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An innovative testing equipment for on-site stress measurement: an application to the monumental masonry building

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ABSTRACT: Masonry is one of the oldest building materials but also one of the least understood. Dealing with brick masonry structures, the problem of mechanical characterization is not easy to solve, because of the considerable heterogeneity of these structures. In the last few years the attention has been focused on the non-destructive in situ test techniques, based on the use of the special flat jacks capable of reading the deformability proprieties of the existing masonry building and thus, the stress which they undergo. This work is meant to provide an alternative equipment for the measurement of the in situ stress inside the masonry structures. It consists in the realization of a cylindrical instrument whose peculiarity consists in its small dimensions which permit us to carry out very low invasive tests.

1 INTRODUCTION

The methodological approach adopted for the analysis of the static conditions of the existing or monumental masonry structures can be carried out only with a deep knowledge of both physical and mechanical characteristics of the components to which the structural functions are given. This approach foresees a preliminary series of analysis based on a first recognition of the conservative state of the structures (cracks, geometry, damage etc.) which it has undergone during its operating life. The second step regards instead a special investigation to determine the right parameters for the definition of the static behavior of the building. Many investigations use some non-destructive tests which have the advantage of being very simple but not enough to solve the structural problem (Binda, 1999). The results in fact, give some interesting data in terms of homogeneity of the masonry. Thus, the use of some destructive tests represents the only way of obtaining some good information of the right parameters that govern the static behaviour of the structure. One of the most common tests, capable of giving the parameters of deformability, is based on the use of flat jacks. This technique permits us to know the exiting solicitation state, the characteristic of deformability and resistance to compression of the whole masonry. This test is based on the stress release caused by the plane cut realized on the masonry. In the slot obtained from the cut a very flat jack (Binda 1997) is inserted and the pressure is gradually increased inside the jack to nullify the deformation measured during the cutting phase. The obtained value of pressure, corresponding to the stress solicitation inside the wall, must be manipulated by means of a coefficient which takes into account the ratio between the jack and cutting print, as well as the influence of the welded border. The proposed technique is based on the same idea of the flat jack but it uses a different equipment whose shape seems to be much less invasive, as well as much simpler to perform, if compared to the previous one.

2 THE BASIC IDEA FOR THE DILATOMETER DESIGN

The regular shape of the instrument capable of restoring the stress in the analysed element of masonry was obtained by studying a block undergoing a load orthogonal to its medium plane. This aim can be reached by using a steel cylinder divided into three different pieces by means of the oblique planes, as shown in following picture.

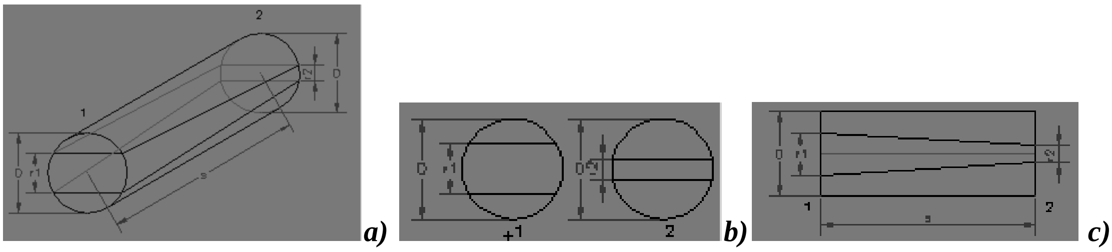


Figure 1. Shape of the proposed dilatometer a) axonometric; b) frontal section; c)lateral section.

The stress inside the hole is generated by sliding the central piece in respect to the others. Obviously the generated stress must be equal to the undisturbed sample. To obtain this a numerical investigation by F.E.M. was previously carried out on a 3-D block. Firstly an intact sample was analysed, then the same sample was studied when a hole was made, finally a distributed load was applied inside the hole in order to restore the original stresses.

