On the characterization of materials and masonry walls of historical buildings: use of optical system to obtain displacement maps in double-flat jack tests.

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ABSTRACT: Among the testing techniques aiming at the mechanical characterization of masonry, the double flat-jack testing method is widely adopted to identify the local value of significant parameters needed to perform structural analyses, such as elastic modulus, Poisson's ratio and compressive strength. The experience gained from many applications has allowed not only to collect experimental data concerning different types of masonry, but also to highlight the difficulty in the interpretation of the results and the limitations of both single and double flat-jack tests. Although the accuracy of the flat-jack technique in detecting strength and deformability behavior of masonry is still debated in the technical literature and practical activities, changes in the testing procedure aiming at ascertaining the validity of the test results have not been formally defined yet. After a brief description of the standard test procedure and its uncertainties, the present paper proposes an upgrade of the test procedure for improving the level of reliability of the test results. In particular, an experimental case study related to a historical brick masonry building located in Italy is presented to point out the additional information necessary to validate the results of the testing process.

1 INTRODUCTION

When dealing with the structural safety assessment of existing masonry buildings, an adequate knowledge of the mechanical properties of masonry is essential to carry out accurate numerical analyses. The strength of masonry under flexural, compressive, tensile and shear stress states can hardly be determined through laboratory tests because of two main reasons. On the one hand, the extraction of undisturbed specimens is not a simple operation. On the other hand, it is very difficult to sample and test masonry components (e.g. bricks and mortar) and correlate their mechanical properties to those of the whole masonry through analytical (Hilsdorf 1969) and numerical (Acito et al. 2008a) models. Furthermore, in the case of historical buildings, there are several restrictions on the application of highly destructive procedures, since the removal of specimens is not in line with the principles of monumental heritage conservation. Among the most performed insitu tests, the flat-jack test allows to characterize the local stress level as well as the deformability properties of masonry. Being only slightly destructive, this testing technique is suitable also for buildings of historical value. Even though the flat-jack method is widely used (Jurina et al. 1980; Rossi 1982; Binda & Tiraboschi 1999) and considered a reliable tool for the estimation of the mechanical parameters of masonry, it involves some uncertainties which may affect the validity of the test results. Several experienced authors, such as Binda et al. (2004) among others, have discussed about the difficulties in the interpretation of the test results due to the anomalies commonly found in the outcomes as well as the lack of a strong theoretical framework to correlate experimental data with actual mechanical properties. Moreover, in the case of double flat-jack test, when the failure of masonry occurs outside the wall specimen (WS) between the two flat-jacks, the correlation between strength of masonry and pressure becomes a difficult task. As a consequence, the definition of objective criteria for ensuring the reliability of the test results is essential. Over the years, test results have been indirectly validated using back analysis and relatively sophisticated numerical models. The choice of the most suitable numerical modeling strategy is usually driven by the simulation purposes, the level of accuracy required and the computational time as well. These aspects have led to the definition of two distinct approaches for the numerical analysis of masonry, namely the micro- and macro-modeling. The micro-modeling is particularly apt to investigate local mechanisms, such as cracking phenomena (Gianbanco et al. 2001; RILEM TC 177-MDT 2004; Lourenço & Pina-Henriques 2006; Chaimoon & Attard 2007), while the global behavior of masonry structures is usually analyzed by macro-modeling, where mean values of stress and strain are considered (Acito & Milani 2012; Acito et al. 2016; Jain et al. 2020; Acito et al. 2020; Acito et al. 2021; Magrinelli et al. 2021). The present work is intended to provide practical suggestions for upgrading the double flat-jack test procedure and improving the reliabilty of the outcomes for a better interpretation of the masonry behavior. To this purpose, a complementary optical-based displacement monitoring method is proposed in addition to the standard displacement measurement through LVDTs. The system allows for the real-time monitoring of the stress-strain evolution in an easy and detailed way thanks to the high-density distribution of the reference nodes, which have to be arranged on a wall surface larger than the WS. In the present work, the results from the experimental campaign carried out on the brick masonry walls of a historical building located in Lodi (northern Italy) are selected to discuss the proposed method and to clarify which additional data are necessary to improve the validation of the results of the testing process (Cucchi et al. 2012). The method presented in this work includes an optical system for the measurement of the relative displacements of the flat-jacks and some reference nodes on the surface of the tested area. The system based on optical measurements can be assumed as a reference, but the position of the reference nodes can be also monitored during the test by additional LVDTs properly arranged.

