Laboratory and In Situ Calibrations of New Flat Jack Method for Assessing Masonry Shear Characteristics

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Abstract. The test methods currently used to assess the shear characteristics of masonry structures does not fit with the execution of in situ tests on existing buildings (especially heritage buildings) because they are usually strongly destructive. Furthermore the method of preparation of the sample causes damages that can reduce the mechanical characteristics of the masonry: for these reasons there are significant doubts about the effective representativeness of the results obtained from these methods. A new in situ testing technique (named FJ-SCT Method) has been developed by the authors based on the use of flat jacks to apply the horizontal load: this allows a great reduction in the impact of the test and therefore it makes the testing technique applicable on existing buildings. A calibration campaign was performed both in laboratory using a special testing frame and in situ (on Italian buildings seriously damaged by the 2012 Emilia earthquake) to evaluate the operability of the defined procedures. This campaign proved the technique to be reliable, the procedures to be efficient and effective and the results to be repeatable. The damages produced to the masonry by this test technique are limited, justified by the level of the results obtained and they can be easily repaired. The analysis of the calibration results, the proposal for the processing of shear strength data and the comparison with reference shear values taken from the Italian codes will be hereafter discussed.

Keywords: Masonry · Shear strength · Flat-jack · In situ test
Minor Destructive Test (MDT)

1 Introduction

The current regulatory frame is lacking in the definition of experimental techniques suitable for in situ determination of the mechanical characteristics that identify masonry shear behaviour. Two methods for executing laboratory tests are currently available: tests on brick triplets [1] and diagonal tension test [2]. However really useful parameters to assess the existing masonry can only come from in situ tests. In this field, the bibliography records the application of some test techniques mostly deduced from previous laboratory methods. The in situ test methods can be categorised in compliance with three methodologies: measurement of masonry bed joint shear strength (sliding test of a single brick) [3, 4], a methodology resulting from [1], diagonal tension tests

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[5], a methodology resulting from [2] and shear-compression tests, usually carried out in accordance with an original testing procedure [6].

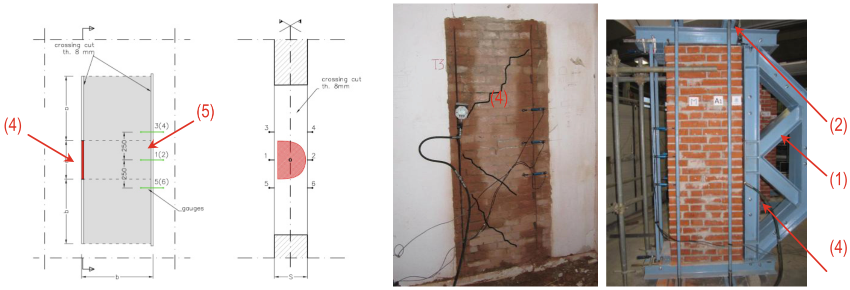
None of these techniques is however satisfactory with the goal of properly defining the mechanical shear characteristics of masonry. Partly due to its executive methods, but even more so according to its denomination, that is “bed joint shear strength”, the first test method is only able to detect the shear strength of bed joints, and is not exhaustive of shear behaviour of the overall brickwork; on the other hand the diagonal ten-sion test and the shear-compression tests are strongly destructive as, according to the procedures currently ap-plied for their execution, they require the use of experimental equipments which cause strong impact in the masonry during their setting. This is unacceptable from a conservation point of view, but a more relevant fact is that the results of these test methods are poorly representative of the actual characteristics of the masonry that is subjected to a considerable rehash during the assembling of the test apparatus.

That’s why a new testing technique, that was named Flat Jack - Shear Compression Test (FJ-SCT), was developed by the authors; it is able to determine the mechanical shear characteristics of the masonry. It reduces the level of damage to the masonry and therefore, being classified as Minor Destructive Testing technique (MDT), it makes the technique applicable to a much wider context [7].

The present paper outlines the new test method and summarizes the results of the calibration campaign carried out both in laboratory and in situ to perfect the operational method and to evaluate the reliability of the results. It also summarizes the numerical calculations which were made through a Finite Element Model (FEM) to evaluate the distribution of stress and deformation status resulting from the load application during the test. It finally presents the results of laboratory calibration tests and proposes the modality of data processing.

