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A new experimental test for the characterization of the masonry shear parameters †

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Abstract: The shear properties evaluation on existing unreinforced masonry structure is usually performed through destructive tests. However, these tests have the characteristics of being very expensive and require significant damage not only on the samples but also on the portion of wall surrounding them. The present work illustrates the design of a new testing procedure for the characterization of the shear properties in masonry panels for application in routine testing. In the aim of preserving the integrity of the area under testing and to reduce the cost of the new testing procedure, it has been decided to use flat jacks. The numerical analyses used to design the test are presented as well as the results of a first application of the procedure.

Keywords: masonry; unreinforced masonry; shear characterization; shear properties; moderate destructive test; MDT; flat jack; FJ.

1. Introduction

Masonry is one of the most diffuse systems of construction. In many countries of the Mediterranean area (like Italy, Greece, Portugal and Turkey) a considerable seismic activity and a high number of unreinforced masonry structures are present.

The behaviour of this type of constructions under seismic actions is markedly dependent on the shear properties of the material. On a masonry panel the shear failure could happen by a diagonal crack or by the failure of the bed joint [1]. In this work the diagonal crack failure is exanimate that, at the moment, has to be determined through destructive tests. These could be performed in laboratory [2] or in situ [3,4]. Tests performed in situ, like the diagonal compression test and the shear compression test, require the isolation of an important part of the wall to create the specimen. Laboratory tests have similar requirements and add the risk of compromising the specimen on the transportation. The greater problem of these tests is the high level and extent of damage that they require. This fact leads to their inapplicability in structures having historical/architectural relevance and their high cost is prohibitive for application to ordinary buildings as well.

Shear strength and stiffness cannot be evaluated using non-destructive techniques. However, in the last two decades some efforts have been done in order to create a moderate destructive test able of measure these characteristics [5-8]. The common feature of these studies is the utilization of flat jacks. In fact, this technique can guarantee a limited destructiveness and its flexibility allows experimentations. However, at the moment these test methodologies are still not very common.

This study presents the first steps for the creation of a new experimental test for the characterization of the masonry shear parameters using flat jacks. The set-up of this new test is implemented using two main parameters: obtain reliable results and contain the invasiveness of the test in order to create a new moderate destructive technique. In this work are also present the results of the first application of the test in situ.

2. Materials and methods

As previously pointed out, the experimental test was designed with the intention of determining the shear characteristics of existing block masonry panels using a moderate destructive technique based on flat jacks. After this design phase was possible execute a first trial test on a masonry structure.

3.1. Test set-up design

In this preliminary phase the geometry of the test set-up was investigated. More specifically, linear elastic FEM (Finite Element Method) analyses were performed on six different geometrical configurations. For these configurations different positions, orientations and numbers of both cuts and flat jacks were taken in to account. The numerical models were performed considering the masonry as a homogenous isotropic material and the configuration were supposed applied on a wall having dimensions of 2x2x0.5m (Figure 1). In order to speed up this design phase, the numerical models were done considering rectangular shaped flat jacks. For the sake of brevity all of these configurations are not shown. The test set-up was chosen among these six layouts accounting for destructiveness, costs and orientation of the principal stresses.

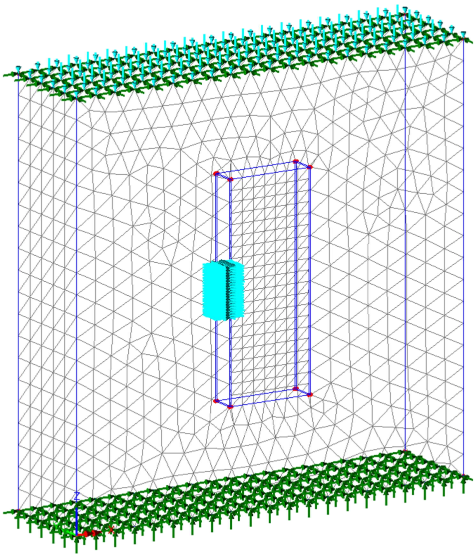


Figure 1. The FEM model for one of the six examined configurations. In the Figure the cyan horizontal arrows show the position of the flat jack and the nearby blue lines are the cuts. The green arrows represent restrains while the top cyan vertical arrows show the vertical load.

