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Possibilities of the experimental techniques for the structural analysis of historical constructions

POSSIBILITIES OF THE EXPERIMENTAL TECHNIQUES FOR THE STRUCTURAL ANALYSIS OF HISTORICAL CONSTRUCTIONS

Pier Paolo Rossi

Ismes S.p.A. - Bergamo - Italy

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SUMMARY

The most important testing techniques used for a non-destructive evaluation of the static conditions of masonry structures are presented in this paper.
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, deformability 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.

1. INTRODUCTION

Knowledge of the physical and mechanical characteristics of the supporting structural elements of an historically significant building or monument is necessary for the performance of a coherent and correct analysis of the static conditions of the structure. These supporting elements (pillars, walls, arches and facades) are made using materials and construction techniques that vary considerably from one geographic area to another, thus, their structural characteristics must be evaluated case by case through a careful diagnostic investigation program.

The methodology typically adopted for analysing the static conditions of an existing masonry structure involves preliminary recognisance surveys that include: a geometric and photographic survey; a detailed survey of existing cracks and other damage induced to the structure during its life and an analysis of the construction history of the building and its various uses. To this initial phase of the investigation, which already highlights the major structural problems, a series of specialised investigations is added to determine the parameters suitable for the definition of the static behaviour of the edifice.

Diagnostic investigations are often conducted using only simple and rapid non-destructive testing techniques. It must be emphasized, however, that the use of only non-destructive tests is not sufficient to satisfactorily resolve structural problems. The results obtained via these techniques are generally qualitative in nature and give only a preliminary evaluation of the mechanical characteristics of the masonry by defining their mechanical "quality indices". Nonetheless, even though these tests cannot provide quantitative evaluation of the mechanical parameters, their use is very interesting in that they consent the acquisition of precious information regarding the homogeneity of the masonry and the eventual presence of local structural anomalies.

The only reliable means for the determination of the parameters related to the static behaviour of a structure is that of utilising a slightly-destructive method that require some intervention, although small, to the structural element. It is necessary that these interventions (coring and cutting) have dimensions such that they do not affect structural integrity and that they are designed such that no superficial scars are evident at the end of the investigation. The slight alteration of the building must be permitted only as a transitory phase.

Diagnostic investigations are often accompanied by the installation of instrumentation for the monitoring of deformational behaviour of the structure with time. Over and above guaranteeing the safety of the structure during the various interventions, this structural monitoring can also be considered a very reliable investigation method itself for the evaluation of the static conditions of the structure.

2. 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 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 survey on a wall of the Cathedral in Pavia and on a bell-tower in Bergamo. Normally, the geometrical survey is extended to foundation structures by excavating small exploratory shafts or by continuous core drilling.

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 inve-

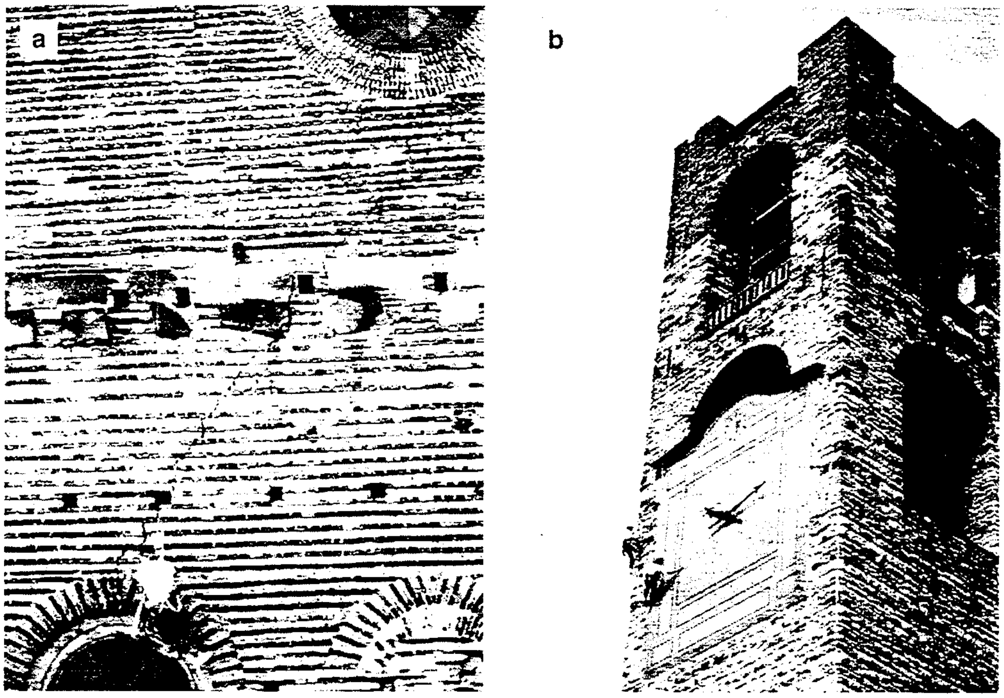

Fig. 1 - Crack pattern investigation
a) external wall of the Cattedral in Pavia b) Bell tower "Campanone" in Bergamo.

stigations 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.

