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TUBE-JACK TESTING: REGULAR MASONRY WALL TESTING

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Abstract. *Tube-jack testing is an enhanced non-destructive test method being developed at the University of Minho as an enhanced version of the traditional flat-jack test method. The tube-jack system consists of several tube-jacks, instead of flat-jacks, roughly aligned in holes drilled into the mortar joints, of the masonry to be tested, forming an equivalent flat-jack. The tube-jack system can be used similarly to the flat-jack system to test the mechanical properties of historical masonry during inspection and diagnosis of a masonry structure.*

In this paper the testing of the complete tube-jack system in a regular masonry wall is presented. Several single tube-jack tests were performed in horizontal joints in a regular masonry wall, made of granite and cement-lime mortar, built in the laboratory for this purpose. The tests were studied to determine if they could accurately estimate the stress level in the masonry. A double tube-jack test was also performed to determine if this method could be an alternative to the double flat-jack test. Finally, these tube-jack tests were compared to single and double flat-jack tests performed next to the tube-jack tests in the same masonry wall. The results and conclusions of each of these tests are discussed and possible future improvements to the tube-jack system are presented

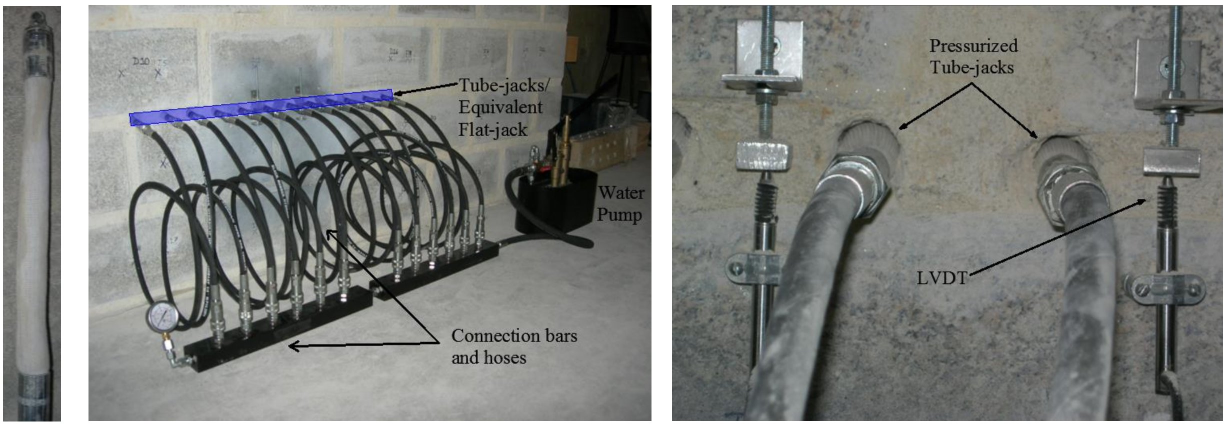
1 INTRODUCTION

Tube-jack testing is a new non-destructive test method being developed as an enhanced version of the traditional flat-jack testing [1], [2], [3], [4]. There are two types of tube-jack tests. The single tube-jack test is comparable to the single flat-jack test and is used to estimate the state of stress in masonry. The double tube-jack test is comparable to the double flat-jack test and is used to estimate the Young's modulus of the masonry. The difference between the flat-jack tests and the tube-jack tests is that in the tube-jack tests lines of holes are drilled in the mortar joints instead of slots and cylindrical tube-jacks are used to apply pressure to the masonry instead of flat-jacks. The tube-jack system has several advantages over the flat-jack system including being able to test the entire thickness of the masonry, flexibility in the length of the line of tube-jacks and the placement of tube-jacks in irregular mortar joints.

The tube-jack system is being developed at the Structural Lab at the University of Minho, in Guimarães, Portugal [5], [6], [7]. The first phase of testing of the tube-jack system is presented in this paper. In this phase tests were performed in a masonry wall of regular typology that was built in the lab for this purpose. Single tube-jack tests were performed in several of the mortar joints on the left side of the wall and then a single flat-jack test performed on the right side of the wall for comparison. Following the single tube-jack tests, a double tube-jack test was performed on the left side of the wall using two lines of tube-jacks. A comparison double flat-jack test was then performed on the right side of the wall.

2 TUBE-JACK SYSTEM AND THEORY

The tube-jack system consists of a series of tube-jacks connected to a water pump via hoses and connection bars. The single tube-jack test system is shown in Figure 1. When a double tube-jack test is performed a second series of tube-jacks is connected via hoses to the connection bars. Linear variable displacement transducers (LVDTs) are placed on the masonry surface to measure the displacement of the masonry. The LVDTs and a water pressure sensor are connected to a data acquisition system and computer for recording the measurements.



