P.P.Rossi

Recent developments of the flat-jack test on masonry structures

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ismes s.p.a.
viale Giulio Cesare, 29 - 24100 BERGAMO - tel. 035/358111 - telex 301249 - BG

1. INTRODUCTION

Some years ago an interesting testing technique, based on the use of flat jacks was developed at the ISMES laboratory for the analysis of the mechanical characteristics of existing masonry structures. The first applications of this technique to some historical monuments clearly showed its great potential. It appeared to be the only way to achieve reliable information on the main mechanical characteristics of a masonry structure (deformability, strength, state of stress). After these first encouraging experiences, the use of the flat-jack test rapidly increased and today more than 30 historical monuments have been studied by means of this test.

This very simple technique, which is carried out by introducing thin flat-jacks into the mortar layers, is certainly "non-destructive" because, after the test is completed, the flat-jack can be easily removed and the mortar layer restored to its original condition. The high reliability of the test is related to the undisturbed conditions of the sample on which the mechanical characteristics are determined, and to the large size of the sample which is representative of the behaviour of the whole structure.

In this paper, the testing techinique, applied both to brick and stone masonries, is described first. Attention is then devoted to the wide range of calibration tests carried out at the laboratory to ascertain the reliability of the flat-jack technique in different test conditions. Recent examples of the application of the flat-jack test on some important monuments are then presented.

2. DESCRIPTION OF FLAT-JACK TESTING TECHNIQUE

The testing technique has been set up in order to give reliable information based on the following parameters:

- measurement of the state of stress

- determination of deformability characteristics

- estimate of compressive strength.

The test is divided into two separate phases. In the first phase, one flat-jack is used to measure the state of stress and, in the second phase, a second jack is inserted in order to determine the deformability modulus and the compressive strength of the masonry.

2.1 First phase - Measurement of the state of stress

The determination of the state of stress is based on the stress release caused by a plane cutting, normal to the surface of the wall. Fig 1 shows the different phases of the test: two reference points are installed on the wall surface and the initial distance (d_i) between the two points is measured. A cut perpendicular to the wall surface is then made and the stress release determines a partial closing of the cutting, the distance (d) after the cutting being $d < d_i$.

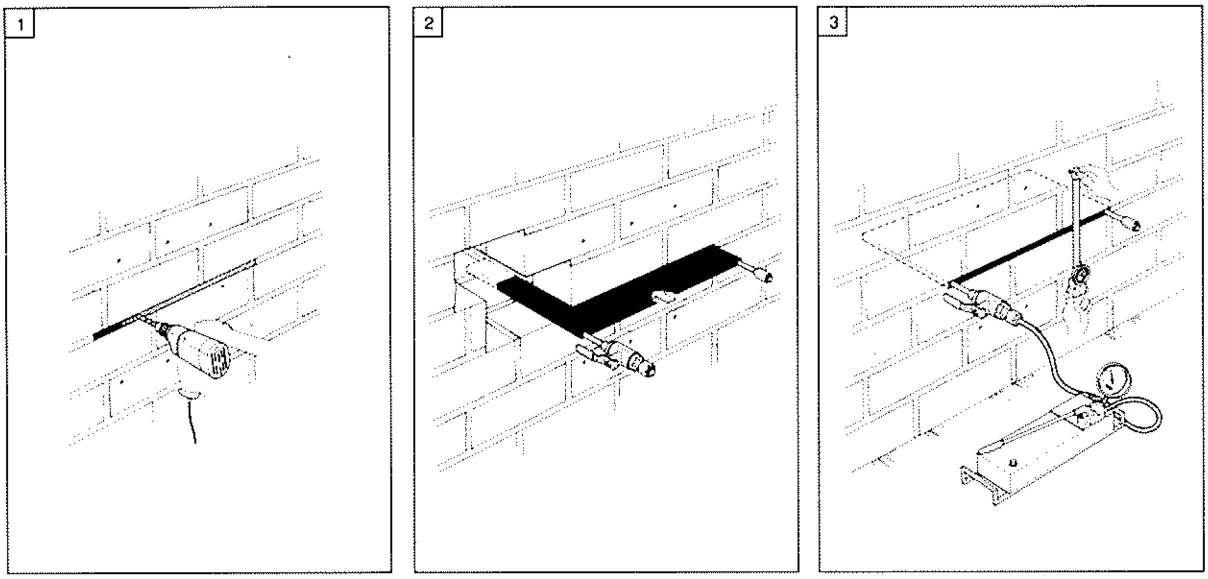


Fig 1 - Scheme of flat-jack test on brick masonry

A thin flat-jack is set inside the cutting, and the pressure is gradually increased to cancel the previously measured convergency. In this condition, the pressure (p) inside the jack is equal to the pre-existing state of stress in a direcion normal to the plane of the cutting. The value obtained must be corrected by a coefficient which depends on the ratio between the flat-jack surface and the cutting surface and on the rigidity of the welded boundary.

The value of the state of stress in the testing point is given by:

$$\sigma = p \, . \, Km \, . \, Ka$$

where:

p = oil pressure

Km = jack constant which must be determined by means of laboratory calibration

Ka = A_J/A_C (ratio between the surface of the jack and the surface of the cutting)

In a brick masonry, the plane cutting can easily be made in the mortar layer between two courses of bricks by means of overlapping holes made by a simple hand tool. In this kind of masonry a rectangular flat-jack is used (40 x 20 cm). Smaller jacks are also used for the measure of the state of stress on structural elements such as: arches, pillars, vaults.

A different cutting technique has recently been set up in the case of a stone masonry with very thin mortar layers. The cut is made by means of a steel plate with diamond tools and the jack has the same shape as the cutting (circular segment with length 32 cm, depth 12 cm and thickness 4 mm). The different phases of the testing technique applied to a stone masonry is shown in Fig 2. It must be pointed out that the very limited thickness of this kind of jack imposed very delicate problems in the design and construction of the flat-jacks.

Fig 2 - Flat-jack testing phases on a stone masonry

2.2 Second phase- Determination of deformability and strength characteristics

In homogeneous isotropic material, the test described at point 2.1 can also be used to determine the deformability characteristics. In the case of a 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 inserted, at a distance of about 50 cm from the other jack. The two jacks delimit, therefore, a masonry sample of appreciable size to which they apply a uniaxial compression stress (Fig 3). 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 transversal deformation of the sample. In this way a uniaxial compression test is carried out on an undisturbed sample of large size which is certainly representative of the behaviour of the structure as a whole. Several loading cycles are carried out at gradually increasing stress levels in order to determine the deformability modulus of the masonry in loading and unloading phases. Fig 4 shows a view of the test applied to brick and stone masonries.

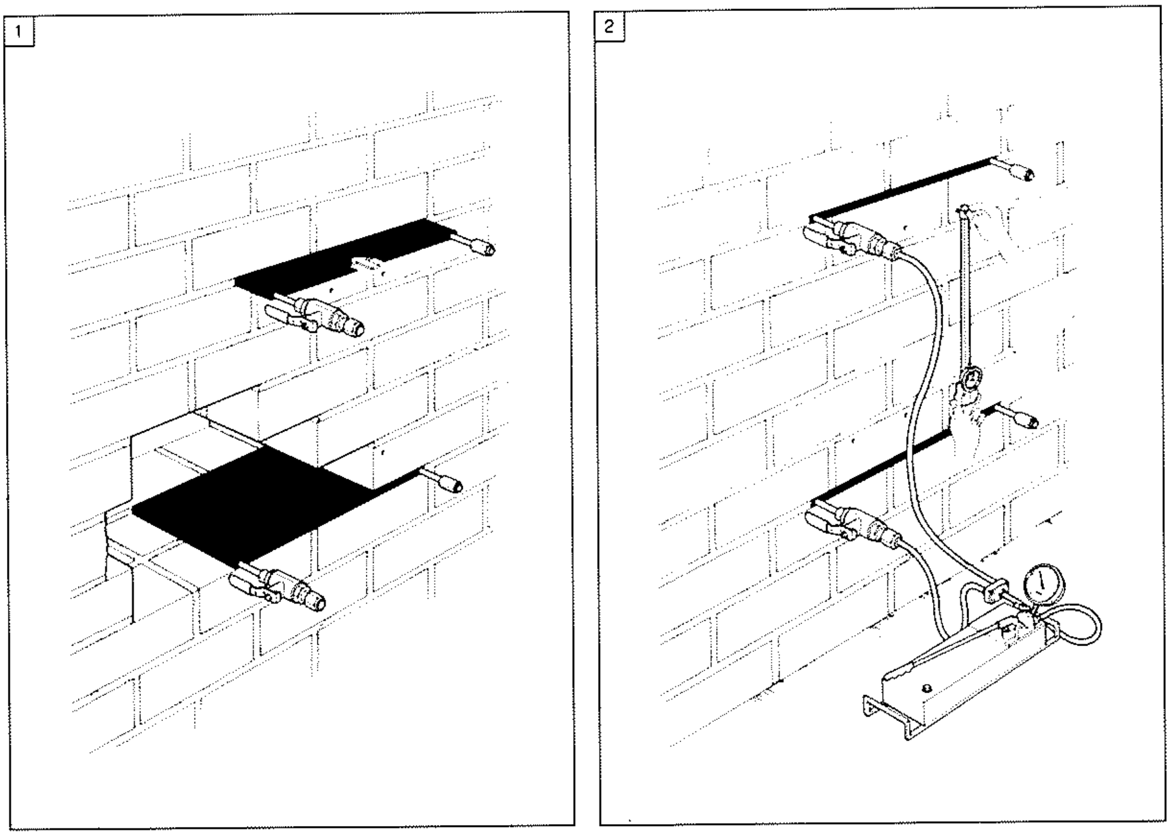


Fig 3 - Scheme of the test with two parallel flat-jacks to determine the deformability characteristics