The dimension of the instrument has been planned by referring both to the stress state which the dilatometer undergoes and the traction force that must be applied in order to generate the original stress condition of the intact block. Only some dimensions are fixed presumptively whereas the others depend on the loads in play. During the design phase we must also consider that on the proposed instruments, some frictions forces, caused by the sliding of the cylinder surfaces that move each other, will occur. This action can be calculated as the vertical component of the load acting on the instrument by means of a particular coefficient of friction whose value varies from 0.010 up to 0.025 because the material used is steel.

By choosing to refer to a block with a hole of 25 mm in diameter and by fixing both the radius r_1 on section number 1 and the depth s of the hole equal to 50 mm, the only dimensions to determine are the α angle (the inclination of the plane along which the cylinder must be cut) and the r_2 dimension on section number 2. These unknown dimensions are connected to each other by a geometrical relationship depending on the shape of the dilatometer and reported in (1):

$$r_2 = r_1 - 2s\tan\alpha \qquad (1)$$

For the α definition we consider the equilibrium condition which is written by referring to the scheme of figures 3. If each piece of the cylinder is analysed (figures 4-5) by applying the resultant of the whole distributed load acting on it, the equilibrium condition gives:

$$\frac{F}{2}\cos\alpha = Q\,\mathrm{sen}\,\alpha + f_a Q\cos\alpha \qquad F = 2Q(\tan\alpha + f_a) \quad \text{where} \quad \begin{array}{l} F_a = f_a Q\cos\alpha \\ f_a = 0{,}10 \div 0{,}25 \end{array} \qquad (2)$$

The same results can be obtained by using the principle of virtual work as reported in (2):

$$\frac{F}{2}x = Qy + F_a z \Rightarrow \frac{F}{2}x = Qx\tan\alpha + f_a Q\cos\alpha\frac{x}{\cos\alpha} \Rightarrow F = 2Q(\tan\alpha + f_a) \qquad (3)$$

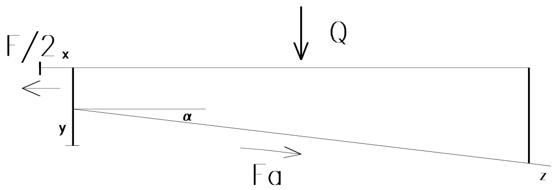


Figure 2. Equilibrium on the upper piece of the cylinder

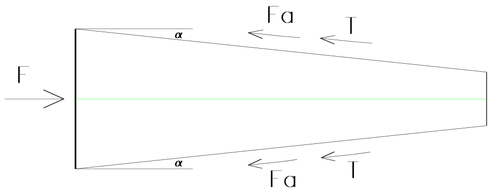


Figure 3. Equilibrium on the central piece of the cylinder

$$F = 2Q(\tan\alpha + f_a)\frac{A_r}{A_t} = 2qs(\tan\alpha + f_a)\frac{A_r}{A_t} \tag{4}$$

3 EXPERIMENTAL INVESTIGATION

In order to calibrate the proposed instrument, firstly a test is carried out on a brick of calcareous stone. In the second part the dilatometer will be tested on a wallet sample and the data obtained were compared with the results obtained from a flat jack test carried out on the same sample.

3.1 Tests On The Calcareous Stone Block

The block was 182.2 mm at the base (b), 340.2 mm in height (h); and 137.9 mm in thickness (s). The compression test, carried out on the instrumented sample up to a normal stress equal to 3.0 N/mm^2, permitted us to know the mechanical characteristic of the sample as: E_0=6683 N/mm^2; initial module of elasticity, E_1=4044.7 N/mm^2 tangent module of elasticity; ν= 0.23 Poisson's module (Anania 2012).

