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Flat jack test for the analysis of mechanical behaviour of brick masonry structures

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FLAT-JACK TEST FOR THE ANALYSIS OF MECHANICAL BEHAVIOUR OF BRICK MASONRY STRUCTURES

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ABSTRACT The paper presents a non destructive testing technique developed by ISMES to determine the state of stress and deformability characteristics of brick masonry structures. The reliability of the test, which is based on the use of special flat-jacks, has been studied by means of calibration tests carried out at laboratory on large size samples. Some examples of application of flat-jack test are briefly presented.

1. INTRODUCTION

The study of the mechanical characteristics of the materials plays a rôle of primary importance in the design of static restoration of old buildings. Dealing with brick masonry structures, the problem of mechanical characterization is not easy to solve, given the considerable heterogeneity of these structures, which consist of layers with high mechanical properties alternated with more deformable layers. Only mechanical tests carried out on undisturbed masonry samples of large dimensions (including at least 4 - 5 mortar layers) could lead to a reliable appraisal of the main mechanical properties. Since the sampling of masonry having such dimensions is often impossible because of the historical interest of the building in question, the research has to be turned to the development of non-destructive mechanical testing techniques.

An important contribution in this field has recently been given by ISMES with the setting up of a non-destructive "in situ" test technique based on the use of special flat-jacks, having small thickness, which are set into the mortar layers. This testing technique makes it possible to determine in situ deformability properties of undisturbed masonry specimens of large dimensions, thus avoiding the sampling. It also makes it possible to acquire another important information concerning the static behaviour of the structure: the measure of the state of stress existing in the testing point.

An extensive series of calibration tests carried out at ISMES laboratories, in collaboration with ENEL's Research and Study Department, made it possible to ascertain the high reliability of the testing technique described in this paper.

This technique has recently and successfully been used to solve many problems relevant to static restoration of buildings having great historical and monumental interest and to check the static conditions of old masonry structures, such as dams, bridges and tunnels.

2. FLAT-JACK TESTING TECHNIQUE

The non destructive test described in this paper is based on the use of thin flat-jacks placed into the mortar layers. This is a well-known testing technique for the determination of the mechanical properties of rock masses. The test is carried out in two separate phases:

2.1 Measurement of the state of stress (1st phase)

The determination of the state of stress is based on the release caused by a plane cutting, normal to the surface of the wall. Fig 1 shows the different phases of the test: two measuring points are installed on the wall surface and the initial distance (d_i) between the two points is read. Then a cut normal to the wall surface is made (2) and the stress release determines a closing of the cutting, the distance (d) after the cutting being $d < di$. A special thin flat jack, is set inside the cutting and the pressure is gradually increased up to cancelling the previously measured convergency (3). In this condition, the pressure p inside the jack is equal to the pre-existing state of stress σ in a direction normal to the plane of the cutting. The value obtained must be corrected by a coefficient which depends on the ratio between flat-jack and the cutting surface and on the rigidity of the welded boundary of the jack.

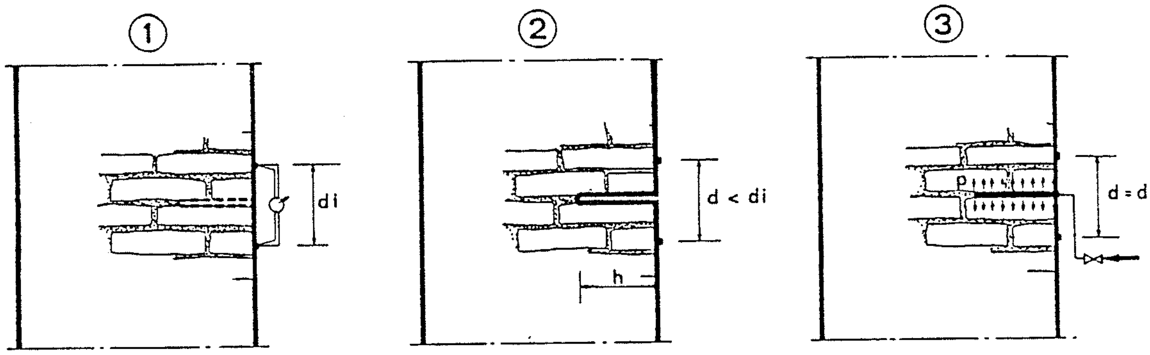

Fig. 1 Scheme of flat-jack test

Two different jack sizes have been considered: 40 x 20 cm and 24 x 12 cm

In brick masonry, the plane cutting can easily be made at the mortar layer between two courses of bricks by means of simple tools.

