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MASONRY STRUCTURAL BEHAVIOUR AT DIFFERENT SCALES UNDER COMPRESSIVE LOADING

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Abstract

This paper discusses the effect of scale on masonry structural behaviour under compressive loading. Reduced scales have been employed to understand masonry structural behaviour over the years, because testing prototype masonry structures is both costly and difficult to control in terms of instrumentation. A programme of tests have been carried out at four scales namely prototype, half, fourth and sixth scale under compression with a view to understanding how each of these conditions affects masonry structural behaviour over the range of scales enumerated. The results show that masonry compressive strength is increased as the scale is reduced but the stiffness is not markedly influenced.

1. Introduction

Small scale masonry model testing has been carried out for many decades. Early researchers in this area include Vogt (1956), Hendry and Murthy (1965) and Sinha and Hendry (1968). Most of these tests have established that it is possible to model masonry behaviour at reduced scales but not the strength and stiffness (Egermann *et al*., 1991, Hughes and Kitching, 2000). Recent programmes of research undertaken using a geotechnical centrifuge (Hughes *et al*., 2002) on sixth and twelfth scale masonry arch bridges as well as various other model studies on masonry-infilled frames, walls and other masonry components and structures has necessitated further investigation into the small scale experimental structural behaviour of masonry. This recent interest in masonry modelling has arisen because of the need to assess and perhaps strengthen existing historic masonry structures like bridges and buildings. One aspect of this study is reported in this paper, looking at masonry behaviour under compressive loading at prototype, 1/2, 1/4 and 1/6 model scales.

Furthermore there is also the need to understand the structural behaviour of masonry structures under extreme natural events like windstorms, floods, earthquakes, etc, since some of these events, like flooding have become recurrent actions posing danger to thousands of people inhabiting or working in masonry structures. Because of the issues associated with the cost implications of full size masonry tests, coupled with the danger of instrumentation destruction at failure, repeatability and difficult boundary conditions, it has become increasingly necessary to carry out such tests at reduced scales.

3. Materials and methods

3.1 Materials

The bricks used in the research were solid clay bricks and some of its important mechanical properties are given in Table 2. Normal building sand was used for making the mortar in the prototype tests while HST 95 Congleton sand was used for making the mortar in the model tests,

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the gradings of the two sands is shown in Figure 1 in relation to the grading limits set by BS13139. It shows that the normal building sand is within the grading limit s and the HST 95 sand is within the sixth scale grading limit (set by simply dividing the sieve sizes for the main grading limits by a factor of 6). Some of the important material properties of the mortars are summarised in Table 3. Other constituents used for making the mortar are Ordinary Portland Cement (OPC) and hydrated lime.

Table 2: Mechanical properties of prototype and model bricks

	Prototype	Half	Fourth	Sixth
Test				
Compressive Strength, N/mm^2	29.2	30.6	41.9	47.4
COV, %	14.3	8.4	9.7	32.7
Modulus of Elasticity, N/mm^2	11500	-	-	-
COV, %	31	-	-	-
Poisson's ratio	0.06	-	-	-
COV, %	48.1	-	-	-

Table 3: Properties of prototype and model mortar (coefficient of variation, COV in brackets)

	HST95iii	MP
Mortar Designation	**iii**	**iii**
Vol. Proportions	1 : 1 : 6	1 : 1 : 6
W/c ratio	1.8	1.55
Water retentivity,%	86	84
Consistence retentivity,%	55	55
Comp. Str. N/mm^2	4.7(8.5)	5.0(1.8)
Flexural Str. N/mm^2	2.3(5.3)	1.8(11.8)
Modulus of Elasticity,	6500(8.7)	6300(17.8)
Poisson's ratio	0.10	0.12

