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ASSESSMENT OF STRUCTURAL REINFORCEMENT TECHNIQUES THROUGH SHEAR TEST PERFORMED WITH FLAT JACKS

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Abstract. *The knowledge of shear characteristics of masonry buildings is fundamental to assess their seismic strength. However the current standardized tests proved not to be suitable for the in situ shear characterization of existing structures, as they are strongly destructive. A new testing method based on the use of flat jacks (FJ-SCT Method) has been developed by the authors: it allows to greatly reducing the impact of the tests on the building. A calibration campaign was performed both in laboratory and in situ to evaluate the operability of the defined procedures and it proved the method to be reliable, efficient and repeatable.*
This technique is particularly useful for the evaluation of the improvement of masonry shear characteristics through the application of strengthening techniques. Specific tests were performed on buildings seriously damaged by the 2012 Emilia earthquake to analyze the efficiency of masonry reinforcements. The shear tests were performed on samples of the original masonry and repeated on consolidated samples: the results were able to point out the effectiveness of the application of these reinforcement techniques and to estimate the improvement of the structural strength of the consolidated masonry.

1 INTRODUCTION

The interventions aimed at improving or conforming the seismic behaviour of buildings, such as deep repointing of mortar joints, grouting accompanied by insertion of metallic connectors, and the application of FRP or FRCM reinforcements, often provides an increase of mechanical characteristics of the masonry, in particular its shear strength. In these cases it is obviously essential, in the planning stage, to have already available the information necessary to evaluate the actual increase in resistance that can be obtained by applying the expected techniques; this information is essential to choose the consolidation technique that is most appropriate and effective in the specific case.

At present, however, in situ testing methodologies useful for the measurement of the shear characteristics of masonry are lacking. As an alternative laboratory tests are carried out: they are certainly suitable for assessing the influence of local phenomena (such as the adhesion between the composite material and the surface of the masonry) but generally do not allow a satisfactory simulation of the actual global behaviour of the in situ masonry and therefore a correct forecast of the effects of the applied consolidation techniques.

The bibliography records the application of further test techniques for the in situ determination of masonry shear characteristics mostly deduced from laboratory standards. 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 laboratory tests on brick triplets [1], diagonal tension tests [5] a methodology resulting from laboratory diagonal tension test [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 suitable to detect the shear strength of bed joints, and is not exhaustive of the shear behaviour of the overall brickwork; on the other hand, the diagonal tension tests and the shear-compression tests are strongly destructive as, according to the procedures currently applied for their execution, they require the use of experimental equipment which cause strong impact in the masonry during its setting. This is unacceptable from a conservation point of view, but furthermore, the results of these test methods poorly represent the actual characteristics of the masonry that is subjected to a considerable rehash during the assembling of the test apparatus.

That is 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 a Minor Destructive Testing technique (MDT), it is 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 presents the application of this technique in the specific case of the assessment of structural consolidation techniques, applied to the seismic improvement of a building seriously damaged by the earthquake that occurred in Emilia (Northern Italy) in 2012.

2 DESCRIPTION OF THE TESTING TECHNIQUE

The Flat Jack - Shear Compression Test (FJ-SCT) 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 displacement gauges (5) suitable for measuring horizontal movements. In this way the test lay-out (Fig. 1) identifies two half-panels, almost squared in shape and b x 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. 2) 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.