(a) (b) (c)

Figure 1 Tube-jack test system: (a) tube-jack; (b) tube-jacks inserted in holes in the mortar joint and their connection to the water hand pump; and (c) pressurized tube-jacks and LVDTs for measuring the displacements

A single tube-jack test is performed by drilling a line of holes in a mortar joint of a masonry specimen, recording the displacement of the masonry over the line of holes as the masonry closes together, inserting the tube-jacks in the holes, and pressurizing the jacks until the displacement returns to zero. At the point where the displacement returns to zero, the pressure in the tube-jack system can be used to calculate the stress state in the masonry. The calculation of the local state of stress within the masonry can be accomplished with the same formula as used for flat-jack testing, Eq. (1).

$$\sigma_m = k_m k_a P_{Applied} \tag{1}$$

where σ_m = local state of stress in the masonry, k_m = jack correction factor, k_a = area correction factor, and $P_{Applied}$ = applied jack pressure required to return the average differential displacements to zero, the state before the holes were drilled.

Since the pressure is being applied to the inside of the holes radially, the portion of the pressure perpendicular to the line of the tube-jacks is less than the pressure inside the tube-jack system. Using trigonometry and calculus the total applied pressure perpendicular to the line of tube-jacks can be calculated using Equation (2).

$$P_{Applied} = P\frac{\pi}{4} \tag{2}$$

where P is the pressure inside the tube-jack system. Other factors that impact the pressure applied to the masonry are the tubing material and the component of the radial pressure applied parallel to the line of tube-jacks. These factors must still be investigated and are not considered in this paper.

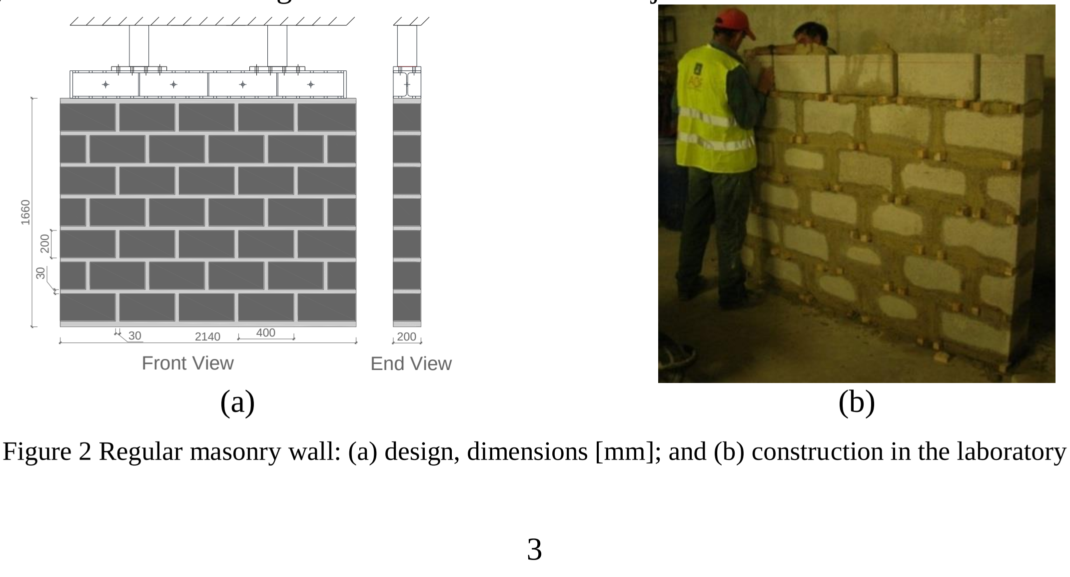
A double tube-jack test can be performed following a single tube-jack test by drilling a second line of holes parallel to the first line of holes, inserting tube-jacks in all of the holes, and pressurizing all of the tube-jacks. By drilling a second line of holes parallel to the first line, a masonry specimen between the two lines are created. When the two lines of tube-jacks are pressurized, the masonry specimen between the lines of tube-jacks is compressed. LVDTs are used on the surface of this specimen to measure the deformation for calculation of the Young's modulus of the material.

3 MASONRY WALL CONSTRUCTION AND CHARACTERIZATION

A large masonry wall was built in the Structural Lab at the University of Minho for the purpose of performing tube-jack and flat-jack tests in a controlled environment. The design for the masonry wall was based on typical granite masonry found in the northern parts of Portugal, though the typology was more regular than most traditional constructions. Future tests are planned in walls of semi-irregular and irregular typologies.

3.1 Construction

The single leaf masonry wall was built of granite blocks having dimensions of 20 cm by 20 cm by 40 cm and low strength cement-lime mortar with joints widths of 3 cm.



(a) (b)

Figure 2 Regular masonry wall: (a) design, dimensions [mm]; and (b) construction in the laboratory

After the construction and curing of the wall, it was loaded using a 2 m long steel profile with two hydraulic jacks, which applied pressure from the reaction floor above (Figure 2).

3.2 Characterization

Mechanical characterization tests were performed on small masonry wallets constructed of the same materials and with the same typology, on granite cylinders drilled from the same granite as was used for the masonry wall, and on mortar cylinders cast from the mortar used to build the wall. These tests were presented in detail elsewhere [8]. Some of the results are presented in Table 1 for reference.