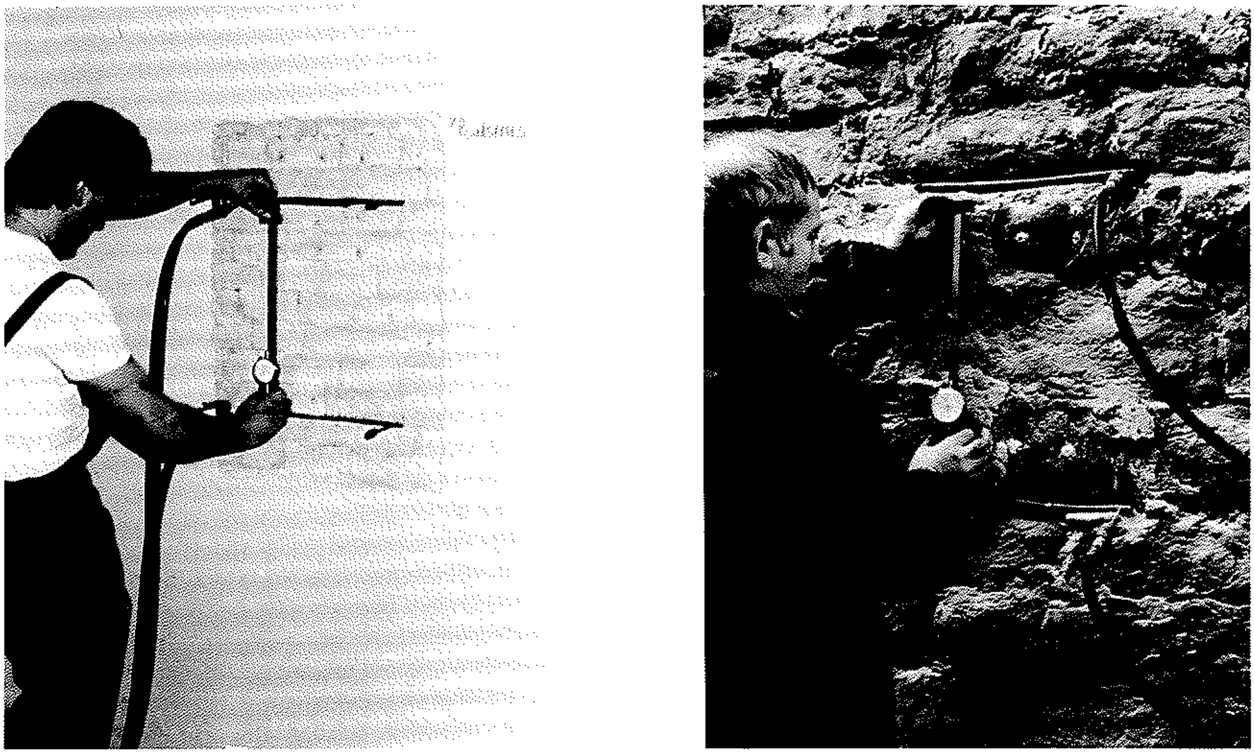


Fig 4 - Deformability tests on brick and stone masonries

The loading test with two flat-jacks can also be used to evaluate the compressive strength of the masonry. For this purpose the load is increased until the appearance of the first cracks in the bricks and the strength limit of the masonry can be estimated with a very good approximation by extrapolating the stress-strain curve. The effect of the lateral confinement of the specimen may be taken into account by means of calibration tests carried out at the laboratory. It must be noted that, when nearing failure conditions some cracks appear in the bricks, but the damage suffered by the masonry is quite negligible and the restoration is easy.

3. LABORATORY TESTS FOR THE CALIBRATION OF FLAT-JACK TESTING TECHNIQUE

A wide program of laboratory tests have been carried out at ISMES, in collaboration with ENEL's Research Dpt, for the calibration of the different test phases using large size masonry samples. Different types of masonry made by bricks and stones have been thoroughly investigated. At first, the values of the constants (Km) relevant to the different flat-jack types were determined. The diagrams of Km values are reported in Fig. 5 as a function of the oil pressure (p).

3.1 Calibration of first phase test: Measurements of the state of stress

3.1.1 Tests on brick masonry with uniformly distributed load

The calibration tests have been carried out on large size samples (150 x 150 x 50 cm) manufactured in the laboratory using hand made bricks (12 x 25 x 6,5 cm) and 1,5 cm thick mortar layers. A mortar composed of siliceous sand, pozzolana, air-hardening lime and water was used. Loading equipment, shown in Fig. 6, was specially designed for the application of the axial stress component to the wall by means of hydraulic jacks.

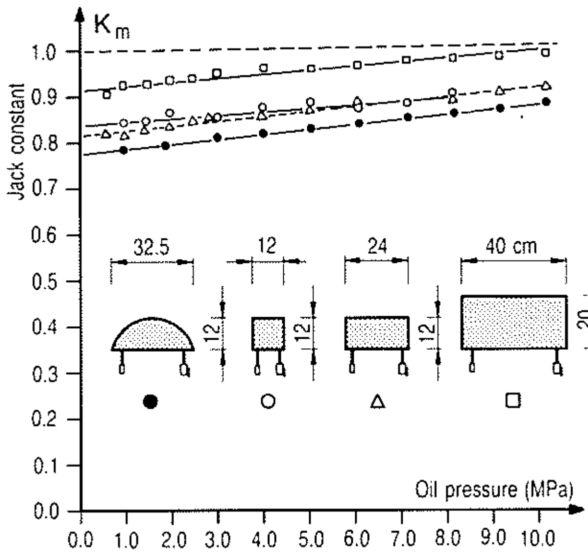


Fig. 5

Calibration curves of the different flat-jack types

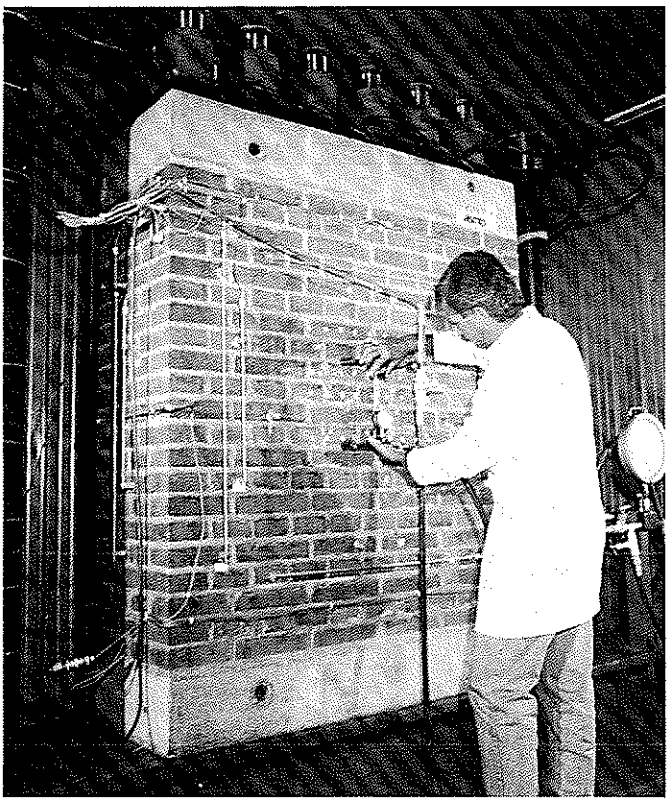


Fig 6

View of the loading equipment for calibration tests

The tests were carried out by applying a known state of stress to the specimen wall and comparing this value with that determined by the flat-jack test at the centre of the wall. In this way, correlations between measured and applied stress values for a wide range of loading conditions were obtained.

The correlation relative to the rectangular jack 40 x 20 cm for stress values between 0.5 - 3.0 MPa, is shown in Fig 7. It can be said that the linear interpolation of the experimental result is practically coincident with the theoric line. This result clearly shows the high reliability of this kind of jack for the measurement of the state of stress. A good agreement between measured and applied stress can also be observed in Fig 8 which shows the results obtained by using smaller jacks (24 x 12 cm and 12 x 12 cm).

During all the calibration tests, the deformations around the flat-jack were carefully studied in the cutting and in the reloading phases by installing a large number of measuring points. Typical deformation diagrams obtained during the test are shown in Fig 9. These curves are relative to a test made by means of a 40 x 20 cm jack with a value of the applied stress equal to 2.25 MPa. It is safe to say that, when at the central base the release deformation is cancelled, the whole diagram of deformations on the reloading phase (dashed line) faithfully follows the diagram plotted on the reloading phase (continuous line).

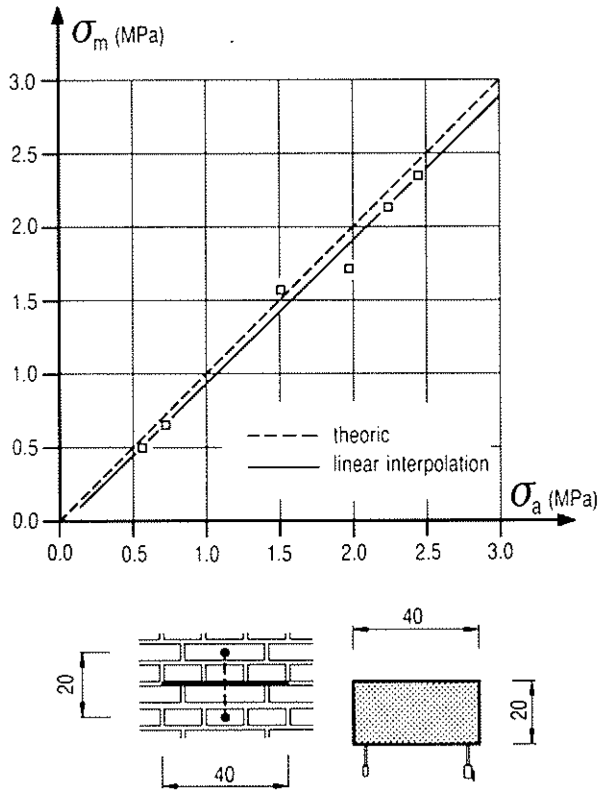


Fig 7 - Results of calibration tests with 40 x 20 cm jacks

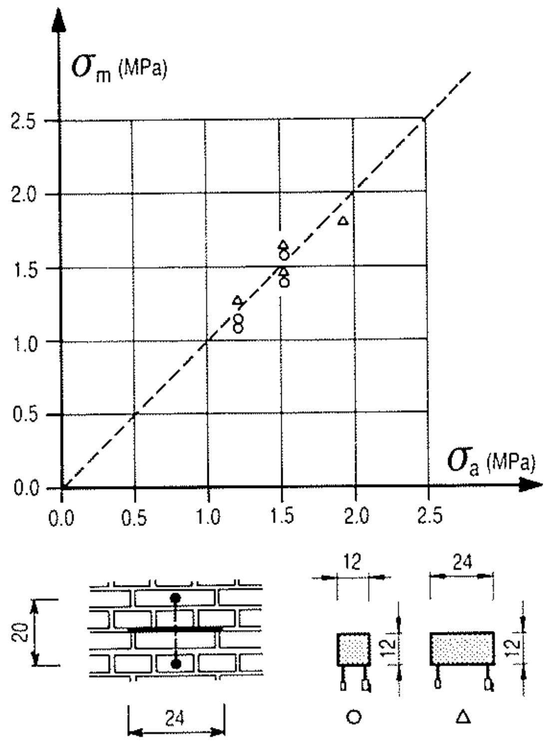


Fig 8 - Results of calibration tests with 24 x 12 cm and 12 x 12 cm jacks

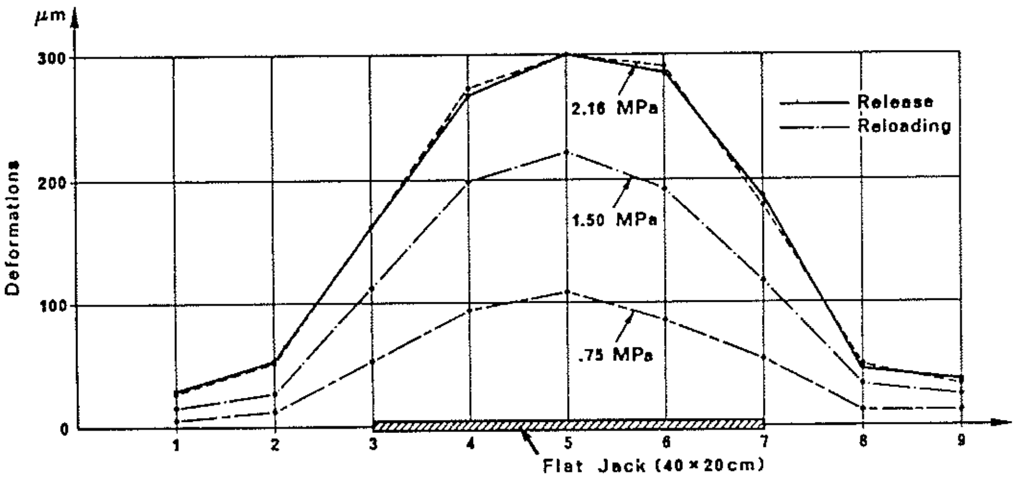


Fig 9 - Comparison between deformation curves in release and reloading phases

This reversible deformation behaviour observed in all the tests is a further confirmation of the reliability of the test.