2 Testing Technique

The Flat Jack - Shear Compression Test is firstly performed making two cuts crossing the masonry under analysis, 160–200 cm in length and 8–10 mm in thickness, placed at mutual distance b = 60–80 cm. At half height of one of the two cuts, a flat jack (4), arranged vertically, is inserted and the opposite cut is instrumented by means of gauges (5) suitable for measuring horizontal displacements. In this way the test lay-out (Fig. 1a) identifies two half-panels, almost squared in shape and b $\times$ b in size, placed one above the other, which are subjected simultaneously to shear stress. Through the vertically arranged jack, the horizontal load is applied to the panel; it is then increased until diagonal cracking is obtained in at least one of the two half-panels. The development of diagonal cracks (Fig. 1b) confirms the correctness of the shear failure mechanism occurring within the masonry. All the tests carried out have shown that, with the proposed lay-out, a horizontal displacement of 8–10 mm is sufficient to produce diagonal cracks in the brickwork.



(a) (b) (c)

Fig. 1. (a) Lay-out of test, (b) masonry sample with the relevant diagonal cracks, (c) set-up of the contrast frame

3 Laboratory and In Situ Calibrations

3.1 Calibration Techniques

The calibration procedure of the FJ-SCT technique was performed both thought laboratory and in situ tests. It is described in [7] and it foresaw the calibration of flat jacks for the specific application, the execution of laboratory tests on materials and panels and the in situ application of the test technique to evaluate its operability and effectiveness. The laboratory calibration was performed on real scale panels with test dimensions 68 × 180 × 23.5 cm, built using new bricks with low nominal resistance, mortar with poor ratio of lime and mortar joints of considerable thickness. It was so possible to obtain walls with poor mechanical properties, similar to those of many buildings in the Italian Pianura Padana, particularly in the area affected by the 2012 earthquake in Emilia. To analyze the basic materials samples of mortar and bricks were taken during construction of the panels and compression and indirect traction tests were performed on them and were then matched with ultrasonic measurements.

To provide the necessary horizontal contrast to the action of the vertical flat jack during the laboratory tests a specific steel contrast frame (Fig. 1c) was designed. The panels arranged within the frame (1) were analyzed with the application of two compression cycles up to the stress level 1.0 MPa (by a large flat-jack placed horizontally (2) between the top edge of the wall and the frame). The vertically positioned flat-jack (4) was then inserted to apply the horizontal load and its pressure was increased until the diagonal cracking of the panel was reached.

For comparison two small panels of the same width, almost squared in size, were built to be subjected to diagonal tension tests in compliance with a procedure deduced from the standard [1].

In situ calibrations were then performed on two buildings damaged by the earthquake that occurred in 2012 in Emilia region (Italy). In this case the state of stress and the mechanical characteristics of masonry were determined though usual flat-jack tests [8]. Further FJ-SCT allowed the measurement of the shear strength and characteristics of the masonry.

3.2 Results of Laboratory Tests

The mechanical compression characteristics (Young modulus E and Poisson's ratio ν) experimentally measured from laboratory tests on the wallets are reported on Table 1; they are matched with ultrasonic pulse velocity measured in compliance with [9]. The mean values of ultrasonic pulse velocity compared between the large panels and the small ones are similar confirming their homogeneity. It is however important to stress the wide dispersion of the results of the mechanical properties of the panels tested.

Table 1. Laboratory calibration: compression tests on the panels.

	$E_{(0.4–0.8)}$* [MPa]	$\nu_{(0.4–0.8)}$* [MPa]	Large panels UT v [m/s]	Small panels UT v [m/s]
Test standard	(Measured)	(Measured)	[9]	[9]
Type A mean (4)	1165	0.20	1843	1836
Type B mean (4)	1826	0.10	1734	1766

* = in the first load cycle in the range σ = (0.4–0.8 MPa)

At the next step of the calibration procedure, diagonal tension tests [1] were performed on the small panels and FJ-SCT tests were performed on the large panels, to which vertical stress was applied by means of horizontal flat jack. The shear characteristics resulting from these tests are summarized in Table 2; in all the cases, the panels have reached the shear failure developing diagonal cracks and showing significant deformations.