Table 1: Mechanical characterization of the materials.

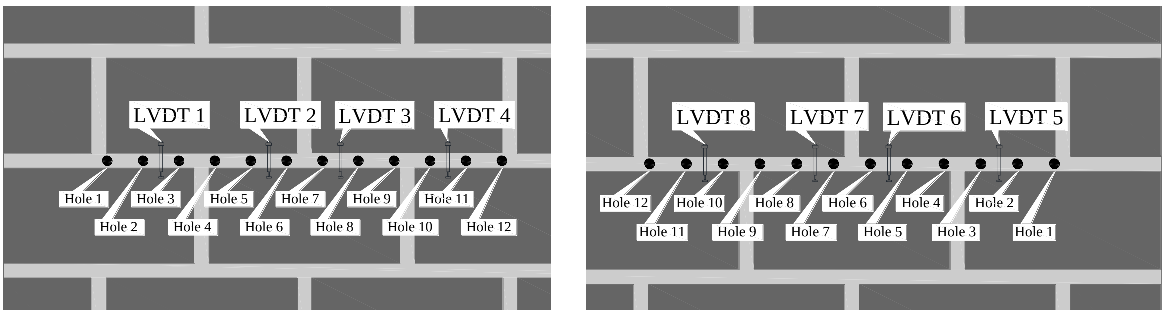
Specimens	Young's modulus [GPa]	Standard Deviation	Poisson Ratio	Compressive Strength [MPa]	Standard Deviation
Masonry Wallet	2.50	-	0.218	4.17	-
Granite Cylinders	29.82	3.140	-	67.90	14.080
Mortar Cylinders	0.28	0.058	-	0.32	0.048

4 SINGLE TUBE-JACK TESTS

Three single tube-jack tests were performed in the horizontal joints of the large regular masonry wall. To prevent holes from one test influencing the results of another test, holes from previous tests were filled with mortar between tests. A preliminary test was performed with an air pressure system. This air pressure system was unable to apply enough pressure to the wall to return the initial displacements to zero. Thus, a water pressure system was used for all subsequent tests and is the system presented in this paper.

4.1 Test set-up and procedure

The test set-up and procedure was similar for all of the single tube-jack tests. Differences in the individual tests are indicated in the results. The wall was loaded using the two hydraulic jacks, as shown in Figure 2a, the day before each test was to be performed to allow the wall to adjust to the loading. Since the tests were performed in different joints, the stress level at each joint was calculated separately and is reported with the results of each test. Twelve rubber tube-jacks were used for each test. The holes for the tube-jacks were spaced approximately 7.5 cm from center to center. Eight linear variable displacement transducers (LVDTs) were used, four on the front of the wall and four on the back (see Figure 3).



(a) (b)

Figure 3 Holes and LVDT positions for the single tube-jack tests: (a) front of the wall; and (b) back of the wall

The holes for the tube-jacks were drilled starting from the center holes and working toward the outer holes. The displacements of the LVDTs were recorded both during the drilling process and after the drilling was completed. The tube-jacks were not inserted into the holes or pressurized until the movement of the LVDTs was nearly zero. The area correction factor, k_A, was calculated to be 0.825 by dividing the area pressurized by the tube-jacks by the (drilled) surface area of the holes. The values used for this calculation were the contact length of the tubing material, 16.5 cm; average diameter of the holes and diameter of inflated tube-jacks, 2.5 cm; number of tube-jacks and holes, 12; and the thickness of the masonry, 20 cm.

4.2 Results

A summary of the results of the single tube-jack tests performed in the 3rd, 4th, and 5th horizontal joints up from the base of the regular masonry wall is presented in this section. Table 2 presents the results of the individual tests that were performed and the subsequent pressurization tests. Values that are presented include the calculated stress at each joint based on the vertical loading, the initial average displacement of the LVDTs caused by drilling the holes, and the test estimated stress. The "test estimated stress" is the effective pressure applied to the masonry when the average displacement has returned to zero. Already accounted for in value of the "test estimate stress" are the area correction factor from Equation (1) and the applied pressure calculated from Equation (2). The values for the "test estimated stress" have also been adjusted to account for an initial inflation pressure of 0.04 MPa (See Figure 5). The inflation pressure is the amount of pressure required to inflate the tube-jacks before they begin to pressurize the wall. The tube-jack tests in the 3rd and 4th joints still show a test estimated stress higher than the calculated stress by approximately 0.05 MPa. Further study must be done to determine what other factors are influencing this result so that they can be taken into consideration for future tests.

Table 2: Summary of single tube-jack test results.

