A Review on Flat-Jack Testing

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ABSTRACT

Flat-jack testing is a versatile and powerful technique that provides significant information on the mechanical properties of historical constructions. In this paper, a state of the art about flat-jack testing is presented together with some experiments carried out by the authors. In particular, ASTM and RILEM standards are reviewed and additional recommendations are set forth.

1. INTRODUCTION

Preservation of the architectural heritage is considered a fundamental issue in the cultural life of modern societies. In recent years, large investments were made in this area, leading to developments in inspection, non-destructive testing, monitoring and structural analysis of monuments. Nevertheless, understanding, analyzing and repairing historical constructions remains one of the most significant challenges to the modern technicians.

The analysis of ancient constructions poses important challenges because of the complexity of their geometry, the variability of the properties of traditional materials, the different building techniques, the absence of knowledge on the existing damage from the actions which affect the constructions throughout their life and the lack of codes. In addition, restrictions in the inspection and the removal of specimens in buildings of historical value, as well as the high costs involved in the inspections and diagnoses, often result in reduced information about the internal constructive system or the properties of the existing materials.

Non-destructive methods are, in fact, necessary to obtain the mechanical characteristics needed for the analysis and understanding of the mechanical behavior of historical constructions, as well as, to validate the analysis itself.

2. A STATE OF THE ART ABOUT FLAT-JACK TESTING

Engineers involved in structural analysis of existing historical structures need information about the compressive stresses, the deformability properties and the loads applied

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to the masonry. This knowledge is necessary for the evaluation of the current condition of structures and can be also useful for stress control during repair operations.

Flat-jack testing is direct and in-situ testing method that requires only the removal of a portion of mortar from the bed joints. It can be, therefore, considered nondestructive because the damage is temporary and is easily repaired after testing.

2.1. Background

Flat-jack testing originates from the field of rock mechanics. Italian researcher Paolo Rossi adapted the method for use with masonry in the early 1980s and, since then, different researchers worldwide focus on this technique, e.g. Abdunur [1] carried out tests with very small semi-circular flat-jacks, and conducted idealized photoelastic stress analyses on plastic models. Atkinson-Noland & Associates [5] has been engaged in the evaluation of flat-jack testing for use in the evaluation of existing old brick masonry buildings in the United States. Qinglin and Xiuyi [10] developed a thick flat-jack with large displacement capabilities for use on very soft masonry materials typically found in China.

Two separate standards for masonry evaluation with flat-jacks were developed in the United States by the ASTM and approved in 1991. ASTM Standard Test Methods C 1196-91, In-Situ Compressive Stress Within Solid Unit Masonry Estimated Using Flat-jack Measurements [2], and C 1197-91, In Situ Measurement of Masonry Deformability Properties Using the F1atjack Method [3]. European practice follows RILEM standards LUM.D.2 [6] and LUM.D.3 [7] , which were first introduced in 1990.

2.2. Description of flat-jack tests

Flat-jack is a “thin envelope-like bladder with inlet and outlet ports which may be pressurized with hydraulic oil” [2] (some typical configurations are shown in Figure 1). A flat-jack may be manufactured in many shapes and sizes - the actual dimensions are determined by its function, slot preparation technique and the properties of the masonry being tested. Flat-jacks with curved edges (types c, d in Figure 1) are designed to fit in a slot cut by a circular saw. Rectangular jacks (types a, b) are used where mortar must be removed by hand or with stitch drilling. Regardless of the shape, a flat-jack must fit the slot well. The thickness of the flat-jack is determined by its specific function: An ideal flat-jack will completely fill the slot in the mortar joint. However, if such flat-jack is not available, then shims are used together with the flat-jack to completely fill the slot thickness.

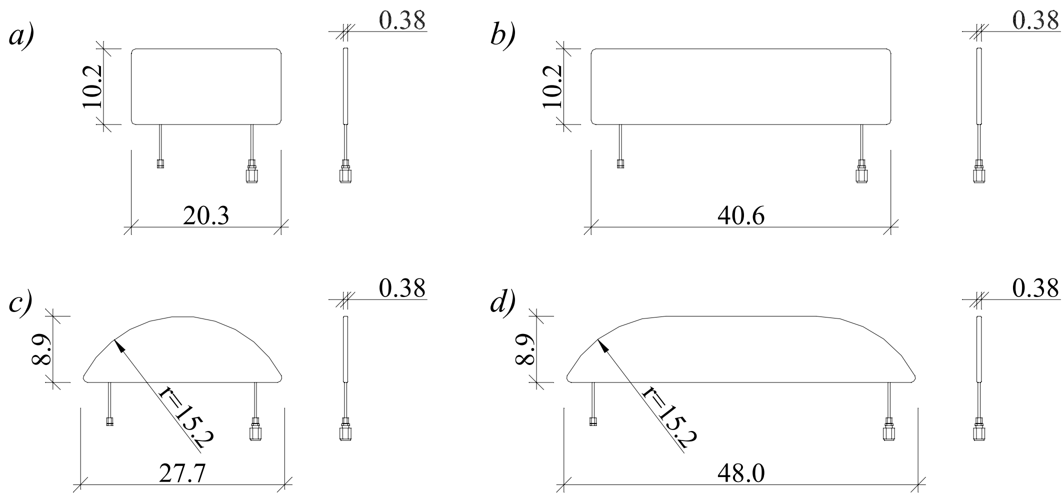


Figure 1 - Different flat-jack configurations.

