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Non destructive evaluation of the mechanical characteristics of masonry structures

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NON-DESTRUCTIVE EVALUATION OF THE MECHANICAL CHARACTERISTICS OF MASONRY STRUCTURES

SUMMARY

The most common testing techniques used in Europe for a non-destructive evaluation of static conditions of masonry structures are presented in this paper, with special emphasis on the methodological approach employed in Italy. The preliminary phase of the investigation includes a geometric survey, crack pattern investigation and an historical analysis. Attention is then given to determining the mechanical parameters of the masonry structures by using non-destructive or slightly-destructive tests. Most non-destructive tests give only qualitative results which can then be used as 'quality indexes' of the masonry. The information obtained by these tests are presented with critical remarks. A reliable evaluation of the mechanical parameters of the masonry structures can be acheived only by employing slightly-destructive tests. For this purpose, emphasis is given to flat-jack testing techniques for determining the state of stress, deformation and strength characteristics of the structures. The important role of dynamic analysis and monitoring for evaluating the static behavior of existing masonry structures is also discussed.

INTRODUCTION

In situ testing for a non-destructive evaluation of masonry structures is a relatively recent technique. In the last ten years, Europe have witnessed a rising interest in this field of research, especially in the area of historical buildings and monument restoration. This is particularly important in Italy where the large number of monuments located in seismic areas call for stricter controls and investigations. Some of the testing techniques used on masonry structures originated from concrete structure testing, whereas others use testing techniques developed from rock mechanics.

This paper examines the tests which allow an evaluation of the static structural behaviour of the structures. Due to the vastness of the topic, the main focus will be on research methods most widely used in Italy. In addition, testing techniques used in other European countries will be briefly summarized, based on information from recent conferences on the subject.

The methodological approach usually adopted in Italy for the static analysis of existing masonry structures initially requires a series of preliminary investigations which provide details of the structure's geometric characteristics, crack pattern, construction phases and use. Following this, a second more investigative series of tests are carried out to determine and define the structural behaviour of the masonry structure. These tests includes both the non-destructive types which allows a quality evaluation of the structural masonry, as well as the slightly-destructive types which permit a quantitative evaluation of the mechanical parameters. Also, the analysis of the response to dynamic forces and the installation of monitoring systems may be considered good tools for the non-destructive evaluation of the mechanical characteristics of existing masonry structures.

PRELIMINARY INVESTIGATIONS

Before determining the mechanical parameters of a masonry structure, a broad knowledge of the structure in question is necessary. First, an accurate geometrical study is needed, which can be carried out by direct traditional measures with reference to datum points, or continuously by photogrammetric techniques. An accurate geometrical study makes it possible to identify eventual irregularities (vertical deviations, etc) by showing both the geometrical defects purposely introduced by the designer to create optical effects, and the effects of bad workmanship. During this study, the constructive and architectural points of interest in the restoration must be thoroughly tested, as well as all the structural materials.Of particular importance is the survey of crack patterns in the building's bearing structures. A detailed survey of the extent of the cracks and their openings allows an early evaluation of the static condition of a structure and recognition of possible causes of instability. Figure 1 shows crack patterns on a wall of the Cathedral in Pavia during one phase of the study. Normally, the geometrical survey is extended to foundation structures by excavating small exploratory shafts or by continuous core drilling.

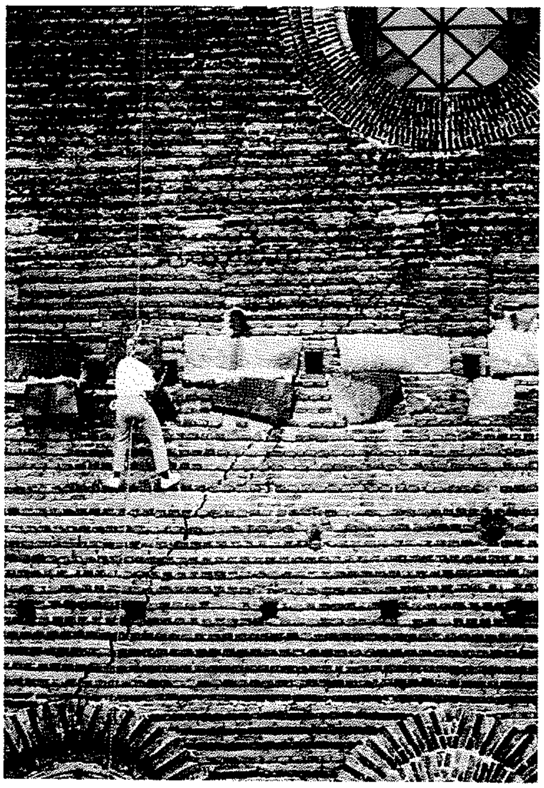


Fig. 1- Crack pattern investigation on the external wall of the Cathedral of Pavia.

Finally, an extensive knowledge of the structure cannot ignore its past history. In fact, it is important to reconstruct the building phases of the structure and to collect information about the construction techniques used in every phase of the construction, including data on the materials used and on subsequent reinforcement work. The information on the construction phases and use of the building may be of great assistance when interpreting its static behaviour and when defining additional investigations to be initiated. It may explain the connection between different types of masonry and when evaluating the crack patterns, will not attribute the cause to actual phenomena, but to overloading which the structure had undergone in the past.

The importance of this phase of the preliminary investigation is widely recognized in all European countries, and in particular those countries like Italy, where the great importance of its architectural heritage demands precaution when instating reinforcement works.

ANALYSIS OF THE STRUCTURAL AND MECHANICAL CHARACTERISTICS

After the preliminary investigation, a second phase testing program is started to determine the structural and mechanical characteristics of the masonry structure. This phase is approached in most cases by using only the **non-destructive** technique (which requires no direct action on the masonry). This is due to the fact that the equipment used for the non-destructive tests is inexpensive and the testing relatively simple. However, it must be pointed out that the use of a non-destructive test, by itself, is not sufficient for resolving the problem satisfactorily. The results obtained by these testing techniques are generally of a qualitative type and give only a preliminary evaluation of the mechanical characteristics through the definition of 'quality indexes' of the masonry. Even though these tests are unable to supply the mechanical parameters necessary for a static analysis of the structure, their use is very important as they provide important information on the homogeneity of the characteristics of the masonry and on the prospective presence of areas of anomalous behaviour.

The only reliable way to determine the parameters that influence the mechanical behaviour of the masonry is by **slightly-destructive** testing techniques which require drilling boreholes and cutting small sections. These actions must be of such an entity as not to change the structure, and must be studied in such a way that the disturbance to the masonry is temporary. At the end of the tests it is important that no visible signs of the work remain on the structure. The necessity of using slightly-destructive testing techniques is now widely recognized in Italy and in many European countries.

Non-destructive testing techniques

Sonic measurements

Among the non-destructive investigation methods, the sonic methods, are without doubt, the most widelyspread tests used. The testing technique is based ,in general, on the generation of sonic or ultrasonic impulses at a point in the structure. A signal is generated by a percussion system or by an electrodynamic or pneumatic transducer, and collected through a receiver, which can be placed in various positions. Elaboration of the data consists in measuring the time the impulse takes to cover the section of material between the generator and the receiver, and in analysing the signal wave.
Ultrasonic waves are preferably used for the study of continuous structures, adopting measurements already coded for non-destructive tests on concrete structures. For masonry structures that are typically unhomogeneous, it is necessary to use sonic impulses, referencing the techniques of the same type used on soil and rock mass. Sonic impulses must be used with masonry structures because the joints present in the masonry would constitute inpenetrable barriers to the ultrasound waves.
The sonic tests can be carried out through the masonry by the application of an impelling force on a surface and receiving a signal on the opposite surface (at an angle) or again, on the same surface. By placing the sensors at different heights on the same wall, it is possible (based on the principle of wave reflection on contact surfaces) to estimate the depth of the foundations.
If there are existing drill marks on the structure to be examined, a cross-hole or down-hole sonic test is possible. Figure 2 shows some possible test schemes.
By using sonic test methods, the following information can be obtained:

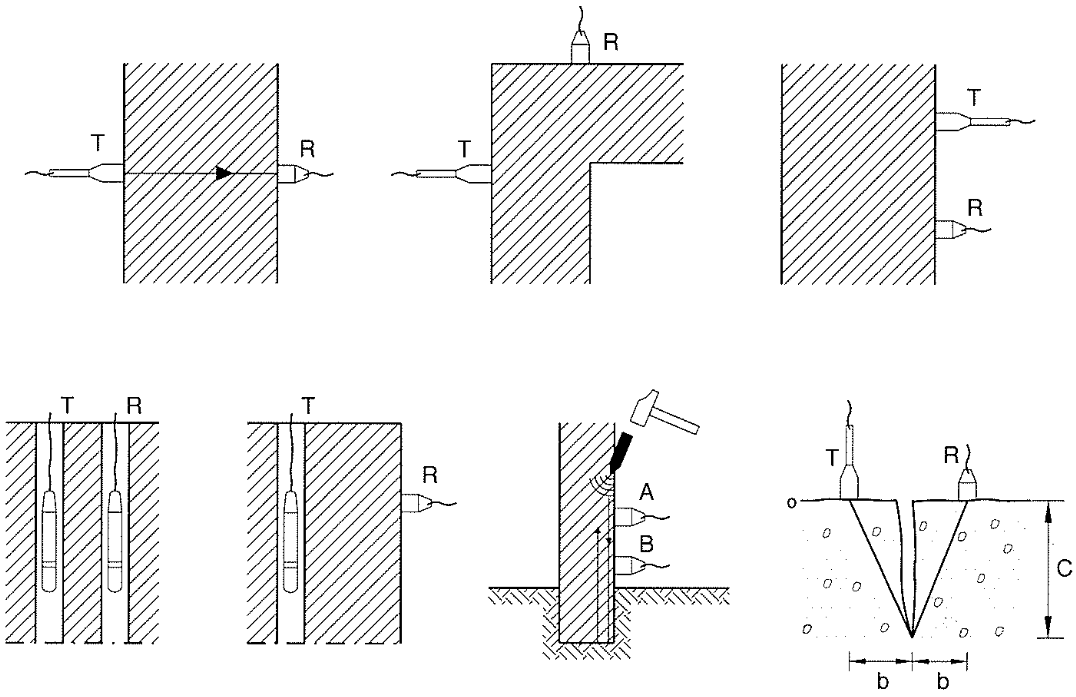


Fig. 2 - Sonic and ultrasonic measurements: different testing schemes

- Mechanical quality index[3] (estimate of deformability modulus);
- Homogeneity of the characteristics of the masonries which a building is composed of;
- Homogeneity of a single structural element (study of an possible bag constitution, the presence of a loosened cortical layer);
- The effect of grouting reinforcements (Fig.3);
- The presence of cracks in continous materials.

Figure 4 shows sonic velocity measurements taken on the masonry structures of the Vezzolano Abbey in Asti.

Sonic Tomography

This testing technique gives a detailed map of the sonic velocity distribution on a plane section of the structure under investigation.
The method consists of obtaining the

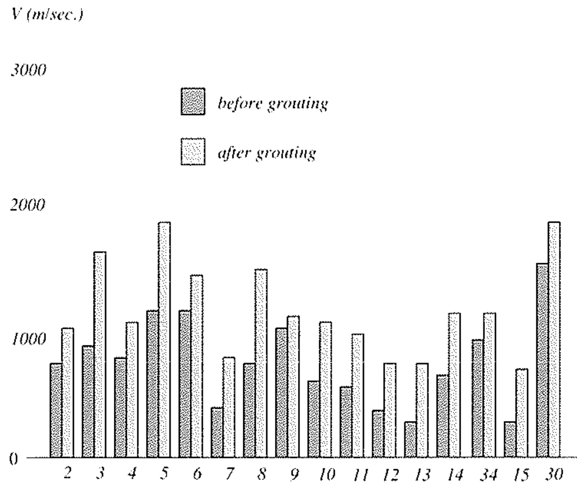


Fig. 3 - Effect of grouting on sonic velocity: Comparison between the rates measured on old masonry buildings in Basilicate before and after grouting.

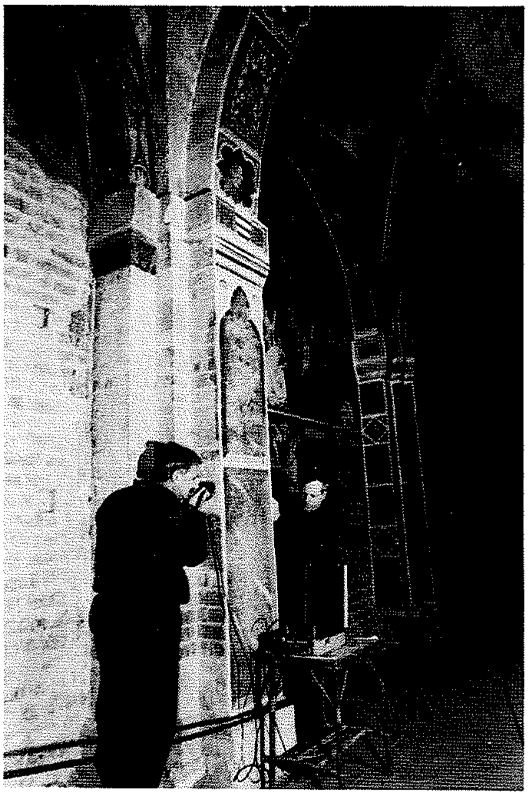


Fig.4 - Measurement of the sonic velocity on the masonry structures of the Vezzolano Abbey (Asti).

time taken by sonic impulses along several directions which uniformally cover the section under investigation. The computation is made by using the inversion process which, starting from the time of sonic signal propagation, reconstructs the field velocity. The section of the masonry is marked by a rectangular mesh grid whose dimension is related to the distance between two subsequent transmissions or receiving points.

The calculation is carried out with the hypothesis that (in a non-uniform velocity field) sonic impulses do not propagate in a straight line but follow a curved line caused by refraction.

This testing technique is widely used for testing concrete structures and is used by ISMES in their investigation of concrete dams to identify areas where the condition of the concrete requires reinforcement. Figure 5 shows the results of a sonic tomography investigation applied on the gravity dam of Careser - the propogation lines are shown as well as the map of the velocities.

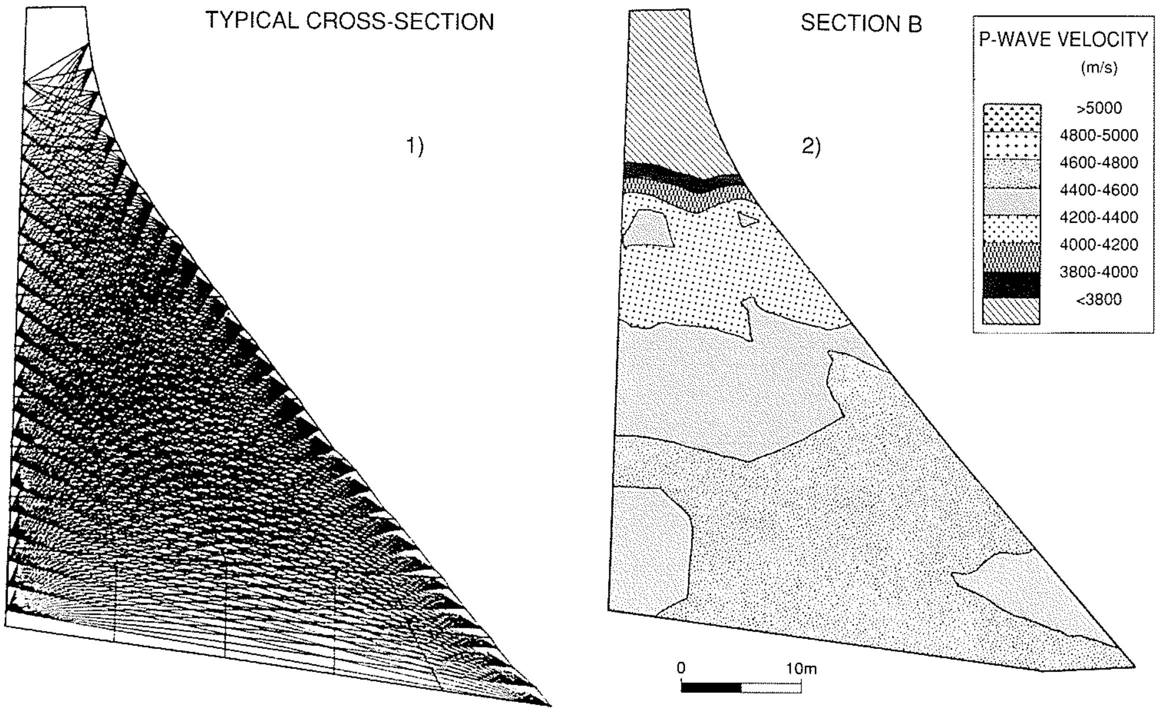


Fig. 5 - Typical results obtained from sonic tomography on a concrete gravity dam.

The use of tomography for masonry structures is still being studied and improved, and its potential is already evident. In Fig. 6 a tomographic study on pillars at the Porta S.Agostino viaduct in Bergamo is shown.

A remarkable improvement can be introduced in the quality and reliability of the results with **tomography for attenuation**, a technique which examines not only the sonic velocity, but also other characteristics of signal transmission (amplitude and frequency). This technique is now being tested, with some promising results being collected from the study of concrete structures.