3.1.2 Tests on brick masonry with eccentric load

The flat-jack test is particularly useful for checking eventual load eccentricity in walls or pillars. For this purpose two tests are carried out on both sides of the wall. A calibration test was carried out at the laboratory using 40 x 20 cm jacks in order to verify the reliability of the test also in non-uniform loading conditions. Fig 10a shows the stress

Fig. 10

Results of calibration test with non-uniform loading conditions

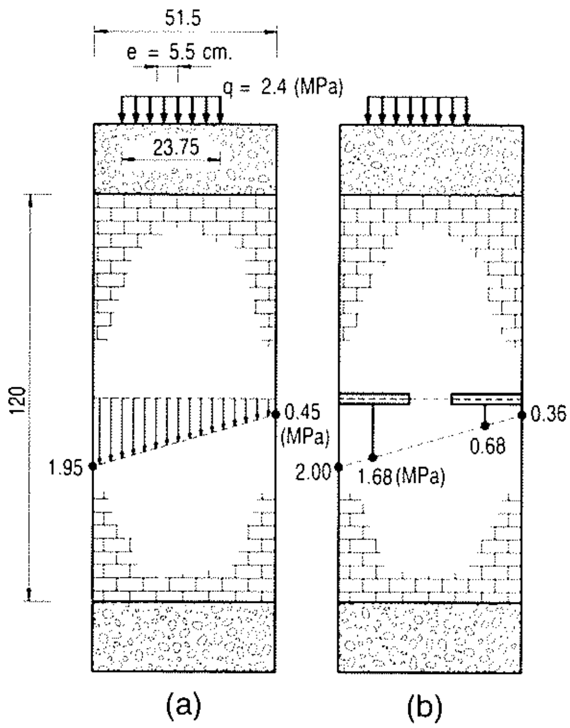


diagram applied to the wall and Fig 10b reports the results obtained by the flat jack tests. At first one test was carried out and the stress value measured was plotted at the center of the jack area. Then the cut was closed by means of expanding mortar and some days later the second test was carried out on the other side thus determining the second stress value. It can be observed that the linear diagram which connects the two measured stress values determines on the surfaces of the wall two stress values which are very closed to the applied ones.

3.1.3 Tests on stone masonry with uniformely distributed load

The testing technique applied to stone masonries was calibrated at the laboratory using 60 x 40 x 40 cm samples made by sandstones (40 x 40 x 20 cm) alternating with very thin mortar layers (about 5 mm) (Fig 11). The results of the tests carried out according to the technique described at point 2.2, are shown in Fig. 12. Also, in this case, it can be observed that the linear characteristic which interpolates the experimental values, is verv close to the theoric line.

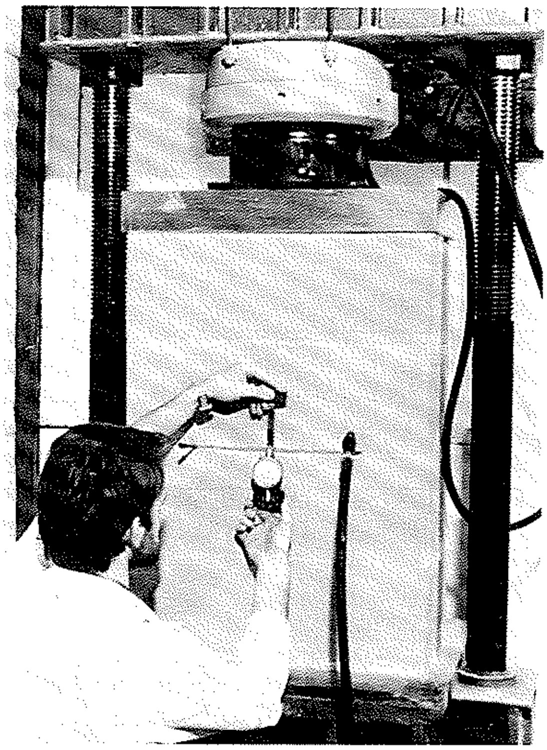


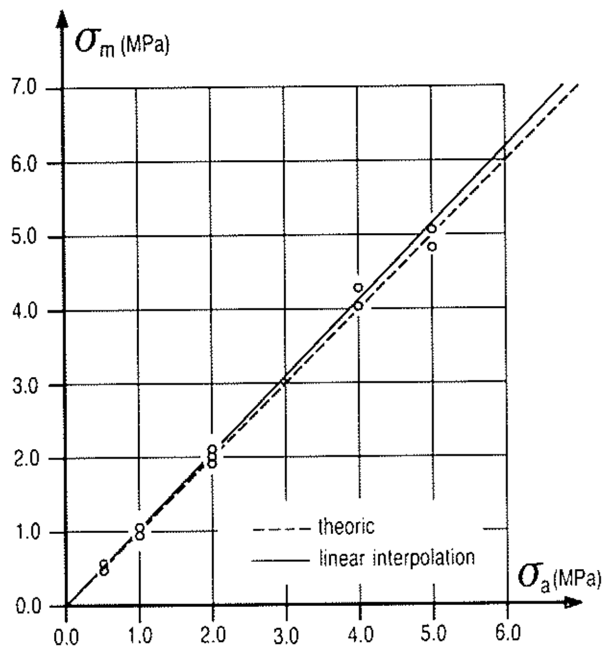
Fig 11

View of calibration tests on large stone samples

The agreement between measured and applied stress is very good in the whole range of stress values examined.

3.2 Calibration of the second phase: Determination of deformability characteristics

For the calibration of the deformability test, a second jack 40 x 20 cm parallel to the first one, was placed at the center of the masonry walls shown in Fig 6. Several tests were carried out on walls with different deformability characteristics.



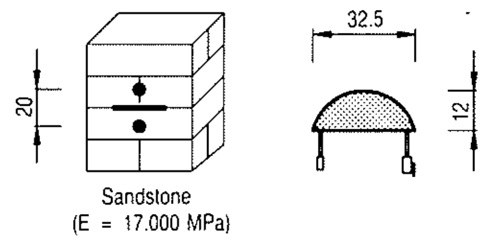
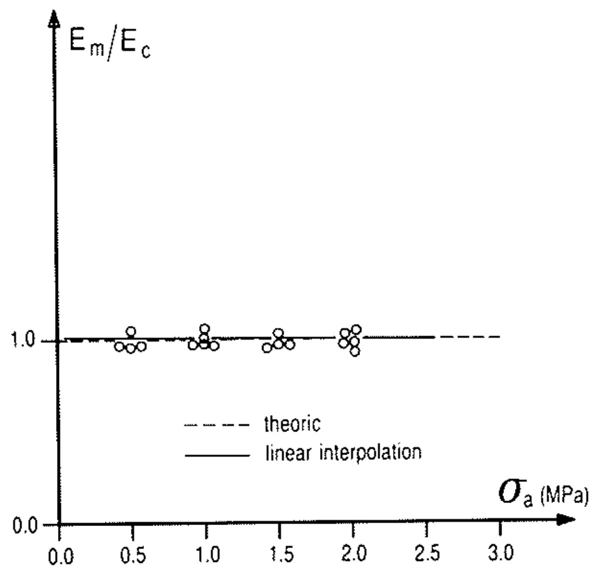


Fig 12

Results of calibration tests on stone masonries

In the diagram of Fig 13 the values of the ratio between the deformability modulus determined by the flat-jack test (Em) and that determined by the conventional compression test (Ec) on specimens having the same size of the specimens included between the two jacks are reported. It can be observed that the values of the ratios Em/Ea are close to unit and this means that the confining effect of the masonry on three sides of the specimen is negligible; therefore the flat-jack test can be considered as a conventional compression test. Some tests were also carried out using smaller jacks (24 x 12 cm). In this case, the values of the deformability modulus determined by the flat-jack test are much higher than those determined by conventional compression test. This is ascribed to the fact that the masonry sample interposed between the two small jacks has a few layers of mortar and, therefore, it is not representative of the overall behaviour of the masonry.



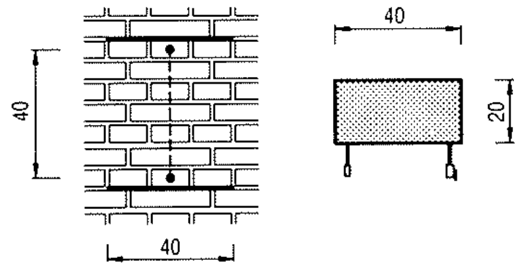


Fig 13

Comparison between the deformability moduli obtained by flat-jacks (Em) and by conventional compression test (Ec)

Fig 14 shows the great difference between stress-strain curves obtained by 40 x 20 cm jacks and 24 x 12 cm jacks on the same type of masonry.

The wide range of calibration tests made it possible to ascertain that 40 x 20 cm flat-jacks give reliable responses concerning both the measurement of the state of stress and the determination of deformability parameters, while the use of flat-jacks of lower size must be limited to the measurement of the state of stress.