2.3. In-Situ Stress test (single flat-jack test)

This test is based on the principle of partial stress release and involves the local elimination of stresses, followed by controlled stress compensation (see Figure 2).

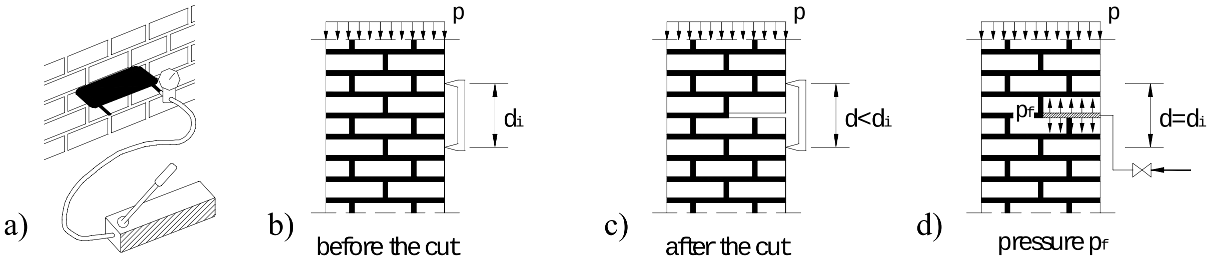


Figure 2 - Phases of the flat-jack test ($p=p_f$ when $d=d_i$).

The reference field of displacements is first determined by measuring distances between gauge points fixed to the surface of the masonry (distances d_i in Figure 2b). Then, a slot is cut in a plane normal to the direction of measured stresses. This allows deformations in a direction normal to the slot. Distances between gauge points decrease (i.e. distance d in Figure 2c is smaller than reference distance d_i). Cutting the slot causes partial stress relief in masonry above and below. Afterwards, a thin flat jack is introduced into the slot. With the aid of this device, pressure (compressive stress) is applied to the masonry. This causes a partial restoration of the initial displacement field, which at some point they reach (approximately) previously measured values (Figure 2d). The necessary pressure p_f (called canceling pressure) can be related to the compressive stress in the direction normal to the slot. The hydraulic pressure in the flat-jack necessary to restore the undamaged state is higher than the actual stress. This is caused by the inherent stiffness of the flat-jack, which resists expansions when the jack is pressurized. Another factor that contributes to this effect is the difference between the area of the jack and the area of the slot (the latter being greater then the former). Both these factors are taken in account when interpreting test results.

The test, as described above, is based on the following assumptions: the stress in place of the test is compressive; the masonry surrounding the slot is homogenous; the masonry deforms symmetrically around the slot; the state of stresses in the place of the measurement is uniform; the stress applied to masonry by the flat-jack is uniform; the value of stresses (compared to compressive strength) allows the masonry to work in an elastic regime.

2.4. In-situ deformability test (two flat-jacks test)

The principle of the test is similar to a standard compressive test. The difference is that it is performed in-situ and two flat-jacks are used to apply the load. A typical setup of the in-situ deformability test is shown in Figure 3.

By cutting two parallel slots, part of the wall is isolated from the surrounding masonry forming a "specimen". Masonry between the flat-jacks is assumed to be unstressed. Flat-jacks are then introduced into both slots, and the initial distances between gauge points are measured. By pressurizing flat-jacks, the load is applied to the "specimen" creating an approximately uniaxial state of compressive stress. With a pressure increase in the flat-jacks, the distances between gauge point pairs decrease. By gradually increasing the pressure, the stress-strain relationship can be determined. Loading-unloading cycles can also be performed.

Based on an experimental stress-strain curve, the value of Young's compressive modulus can be calculated. If extended damage in the specimen is acceptable, the compressive strength of masonry can be obtained. Obviously, this can only be done if the strength of masonry is lower than the maximum pressure for the flat-jacks. During testing, the load-displacement diagram is monitored and, when it becomes highly nonlinear (indicating imminent failure), loading is usually terminated. Even in this case, it is possible to estimate peak compressive strength by extrapolation of the stress-strain curve.