4 Finite Elements Modelling

Data taken from the laboratory calibrations were used for implementing FEM models aimed at evaluating the distribution of the stress and deformation pattern during the test procedure, with specific reference to the following quantities: b/h ratio related to the shear stress distribution; horizontal load vs. deformation pattern at the top edge of the wallet; horizontal load vs. vertical stress distribution at the top edge of the wallet. Shell/plate finite elements (plain, bi-dimensional, isotropic, elastic and linear) have been used and models of size equal to twice the panels size have been implemented in order to provide a better estimation of the in situ lay-out and to reduce the effects of the choice of boundary conditions.

From a geometrical point of view four models were then implemented with the following characteristics: model nr. 1 = standard diagonal tensile test; model nr. 2 = FJ-SCT with reduced dimensions; model nr. 3 = FJ-SCT with standard dimensions; model nr. 4 = FJ-SCT with standard dimensions and horizontal crack).

Table 2. Laboratory calibration shear tests on the panels.

Panel tag nr.	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6
Procedure	FJ-SCT				[1]		FJ-SCT				[1]	
σ_v [MPa]	0.4	0.4	0.6	0.6	0	0	0.4	0.4	0.8	0.8	0	0
τ_v [MPa]	0.289	0.314	0.42	0.405	0.155	0.150	0.366	0.382	0.426	0.396	0.174	0.182
$G_{(0-0.07)}$** [MPa]	750	539	492	663	–	–	1037	750	545	339	–	–

** = in the first load cycle in the range τ = (0–0.07 MPa)

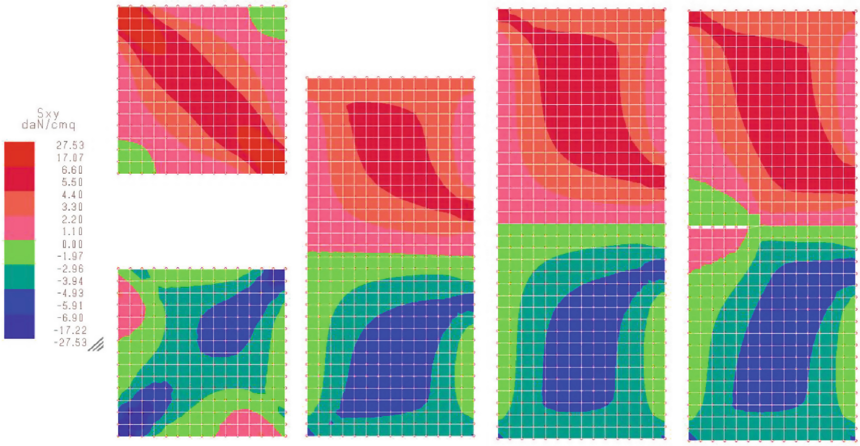
The mechanical characteristics of the models, in the first instance, were taken equal to the average of the mechanical values deduced from the laboratory test (characteristics I - Table 3), calculated in the vertical stress range from 0.4 to 0.8 MPa. The first iterations obviously proved these conditions to produce horizontal displacements lower than the experimental values. Shear stress-displacement diagram (Fig. 3a) shows G secant value calculated in the range from 0 to 0.07 MPa to be much higher than the value calculated at the range closer to the shear ultimate strength.

Table 3. Mechanical characteristics used in the F.E.M. model

	E [MPa]	ν [MPa]	G [MPa]
characteristics I	1500	0.15	652
characteristics II	375	0.25	150

To provide a better representation of the non-linearity of the structural behaviour of the masonry, the two following strategies have been implemented: reducing to 25% the mechanical parameters (as indicated in characteristics II - Table 3) in order to allow the panel horizontal deformations comparable with that obtained by laboratory tests; disconnecting the nodes at half height of the panel in order to simulate the formation of a horizontal crack (model nr. 4). It is evident that a model with such mechanical characteristics is not suitable to accurately simulate the actual behaviour of the masonry close to the shear failure; furthermore it allows to collect useful qualitative information about stress distribution and deformation pattern. The shear stress distribution is similar among the different models, as resulting from the patterns in Fig. 2; it highlights the test methodology to be satisfactorily in approximating the stress distribution of the standardized tests.