Test	Horizontal Joint	Calculated Stress [MPa]	Initial Displacement [μm]	Tubing Material	Test Estimated Stress [MPa]
Tube-jack test 1	3rd	0.230	8.5	Rubber	0.28
Pressurization	3rd	0.230	-	Rubber	-
Tube-jack test 2	4th	0.224	6.5	Rubber	0.28
Pressurization	4th	0.224	-	Latex	-
Tube-jack test 3	5th	0.421	53.6	Rubber	-
Pressurization	5th	0.421	-	Latex	-

One of the advantages of tube-jack testing is being able to measure the displacement of the wall during the drilling process. Measurements during the first test revealed that the front of the wall had much more downward movement during the drilling than the back of the wall (Figure 4a). After concluding the first test, the hydraulic jacks on top of the wall were adjusted and the wall reloaded. The measurement of the downward displacements during the second single tube-jack test showed similar displacements on both sides of the wall, confirming the hypothesis that there was an eccentricity in the vertical loading on the wall (Figure 4b).

One of the main successes of these first single tube-jack tests in the regular masonry was their consistency. When plotting the pressurization cycles from the first tube-jack test in the 3rd joint (Pressurization 1-3) and the pressurization test following (Pressurization 4), all but the first cycle follow the same curve (Figure 5a).

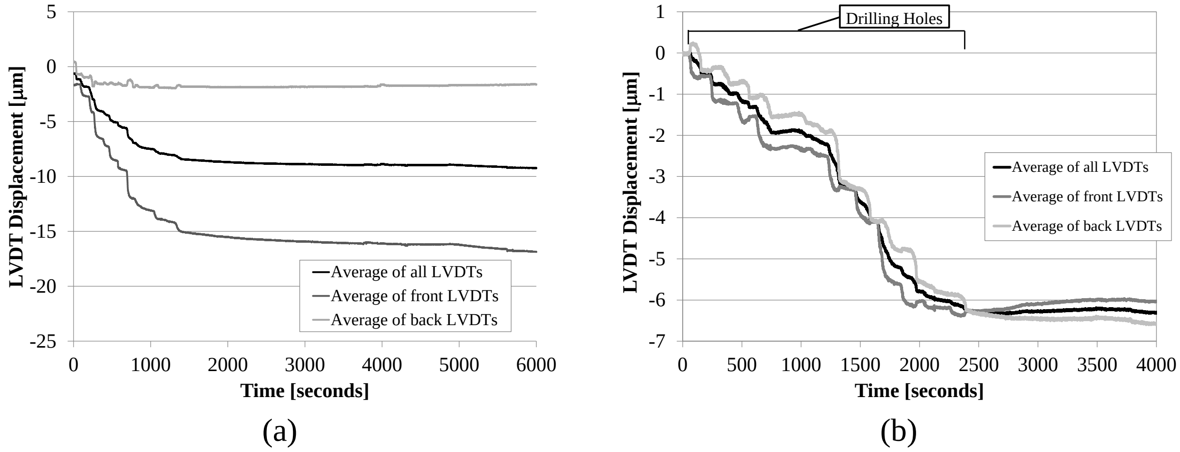


Figure 4 Average displacement of LVDTs during hole drilling: (a) in the 3rd horizontal joint; and (b) in the 4th horizontal joint

Similarly, in the tube-jack test in the 4th joint the two pressurization cycles follow the same curve (Figure 5b). In addition, the tube-jack tests in the 3rd and 4th joints, which had similar calculated stress levels, estimated the stress to be nearly the same value, 0.32 MPa (Table 2).

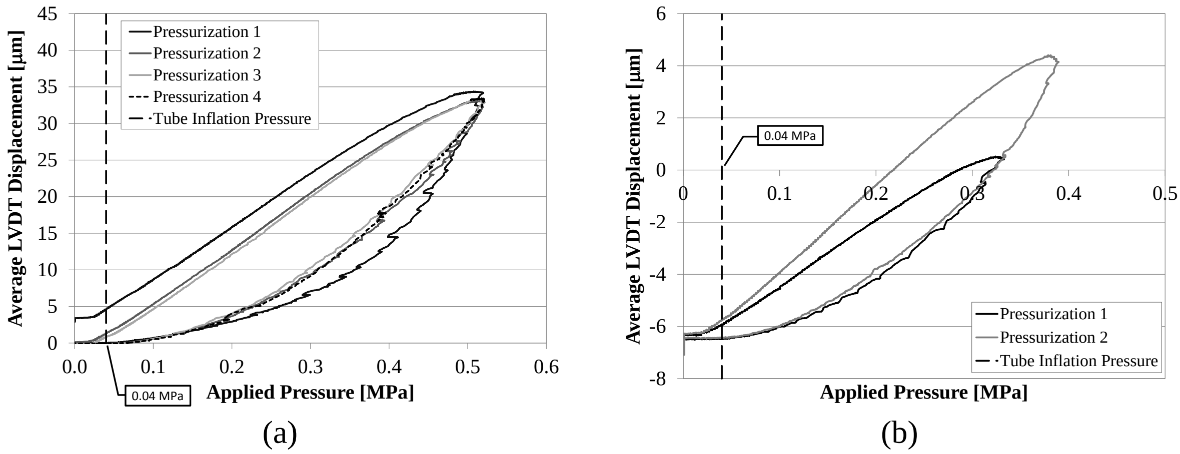
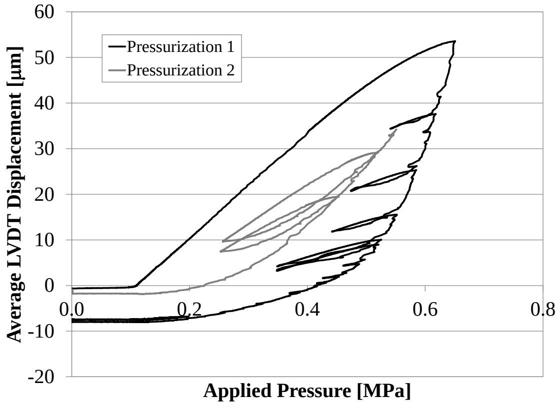