2 INSIGHT INTO THE FLAT-JACK TESTS

2.1 *Test description*

The flat-jack testing method was originally calibrated to test brick masonry, but then it has been largely applied also to irregular stone masonry (Bettio et al. 1993). Moreover, this testing technique was firstly used for the in-situ detection of the local stress level of masonry and then adapted to determine the deformability properties of masonry and its strength, whenever possible. The test procedure of the single- and double flat-jack test were codified in ASTM C 1196 (1991) and ASTM C 1197 (1991) respectively. During the test, removable extensometers or displacement transducers (LVDTs) applied on the WS surface are used to provide information on vertical and lateral displacements of some reference points. Loading and unloading cycles can be performed at increasing stress levels in order to determine the deformability modulus of masonry. In order to estimate the compressive strength value, the maximum value of stress applied during the last loading cycle can be increased until the masonry strength is reached and the failure of the specimen occurs. The results of several experimental campaigns including both single and double flat-jack tests have been used to discuss the test procedure, as described in the research work by Gregorczyk & Lourenço (2000). Double flat-jack tests are usually combined with non-destructive tests, such as sonic and impact tests. As a matter of fact, a combined approach consisting of non-destructive and semi-destructive tests allows to extend the knowledge of the mechanical characteristics of masonry; moreover, the correlation between results of different tests can be useful to corroborate the validity of the results themselves.

2.2 *Review of the significance of the flat-jack tests*

Interpreting double flat-jack test results is a challenging step of the test procedure not only when clear anomalies affect the outcomes but also when they are apparently highly reliable. The uncertainties concerning the validity of the test results may impair the definition of the correspondence between the mechanical properties determined by flat-jack tests and the actual ones. Several experimental campaigns (Acito et al. 2008a; Binda et al. 2004) demonstrated that the outcomes are highly dependent on the type of the tested masonry, which may be affected by hidden irregularities. As far as the double flat-jack test is concerned, some considerations well clarify when the test is considered to be not valid. Firstly, the stress-strain relationship detected by the double flat-jack test could be characterized by apparent high stiffness. According to Binda et al. (2004), this behavior is typical of tests carried out on low-rise buildings (one- or two-story high) and due to the lack of reaction in the upper masonry caused by the low stresses acting on it (Fig. 1).

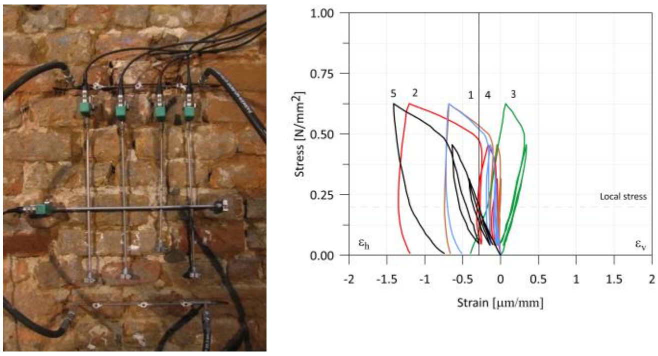


Figure 1 – Execution of a double flat-jack test (J2) (left); example of stress-strain relationship detected by double flat-jack test when the upper stresses are low or in presence of irregularities (Sommariva Palace, Lodi) (right).

