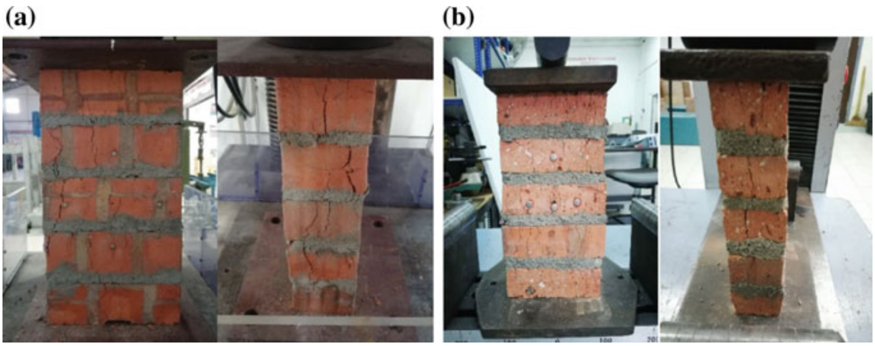


**Fig. 2** Failure mode of **a** full scale masonry prism and **b** half scale masonry prism

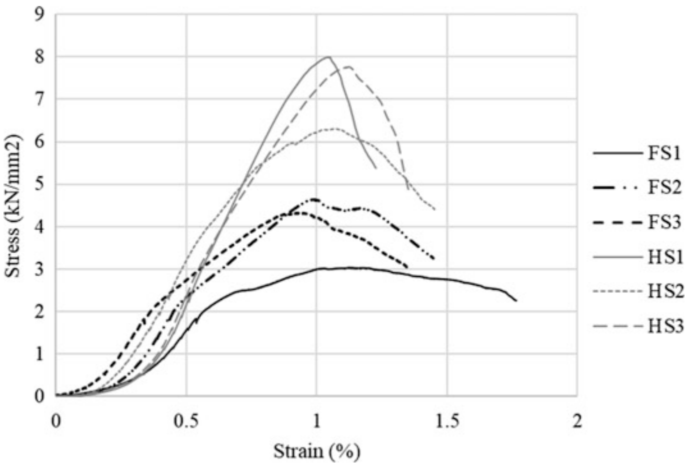


**Fig. 3** Stress-strain curve of prototype and half scale masonry prisms under compressive loading

### 3.2.2 Compressive Strength, Elastic Modulus and Horizontal to Vertical Strain Ratio of Masonry Prism

Stress-strain curve of all specimens subjected to compressive test is shown in Fig. 3, with 'FS' and 'HS' denoting full scale specimens and half scale specimens, respectively. On average, full scale masonry prisms showed strain hardening before reaching peak strength while half scale masonry prisms have sharp peak stress. The result from compressive test for masonry prism was tabulated in Table 3. It is observed that average compressive strength of half scale prisms is 83.75% higher than full scale prisms. Though, compressive strength of half scale prism is less scattered. Elastic modulus is calculated from 5 to 33% of the maximum load. The elastic modulus of half scale prism is about 17.9% lower than that of full scale prisms. In contrast, ratio of horizontal strain across brick units to vertical strain of middle brick unit of both prism scales is similar. Unlike homogenous quasi-brittle materials, the horizontal expansion within a brick unit is rather high in

**Table 3** Compressive strength, elastic modulus and horizontal to vertical strain ratio of full scale and half scale masonry prisms

| Specimen | Masonry compressive strength, $f_m$ (MPa) | | Elastic modulus, $E_m$ (MPa) | | Horizontal to vertical strain ratio, $\varepsilon_H/\varepsilon_V$ | |
|---|---|---|---|---|---|---|
| | Full scale | Half scale | Full scale | Half scale | Full scale | Half scale |
| S1 | 3.04 | 7.99 | 1606 | 1261 | 0.36 | 0.48 |
| S2 | 4.64 | 6.30 | 1651 | 1312 | 0.45 | 0.44 |
| S3 | 4.33 | 7.76 | 1577 | 1376 | 0.43 | 0.49 |
| Mean | 4.00 | 7.35 | 1603 | 1316 | 0.41 | 0.47 |
| COV | 0.21 | 0.12 | 0.17 | 0.15 | 0.12 | 0.15 |

corresponding vertical shortening across brick units and mortar layers. This shows the building up of lateral tension within a brick unit, which eventually leads to vertical splitting failure of the masonry prisms as observed in this study.

### 3.2.3 Comparison with Past Studies

Table 4 exhibits the comparison of result obtained from present study with past studies by other researchers. The increase in compressive strength and elastic modulus of half scale masonry prisms as compared to full scale masonry prisms in present study is supported by results from past studies. It is observed that present study shows the highest increase of masonry prism compressive strength when the masonry prism is downscaled to half as compared to results from past studies. Present study also has the highest ratio of mortar strength to brick unit strength for both full scale and half scale masonry prisms among all references. Figure 4 illustrates the higher the ratio of mortar strength to brick unit strength of full scale masonry prism, the higher the increase of masonry prism compressive strength when the masonry prism is downscaled from full scale. One should take note that the ratio of mortar strength to brick unit strength will drop when the scale for masonry prism is reduced but mortar mix is kept constant. This is because the strength of brick unit strength increases as the size decreases.