As introduced the main purpose of this work was the creation of a new moderately destructive test for the shear characterization. For this reason the destructiveness of the different layouts was deeply examined. For the definition of the optimal configuration the destructiveness was taken into account considering the volume of the sample and the length, number, type and orientation of cuts. For example, in configurations that use rectangular flat jacks the cuts can be performed using a drill that usually doesn't need water to cool and they can have limited depth (about 120 mm). On the contrary, cuts for semi-circular flat jacks are usually performed using circular saws that normally are cooled using water that penetrates in the masonry resulting more invasive.

The limitation of the destructiveness was not the only factor considered for searching the best layout. The most important goal for the choice was the achievement of a 45° orientation of the principal stress in order to have a diagonal direction of the stresses on the sample. Costs were also taken in to account because are one of the limitations for the application of destructive tests.

The found optimal configuration was a simple rotation of 45° of the standard double flat jack set-up (Figure 2). In fact, this configuration better fulfilled all the objectives. For this configuration FEM analyses considering semi-circular flat jacks were also performed. Due to the similarity with the double flat jack test, some recommendations given for the deformability test by RILEM [9] and ASTM [10] were adopted. One of these recommendations is the relative position between the two flat jacks.

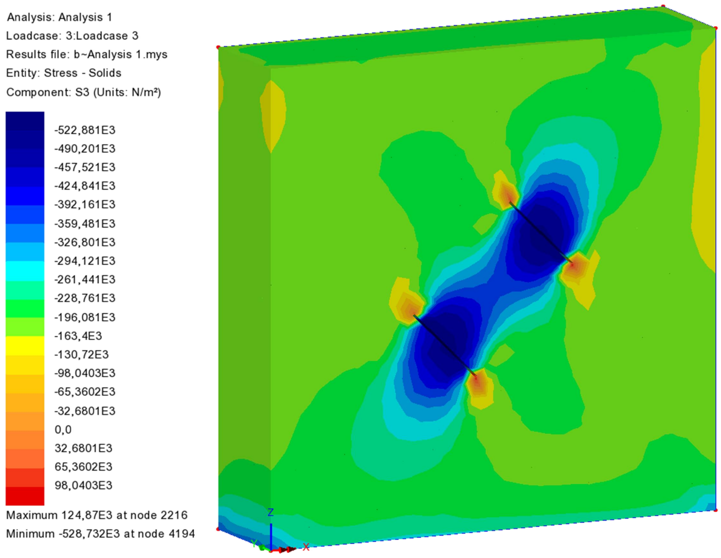


Figure 2. A FEM result obtained for the chosen configuration. The model was created considering a homogeneous elastic material having E=1200 MPa, υ=0.25. In order to simulate the vertical load coming from the upper part of the structure a vertical stress of 0.2 MPa was considered. The figure shows the result obtained considering a stress of 0.5 MPa applied by the flat jacks.

3.1. First trial test

A first experimentation was performed in the "ex Teatro dei Nobili" (Vercelli, Italy) (Figure 3). This test was executed in collaboration with the Companies Cismondi Srl and ARCOS Engineering Srl. The building, made of brick and lime mortar masonry, has a long story started in 1787. This structure was interested by a collapse with associated injuries and victims. Successively it was rebuilt but a fire burned it. Finally, at the beginning of the last century the municipality repaired the structure but it was abandoned after some years of utilization.

The trial test was executed during a deep field investigation of the theatre, which involved also two couples of single and double flat jack tests. One of these couples of investigations was performed near to the experimental test in order to obtain the vertical stress, the Young modulus, the Poisson's ratio and the compression strength.

All tests were performed using the same equipment. The used measurement system included: a strain gauge having a base length of l=250 mm (resolution of +/-0.001 mm), seven measure bases (four parallel and three perpendicular to the flat jacks) and two pressure gauges: the first for pressures up to 1.60 MPa (+/-0.01 MPa) and the second for pressures up to 6.00 MPa (+/-0.05 MPa). The flat jacks were semi-circular with dimension 350x250 mm.

After the individuation of the test location, the positions of the flat jacks and of the seven measure bases were defined. The flat jacks positions were marked considering a relative distance of 500 mm and the gauge points where glued at a distance equal to the base length. Subsequently to the glue hardening it was possible to create the slots using a circular saw. The flat jacks were then inserted in to the slots and the hydraulic system was connected. Following the advice of the operator, instead of using oil, a solvent was used in order to exploit its lower viscosity. Before rising the pressure the upper plug of the upper flat jack was opened and the solvent was pumped until the first liquid spilt allowing the exit of all the internal circuit air.

