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Experimental Investigation of the Mechanical Properties of Historic Stone Masonry Walls

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ABSTRACT

Many existing historic stone masonry buildings have great cultural value and should be preserved. These buildings were not designed or built to resist earthquakes, at least not in a way similar to today's methods. Many of these buildings,, built in the nineteenth or eqrlier centuries, are thought to require strengthening to be able to resist potential earthquakes. An upgrade for earthquake resistance requires identification of the characteristics of the masonry and the structural load paths in the existing buildings.

The mechanical characteristics of rubble-filled, double-wythe stone masonry walls are therefore being investigated. Eight rubble-filled, double-wythe stone masonry walls were built. One wythe is of sandstone, and the other of limestone. The space between the two wythes is filled with rubble masonry, consisting of smaller stones and lime mortar. Two of the walls were plain, and different strengthening techniques were applied to the remaining six walls. An extensive experimental program has been designed comprising of several static and dynamic tests to determine basic mechanical characteristics of the walls, before and after cracking, and to assess the ability of the walls to resist earthquake loading. The experimental program adopted in this research is explained in this paper.

KEYWORDS

Heritage masonry, stonework, Experimental, Mechanical properties, Shake table

1 INTRODUCTION

Historic buildings are part of our cultural heritage that must be preserved. Preservation of historical buildings requires that they first be assessed, and that their mechanical characteristics be determined. Binda and Maierhofer [2007] reported the development and improvement of methodologies for the evaluation of structural and material properties. These methodologies are mostly based on non-destructive testing, and minor destructive testing methods. Corradi et al. [2003] tested some historic masonry walls in-situ to determine their characteristics and strength. They determined values for the Young's modulus and shear modulus for those particular walls.

Many researchers (eg: Tomazevic et al. [1991], Binda et al. [1997], Valluzi et al. [2005], Maurenbrecher and Rousseau [2000]) have suggested repointing mortars and/or grouting as a method of strengthening existing masonry structures. Tomazevic et al. [1991] concluded that grouting to fill the voids in masonry walls is an efficient method for strengthening historic masonry, but that the strength of the grout does not have a significant effect on the lateral behaviour of the walls. Binda et al. [1997] indicated that the grout should be compatible with the original materials. Other researchers (eg: Corradi et al. [2002], Juhasove et al. [2007]) accompanied the

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grouting with the gluing of carbon or glass fibre reinforced polymers (FRP) to the masonry. This last technique can be effective in strengthening the masonry but is very likely to interfere with guidelines for the preservation of heritage structures. For example, according to Standards and Guidelines for the Conservation of Historic Places in Canada [2003] "*preservation involves protecting, maintaining and stabilizing the existing form, material, and integrity of a historic place, or of an individual component, while protecting its heritage value*." The Standard also calls for *minimal intervention*.

Failure mechanisms of masonry structures and observed damage patterns have been summarized by Karantoni and Bouckovalas [1997], and Bayraktar et al. [2007].

- Vertical cracking over windows and doors
- Out of plane failure at upper floors
- Diagonal cracking of the piers
- Separation and collapse at the corners

Out of plane failure is observed mainly in the walls of upper floors where the earthquake is amplified, while in-plane diagonal cracking is a typical failure for the walls of lower storeys due to in-plane shaking.

It has been reported that building specimens representative of such historic buildings is very difficult to achieve in a laboratory. We have designed a testing programme to assess such specimens under both in-plane and out of plane loading conditions. The objective of the test programme is to identify the static and dynamic characteristics of the masonry. The specimens and testing programme are described .

2 SPECIMENS

Eight stone-masonry double-wythe walls were built, where one wythe was of sandstone in a sneck pattern, while the other was of limestone roughly in running bond, Figure 1. The space between the two wythes was filled with lime mortar and rubble masonry, as can be seen in the right hand picture of Figure 2.. The mortar was chosen to replicate the mortar used for heritage structures of this type built around the middle of the nineteenth century and was composed of sand: lime: water in proportions of about 3: 1: 1. The walls are about 2.75 m high, 2.0 m wide and 0.54 m thick.