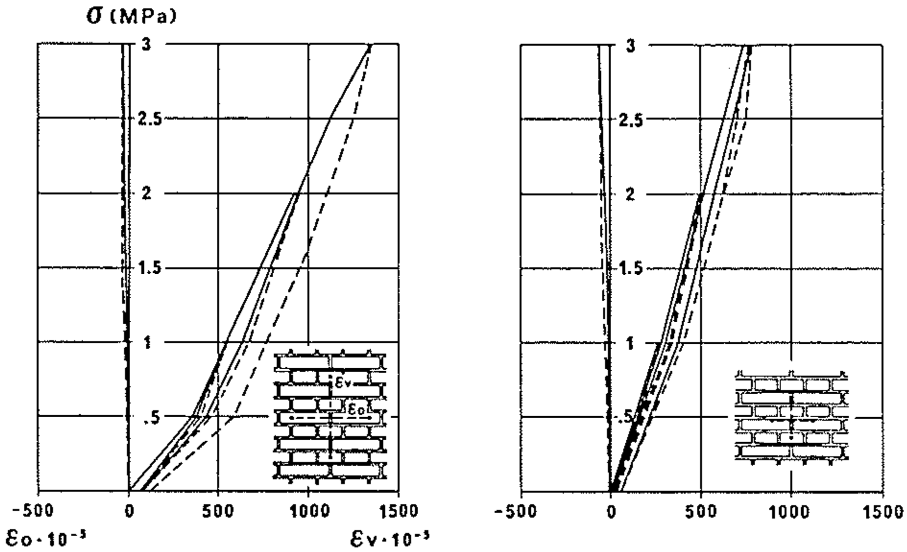


Fig 14 - Calibration of the tests with two flat-jacks for the determination of deformability characteristics. Stress-strain curves obtained by 40 x 20 cm and 24 x 12 cm jacks

3.3 Estimate of compressive strength of the masonry

To evaluate the compressive strength, the load applied to the masonry by the two flat-jacks can be progressively increased until some cracks appear in the bricks. A typical stress-strain diagram thus obtained is shown in Fig 15 which is relevant to a test with 40 x 20 cm jacks carried out on a wall built with a low strength mortar. It may be noted that the deformation behaviour of the masonry sample between the two jacks is well described by a bilinear characteristic. This diagram is similar to the stress-strain characteristic obtained by means of a conventional uniaxial compression test carried out on a specimen having the same volume (50 x 50 x 25 cm) of that included by the two flat-jacks. The comparison between the two diagrams shows that, after the first elastic phase, the stress-strain curve obtained by the flat-jack test is about 10-15% higher than that determined by the conventional compression test. This result, which has been confirmed by two additional tests, clearly shows that the flat-jack test can also be used to estimate the compressive strength of a masonry.

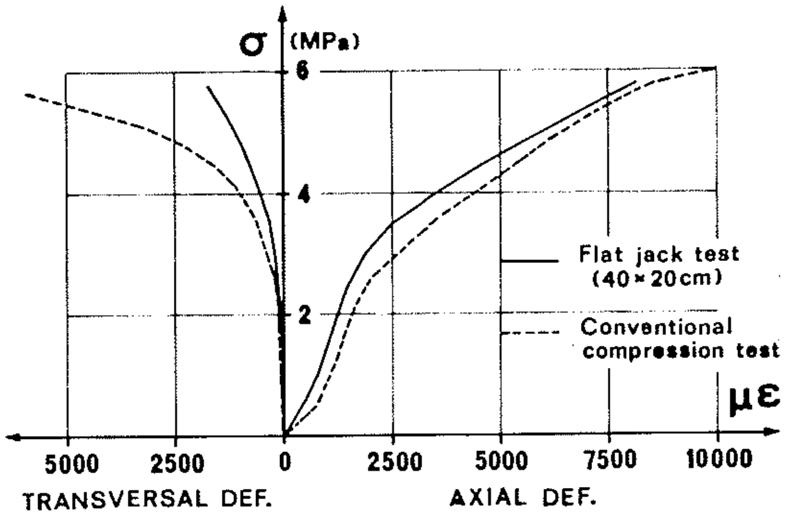


Fig 15 - Determination of compressive strength of the masonry. Comparison between stress-strain diagrams obtained by flat-jack tests and by conventional compression test

4. SOME INTERESTING EXAMPLES OF THE APPLICATION OF THE FLAT-JACK TEST

Recently the flat-jack testing tecnique has been successfully used to study the static behaviour of many important monuments made with brick and stone masonries.

Brick masonries

Wall of Leonardo's "Last Supper" (Milan) - "Palazzo della Ragione" (Milan) - "S.Eustorgio" Cloisters (Milan) - "S.Eufemia" Church (Verona) - Romolo's Temple (Rome) - "Madonna del Prato" Church (Gubbio) - "Classense" Library (Ravenna) - Some important palaces in Milan and Rome.

Stone masonries

Tower of Pisa - Cathedral of Orvieto - "S.Maria di Collemaggio" Church (L'Aquila) - "S.Maria in Valle Porclaneta" (Abruzzo) - "S. Fruttuoso" church and cloister (Portofino) - "Forum of Augustus" (Rome) - "Madonna della Consolazione" church (Todi) - "S. Francesco" church (Arezzo) - "S. Giacomo Gate and "S.Agostino church (Bergamo).

4.1 Wall of Leonardo's "Last Supper" in the Refectory of S.Maria delle Grazie - Milan (Brick masonry)

The famous fresco was painted by Leonardo on the north wall of the Dominican Monastery's refectory, the construction of which was completed in 1496.

In 1943 the wall was damaged by a bomb which partially destroyed the refectory. The restoration of the whole complex was started in 1945 and completed in 1948.

To-day, the stability of the wall is uncertain. It presents an expanding pattern of cracks and marked non-verticality (up to 10 cm on the top). These precarious static conditions of the wall necessitated the installation of a provisional supporting structure which was realized by a steel frame built at the back of the wall.

A diagnostic analysis of the static behaviour was then carried out for the design of final consolidation works. At first, a geometric and photogrammetric survey was carried out with a detailed representation of the crack patterns. The results of the photogrammetric survey on both faces of the wall are reported in Fig 16. The attention was then devoted to the mechanical characterization of the foundation and the masonry. The flat-jack testing technique was successfully used to determine the deformability characteristics of the masonry and to analyse the state of stress at the different levels (Fig 17). To check the effect of load eccentricity, flat-jack tests were carried out on both faces of the wall (10 tests on the back side at two different levels and 2 on the fresco's side). A good homogeneity of the measures at each level was noted, as well as a good agreement between the average values measured on both sides of the wall and those calculated taking into account the load eccentricity.

The deformability modulus (Ed) and the compressive strength (σ_R),

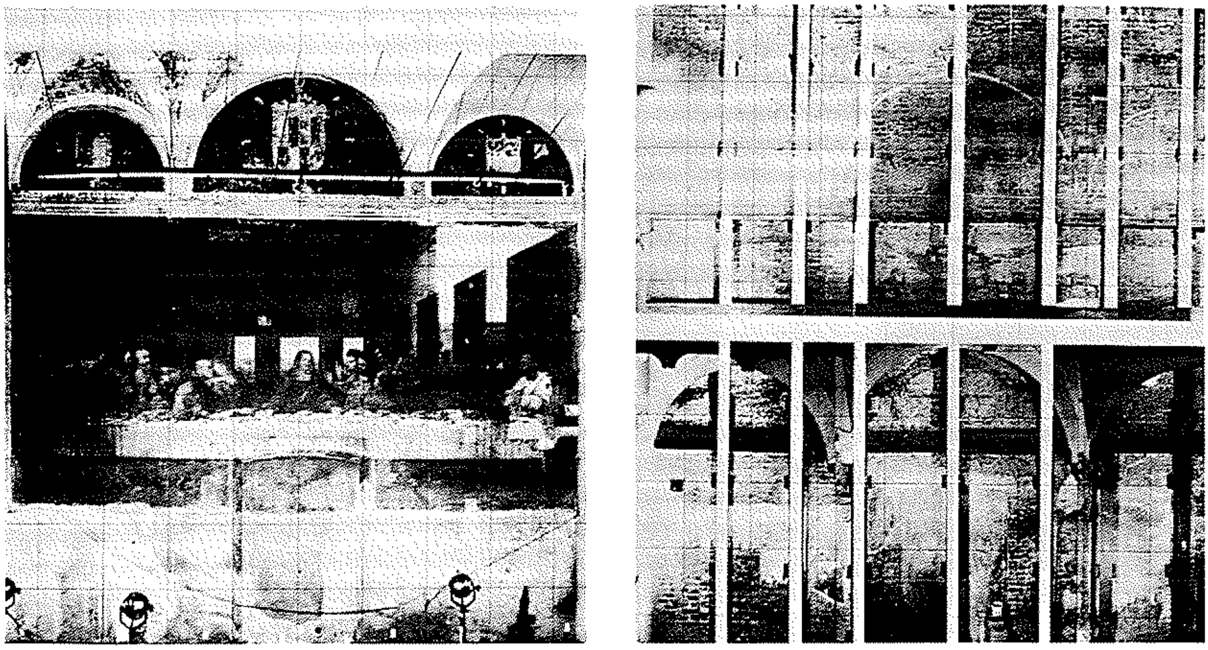


Fig 16 - Photogrammetric survey of both faces of the wall of Leonardo's "Last Supper"

Fig 17

View of a flat-jack test at the base of the wall of Leonardo's "Last Supper"

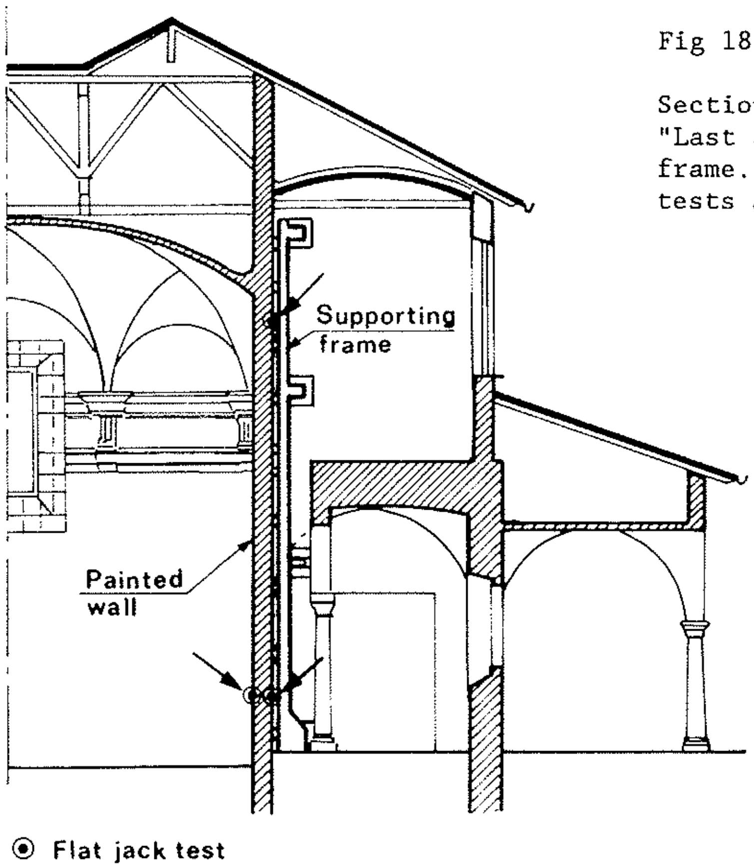


Fig 18

Section of the wall of Leonardo's "Last Supper" with the supporting frame. The positions of flat-jack tests are indicated.

determined at two points, have the following values:

$$E_d = 4000 \text{ MPa}$$

$$\sigma_R = 3.0 \text{ MPa}$$

In Fig 18 a section of the wall and of the supporting frame is shown with the indication of the testing points.