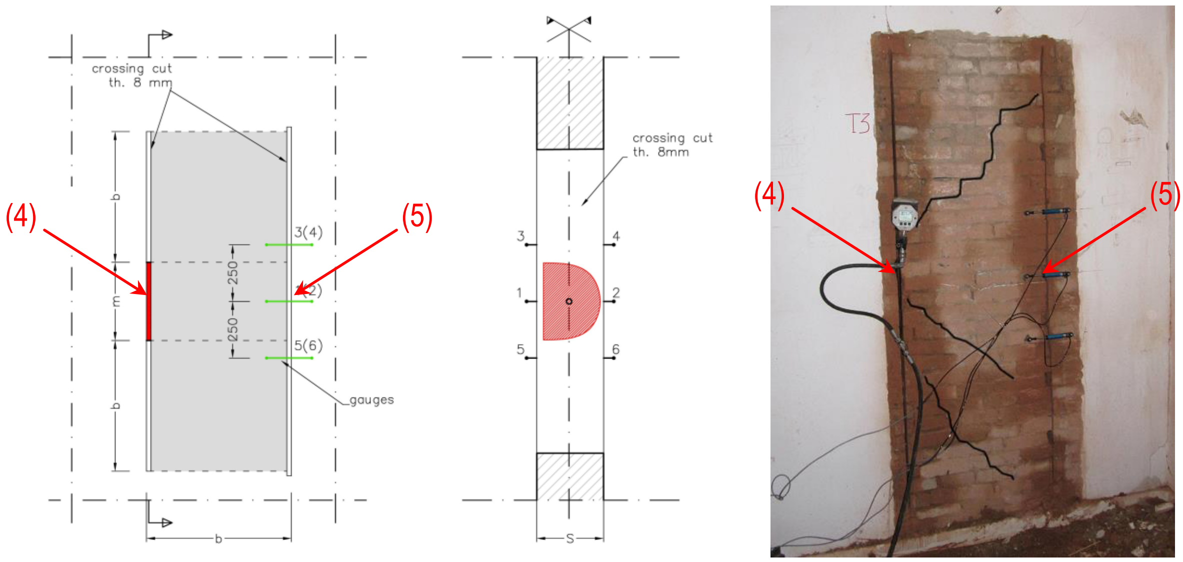

Figure 1 - 2: Lay-out of shear compression test - Diagonal cracks developed during the test

3 DESCRIPTION OF LABORATORY CALIBRATIONS

3.1 Calibration techniques

The calibration procedure of the FJ-SCT technique was performed both through 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 (Fig. 3) with test dimensions 68x180x23,5 cm, built using new bricks with low nominal resistance, mortar with poor ratio of lime and mortar joints of considerable thickness. It was thus 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. They 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 metal frame (Fig. 4) was designed. The panels fitted within the frame (1) were analyzed with the application of two compression cycles up to the stress level 1.0 MPa (applied by a large flat-jack placed horizontally (2) between the top edge of the wall and the frame). A 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.

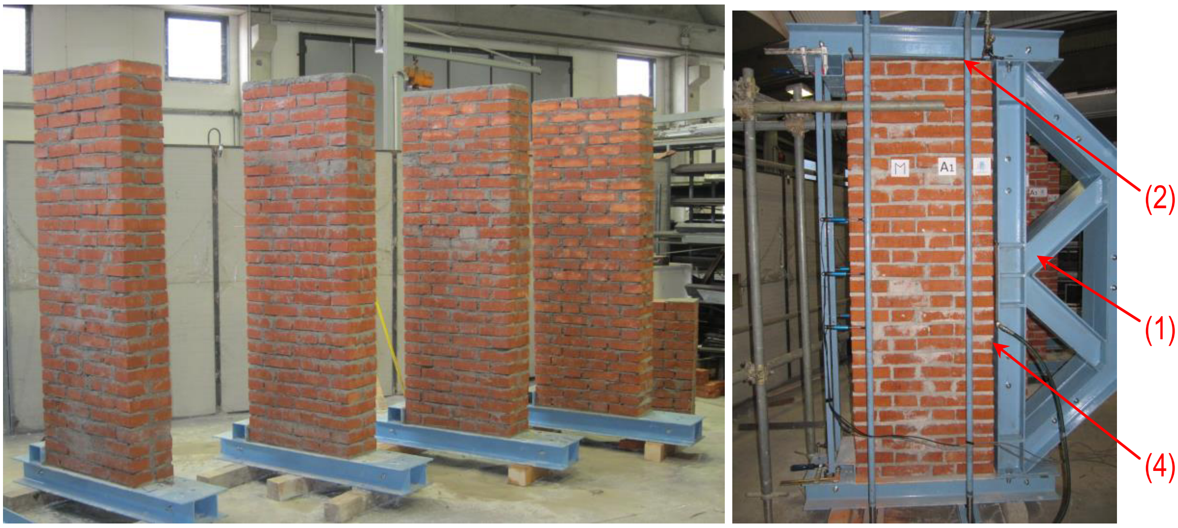

Figure 3 - 4: Laboratory wallets, contrast frame used for the laboratory tests.