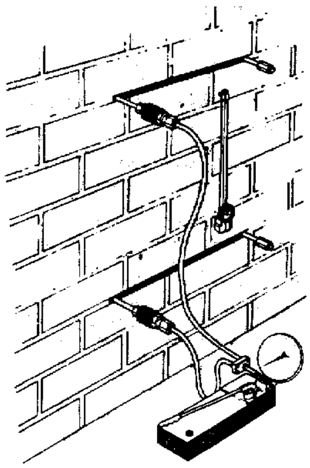


Figure 3 - Typical test set-up for in-situ deformability.

The deformability test method is based on the following assumptions: masonry surrounding the slot is homogenous; the stress applied to masonry by flat-jacks is uniform and the state of stress in test “prism” is uniaxial, i.e. a lateral constraining effects of adjacent masonry can be neglected.

2.5. Equipment

The following equipment is required: one or more flat-jacks; a hydraulic system with a pump, a gauge and hoses; a displacement measurement equipment with an appropriate number of gauge points, brackets and plugs; tools for mortar removal such as a masonry saw or a drilling machine, a hammer and a chisel; safety equipment. Additional optional equipment includes shims (single or multi-piece), a data acquisition unit and a power source.

2.6. Flat-jacks

Flat-jacks for masonry evaluation are typically made of stainless steel with welded seams along the edges. Typically, the thickness ranges from 1 mm to 6 mm. Flat-jacks incorporate inlet ports. Typically, two ports are found as this allows removal of air from flat-jack by supplying fluid to one port when the other (“bleeding port”) is open. However, some flat-jacks are fitted only with one port. The shape of the flat-jack depends of the equipment used to create the slot, see Figure 4. The size of the flat-jack depends on the application, ranging from a few centimeters to more than a meter (mainly rock mechanics).

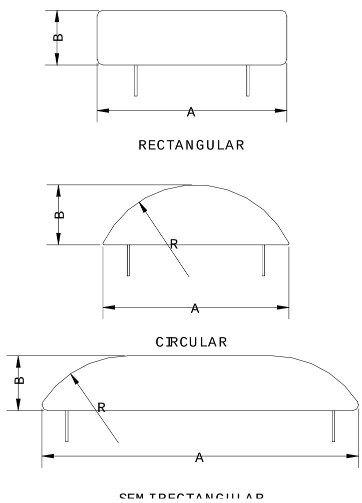


Figure 4 - Flat-jack dimensions.

For the stress test, the ASTM standard [2] requires dimension *A* to be equal to or greater than the length of a single masonry unit but not less than 8 in. (20.3 cm). For the deformability test, it should be equal to or greater than the length of two masonry units, but as shown above, not less than 8 in. (20.3 cm). The width of the flat-jack (dimension *B* in Figure 4) must be equal to or greater than the thickness of one leaf and not less than 3 in. (7.6 cm). According to RILEM [6]-[7], for both the stress test and the deformability test, the area of the jack must not be less than that of one of the masonry units. If the flat-jack is rectangular then its length should be equal to twice the width. Both standards require the radius *R* of circular and semi-rectangular flat-jacks to be equal to the radius of the circular saw blade used to cut the slot. For the deformability test, only rectangular and semi-rectangular flat-jacks should be used as the circular jack does not apply a uniform state of stress. For stress measurements in elements like arches, vaults and pillars smaller flat-jacks can be used.

2.7. Calibration factor

Flat-jacks are designed to have an output pressure (one that is applied to masonry) that is linearly dependent on the internal hydraulic pressure. The coefficient that provides conversion (K_m) is determined during the calibration process. An example of a curve obtained during calibration, illustrated in Figure 5, shows the relationship between the internal hydraulic pressure in the flat-jack and external pressure.

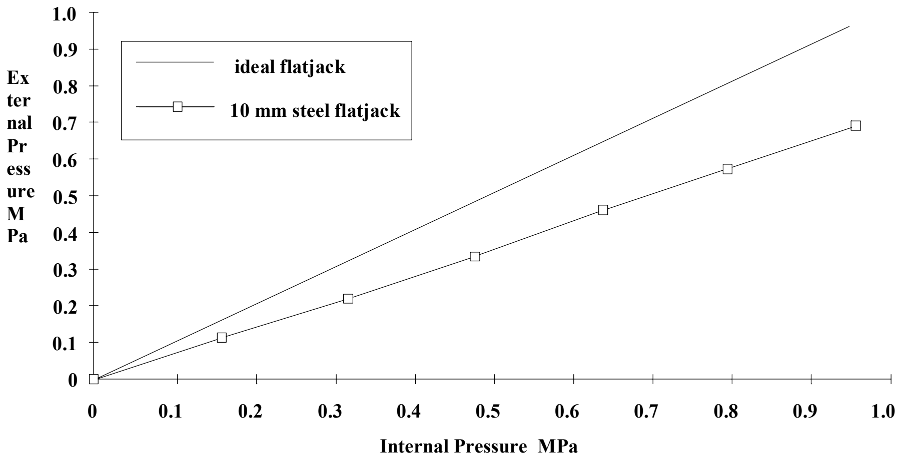


Figure 5 - Flat-jack calibration curve.