3. 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 not very expensive 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.

3.1 Non-destructive testing techniques

(a) 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 ultrasonic 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 boreholes on the structure to be examined, a cross-hole or down-hole sonic test is possible. Figure 2 shows some possible test schemes.

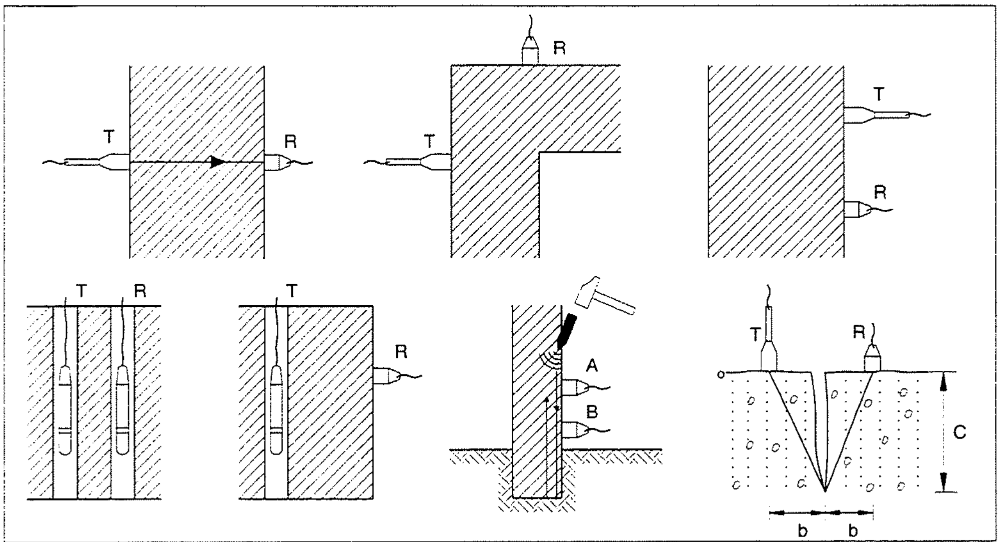

Fig. 2 - Sonic and ultrasonic measurements: different testing schemes.

By using sonic test methods, the following information can be obtained:

- Mechanical quality index' (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.

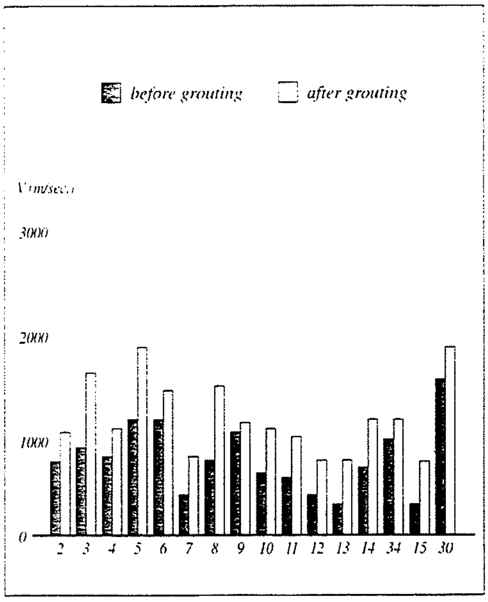

Fig. 3 - Effect of grouting on sonic velocity: Comparison between the rates measured on old masonry buildings before and after grouting.

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

(b) 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 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.

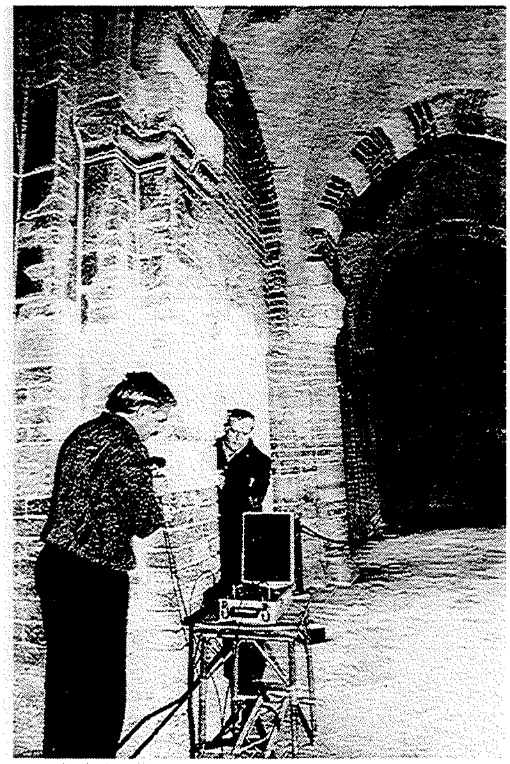

Fig. 4 - Measurement of the sonic velocity on the masonry structures of the Vezzolano Abbey (Asti).

This testing technique is widely used for testing concrete structures and is used by ISMES in the 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 a concrete gravity dam - the propogation lines are shown as well as the map of the velocities.