2.2 Determination of deformability characteristics (2nd phase)

In homogeneous isotropic material, the test described at point 2.1 can also be used to determine the deformability characteristics. In the case of brick masonry, which is a highly anisotropic material, it is advisable to introduce some changes in the testing technique. For this purpose, a second cutting is made, parallel to the first one, and a second jack is set in it. The two jacks delimit therefore a masonry sample of appreciable sizes (40x40x20 cm) to which they apply a uniaxial state of stress (Fig. 2). Several measurement bases for removable mechanical strain-gauge installed on the sample free face make it possible to obtain a full picture of axial and transverse deformations of the sample. In this way, a uniaxial compressive test is carried out on undisturbed sample of large size which is certainly representative of the behaviour of the structure as a whole.

The testing technique proposed is certainly non-destructive because, after the test is completed, the jack set in the masonry can easily be removed and the mortar layer restored to its original condition. The instrumentation (mechanical strain-gauge) and the loading equipment are very simple and their rapid installation makes it possible to carry out a complete test (1st and 2nd phase) in about 7-8 hours.

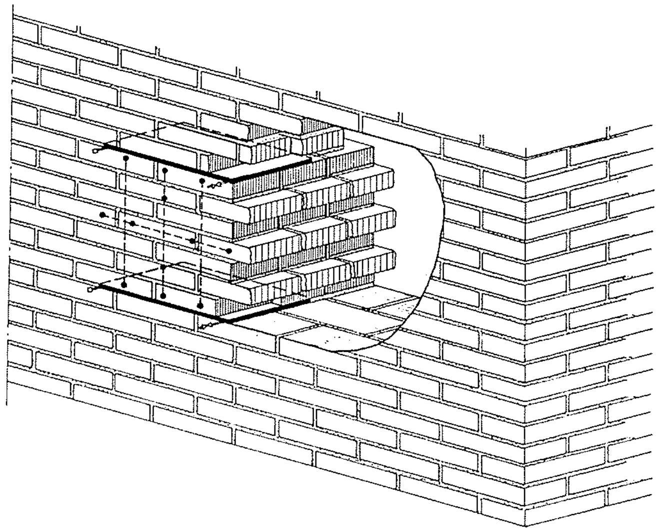

Fig. 2 Deformability test with two flat-jacks

The loading with two jacks can also be used to evaluate the strength limit of the masonry by increasing the load up to appearance of the first cracks in the bricks. A last but not least advantage of the test consists in the possibility of using flat jacks as pressure-cells during the restoration works, in order to control any change of the state of stress.

It must be pointed that the masonry sample on which the uniaxial test is carried out is confined on three sides and free on the fourth one, therefore some difficulties arise in the interpretation of the results. For this reason a wide program of calibration tests is being carried out at the laboratory on brick masonry samples in order to evaluate the reliability of the flat-jack test in different loading conditions.

3. CALIBRATION OF FLAT-JACK TEST BY PHYSICAL MODELS

The calibration of flat-jack testing technique has been carried out on large-size brick masonry specimens built in the laboratory.

A mortar having the following weight composition was used:

Siliceous sand	56.6%
Pozzolana	23.5%
Air-hardening lime	5.9%
Water	16.0%

The average value of mortar uniaxial compressive strength, determined on 10x10x10 cm specimens is equal to 3.7 MPa after 28 day curing. This value rises up to 6.3 MPa after 60 day curing and is stabilized at 10.5 MPa after 180 day curing. The mortar was placed with 1.5 cm thick layers to prepare masonry specimens.