Figure 4. Dilatometer view inside the brick hole

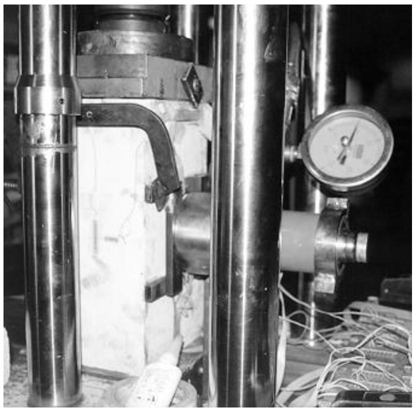


Figure 5. Setting of the test on the masonry

Once these characteristics are known, the brick was instrumented by strain gauges located along the horizontal, vertical and 45° direction. The latter were placed on the four points under observation with co-ordinates in respect to the hole centre of x=±21.6 mm and y==±21.6 mm. Previously the numerical analysis discussed before was repeated for the analysing block by introducing the right dimensions and the real mechanical parameters of the tested material. The numerical investigation gave back a distributed load on the hole of 2.175 N/mm^2. During the experimental phase the brick had a distributed load on the upper surface equal to 2.0 N/mm^2 and the related distribution of the stresses were recorded in the four points chosen for the observation. The numerical and experimental data are very close. Consequently a calibrated hole with a diameter of 25 mm was made for a depth equal to 60 mm. Then a new test was carried out by measuring the solicitation state in the four chosen points, under a distributed load of 2.0 N/mm^2. Finally, the proposed instrument was inserted in the hole as shown in picture above (figure 6). The traction force capable of restoring the original stress condition was applied by the pull-out machine (figure 7).

3.2 Tests on a masonry panel

A masonry panel was used for the test. The data obtained from this investigation were compared with those given by the flat jack test (ASTMC 1196, 1991).. The masonry wallet is constituted by calcareous stone 70x70x105 mm^3 in dimension, as bricks and mortar 15 mm thick. The total dimensions of the tested wallet were 740 mm at the base 1250 mm in height and 240 mm in thickness. A hydraulic jack was placed on the upper surface in order to simulate the real operating load caused by weight acting on it during its lifetime. The applied load was of 350 kN distributed by means of a steel beam. Some tests capable of giving the mechanical characteristics of the wall were carried out on the instrumented panel. The elasticity module obtained was E_1=3581.8 N/mm^2. Then, the flat jack test was carried out, and the pressure necessary to lead the wall to the original condition was equal to 4 N/mm^2. This value must be multiplied by two corrective coefficients depending respectively on the ratio between jack area and cut area (k_1=0.78) and on the jack calibration (k_2=0.78) by (5):

$$\sigma = k_1 k_2 p \tag{5}$$

that gives back a pressure of 2.4 N/mm^2. For the second part of the investigation the flat jack was replaced by the proposed dilatometer. For this scope some omega transducers capable of measuring the vertical displacement of the brick-mortar set were added and other strain gauges for the deformation control were placed very close to the hole. The traction force to be applied to the proposed instrument in order to regenerate the original deformative condition is equal to 3.5 kN against the numerical values that vary from 0.8774 kN (fa=0,1) up to 1.52 kN (fa=0,25).

Figure 6. Flat jack test on the masonry

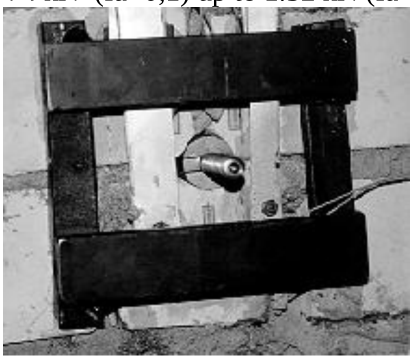


Figure 7. Dilatometer test on the masonry

3.3 Analysis of the results

The difference between numerical and experimental investigation must be deleted by introducing the corrective coefficients in analogy to the flat jack investigation. So, we define k_1 as the ratio between the lateral surface of the dilatometer (A_D) and the lateral surface of the hole (A_F) k_2 as the ratio between effective contact area (A_{Deff}) and theoretic area of the instrument (A_{DTheor}), the correct formula for the evaluation of the stress condition inside the tested sample is given by the (6):

$$\sigma = \frac{F * k}{2 * A_D(\tan\alpha + f_a)} \tag{6}$$

By applying this expression and considering a friction coeff. of 0.15, we obtained the table 1:

Table 1. Data obtained from the tests revised by using the corrective coefficients

	K1	K2	Traction force (kN)	Stress [N/mm^2]
Test on the Brick	0,56	1	2.5	2.42
Test on the masonry	0,53	1	3.5	2.40

The expression (6) does not depend on the material used nor on the sample dimensions and it can give results very close to the numerical ones although they are slightly higher. This fact is due to the choice of the friction coefficient whose value should be determined experimentally. The data correction is greater in the case of masonry test because it is more difficult to make a calibrate hole. In fact, also in the case of the flat jack test the experimental data must be corrected by introducing coefficients similar to the dilatometer ones.