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

The mechanical compression characteristics (Young modulus E and Poisson's ratio ν) experimentally determined through laboratory tests on the wallets are reported in [7]. The shear characteristics (σ_v, τ_v and G) determined through FJ-SCT are also reported in [7] together with the data taken from the small panels tested in compliance with [2].

3.2 Finite elements modeling

Data taken from the laboratory calibrations were used for implementing different FEM models aimed at evaluating the stress distribution and the deformation pattern during the test procedure. For this purpose, shell/plate finite elements (plain, bi-dimensional, isotropic, elastic and linear) have been used and models of size equal to twice panel 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.

It is evident that models with such mechanical characteristics are not suitable to accurately simulate the actual behaviour of masonry close to the shear failure. They do, however, create useful qualitative information about stress distribution and deformation pattern.

The shear distribution is similar among the models simulating different situations, as resulting from the sketches in Fig. 5 which highlights the new test methodology as being satisfactory in approximating the stress distribution of the standardized tests.

Furthermore, the F.E.M. calculations highlight that the top edge of the panels rotates so influencing the vertical stress distribution. Vertical stress is substantially constant for a central stretch with the width that equals half the specimen; 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 actual case, reduces the rotation highlighted by the model (due to its elastic and linear hypothesis) and it uniformly redistributes the vertical stress. The values provided from the calculations have therefore to be considered as the upper limit of the actual behaviour of the masonry.

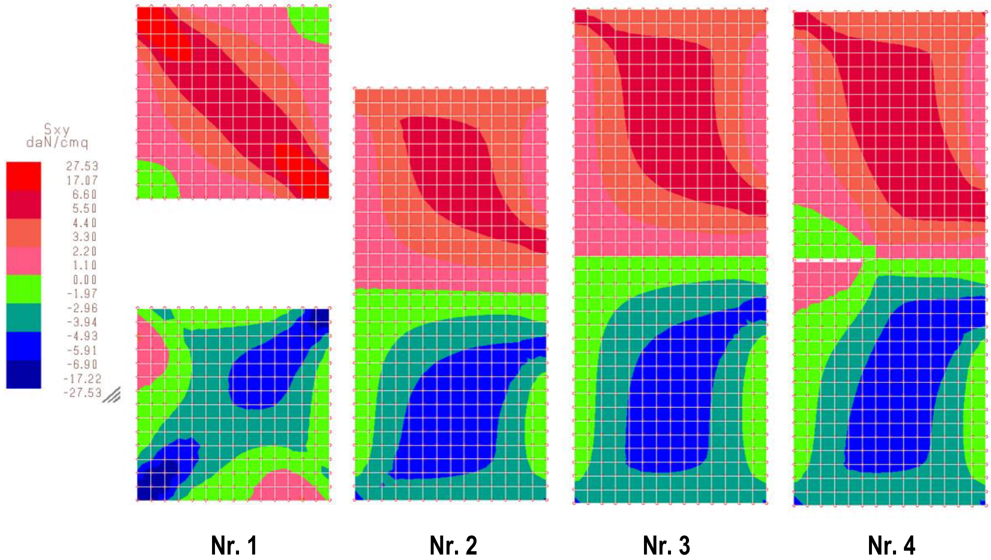

Figure 5: Shear stress distribution Sxy (daN/cm²) – mod. 1-2-3-4 charact. II.

The models have highlighted, in correspondence with the half height of the panel, the developing of traction stress; in this case, non-linear behaviour has been considered by simulating the presence of a crack (model nr. 4). Here again, 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%.

4 DESCRIPTION OF ON SITE CALIBRATIONS

In situ calibrations were performed on two buildings damaged by the 2012 earthquake [10], *La Bertusa* manor at Rovereto (TB) and *Bonasi Benucci* manor at Stuffione (TS).