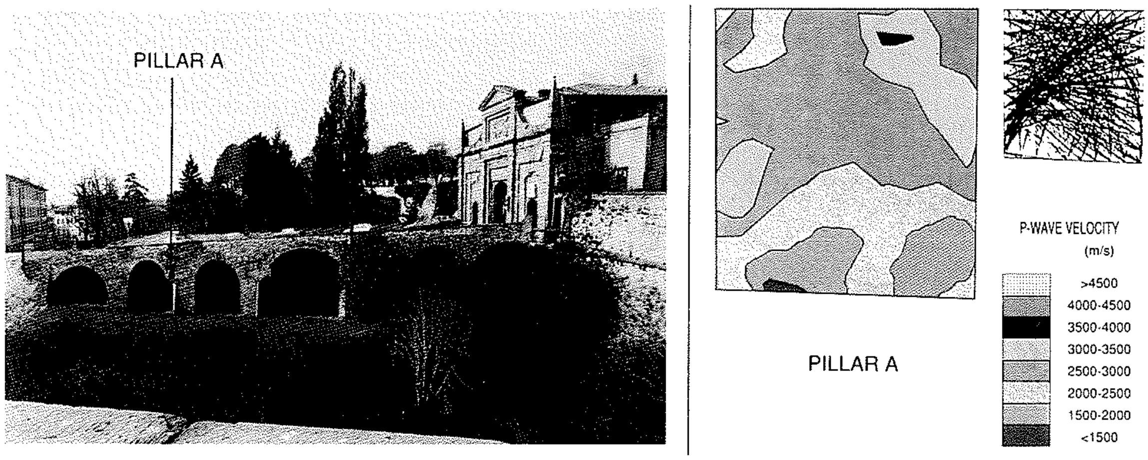


Fig. 6 - Use of sonic tomography on the masonry pillars at the Porta San Agostino viaduct in Bergamo.

Acoustic emissions

This is a method for checking the degradation progress in structures. The acoustic signals studied are composed of the elastic waves emitted by the deformation of a solid body. The propagation of cracks, in fact, are always accompanied by emissions of elastic waves transmitted in the structure and received on the surface. The study of acoustic emissions is initiated by suitably placing a receiving network connected to a recording apparatus on the structure. This method localizes cracks and within certain limits, evaluates their extent. The employment of this technique in checking masonry structures is very limited due to the high cost of installing a data collection system.

Radar Investigation

The radar testing technique uses high-frequency electromagnetic waves (100 MHz - 1GHz) emitted through an antenna with very short impulses (0.5 - 5 μs) and permits us to determine location of separate surfaces between materials with different dielectric constants. The investigation is based on reflection (the reflected waves from the contact surfaces between materials of different dielectric constants are received through an antenna and are transformed into electric signals) so internal defects in the masonry (damp areas, cavities, presence of metal structures, piping, flues) can be located. This technique permits the determination of the depth of the

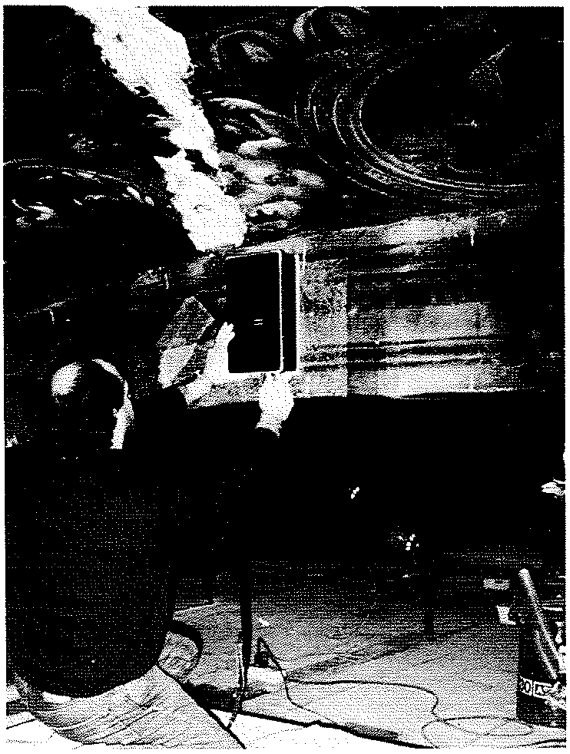


Fig. 7 - Use of radar technique to study structural characteristics of the arches supporting the roof of the Cathedral at Parma.

foundation surface of a building.
Recently the radar technique has been used on the arches which support the roof of the Cathedral in Parma to determine the position of the joints between the blocks of stone that are covered by a fresco (Fig.7).

Thermographic analysis

The thermographic analysis is based on the thermal conductivity of the material and may be passive or active. In the former case it analyses the radiation of the work during the cycle of thermal stress due to natural phenomena (insulation and subsequent cooling). If the survey is active, forced heating of the surfaces analysed are applied. The thermal radiation is collected by apparatus sensitive to infrared radiation, and is then trasformed into electric signals, which in turn are converted into images in different shades of colour.

Thermovision is used to identify areas where morphological structures are covered by plaster that hide construction anomalies (blocked openings etc.). It is particularly interesting for studies on frescoed walls, where it is not possible to take samples or use testing techniques that come in contact with the frescoed surfaces.
Other applications are the survey of the presence of cavities, such as flues, ducts, and water and heating systems, by distinguishing the areas of thermal dispersion and moisture.
It is necessary to point out that the penetration depth of this technique is only a few centimetres so it is unable to locate anomalies which are hidden in the central part of the masonry.

Rebound tests

The rebound tests are aimed at a qualitative evaluation of the compressive strength of mortar and of the superficial strength of stones or brick materials. They can also provide information on local damage of the material. For information on the hardness of the sampling material, pendulum sclerometers (low energy) or Schmidt hammers, may be used. The results obtained with this test can be considered a 'quality index' which must then be correlated with results obtained through mechanical tests on samples.

Magnetometric analysis

Magnetometry locates the presence of metallic elements within the masonry structu-

res. The test includes a magnetic probe which is placed on the masonry surface; then iron bearing materials are identified by anomalies appearing on the instrument's magnetic field.
The technique was set up to study the reinforcement in concrete structures and transferred to masonry buildings, where it is used to locate chains, tension bars or metal connecting pins between blocks of stone.

Slightly-destructive tests

The non-destructive testing techniques described in the previous paragraphs are not sufficient to determine the parameters necessary to evaluate the static condition of a structure and to design reinforcement work.
The evaluation of these parameters is possible only by using special mechanical tests which require, unfortunately, small operations on the masonry. It is necessary for this work to be as little as possible and visible only during testing. Moreover the tests must be simple and finished quickly to reduce the costs of the investigation and to entirely restore the structure in the shortest possible time.
Research into these testing methods have recently seen great developments in Italy due to the strong beleif that they represent the only way at our present disposal to evaluate the structural and mechanical properties of a masonry structure.

Coring techniques

To understand the structural properties of the different types of masonry of which a building is composed, it is important to core small diameter boreholes taking samples in the most representative points of the structure. This operation becomes indispensable in the very frequent case when the masonry consists of two surface layers in regular bond with internal irregular packing. Coring must be done with a rotary saw using a diamond cutting edge. By using a very light, handy perforation tool, corings can be obtained from inaccessible areas (Fig.8). This coring operation allow samples to be extracted from the material on which laboratory tests can be made; this is particularly important when identifying the chemical-physical and mechanical characteristics of mortars. Inside the boreholes additional investigations can be made which help define the structural and mechanical properties of the masonry.

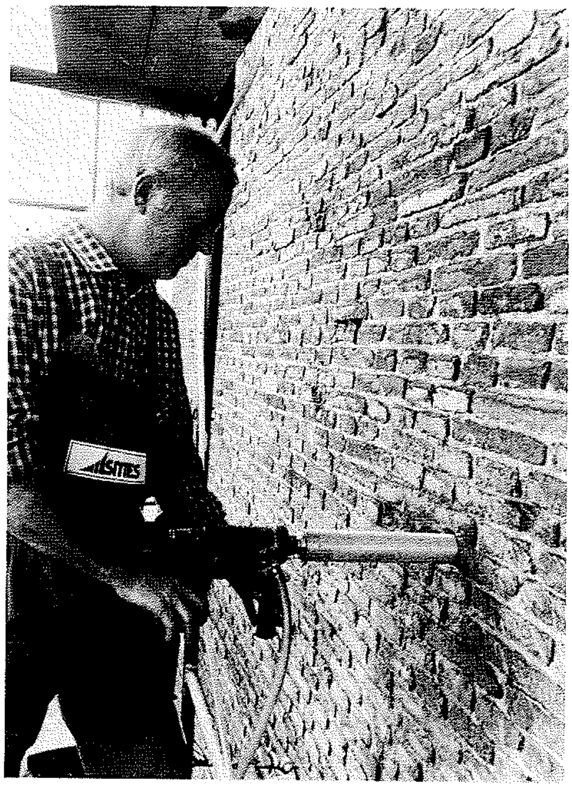


Fig.8 - Light drilling equipment for coring masonry walls.