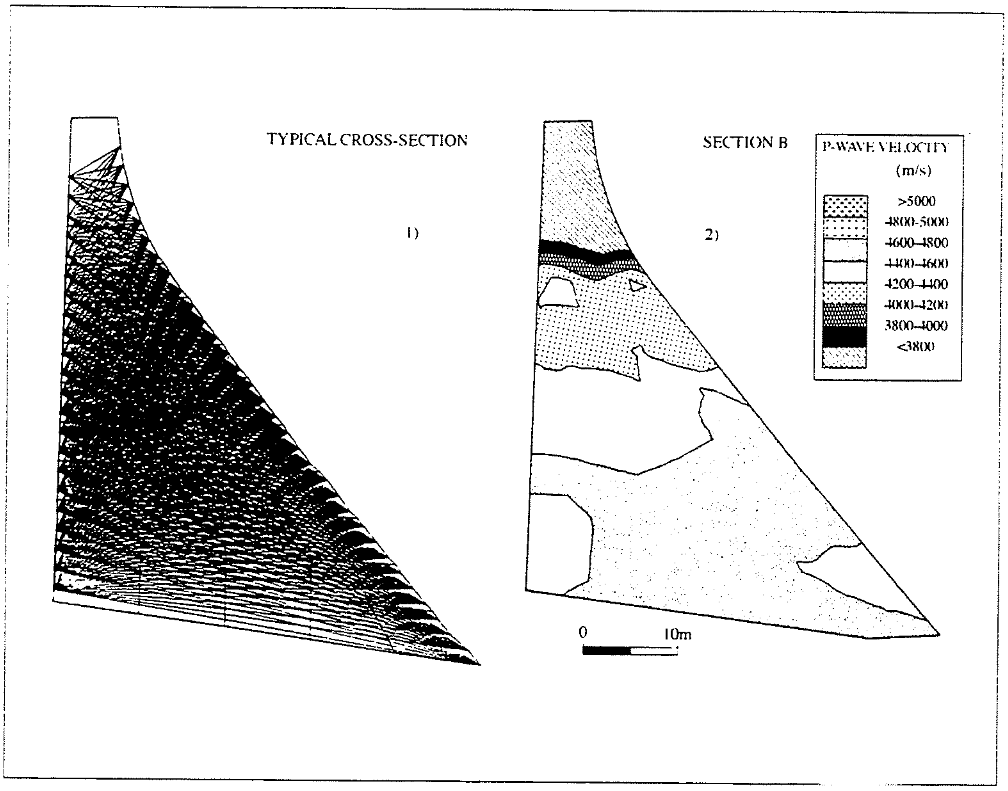

Fig. 5 - Typical results obtained from sonic tomography on a concrete gravity dam.

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.

The sonic tomography has recently been used for the analysis of the structural characteristics of St. Mark's Basilica in Venice providing a clear mapping of the different velocity zones. As an example, Fig. 6 shows the results obtained on pillars 1 and 2. It can be clearly observed that pillar 1, which was consolidated by grouting about 30 years ago, shows high velocity values, especially in the internal zone which was involved in the grouting operation. On the contrary, the velocity values obtained for pillar 2 show that the mechanical characteristics of this pillar are very poor (in fact no consolidation work was performed on this pillar in the past).

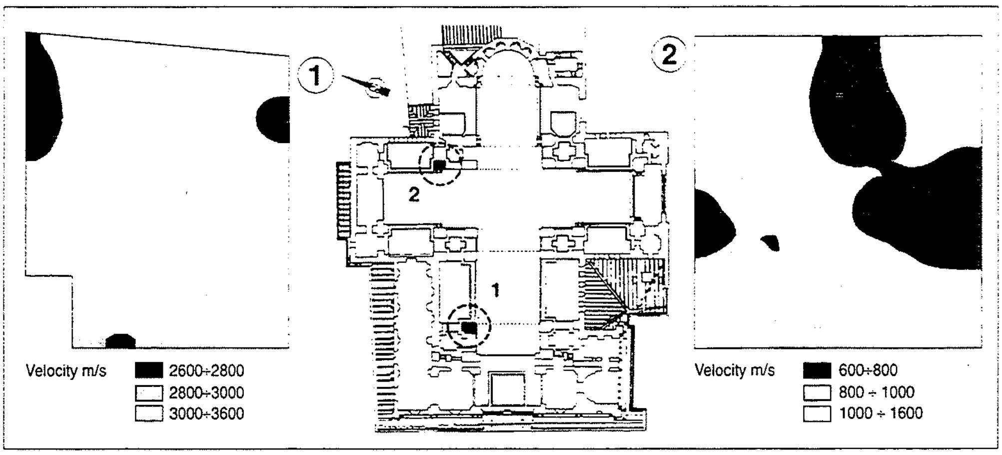

Fig. 6 - Results of tomographic survey in two pillar of St. Mark's Basilica in Venice. The pillar 2 has very poor mechanical characteristics while pillar 1, which was consolidated by grouting 30 year ago, shows high velocity values.

(c) 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 allows to determine location of separation surface between materials with different dielectric constants. The investigation is based on reflection of the electromagnetic waves from the contact surfaces between materials of different dielectric constants so internal defects in the masonry (damp areas, cavities, presence of metal structures, piping, flues) can be located.