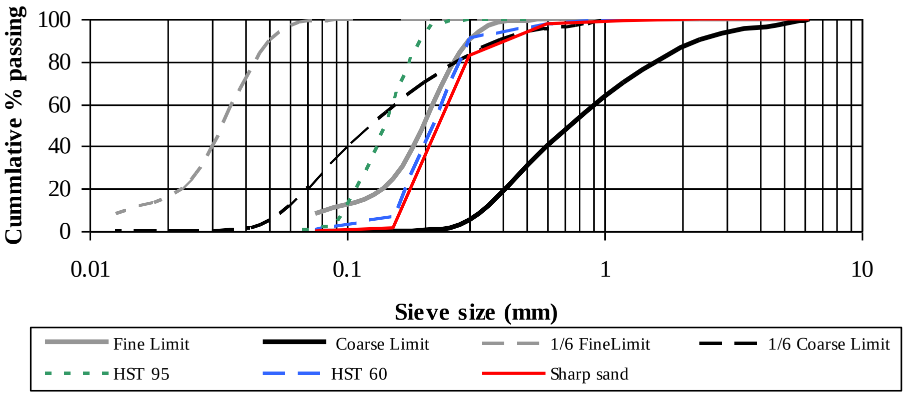

Figure 1: Grading curves for prototype and model sands within the BS limits

3.2. Experimental design

Because of issues regarding the firing of model bricks as reported by Taunton (1997) and Mohammed (2006), a cutting procedure developed and used successfully by Hughes and Kitching (2000) and Taunton (1997) was employed for the manufacture of the model bricks from a standard solid prototype of approximately 215 x 102.3 x 65 mm. Cutting dimensions of the model bricks are shown in Table 1. The table shows that the dimension for a "half" scale brick is 0.45 times that of a prototype brick. This is because obtaining the ideal 0.45 scale factor will result in getting only one half scale brick from a prototype brick, which implies a lot of wastage. Thus the 0.45 factor was used which resulted in getting 8 half scale bricks from a prototype brick. The selection of the prototype brick was made based on consideration of its suitability for cutting considering factors like lack of manufactured voids, strength, internal structure (whether full of cracks or not) and ease of cutting. A mortar of designation (*iii*) equivalent to M4 was selected as a suitable mortar because of its medium compressive strength. Two types of sands were used in making the mortars; normal builder's sand for the prototype mortar and a finer sand, Congleton HST 95 with an average grain size of 130 μm for the model scale mortar. This sand was chosen because of the very small joints in the 1/6 scale (1.6mm) and 1/4 scale (2.5mm). Further considerations on the experimental design are provided in Mohammed (2006).

Table 1: Average dimensions of prototype and model bricks

Scale	Length ,mm	Width, mm	Depth, mm
Prototype	215.0	102.5	65.0
Half	96.8	46.1	29.3
Fourth	53.8	25.6	16.3
Sixth	35.8	17.1	10.8

The compressive strength test was chosen because masonry is loaded in compression in the majority of the situations under which it is used. Therefore it is necessary to understand the mechanics of brickwork in compression for both prototypes and models. In addition to the compressive strength, the stiffness of the masonry under compression would also be investigated in order to compare the stiffness behaviour of prototype and model scale masonry.

3.2 Construction method

The bricks were first pre-wetted by totally immersing in a water tank for 20 minutes before laying them on their sides in a horizontal position as is usually done in prefabricated masonry panels. Pre-wetting of the units was necessary so as to condition the suction properties of the units in order to achieve a good bond between the units and mortar bed. The horizontal method of construction was employed for both the prototype and models, in order to achieve a repeatable and controllable way of making the specimens since the traditional laying method is amenable to significant workmanship variations that could mask the structural behaviour of brickwork. Another benefit of this method of construction is the cancelling of the differential compaction of the mortar beds during curing because of the different weights of the units across the four scales. Otherwise some form of simulating gravity stresses would have to be resorted to; for example by undertaking the tests in a centrifuge, which could bring about complexities into testing programme. The bricks were separated by wooden spacers cut to the desired mortar bed joint thickness of 10mm in the prototype tests, while tile spacers of 5 mm, 2.5 mm and 1.6 mm were used for the 1/2, 1/4 and 1/6 model scales respectively. Mortar was then placed into the bed spaces defined by the spacers whilst the units were laid on their sides in specially made moulds placed on top of a vibrating table. The whole assembly was vibrated gradually as the mortar was placed to fill up the bed spaces defined by the spacers used. This method of construction ensured uniformity in the bed joints of the specimens.

