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The effect of scale on the structural behaviour of masonry under compression

A. Mohammed [a,*], T.G. Hughes [b,1], A. Mustapha [c]

[a] Civil Engineering Programme, Abubakar Tafawa Balewa University Bauchi, PMB 0248, Bauchi, Bauchi State, Nigeria
[b] Civil Engineering Department, Cardiff School of Engineering, Cardiff CF24 0YF, UK
[c] Civil Engineering Department, University of Maiduguri, PMB 1069, Maiduguri 600001, Borno State, Nigeria

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ABSTRACT

This paper discusses the effect of scale or size effect on the structural behaviour of masonry under compression. Small scale modelling has been employed as a means to understanding masonry structural behaviour over the years, because testing prototype masonry structures is both costly and difficult to control in terms of instrumentation. An experimental programme involving tests at four scales namely prototype, half, fourth and sixth scale were undertaken under compression with a view to understanding how compressive action affects masonry structural behaviour over the range of scales under consideration. The results show that masonry compressive strength is increased as the scale is reduced but the stiffness is not significantly affected.

1. Introduction

Small scale masonry model testing has been carried out for many decades. Early researchers in this area include [1–3]. Tests by these authors has established that it is possible to model masonry behaviour at reduced scales but not the strength and stiffness, this has also been reported by Refs. [4,5]. Recent interest in masonry modelling has arisen because of the need to assess and maybe strengthen existing historic masonry structures like bridges and buildings. For instance there are over 40,000 masonry arch bridges in the UK. Most of these bridges are over 100 years old, while some are as old as 500 years. Increasing traffic speeds and weights have made assessing both the ultimate and serviceability requirements of these bridges necessary.

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. For example in January 2005, up to £250 m worth of damage was caused by flooding due to very heavy rainfall in Carlisle, England [6]. In Iran an earthquake in Bam killed about 35,000 people and flattened about 90% percent of the city's mainly masonry houses [7]. 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.

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. This paper primarily aims to compare masonry structural behaviour at prototype and small scales.

2. Experimental design

The aim of this research as it has been stated is to compare experimentally brickwork structural behaviour at prototype and model scales. However a reference scale was needed that provides significant opportunities for modelling overall structural behaviour of, for example arch bridges, whole buildings, retaining walls etc., as well as for undertaking the parametric study. Ref. [8] has suggested twelfth scale as a limiting scale in small scale masonry modelling while other authors [2,4,9] have reported reasonable model to prototype scale correspondence using half, third, fourth and sixth scale model masonry. An examination of the different factors led to the choice of the sixth scale as the limiting scale for this research, because it is most suitable for modelling whole masonry structures and components in a controlled laboratory environment. Two further scales of half and fourth scale were also investigated for the first programme of tests in order to get a complete picture of masonry behaviour across the range of scales. It was intended that material tests would be first carried out to

* Corresponding author. Tel.: +234 80 35145747.
E-mail addresses: abba_gm@yahoo.com (A. Mohammed), Hughestg@cardiff.ac.uk (T.G. Hughes).
[1] Tel.: +44 2920 875716.

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determine the properties of the constituent materials that make up the masonry; the bricks and mortar e.g. compressive strength and flexural strength etc. Knowing the individual material properties will aid in understanding the composite behaviour of the masonry assembly; by determining how properties of the components contribute to overall brickwork behaviour under various conditions of loading.

In order to fully understand the composite behaviour of the masonry specimens, consideration was made of how best to capture the structural behaviour of a masonry structure, because in any masonry structure, its various elements are under the influence of a variety of actions. For instance a masonry wall could at any point be under a vertical compressive load, out-of-plane and or in-plane lateral forces, etc. Even though most of these forces act together, it is better to isolate each one to understand the mechanics of its action. Therefore to understand the fundamental behaviour of masonry, each of the actions was taking separately and considered for each of the chosen scales. Consequently in order to understand the behaviour of masonry under some of the most common actions to which it is subjected to, the following tests were chosen; compressive strength, flexural strength, shear strength and bond strength tests. Only the effects of scale on the structural behaviour of masonry in compression is reported here since that is the primary aim of the paper, in depth discussion on the other effects are discussed in [10].

2.1. Choice of bricks and mortar

Refs. [8,10] have reported some issues regarding the firing of reduced scale model clay bricks. These issues included the fired model bricks being irregular in shape as well as some bricks more burnt than the others. Because of these problems a cutting procedure developed and used successfully by Refs. [5,8] was employed for the manufacture of the model clay bricks from a standard solid prototype clay burnt brick of approximately 215 × 102.3 × 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 eight 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 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 (1.6 mm) and 1/4 scale (2.5 mm). Further considerations on the experimental design are provided in [10].

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.

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

3. Materials and methods

3.1. Materials

The bricks used in the research were solid burnt 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, a very fine sand with an average grain size of 120 μm was used for making the mortar in the model tests, the gradings of the two sands is shown in Fig. 1 in relation to the grading limits set by BS13139, it shows that the normal building sand is within the grading limits and the model sand is within the sixth scale grading limit (set by simply diving 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.

3.2. Construction procedure

The bricks were first pre-wetted by totally immersing in a water tank for 20 min 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 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 10 mm 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. A picture of the triplet specimens in the four scales is shown in Fig. 2.

3.3. Test procedure

Three brick high triplet specimens were tested in the in load controlled testing machine at a loading rate of 0.18 kN/s, 0.04 kN/s 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 [5]. The stiffness of the masonry was calculated as the secant modulus at a third of the maximum stress reached.

Table 2
Mechanical properties of prototype and model bricks.

Test	Prototype	Half	Fourth	Sixth
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)	11,500	–	–	–
COV (%)	31	–	–	–
Poisson's ratio	0.06	–	–	–
COV (%)	48.1	–	–	–