Recently the radar technique has been used on the pillars of St. Mark's Basilica in Venice (Fig. 7) in order to determine the location of eventual anomalies in the masonry (voids, etc.).

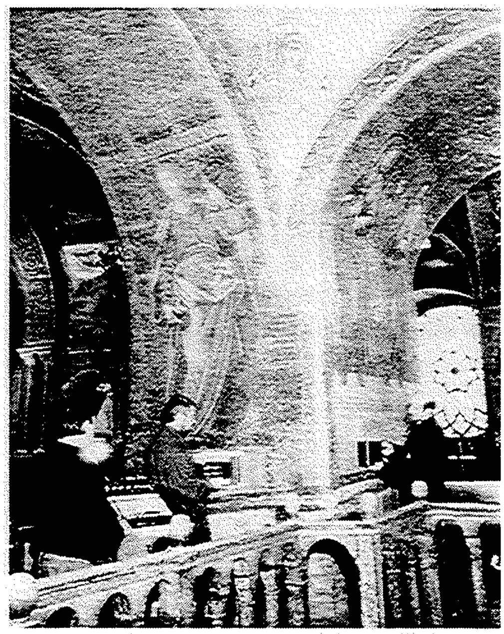

Fig. 7 - Use of radar technique to study structural characteristics of the pillars of St. Mark's Basilica in Venice.

(d) 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 the 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.

(e) 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 result obtained with this test can be considered a 'quality index' which must then be correlated with results obtained through mechanical tests on samples.

(f) Magnetometric analysis

Magnetometry locates the presence of metallic elements within the masonry structures. 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.

3.2 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.

(a) 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. This coring operation allow samples to be extracted from the material on which laboratory tests can be made; this is particularly important to analyse the chemical-physical and mechanical characteristics of bricks, stones and mortars. The boreholes can then be used for additional investigations (video camera survey, dilatometric tests, sonic measurements) which help to define the structural and mechanical properties of the masonry.

The coring technique is also very important to evaluate the characteristics of the foundation masonries. Fig. 8 shows the drilling equipment which was used to investigate the foundations of St. Mark's Basilica in Venice. In the same figure the structural scheme of the foundation masonry is shown.

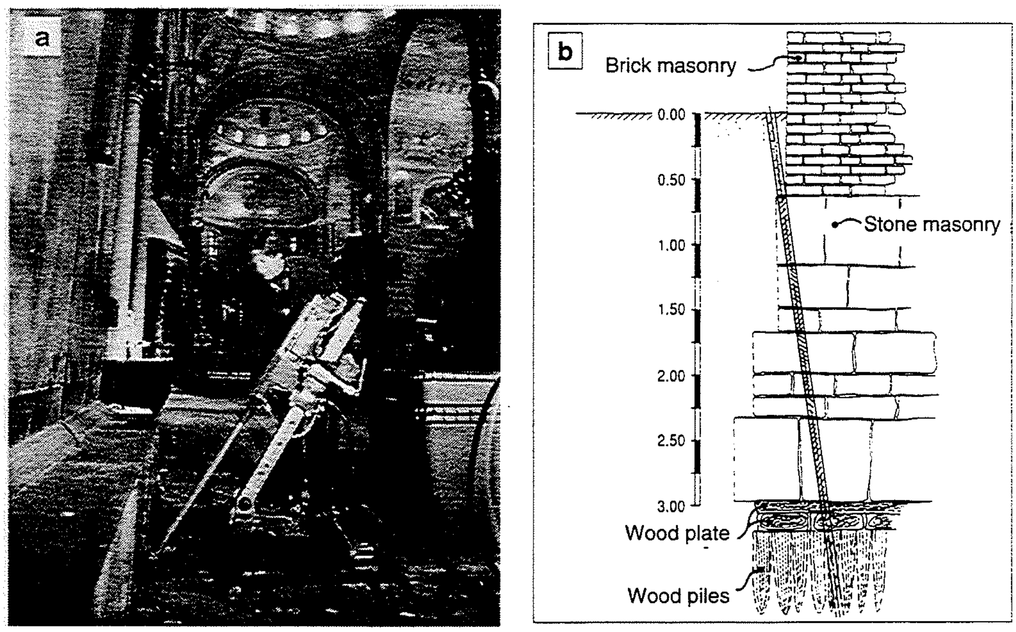

Fig. 8 - Analysis of the structural characteristics of the foundation masonry of St. Mark's Basilica in Venice: a) drilling equipment b) structural scheme of the foundation masonry.

(b) Borehole video surveys

A small colour video camera 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 an example of the video camera survey carried out on the foundation masonry of St. Mark's Bell Tower in Venice.