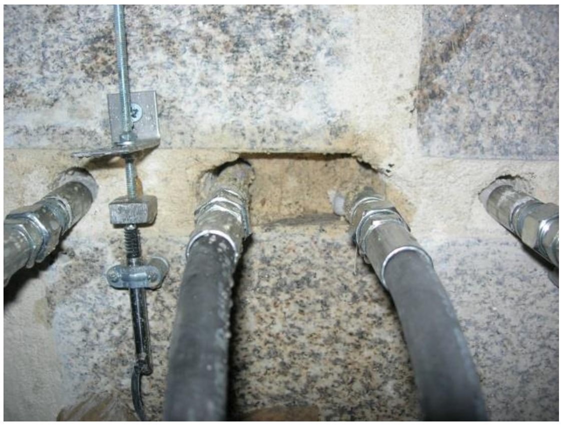
Figure 5 Consistency in the tube-jack tests; (a) pressurizations in the 3rd horizontal joint; and (b) tube-jack test results in the 4th horizontal joint

The results of the pressurization test using the latex tube-jacks in the 4th horizontal joint were not as consistent as the previous tests with the rubber tube-jacks (see Figure 6a). During the pressurizations the tube-jacks were leaking causing a loss in pressure whenever water was not being actively pumped into the system. Another issue was the damage that the latex tube-jacks caused when one burst during the second pressurization (see Figure 6b).

In the test in the 5th horizontal joint, the loading on the masonry wall was doubled, as indicated by the calculated stress. During this test and pressurization, the tube-jacks were not able to apply enough pressure to the masonry to return the displacements to zero; consequently, the test estimated stress results are not displayed.



(a)



(b)

Figure 6 Latex tube-jack pressurization in the 4th horizontal joint: (a) Applied pressure versus average LVDT displacements; and (b) rupture of a latex tube-jack and damage to the mortar joint during the 2nd pressurization.

5 SINGLE FLAT-JACK TEST

A single flat-jack test was performed in the 3rd horizontal mortar joint on the right side of the wall with the same loading on the wall as for the tube-jack test performed in the same joint. A flat-jack with dimensions of 40.5 cm long and 10 cm deep and jack correction factor, k_m, of 0.77 was used. The test was performed in accordance with the standards for the test [1].

5.1 Test set-up and procedure

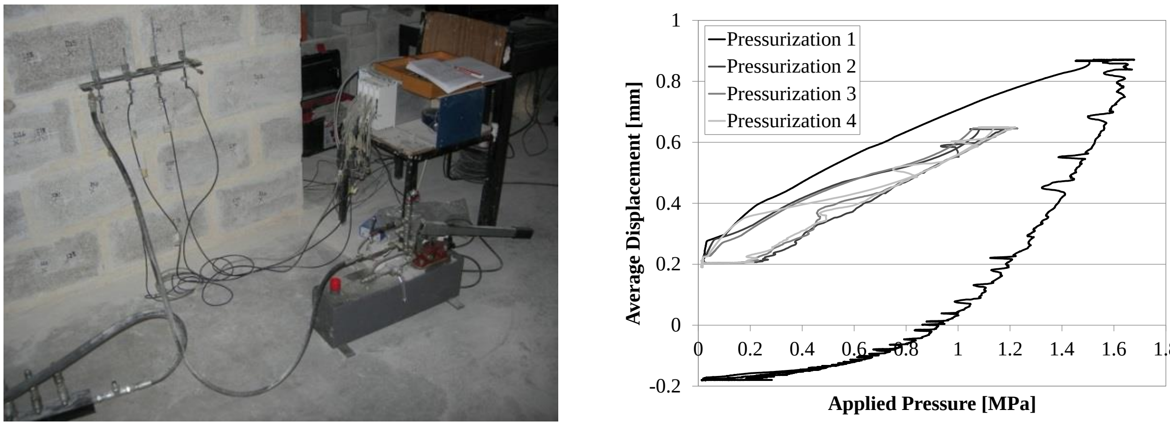
A demountable mechanical strain gage (DEMEC) was used to measure the displacement of the wall over the flat-jack slot location before and after the slot was created. After the slot was opened and the flat-jack inserted, LVDTs were attached and used to record the displacements during the pressurization of the flat-jack. The slot was initially created using a circular saw but was then enlarged using a chisel. It was also necessary to add several plates above and below the flat-jack to fill in the slot due to the uneven slot thickness. The area correction factor, k_a, was calculated to be 0.76. The complete test set-up is shown in Figure 7a.