3.3 Test procedure

Three brick high triplet specimens were tested in the load controlled testing machine at a loading rate of 0.18, 0.04 and 0.02 kN/s in the prototype, 1/2 and 1/4 scales respectively. In the 1/6 scale the test was undertaken at a displacement control of 0.006 mm/s, this was because testing in load control was not achievable in that particular testing machine which was most suitable for testing the 1/6 scale specimens. The chosen displacement rate was arrived at by first conducting trial tests to determine the time taken to achieve failure in the 1/6 scale tests, and then adjusting the rate of displacement in order to achieve failure in a comparable time to the load controlled tests.

Linear Variable Displacement Transducers (LVDTs) were attached to both faces of the specimens in the prototype, 1/2 and 1/4 scale specimens for the determination of their stiffness properties, while specially made Model Masonry Clip Gauges(MMCGs) were used in the 1/6 scales because of the small size of the specimens. Details of the clip gauges are given elsewhere (Hughes and Kitching, 2000). The stiffness of the masonry was calculated as the secant modulus at a third of the maximum stress reached.

4. Results and data analyses

4.1 Compressive strength

Typical failure of the specimens across the four scales is by tensile splitting cracks in the axial direction. The cracks passed through the unit and mortar bed on both the faces and ends of the specimens. Failure is sometimes occasioned by spilling off of the units prior to failure. The observed failure mechanisms in the four scales were all similar and agree with the known failure mechanisms for masonry in compression.

Most small scale masonry model tests to date have shown that the models are stronger than the prototypes, as seen in Egermann *et al*. (1991). But current masonry theory assumes that if the mechanical properties of the brick and mortar are similar then there should not be a significant strength difference between models and prototype (Hilsdorf, 1969; Egermann *et al*., 1991).

From Table 4 (which shows a summary of the triplet compressive strength test result) and Figure 2 (which shows the variation of the triplet compressive strength across the four scales), it is seen from the fitted trend line in the figure that, generally there is an increase in the compressive strength as the scale is reduced as reported by various authors. There is also evidence of strength anisotropy, because it is seen that the masonry strength in the half and prototype scales are somewhat similar on one hand and in the quarter and sixth scales on the other. This supports findings by Mohammed (2006) on the possible anisotropy of masonry unit strength as well as other authors (Jessop, *et al*., 1978; Shrive and Jessop, 1980). This behaviour could be due to the manufacturing process of extruded clay units in which plastic clay is forced through a die, thereby possibly bringing about anisotropy in the unit properties because of the extrusion process. In order to reduce the effect of the unit strength, the masonry strength in Figure 2 is re-plotted with the masonry strength normalised with respect to their respective strength as shown in Figure 3. This figure shows a reduced rate of increase of masonry strength as the scale is reduced. This suggests that there is still some additional factor that is responsible for the high increase in strength, apart from the effect of unit strength alone.

Table 4: Summary of triplet masonry compression test results in the four scales

Scale	Mortar Type	Bed thickness mm	Compressive Strength,N/mm^2	COV %	Stiffness N/mm^2	COV %	Mortar Cube Strength,N/mm^2
Prototype	MP-iii	10.0	9.2	10.8	5500	22.6	4.6
Half	M95-iii	5.0	11.0	9.1	5200	26.9	4.9
Fourth	"	2.5	23.0	9.1	5400	6.6	4.7
Sixth	"	1.6	20.3	11.6	6000	20.1	4.7