Borehole video surveys

A small colour video camera (d = 11 mm) may be inserted into the borehole allowing a detailed study of both the front and sides of the hole. The results of this study may be recorded and archived for further analysis after the boreholes have been sealed.

The information obtained by this survey include:

- the structural characteristics of the masonry.
- the measurements of the internal cavities of the masonry.
- the analysis of the propagation of internal cracks and measurements of their openings.

Figure 9 shows the testing equipment and an example of a frontal view in a borehole cored into the external wall of the Church of San Francesco in Arezzo.

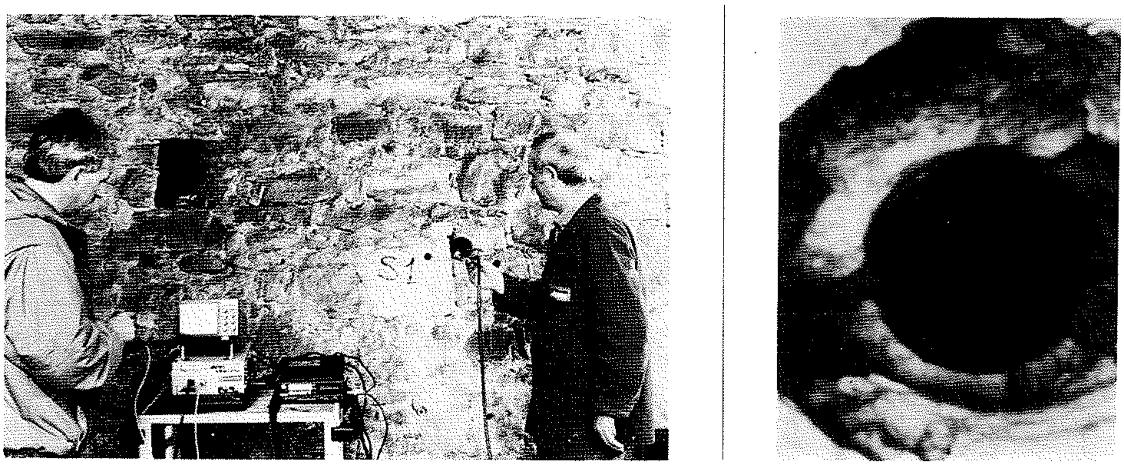


Fig. 9 - Downhole video camera survey: View of the equipment and survey into a borehole.

Flat jack tests

An interesting testing technique based on the use of flat jacks, was developed at the ISMES laboratory a few years ago for the analysis of the mechanical characteristics of existing masonry structures. The first applications of this technique on 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 (ie. deformability, strength, state of stress). After these first encouraging experiences, the use of the flat-jack test rapidly increased and today more than 50 historical monuments have been studied by this procedure.
This very simple technique, which is carried out by introducing a thin flat-jack into the mortar layer, is only slightly destructive. After the test is completed, the flat-jack can easily be 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 area of measurement whose behavior is represented.
The testing technique has been organized to give reliable answers for the following:

- measurement of the state of stress
- determination of deformability and strength characteristics
- determination of the shear strength along the mortar layers.

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. 10 shows the different phases of the test. Two reference points are installed on the wall surface and the initial distance (di) between the two points is measured. A cut perpendicular to the wall surface is then made and the stress release is determined by a partial closing of the cutting, the distance (d) after the cut being d < di. A thin flat-jack is placed inside the cut, 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 direction normal to the plane of the cut. The value obtained must be corrected by a coefficient which depends on the ratio between the flat-jack surface and on the rigidity of the welded boundary.
The value of the state of stress (σ) in the testing point is given by:

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

where:
p - oil pressure
Km - jack constant which must be determined in the laboratory
Ka - AJ/AC (ratio between the surface of the jack and the surface of the cut)
In a brick masonry, the plane cut can be easily made in the mortar layer between two layers of bricks by overlapping holes made with a hand tool. In this type of masonry a rectangular flat-jack is used (40 x 20 cm.). Smaller jacks are also used for measuring the state of stress on structural elements such as arches, pillars, and vaults. A different cutting technique is used in the case of a stone masonry with very thin mortar layers. The cut is made by a steel disc. with a diamond cutting edge, and the flat-jack has the same shape (circular segment with length 32 cm.,

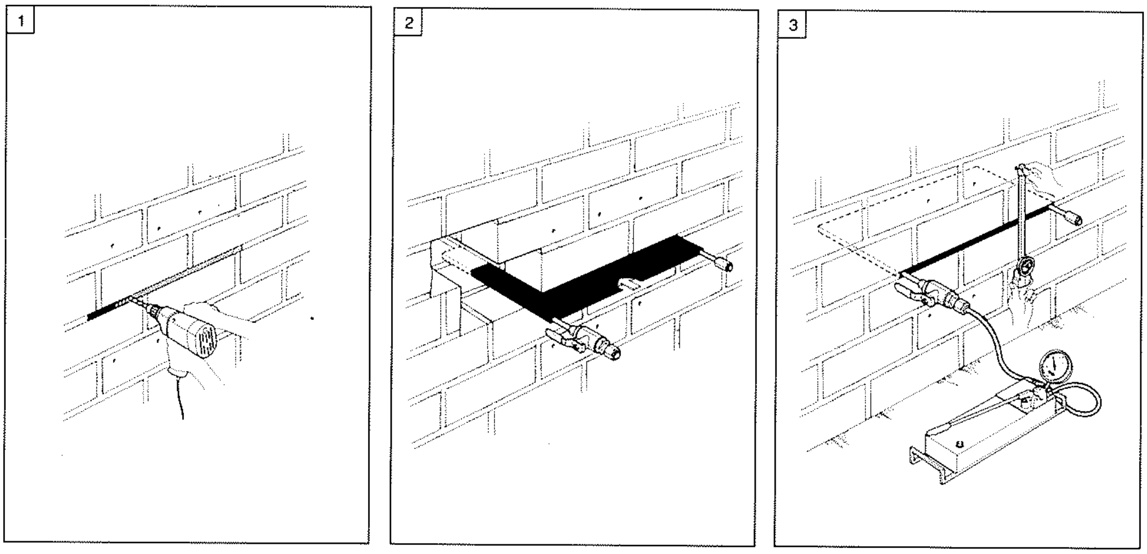


Fig. 10 - Scheme of the flat-jack testing phases on brick masonry.

depth 12 cm. and thickness 3 mm.) The different phases of this testing technique are shown in Figure 11. It must be pointed out that the very limited thickness of this kind of jack required the solution of delicate problems in its design and construction phases.

Fig. 11 - Scheme of the flat-jack testing phases on stone masonry.

An example of the state of stress measured by this technique is shown in Figure 12, which illustrates the results of the measurements taken on the pillars and lateral walls of the Cathedral at Orvieto.