5.2 Results

A summary of the single flat-jack test results are presented here. The DEMEC measurements showed greater downward movement on the back of the wall than on the front. This could have been again due to some eccentricity in the loading on the wall or movement of the granite units relative to each other. The average initial downward movement was 0.18 mm.

After inserting the flat-jack and plates into the slot, the jack was seated in the slot and then four pressurization cycles were performed, the first up to 2.8 MPa and the subsequent cycles up to 2.0 MPa. The applied pressure, which includes the area correction factor and the jack correction factor, versus the average LVDT displacement is shown in Figure 7b.

The flat-jack test estimate of the state of stress in the masonry would be 0.9 MPa as shown by the first pressurization cycle of these results. This is clearly not close to the calculated value or the value estimated by the single tube-jack tests. The reason for the error in the flat-jack test is that it was only measuring the width of one granite unit. In addition, the flat-jack was only able to measure half of the thickness of the wall.



(a) (b)

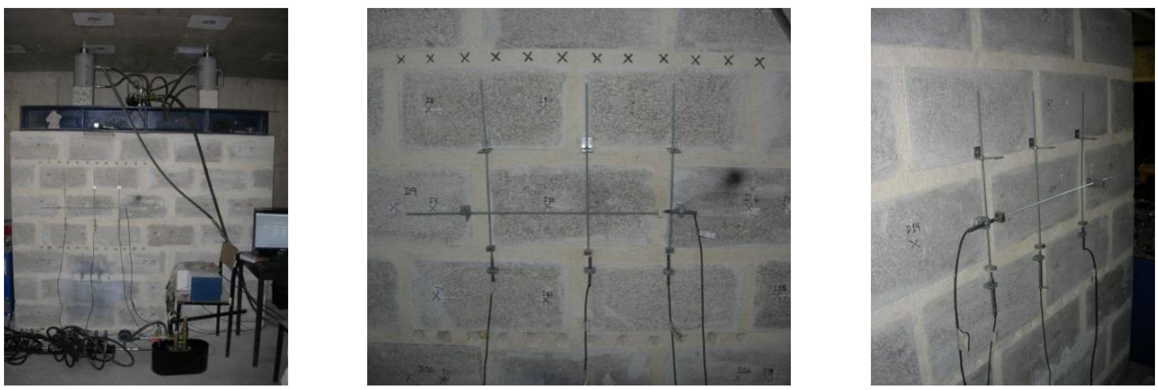
Figure 7 Flat-jack test: (a) complete set-up with the flat-jack and additional plates inserted in the slot, oil pump, LVDTs measuring over the slot, and data acquisition system; and (b) applied pressure vs. displacement results

6 DOUBLE TUBE-JACK TEST

A double tube-jack test was performed for the first time in the regular masonry wall. In this test a second row of holes was drilled in a mortar joint above the first row of holes, made for the single flat-jack test. The two rows of holes vertically separate a masonry specimen within the wall. Tube-jacks were inserted in both rows of holes and pressurized simultaneously compression the specimen. Using the stress and strain measurements from LVDTs placed on the masonry surface, the Young’s modulus and Poisson ratio can be calculated for the masonry.

6.1 Test set-up and procedure

The double tube-jack test was performed following the single tube-jack test and pressurization in the 3rd horizontal masonry joint. The 6th horizontal joint above the floor was chosen for the second row of tube-jacks because this would create a specimen of similar height, 3 courses high, to the ones used for the small masonry wallet tests and specified in the British standard for testing masonry in compression [9]. Due to the length of the equivalent flat-jack formed by the line of tube-jacks, the second line of tube-jacks could have been placed one course higher and still be within the height limits for the current flat-jack standards and recommendations ([4]and [3]) but, due to the height of the wall, this was not possible for this test.



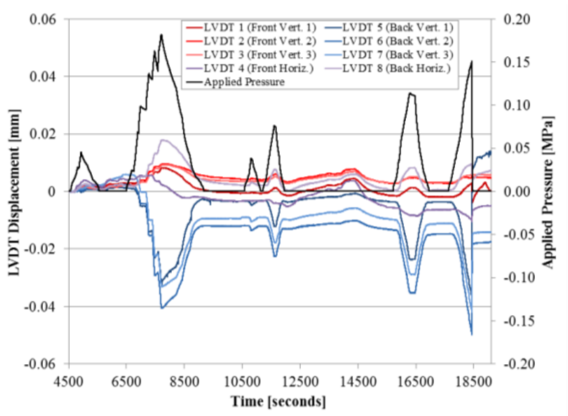
(a) (b) (c)

Figure 8 Double tube-jack test set-up: (a) complete set-up; (b) close-up of front of the wall; and (c) LVDT set-up on the back of the wall

LVDTs were placed on the front and back of the wall to measure the strains. Three vertical LVDTs were placed measuring a vertical distance of 31cm and a horizontal LVDT was placed spanning a horizontal distance of 51 cm (See Figure 8). The load on the wall was the same as during the single tube-jack test in the 3rd horizontal joint. The double tube-jack test set-up is shown in Figure 8.