4 AN APPLICATION TO A MONUMENTAL BUILDINGS

Once the innovative instrument was calibrated, it was used in the real structures. It was applied in the "Chiesa del Colleggio" a monumental baroque Sicilian church, in Caltagirone (CT) opened for worship by the Jesuits in 1593, and rebuilt after the earthquake of 1693. The interior has a nave with deep chapels.

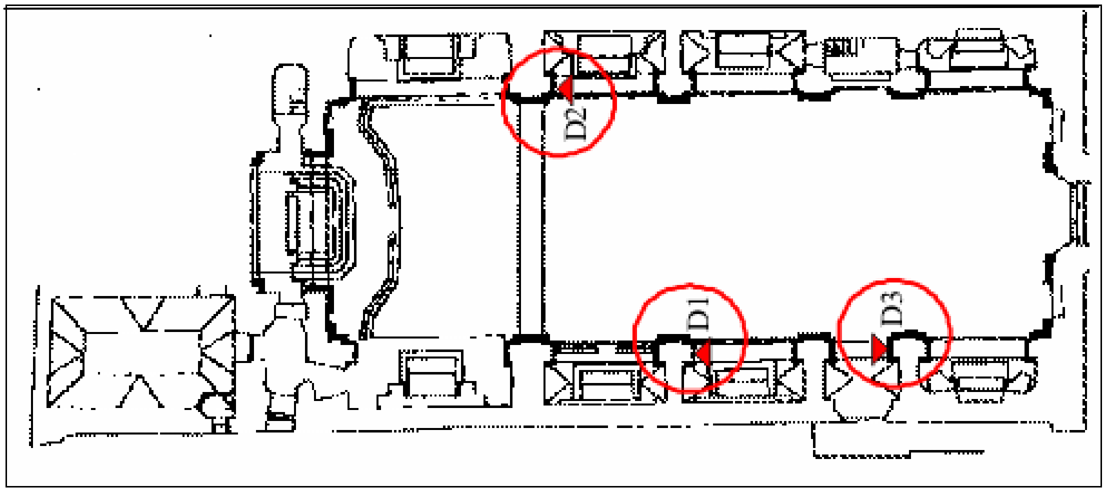


Figure 8. Chiesa del Colleggio" Test points

The aims of the investigation were to assist the designers in understanding the safety level of the monumental building as well as to suggest the most adequate techniques for the intervention, on the basis of the laboratory tests on original materials and structures and also in terms of the characteristics of the new materials for repairing. The aim of the tests were to define the state of stress in compression on the external leaf at the bottom of a pillars. The test points are reported in Fig 8 . The D1" test was located in two mortar bed joints higher respect to a previous flat jack location in order to compare the methodologies applied. The arrangement of the strain gauges was aimed at the evaluation of the stress state around the investigated point. But if the principal strains, principal directions or the elastic modulus of the material are to be evaluated, it would be necessary to orchestrate the hole with rosettes to 120 or 45 degrees.

Figure 9. Strain gauges disposition around the point to be investigated

Figure 10. Point test instrumentation sequence

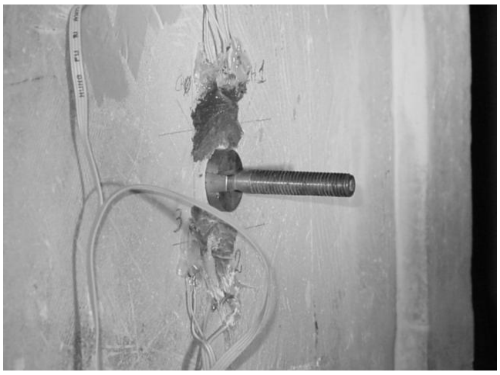


Figure 11. Instrument disposition in the hole and test equipment for the load measurement

