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COMPARISON OF PROTOTYPE AND 1/6th MODEL SCALE BEHAVIOUR UNDER COMPRESSIVE LOADING

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ABSTRACT

This paper presents an experimental comparison of brickwork behaviour at prototype and 1/6th model scales under compressive loading. Two different specimen formats were tested for both prototypes and models; a three brick high, standard triplet and a 2 brick by 6 courses high wallette specimen. The prototype brick used is a solid, wire cut brick.

The normalised compressive strength for both wallettes and triplets were in good agreement even though the compressive strength for the cut model scale units was 60% more than that of the prototype.

The results show that it is possible for small masonry models to predict the elastic behaviour as well as the failure modes of prototypes.

KEYWORDS: model scale, prototype, stiffness, strength

INTRODUCTION

Research using a geotechnical centrifuge on 1/6th and 1/12th scale masonry arch bridges has necessitated further work to be carried out to understand the small scale experimental modelling of masonry. This is because full size tests on brick masonry components and large building components has proven costly in terms of materials and labour together with significant challenges associated with the destruction of instrumentation and facilities at failure; this has necessitated the carrying out of such tests at reduced scales. Therefore, to develop the results of such tests fully, a better appreciation is needed of the properties of brick masonry at a smaller scale with a view to comparing the same properties of full scale masonry assemblies**.**

The present work compares the behaviour of triplet and wallette specimens at 1/6th scale and full scale (prototype) under compressive loading, considering both their compressive strength and stiffness.

Model tests on masonry components have been widely reported in the literature. The main conclusion of most of these experiments is that it is possible to model the behaviour and failure modes of full scale masonry components at reduced scales. In addition, as has been suggested by [1], it is also possible to model the compressive strength of full scale masonry work at smaller scales to a reasonable degree of accuracy, provided that the strength of 25 mm mortar cubes is considered instead of the larger size 71 mm cubes. The only problem reported is the relative stiffness of the model, which was found to be more flexible by [1, 2, 3]. The latter suggested that this may be due to higher bedding stress applied by the prototype bricks on the mortar bed during the curing of the mortar.

THEORY

The empirical formula specified in Eurocode 6 [4] for the determination of the characteristic strength of un-reinforced masonry is given by Equation 1

$$f_k = K f_b^{0.65} f_m^{0.25} \qquad \text{Equation 1}$$

where

f_b is the normalized compressive strength of the masonry units in N/mm^2

f_m is the compressive strength of the mortar in N/mm^2 and

K is a constant in $(N/mm^2)^{0.10}$ that depends on the volume of holes in the unit and the way the walls are made (with or without perpend joints)

It is seen from Equation 1 that provided the mortar strengths are the same, the compressive strength of a full scale masonry assembly will differ from another at reduced scale only if the brick strengths are different. Therefore the ratio $\frac{f_k}{f_b}$ should be similar for both full and model scales.

It is stated in the same Eurocode that the short term secant modulus of elasticity of masonry under service conditions is given by Equation 2,

$$E = 1000 f_k \qquad \text{Equation 2}$$

Equation 2 shows that for the same values of compressive strength for the constituents, the stiffness of a full scale and of model scale masonry assembly should be similar.

Rearrangement of Hilsdorf's [5] failure criterion by [3] also yielded similar conclusions, that is, if the mechanical properties of the brick and mortar in the scales are the same, there should not be a significant difference of strength between the model and the prototype.

EXPERIMENTAL DESIGN

To meet the objectives of the research, compressive strength tests were carried out on masonry triplets and wallettes at prototype and $1/6^{th}$ model scale to determine their stiffness and strength properties. Because of issues regarding the firing of small bricks as reported by [6], a cutting method used successfully in Cardiff by other researchers [2, 6] was employed for the manufacture of the $1/6^{th}$ scale model bricks from the standard prototype of approximately 215 x 102.5 x 65 mm. Full discussion on the cutting method employed is given in [2]. The selection of the prototype brick was governed by its suitability for cutting considering factors such as lack of manufactured voids, strength, internal structure (whether full of internal cracks or not) and ease of cutting. Since much masonry modelling work involves modelling old masonry structures, the strength the prototype brick chosen for the current work is of medium compressive strength as is the chosen mortar designation so that the properties of the existing masonry structures could be realistically modelled. M4 (minimum compressive strength of 4 N/mm^2) was selected as a suitable mortar.