6.2 Results

The LVDT and applied pressure results over the duration of the double tube-jack test are shown in Figure 9a.

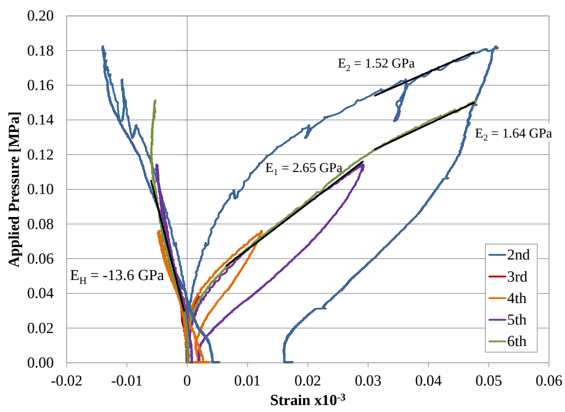


(a)

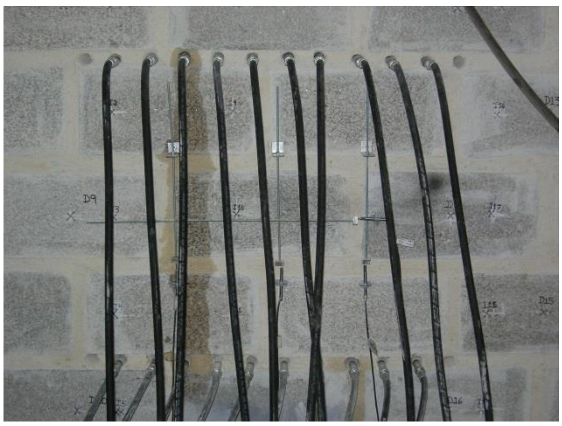
(b)

Figure 9 Double tube-jack testing: (a) LVDT displacement and applied pressure throughout the double tube-jack test; and (b) tube-jacks inserted into two horizontal rows of 12 holes each

Six pressurizations were performed. The first two pressurizations were performed with 12 rubber tube-jacks in each line of holes (Figure 9b). After these two cycles four tube-jacks were removed, two from each row, due to water leakage from the tube-jacks. Pressurization three through six were performed with 10 rubber tube-jacks in each line (Figure 10b). Each of the last four cycles was performed with successively higher water pressure peaks until one of the tube-jacks burst (Figure 10b). The LVDTs on the back of the wall had large negative displacements while the LVDTs on the front of the wall had small positive displacements during pressurizations. This uneven pressurization from the front to back of the wall must be investigated for future testing.



(a)



(b)

Figure 10 Double tube-jack test results: (a) strain versus applied pressure; and (b) rupture of a tube-jack

The applied pressure versus the average strain for the second through sixth pressurizations is shown in (Figure 10a). In this graph the average strain was set to zero before each cycle. Even though the data was adjusted for the number of tube-jacks in each test, the results show that the second pressurization with 12 tube-jacks in each row was able to apply a higher pressure to the masonry than the other pressurizations with just 10 tube-jacks in each row.

Several approximate trend lines were fit to the data to approximate the Young's modulus. The third through sixth pressurizations followed approximately the same curve with an initial Young's modulus of 2.65 GPa. This value compares most closely to the results of the small masonry wallet tests, which estimated the Young's modulus at 2.50 GPa. The results show a second slope that is similar for both the second pressurization and following pressurizations. The Poisson ratio was calculated to be 0.195 based on the horizontal modulus, E_H, and the initial vertical elastic modulus, E_1.

7 DOUBLE FLAT-JACK TEST

A double flat-jack test was performed in the regular granite masonry wall by creating a second slot above the slot used for the single flat-jack test. The purpose for this test was to compare the test procedure and results of the double tube-jack test with the traditional double flat-jack method. As much as possible, this test followed the standards [3] and [4].

7.1 Test set-up and procedure

The double flat-jack test was performed on the right side of the same regular masonry wall as was used for the single and double tube-jack tests and the single flat-jack test. The standards require that the distance between the slots is no longer than 1.5 times the length of the flat-jack. Thus, the slot was made two joints above the single flat-jack slot. This made a much smaller separated specimen than was created in the double tube-jack test. In the case of the double flat-jack test only three masonry units were being tested.