The walls were built by skilled masons who work in the repair of heritage masonry structures. This was to ensure that the walls were truly representative of this type of historic structure. Construction of the walls is shown in Figure 2. The walls were built on specially designed steel base beams to allow for subsequent transportation. Each wall was built on a separate base beam (Figure 2) After the walls were built, a concrete cap was cast on the top of each wall, making the total height of the wall and cap, 3 m. The purposes of the concrete cap, other than to adjust the height of the wall, were to permit the placement of a top steel beam for transportation (Figure 3), and to allow fixation of the attachments required to connect the wall to the actuator in preparation for testing.

3 INSTRUMENTATION

The walls are being instrumented extensively during each test to capture movements, and accelerations. The instrumentation for each test is explained with the relevant test below. During each test, the data from all the sensors are collected simultaneously with the loads and displacements recorded by the loading actuators through a high speed data acquisition system.

4 EXPERIMENTAL PROGRAMME

The experimental programme consists of two parts: In-plane testing, and out-of-plane testing.

4.1 In-Plane Tests

A testing rig was designed and assembled for the in-plane testing of the walls, shown in Figure 4. Two actuators, each of 1.5 MN capacity, are fixed to the top of the test frame to produce compression on the walls, while one 150 kN capacity actuator is fixed laterally to produce the lateral loads on the walls. The in-plane testing is designed to evaluate different properties of the walls: Young's modulus, shear modulus, damping ratio, and energy dissipation. To determine these properties a series of tests is carried out on each wall.

Figure 1 The walls after casting the concrete cap. Sandstone faces are visible in the two walls to the right of the figure, and limestone faces on the two walls to the left.

Figure 2 The walls in different stages during of construction.

The tests start with three different compression tests. First, two eccentric compression tests, one towards the limestone side, and the other towards the sandstone side are performed. Then a concentric compression test is performed. The concentric compression test should be enough to evaluate the Young's modulus of the wall. However, the three tests are performed in an attempt to obtain Young's moduli for the individual components of the walls. In each of these tests the walls are compressed to a total load of 600 kN distributed over 4 loading points. This load produces average stresses of about 0.6 MPa. During the compression tests the walls are instrumented with displacement transducers at set points to measure the strains occurring in the wall. The strains are measured at different locations over both the whole length of the wall, as well as over the middle third, as shown in the schematic in Figure 5. Transverse strain is also measured so that Poisson's ratio can be determined.

After the compression tests, an in-plane free vibration test is performed to determine the natural frequency of vibration of the wall, together with the damping ratio. In this test the top of the wall is displaced in-plane by less than 1 mm, and the wall released to vibrate freely. During this test, the wall is instrumented with accelerometers and displacement transducers mounted on both the sandstone and the limestone wythes, at four equally spaced locations along the side of the wall.

Figure 3 The lifting system designed for the walls. The base beam and the top beam are connected with four Dywidag bars visible connecting the outer corners of the beams, the system slightly stressed and the wall lifted.

In-plane racking is performed next, where the wall is subjected to a compressive load of 300 kN, while lateral load is applied at the top causing the wall to be displaced laterally. Once the wall has been loaded to 300 kN, the two top actuators are set to hold their position, such that rotation of the top of the wall is constrained. This provides a simple boundary condition for analytic purposes, allowing the shear modulus of the wall to be determined. The lateral movement of the wall is recorded at four positions along the side of the wall, as is displacement along the diagonals of the walls and the loads from both the lateral and vertical actuators.

