ON SITE TESTS FOR THE MECHANICAL CHARACTERIZATION OF MASONRY WALLS WITH CHAOTIC TEXTURE

Marco Andreini, Anna De Falco, Mauro Sassu

ABSTRACT

A campaign of on site experimental tests has been carried out for the mechanical characterization of the building stonework dated back to the 20’s – 40’s in the hospital complex of Volterra (Pisa). The presence of a disused masonry construction with mechanical properties similar to the surrounding buildings offered the opportunity to perform destructive and no-destructive tests and to extend results for the set of used buildings. The research deals with the comparison of several test methods on chaotic texture panels, to develop innovative test procedures to determine the best methodology for this particular masonry type.

In this context, in addition to the conventional diagonal compression test, the Twin Panels Test (TPT) has been applied and developed. With the help of the various techniques employed (flat-jack, penetrometric tests), the failure mode of the panels under shear and compression forces has been interpreted and, starting from the observation of the results of the tests, the safety domain shear vs. compression for the rubber masonry typology has been drawn up.

The cross validation of several testing techniques suggests strategies to determine the shear strength, deformation properties and ductility capacity of the walls with highly irregular texture. At the same time, the results are able to provide support for the calibration of the different NDT methodologies.

Keywords: Masonry strength, On site tests, Twin Panels Test, TPT

1. INTRODUCTION

The common feature of different types of unreinforced masonry is its very low tensile strength: in the past masonry structures were primarily designed to be stressed in compression. Nevertheless unreinforced stone masonry was used in the seismic region, as well. So, in order to evaluate the seismic behaviour of masonry buildings with predictive models of the load-bearing capacity of masonry panels, a preventive calibration of the basic mechanical parameters is needed.

When the in situ tests are feasible, they are the only one way to obtain actual values of the mechanical characteristics of a particular type of masonry work, in spite of the high level of uncertainty in the evaluations with different test types: although the methodologies for the interpretation of various tests are regulated by codes of standards they frequently show inaccuracy and incompleteness.

The aim of this work is to compare the results obtained from the application of different experimental tests methods to a masonry work with chaotic texture and poor mortar. So, in this paper a campaign of on site experimental tests for the mechanical characterization of the building stonework dated back to the 20’s – 40’s in the hospital complex in Volterra (Pisa) is presented. In particular, the Local Sanitary Company of Pisa (ASL 5) offered us the opportunity to have at our disposal a disused pavilion, which has to be demolished, on which to carry out a series of different on site tests (Fig. 1).

The characterization of this masonry type is crucial to assess the seismic vulnerability of most currently well-utilized buildings of the hospital complex.

1 Ph.D. Student, Department of Civil Engineering, University of Pisa, marco.andreini@dic.unipi.it
2 Assistant Professor, Department of Civil Engineering, University of Pisa, a.defalco@ing.unipi.it
3 Associate Professor, Department of Civil Engineering, University of Pisa, m.sassu@ing.unipi.it
The test site is a disused mental hospital dated back to 20's – 40's, the pavilion “Livi”, a three storey and "C" shaped masonry construction, with reinforced concrete bond beam at the roof levels. The masonry with chaotic texture is made up of rough sandstone and limestone blocks from various shapes and dimensions, rare pieces of clay bricks and poor lime mortar. Several destructive, semi-destructive and no destructive tests have been carried out: penetrometric tests (PNT-G) on the mortar, flat jack tests, diagonal compression tests and shear-compression tests on panels. The latter have been performed in two original versions, the Twin Panels Test (TPT), reported in [1], and the sliding test with flat jack, proposed by [2] and described in others further papers. The positions of the tests are shown in Fig. 1.

In order to understand the most basic resistance mechanism of masonry panels under compression and shear forces and to clarify some fundamental aspects regarding the parameters achievable from every technique, the interpretation of the results of every test method has been performed through the most conventional simplified models present in the literature. The interpretation of several on site tests allows us to identify a safety domain (shear – compression) for the panel, useful to calibrate simplified phenomenological or mechanical macro elements.

2. PNT-G TESTS PERFORMED ON THE MORTAR JOINTS

The PNT-G technique is an indirect no-destructive method to investigate the mortar load capacity in-situ, developed by [3], based on the recording of the energy amount required to bore a small cavity (4 mm diameter × 5 mm depth) in a mortar layer, with a lightweight device that is quite similar to a standard drill. This method can determine the in situ value of the compressive strength of the mortar, in absence of transversal stresses due to the confining effect of the blocks.

A great number of measurements has been performed on the mortar joints of the pavilions "Livi", "Baccelli" and "Biffi", in the zones where masonry texture and materials seem quite similar (Fig. 2). The average values of the compressive strength ($f_m$) of the mortar joints resulted equal to 0.83 MPa, 0.86 MPa and 0.93 MPa, with standard deviations of 0.32 MPa, 0.25 MPa and 0.48 MPa, respectively.