More precisely, according to Acito et al. (2008b), anomalies in the stress-strain relation are most likely due to the heterogeneity of the WS. As a consequence, special care must be taken in testing masonry walls characterized by irregular composition, such as brick or stone masonry with irregular mortar joints and/or high thickness. Secondly, the choice of the position of the cut for inserting the flat-jacks is another important aspect to take care of. According to Binda et al. (2004), the slots should be positioned in the brick course when the joint thickness is greater than 2 cm, while in the case of stone masonry the cutting operations should not be performed through the joints – due to their irregularity and softness – but through the stones. Considering the many case studies described in the literature, it can be concluded that the main aspects which have great influence on the validity of the results of the double flat-jack tests are:

1. the state of stress in the masonry portion above the top flat-jack, which may be significantly lower than the pressure applied by the flat-jack;
2. the improper choice of the slot positions and the arrangement of the reference points;
3. the irregular composition of the wall, whose deformability properties may be significantly variable;
4. the masonry texture and the type of mortar.

While the first two issues deal with the level of experience of the technicians, the others are intrinsic to masonry, whose internal texture is not always visible. As a consequence, particular attention must be taken in performing double flat-jack tests on clearly irregular masonry but also on brick or stone masonry with regular mortar joints. As mentioned above, even when irregularities are not evident, anomalies in the stress-strain behavior of a tested masonry wall may occur because of the insufficient stress state above or under the WS and/or the poor quality of the material in contrasting the pressure given by the flat-jacks. In this sense, the execution of sonic tests by trasparency prior to the flat-jack ones is useful to detect masonry irregularities and, therefore, to choose the most suitable position for the flat-jack tests.

3 STRESS-STRAIN RELATIONSHIP

3.1 *Experimental σ-ε relationships*

Experimental uniaxial $\sigma-\varepsilon$ relationships are needed for realistic static and seismic assessment of existing masonry buildings, as they allow for the formulation of the material behavior models in structural analyses, both in the linear and non-linear field. In light of this, it is essential to define a procedure aiming at ascertaining the validity of the experimental results coming from in-situ double flat-jack tests.

3.2 *Limitations of experimental σ–ε relationship detected by double flat-jack tests*

The $\sigma-\varepsilon$ relationship obtained from double flat-jack test may be affected by the material peculiarities characterizing the WS. The double flat-jack test, indeed, is not comparable to the classical uniaxial test and the results may be unreliable for the following reasons. Firstly, the double flat-jack test is usually performed on masonry walls thicker than flat-jack dimensions (Fig. 2a). Therefore, the flat-jacks transfer an eccentric load to the WS in the initial loading and unloading phases. Secondly, being the WS confined, the experimental $\sigma-\varepsilon$ relationship comes from a multiaxial stress state and its correlation to uniaxial state could be considered improper. Thirdly, the $\sigma-\varepsilon$ relationship is determined by measuring the WS deformations, without considering that they can be affected by geometrical effects due to flat-jack displacements. During the test, indeed, the relative distance between the flat-jacks can increase or decrease depending on the stress-strain scenarios in the masonry surrounding the WS. In particular, when the distance between the flat-jacks increases, the $\sigma-\varepsilon$ relationship of the WS could be more rigid than the actual one (hardening behavior). On the contrary, when the distance between the flat-jacks decreases, the $\sigma-\varepsilon$ relationship of the WS could be less rigid than the actual one. With the aim of highlighting how the stress-strain state of the surrounding masonry can affect the test results, three different scenarios are herein considered (Fig. 2b):

- case 1: the WS, the wall volume above the top flat-jack and the wall volume under the bottom flat-jack are characterized by the same stress-strain behavior ($K_B(\varepsilon)=K_T(\varepsilon)=K_{WS}(\varepsilon)$);
- case 2: the WS is less rigid than the wall volumes above and under the tested area ($K_B(\varepsilon)=K_T(\varepsilon)>K_{WS}(\varepsilon)$);
- case 3: the WS is more rigid than the wall volumes above and under the tested area ($K_B(\varepsilon)=K_T(\varepsilon)<K_{WS}(\varepsilon)$).