The static behaviour of the wall and of the supporting frame was controlled by means of a long-term automatic monitoring system, installed by ISMES, specially designed for measuring: a) the absolute displacements between the fresco's wall and the lateral ones; b) the loads transferred by the wall to the supporting frame; c) the movements of the principal cracks and the temperature at several points of the structure. The monitoring system, which is still in operation, will provide useful information for the design of final consolidation works.

4.2 "St. Eustorgio Cloisters" Milan (Brick masonry)

The St. Eustorgio Cloisters are attached to the homonymous church. The construction of the first cloister (Fig 19) dates back to the first half of 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 occupation, and rebuilt in 1600.

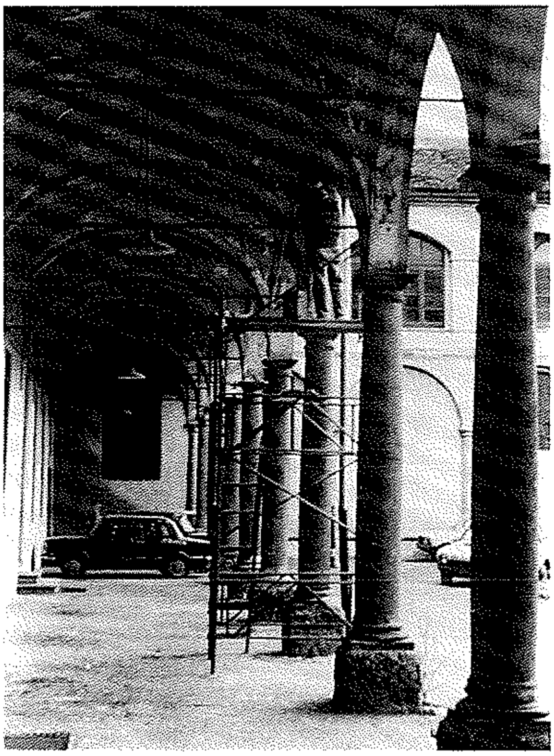


Fig 19

View of the first cloister of St. Eustorgio Church - Milan

After that time, they underwent further damages, the latest ocurred during the Second World War when one side of the second cloister was destroyed. At present, the supporting structures of the cloisters are cracked at many points, and some of them show a marked non-verticality.

For the study of consolidation works, a structural analysis was carried out with the aid of the following "in situ" investigations procedures:

- Determination of geometrical features and their graphical display together with an appropriate photographic record;

- Photogrammetric survey;

- Crack pattern representation;

- Historical research to investigate the changes undergone by the structures and the consequent modification in stress-strain conditions.

After this first series of preliminary investigations, the attention was devoted to the analysis of the mechanical characteristics of the masonry structures. For this purpose, the flat-jack testing technique was used. The state of stress was measured at several points of the structures;on the vertical walls by means of 40 x 20 cm jacks, and on the vaults (Fig 20)

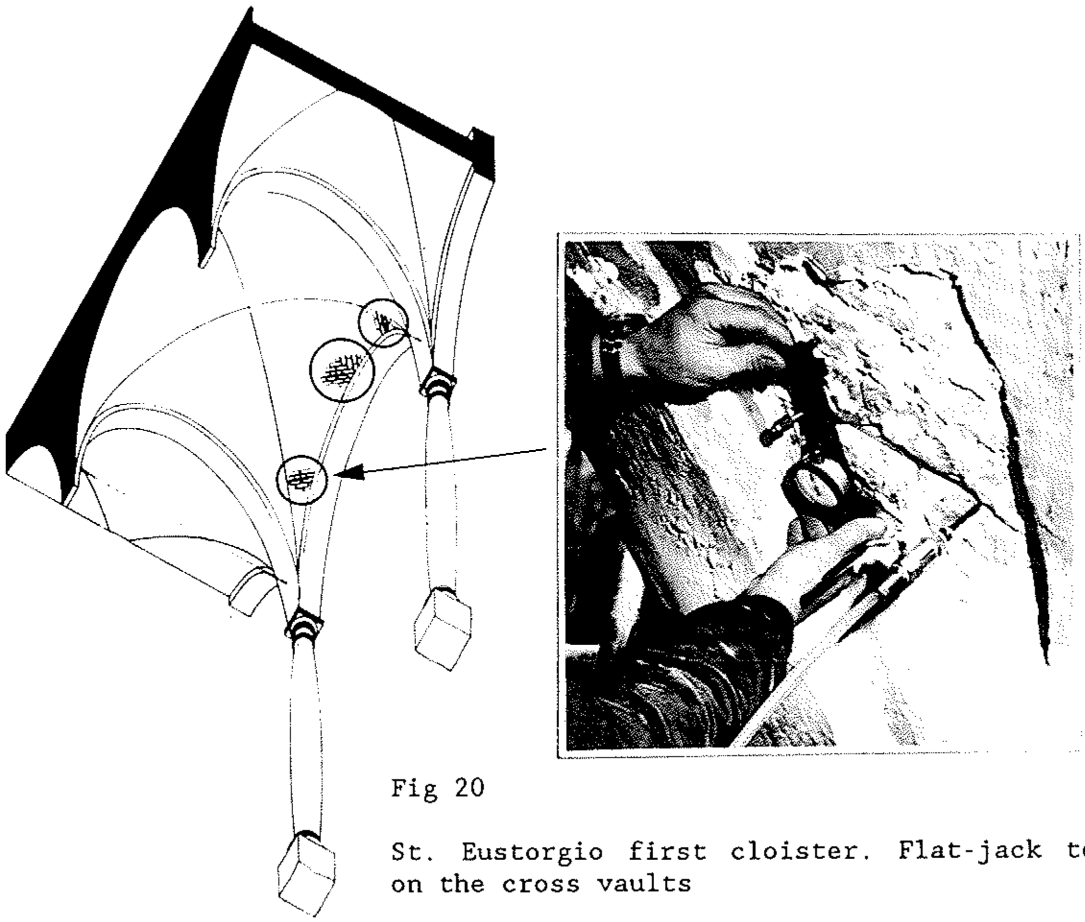
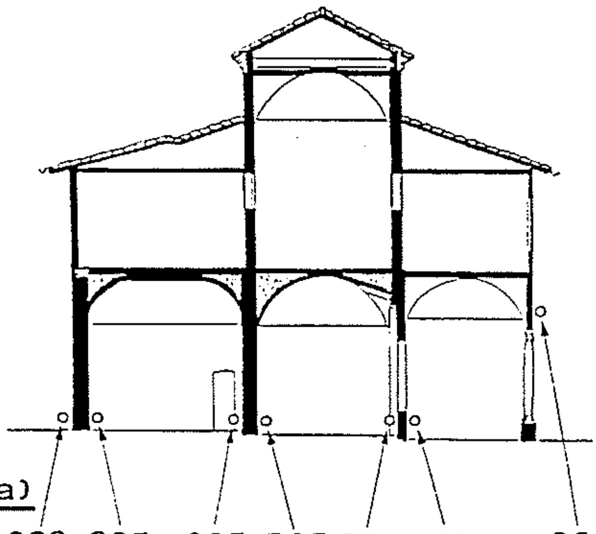


Fig 20

St. Eustorgio first cloister. Flat-jack tests on the cross vaults by means of smaller jacks (24 x 12 cm). The measured state of stress was compared with the corresponding stress values calculated by means of a statically determined solution. The comparison is shown in Fig 21 which is relevant to a transversal section of the second cloister. A good correspondence between measured and calculated values may be observed.

Fig 21

St. Eustorgio second Cloister. Comparison between measured and calculated stress values on a transversal section



STRESSES (MPa)							
measured	0,66	0,85	0,95	0,95	0,95	1,14	0,81
calculated by stat. det. solution	0,84		0,79		0,98		0,89

Using two flat-jacks at some points in the vertical walls, the deformability characteristics of the masonry have been determined. Then the load applied has been increased, until the appearance of the first cracks in the bricks in order to estimate the compressive strength of the masonry. Fig 22 shows the typical stress-strain curve obtained at a test point and the corresponding crack patterns. It can be observed that the damage undergone by the masonry is quite negligible.

4.3 "Madonna del Prato" Church - Gubbio (Stone masonry)

The church, designed by Borromini, presents stone-masonry perimetral walls, surrounded by a dome. The plan and section of the church are shown on Fig 23. Long cracks are present in the central part of each side of the perimetral walls and on the dome. For the study of the statical consolidation works an experimental investigation was carried out in order to determine the structural and mechanical characteristics of the different types of masonries.

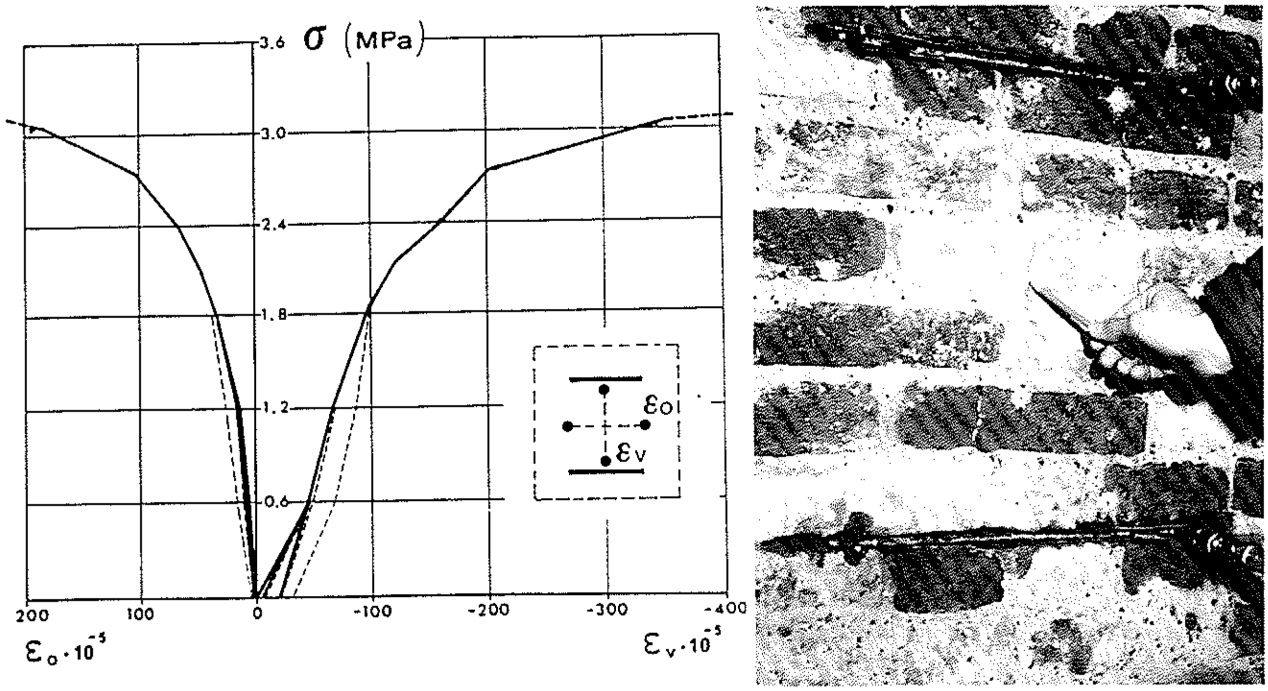


Fig 22 - Deformability test with two flat-jacks on a wall of St.Eustorgio cloisters. Stress-strain diagram up to failure and view of the masonry sample after the test

In this case, the flat jack technique was applied to stone masonry with very satisfactory results (Fig 24).

