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The development of a new method for testing the lateral load capacity of small-scale masonry walls using a centrifuge and digital image correlation

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ABSTRACT

A new method is presented for the manufacture and testing of 1/6th scale masonry wall panel specimens using a centrifuge to correctly model self-weight. The test procedure allows application of either uniform lateral load using an air bag or non-uniform hydraulic loading. A novel approach has been taken to measure deflections during testing using digital image correlation and has proved successful. Results of three initial uniform lateral loading tests of specimens manufactured from autoclaved aerated cement blocks and M2 strength class mortar are detailed. The experimental failure loads compared reasonably well to values calculated using yield line analysis.

1. Introduction

Masonry walls of domestic and commercial properties can be subjected to imposed lateral loading due to the effect of wind and flood water. Generally the walls of such buildings will be unreinforced and comprise of brick or block masonry units laid using a cement based mortar. The effect of uniform wind loading has been well investigated by a number of researchers in the field and has been studied both experimentally and analytically [1–8]. The majority of the experimental research has been completed at full (prototype) scale, but the problem has also been studied at reduced (model) scales of 1/2 and 1/6th [1,4]. A large proportion of this research was completed in order to develop suitable methods to calculate the lateral load capacity of masonry wall panels [3,5]. A number of different approaches have been taken by researchers in the field to establish the theoretical failure loads and have included yield line, fracture line, elastic plate, finite element and strip analysis [3,9,10]. The method detailed in the current European Code for the design of masonry structures (EC6) is based upon a yield line analysis [11]. More recently, research has focussed upon the effect of openings within the masonry panels [12,13].

Very limited research, however, has been completed to assess the effect of non-uniform hydraulic loading on masonry structures. A single experimental study has been identified in the literature, which suggested sealing masonry to a height of no more than 0.9 m to avoid structural failure [14]. Later to this, analytical research was presented that suggested properties could be sealed to a height of 0.9–1 m [15]. Guidance for calculating the lateral capacity due to flood-water is not currently provided in EC6 [11]. Currently designers are only able to take an overly conservative approach by using the EC6 method with an equivalent uniform load. Systems that provide resistance to flood water frequently utilise the structure of the property, so there is a need to deliver a suitable and reliable method to determine the lateral load capacity of masonry.

Carrying out experimental work at a reduced scale has considerable advantages over prototype scale testing. Research programmes can be delivered more economically and a greater number of samples can be considered in a similar time frame, allowing repeatability [16–19]. At small scales testing procedures will be safer and failure of the specimen is unlikely to cause damage to instrumentation [16–18]. Careful consideration, however, needs to be made when working at reduced scales to ensure material properties, loading rates, scale effects and details are properly accounted for. Small-scale masonry models are generally constructed from prototype material units, which are either cut or manufactured at a reduced size. The disadvantages of this approach are that the material density (effect of self-weight) and stiffness are not scaled [19,20]. To correctly model self-weight several approaches can be taken that include: the addition of mass to the structure, testing under artificially enhanced gravity or manufacture of special masonry units. Complete or true masonry units that correctly model the increased density and reduced stiffness are however complex and costly to develop [20]. The constituents of model mortars and concrete are generally only dimensionally scaled [16,21]. Time is scale dependant so to correctly model the prototype behaviour the strain rate should be increased with a reduction in scale [19]. The response of masonry and concrete has shown to be affected by the loading or strain rate during

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testing, where higher strain rates provide stiffer responses [19]. Conservative results are also likely if the strain rates applied to the model are lower than those expected in the prototype [19].

Contradictory information regarding scale effects in masonry is apparent in the literature and results presented in a number of studies varied with loading configuration. Compressive tests completed on 1/3rd and 1/6th scale model brickwork piers and walls were found to be similar to previous results of tests at prototype scale [22,23]. Deflections in the model scale specimens were higher than prototype values indicating a reduction in stiffness with a reduction in scale [22]. No explanation was offered for the reduction in stiffness with scale. Tests on adobe brick specimens showed an increase in both compressive strength and flexural strength with a reduction in scale [19]. The results are suggested to be due to an increased mortar and bond strength with reduction in scale [19]. It is also stated that material tests at prototype and model scale should be completed alongside structural tests to allow comparisons to be established during analysis [19]. A study of prototype, 1/2 and 1/4 scale masonry walls under compression found that the strength and failure modes were similar, but the stiffness reduced with scale [21]. The reduction in stiffness was attributed to a reduced compaction of the mortar with scale due to a diminishing self-weight effect, and differing gradings of mortar constituents between scales [21]. Later to this, results of compressive strength tests of masonry specimens at prototype, 1/2, 1/4 and 1/6th scale have shown a slight increase in strength with a reduction in scale [16,24]. The increase in compressive strength was suggested to be partly affected by the brick cutting method, where weaker bricks would fail during the process [16].