This fact confirms the close similarity between the masonry works of the three buildings and demonstrate the accuracy in the appreciation of the compression strength of the mortar joints, as well.
3. DOUBLE FLAT JACK TESTS

Several double flat jack tests have been performed in order to evaluate the compression strength and the deformation modulus \((E)\) of the masonry. Due to the chaotic texture and the non-homogeneity of the masonry, the test with double flat jack has been highly complicated regarding the wall-cuttings, the positioning of the measurement bases and the interpretation of the crushing failure. Moreover, in presence of a mortar highly vulnerable, the cooling water can wash away and weaken the material.

In Fig. 3 the most significant tests and results are presented. As it can be observed, the values of the compressive strength obtained are rather variable, from 0.81 MPa to 1.14 MPa, with tangent deformation modulus from 500 MPa to 850 MPa. The average values of the Poisson coefficient are about 0.5.

From the single flat jack test, the existing load at the base of the building has been deduced and is about 0.25-0.3 MPa.

![Fig. 3 a) Double flat jack test, b) and c) Resulting stress-strain curves](image1.png)

4. DIAGONAL COMPRESSION TESTS

Two diagonal compression tests have been executed on panels with dimensions of 120 cm x 120 cm x 50 cm, performed using wall saw with diamond blades. The loading system is presented in Fig. 4 and it is constituted by hydraulic jacks contrasting with pulley bars anchored on the corners. The measurement of the load have been performed by load cell, whereas the displacements on the diagonals have been measured by inductive transducers on both faces of the panel.

![Fig. 4 a) The layout of the test, b) Masonry panels after the test, c) Modulus G* vs. shear strain](image2.png)

The collapse load has been reached after several load cycles and the value is 87 kN and 75 kN for the specimens 1 and 2, respectively.

The interpretation of diagonal compression test has been performed according to RILEM standards, which assumes as reference state of stress the maximum principal (tensile) stress at the centre of the panel. According to this assumption, the value of the shear deformation modulus \((G^*)\) has been calculated from the ratio between shear stress \((\tau)\) in the centre of the panel corresponding to the collapse load and the shear strain \((\gamma)\) measured by diagonal transducers. Finally,

\[
G^* = 1.05 \frac{P}{A\gamma} \tag{1}
\]
In Fig. 4c $G^*$ versus $\tau$ is shown. It may be observed a noteworthy variability of $G^*$, from 1500 MPa to zero, and a different behaviour of the two panels, which however exhibit similar strength: the average values of shear stress attained at the collapse are 0.145 MPa for panel 1 and 0.125 MPa for panel 2. Moreover, in order to evaluate the tensile strength ($f_t$) of masonry, a methodology proposed in [4] has been adopted, where its value can be obtained with the following formula

$$f_t = \alpha \frac{P}{A}$$  \hspace{1cm} (2)

where: $\alpha$ is a coefficient derived from the results of detailed non-linear analyses and it is equal to 0.35 for rubble stone masonry.

In particular, the resulting tensile strength is equal to 0.05 MPa and 0.045 MPa for the two panels. Finally, following a particular interpretation, the diagonal test provides a value of the compressive strength, as well: a diagonal strut having a depth equal to that of the loading device can be detected within the panel. In the two cases the maximum compression at the collapse results 0.75 MPa and 0.65 MPa for panel 1 and 2, respectively, not so far from the previously obtained strength values.

5. THE TWIN PANELS TEST (TPT)

5.1. Test layout

The TPT test is a shear-compression test on masonry panels mutually contrasting. The method offers the possibility to compare the behaviour of twin specimens subjected to the same lateral load process and loaded by different vertical forces. The test has been carried out on specimens of about 120 cm × 120 cm × 50 cm, prepared using wall saw with diamond blades and loaded as shown in Fig. 5a. Two hydraulic jacks vertically placed on every panel applied the vertical loads thanks to a contrasting device equipped by pulley bars anchored on the underlying reinforced concrete bond beam (Fig. 5b). The lateral force has been applied by an hydraulic jack which has been placed at the half-height of the specimen, to avoid rocking in presence of low vertical loads (about 0.2-0.3 MPa) due to the low compressive strength of the material.

![Fig. 5 a) The loading system of the TPT, b) Global setting of the TPT, c) Panels with the instrumentation](image)

A measuring instrumentation, constituted by two pressure transducers for the vertical jacks, a load-cell for the lateral one and four inductive displacement transducers on every face of the panels has been employed.