Hand made bricks, 12x25x6.25 cm in size were used. Their mechanical properties were as follows:

- Uniaxial compressive strength = 12 - 16 MPa
- Young's modulus = 4.000 - 5.000 MPa

Specimens of different size were manufactured in the laboratory:

A	150 x 150 x 50 cm
B	25 x 25 x 25 cm
C	25 x 25 x 50 cm
D	50 x 50 x 25 cm

Type A specimens were used for calibration of flat jack test whilst specimens B, C and D aimed at furnishing a more complete mechanical characterization of the masonry used. Uniaxial compression tests were carried out on these specimens after 180 day curing to determine deformability and strength properties. All masonry samples were cured under the following conditions: temperature = 20° ± 2°; relative moisture = 68 - 75%.

Type B and C specimens were used to study strength properties of masonry. The average value of uniaxial compressive strength determined after 180 days on type B specimens was equal to 11 MPa, whilst the strength obtained on 50 cm-hight specimens (type C) was equal to 9 MPa. A remarkable effect of the specimen shape on the uniaxial compressive strength values may be notice. Fig 3 shows, for type B and C specimens, the curves of axial and transversal deformations versus axial stress.

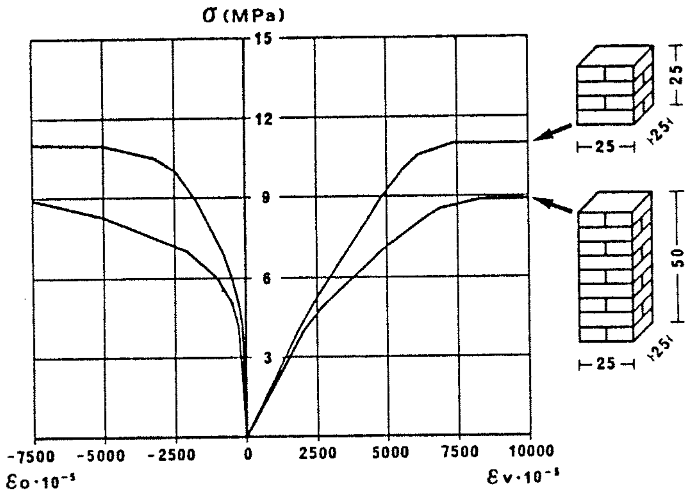

Fig. 3 Stress-strain curves obtained on masonry specimens of different size (B and C)

The values of the ratios between deformability modulus E and the uniaxial compressive strength σ_c, were equal to:

$$E/\sigma_c = \begin{cases} 254 & \text{for type B specimens} \\ 320 & \text{for type C specimens} \end{cases}$$

Deformability characteristics of masonry were studied in detail directly on the large size specimens (type A) and on type D spècimens which present nearly the same dimensions of the masonry specimen delimited by the two jacks (see point 2.1).

The deformability moduli values, determined on type A (E_A) and on type D (E_D) specimens, are reported in Table 1 for different stress levels.

$\Delta\sigma$ (MPa)	E_A (MPa)	E_D (MPa)	$\frac{E_A - E_D}{E_A}$ %
0.0 ÷ 0.5	1800	1850	-2.7
0.5 ÷ 1.0	2200	2100	+4.5
1.0 ÷ 1.5	2800	2650	+5.3
1.5 ÷ 2.0	3200	3050	+4.7

TABLE 1 Deformability moduli determined on A and D specimens

A good agreement between the values of moduli E_A and E_D my be noticed, with differences contained within 5%.

Fig. 4 shows loading and measuring equipment for calibration tests on type A specimens. The axial stress component is applied to the wall by means of hydraulic jacks and deformations are measured on the specimen faces through special electrical strain gauges connected to an automatic data acquisition and processing apparatus.