Racking tests are performed to the extent of displacement expected in an earthquake for the Toronto – Quebec region of Canada. The racking does cause damage to the walls. Quasi-static cyclic push-pull in-plane loading is first applied to the wall where cycles of push and pull are applied to the top of the wall while the base is bolted to the strong floor in the laboratory. The cycles start with applying a 1 mm top displacement to the wall in each direction for two cycles. The top displacement is increased by 1 mm every two cycles. This loading is to simulate the ground motion in an earthquake which can cause displacement of up to 5 mm, the maximum displacement applied to the top of the wall in this test. This type of loading introduces diagonal cracking into the wall. The instrumentation for this test is similar to that for the shear test, where the displacements of the wall are measured along the sides and diagonals of the wall.

After the quasi-static test, high frequency cyclic displacements are applied to the wall. In this test a cyclic push-pull load is applied to the wall at a frequency of 5 Hz. The cycles start with applying a load of 1 kN, and increases of 1 kN increments are made up to 10 kN. For this high frequency vibration test the wall is instrumented similarly to the free vibration test. After this test the wall is tested again in compression, static shear, and free vibration to evaluate its properties after cracking, as a measure of the deterioration the wall has suffered.

4.2 Out-of-Plane Tests

After the in-plane testing above, the walls are moved to a one degree of freedom shake table. The setup for the shake table is designed such that the wall is restrained at the top and bottom, simulating a wall between two floors in a building. The steel base beam on which the wall is built is bolted to the shake table. A frame is designed to tie the top of the wall to the corners of the shake table using 4 Dywidag bars to restrain the top, as shown in Figure 6. On the shake table, the walls are subjected to an earthquake simulation which is typical of eastern Canada. Such an earthquake is characterised by low amplitude and high frequency. The walls are subjected to two earthquake simulations. One is an actual earthquake scaled to match the design spectrum for 1:2500 years as specified by the NBCC-2005, and the other is a synthetic earthquake with frequencyas shown in Figure 7. The walls are first subjected to 60% of each of these two earthquakes, followed by the 100% and a 110 %. During these tests, the walls are instrumented with accelerometers and displacement transducers to measure the accelerations and movements at different points of the wall. If the walls survive this shake table test, they will be subjected to a final compression test to determine if they can still carry an average stress of 0.6 MPa and thereby avoid collapse of the building, and as a measure of the level of deterioration incurred.

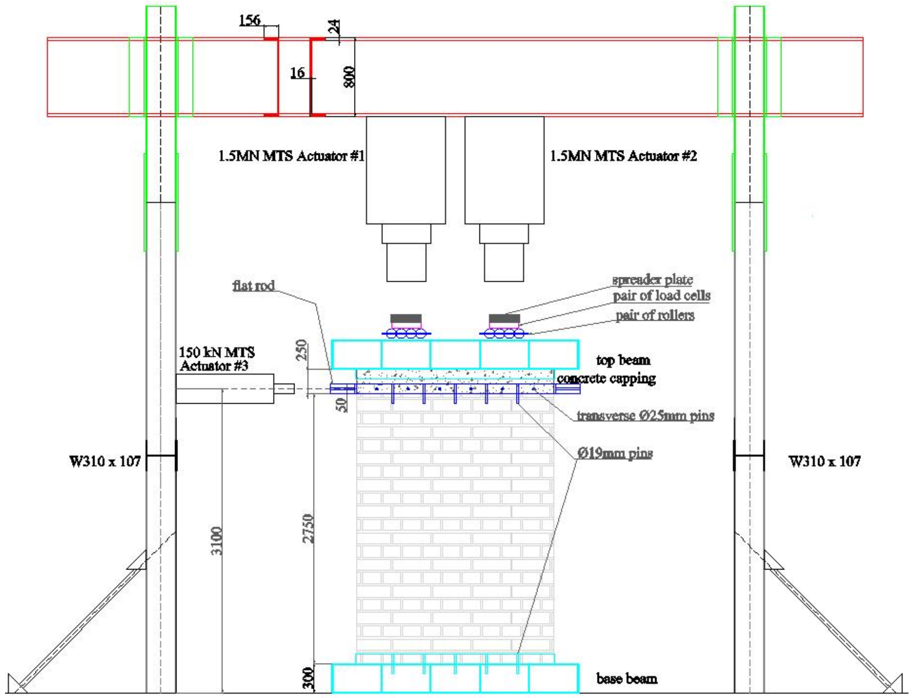

Figure 4 Schematic of the testing rig above, showing the two actuators at the top and one actuator to the side for lateral loading. A wall is shown in the rig in the picture below.