(a) (b)

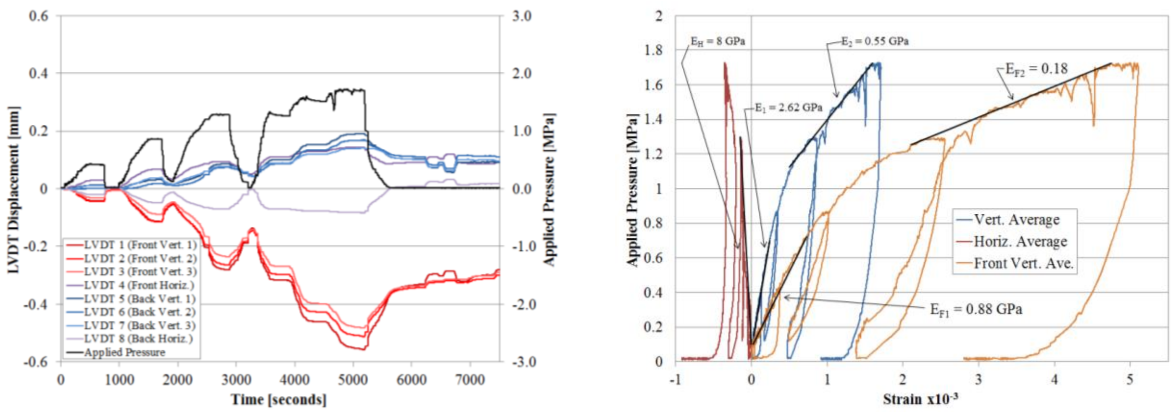
Figure 11 Double flat-jack test set-up: (a) drilling the second slot; and (b) the complete set-up

When the single flat-jack slot was made a large amount of dust was created sawing the slot, so for the second slot the stitch drilling method was used. This method worked much better for this type of mortar. The drilling is shown in Figure 11a. The drilling of the slot resulted in a wider slot than was necessary to for the flat-jack so additional plates were added above and below the jack. One horizontal and three vertical LVDTs were placed between the flat-jacks on both sides of the wall. The complete set-up is shown in Figure 11b.

7.2 Results

Once the jacks were seated in the slots, four pressurization cycles were performed with increasing maximum pressure. The results of all of the LVDTs and the applied pressure over the length of the test are shown in Figure 12a. The results show that in the front of the wall the masonry was being compressed and in the back of the wall the stress was being relieved and the joints opening slightly. Thus, the flat-jacks, which only reach half way through the wall, are applying an uneven stress distribution across the thickness of the wall. The double tube-jack test also had an uneven stress distribution across the thickness of the wall, as the tube-jacks applied more pressure to the back of the wall than the front Figure 9a. The double tube-jack test does have the potential, however, to apply equal pressure across the joint thickness and can be improved with future testing.

It can also be observed from these results that, as the maximum pressure increased with each cycle, the LVDT displacements did not return to zero. This indicates that the masonry was entering the inelastic phase resulting from pressurizing it to levels not yet seen by the masonry. The vertical load on the wall was held constant throughout the test.



(a) (b)

Figure 12 Double flat-jack test results: (a) LVDT displacement and applied pressure throughout the double flat-jack test; and (b)

The stress versus strain results from the double flat-jack test are shown in Figure 12b. Taking the initial slope of the average vertical LVDTs the Young's Modulus was calculated to be 2.62 GPa. This is close to the Young's modulus values found in the double tube-jack test and small masonry wallet tests (2.50 GPa). The second slope is much lower than the value found using the tube-jack test. The continued horizontal widening of the specimen, shown by the increasing negative strain following the final pressurization, is likely due to the close proximity of the specimen to the edge of the wall. The Poisson ratio was calculated to be 0.328 based on the horizontal modulus, E_H, and the initial vertical elastic modulus, E_1.

The average of only the front vertical LVDTs has also been added to Figure 12b. In-situ double flat-jack tests often only measure the strain on the front face of the wall. In this case, only considering the front LVDTs greatly influenced the results obtained. The estimated Young's modulus from this data is less than half that found using the average of all LVDTs.

8 CONCLUSIONS

Several conclusions can be made from the results of this first phase of testing the tube-jack system. The first important conclusion is that the tube-jack system is able to apply pressure to the surrounding masonry and, in the case of the single tube-jack test, return the average displacements to zero, as they were before drilling the holes. The single tube-jack tests were not successful when the compressive stress was higher. Thus, the tube-jacks will be improved for the next phase of testing so that they can withstand higher pressures. The single tube-jack tests estimated that the stress level was higher than it should have been. Additional factors will be studied for future tests including the influence of the tubing material. The single flat-jack test did not give an accurate estimate of the state of stress in the masonry. This was likely due to the small size of the jack in relation to the masonry unit size.

The double tube-jack tests were a success. The lines of holes were able to separate a masonry specimen between them and then the tube-jacks were able to compress that specimen. Even though the application of the pressure was not equal across the thickness of the wall, the average results showed similar curves for each pressurization and an initial Young's modulus estimation very close to results found by testing small masonry wallets of the same materials and typology. Due to the limited size of the flat-jacks, the double flat-jack test only applied pressure to the front half of the wall was not able to apply an equal pressure across the thickness of the wall. However, using the average strain results from both sides of the wall, the double flat-jack test came up with a very similar Young's modulus to the tube-jack test. The focus for future double tube-jack testing will be improving the pressure distribution throughout the thickness of the wall and applying the system to other masonry typologies.

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