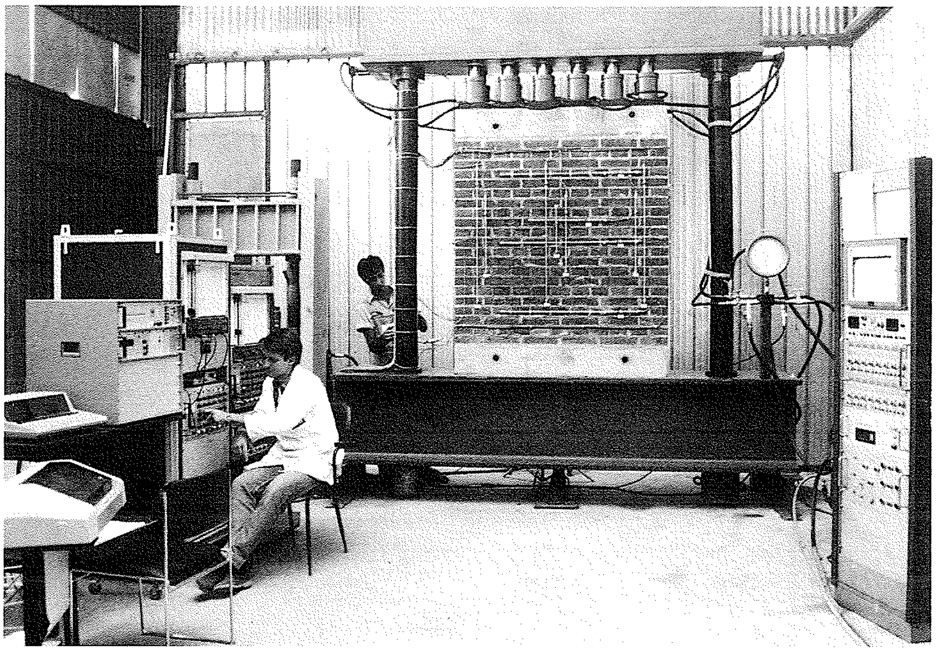

Fig. 4 Loading and measuring equipment used for the calibration of flat-jack test

3.1 <u>Calibration of 1st phase testing: measure of the state of stress</u>

Test was carried out by applying a known state of stress to the specimen wall, and comparing this value with that which was determined at the wall center by flat jack testing.

Calibration was carried out on three walls to which stress states (σ_a) equal to 0.75, 1.5 and 2.25 MPa, were respectively applied. The values of the state of stress measured on the three walls by flat jack (40x20 cm) are reported on Table 2 and compared with the values of the stress applied.

N°	σ_a (MPa)	σ_m (MPa)	$\frac{\sigma_m - \sigma_a}{\sigma_a}$ %
1	0.75	0.66	-12.0
2	1.50	1.55	+3.3
3	2.25	2.16	-4.0

TABLE 2 Comparison between applied and measured state of stress

It may be noted that the agreement between measured and applied stresses is quite good. The difference is slightly over 10% for low stress levels and decreases to 3 - 4% for stress levels between 1.5 and 2.2 MPa. The reliability of testing technique to determine the stress state may thus be considered entirely satisfactory.

A fourth wall was used for the calibration of the test by flat jack of lower size (24x12 cm). A stress σ_a = 1.5 MPa was applied to this wall and a stress σ_m = 1.61 MPa was measured, the difference being equal to 7.3%. It can be observed that the lower size jack is also suitable for providing reliable measurements of the state of stress.

Deformations around the flat jack were carefully studied during the tests, both during the cutting and the reloading phases (see fig. 5 which shows the deformation diagrams relevant to test 3). It is safe to say that the diagram of deformations on the reloading phase faithfully follows