Measures between the gauge points were taken before and after the first cut, after the second cut and in correspondence to each step of pressure up to 2.60 MPa. It has to be remarked that for each step the pressure was hold until the measures were stable and then the measures were recorded. This procedure was chosen to give time to the sample to end viscose deformations. Figure 3 highlights in green the perpendicular measure bases to the flat jacks and in yellow parallel ones. The measurements allowed for the identification of the perpendicular strains $\varepsilon_{\perp}$ and parallel $\varepsilon_{//}$ to the flat jacks. These strains were evaluated averaging the measures; for example $\varepsilon_{\perp}$ is computed as:

$$\varepsilon_{\perp} = (d_{\perp,1} + d_{\perp,2} + d_{\perp,3})/(3\ l), \tag{1}$$

where $d_{\perp,1}$ is the relative displacement of the first measure basis. The strain $\varepsilon_{\perp}$ is evaluated in the same way but averaging on four measures. After this first operation the shear strain was evaluated as:

$$\gamma = \varepsilon_{\perp} - \varepsilon_{//}, \tag{2}$$

following (with another symbolism) the ASTM recommendation [2].
For the presented results every relative displacement $d_{i,j}$ was evaluated as the difference between the measure taken at a defined pressure step and the measure taken after the realization of the two cuts.

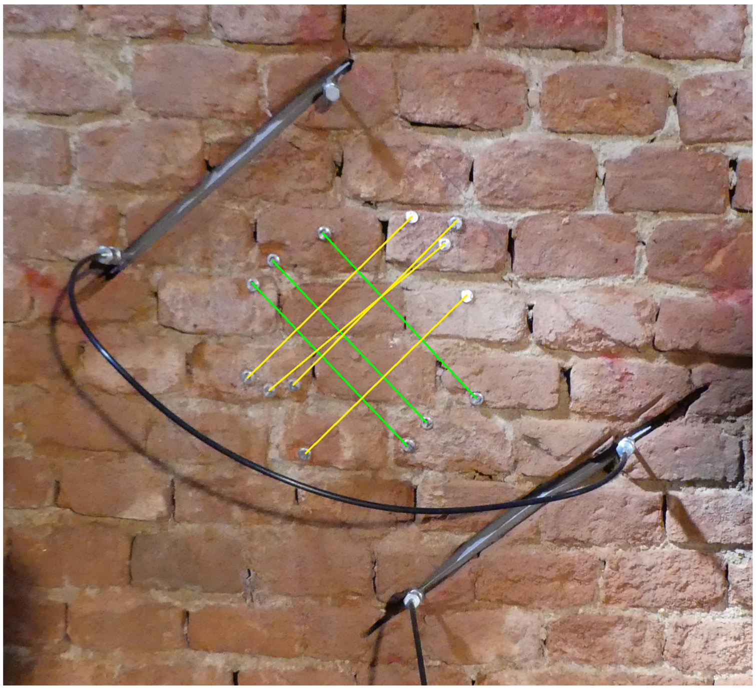


Figure 3. Equipment set-up of the first trial test performed on the "ex Teatro dei Nobili" (Vercelli, Italy). In this image is possible to recognize the slots with the inserted flat jacks and the hydraulic connection between them. The positions of the gauge points and the direction of the seven measure bases are highlighted (three perpendicular in green and four parallel in yellow).

The stress σ applied to the masonry is evaluated considering the well-known formulation used for the double flat jack test [9,10]:

$$\sigma = p\ K_a\ K_m, \tag{3}$$

where p is the hydraulic pressure, K_m (<1) is the dimensionless constant of the flat jack that takes in to account its stiffness, and K_a (<1) is the dimensionless constant evaluated with:

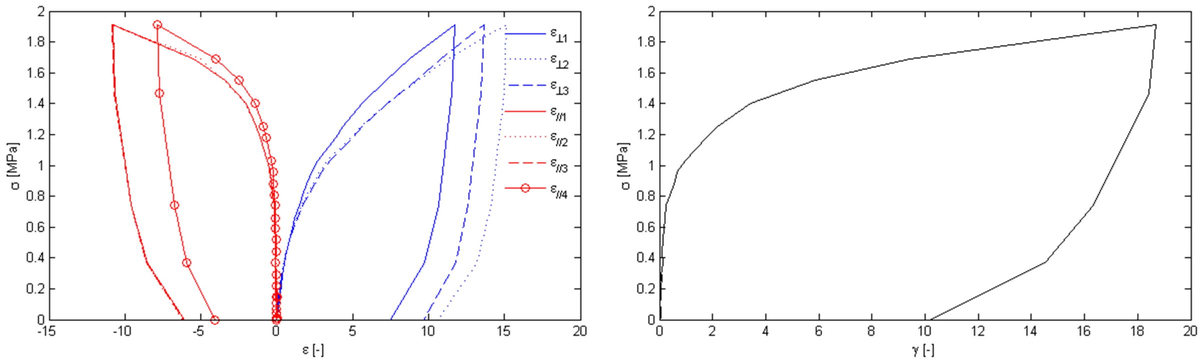
$$K_a = A_{FJ} / A_{AV,SLOTS}, \tag{4}$$

in which A_{FJ} is the flat jack area and $A_{AV,SLOTS}$ is the averaged area of the slots.

3. Results

Results obtained from the new testing procedure are promising. The designed set-up has allowed to determine the behaviour of the masonry under test giving the relation between the applied stress and the measured strains (Figure 4a.b).

In the first part of the test three cycles were performed in which the pressure was kept at low levels (0.11, 0.15 and 0.29 MPa). This procedure was applied in order to have a better characterization of the linear regime of the masonry. It is possible to identify in both the Figures 4a.b an initial elastic behavior. At a stress of approximately 0.80 MPa the sample starts to show a plasticization and a hardening behaviour. This is a classical behaviour of the double flat jack test and is due to the confinement given by the masonry surrounding the specimen. The stress was then rose up to 1.91 MPa. At this point it was impossible to have stable measures and for this reason it was decided to end the test and take some measures during the unloading process.



(**a**) (**b**)

Figure 4. Results obtained in the trial test: (**a**) plots of the stress applied to the masonry σ versus the deformation of the three perpendicular basis $\varepsilon_{\perp}$ (in blue) and (in red) the four parallel basis $\varepsilon_{//}$ (elongations are considered negative); (**b**) plot of the stress applied to the masonry σ versus the shear strain γ.

The stress-shear strain curve (Figure 4b) was the greater achievement of this trial test. The plot shows clearly the initial elastic behaviour of the sample and then it is quite easy to notice the plasticization phase of the material. The individuation of these two phases is important for the evaluation of the shear strength and modulus of the masonry.

4. Conclusions

For this first test, some small criticalities were identified. The first is the difference among the three strains $\varepsilon_{\perp}$ and among the four $\varepsilon_{//}$. Differences of this magnitude are quite normal for flat jack testing. In this case, the problem is connected to two principal facts. First of all, was impossible to apply the measure bases perfectly perpendicular/parallel to the flat jacks. Secondly, the measure bases were only approximately near to the centre of the specimen. These two facts occurred because the masonry showed relative thick joints and in the used equipment the measure basis had a fixed length. These facts limited the possible positions of the gauge points (because is not recommended to place the gauge points in joints) and leaded to this first criticality. A second issue was the creation of the slots that resulted not perfectly parallel. This fact was related to the non-smooth operation of the saw when cutting in a direction not aligned with bed joints.

However, results are very promising. In fact, the first trial test has highlighted the potential of the configuration chose for the shear characterization. The obtained data point out that, using this test, is possible to recognize the linear and the non-linear behaviour of the material. The identification of the linear regime of the masonry and the measurement of the shear strain can identify the shear modulus of the material. Similarly, the detection of the zone in which the transition between the linear and the non-linear behaviour is present should be related to the shear strength of the masonry. These facts underline clearly the possibility to use this set-up as a new moderately destructive test for the shear characterization.

Authors have already planned further activities having the purpose of validating this new shear test. These activities are:

- A special frame was designed and built to guide the creation of the slots and the placement of measuring instruments. Moreover, a special data acquisition system to log real-time data has been developed and monitoring of the specimen using acoustic emission technique and digital image correlation is planned.
- Further numerical analyses are being executed in order to have a better comprehension of the sample behavior and correlate in-situ results with shear strength and modulus.

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Conflicts of Interest: The authors declare no conflict of interest.

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