Usually, for new flat-jacks, the calibration factor K_m is supplied by the flat-jack manufacturer. However, since flat-jacks softens with repeated use, they must be re-calibrated after 4 or 5 tests, or sooner, if during test, flat-jacks develop excessive deformations. Flat-jacks should be restored to the original thickness following each test to ensure that the calibration factor remains unchanged. The flat-jack calibration procedure is described in [2].

2.8. Hydraulic system

The pressure provided by a hydraulic pump (manually or electrically operated) can be measured by means of a pressure gauge or a pressure transducer cell, with a range similar to the maximum operating pressure of the flat-jack, and accuracy of 1% of the full hydraulic scale. The system should be capable of maintaining a constant pressure (within range of 1% of full scale) for at least 5 minutes.

Maximum operating pressure for typical flat-jacks is 6.9 MPa (1000 psi) [2]-[3].

2.9. Displacement measurement equipment

Deformations can be measured by mechanical gauges or by LVDTs. The displacement measurement equipment should have an accuracy of at least 0.0005 cm (the ASTM standards require that it should be ±0.005% of the gauge length while the RILEM standards require an accuracy of only 0.1% of the gauge length). The equipment should be capable of measuring displacements up to 0.5 cm. In the case of the stress test, reference points on masonry are placed above and below the slot. Since first measurements must be taken before cutting of the slot, the instrumentation cannot interfere with the mortar removal equipment.

The RILEM standards require the gauge length for the stress test to be equal to 20 cm and for the deformability test to be equal to 40 cm. The ASTM standard for the stress test [2] require the gauge length to be between $0.3{\cdot}A$ and $0.6{\cdot}A$ where A is the length of the flat-jack. The ASTM standard for the deformability test [3] does not contain direct requirements for the gauge length, but this length is indirectly fixed by the requirements for the distance between the slots and gauge points placement. Gauge points or brackets for mounting electronic measurement devices must be fixed firmly to the surface to ensure the measurement accuracy. A selection of tools for a mortar removal depends of the method for slot preparation as slots can be prepared by cutting with a masonry saw or by stitch drilling, see Figure 6. Regardless of the method used for slot preparation, care must be taken to ensure, that all mortar was removed from the slot, because flat-jacks must contact with cleaned surfaces of masonry units. Remaining particles of mortar can be removed with an air hose or vacuum.

2.10. Slot preparation

Stitch drilling is only appropriate for weak mortars (as usually found in old masonry structures) and not for modern, strong, cement-based mortars. The use of high-power hammer drills is not recommended due to the possible disturbance caused to surrounding masonry. In the case of strong mortars, irregular stone masonry, thick joints, or need of cutting through units, a masonry saw should be used. A water-cooled saw with a carbide or diamond tipped disk is suitable.

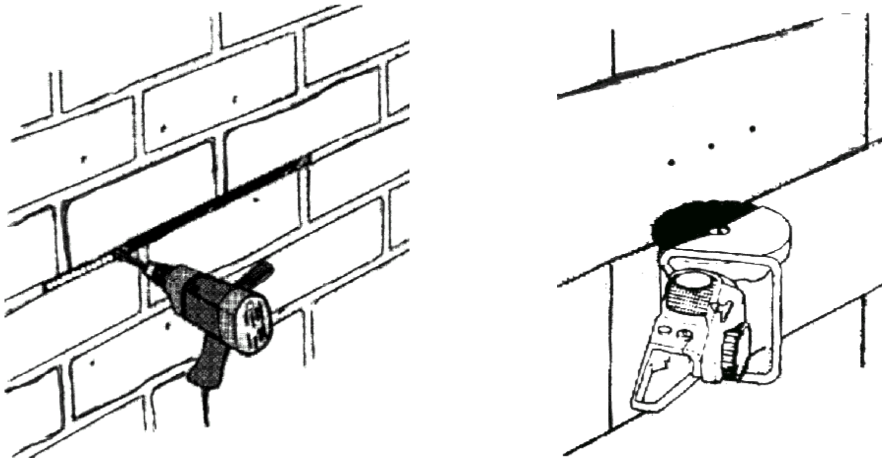


Figure 6 - Methods of mortar removal: stitch drilling and saw cutting.