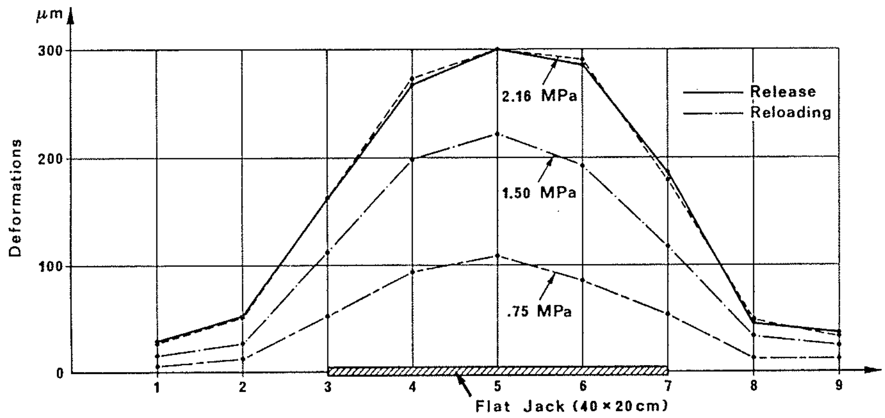

Fig. 5 Comparison between deformations in release and reloading phases (stress applied and 2.25 MPa)

the diagram plotted on the release phase. The good agreement of deformation behaviour between release and reloading phases is also noted at the two sides of the jack.

3.2 <u>Calibration of the 2nd phase: determination of deformability characteristics</u>

After the 1st phase was carried out, a second flat jack was installed for the calibration of the 2nd testing phase (Fig. 6). Test was performed at stress levels up to 2.0 MPa, using both 40x20 cm and 24x12 cm flat jacks. Fig 7 shows load-deformation diagrams relevant to the two different types of jacks. Values of deformability modulus E' (relevant to 40x20 cm jacks) and E" (relevant to 24x12 cm jacks) are compared in the Table 3, for various stress levels, with the values of deformability modulus determined on specimens A by conventional uniaxial test.

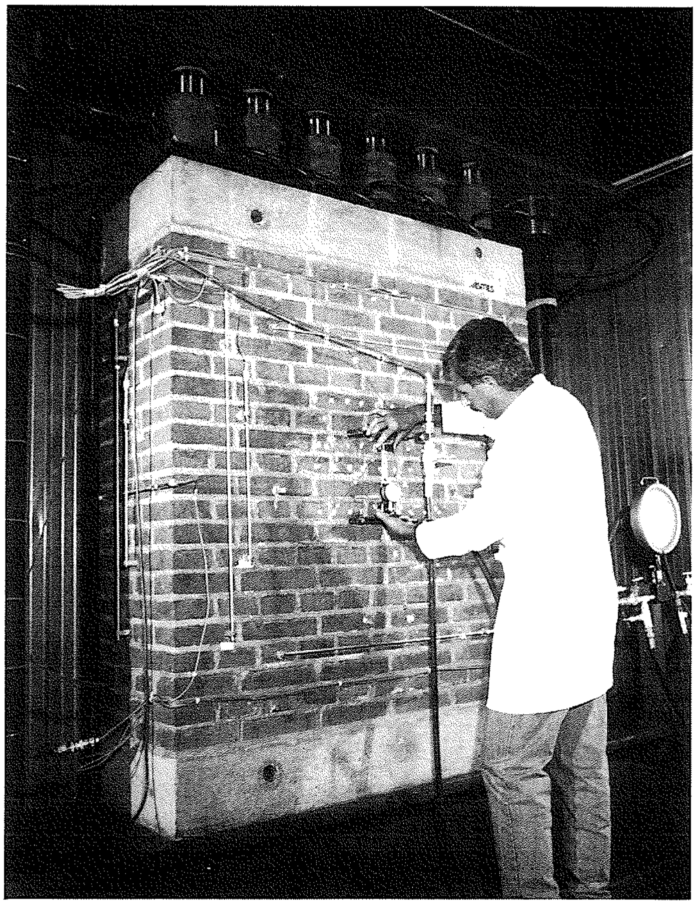

Fig. 6 Calibration of the testing technique for the determination of deformability characteristics