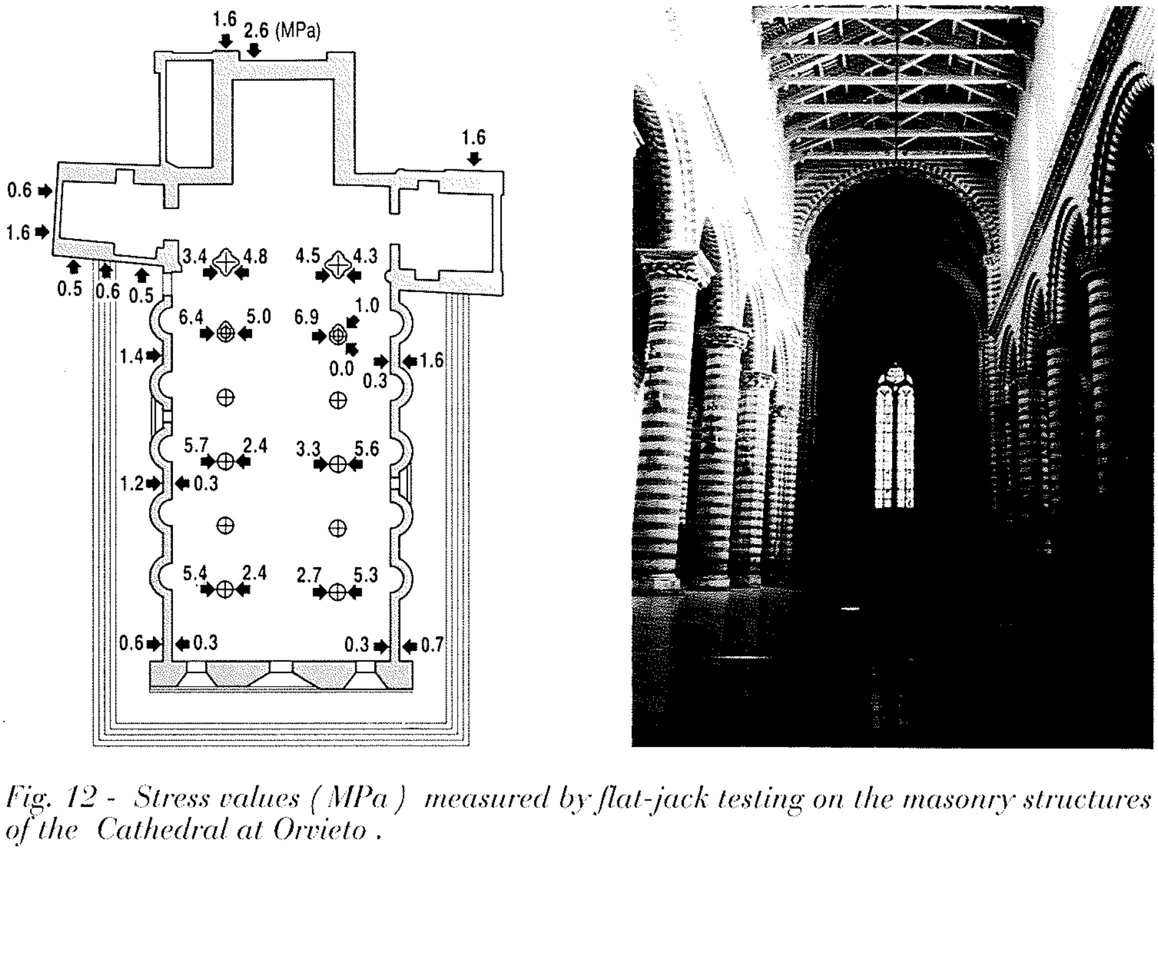
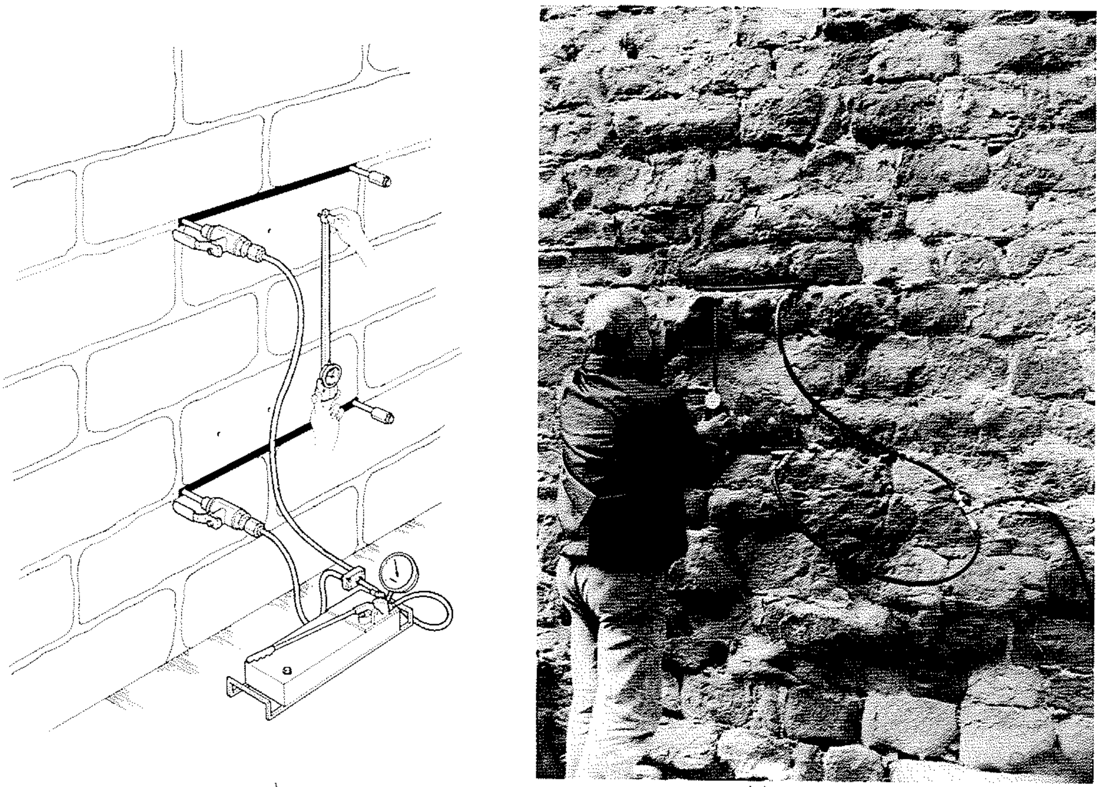


Fig. 12 - Stress values (MPa) measured by flat-jack testing on the masonry structures of the Cathedral at Orvieto.

Determination of deformability and strength characteristics

In a homogeneous isotropic material, the test described previously can also be used to determine its deformability characteristics. In the case of 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 . The two jacks delimit, therefore, a masonry sample of appreciable size to which they apply a uniaxial compression stress (Fig.13). 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 area.



a) b)

Fig. 13 - Test with two parallel flat-jacks to determine deformability characteristics.
a - scheme of the test
b - example of a deformability test performed on the external wall of the San Francesco Church in Arezzo

Several loading cycles are performed at gradually increasing stress levels in order to determine the deformability modulus of the masonry in its loading and unloading phases. Fig.14 shows a view of the test applied to a stone masonry (The lateral wall of San Francesco Church in Arezzo).The loading test above can also be used to evaluate the compressive strength of the masonry. The load is increased until the first cracks in the brick appear, then the strength limit of the masonry can be approximated by extrapolating the stress-strain curve. The effect of the lateral confinement of the sample may be taken into account by calibration tests done in the laboratory.

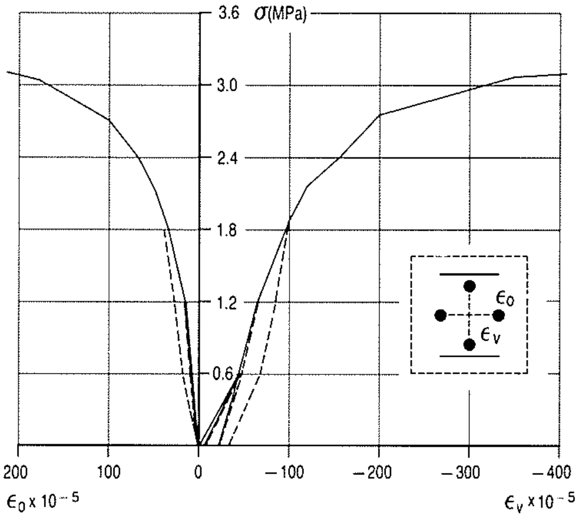


Fig. 14 - Typical stress-strain curve obtained by flat-jack test up to failure, and view of the testing point after the test.

It must be noted that, when nearing failure conditions some cracks appear in the brick, but the damage suffered by the masonry is quite negligible and can be repaired easily. Fig. 14 shows an example of the results of a test made on the masonry walls of St. Eustorgio Cloisters in Milan. The typical stress-strain curve up to failure is presented and the corresponding testing point after the test is shown . It can be observed that the damage undergone by the masonry in quite negligible.

Determining the shear strength along a mortar layer

The flat-jack testing technique (combined with a hydraulic jack) can also be used to determine the strength characteristics of the mortar between the brick layers.
A brick is extracted from the center of the masonry sample delimited by two flat-jacks and a hydraulic jack of the same size is inserted in its place for the application of shear force (Fig.15). The testing technique determines the peak and residual shear strength of the mortar layers.

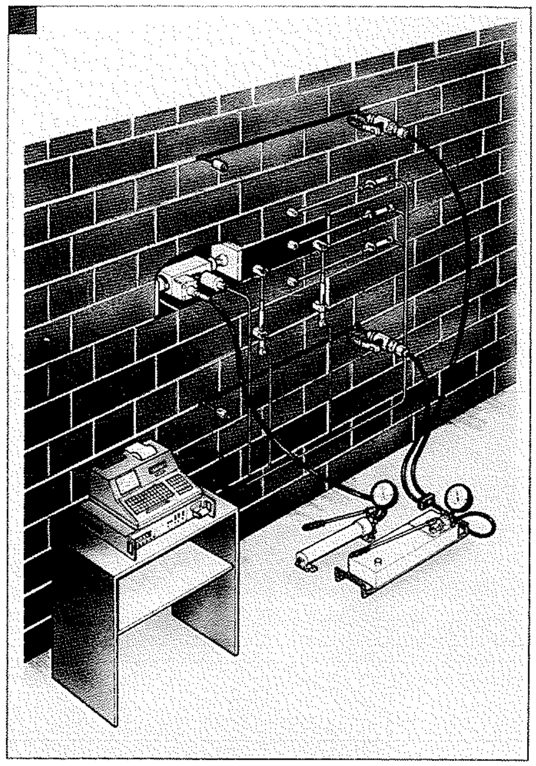


Fig. 15 - Scheme of a shear test along the mortar layers: the normal stress is applied by two flat-jacks and the shear stress is applied with a hydraulic jack.