The stress-strain curves of the WS obtained from hypothetical double flat-jack tests performed on these three masonry scenarios are depicted in Figure 2c. The analytical stress-strain curves depicted in Figure 2c are obtained from the well known Sargin's model, properly adapted to masonry (Lenza & Ghersi 2013). The stress-strain curve n. 1 in Figure 2c is given by E_p = 3000 MPa, f_p = 3 MPa and ε_p=0.2% and corresponds to the case 1 previously listed. In the stress-strain curve n. 2 in Figure 2c an increment of 50% with respect to the ε values of curve n.1 is considered, supposing that the relative distance between the flat-jacks decreases during the test when the WS is less rigid than the surrounding area. In the stress-strain curve n. 3 in Figure 2c a reduction of 50% with respect to the ε values of curve n.1 is considered, supposing that the relative distance between the flat-jacks increases during the test when the WS is more rigid than the surrounding area. The stress-strain curve n. 4 in Figure 2c is obtained when an increment of 200% with respect to the ε values of curve n.1 is considered. In light of this, it can be stated that the σ-ε relationship obtained from a double flat-jack test well fits the actual one only when the flat-jacks do not move with respect to each other during the test, otherwise the measured σ-ε relationship can be considered only representative of the real one. Differently from the σ-ε relationship, the masonry strength estimated by the double flat-jack test is not significantly affected by the relative displacement between the flat-jacks.

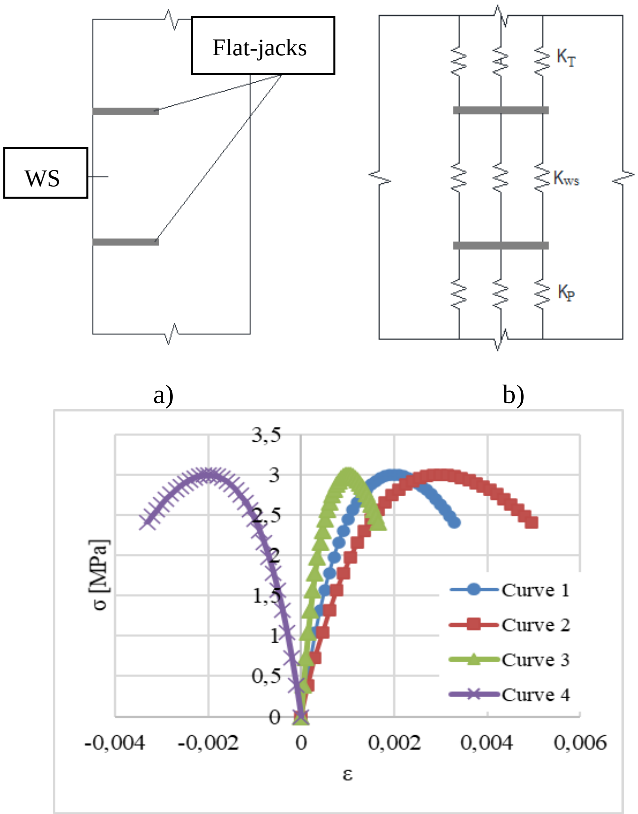


Figure 2 – Double flat-jack test: a) geometrical aspects; b) simplified schematization of the stiffness scenarios; c) hypothetical σ-ε relationships of the WS.

Figure 3 – Main façade of Sommariva Palace, Lodi.

Considering that, as known, the masonry failure may take place in the WS or in the surrounding area during the test, it can be supposed that failure occurs in the WS in cases 1 and 3, while it occurs in the masonry surrounding the WS in case 2. Therefore, the monitoring of the displacements of the flat-jacks and the strain diffusion is a necessary step to verify and validate the test results. In particular, this paper focuses on the optical system for the acquisition of the displacement field of the tested area and the results of its application during the double flat-jack tests performed on the masonry walls of Sommariva Palace located in Lodi (Fig. 3) are provided.

4 EXPERIMENTAL CAMPAIGN ON THE MASONRY WALLS OF SOMMARIVA PALACE IN LODI, ITALY

4.1 *Program of the in-situ tests*

Within the rehabilitation intervention of Sommariva Palace in Lodi, Italy, different tests aiming at the material characterization of stone columns, brick masonry walls, wooden floors and roof were performed by the Material Testing Laboratory at Politecnico di Milano. In particular, sonic tests, single and double flat-jack tests were performed on the masonry walls of the ground floor (Fig. 4). The sonic tests were carried out not only in the same positions of the flat-jack tests (Figs. 6a, 7a) but also in other areas, in order to extend the masonry qualification results in a semi-quantitative/qualitative way.