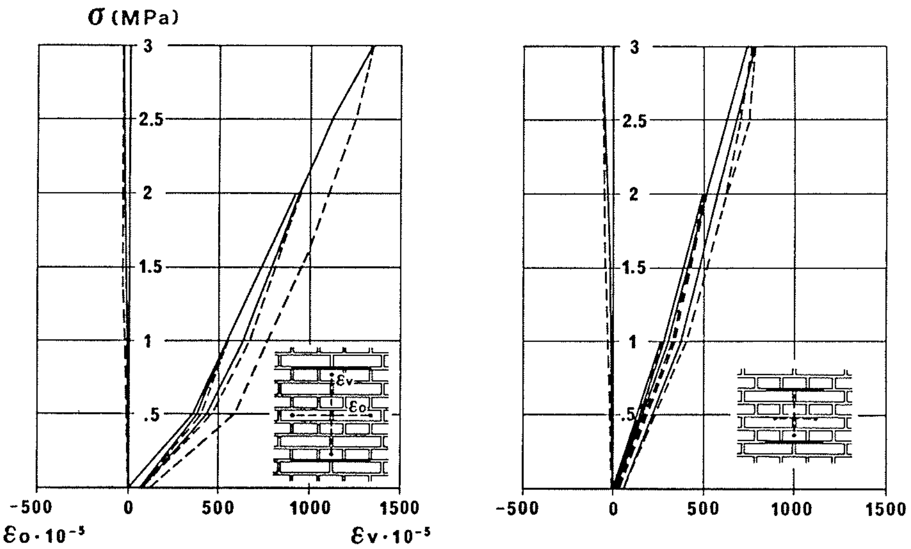

Fig. 7 Calibration of the test with two flat-jacks for the determination of deformability characteristics. Stress – strain curves obtained by jacks 40x20 cm (a) and 24x12 cm (b)

Comparison between deformability modulus E" obtained with 40x20 cm jacks and modulus E_A values is completely satisfactory, the differences being contained within 9%. Very high are, on the contrary, the differences between the values of modulus E_A and those of modulus E" determined by flat jack of lower size. This is certainly to be ascribed to the fact that the masonry sample interposed between the two jacks has a few layers of mortar and therefore it is not representative of the overall behaviour of the masonry. Calibration test made it, therefore, possible to ascertain that 40x20 cm flat jacks furnish reliable responses concerning both the measure of the state of stress and the determination of deformability properties, whilst the use of flat jacks of lower size must be limited to the measure of the state of stress.

$\Delta\sigma$ (MPa)	E_A (MPa)	E' (MPa)	E" (MPa)	$\frac{E'-E_A}{E_A}$ %	$\frac{E''-E_A}{E_A}$ %
0.0 ÷ 0.5	1800	1750	3900	-2.8	+116
0.5 ÷ 1.0	2200	2400	3900	-9.1	+77
1.0 ÷ 1.5	2800	3000	4300	+7.1	+53
1.5 ÷ 2.0	3100	3300	4500	+6.4	+45

TABLE 3 Comparison between deformability moduli (E', E") determined by flat-jacks (40x20 cm and 24x12 cm respectively) and those determined by conventional compression test on specimens A

Experimental investigation for the calibration of testing technique is still being carried out at ISMES laboratory. A series of tests on masonry samples having much poorer mechanical properties is devised, also varying the thickness of mortar layers. Tests will also be completed to verify the suitability of the jack to work for long periods as pressure cell during consolidation work.

4. EXAMPLES OF APPLICATION OF FLAT-JACK TEST

In the past few years this technique was successfully used to study many static restoration problems concerning buildings of historical and monumental interest and to check static conditions of old masonry structures.

4.1 Static restoration works

4.1.1 "Palazzo della Ragione" - Milan

The XIII century building underwent important changes during the XVIII century to house the Notaries' Archieve. Because of the overloads induced by the Archieve, some cracks occurred in the bearing structures of the building. Before consolidation work was planned, a set of tests by flat jacks was carried out to analyse the static behaviour of bearing structures involved by cracks.

4.1.2 "St. Eustorgio Cloisters" - Milan

The construction of the first cloister dates back to the first half of the 13th century; the construction of the second one started in 1380. Both cloisters, were repeatedly damaged and restored in the following centuries during Spanish and French domination, and rebuilt in 1600. After that time, they underwent further damages and rehabilitations, the latest of which in 1950.