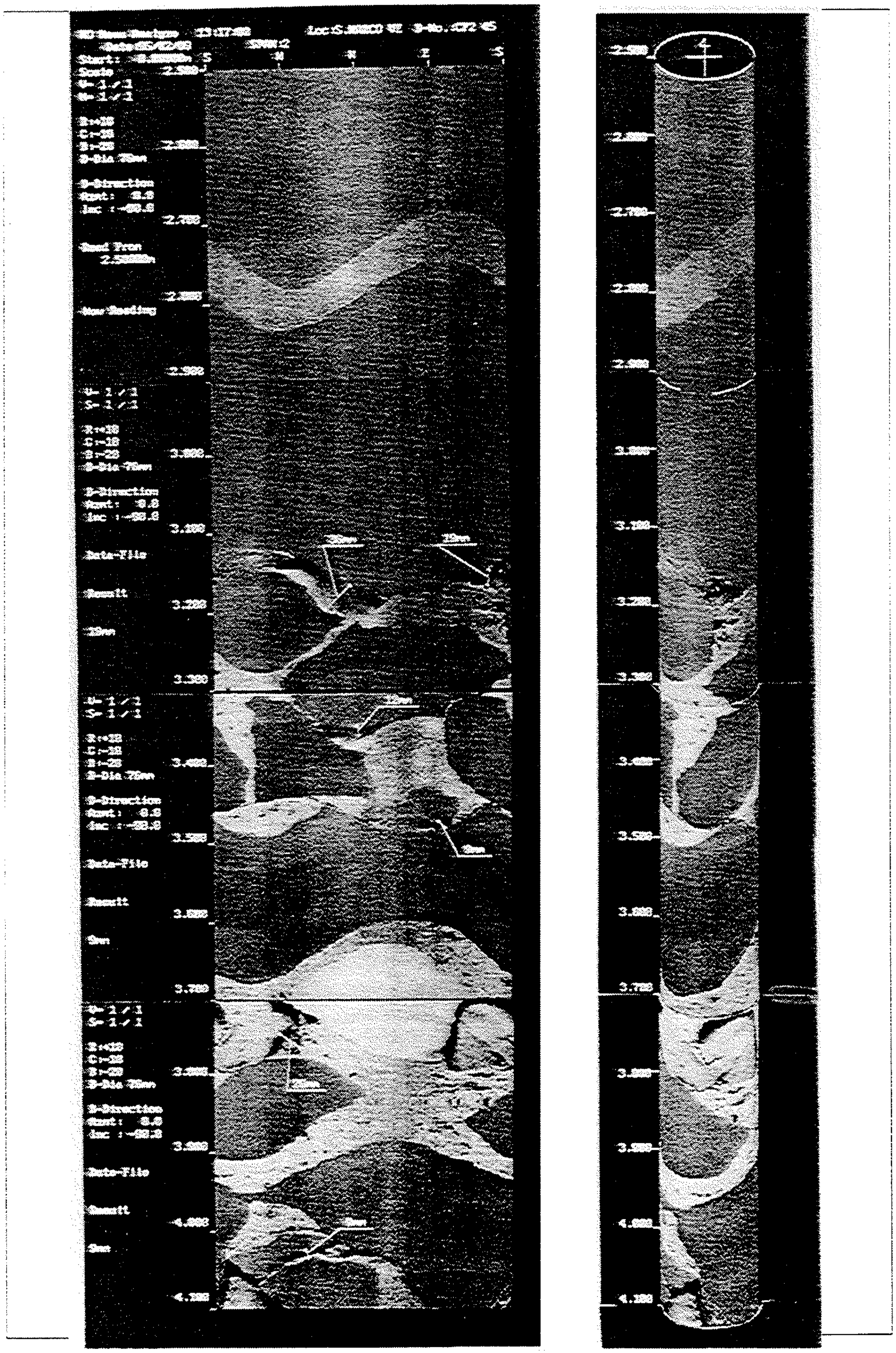

Fig. 9 - Video camera survey carried out on the foundation masonry of St. Mark's Bell Tower in Venice: a) lateral view of the surface of the borehole b) reconstruction of the specimen by computer programm.

(c) Flat jack tests

An interesting testing technique based on the use of flat jacks, was developed at the ISMES laboratory about 15 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).

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 (d_i) 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 $d < d_i$. A thin flat-jack is placed inside the cut, and the pressure is gradually increased to cancel the previously measured convergency.

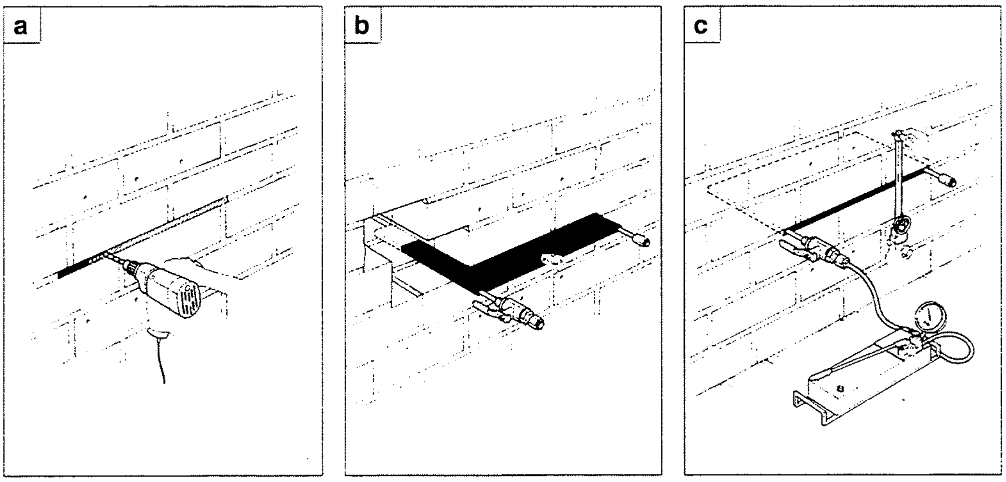

Fig. 10 - Scheme of the flat-jack testing phases on brick masonry.