Research has recently been published that compares the behaviour of masonry specimens at model scales of 1/2, 1/4 and 1/6th to the prototype scale [17,18]. Compressive strength tests of triplet brickwork specimens showed an increase in compressive strength with reduced scale although a similar failure mechanism was observed [17]. The increase in compressive strength was attributed to a brittle materials type size effect and anisotropy in unit strength due to the manufacturing process [17]. The stiffness of the triplet specimens was found to be similar across the scales, differing to the reduction in stiffness with scale found by previous researchers [17]. The difference in stiffness was attributed to the construction technique used in the study, which involved the specimens being constructed flat rather than vertically [17]. Flexural strength tests of wallette specimens showed there was, depending on test orientation, a slight reduction or no significant difference in strength through the scales [17].

The use of small-scale masonry models has been adopted by a number of researchers to examine different structural problems. Lateral loading tests of storey height masonry panels have been conducted at scales of 1/2 and 1/6th and were found to accurately model the prototype structural failure modes and showed acceptable repeatability [1,4]. Masonry arch bridges have been constructed at small scales and testing has been completed using a centrifuge to correctly model the self-weight of the masonry arch and fill material [16,25]. Prior to this researchers had neglected the effect of self-weight in models or attempted to compensate for it by adding mass to the masonry before testing [25]. Comparison of the results from 1/6th scale masonry arch models tested in the centrifuge and prototypes of corresponding dimensions showed good correlation between the peak load and failure mechanism, but the stiffness was found to be lower in the model [25]. The reduction in stiffness in the model arch was attributed to the grading of the constituents of the model mortar. Later to this, researchers have successfully constructed and tested masonry arches at scales as low as 1/55th [16].

A number of researchers have used scale models to assess the effect of seismic action on masonry built structures. Shake table tests of 1/2, 1/4, 1/5 and 1/7th model scale masonry structures have been performed [20,26,27]. The dynamic responses were found to compare well to theoretical values determined for the prototypes. The failure modes identified in the tests were also shown to simulate those seen in real structures that have been subjected to natural earthquakes [20]. Both prototype and complete masonry materials have been used in the studies. To avoid changing the dynamic response of the former, prestressing cables rather than weights were used to maintain stress levels in the walls [20]. Material tests were also completed in addition to structural tests to provide parameters for theoretical analysis [20,26,27].

The review of the literature illustrates that small masonry specimens can be used to model the prototype with good agreement in terms of failure modes and loads, but may yield a response of lower stiffness. Material tests should always be completed alongside the structural model tests to enable comparison of the model and prototype response. This paper presents the development of a research programme that has been initiated to examine the effect of lateral loading on 1/6th scale masonry wall panels. The main aim of the programme is to assess the load capacity of wall panels when subjected to hydraulic loading, but uniform wind loading tests will also be completed to allow verification of the experimental design to published methods and results. Wall panels will be tested using the centrifuge to correctly model the self-weight of the masonry as previously discussed. Hydraulic loading tests will demand the use of the centrifuge to ensure that the correctly scaled gravitational force is applied to the water. Full details of the testing programme are shown in Table 1, including details of the small specimen tests. The findings of the study will be used to develop a suitable model of the system likely utilising yield line analysis methods. The following sections detail the development of the programme detailing the issues with masonry unit and specimen manufacture, centrifuge testing and instrumentation. Initial results from the uniform lateral load testing programme are also presented.

2. Experimental design

2.1. Overview

The main aim of the experimental programme, as presented in Section 1, was split into six tasks as follows:

2.1.1. Examine the effect of vertical load on lateral load capacity

The current design method for lateral loading in EC6 is based upon yield line analysis where the moments of resistance, in parallel (x) and perpendicular (y) directions to the bed joints, are obtained from masonry's flexural strength [11]. The orientation of the co-ordinate system is shown by Fig. 1. Values for flexural strength are provided in EC6, but may also be determined from bending tests upon wallette specimens [28]. Vertical loading (self-weight and imposed) is allowed for in this method, but only affects the moment of resistance in the x direction. Few researchers have significantly considered the effect of vertical loading to date [4]. Recently, a method has been developed that bases the lateral capacity of the wall purely on the vertical load [15,29]. An equivalent moment of resistance is developed in the x direction based upon the section's resistance to overturning. In the y direction it is based on the frictional resistance developed as the masonry units rotate against each other at failure. The vertical load affected the moment resistance in both directions and the resistance increased towards the base of the wall and this highlights the importance of studying the effect of the vertical load to understand its implications on the failure mechanism.

2.1.2. Test model scale specimens using the centrifuge

To enable the effect of vertical load to be properly studied at model scale requires the use of a centrifuge. Scale models can be tested outside the centrifuge, but due to their small size the vertical load generally results in an approximately constant stress through the specimen, which is not consistent with the prototype scale. The increased gravitational force applied by the centrifuge, expressed here in multiples of the earth's gravitational force (ng), correctly models the increase in stress towards the base of the wall. If undertaken at prototype scale it would be hard to achieve consistency in manufacture, be time consuming, require significant laboratory space, and could be potentially dangerous when testing with significant applied vertical loads. Therefore, the development of a suitable method to allow rapid and consistent manufacture of model scale wall panel test specimens