Interesting measurements of the state of stress were performed not only on vertical masonry structure, but also on cross vaults and on the "pulvino" above the columns (Fig. 8).

Fig. 8 Determination of the state of stress on a "pulvino" of "St.Eustorgio Cloisters" Milan

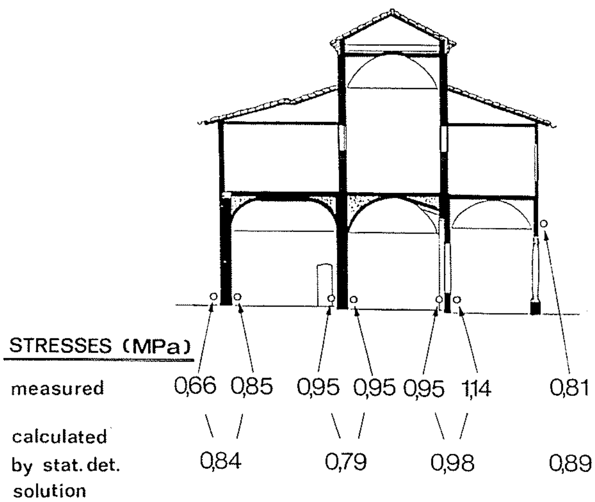

Fig. 9 " St. Eustorgio Cloisters" Comparison between measured and calculated stresses on a transversal section

As an example Fig. 9 shows the comparison between the values of the stresses measured by flat jacks on a transeversal section and those calculated by statically determined solution. A good agreement can be observed.

4.1.3 Walls of Leonardo's "Last Supper"

The famous fresco was painted by Leonardo on the north wall of the Dominican Monastery's refectory. The building of the monastery was completed in 1496. In 1943 the wall was damaged by a bomb which partially destroyed the refectory. Following the design of wall supporting work, tests by flat jacks were carried out to determine the state of stress on the two faces of the wall, as well as deformability and strength characteristics (Fig. 10). Tests brought to light an eccentricity of loads in good agreement with the geometric survey results.

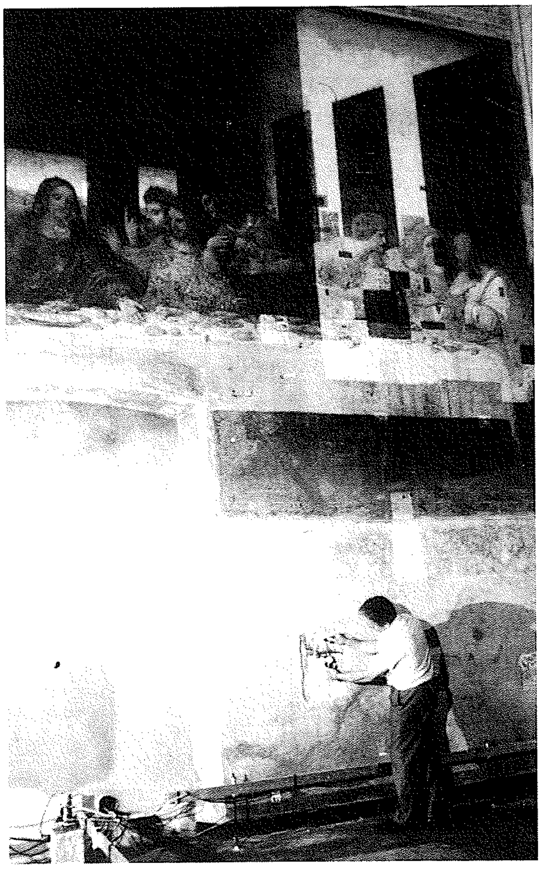

Fig. 10 Flat-jack on the wall of Leonardo's "Last Supper" in the Refectory of "S.Maria delle Grazie"- Milan

4.1.4 "Classense" Library - Ravenna

The Library, which dates back to the XVI century, was recently concerned with a restoration design which foresees the opening of some arches in a wall supported by masonry columns. Stresses were measured by flat jacks at two of these columns before and after restoration work was carried out.