It is not allowed to grout the flat-jack in the slot because grout would flow into void and cracks resulting in local change of masonry behavior. To ensure a uniform transfer of pressure over the complete area, the flat-jack must fit tightly into the slot. ASTM standards allow a difference in plane dimension up to ½ in. (1.25 cm). Shims are used to fill completely the thickness of the slot. Shims should have the same size and shape as the flat-jack being used and can be of three types: single piece, multiple pieces and fluid cushion, see Figure 7.

Figure 7 – Example of single piece and multiple pieces shims.

Several tests (3 to 5) in each area of interest should be performed to obtain a statistically significant sample. Places of stress concentrations such as changes in a cross section and vicinity of wall openings should be avoided. ASTM standards require slots to be at least 1 ½ flat-jack length away from wall openings or ends.

It is not necessary and often not possible to load the full thickness of the wall. However, in all cases at least one leaf of the masonry wall must be tested. Please note, that the results obtained refer only to leaf that was tested. External leafs are often made from a high-quality face brick while internal may be built with lower-quality materials.

2.11. Position of reference points and distance of slots

For the stress test, both the RILEM and ASTM standards recommend placing reference points symmetrically on second courses (counting from the slot) above and below the slot. The ASTM recommends placement of at least four pair of equally spaced points and RILEM recommends that at least three pairs, placed in the middle part of flat-jack length. For the deformability test, both standards require that reference points are placed symmetrically in the masonry courses immediately above and below slots.

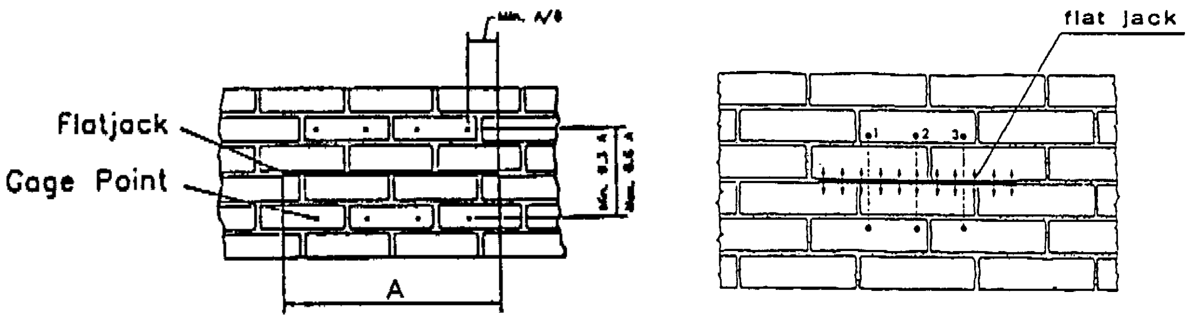
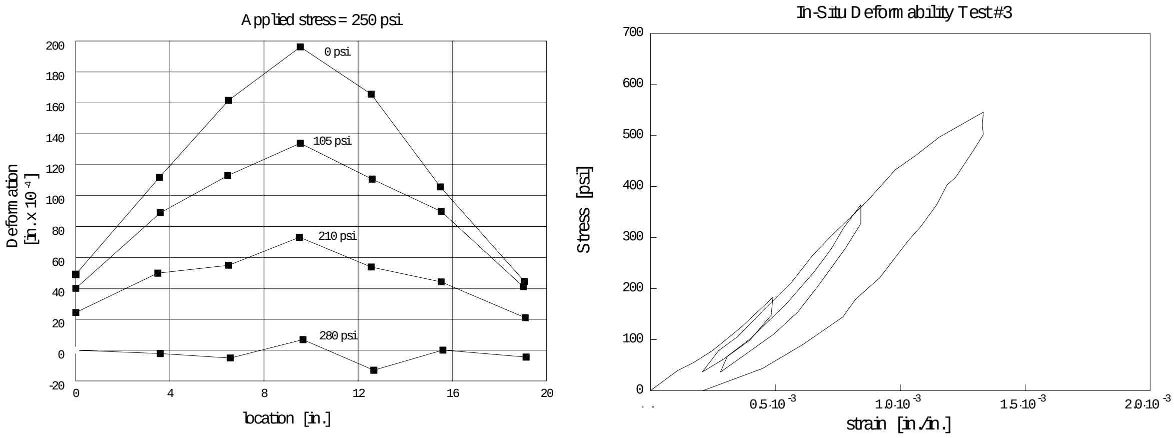


Figure 8 - Position of strain reference points for stress test ASTM and RILEM proposals.