Very fine sand, Congleton HST 95, with an average aggregate size of 130 μm was used in preparing the mortar for the model scale masonry because of the very thin joints (1.6 mm) necessary to model standard UK brickwork joint construction (10 mm). However, normal building sand was used in making the prototype mortars. More detailed discussion on the sand is given below.

Deformation measurements for the determination of stiffness properties were carried out with Linear Variable Displacement Transducers (LVDTs) for the prototype specimens and Model Masonry Clip Gauges (MMCGs) for the model scale specimens [2]; both were fixed to the front and back faces of the specimen in order to identify any effects due to bending.

MATERIALS

The prototype bricks used were Mellowed Red Stock, which are solid, wire cut bricks, suitable for cutting into model bricks and had minimal internal cracks. Model bricks of $1/6^{th}$ scale of approximately 35.8 x 17.1 x 10.8 mm were cut from the standard prototypes. The cutting method ensured that consistent model bricks were produced with good dimensional accuracy.

Mortar designation (iii) BS 4551 [7] corresponding to a strength class M4 in Eurocode 6 [4] was used for both the model and prototype tests. The mortar for the prototype specimens was prepared with normal building sand having a grading curve inside the limits of BS EN 13139 [8] while the mortar for the model scale specimen was made using HST 95 sand having a grading inside the $1/6^{th}$ of the grading limits of BS EN 13139 [8]. Figure 1 shows the model and prototype sand gradings as well as the standard limits and scale equivalents. It can be seen from the figure that both sands have similar distributions, the main difference being the finer sizes of the HST 95 sand. Twenty five mm mortar cube specimens were used as quality control cubes for both model and prototype specimens because of the small quantities of mortar used for the specimens. Mortar cubes were demoulded after two days of casting and submerged in water curing tanks for the remainder of the 28 days of curing. The quality control specimens were manufactured to a uniform but not standardised specification.

SPECIMEN PREPARATION AND TESTING

All brick units for both the prototype and model scale tests were first wetted for 20 minutes prior to being placed in special moulds. It was decided that laying the units on their sides and vibrating the mortar into the joints would limit the variations in workmanship and eliminate any effects due to the differential compaction of the mortar bed by the units [3]. Spacers (10 mm for the prototype specimens and 1.6 mm for the model scale specimens) were used to separate the units as well as to hold them in place whilst the mould was vibrated as mortar was placed along the bed spaces. The mould and contents were left undisturbed for two days before demoulding and storing the specimens in the laboratory for a minimum of 28 days curing at ambient room temperature and humidity. This process ensured that all joints were of the same thickness and facilitated speed of fabrication. This process has been used by others [9] to make and test the effect of lateral load on model scale wind panels. They concluded that making brickwork in this way was faster and more consistent than the traditional way.