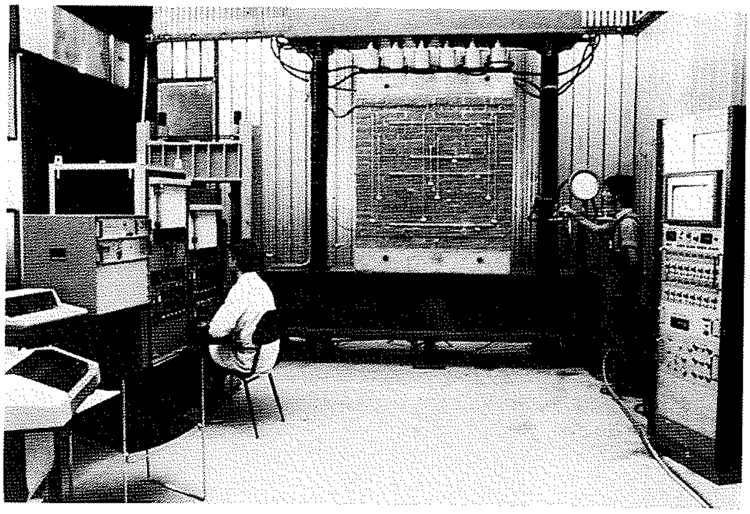


Fig. 16 - View of the loading and measuring equipment for the calibration of flat-jack tests.

By doing several tests with different values of the stress in a direction perpendicular to the joint, the friction angle and the masonry cohesion can be determined. This test is important for the study of masonry resistance to seismic movement.

At the end of the test the jacks are extracted and the masonry is restored to its original state. The brick removed for the implacement of the hydraulic jack is replaced, and the space between the bricks are filled with mortar of the same color as the original.

All of the flat- jack testing phases have been calibrated at the laboratory by a wide series of tests on very large masonry samples. In fig. 16 the loading frame and the measuring equipment used for the calibration tests are shown. It is necessary to point out the high reliability of these tests and the great importance of the results. Their use is highly recommended even if small cuts on the masonry surface are required.

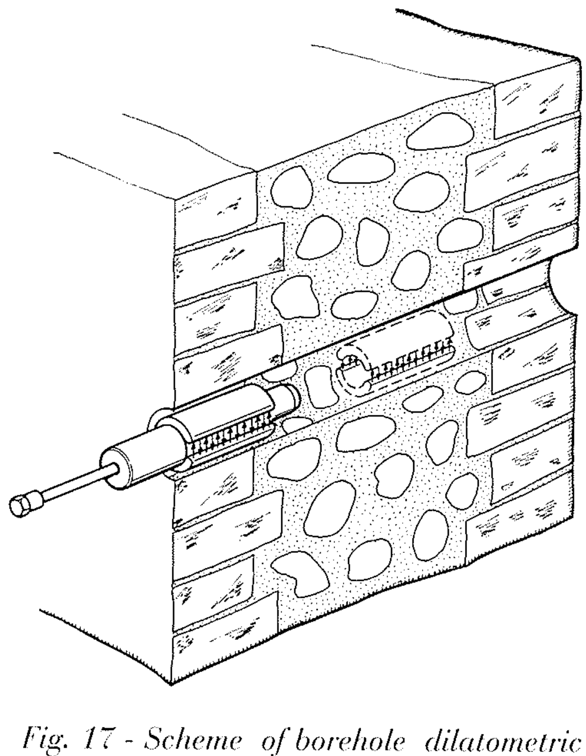


Fig. 17 - Scheme of borehole dilatometric test that determines the deformability characteristics of the surface and inner layers.

Borehole dilatometer

Using the tests with parallel flat jacks one can only determine the deformability characteristics of the superficial layer of masonry. In order to acquire information on the deformability characteristics of the internal masonry it becomes necessary to conduct dilatometric tests using boreholes made by coring. A special probe about 25 cms long applies uniform hydrostatic pressure on the borehole surface, and the measurement of the consequent deformation determines the modulus of deformability (Fig.17). As the portion of masonry used for this test is very limited, the values obtained by the dilatometric test are less representative than those obtained by the flat-jack tests. This testing technique, however, is undoubtedly useful as it determines the ratio of deformability of the internal masonry to the outer layer. Dilatometric testing is also important for testing the deformability characteristics of the foundation structures. Figure 18 shows the testing scheme used on the foundation ring of the Tower of Pisa. Numerous tests, including dilatometric, as well as, sonic-logs and cross-hole measurements were completed in radial boreholes. The values of deformability modulus are shown in

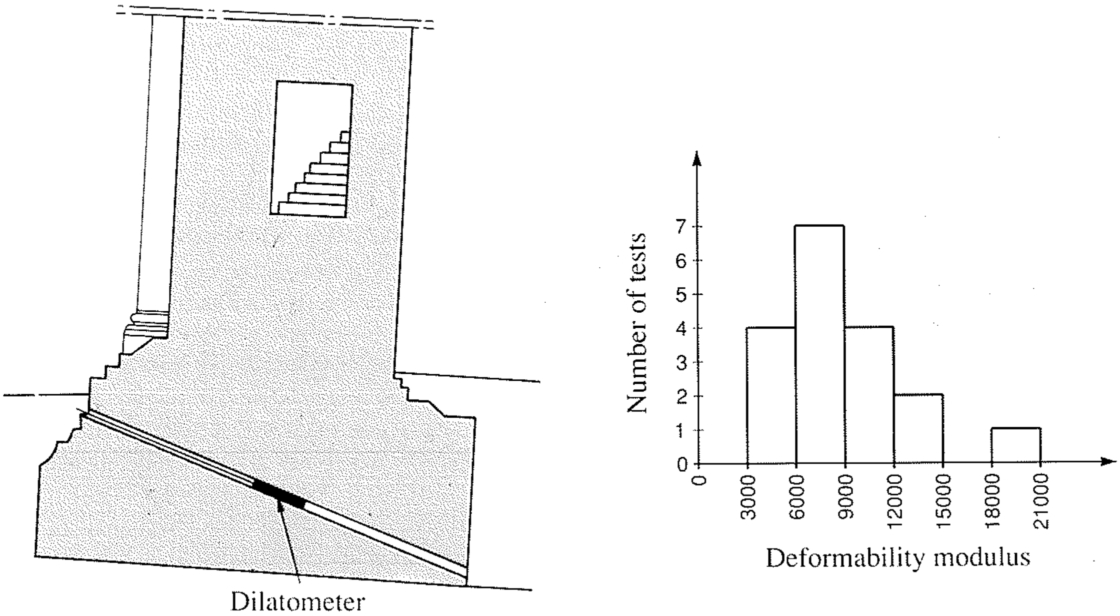


Fig. 18 - Use of the borehole dilatometer for analyzing the deformability characteristics of the foundation of the Tower of Pisa - Histogram of the deformability moduli.

the histogram in Figure 18. It was revealed that the foundations, which in the past had undergone strengthening by grouting, still had good mechanical characteristics throughout its thickness. Therefore, the grouting procedure is believed to have been effective.

DYNAMIC ANALYSIS

The in-situ testing using dynamic methods can be considered a reliable instrument of a non- destructive type, to verify the structural behavior and integrity of a building.
Dynamic investigations can be carried out according to the following procedures:

a) Through the analysis of data gathered as a response to dynamic loads continuously imposed on the structure (urban and railroad traffic, bells ringing, etc.) or from irregular actions. A seismometric network is installed in different parts of the structure and the signals are analysed in terms of amplitude and frequency

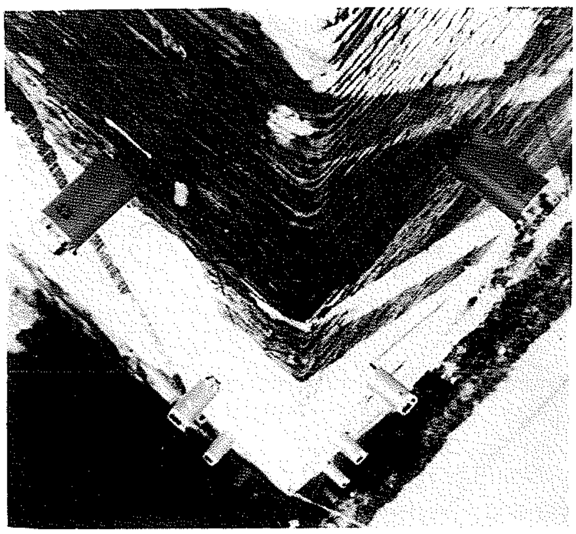


Fig. 19 - Dynamic analysis in a corner of the 'Terme di Caracalla' in Rome, to assess the behavior of the structure in responce to traffic.