It was then evaluated the masonry deformation pattern at the top edge of the panels during the test (that means with horizontal load increasing from 50% to 75% to 100% of its maximum value) and consequently the resulting distribution of the vertical stress, that at the beginning of the test is applied with a uniform pattern.



Nr. 1 Nr. 2 Nr. 3 Nr. 4

Fig. 2. Shear stress distribution Sxy (daN/cm^2) – mod. 1-2-3-4 characteristics II

The F.E.M. calculations highlight that the analyzed section (the top edge of the panel) rotates so influencing the vertical stress distribution. The vertical stress is substantially constant for a central stretch with width equaling half the specimen (excluding the boundary effects); so the overestimation of the mean value of the vertical stress is less than 5% of the applied stress. It is useful to observe that the plasticization that, of course, occurs in the real case, reduces the rotation highlighted by the model (analyzed with elastic and linear hypothesis) and it uniformly redistributes the vertical stress. The values taken from the calculations have therefore to be considered as the upper limit of the actual behavior of the masonry.

The elastic, linear and symmetric model has highlighted, in correspondence with the half height of the panel, the developing of traction stress; as was already said their non-linear effects have been considered by modelling the presence of a crack (model nr. 4). In this case the results are similar to the previous ones, despite the dissymmetry of the deformation status resulting from the presence of the slot; the overestimation of the mean value of the vertical stress in this case is higher than the previous, but still less than 10%.

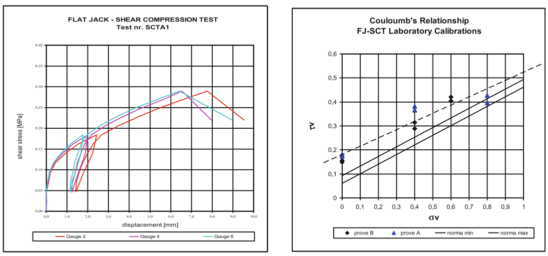
5 Data Processing

In compliance with the Italian structural codes [10], the masonry shear strength vs. vertical stress ratio is determinated by Coulomb relationship (Eq. 1); so the interpretation of the shear test requires the calculation of the parameters τ_{v0} = shear strength with no vertical stress and $\tan\phi$ = tangent of internal friction angle.

$$\tau = \tau_{v0} + \sigma \tan \phi \quad (1)$$

The performed tests provided shear stress-displacement diagrams as plotted in Fig. 3a, that allows the determination of shear strength and its correlation with the vertical stress applied to the masonry as represented on Table 2. The results taken from the twelve laboratory wallets were linearly interpolated (Fig. 3b) and it was possible to calculate the values: τ_{v0} = 0.179 MPa and tanϕ = 0.34. The interpolation line plotted with a dashed line can be compared with the continuous lines plotted with data provided by the code (which assumes the value tanϕ = 0.4). It is clear that the value τ_{v0} experimentally calculated is greater than the values taken from the code; it is however matched with data provided from four diagonal tension tests (average 0.165 MPa), which means that it is coherent with data provided from the standard methods used in the calibration procedure as reference. The underestimation of the values available from the code is known and further proved by bibliographic references [11].

The qualitative observation of the crack pattern detected during the tests highlights some additional observations. From a theoretical view point the failure of a panel can develop under two circumstances: 1. sliding along a mortar joint; 2. developing diagonal cracks. The second occurrence can be furthermore divided as follows: 2a. diagonal cracks simultaneously developed within both the two superimposed samples; 2b. diagonal cracks developed only within one of the samples. During the calibration activities the failure mode (1) was never detected; the laboratory tests only presented the failure mode (2b); the in situ tests often presented the failure mode (2a) as well. From a theoretical point of view both these alternative failure modes (2a and 2b) allow the determination of the shear strength of the sample as it is reasonable to assume that, until the moment immediately preceding the crack formation, the shear stress is equally distributed both in the upper and in the lower sample: definitely, the less resistant of the two samples breaks first. This is therefore equivalent to testing two samples at the same time, taking in account only the value of the less resistant one, in favour of safety. The laboratory tests sometimes developed a horizontal crack at the half height mortar joint; this phenomenon, whose effects is so limited to be undetected by the transducers, never prevented the successive development of diagonal cracks; FEM has shown that it does not have a significant influence on stress distribution.