Different vertical loads have been applied on the top of the panels and, at the same time, three series of cyclic lateral loads have been performed. Thanks to the first series it has been possible to assess the behaviour of the masonry far from the collapse of the panel and thanks the others series it has been possible to produce the crisis in the two specimens. Firstly, a vertical load of 240 kN, that is one half of the collapse load in compression, has been applied on the panel 1 and it has kept constant during the whole test, whereas a vertical load of 160 kN has been applied on panel 2. Successively, a series of cyclic lateral loads with increasing intensity up to 60 kN has been performed, without cracking or visible damages.
In turn, the specimen 2 has been completely unloaded and a different value of vertical load of 80 kN has been applied. With the second series of cyclic lateral loads the specimen 2 collapsed. In particular, when the lateral load overcome 35 kN, the panel started to rotate and the vertical load started to increase, due to the restraint performed by pulley bar. The first diagonal crack pattern appeared when the lateral load reached 70 kN. The test were stopped when the crack pattern increased considerably, and the loss of mortar fragments from the surfaces occurred, even if a substantial decrease of the load bearing capacity of the panel did not occur. The lateral and vertical loads at the end of the test were 80 kN and 150 kN, respectively.

Successively, the collapsed panel were supported laterally with metal struts, loaded with 300 kN, and used as a contrasting device. The panel 1, subjected to the third series of lateral loads, collapsed when the horizontal force and a vertical one were of 113 kN and 240 kN, respectively (Fig. 6). The crisis occurred with many diagonal cracks at the base of the panel which appeared for a lateral load higher than 90 kN.

5.2. Interpretation of the results

For both panels the ratio between horizontal and vertical load at the collapse is about 0.5, slightly higher for panel 2, and the crisis was well demonstrated by straightforward diagonal cracks without pronounced sliding. In Fig. 6a the crack pattern on the panels at the collapse is shown with a scheme of an hypothetical distribution of normal stresses.

![Fig. 6 a) Crack pattern and stress distribution for the two panels at the collapse, b) Panel 1 after the failure](image)

![Fig. 7 τ vs. γ for the two specimens during the first two series of lateral loads](image)

The scheme at the base of panel 1 has been calculated from the equations of the one-dimensional constitutive law for a no-tension material with limited compressive strength, developed in [5], taking into account the compressive strength of 0.8 MPa. As alternative interpretation, the different stress distribution which does not respect the hypothesis that the sections remains plane is reported below. In both panels the crisis occurred with crushing at the base, where the minimum principal (compression) stress attains the limit value for the material. This experimental evidence suggests a different possible evaluation of the shear strength, starting from the compressive strength which, in this case, should be the cause of the crisis.
In Fig. 7 the law shear stress vs. shear strain \((\tau - \gamma)\) is shown. At the first loading, until the average shear stress attains 0.06 MPa, both panels exhibit the same behaviour, although they were compressed by different vertical loads. Beyond the threshold cited before, the decrease of \(G\) for specimen 2 is well clear. This fact is more evident when the vertical load is 80 kN. In Fig. 8 the behaviour of \(G\) versus \(\tau\) is presented.

![Graph showing shear stress vs. shear strain for both panels under different loads](image1)

**Fig. 8** \(G\) vs. \(\tau\) for both specimens loaded with different vertical forces (line colours are referenced in Fig. 7)

At first, one can observe that as \(\tau\) increases, \(G\) strongly decreases, starting from values higher than 3000 MPa, to values lower than 100 MPa. Moreover, \(G\) increases with the vertical load, as already observed.

Moreover it can be observed that the shear stiffness of the panel increased from the first series of horizontal loads to the third one, although the vertical load remains constant. This fact appears clear in Fig. 9a, where the \(\tau - \gamma\) behaviour is presented for the specimen 1. So, generally, the assumption of a certain value of deformation modulus \(G\) requires the knowledge of the relative stress state.

In Fig. 9b the stress - strain law \((\sigma - \varepsilon)\) measured during the cycles of only vertical load is shown. It can be noticed that the behaviour is markedly linear and \(E\) is very similar for the two virgin panels, whereas is lower by 1/3 in the panel 2 after the application of the cyclic lateral loads.

In order to evaluate the shear strength, some considerations can be drawn for the two specimens. Regarding the specimen 1, the average value of the shear stress on the compressed zone of the section at the collapse is about 0.35 MPa. Interpreting the collapse with the sliding criterion, in sight of a friction coefficient 0.4, the value of the cohesion \(t_v\) is 0.053 MPa. For the specimen 2, from the above considerations, the value of the cohesion is 0.048 MPa.

As the collapse did not occur with sliding mode, the shear strength has not been reached for both specimens and the cohesion value is surely higher than 0.053 MPa.

Finally, one can note the high ductile behaviour of the shear stress-shear strain law presented in Fig. 9a and the great amount of the permanent deformations due to the shear forces during the cyclic loading.