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 = A_J/A_C (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., 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.

Fig. 12 shows the different shapes of flat-jacks used to measure the state of stress on brick and stone masonries.

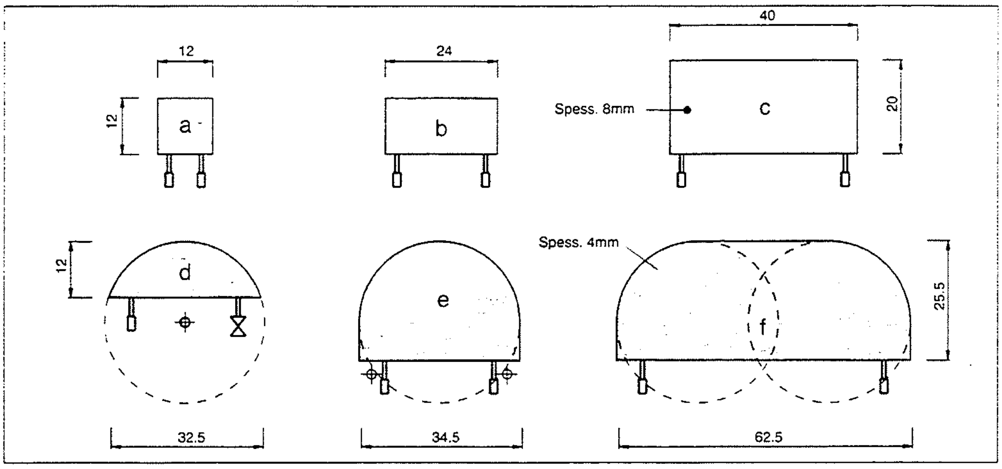

Fig. 12 - Shapes an sizes of the flat-jacks used for the measurements of the shot of stress: a) b) c) brick masonries, d) e) f) stone masonries.

With the aid of the flat-jacks types e) and f) it is possible to analize very irregular and non-homogeneous stone masonry, as shown in Fig. 13.

An example of the results obtained by flat-jack test is shown in Figure 14, which illustrates the results of the measurements taken on the pillars and lateral walls of the Cathedral in Orvieto.

Fig. 13 - Test with a flat-jack of the type e) on a very week and irregular stone masonry.

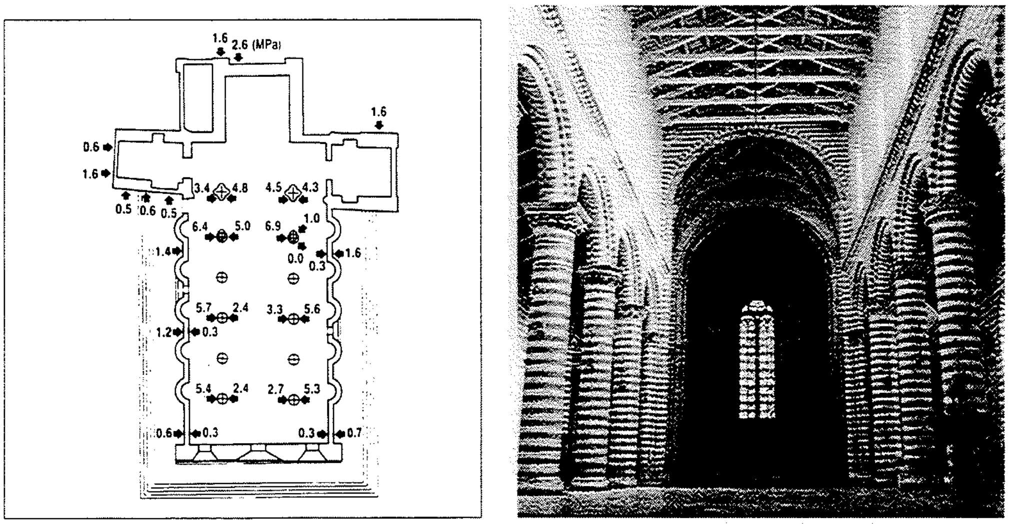

Fig. 14 - Stress values (MPa) measured by flat-jack testing on the masonry structures of the Cathedral in Orvieto.

Determination of deformability and strength characteristics

In a homogeneous isotropic material, the test previously described 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. 15a). 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.