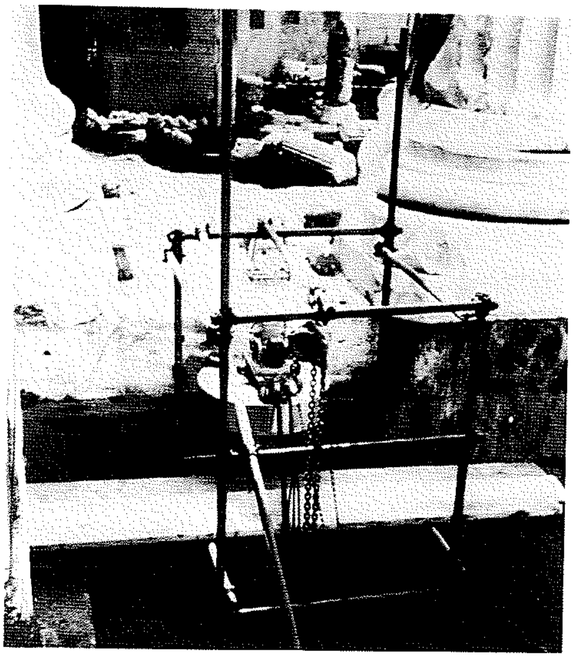


Fig. 20-Dynamic analysis by forced vibration on the Roman temple of Marte Ultore.

content. Through spectral analysis techniques it is then possible to evaluate the dynamic model parameters. As an example, Figure 19 shows the seismometers installed in a corner of the "Terme di Caracalla" in Rome, to assess the response behaviour of the masonry structure to the urban traffic.

b) Subjecting the construction to low intensity forced vibration tests (so as to produce vibrational levels that do not affect the structural integrity) and recording the system response in terms of displacements, velocities and accelerations.
The forced vibrations are induced by vibrodynes and the response measured by seismometric sensors. This second kind of analysis allows the identification of the dynamic behaviour of the structure through the evaluation of its modal parameters (natural frequencies, modal shapes, damping ratios). The knowledge of these parameters allows the computation of the structural response to any type of dynamic load with known characteristics, and in particular for evaluating the seismic vulnerability of the masonry construction. Forced vibration tests repeated over a length of time, allow the evaluation of possible modal parameter variations. These variations may be associated with modifications in the structural integrity, enabling the actual structural degradation of the masonry elements to be quantified. It must be stressed that the information collected not only quantifies the structural degradation of the buildings or parts of them, but they are also important in the planning stage of any structural adaptations, when choosing the type and size of the appropriate strengthening works. Figure 20 shows the forced vibration test carried out on the pillars of the Roman temple of "Marte Ultore".
The forced vibration technique using a vibrodine was recently employed by ISMES to analyse the structural condition of several towers in the town of Pavia. The obtained results from these tests, together with those supplied by the flat-jack test, have permitted the discovery of anomalies in the structural behaviour in some of the towers examined.

MONITORING

Installing measuring instruments to monitor the structural behaviour of a building can be considered a reliable method for a non-destructive evaluation of the static condition of the structure. This investigative technique is gaining popularity because, besides supplying information on the static conditions of the building, it is considered the only way to guarantee the safety of the structure before, during and after the consolidation work.
The principal features which are monitored in Italy are the following:

- openings of the main cracks in masonry structures;

- absolute and relative horizontal movements of vertical structures;
- rotation of vertical and horizontal structures;

- internal and external temperature;

- behaviour of soil and rock foundations;

The evolution of the deformation, in function of time and temperature, allows one to separate the thermal effect from the deformation due to other causes (foundation settlement, structural modifications, new forces induced on the structure, aging of the materials). Measuring the openings of cracks is by far the most widespread method. The easiest measuring technique is using a removable mechanical extensometer which is positioned on two small metal plates positioned on opposite sides of the crack. To improve the reliability of the measurements, fixed extensometers can be used that are provided with electric transducers connected to an automatic data collection system. In Figure 21 an extensometer, recently installed by ISMES at the San Benigno Tower (Turin) is shown. The extensometer is constructed with two spherical devices at its two ends and is completely waterproof, for use on surfaces outside.

Fig. 21 - Special extensometer for measuring the principal cracks in the Tower of San Benigno Canavese (Turin).

To measure absolute horizontal movements of vertical elements, a fixed pendulum is used with a measuring system based on a telecoordinometer.
Less expensive and easier to install, are the instruments for measuring relative movements of vertical structures. In this case, a long base extensometer is used which is equipped with an invar wire kept in tension by a weight. The movements of the weight are easily measured by means of electric transducers. In Figure 22 this instrument is used to measure the relative displacements of the main walls of the Abbey of San Fruttuoso near the town of Portofino. A long-base extensometer installed on the lateral wall of the San Bernardino Church in Bergamo is shown in Fig. 23.

Rotation changes of vertical or horizontal elements can be measured by installing either fixed or removable clinometers of the type shown in Fig.24.
In constructions of great historical or monumental interest, the instruments are usually connected to automatic collecting and recording systems which can quickly

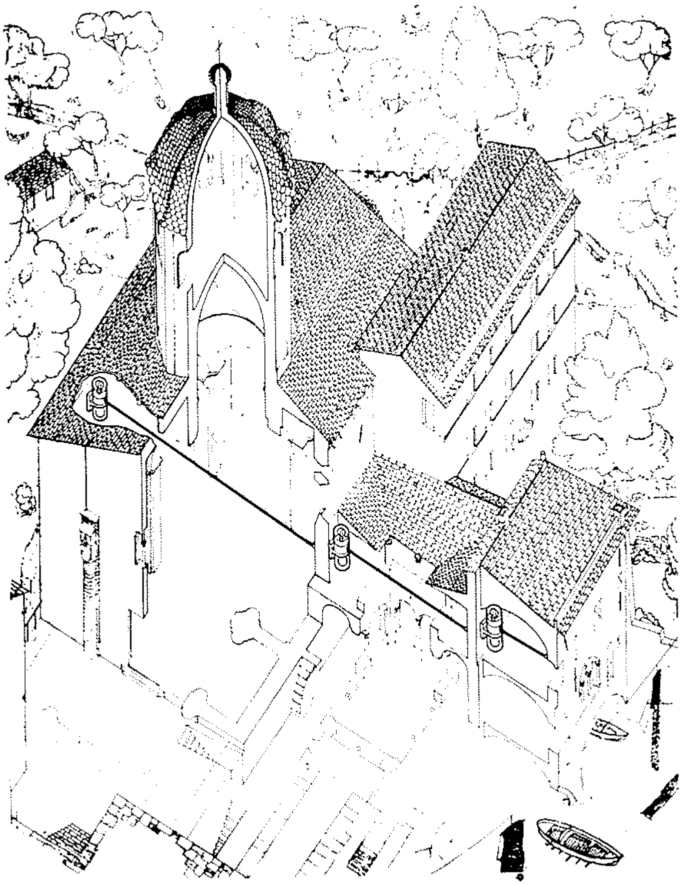


Fig. 22 - Use of long-base extensometer with invar wire for measuring the relative displacement of the vertical walls at San Fruttuoso Abbey in Portofino

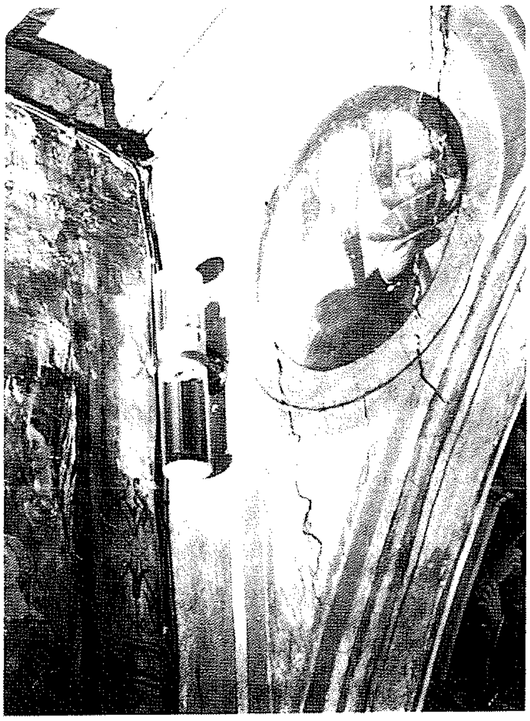


Fig. 23 - View of long-base extensometer installed on the lateral wall of San Bernardino Church in Bergamo.

