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Experimental study on scale effects in clay brick masonry prisms and wall panels investigating compression and shear related properties

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HIGHLIGHTS

- Experimental tests of full scale and half scale unreinforced masonry were presented.
- Varying level of scaling influence depending on the failure mode of the masonry element.
- Minimal influence due to scale on the brick strength, masonry strength, and Young's Modulus.
- The scaling have an effect on diagonal tensile strength and shear modulus.

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ABSTRACT

Scaled masonry model testing has been performed for many decades, with earlier researchers establishing that it is possible to model masonry behaviour at reduced scale, but that strength and stiffness are affected and with many studies suggesting that masonry is anisotropic. The effects of scale on clay brick masonry compressive strength, Young's Modulus, shear modulus and diagonal tensile strength was investigated through material and component testing at two scales. Firstly, the effect of scaling the brick and mortar joints to half scale was assessed, and secondly, the effect of scaling the size of the specimen without scaling the brick and mortar size was assessed. Scale was found to have minimal to no effect in both test cases on the compressive strength characteristics of masonry and brick, and to have no effect on the stiffness of masonry in compression. The effects of scale were found to be significant for diagonal shear strength and shear modulus.

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1. Introduction and background

Small scale masonry model testing has been performed for many decades in recognition of the fact that large or full scale tests are typically expensive and resource intensive, particularly for assemblies of large masonry buildings or building parts. Earlier researchers of scale effects established that it is possible to model masonry behaviour at reduced scale, but that strength and stiffness are affected [33,12,14]. The original notion was that masonry is an isotropic material and that scaling has a negligible effect on strength and stiffness [24,13,23,11]. However, many studies suggest that masonry is anisotropic and that strength increases with reducing scale [28,14,19,20,21,30]. Hughes and Kitching [14] completed a programme of testing primarily at 1/6 scale to support a study of masonry arch bridges that was performed at 1/6 and 1/12 scale. Previous work had identified the difficulties in firing small scale bricks, noting that the firing process resulted in model bricks that were slightly stronger and more burnt than full scale bricks [33,11,31]. For this reason, Hughes and Kitching [14] cut their model bricks from prototype bricks, following a standardised method. A statistical analysis of the compression strength of the small scale units showed that there was no correlation between either the position of the cut within the prototype or its orientation to the original surfaces. From compression strength tests, it was concluded that 1/6 scale masonry prisms had a higher compression strength in comparison to the prototype. Hughes and Kitching [14] also concluded that the Young's Modulus of masonry was reduced by a factor of 2 for the scaled brickwork when compared to the prototype stiffness.

Mohammed et al. [20] and Mohammed and Hughes [20] compared the compressive strength and stiffness of three brick high prisms for ½, ¼ and 1/6 scale models. The results showed no significant difference between the prototype and half scale prism compressive strengths, but did show an increase in compressive

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strength for the ¼ scale model and 1/6 scale model, which is in agreement with the findings of Hughes and Kitching [14]. One explanation given for this increase is the Griffith theory of brittle fracture, which states that the smaller the surface area of a material, the stronger it is, due to the reduced probability of flaws occurring [22]. A further explanation for the increase in strength for reduced scale models is the presence of thin mortar joints. Da Porto et al. [9] found that masonry prisms with thin layer joints (1.3 mm) were 20% stronger in compression when compared to prisms having 12 mm joints.

The half scale bricks used in the material testing by Mohammed and Hughes [20] were formed by cutting prototype bricks in half length-wise, height-wise and width-wise, resulting in 8 model bricks per prototype brick, whereas the cutting pattern for the ¼ and 1/6 scale model bricks resulted in the length axis of the model bricks being rotated 90 degrees from the prototype length axis. When the results of the compression tests were grouped by orientation of the brick length to the original prototype orientation, there was evidence of anisotropic brick behaviour. This suggestion of strength anisotropy in the brick is supported by Shrive and Jessop [28], who proposed that anisotropic behaviour was due to the manufacturing process of extruded clay bricks through a die.