4.1.5 "St. Eufemia Church"- Verona

This church, whose construction was completed in 1300 presents now some subvertical cracks at the apse. Tests were performed by flat jacks for a detailed analysis of the static conditions of the structure on external and internal masonry of the bell-tower and abse section. Fig 11 shows a testing point at the base of the bell-tower and Fig 12 illustrate the measure of the stress on internal arch. Measurement bases were also installed on the main cracks of the church to check deformations versus time.

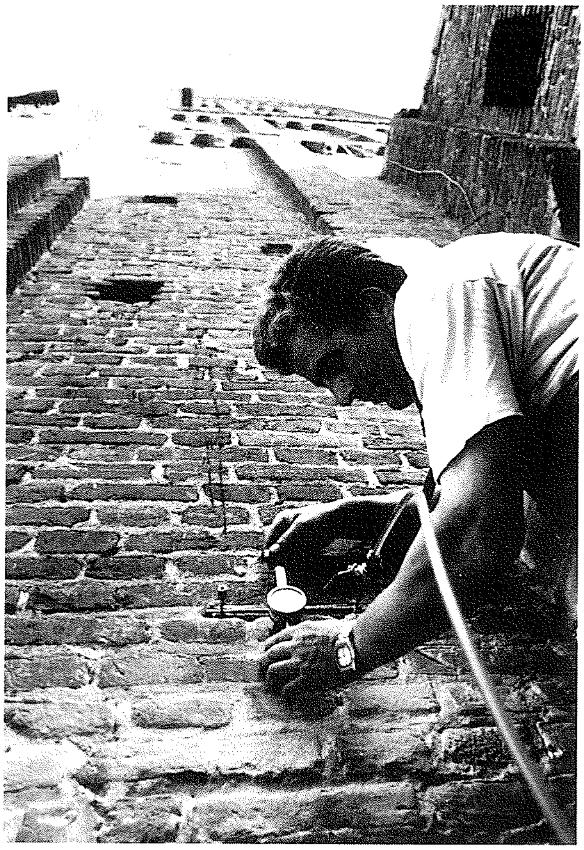

Fig. 11 "St.Eufemia Church"- Verona
Measure of the stress at the base of the bell tower

Fig. 12 "St.Eufemia Church"
Measure of the stress on

4.1.6 "Madonna del Prato" Church - Gubbio

The church, designed by Borromini, presents some cracks on the bearing stone masonry and on the dome. To check the static conditions of the structure and plan restoration work, use was made of information provided by flat-jack test carried out on the external wall and on the arches supporting the vaults (Fig 13). In this example flat-jack testing technique was applied on a stone masonry with very satisfactory results. The mechanical parameters determined in situ were used as imput data for a tridimensional finite element model carried out by ISMES.

Fig. 13 Madonna del Prato - Gubbio
Measure of stress an a stone masonry

4.2 Recovery of old building for habitation purpose

4.2.1 Building in "Piazzale Dateo" - Milan

This is a square-plan building built at the beginning of XX century, and presenting evident signs of deterioration. To carry out a restoration plan of the building for habitation purpose, an extensive investigation was conducted to analyze the static behaviour of the structure.

4.2.2 "Collegio Massimo" - Rome

The building, which dates back to the XVIII century, is at present concerned with a plan for total rehabilitation. This has called for a detailed analysis of the static conditions of the bearing structures. Fig 14 shows a test with two jacks on a wall of the building. In this case the masonry was made by alternating layers of bricks and volcanic stones.

Fig. 14 "Collegio Massimo"- Rome Deformability test on a composite masonry

4.3 Control of static behaviour of old structure

Flat-jack testing technique has recently been used for the study of static behaviour of masonry linings of two tunnels;

- "St. Pedrino" Railway Tunnel (length 16 km - diameter 5 m)
- Tunnel of an old aqueduct in Puglia (length 16 km - diameter 3 m)

Also the stone masonry of the old dam of Lake Ballano in Emilia Romagna was successfully studied by using 60 x 30 cm flat-jacks.

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