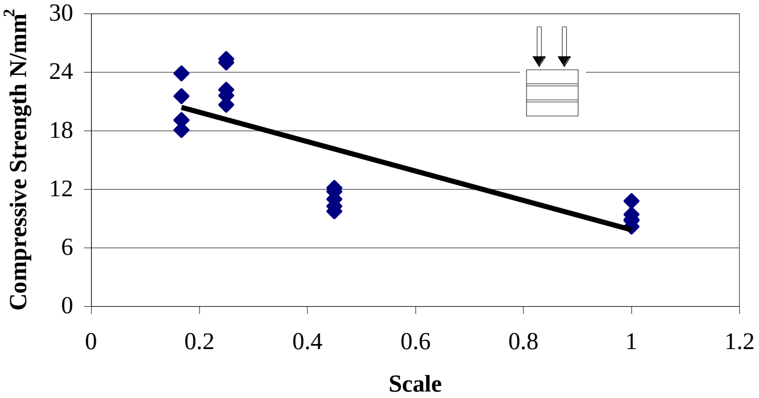

Figure 2: Triplet compressive strength in the four scales

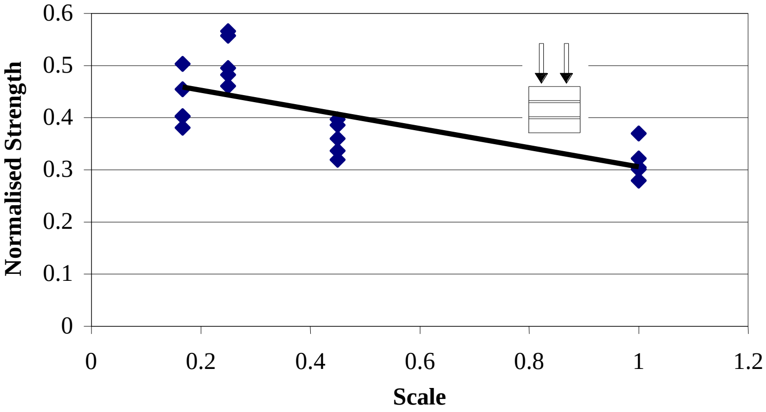

Figure 3: Normalised triplet compressive strength across the four scales

Studies of the fracture of brittle materials (mostly concrete) have shown that smaller sized specimens have higher strengths than larger specimens (Sabnis and Aroni, 1971). According to the Griffith theory of brittle fracture, the less the surface area of a material the stronger it is, since there is less probability of flaws occurring (Moss, 1971). Therefore, this size effect seen in testing brittle materials may also be one of the reasons for the strength differences. But curiously there is little scale effect seen in the half scale results. This suggests a possible interplay of two factors at the smallest scales; firstly a possible anisotropy with respect to strength due to the manufacturing process of clay brick and secondly the size effect phenomena.

The thinness of the mortar joint at the smallest scales; that is fourth and sixth scales, could also contribute to the higher masonry strength in the smallest scales. As stated by many authors, the tensile stresses that cause failure in the brick are due to the stresses induced by the mortar joint. Again using the Griffith concept that smaller sized elements are stronger than larger ones, it would be expected that thinner joint should be able to withstand higher stresses than thicker ones; consequently the brick would be able to carry higher tensile forces in masonry with a thinner joint. This has been corroborated by Porto *et al*. (2005) who found that prototype masonry with thin layer joints (1.3 mm) were 20% stronger in compression than those with 12 mm joints. This suggests that model masonry could show a stronger compressive strength due to the thinness of their joints alone. However, this may be applicable to only the very small scales like the sixth and fourth scales in this study, because as we see from the results, the half scale strength is similar to the prototype strength.

From Table 4, it can be seen that the mortar cube strengths for the tests are similar to each other. The highest cube strength of 4.9 N/mm^2 was in the half scale test. This is marginally higher than the mortar cube strength in the prototype test by about 6% and fourth and sixth scale tests by about 4%. Therefore, since the mortar strengths are comparable to each other in the four scales, the difference in masonry strengths seen could be principally due to the unit properties and the size of the joints at the smallest scales.

4.2 Stiffness

The variation of masonry stiffness across the four scales are shown in Figure 4 and Table 4. They show that all the stiffness results are similar; the half and fourth scales stiffness were 6% and 2% more than the prototype stiffness, while the sixth scale stiffness was 9% more than the prototype stiffness. Even though we have seen substantial variations with regards to their strength properties, their deformation properties are very similar. This is further illustrated in Figure 5, a combined plot of stress/strain curves for the four scales. It is seen from Figure 5 that the slope of their elastic region are markedly similar.