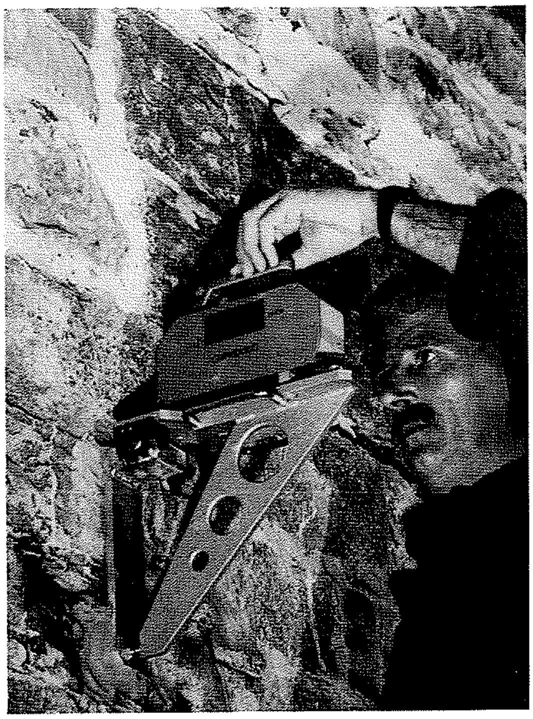


Fig. 24 - Measuring the rotation of the vertical walls by a removable clinometer.

indicate possible irregularities in the structural behavior.
ISMES has recently installed numerous monitoring systems in buildings and monuments of great importance.
These are:

- Milan Cathedral (during the reinforcement work on the pilars) (Fig. 25)
- Dome of S.Maria del Fiore in Florence
- Towers and Cathedral in Pavia
- Church of San Francesco in Arezzo
- Cathedral of Perugia
- Walls of Leonardo's Last Supper in Milan

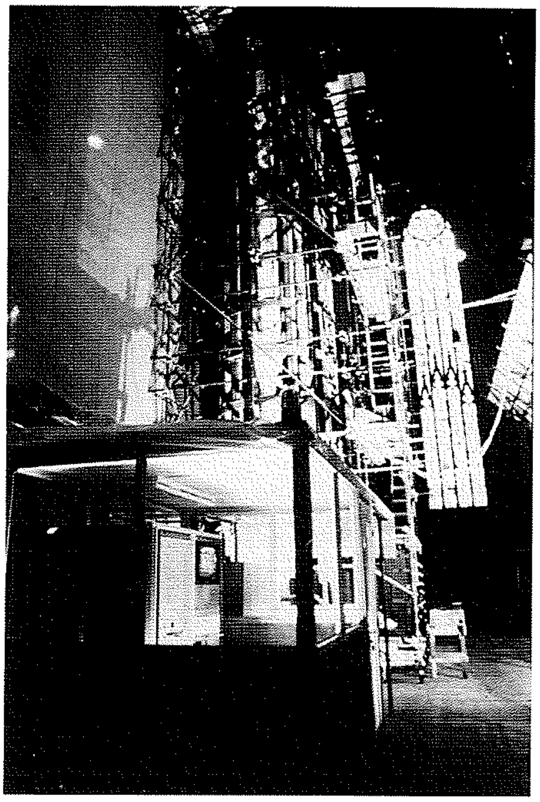


Fig. 25 - Automatic data acquisition and recording system installed to monitor the consolidation work on the pillars of the Cathedral in Milan.

NON-DESTRUCTIVE TESTS USED IN OTHER EUROPEAN COUNTRIES

In this chapter, a summary of the testing techniques used by other European countries to determine the mechanical characteristics of masonries is presented. Due to the enormity of the subject, only the most significant methods will be mentioned; using material from the most recent international conferences on the subject and from members of the International Commission on Masonry Structures. Testing techniques that were not previously mentioned in this text will be briefly described.

BELGIUM

- SONIC MEASUREMENTS
- THERMOGRAPHY
- GEO-ELECTRIC MEASUREMENTS IN COMBINATION WITH CORINGS

  Geo-electric measurement tests give the distribution of the resistivity over the masonry mass. Using calibration corings, the resistivity is related to void content, porosity and composition. After grouting, the same procedure is used to check the consumption and uniform quality of the treatment.

FRANCE

- FLAT-JACK TESTS (measuring the state of stress)
- SONIC MEASUREMENTS
- RADAR INVESTIGATION
- CORING AND VIDEO SURVEYS
- REBOUND TESTS

GREAT BRITAIN

- RADAR
- FLAT-JACK TESTS (measuring the state of stress)
- SONIC MEASUREMENTS
- ACOUSTIC-EMISSIONS (to test the integrity of masonry arch bridges)
- ACOUSTIC FREQUENCY RESPONSE
- PULL-OUT TEST (helical probe for determining mortar quality)
- BOND-WRENCH
  This test (developed at the UK Building Research establishment) measures the force needed to debond a masonry unit, assessing the mortar bond and calculating the flexural performance of the masonry (Fig.26).
- INTERNAL FRACTURE
  This is an adaption of the pull-out test. An object is fixed into the material and then pulled out, using a standard diameter reaction ring and a force measuring device. The subsurface tensile strength is measured by the force required to separate a cone of material from the main body. The use of this test for masonry materials is now being developed.

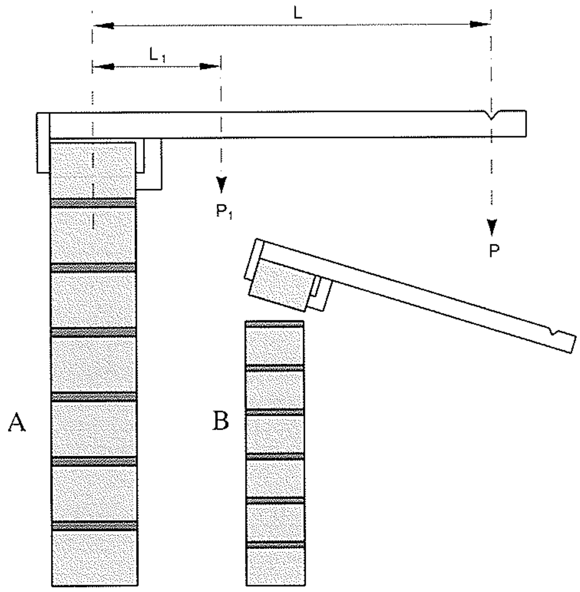


Fig. 26 - Scheme of the bond-wrench test: a) start of test with load p applied; b) after failure of the bond between unit and mortar.

GREECE

- SCRATCH-WIDTH METHOD
  This test is used to estimate the compressive strength of stones and/or mortars.
  A standard pointed steel bar (held against the wall by a standard load) is dragged along a mortar surface. The width of the scratch produced in the mortar is measured, using appropriate sized lenses.

- FRAGMENTS TEST METHOD

  Small mortar fragments are taken from the joints and arranged in a special mold by a strong matrix. Then a direct-tension test is made on the mold. The fragment-test is used in combination with the scratch-width method.

- BONDING CAPACITY

  This test is used to evaluate the bond between the mortar and its support, andto control subsequent treatment of the surface layer of bricks and stones. A circular steel plate is positioned on the surface of the mortar (after a hole has been drilled) and tensile stress is then applied (Fig.27).

- RADIOGRAPHY

  This method is used to identify internal irregularites (voids, inclusions) and to measure the depth and width of cracks. A radioactive source is positioned in front of the feature under investigation, and a photographic film is placed behind the feature. The use of this technique is complicated by the safety precautions that must be adhered to. It has been used to investigate important statues.

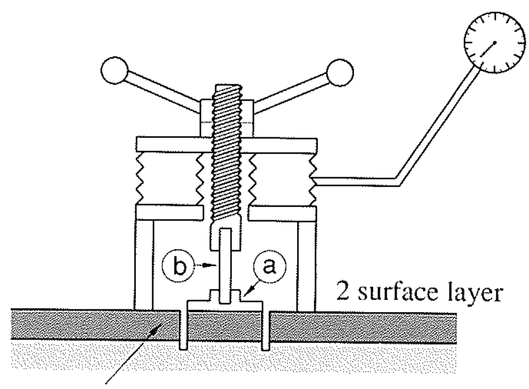


Fig. 27 - Scheme of bonding capacity test.

GERMANY

- SONIC MEASUREMENTS
- ACOUSTIC EMISSION
- RADAR INVESTIGATION
- GEO-ELECTRIC INVESTIGATIONS
- CORING AND VIDEO SURVEYS

ROMANIA

- ULTRASONIC PULSE VELOCITY
- REBOUND TESTS
- COMBINED TECHNIQUE BASED ON PULSE VELOCITY AND REBOUND INDEX
- PULL-OFF METHOD

  Measuring the force necessary to pull a metal disc, glued by esposy resin, off a stone surface.

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