In the first phase of this calibration, to evaluate the in situ applicability and effectiveness of FJ-SCT technique, for each of the two cases three tests were performed located on masonry samples respectively with dimensions 68x176x28 cm and 60x160x28 cm, that means close to the dimensions of the laboratory panels. In this case, the state of stress and the mechanical characteristics of masonry were determined though usual flat-jack tests [11]. FJ-SCT method was then applied to estimate the shear strength of the masonry.

Before the execution of the calibration tests, plaster was pulled out to avoid any experimental uncertainty. However it has to be noted that, from a theoretical point of view, it is not necessary to remove plaster, unless its characteristics have a significant influence on the shear strength (e.g. in the case of cementitious plasters and very thin walls): this possibility obviously reduces significantly the expected damage to the wall.

Cuts were performed with a diamond blade saw. Also in this case the crack patterns resulting from the tests were completely in line with the expected shear failure of the samples (Fig.1).

The mechanical compression characteristics (Young modulus E and Poisson's ratio ν) experimentally measured from in-situ tests are reported in Tab. 1; they are matched with ultrasonic pulse velocity measured in compliance with [8]. The very high value of Young modulus detected at *La Bertusa* is due to the reinforcement of masonries of this building, though repointing of mortar joints with cementitious-based mortar, which occurred in the nineties. Of course, because of the bad compatibility between cement and old lime mortar, this was not a proper application, specifically with respect to the conservation of the historical building.

	$E_{(0.4-0.8)}$* [MPa]	$\nu_{(0.4-0.8)}$* [MPa]	UT v [m/s]
test standard	[11]	[11]	[8]
(TS) *Bonasi* manor (6)	2936	0,11	2755
(TB) *La Bertusa* manor (6)	4489	0,20	n.d.

* = calculated in the first load cycle in the range σ = (0.4-0.8 MPa).

Table 1: In situ calibration: compression tests.

Panel tag nr.	S1	S2	S3	B1	B2	B3
procedure		FJ-SCT			FJ-SCT	
σ_v [MPa]	0,4	0,28	0,18	0,52	0,3	0,3
τ_v [MPa]	0,571	0,165	0,162	0,466	0,433	0,447

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

Table 2: In situ calibration: shear tests.

The shear characteristics resulting from in situ calibration through FJ-SCT are reported in Tab. 2. In compliance with the Italian structural codes [10], the masonry shear strength vs. vertical stress ratio is determined 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.

$$\tau = \tau vo + \sigma \tan\phi \tag{1}$$

Both in laboratory [7] and in situ test results are plotted in Fig. 6 in compliance with Eq. (1); the continuous lines are defined on the basis of the range provided from the values taken from the code [12].

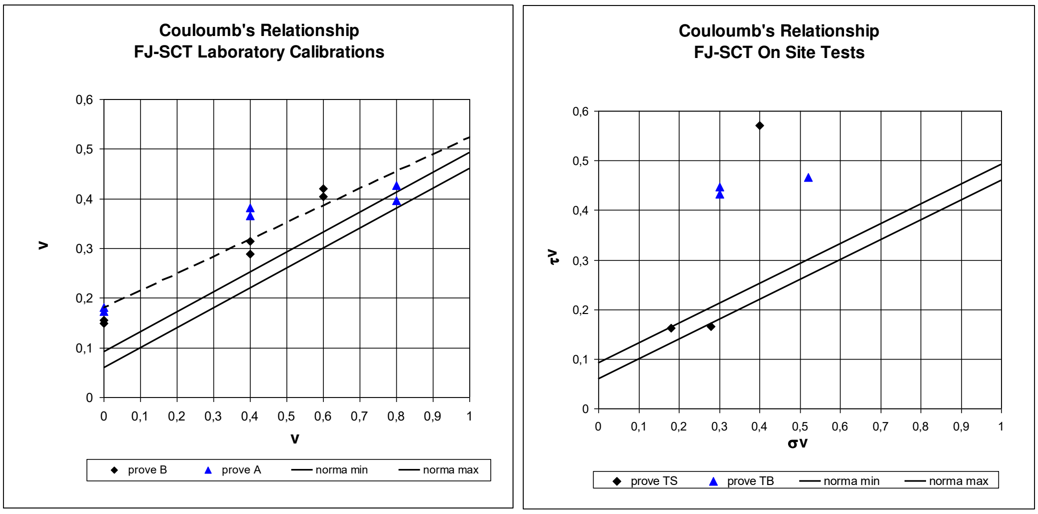

Figure 6: Laboratory and in situ calibrations: Coulomb relationship vertical stress vs shear stress