4.1 Test on pillar D1

The load strain diagram is plotted in fig 11. Then, it is possible to determine the vertical stress corresponding to the load applied using the equation [6]. The data obtained is reported in table 2. From the examination of the load history the most probable value of in situ vertical stress in the investigated element, is the one corresponding to the tensile force F equal to *2,30 kN* (Fig.10), and so it will be equal to *1,45 N/mm²*. In this case, it was:

$K = K_1\ K_2 = 0{,}48$; $K_1 = A_R/A_F = 0{,}60$; $K2 = A_{Deff}/A_{Dteo} = 0{,}80$

A_D= plan contact surface = 10,70 cm^2

A_R = real contact surface = 10,05 cm^2

A_F= hole real lateral surface = 16,50 cm^2

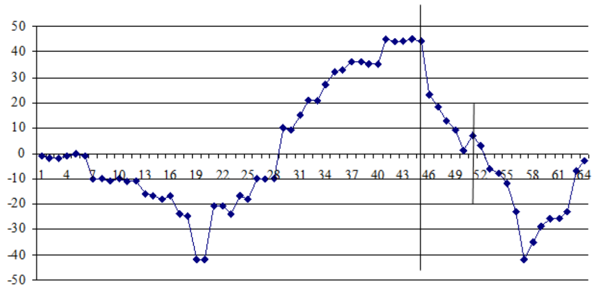
A_{Deff}= effective plan contact surface of the device;

A_{Dteor}= Theor. contact surface in plane ;

$Tan\ \alpha = 0{,}105$; $F_a = 0{,}25$

Load Applied [kN]	σ_y [N/mm^2]
0,75	0,469
1,52	0,961
1,91	1,206
2,69	1,697
1,52	0,961
2,30	1,452
2,69	1,697
3,08	1,943

Table 2. Data obtained on D1 pillar



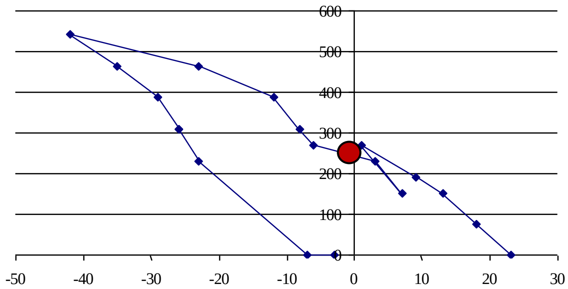


Figure 12. Load history during the hole drilling in terms of strains (vertical axes) vs number of readings

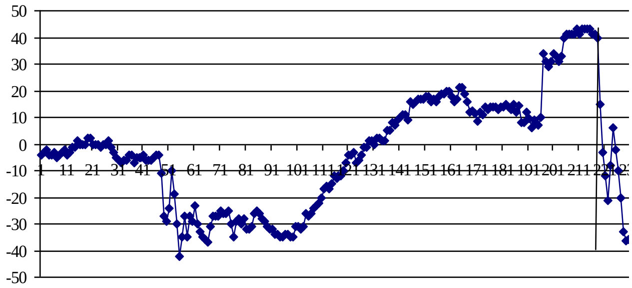
Figure 13. Load [kN] strains [μm/m] curve for SG1 in D1 pillar

4.2 Test on pillar D2

The load strain diagram is plotted in fig 13. At that point, it is possible to determine the vertical stress corresponding to the load applied using the equation [6]. The data obtained is reported in table 3 From the examination of the load history the most probable value of in situ vertical stress in the block investigated, is the one corresponding to the tensile force F equal to *1,30 kN* (Fig.11), and is equal to 0,*65 N/mm²*. But this test was not very reliable since the pillar without rendering was badly cracked and it was impossible to set the test in a good position so that the displacements calculated after drilling was not all recovered during the test.