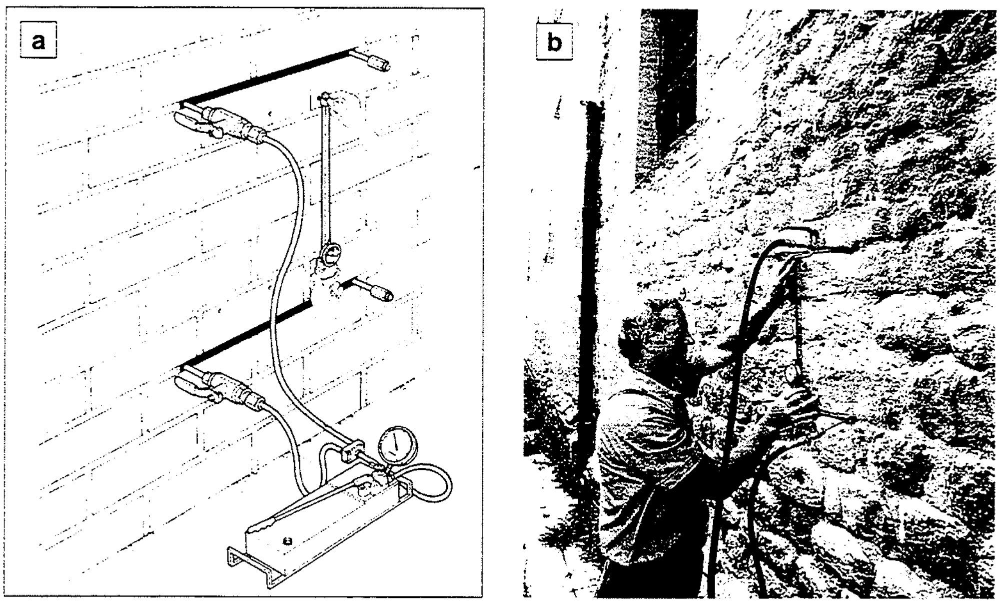

Fig. 15 - Test with two parallel flat-jacks to determine deformability characteristics:
a) scheme of the test b) example of a deformability test performed on the external wall of the Church of "San Francesco" in Arezzo.

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. 15b shows a view of the test applied to a stone masonry. 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.

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. 16 shows an example of the results of a test made on the

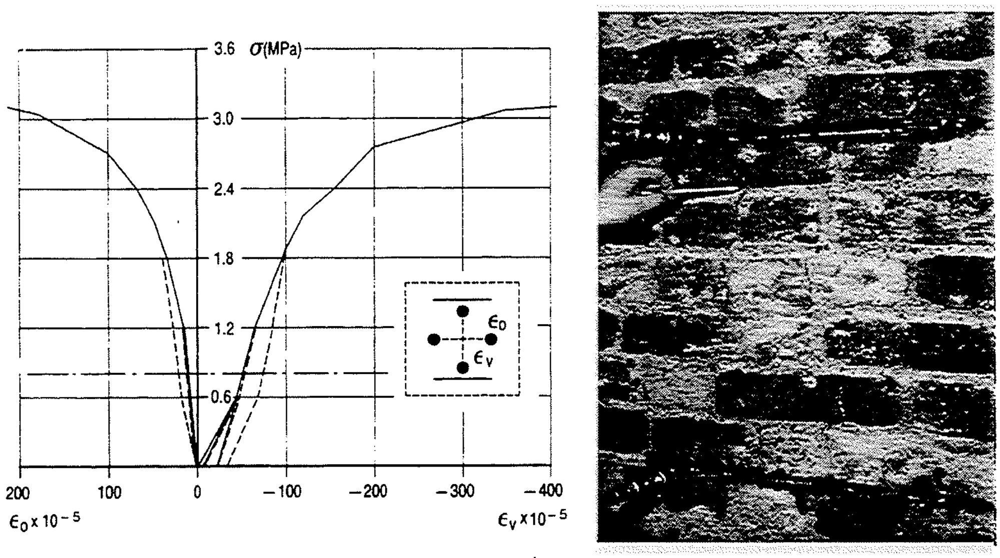

Fig. 16 - Typical stress-strain curve obtained by flat-jack test up to failure, and view of the testing point after the test.

masonry walls of the Cloisters of St. Eustorgio in Milan. The typical stress-strain curve up to failure is presented and the testing point after the test is shown. It can be observed that the damage undergone by the masonry in quite negligible.

Recently the testing techniques have been developed in order to allow their execution also in points where the conditions of access are very difficult (i.e. the high buildings and the towers). A special training to the technicians, combined with climbing techniques, to day allows to carry out all the investigations, including coring and flat-jack test, on the high structures without the aid of scaffoldings (Fig. 17).