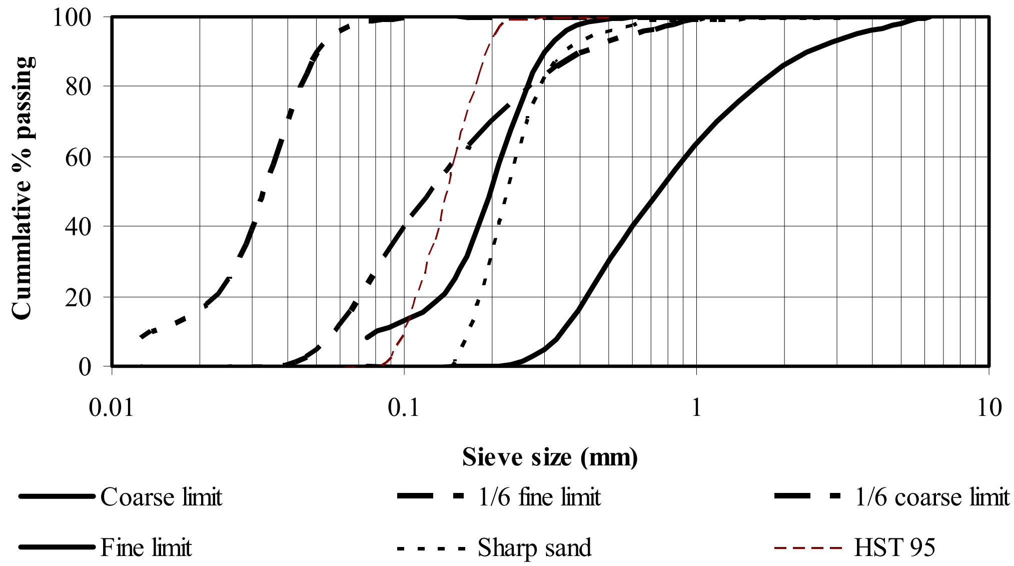
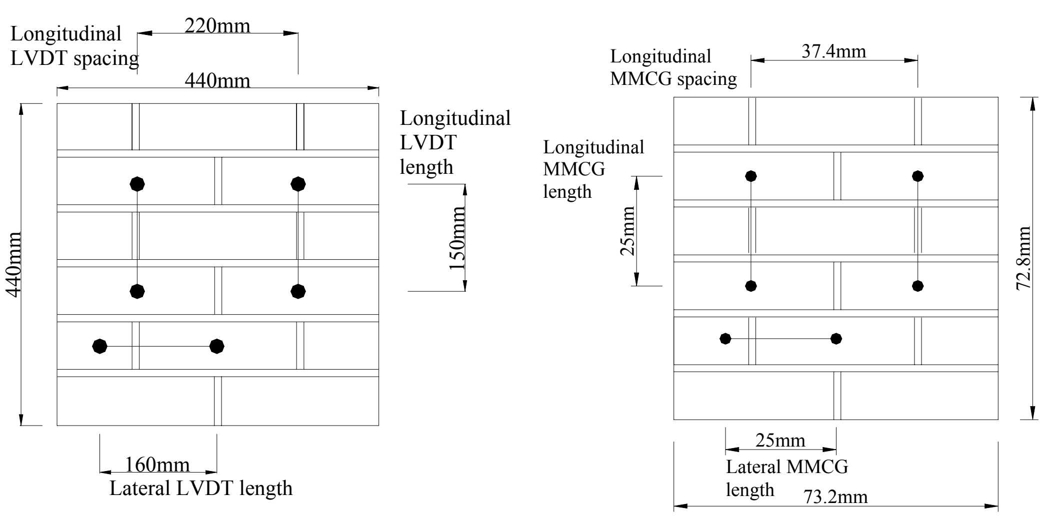


Figure 1 - Grading curves for model and prototype mortar sands



(a) Prototype **(b) Model scale**

Figure 2 - Details of wallet specimens showing the position of transducers and gauges

Two specimen formats were made for both the prototype and model scales; a three brick high standard triplet and a 2 brick by 6 courses high wallette specimen. The latter were made and tested according to the guidelines of BS EN 1052-1:1999 [10] . LVDTs were fitted onto the specimens as shown in Figure 2a to measure the vertical and horizontal deformations in the prototype wallette. In the case of the model scale walls, MMCGs were used as shown in Figure

2b to measure the lateral and longitudinal deflections along a length of 25 mm. Testing was carried out under load control with deformations measured to failure of the specimens. Fibre board was used on top and bottom of the prototype specimens to even out the planar variations on their surfaces and a similar scaled material used for the model tests. Five specimens each were tested for the compressive strength while only three of these specimens were considered for the determination of the deformation characteristics of the assemblies. Twenty specimens were tested in total.

RESULTS

In order to determine how the strength of a 25 mm mortar cube compares to a standard 100 mm cube, a series of compressive strength tests were carried out on both model and prototype mortars. The results presented in Figure 3 show very good agreement between the strength of the 25 mm and 100 mm cubes. For tests using prototype mortar, the compressive strength of the 25 mm cube was 2% more than that of 100 mm cube. While in the case of the model scale mortar, the compressive strength of the 100 mm mortar cube was about 4 % more than that of the 25 mm mortar cube.