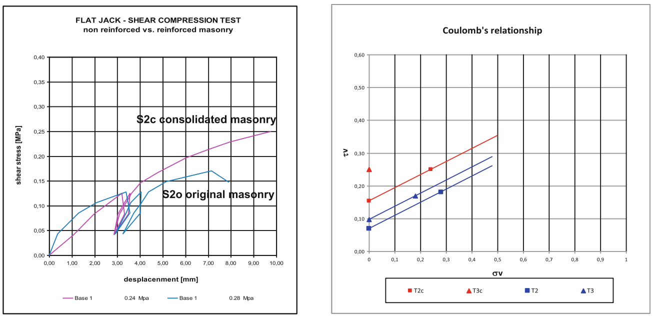


(a) (b)

Fig. 3. (a) Experimental Diagram shear vs. displacement, (b) data interpolation though the Coulomb relationship

6 Practical Application and Recommendations

The calibration campaign involved also in-situ tests, and, on the basis of the good results, the method was applied during some diagnostic campaign to assess the shear characteristics of masonry. Il was used both on brick masonry and on stone masonry, proving to be effective and efficient. As a relevant example it is possible to refer to the FJ-SCT used method to assess structural reinforcement techniques on Bonasi Benucci Manor field (a building damaged by 2012 Emilia earthquake). In this case a calibration campaign was performed with the goal of characterising the brick masonry shear characteristics before and after the application of structural reinforcement techniques [12]. The masonry, that resulted to be damaged by earthquake, was firstly tested until the shear failure of the panels; then the panels were reinforced through the application on both the external surfaces of FRCM plating with lime mortar matrix and alkali-resistant fibre-glass wire. Finally they were newly tested to evaluate the improvement of their structural shear strength. An example of the results (on sample S2) are reported in Fig. 4a–b, were the test diagrams and the Coulomb's relation of original (blue line) and consolidated (red line) masonry were plotted. This example shows the great potentiality of this test method, e.g. for obtaining a reliable in situ evaluation of actual effects of reinforcement techniques.



(a) (b)

Fig. 4. Original vs. Consolidated Masonry: (a) shear vs displacement, (b) Coulomb's relationship

Finally it is possible to underline some recommendations highlighted by the tests carried out [7]:

– FJ-SCT is a Minor Destructive Testing technique, but produces nonetheless a limited destructiveness, so it is necessary that the test points are accurately assessed from both the conservative and the structural point of view, not to cause damage to the building; furthermore restoration of test points is a simple but important operation and have to be done carefully after running the test, with grouting and "cuci-scuci" techniques;

– test results are very sensitive to the method for determining vertical stress: if it is measured by performing a flat jack test, the test location should be chosen on the basis of structural considerations and correlated to the FJ-SCT test position;
– standard [4] contains a generic reference to "thickness of the type of wall to be tested" without giving any information about requested thickness of the panel to be tested: the range of validity of the laboratory calibrations performed covers for the panels a minimum ratio width/thickness = 2.5, but the tests carried out on field confirm the applicability of this technique even with lower ratios.

7 Conclusions

The experimental laboratory campaign allowed a good correspondence between the shear strength values obtained with standard methods (diagonal tension test) and the values obtained with the new FJ-SCT method. The new test method has furthermore proved to produce limited damage to the masonry so resulting effectively applicable to in situ buildings like an usual MDT. The mathematical modeling allowed the best evaluation of the stress and deformation distribution within the masonry during the tests. It shows that the vertical stress pattern is uniform in the area of interest of the test while applied load varies.

The in situ campaign proved the proposed technique to be efficient and effective; it was further applied also on masonries different from those used in the described experiment (for example rubble stones or split stones masonry) with good results.

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