2.12. Testing procedure for the in-situ stress test

The ASTM standard recommends the value of pressure increment to be equal to 25% of estimated maximum flat-jack pressure, while the RILEM standard recommends small increment without specifying its value. Authors of reference [8] recommend increments of 70 to 140 kPa. The pressure at which original distances are restored (the canceling pressure) is the base for compressive stress calculation An acceptable difference (deviation) between original and restored distances is [2]: – for each deviation less than ±0.0025 cm or 0.1 of maximum initial deviation – for average deviation less than ±0.0013 cm or 0.05 of maximum initial deviation. In order to reduce the creep effect, the time taken for the load application should be approximately the same, as the time required for making the cut and preparing the test (after strain measurements are stable). In this case creep deformation will be symmetrical and balance itself out, as stated by ASTM and RILEM standards. Figure 9 presents typical examples results obtained in a stress and a deformability test.



(a) (b)

Figure 9 - Example test results from: (a) in-situ stress test (deformations at different stress levels) and (b) cyclic in-situ deformability test.

2.13. Interpretation of test results

For both the stress and deformability tests it is necessary to convert the flat-jack pressure to the actual compressive stress. The stress can be calculated by

$$\sigma_m = K_m \, K_a \, p \qquad (1)$$

where K_m is the calibration factor (<1), K_a is the ratio of measured area of the flat-jack to the average measured area of the slot (<1) and p is the flat-jack pressure.

2.14. Accuracy of the flat-jack technique

For the stress test [2], states that this test shows a 20% coefficient of variation and no inherent bias in predicting the state of compressive stress present in the masonry. That is, this method can as well <u>over</u> and <u>underestimate</u> actual stress. Authors of reference [8] state that: "laboratory testing has shown that the in-place stress test has a margin of error of up to 20%". For the deformability test, [3] gives a coefficient of variation of 24% but the test typically <u>overestimates</u> the average Young's modulus of masonry up to 15%. This is due to the actual boundary conditions. Influence of surrounding masonry (including effect of collar joints when only part of wall thickness is tested) decreases toward the middle of the loaded area. For this reason, location of strain reference points only in middle part of loaded area (as found in the RILEM standard) would lead to more accurate results than equal distribution (recommended in the ASTM standard).

2.15. Measurement of tensile stresses

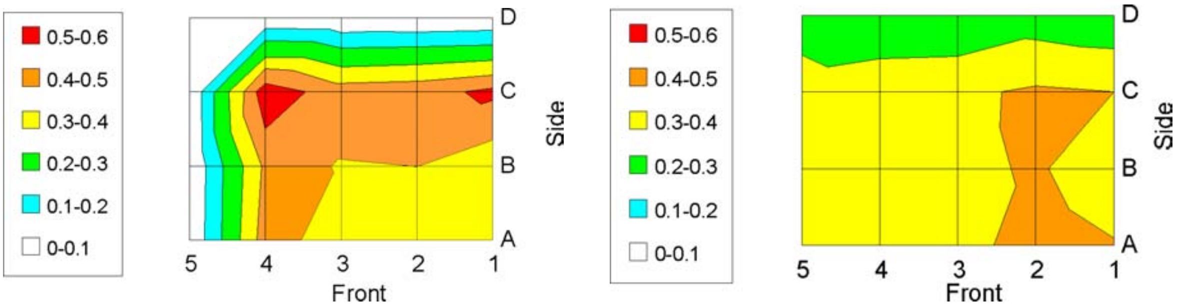
Although flat-jack stress test was originally proposed to measure only compressive stresses, it can be also used to estimate tensile stresses [1].

2.16. In-situ shear test

Flat-jacks can also be used to perform the in-situ shear test ("shove test" or "push test"). This is achieved by horizontally displacing a single masonry unit with a hydraulic jack.

2.17. The distribution of normal stresses induced by the flat-jack

Load applied to masonry by a flat-jack is assumed to be constant over its area. Actual stress distribution for typical stainless steel flat-jack is however different. Example of pressure contours on surface of the flat-jack, obtained experimentally, is shown in Figure 10. In this test, internal flat-jack pressure was 0.396 MPa. A more uniform stress distribution can be achieved, with the use of a rubber jack. The relationship between internal and external pressures of the rubber flat-jack provides a calibration factor K_m close to 1.



(a) (b)

Figure 10 - Pressure Contours for: (a) Steel Flat-jack and (b) for Rubber Flat-jack[2] [4].

3. EXPERIMENTAL RESULTS AT UNIVERSITY OF MINHO

It must be noted that the objective of the tests carried out at University of Minho was not to confirm the suitability or accuracy of the flat-jack method as this has already been done in many laboratory experiments worldwide. Since there is some disagreement in recommendations for flat-jack tests between standards and authors, these different recommendations were followed in different experiments. Additionally, it is known that good slot quality is essential for obtaining correct test results. Since knowledge of the true contact area during the flat-jack testing is valuable for decisions about test validity, a very simple and inexpensive method was introduced which allowed that information to be obtained. To investigate the existing possibilities, also different techniques and tools for mortar removal were used during experiments.