The values of the state of stress measured at the base of the perimetral walls, are reported in the plan of Fig 23. The average value of measured stress was about 0.83 MPa on the right side and 0.63 MPa on the left side. Very high states of stress (higher than 3.0 MPa) were measured at the base of the brick masonry arches which support the dome. The deformability modulus determined by two flat-jacks at two points of the stone masonry was about 3.500 MPa.

The mechanical parameters determined by the "in situ" test, were used as input data for a three-dimensional finite element model carried out by ISMES for the study of the static behaviour of the structure in the actual conditions, under the effect of dead load, thermal variations and seismic event (Fig 25). This model will be able to verify the effect of different design solutions, therefore it will be a very useful tool for the study of the consolidation works. It was observed that the stress values measured by the flat-jack at the base of the lateral walls are higher than those calculated by FEM model. This is due to the structural characteristics of the walls which present a regular masonry made of cut stones on the two faces and a very irregular and porous masonry in the inner part. The higher deformability of the inner part is the cause of stress concentration on the faces.

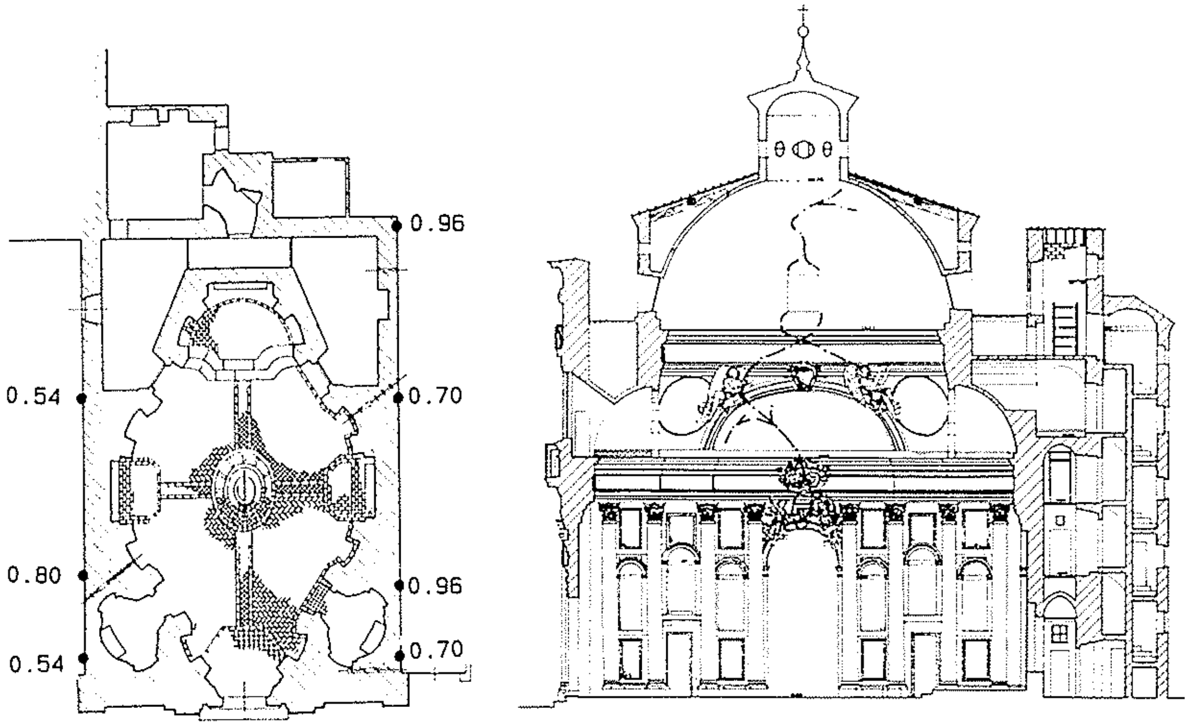


Fig 23 - "Madonna del Prato" church - Gubbio
Plan and section of the church. The scheme of the test points is shown with the indication of the measured values of the state of stress (MPa). In the section the main cracks on the vaults are shown

Fig 24

Measurement of the state of stress on the stone masonry of the "Madonna del Prato" church

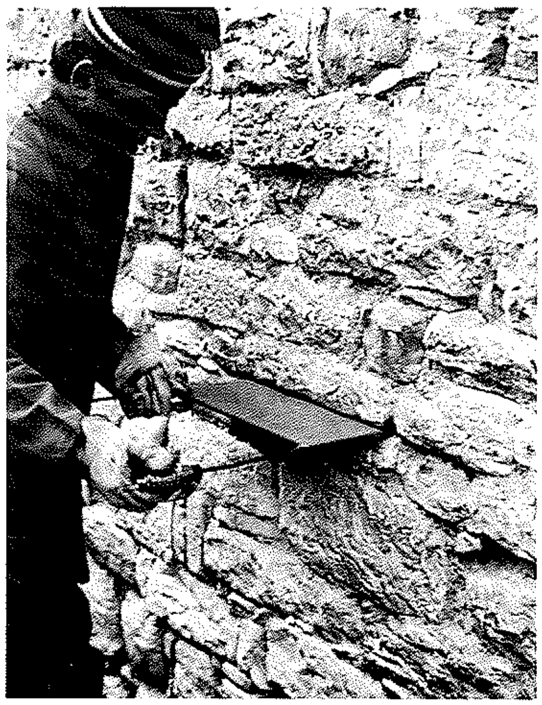
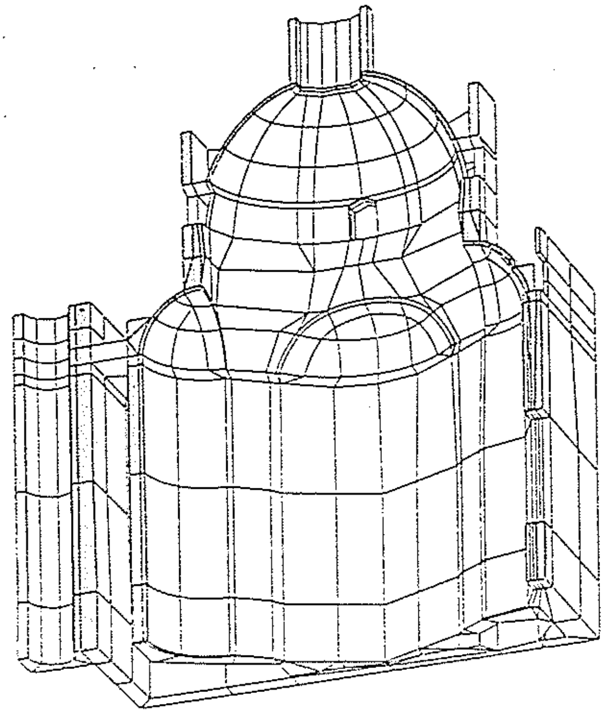


Fig 25

Three-dimensional Finite Element model of the "Madonna del Prato" Church



4.4 Romolo's Temple - Roman Forum (Brick masonry)

The so called Romolo's Temple (Fig 26), the construction of which started in 309 a.c. during the age of the emperor Massenzio, presents a cylindrical structure (external diameter 14,70 m, height 9,10 m and wall thickness 1,22 m) surrounded by a hemispherical dome which is considered one of the largest brick masonry Roman domes in the world.

Fig 26

View of the Romolo's Temple - Rome

Two lateral rectangular rooms, sorrounded by vaults were connected to the cylindrical structure. In the XVII century the temple suffered some changes with the construction of an intermediate floor, resting on four pillars and brick masonry vaults, and of a sky-ligth on the top of the roman dome.

Today the Temple shows clear sings of static decay; long vertical cracks, from the ground up to the top of the dome, are present as well as a marked non-verticality in some parts of the perimetral wall.

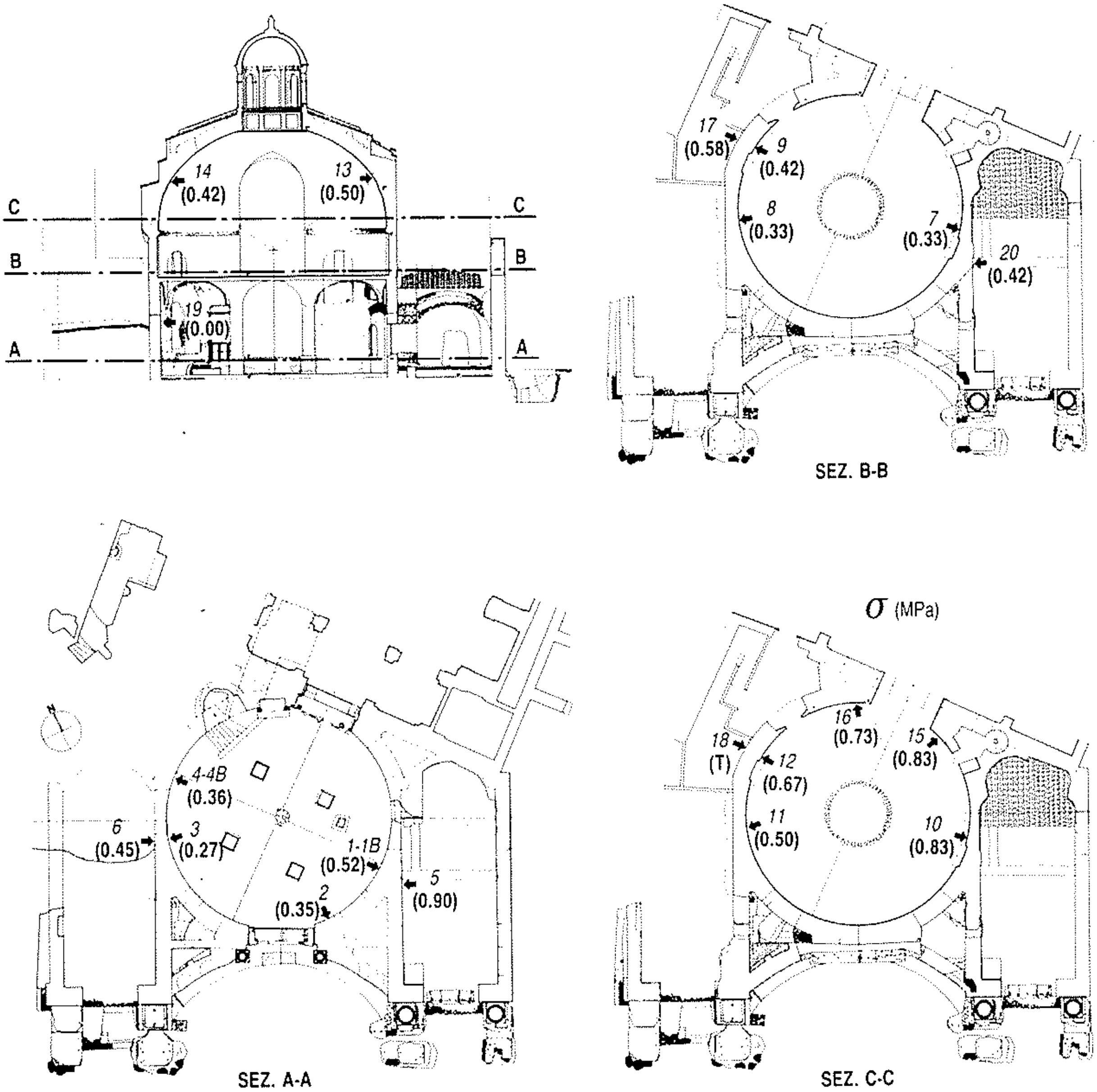


Fig 27 - Different sections of Romolo's Temple with the indication of the flat-jack test points. The measured stress values are also indicated (MPa)