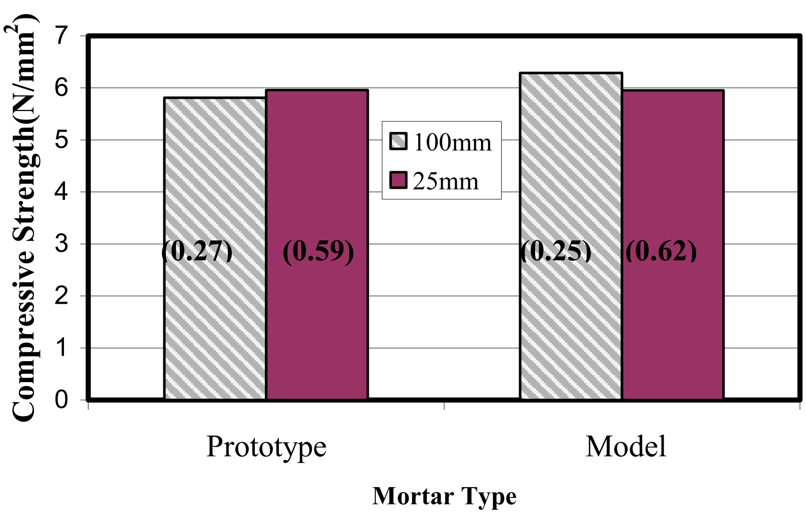


Figure 3 - Comparisons of 100 and 25 mm cube mortar strengths with their Standard deviations in brackets

The results of the mean compressive strengths shows a greater degree of correspondence between the strength of the two mortar sizes than the results reported by [2], where the 25 mm mortar cube specimens were on average 14% stronger than the 100 mm mortar cube specimens. All mortars tested for quality control had strengths more than the minimum recommended for their strength class as given in Eurocode 6 [4]. The average strength of the model scale mortar was 4.2 N/mm^2 while 4.8 N/mm^2 was average strength for prototype mortars. Strength properties of the bricks and mortar are summarised in Table 1.

The test results for the wallettes and triplet specimens are summarised in Tables 2 and 3. Figure 4 is the plot of the compressive strength against the mortar strength for both the prototype and 1/6th scale wall specimens normalised with respect to the unit compressive strength. It is seen that there is very good agreement in the normalised brickwork strength for the two scales. But the mean compressive strength of the 1/6th

Table 1 - Material properties of prototype and model bricks and mortars

		Compressive Strength, N/mm^2	Modulus of Elasticity, N/mm^2	Poisson's Ratio
Brick	**Prototype**	29.2	11500	0.06
	Model	47.4	-	
Mortar	**Prototype**	4.8	6700	0.12
	Model	4.2	6200	0.12

Table 2 - Compressive strength (N/mm^2), modulus of elasticity (N/mm^2) and Poisson's ratio respectively for prototype and models scale wallettes

	Prototype			**1/6 Scale**		
	Compressive Strength	**Modulus of Elasticity**	**Poisson's ratio**	**Compressive Strength**	**Modulus of Elasticity**	**Poisson's ratio**
1	10.3	5200	0.07	15.3	7700	0.12
2	10.1	5100	0.05	17.7	6700	0.12
3	10.7	5900	0.05	16.9	8000	0.27
4	10.0			17.2	4800	0.23
5	10.1			16.8		
Mean	**10.2**	**5400**	**0.06**	**16.8**	**6800**	**0.19**
±SD	**0.3**	**436**	**0.01**	**0.9**	**681**	**0.09**

Table 3 - Compressive strength (N/mm^2) and modulus of elasticity (N/mm^2) for prototype and model scale triplets.

	Prototype		**1/6 Scale**	
	Compressive Strength	**Modulus of Elasticity**	**Compressive Strength**	**Modulus of Elasticity**
1	8.9	4600	23.9	6500
2	9.4	6900	15.1	6800
3	10.8	4900	19.1	4600
4	8.2		18.1	
5	8.8		17.1	
Mean	**9.2**	**5500**	**18.7**	**6000**
± SD	**1.0**	**1250**	**3.3**	**1193**

scale walls are 60% more than the mean strength of the prototype wallette, which is the same percentage difference between the brick unit strengths in the two scales. This suggests that the difference in the brickwork strengths is mainly due to the brick strength as seen in the difference of only 3% between the normalised brickwork strengths in the two scales. The cluster of points in the case of the model scale wallette specimens shown in Figure 4 is possibly because they were made in two batches and have similar strengths; therefore the mortar strength will be the same for the specimens in each batch. The prototype specimens however, were individually made on different days and therefore had differing strengths. Typical failures in both scales are by vertical splitting and cracking of the specimens on their ends.