3.1. Description of the experiments

Rectangular flat-jacks, with dimensions 40.6 × 10.2 × 0.42 cm^3, supplied by Atkinson-Noland & Associates were adopted in the tests. The flat-jack was pressurized using a manually operated hydraulic jack. Displacements were measured using a removable Whittemore Gauge with a resolution of 0.0001 cm. Three different gauge lengths were used during experiments: 11, 25, 31 cm. Square metal plates with dimensions of 2 × 2 × 0.2 cm^3 served as gauge points. Each plate had a conical depression compatible with pointing elements of the removable extensometer. Before testing, all reference points were attached to surface of masonry with an epoxy glue. Both, multiple and single piece shims were used.

Two test walls (further referenced as TW1 and TW2) were constructed with the same type of masonry units (YTONG blocks) and two different mortars: a cement-lime mortar for the specimen TW1 and lime-mortar provided by Weber & Broutin for the specimen TW2. YTONG blocks were chosen due to a small weight of this material as well as because this material was readily available, see Figure 11.

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[2] The significant area of high pressure, shown as 0.4-0.5 MPa, is somewhat misleading as the pressure only just creeps into that range.

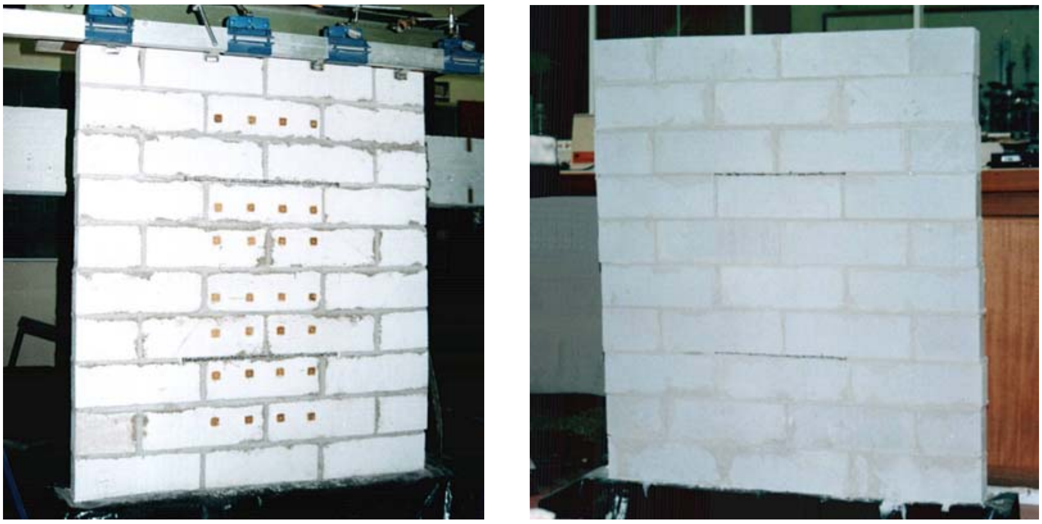


Figure 11 - Test walls with position of slots and reference points.

The load was applied on top of the wall by an external hydraulic jack. The load was distributed along the length of the wall with a rigid steel element. The load cell was placed between the jack and the steel element. Three different stress tests have been carried out in the two walls. The slot for the first test was made partly by stitch drilling and partly by saw cutting. Stitch drilling proved not adequate at all for the combination of masonry units (soft YTONG blocks) and modern hard mortars. The drilling was quite irregular and difficult. For this reason, the slot was further opened by saw cutting. The second and third tests were fully carried out in a saw cut slot, see Figure 12. Four pairs of reference were adopted, following ASTM (test no. 2) and RILEM (test no. 3) proposals.

(a) (b)

Figure 12 - Mortar removal: a) by stitch drilling b) saw cutting.

3.2. Measurements of the contact area

Since knowledge of the contact area during flat-jack testing is important when deciding about test validity, to gain better understanding of this area, a very simple and inexpensive method was introduced in experiments following experiment no. 1: a sheet of carbon paper, sandwiched between two sheets of ordinary paper, was placed between the flat-jack and a surface of the shim. The paper was marked in places of contact, conversely to places without contact, where the paper remained white. Examples of the contact area contours obtained with this method are shown in Figure 13.

The first test contact area, represented in Figure 13a, indicates a extremely poor slot (partly made with stitch drilling and partly made by saw cut) with a very low contact area between the jack and masonry, whereas the second and third tests contact areas, represented in Figure 13b, indicate the good quality slot (fully made by saw cut).