The variation in elastic stiffness across the four scales tested by Mohammed and Hughes was found to be minimal, as the maximum difference was in the 1/6 scale model where the stiffness was 9% greater than the prototype stiffness. This trend is not supported by the finding of Egermann et al. [11], Hendry and Murthy [12] and Hughes and Kitching [14]. A reduced compaction of the bed joints in the scaled models, when compared to the prototype model, was suggested as a reason for the reduced stiffness in the scaled masonry models. Mohammed and Hughes [20] constructed their prisms horizontally, as opposed to vertically which is the general construction method, to eliminate variation in bedding stress between the different scaled models.

The scale effect on diagonal tensile strength was investigated by Mohammed and Hughes [20] using the standard protocol of ASTM 519. A One Way Anova test found that there was no significant difference in the means of the shear strengths across the four scales tested, suggesting a negligible scale effect.

2. Scaled material testing

The effects of scale on the masonry compressive strength (f'_m), Young's Modulus (E), shear modulus (G) and diagonal tensile strength (τ_s) was investigated through component and material testing at two scales.

2.1. Materials for scale effect testing

The bricks used in the construction of the samples for scale effect testing were solid clay bricks, recycled from the demolition of a heritage URM building in Auckland, New Zealand. The half scale bricks were formed by cutting the full scale bricks in half length-wise, width-wise and height-wise, which resulted in eight half scale bricks per full scale brick. Where the full scale brick had imperfect form (was cracked or had missing corners), the affected half scale unit was rejected. A wet cut skill saw with a 2 mm wide blade was used to cut the bricks. The average dimensions of the half scale bricks were 110 mm by 52 mm by 35 mm. By using a geometric scale factor of 2, and adopting the suggested cut procedure of Hughes and Kitching [14], the half scale bricks had the same orientation as the full scale bricks. A weak mortar mix, being ASTM type 'O', was selected to simulate weather deteriorated mortar in heritage URM buildings [10]. Standard Portland cement, hydrated lime (Calcium Hydroxide) and river sand were used in the mortar mix, which had proportions of 1:2:9 (cement: lime:sand) by volume.

2.2. Compressive strength and Young's Modulus

Compressive strength and Young's Modulus were both determined from the compressive testing of three brick high prisms. Six full size brick prisms and six half scale brick prisms were constructed by an experienced mason, under supervision. The bricks were pre-wetted to ensure a good bond between the brick and the mortar. The prisms were constructed vertically as this orientation is most representative of the construction method for component and system level testing at full-scale. Additionally, six half bricks, of both scales, were randomly selected and tested to determine brick compressive strength. ASTM International details a standard test procedure for determining the compressive strength of masonry prisms and clay brick samples [3,4]. Mortar cube samples were tested in accordance with ASTM C109/C109M-02 [1].

The results from the prism testing are shown in Table 1. In general, the indicators of data spread for the Young's Modulus of the full scale and half scale brick prisms were comparable, suggesting minimal effect of scale. This observation is also confirmed by the Tukey interval plot shown in Fig. 1(a). Mortar compressive strength of 2.9 MPa (COV 41%) was achieved. The masonry compressive strength data reported in Table 1 and graphically shown in Fig. 1(b) suggest that the compressive strength of the prism constructed from half scale bricks generally gave higher results when compared with the measured strength of the full scale brick prisms. The variance of the observations show large scatter. The analysis of the results from the brick compression testing is reported in Table 2. From the table and the Tukey interval plot shown in Fig. 1(c), it is determined that the half scale brick compressive strength had a larger spread than the full scale brick compression strength, but also generally had higher compressive strengths when the mean, upper quartile, lower quartile and maximum values are compared.

Table 1
Masonry prism testing results.

	f'_m (MPa)		E (MPa)	
	Full scale bricks	Half scale bricks	Full scale bricks	Half scale bricks
Mean	6.4	8.0	1931	1817
Median	5.8	8.1	2075	1939
Max	8.7	10.8	2304	2288
Min	4.5	6.4	1389	1181
Lower quartile	5.4	6.9	1637	1582
Upper quartile	7.6	8.1	2207	2054
Standard deviation	1.7	1.6	386	410
Coefficient of variation (%)	26.1	19.8	20.0	22.5
Sample size	6	6	6	6

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