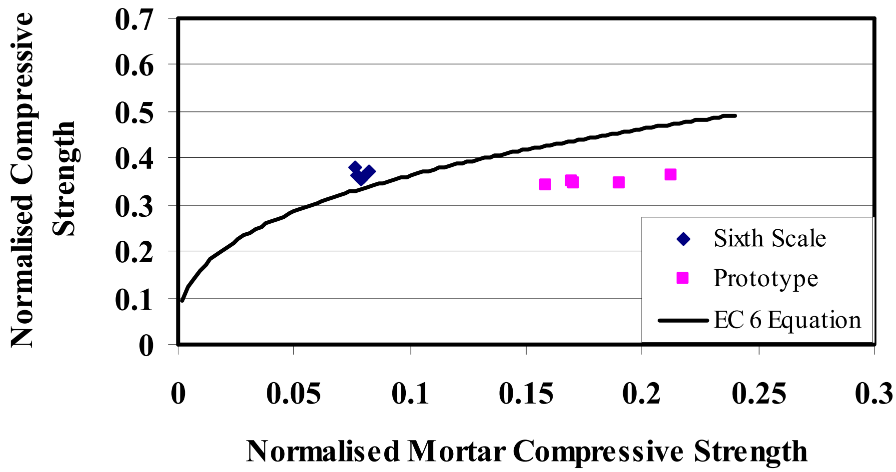


Figure 4 - Normalised plot of wallette compressive strength against mortar compressive strength for prototype and model scale.

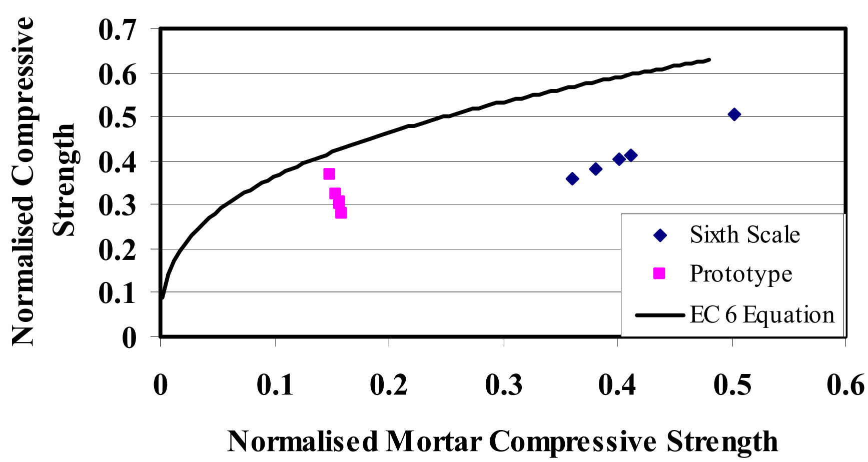


Figure 5 - Normalised plot of triplet compressive strength against mortar compressive strength for prototype and model scale.

The normalised plot for the compressive strength against the mortar strength for both the prototype and 1/6 scale triplet is shown in Figure 5. Similar to the normalised plot for wallettes, this plot also shows good agreement in the normalised values of the triplet strengths.for the two scales (normalised triplet compressive stress about 20% higher than the prototype strength). There is a greater divergence in the strength values in this case. One possible explanation for the greater spread of results for the triplets than for the wallettes is the simple material variation resulting from the reduced number of units in the experiment.

The Typical average vertical and horizontal strains in the prototype and model scale wallettes are shown in Figures 6 and 7, respectively. The values of the modulus of elasticity for the specimens have been rounded up to the nearest 100 N/mm^2 as recommended by the code. Figures 8 and 9 show the relationship between the stiffness of the wallette and triplets against their respective compressive strengths. The slight difference in the strength of the two specimen formats is possibly due to their different aspect ratios and natural variability due to their material properties. In the triplet specimens, the prototype stiffness is 10% lower than the model scale value while in the wallette specimens; the model scale stiffness is 25 % higher than the prototype value. Better agreement between the stiffness values at model and prototype scales has been achieved here compared with the findings of other authors, as stated earlier. This result reinforces the possible effect the differential compaction of the mortar beds might have on the stiffness properties of the masonry at different scales. However because the influence of this effect has been effectively cancelled by the manner in which the masonry was made in the current study, the stiffness in the two scales is remarkably similar for both formats of specimens.