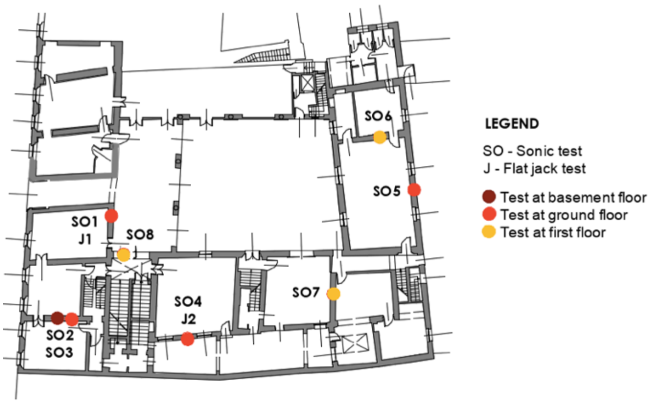


Figure 4 – Basement floor with localization of sonic and flat jack tests.

4.2 *Double flat-jack test results*

Flat-jack tests were carried out on two different masonry typologies, in the J1 and J2 positions shown in Figure 4. As to the results of the single flat-jack tests, the stress state measured in the J1 position was 0.35 MPa, only slightly higher than the value estimated by the static analysis, while the stress state measured in the J2 position was about 0.20 MPa. As to the results of the double flat-jack tests, the elastic modulus measured in the J1 position was 1450 MPa (average of the four transducers) and the stress state measured was 0.1-0.6 MPa (Fig. 5).

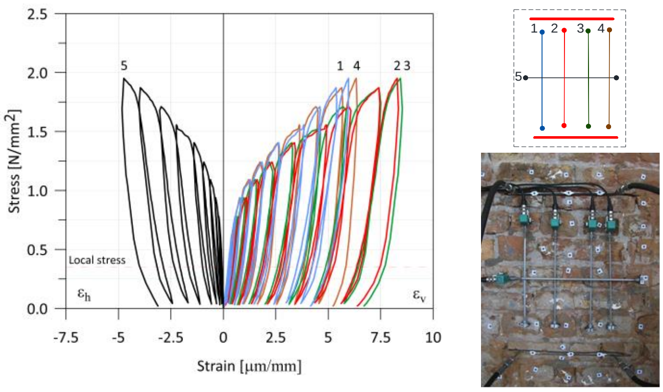
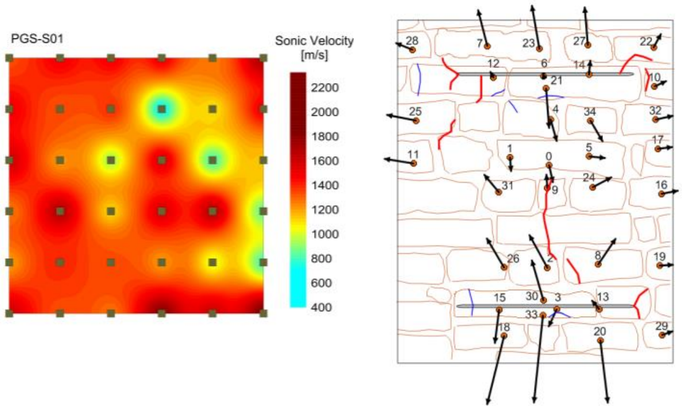


Figure 5 – Experimental σ-ε relationships obtained from J1 double flat-jack test.