For this reason a wide research on the static conditions of the structure has been decided by the "Soprintendenza Archeologica" of Rome in collaboration with Prof. Chiarugi of the University of Florence and ISMES. At first, the state of stress was measured in several points at the base of the monument and at four different elevations. Fig 27 shows the horizontal sections examined with the indication of the stress values measured by means of 40x20 cm flat-jacks. It can be observed that at the base of the monument an eccentric load toward the external side is present as well as in the section just above the intermediate floor. At the base of the dome the external surface presents a small tensile stress while high compressive stress values have been measured at the inner surface (up to 0.8 MPa). Fig 28 shows one of the tests carried out on the external surface of the temple.

Fig 28

View of a flat-jack test on the external side of the perimetral wall

In two points at the base of the monument the deformability characteristics of the masonry have been determined by means of two parallel flat-jacks. Several loading cycles have been carried out with increasing stress levels up to a maximum value of 2.4 MPa in order to evaluate the deformation behaviour of the masonry under very severe stress conditions. Fig 29 shows the stress-strain diagrams obtained in the two testing points with the indication of the deformability moduli. It is safe to say that in the testing point 1 the mechanical characteristics of the masonry are much lower than those at point 4. While at point 4 the masonry presents a linear elastic behaviour up to 2.0 MPa, at point 1 the limit of the elastic behaviour is reached at a stress level of 1.2 MPa.

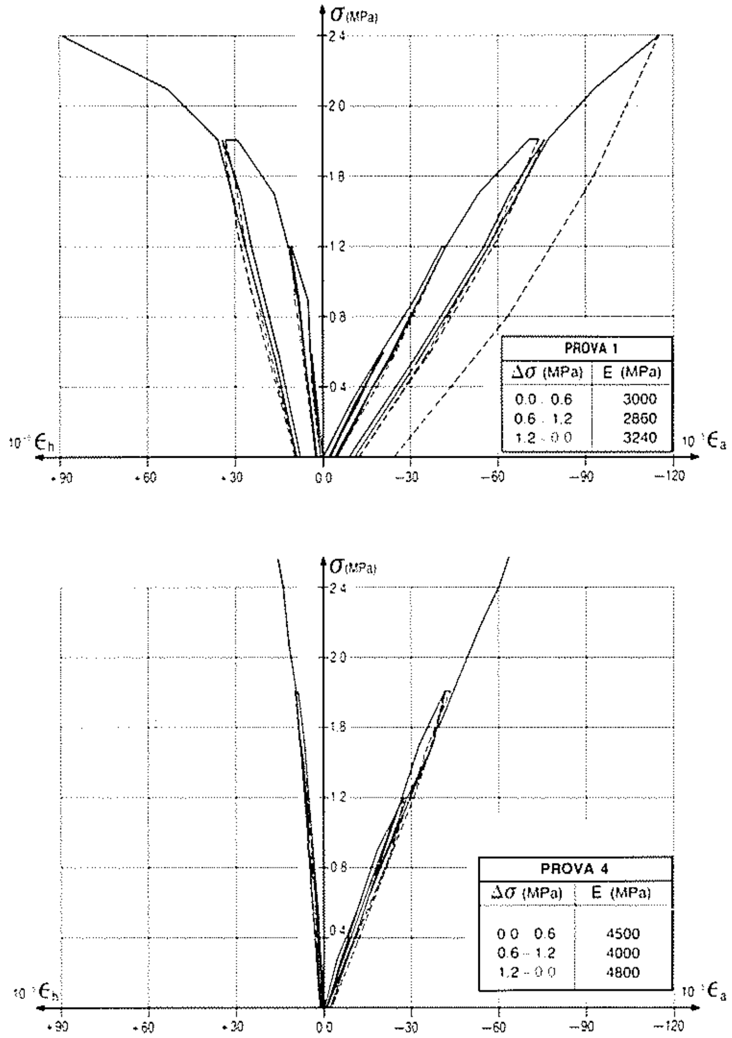


Fig 29 - Determination of deformability characteristic: stress-strain diagrams obtained in two different testing points

The study of the deformability characteristics, besides giving a great help for the analysis of the static conditions, may represent a very useful guide to the Archeologist for the identification of the different types of masonries.

The mechanical parameters determined by flat-jack tests have been used as imput data for a Finite Element elastic three-dimensional model. A very good agreement between the measured stress values and the calculated ones has been observed. Fig 30 shows a section with the indication of the stress values determined by Finite Element model and those measured by flat-jack test (in parenthesis).

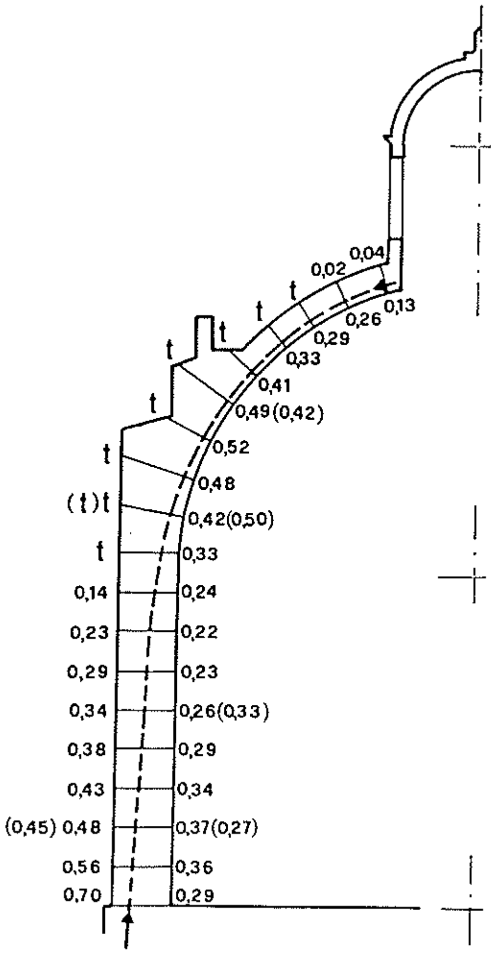


Fig 30

Section of Romolo's Temple with the indication of the stress values (MPa) determined by FEM model and those measured by flat-jack test (in parentesis)
t = tension

4.5 <u>Cathedral of Orvieto (Stone masonry)</u>

The construction of the Cathedral, a masterpiece of the Gothic architecture, started in 1290 (probably designed by Arnolfo di Cambio) and was completed by Lorenzo Maitani in 1330 (Fig 31).

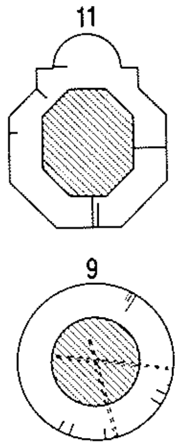
Subsequently and up to the present day, the Cathedral has been subjected to continuous modifications. The first problem of stability was recorded in 1308 when, after the construction of the three aisles and the transept, Architect Maitani was commissioned for the construction of consolidation works with rampant arches and buttresses. In 1620 some columns were bound for the presence of cracks which had appeared earlier. During the past 30 years new cracks have been observed in some columns therefore it was decided by the "Soprintendenza ai beni architettonici e artistici" of Perugia to carry out a detailed analysis of the static conditions of the Cathedral. The static analysis , carried out by the Technical University of Turin in collaboration with ISMES, was carried out with aid of the following investigation procedures:

- Determination of geometrical features
- Topographic survey
- Crack pattern representation
- Geotechnical investigations

Fig 31 - Facade and internal view of the Cathedral of Orvieto

- Determination of structural and mechanical characteristics of perimetral walls, columns and pillars
- Finite element three-dimensional model
- Monitoring of the main cracks of pillars.

Flat-jack tests were carried out at 17 points of the perimetral walls by using the circular shaped jacks and at 17 points of the colums by using smaller jacks (12 x 12 cm and 24 x 12 cm). The testing points on walls and pillars were chosen in order to check eventual load eccentricity. Fig 32 shows the plan of the Cathedral with the indication of the testing points and the stress values measured by the flat-jack tests. Fig 33 shows a view of flat-jack test on the external wall and on a column.
In the lateral walls, a symmetrical load eccentricity with an average stress value of 0.3 MPa on the internal surface and 1.1 MPa on the external one can be observed. This load eccentricity seems to be ascribed to the different structural characteristics of the two sides of the lateral walls (the external side is made by alternating layers of "basaltina" and "travertino", the internal one is made by tuff blocks and therefore its deformability is much higher).