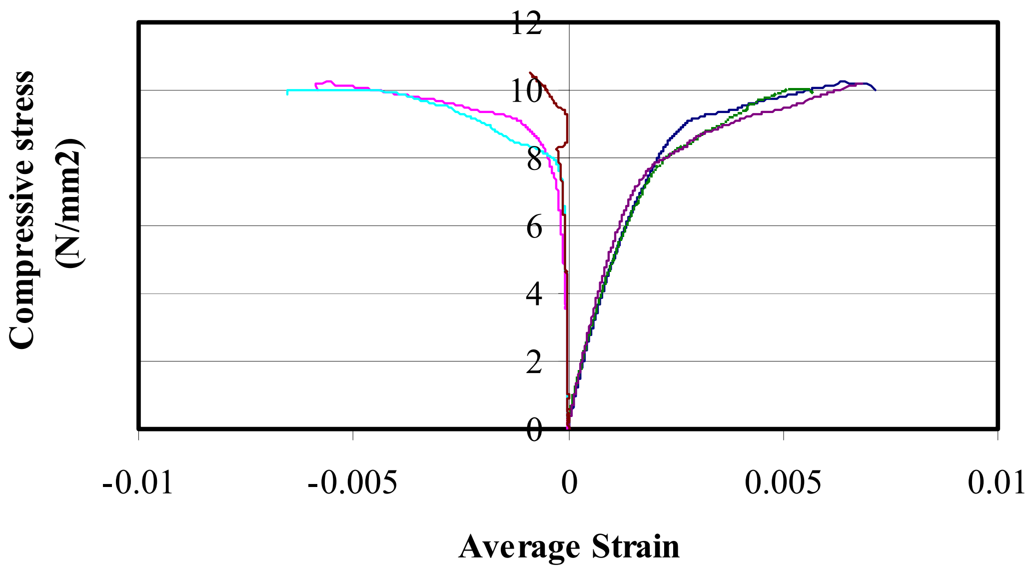


Figure 6 – Average vertical (right) and horizontal (left) strains in prototype wallettes

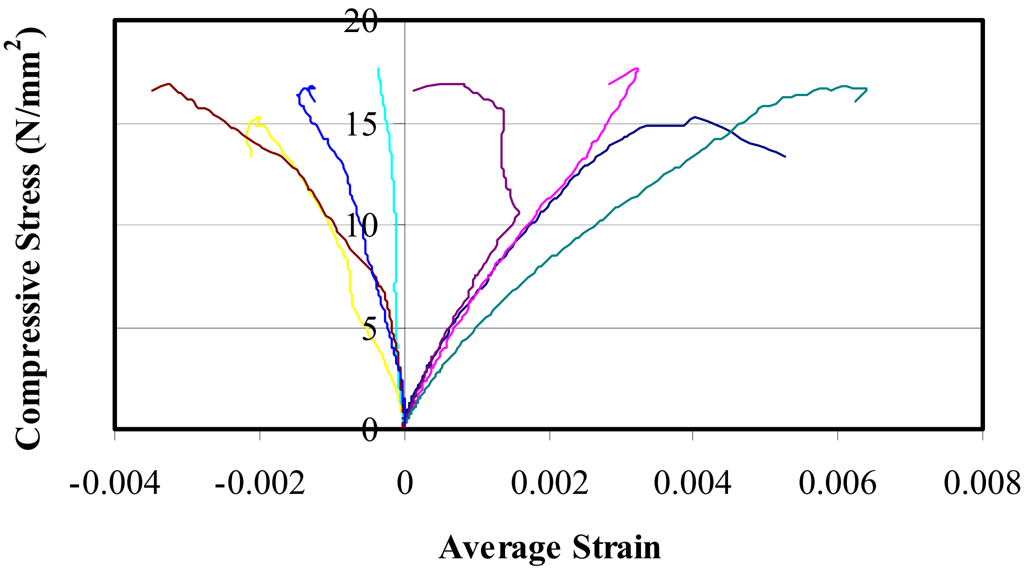


Figure 7 – Average vertical (right) and horizontal (left) strains in model scale wallettes

This is possibly due to the heavier units in the prototype compacting the mortar beds during curing to a greater degree when brickwork is made in the traditional way than the lighter units in the models. Since the mortar is less compacted in the model scale, it results in higher strains and consequently lower stiffness under the applied load.