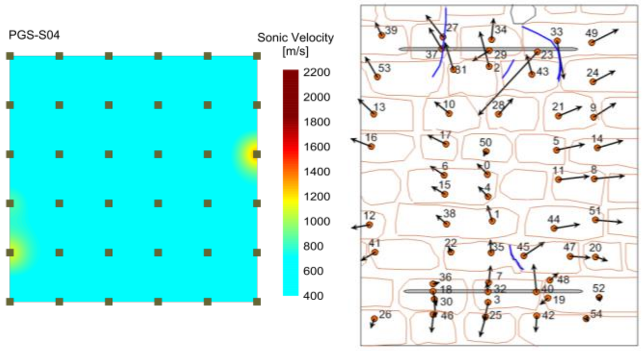
The J1 double flat-jack test was interrupted at an applied stress equal to 1.4 MPa, when the opening of cracks occurred in the WS. The J2 double flat-jack test was clearly affected by anomalies (Fig. 1) because of the poor masonry quality and the insufficient confinement effect provided by the volume above the WS.



a) b)

Figure 6 – S01 Sonic test by transparency: velocity contour lines obtained by linear interpolation (a); optical displacement monitoring during the J1 double flat-jack test (σ_{max} = 1.95 MPa, X50) (b).

During the J1 and J2 double flat-jack tests, the measurement of the displacements was carried out not only by traditional LVDTs, but also by arranging an optical system which allowed to fix absolute coordinates and to acquire information like displacement vectors of selected points. As it can be observed in Figure 6b, the displacement trend measured during the J1 test was quite regular. Very small displacements were measured at the reference points n. 12, 6, 14 and n. 15, 3, 13, located on the upper and lower flat-jack respectively. According to paragraph 3, the experimental behavior detected by the J1 double flat-jack test can be considered well representative of the actual behavior of the WS.



a) b)

Figure 7 – S04 Sonic test by transparency: velocity contour lines obtained by linear interpolation; optical displacement monitoring during the J2 double flat-jack test (σ_{max} = 0.6 MPa, X200) (b).

The displacement trend measured during the J2 double flat-jack test was quite irregular, as shown in Figure 7b. Indeed, displacements of reference points n. 37 and 29 on the upper flat-jack were negligible, while an anomalous displacement directed downward was measured at reference point n. 23. Similarly, displacements of reference points n. 18 and 32 on the lower flat-jack were negligible, while an anomalous displacement directed upward was measured at reference point n. 40. Since, in general, displacements are directed upward on the monitored points, it can be deduced that the WS is pushed upward because of an insufficient confinement effect provided by the masonry volume above the WS. Moreover, the low sonic velocity (Fig. 7a) confirmed the presence of irregularities in the WS. Indeed, the second test did not allow to acquire useful information on the mechanical characteristics. After the local removal of the bricks near the lower jack, it was observed a facing regular wall of only 10 cm thick (the outer leaf), beyond the masonry was composed of fragments of bricks and inconsistent clay mortar. This observation combined with the particularly low value of the sonic velocity and the very low value of the stress state largely explains the detected behavior. As a consequence, according to paragraph 3, the experimental behavior detected by the J2 double flat-jack test can be considered not representative of the actual behavior of the WS.

5 CONCLUSIONS

Experimental flat-jack tests are valid tools to detect the local state of stress (single flat-jack test) and the stress-strain behavior (double flat-jack test) in masonry walls. The reliability of the results obtained from double flat-jack tests has been debated in the literature since very first experimental applications.

The original test standardization has not been substantially modified over the years and the interpretation of outcomes depends strickly on the technicians' experience. In this sense, this work proposes an upgrade of the procedure aiming at ascertaining the reliability of the results objectively. The upgrade requires monitoring the relative displacements of the flat-jacks during the test, in order to account for the effect of some peculiarities in the tested masonry. Indeed, the control of the reliability of the test results allows for a more precise definition of the stress-strain behavior of the masonry wall specimen included between the two flat-jacks. As to the estimation of the masonry compressive strength, it is well known that masonry failure can occur in the WS and/or in the masonry volume surrounding the WS. In any case, the peak stress is independent of the possible relative displacements of the flat-jacks. The experimental-analytical considerations developed in this work, although preliminary, allow to highlight that monitoring the displacements of the WS, as well as of the surrounding masonry and flat-jacks, is important to validate the test results. Anyway, further experimental applications and numerical simulations are necessary to corroborate the promising considerations presented in this work.

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