The data obtained from laboratory calibrations (dashed lines) could be interpolated providing a consistent estimation of the values τ_{v0} (=0,179MPa) and tan ϕ (=0,34). It has to be underlined that the measured values are greater than the ones expected from the codes; this fact is confirmed by some bibliographical references [9] as well.

As expected, the masonries tested in situ were less homogeneous than previous ones, so it was not possible to have a sufficiently large set of data available to perform their statistic interpolation. The data resulting from tests performed at *La Bertusa* manor are high due to the previous repointing intervention as already explained; some of the data taken from *Bonasi Benucci* manor (specifically the ones measured at the upper floors) have a good compliance with those resulting from the code.

5 ASSESSMENT OF STRUCTURAL REINFORCEMENT TECHNIQUES

In the second phase of the in situ campaign, on the masonry samples of *Bonasi Benucci* manor specific consolidation techniques were applied:

- three masonry panels of the farmer house (*acetaia*) located close to the panels previously tested with flat jack were reinforced through deep repointing of mortar joints;
- three masonry panels of the manor house, the same previously subjected to shear-compression tests, were reinforced through the application on both the surfaces of FRCM plating with lime mortar matrix and alkali-resistant fibre-glass wire.

It is useful to underline that these last samples have been failed during the first phase of the tests, so their consolidation can be considered actual reinforcement on masonry damaged by earthquake.

After 28 days curing the samples were subjected to the following tests:

- on the farm house panels were performed three in situ flat jack test for the measurement of masonry deformability properties that provided the results reported in Tab. 3;
- on the manor house panels (located at first and second floor) were performed two FJ-SCT.

The masonry at the lower floor of *Bonasi Benucci* manor proved to be not homogeneous with the others (Tab. 2), so the relevant test is not reported because it has no comparative significance.

Test nr.	Original masonry [MPa]	Consolidated masonry [MPa]	Improvement
S4B	1.00	1.60	
S5B	1.20	1.20	
S6B	N.A.	2.20	
average	1.10	1.67	+ 24,5%

Table 3: Flat Jack tests results - masonry strength on farm house samples

Panel tag nr.	TS1	TS2	TS3	TS1c	TS2c	TS3c
procedure	Original masonry			Consolidated masonry		
σ_v [MPa]	--	0,28	0,18	--	0,24	0,00
τ_v [MPa]	--	0,181	0,169	--	0,25	0,23

Table 4: FJ-SCT tests results - vertical stress and shear strength - G modulus

Before carrying out the shear-compression tests, a further estimation of compressive stress within the masonry (σ_v) was performed by means of flat jack tests carried out close to the sample in compliance with [11]. First phase tests carried out on the original walls resulted in their cracking as it was previously noted and consequently led to the redistribution of vertical stress. It is therefore consistent that the vertical stress values resulting from second phase tests (on consolidated walls) are lower than the previous ones (sometimes even null, when the consolidation methods has involved the complete unloading of masonry).

Masonry panels were then subjected to a horizontal load, gradually increasing until the failure. Both the reinforced samples developed a horizontal crack at the half height mortar joint; this indicates the occurrence of a failure mechanism involving bending, different from the shear failure mechanism that is indicated by diagonal cracks, usual in the tests performed on unconsolidated samples. Anyway this means that the actual shear strength is higher than the measured values, which can therefore be considered in favour of safety. In Tab. 4 the results of the two set of tests are reported.