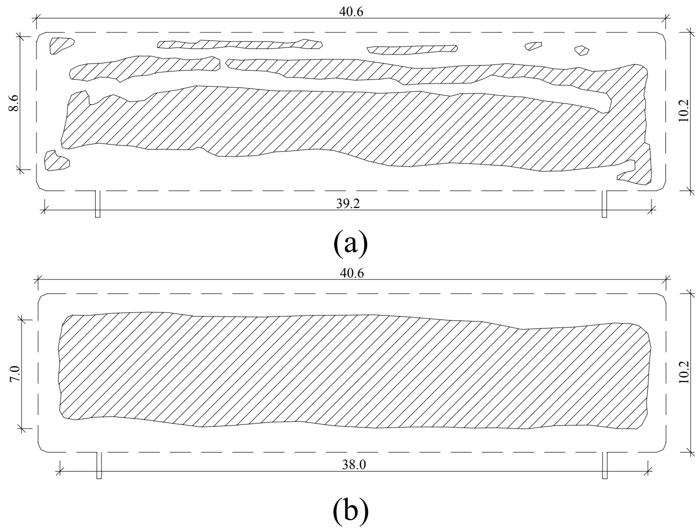


Figure 13 - Contact contours (max. pressure 0.5 MPa) for two different tests.

3.3. Stress measurements

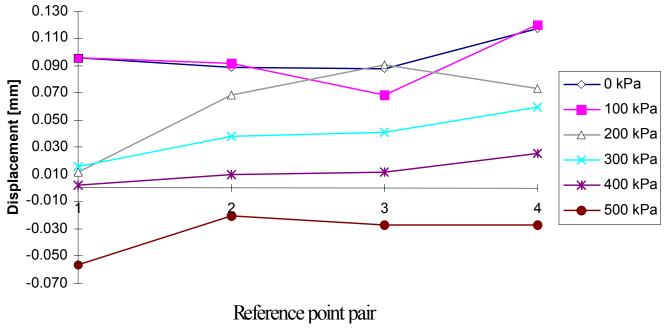
As reported before, the first test must be ignored due to the inadequacy of the slot. Only the results of the second and third tests will be given here.

Figure 14a shows that the distances between reference points at 0 and 100 kPa were practically the same for reference point pairs 1, 2, 4. Probably, there was no contact between the flat-jack and the masonry at this pressure level. Please note that an error in reading at pressures below the canceling pressure (in this case at 0, 100, 200, 300 kPa) does not have any influence on the calculation of test results (i.e. estimated value of compressive stress).

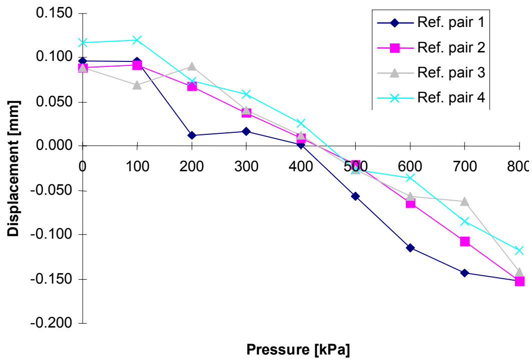
The result of the flat-jack test is calculated based on the value of the *canceling pressure*. Note that, because during the stress test, displacement measurements are not taken continuously, but at pressure intervals that there are two possible ways of determining the canceling pressure. One possible approach is to recognize certain pressure level as the canceling pressure when displacements at this level and initial displacements (measured before slot creation) does not differ more than certain tolerance value. Such an approach is recommended by ASTM standards, which contain requirements for allowable tolerance. Another possibility is to determine pressure corresponding to the zero displacement by interpolation between two pressure levels (corresponding to displacements greater and lower than initial displacements. In other words to find point of intersection between the pressure/displacement graph (as one shown in Figure 14b) and the pressure axis.

Here, the latter approach was used and the canceling pressure was determined as $p_f =$ **420** kPa. Note that in the case when inelastic deformations are present, the "zero displacement" for each pair of reference points will be reached at different pressure level. In this case, a criterion of "equal residual displacements" of points affected by similar load-displacements history should be used [8].

The results for test no. 3 are similar to the results above and will not be shown here, see [9] for a complete report. The obtained canceling pressure was 400 kPa.



(a)



(b)

Figure 14 – Results for test no. 2: (a) deformations at different pressure levels; (b) Pressure/displacement diagrams for each pair of reference points

The obtained stress values are close and represent an error of +22% (test no. 2) and +18% (test no. 3). These values are expected according to the standards, even if it is peculiar that the results of both tests are similar and biased to the overestimation side. For practical applications in historical constructions such error in the stress estimation is reasonable and represents valuable information for the analyst / designer.

4. CONCLUSIONS

A state-of-art on flat-jack testing has been presented. This non-destructive technique is a powerful tool for the mechanical characterization of historical masonry structures. Experimental results recently carried out at University of Minho confirmed the adequacy of the stress test and allowed to illustrate the actual contact area of the jacks with the masonry.

5. REFERENCES

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