Load Applied [kN]	σ_y [N/mm^2]
1,52	0,762
2,30	1,152
2,69	1,347

Table 3. Data obtained on D2 pillar



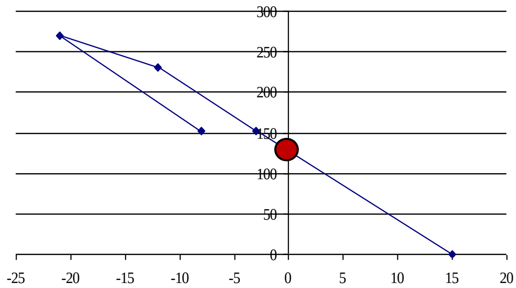


Figure 14. Load history during the hole drilling in terms of strains (vertical axes) vs number of readings

Figure 15. Load [kN] vs strains [μm/m] curve for SG1 in D2 pillar

4.3 Test on pillar D3

The load strain diagram is plotted in fig 12. Then, it is possible to determine the vertical stress corresponding to the load applied using the equation [6]. The data obtained is reported in table 4. From the examination of the load history the most probable value of in situ vertical stress in the block investigated, is the one corresponding to the tensile force F equal to *3,08 kN* (Fig.12), and so it will be equal *to 1,76 N/mm²*. In this case, it was:

$K = K_1 \; K_2$ =0,44; $K_1 = A_R/A_F$ =0,56; K2= A_{Deff}/A_{Dteo}=0,80

Load Applied [kN]	σ_y [N/mm^2]
1,52	0,869

A_D= plan contact surface = 10,70 cm^2

A_R = real contact surface = 9,40 cm^2

A_F= hole real lateral surface = 16,50 cm^2

$Tan\ \alpha = 0{,}105;\ \ F_a = 0{,}25$

1,91	1,091
2,30	1,314
2,69	1,536
3,08	1,758
4,02	2,291
4,64	2,647

Table 4. Data obtained on D3 pillar

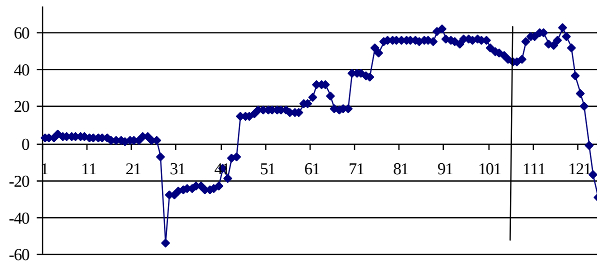


Figure 16. Load history during the hole drilling in terms of strains (vertical axes) vs no. of readings

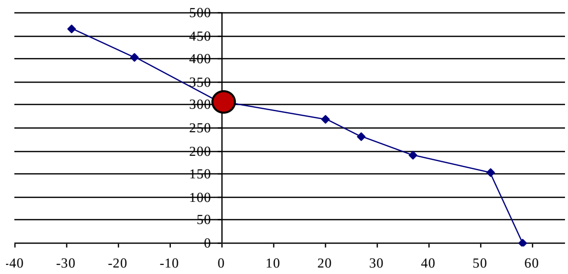


Figure 17. Load [kN] vs strains [μm/m] curve for SG2 in D3 pillar

5 CONCLUSIONS

One of the most important steps in the retrofitting of masonry structures regards special investigation to determine the right parameters for the definition of the static behaviour of the building. For this reason some destructive test represents the only way of obtaining good information of the right parameters in play capable of allowing the designers to make the right choice. In this paper a new instrument for the evaluation of the in site stress condition, calibrated and applied to a real structure, was proposed. The results obtained, compared to similar procedures as that of the flat jack one, permit us to say that the proposed instrument seems to be much more simpler to use and overall it gives a less invasive tests respect to the flat jack. Besides it can be applied not only to masonry structure but also to concrete or stone elements. Its application in the monumental structure was capable of catching the real stress conditions in the vertical direction acting on the stone blocks that form the pillars of the Church of the College in Caltagirone. In fact the stresses recorded in D1 and D3 pillars seem to be almost homogenous and they show a good quality of the brick material investigated. The results obtained in D2 pillar have shown a lower strength due to the presence of some cracks. The latters produce a partial unloading in the nearby of the damaged element and then, a redistribution of the strength in a new configuration of equilibrium.

6 REFERENCES

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