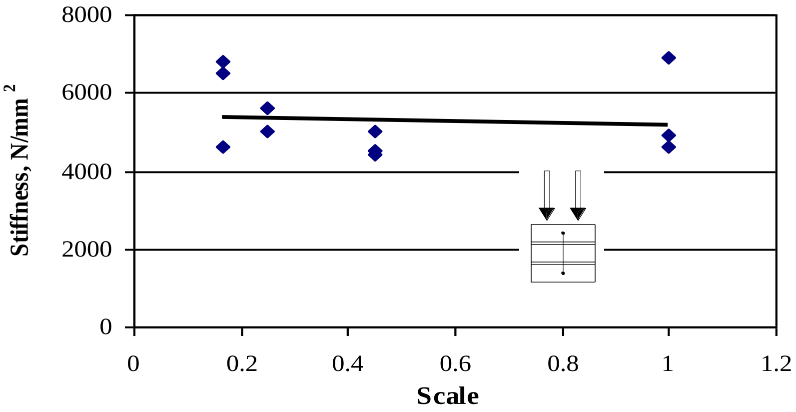

Figure 4: Stiffness of masonry triplets in the four scales

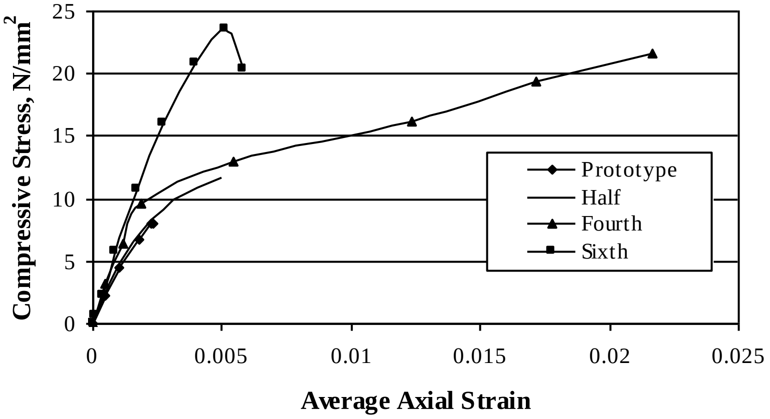

Figure 5: Stress/strain curves for selected triplet tests across the four scales

However, results from other researchers (Hughes and Kitching, 2000; Hendry and Murthy, 1965; Egermann *et al*., 1991) show a different trend. Their results show that reduced scale masonry models are softer than prototype by a factor approximately equal to the scale factor. This may be due to the manner in which the models were constructed in our case which is different to the way the other researchers made their specimens. They all used conventional brick laying. Because in conventional brick laying, the light weight of model bricks subject the mortar bed to a lower bedding stress than the heavier prototype bricks, as a result, the bed joints in the model scales are compacted to a lower degree during curing than the bed joints in the prototype. Consequently, the bed joints in scaled masonry models are less compacted which could lead to a softer masonry response under compression. Egermann *et al*. (1991) have suggested this as a possible reason for the softness of small masonry models and it has also been reported by Mohammed and Hughes (2005). By comparing it to the stiffness of its constituent elements, it is seen that the average stiffness of the masonry in the four scales (5500 N/mm^2 in this case) is about half of the brick stiffness (11500N/mm^2) and roughly similar to the mortar stiffness (6300N/mm^2 for prototype mortar and 6500N/mm^2 for benchmark mortar). This shows the influence of mortar in determining the stiffness properties of masonry.

5. Conclusions

The results of the masonry tests at different scales has shown that the strength of masonry triplet in compression was higher than the prototype in the fourth and sixth model scales but similar to the prototype in the half scale. The same pattern was also repeated in the tests of the unit strengths, indicating the strong influence of the unit in determining the masonry properties. There is evidence of anisotropy of strength in clay brick masonry possibly due to the manufacturing process of extruded clay units which therefore makes the direction of loading on a cut model brick important. It can then be suggested that the increase in model unit strength, could be attributed to two factors, namely; strength anisotropy and the energetic size effect in quasi-brittle materials.

It was found that triplet stiffnesses in the four scales were identical to each other and no scale effect was observed. The prototype masonry and model stiffness were in good agreement with the prototype and model mortar stiffness respectively. This may be attributed to the way the specimens were constructed, which has effectively cancelled any differential compaction of the joints due to the different weight of the unit bricks in the various scales. The good agreement in the stiffness of the four scales may be evidence of the importance of the mortar bed in determining the stiffness properties of masonry. This finding is very significant bearing in mind that model tests by other researchers showed a much softer model response to the prototype under axial compression.

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