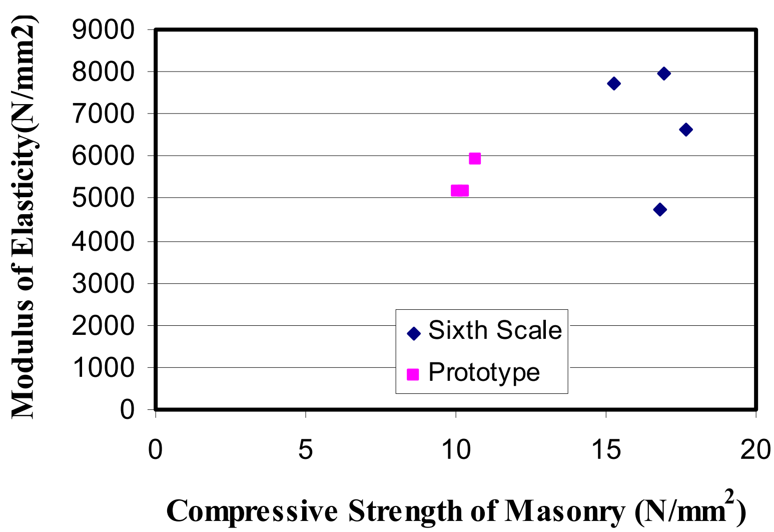


Figure 8 - Wallette Modulus of elasticity versus compressive strength

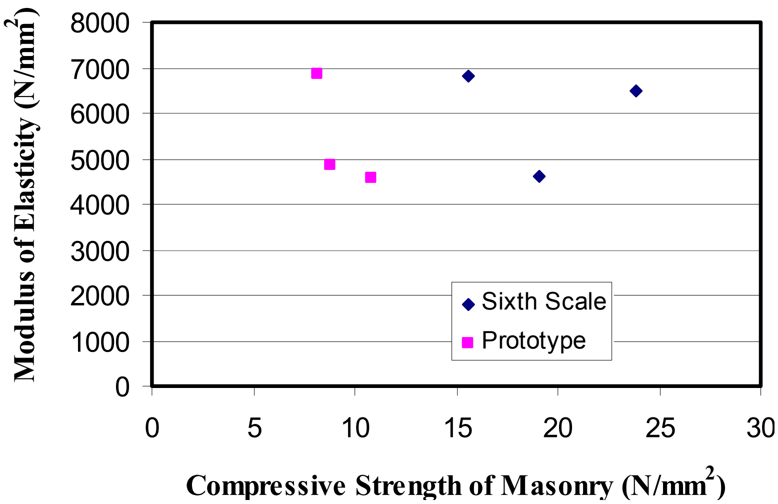


Figure 9 - Triplet Modulus of elasticity versus compressive strength

The overall close agreement of the results for the triplet specimens as compared to the wallette specimens at both scales again supports the use of the triplet tests as a simple and reliable test for the strength and stiffness of masonry assemblies in axial compression, as has been reported by [11] and [12]

It is also seen that the Poisson's ratios for the model scale wallettes are higher than for the prototype wallette. This could be attributed to the manner in which the MMCG's were located on the model scale specimens; because of space constraints the gauges were located very close to the perpend joints or almost at the joints. Consequently as mortar is softer than the brick material it undergoes greater deformations under loading, which subsequently results in an apparently larger Poisson's ratio for the model wallettes. However the imprecise location of the small scale pins due to their large surface compared to the gauge length makes comparison difficult.

CONCLUSIONS

The results indicate that it is possible for model scale masonry to accurately model the strength and stiffness of a similar prototype model. Laying the units on their sides had effectively cancelled effects due the differential compaction of the mortar bed in the two scales and had resulted in model stiffness values that are about 11-26% higher than the prototype.

Normalised brickwork strengths in terms of the unit brick strength for both the prototype and model scales are in very good agreement. This is further evidence that the model brickwork behaviour is remarkably similar to the prototype.

Model bricks could be produced from a prototype brick by the cutting method used in this research for the production of various sizes of model brick units.

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