**Table 4** Comparison of present results with past studies

| Author | Scale | Brick size (L × W) | Mortar ratio | $f_j$ (MPa) | $f_b$ (MPa) | $f_j/f_b$ | $f_m$ (MPa) | $E_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|
| Egermann et al. [4] | Full | – | – | 3.4 | 25.1 (clay) | 0.135 | 15 (13-course) | 9840 |
| | Half | – | – | 3.4 | 27.8 (clay) | 0.122 | 15.7 (13-course) | 4600 |
| Jahangir and Shamala [7] | Full | 217 × 94 | – | 6.29 | 21.89 (clay) | 0.287 | 11.6 (5-course) | 7680 |
| | Half | 108 × 47 | – | Not tested | | – | 16.4 (5-course) | 7750 |
| Mohammed and Hughes [10] | Full | 215 × 102.5 | 1:1:6 | 4.7 | 29.2 (clay) | 0.161 | 9.2 (3-course) | 5500 |
| | Half | 96.8 × 46.1 | 1:1:6 | 5 | 30.6 (clay) | 0.163 | 11 (3-course) | 5200 |
| Knox et al. [8] | Full | 220 × 104 | 1:2:9 | 2.9 | 13.1 (clay) | 0.221 | 6.4 (3-course) | 1931 |
| | Half | 110 × 52 | 1:2:9 | 2.9 | 17.7 (clay) | 0.164 | 8.0 (3-course) | 1817 |
| Present study | Full | 221 × 94 | 1:0:6 | 8.1 | 19.0 (clay) | 0.426 | 4.0 (5-course) | 1603 |
| | Half | 109.5 × 46 | 1:0:6 | 8.1 | 26.1 (clay) | 0.310 | 7.35 (5-course) | 1316 |

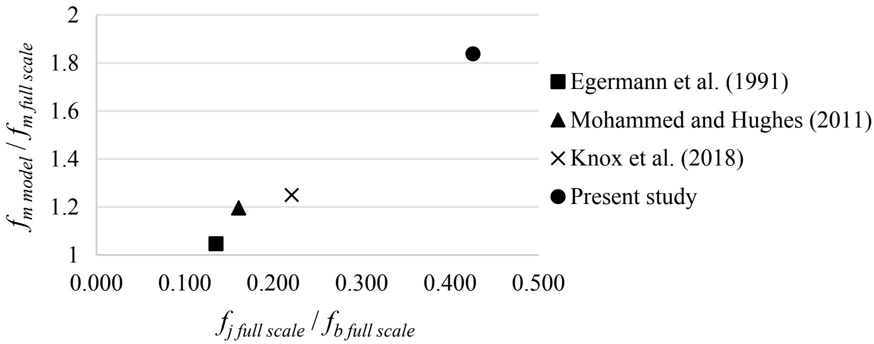


**Fig. 4** Relationship of mortar to brick strength ratio of full scale masonry prism with half scale prism to prototype prism strength ratio

## 4 Conclusion

Experimental study of scale effect on brick units, and masonry prisms under uniaxial compressive loading has been conducted. Based on results, compressive strength of half scale brick units is higher than full scale brick units. Both full scale masonry prisms and half scale masonry prisms show vertical tensile splitting cracks under vertical compressive test. Despite of this, half scale masonry prisms show higher compressive strength as compared to full scale masonry prisms. Based from the stress-strain curve, half scale masonry prisms have sharper peak while full scale masonry prisms exhibit strain hardening behaviour before approaching peak stress. Mean elastic modulus of half scale prisms drops to only 82.1% of full scale masonry prisms. The results on ratio of horizontal expansion of middle brick units to vertical shortening across brick units and mortar layers obtained in this study explains the failure mode mechanism of masonry prisms under vertical compressive loading. By comparison with past studies, it is found that ratio of mortar strength to brick unit strength has considerable effect on ratio of compressive strength of half scale masonry prisms to full scale masonry prisms. As a conclusion, half scale masonry could simulate the failure mode of full scale masonry subjected under uniaxial compressive loading and small ratio of mortar strength to brick unit strength could minimize the scale effect on strength of masonry.

**Acknowledgements** The authors would like to acknowledge the financial support from the School of Civil Engineering, Universiti Sains Malaysia for conducting the experimental study.

## References


1. ASTM C109/C109M-07 (2007) Standard test method for compressive strength of hydraulic cement mortars (Using 2-in. or [50-mm] cube specimens)
2. ASTM C1314-14 (2014) Standard test method for compressive strength of masonry prisms
3. BS-EN772-1:2011 + A1:2015 (2015) Method of test for masonry units—part 1: determination of compressive strength
4. Egermann R, Cook D, Anzani A (1991) Investigation into the behavior of scale model brick walls. Brick Block Masonry 1:628–635
5. Harris HG, Sabnis G (1999) Structural modeling and experimental techniques. CRC Press
6. Hughes T, Kitching N (2000) Small scale testing of masonry. In: Proceedings of 12th international brick/block masonry conference, pp 893–902
7. Jahangir B, Shamala S (2003) Mechanical behavior of structural brick masonry: an experimental evaluation. In: Proceedings of the 5th Asia-Pacific structural engineering and construction conference, 2003 Johor Bahru, Malaysia, pp 305–317
8. Knox C, Dizhur D, Ingham J (2018) Experimental study on scale effects in clay brick masonry prisms and wall panels investigating compression and shear related properties. Constr Build Mater 163:706–713
9. Mohammed AG (2006) Experimental comparison of brickwork behavior of prototype and model scales. Cardiff University
10. Mohammed A, Hughes T (2011) Prototype and model masonry behavior under different loading conditions. Mater Struct 44(1):53–65
11. MS76 (1972) Specification for bricks and blocks of fired brickearth, clay or shale—Part 2: Metric units
12. Signhal V, Rai DC (2013) Suitability of half-scale burnt clay bricks for shake table tests on masonry walls. J Mater Civ Eng 26(4):644–657