Depending on Eq. (1) masonry shear strength is a function of a couple of parameters (τ_{v0} and tan ϕ); so the interpolation of only two sets of data has no statistic significance.

A qualitative evaluation of the improvement of masonry shear behaviour due to the performed strengthening can be achieved matching for example the diagrams of TS2 test, where vertical stress σ_v is quite uniform, having a difference minor than 15%, before and after the consolidation procedure. From the diagram in Fig. 7 the improvement of the shear characteristics of the consolidated masonry (red line) is evident.

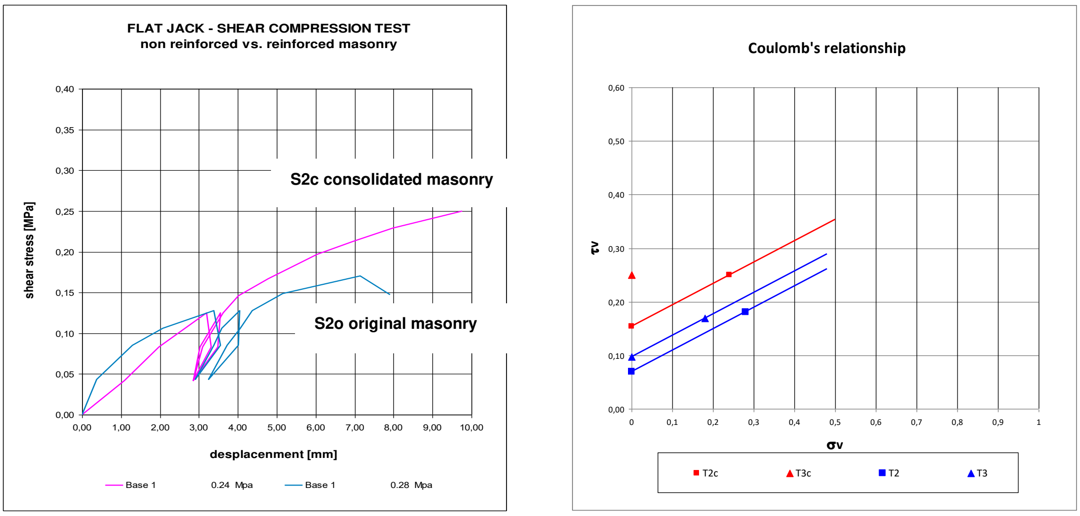

Figure 7 - 8: Original vs. Consolidated Masonry: Shear vs displacement - Coulomb's relationship

Its magnitude can be evaluated by the calculation of τ_{v0} based on the data of each single test, on the use of Eq. (1) and on the assumption that tan $\phi = 0{,}4$, as stated from the code [12]. The results are presented in Fig. 8 where red dots and line indicate the consolidated masonry. In Tab. 5 the further comparison between the data taken from original masonry and consolidated masonry highlights the improvement of the shear strength of the structural elements.

Test nr.	Original masonry [MPa]	Consolidated masonry [MPa]	Improvement
TS2	0.069	0.154	
TS3	0.097	0.233	
average	0,083	0.193	+ 132%

Table 5: FJ-SCT tests results - τ_{v0}

6 CONCLUSIONS

The laboratory calibration campaign tuned the proposed FJ-SCT (Flat-Jack Shear Compression Test) technique and proved the test results are coherent with the ones provided from already standardised test techniques. The FEM give qualitative and quantitative confirmation of these considerations. The in situ calibration campaign showed the method is reliable, efficient and repeatable.

The additional tests performed proved the method is useful in having a consistent in situ estimation of shear mechanical characteristics of masonry samples and it can be usefully exploited to compare masonry characteristics before and after the execution of strengthening interventions, so to obtain the preliminary evaluation of their efficiency, the focusing of the best operational technique and the final evaluation of the correctness of the application.

Further diagnostic application of the same test technique has already been performed on masonry with different typology (rubble stones or split stones masonry) and with different ratio width/thickness (less than 2.5, that is the range of the performed calibrations) providing positive outcomes. Future testing shall be performed for calibrating the method on stone masonry and masonry with lower ratios width/thickness.

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