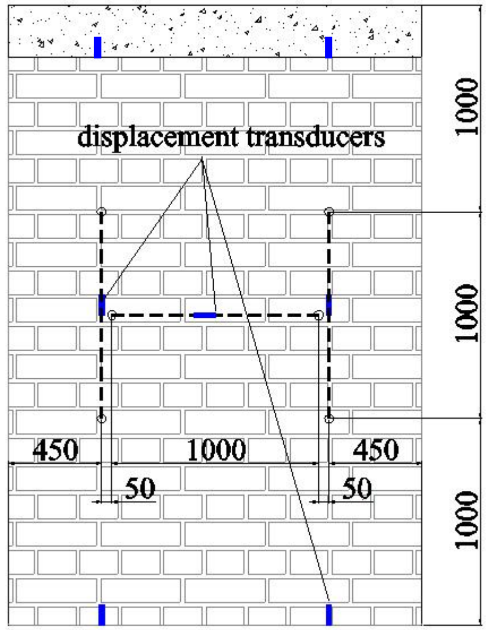

Figure 5 The instrumentation on each side of the wall for compression testing

Figure 6 A wall placed on the shake table (left) and the frame designed to restrain its movement and its instrumentation on the shake table (right).

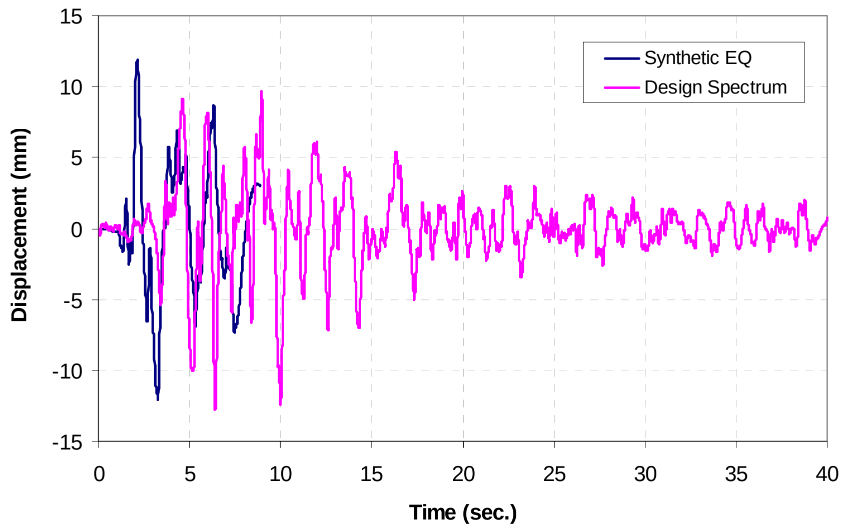

Figure 7 The earthquakes simulated by the shake table.

5. SUMMARY AND DISCUSSION

The experimental programme adopted to evaluate the different mechanical and dynamic properties of heritage masonry walls has been described. The testing programme also evaluates the strength of such walls, under different levels of deterioration. The program subjects the wall specimens to earthquake simulations both in the in-plane, and the out-of-plane. This research is essential to determine if buildings constructed with this type of masonry need to be upgraded in some way to be able to resist the relevant possible earthquake safely, Different upgrading and strengthening methods will be evaluated in the test series. Results from the tests will be reported in the future.

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