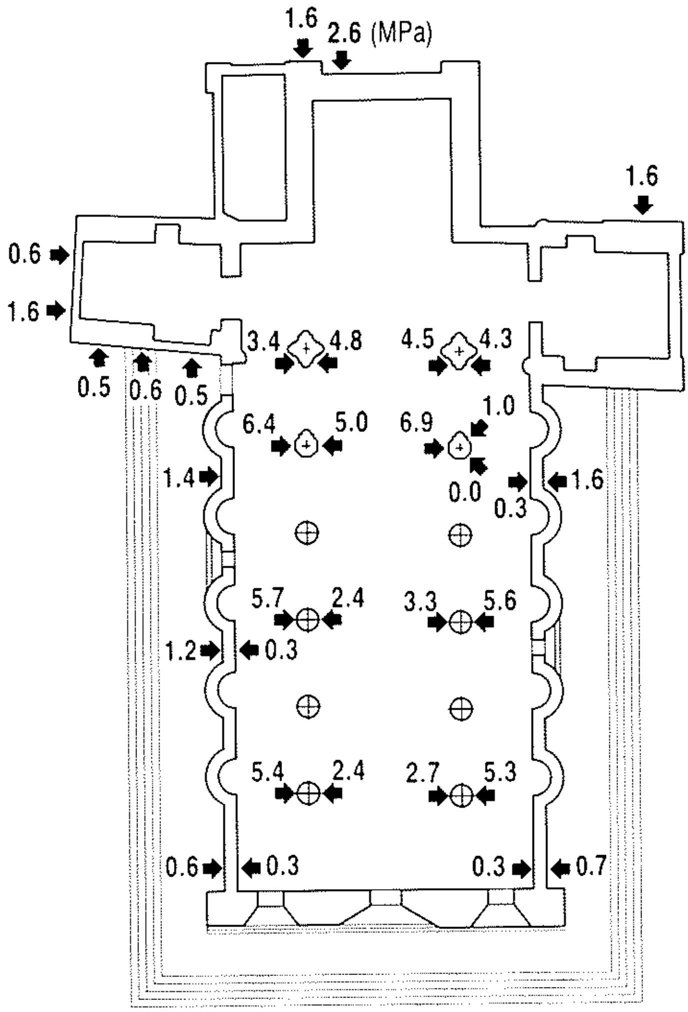


Fig 32

Plan of the Cathedral of Orvieto with the indication of the stress values measured by flat-jack test (MPa)

At the base of columns 1, 3, 7, 9 a constant load eccentricity was measured with an average value of 2.7 MPa on the side towards the main aisle and 5.5 MPa on the apposite side. Particular attention must be devoted to the results obtained in pillar 11 where some deep cracks, shown in the section of Fig 32, have been observed. The flat-jack test carried out on the portion between the two cracks seems to indicate that this zone is completely destressed. This reduction of the reacting section of the pillar induces a considerable increase in the value of the maximum compressive stress (6.9 MPa) on the apposite side. Uniform stress distribution with an average value of 4.2 MPa has been observed on the two pillar (6,12) near the transept.

Tests with one flat-jack on the perimetral walls were also used to evaluate the deformability modulus of the masonry composed by alternating layers of "basaltina" and "travertino". The very thin mortar layers of this masonry justify the assumption of homogeneous and hisotropic material which is required for this calculation. The average value of the deformability modulus obtained by flat-jack test on this masonry was:

$$E_1 = 13.000 \text{ MPa}$$

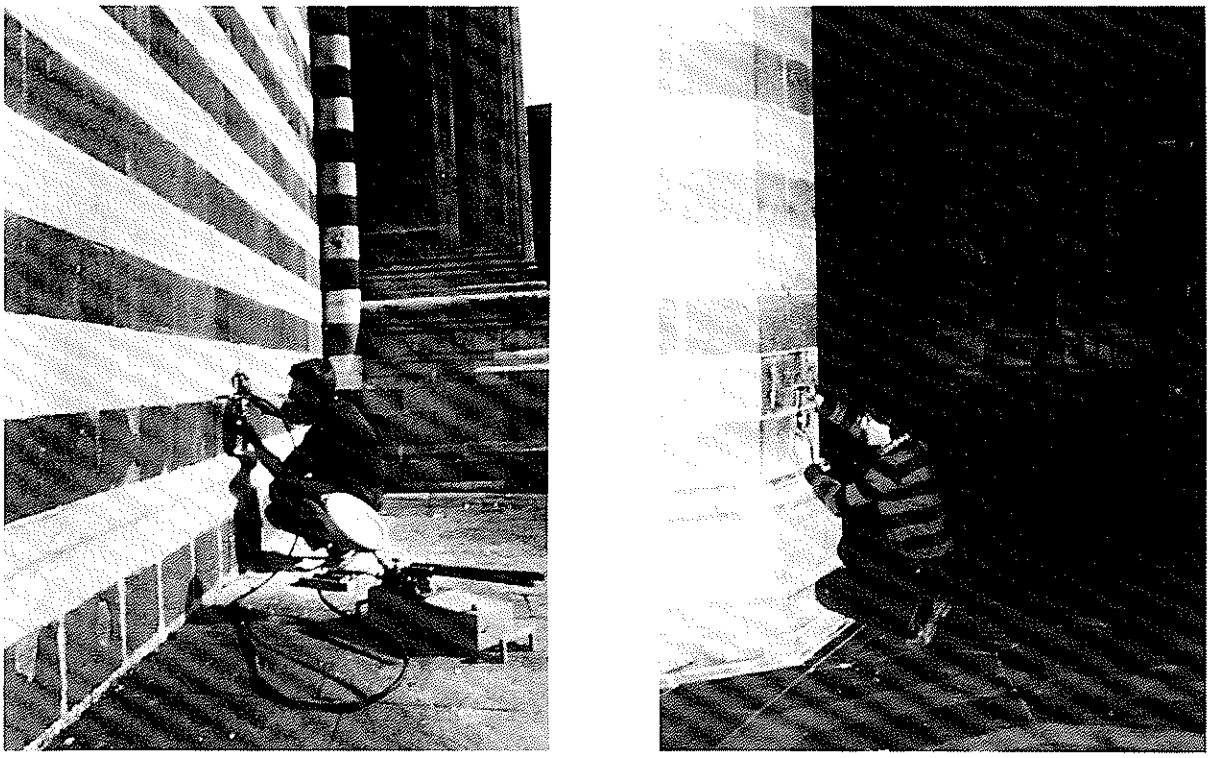


Fig 33 - View of flat-jack test on a lateral wall and on a column

The deformability of the foundation masonry, made by tuff blocks (cemented with mortar, lime and pozzolanic sand), was, on the contrary, determined by means of two parallel flat-jacks. This test was carried out on the foundation masonry of the pillar 11. The deformability modulus, determined for a stress range 0 - 1.2 MPa, was:

$$E_2 = 1.800 \text{ MPa}$$

The stress-strain diagram of the test shows a linear elastic behaviour of the masonry up to a stress level of 1.2 MPa. For higher stress levels a plastic behaviour is observed. The same testing technique was used to determine the deformability characteristics of the pozzolanic material which represents the foundation ground of the Cathedral (Fig 34). Two tests were carried out using small tunnels excavated near the Cathedral. The following results were obtained:

Deformability modulus:	500 MPa
Compressive strength:	0.4 MPa

The mechanical parameters determined by flat-jack tests were used as imput data for a Finite Element three- dimensional model reproducing one column, the masonry foundation and the pozzolanic soil.

Fig 35 shows a standard vertical section of the Cathedral on the right aisle with the comparison between the calculated and measured stress values on a column.

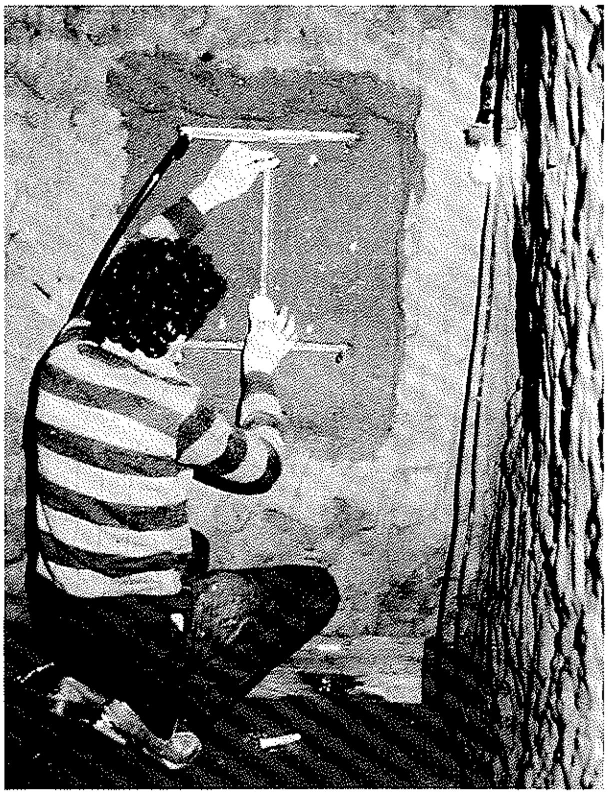


Fig 34

Deformability test with two flat-jacks on the pozzolanic sand layer on which the foundations of the Cathedral have been built

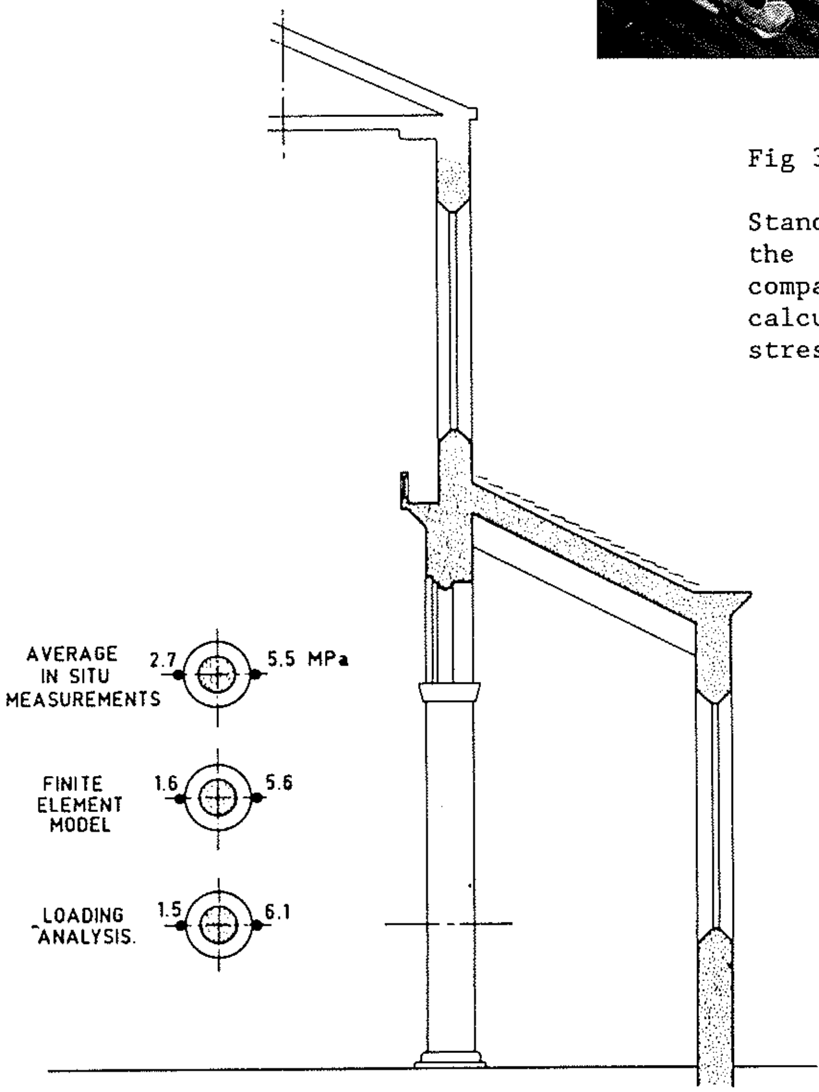


Fig 35

Standard vertical section of the Cathedral with the comparison between calculated and measured stress values on a column

The average values of the measured stress are compared with the results of FEM model and with the values obtained by a loading analysis. It can be observed that the agreement is very satisfactory.

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