![Graph showing shear stress vs. shear strain for both specimens under different loads](image2)

**Fig. 9** a) \(\tau\) vs. \(\gamma\) behaviour for the specimen 1, b) \(\sigma\) vs. \(\varepsilon\) law for both specimens
6. COMPARISON AMONG DIFFERENT TESTS

From the analysis of the obtained results, some preliminary conclusions on the capability of each test have been drawn. First of all, one note that the masonry with chaotic texture presents a noteworthy dispersion of values of mechanical characteristics, and this fact imply particular difficulties and uncertainty in the interpretation of tests. The double flat jack method allows an adequately reliable prediction of the compressive strength of the masonry, and, in this case, the results are in good accordance with the penetrometric PNT-G test on the mortar: the weak mortar strongly characterizes the behaviour of the masonry in compression, so the value of the strength of the mortar is similar to that of the whole masonry work. A good agreement has been found with the results of the diagonal test too, if it is interpreted as a compression test on the diagonal strut. The PNT-G test can thus be considered sufficient by oneself to roughly predict the compressive strength of the masonry with chaotic texture and poor mortar. Nevertheless, double flat jack test is not capable in this case to correctly evaluate the deformation modulus of the masonry. It can be demonstrated by the comparison of the obtained results with the TPT test ones. This fact is probably due to the non homogeneity of the wall, to the small size of the specimen, in addition to the damaging of the material caused by the wall cutting with water cooling. The TPT shear-compression test, which employs large size specimens, can perform the best identification of the mechanical characteristics of the real masonry panels with chaotic texture. In this case, the deformation moduli of the masonry (E and G) have been easily obtained, whereas the assessment of the shear strength involves many uncertainties: for this masonry with very high frictional resistance, the low compressive strength caused the crushing of the diagonal strut before the sliding of the panel. Only a pure shear test will allow us to achieve the actual value of the shear strength together with friction ad cohesion parameters. However The TPT test has highlighted some interesting features of the failure mode to be taken into account for further researches. The diagonal test in his turn, although it is difficult to be interpreted, has been capable to provide the value of tensile strength, that is useful to calibrate the diagonal cracking criterion. The value of the shear deformation modulus has been achieved in a roughly accordance with TPT test, too. Nevertheless in this case the diagonal compression test is not capable to provide the ultimate value of shear stress: the comparison with TPT test confirms this statement. It may be concluded that in the case of masonry with chaotic texture and poor mortar the low compressive strength always influences the failure mode and this fact has to be taken into account for the interpretation of different test methods.

7. A SAFETY DOMAIN FOR THE MASONRY PANEL

On the basis of the obtained results, a safety domain for the masonry panel can be drawn (Fig. 10), where the loading conditions of the TPT and the diagonal compression tests are collected and regarded from a global point of view.

![Fig. 10 Lateral-Vertical loads domain (V, N) for the masonry panel](image-url)
The selected parameters resulting from the tests allow us to build a graph lateral-loads ($F$) vs. vertical-loads ($N$), using the most common tools available in the literature. In particular, the failure criteria accounted for are sliding, diagonal cracking and crushing and are expressed by the curves which mark the border of the domain. Within the graph the equations of the curves are reported, where the lateral dimension ($d$) of the panel is equal to 120 cm, his depth ($t$) is equal to 50 cm, the distance of the application point of the lateral load from the base of the panel ($h$) is equal to 60 cm, the tensile strength ($f_t$) is equal to 0.053 MPa, the compressive strength ($f_c$) is equal to 0.8 MPa, the cohesion ($\tau_0$) is equal to 0.053 MPa and the friction coefficient ($\mu$) is equal to 0.4. In addition, the rocking failure has been highlighted.

As sliding failure has not occurred during the tests, the relative parameters have been estimated by exclusion. A new pure shear test will allow us to improve their estimation.

The domain can be further verified by the results that will be obtained by sliding test with flat jack on masonry panels whose size will be similar to those of diagonal and TPT tests.

8. CONCLUSIONS

Correct modeling of masonry panels under vertical and horizontal loads is of extreme importance for the evaluation of seismic safety of masonry structures. To this goal, the present paper furnishes a preliminary contribute for a reliable interpretation of the mechanical characteristics of a particular rubble masonry type through on site tests.

Other tests are scheduled in the near future. Further sliding test with flat jacks on panels [1] and pure shear test should improve the knowledge of the examined masonry and would allow us to further develop the roughly expressed concepts.

This further activity will make it possible to refine a safety domain for masonry panels with chaotic texture, that will be useful to calibrate adequate simplified models for the seismic evaluation of masonry buildings.

ACKNOWLEDGEMENTS

The authors acknowledge the Consortium RELUIS AT1.1. with Dept. of Civil Protection together with Tuscany Region and Local Sanitary Company of Pisa (ASL 5) for sponsorship and support activities.

REFERENCES