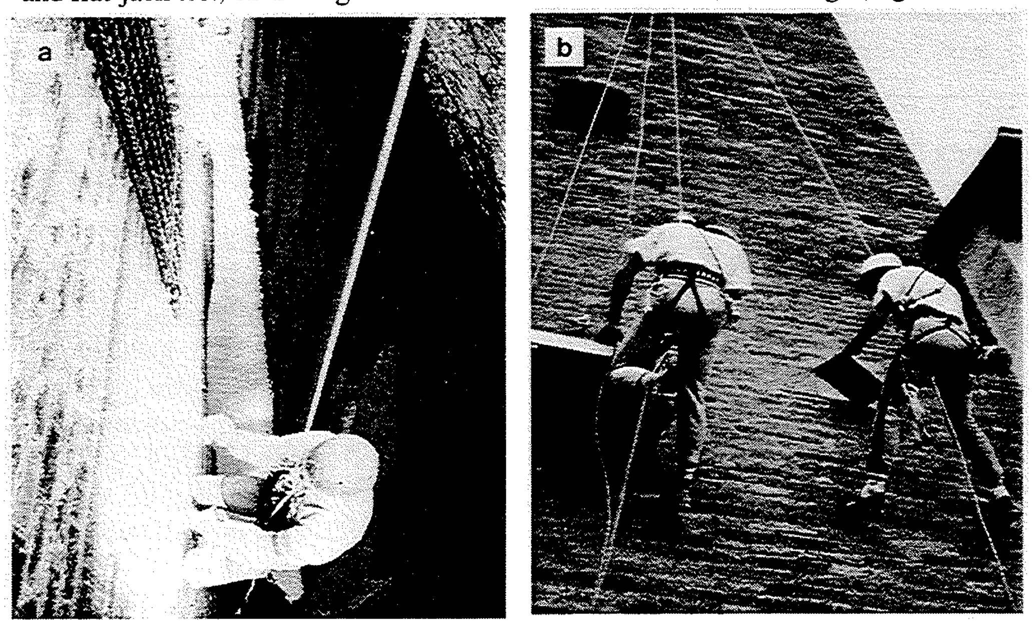

Fig. 17 - Flat-jack test on high structures without the aid of scaffoldings:
a) Bell Tower of St. Stephen in Venice b) Tower "Fraccaro" in Pavia.

Shear test 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. 18). The testing technique determines the peak and residual shear strength of the mortar layers.

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.

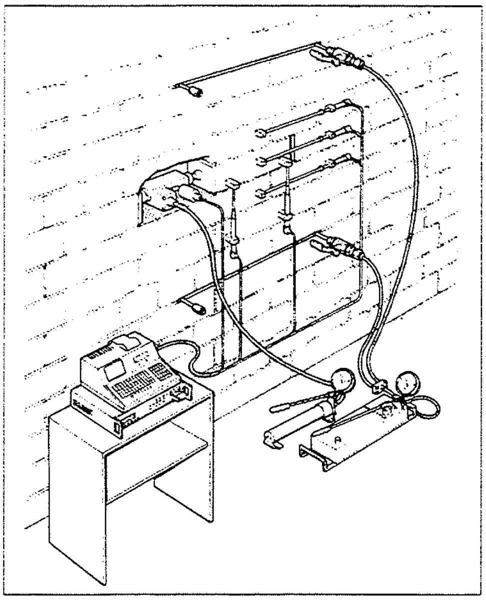

Fig. 18 - Scheme of a shear test along the mortar layers: the normal stress is applied by two flat-jacks and the shear stress is applied by a hydraulic jack.

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. 19 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.

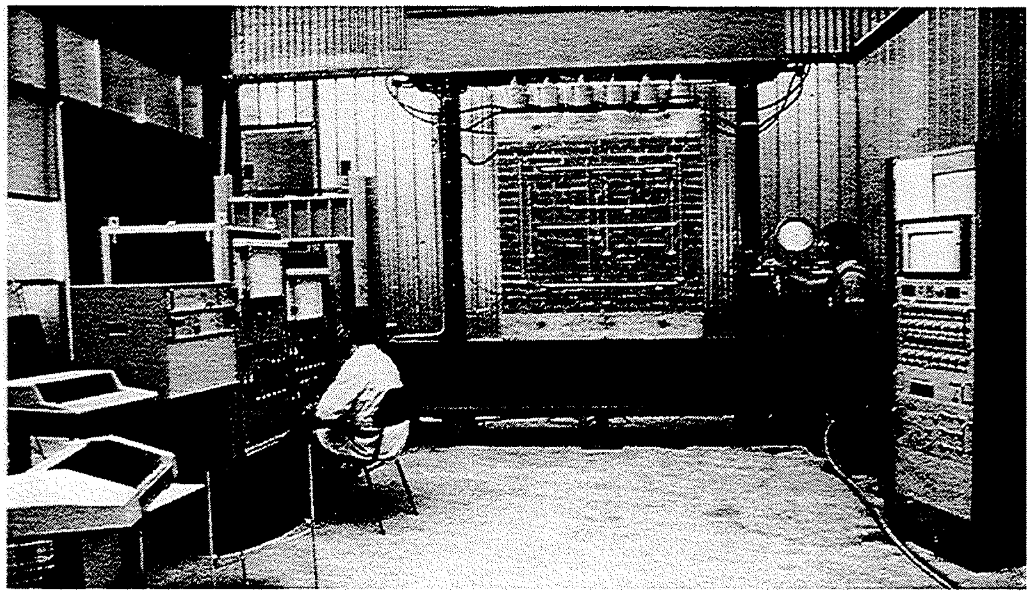

Fig. 19 - View of the loading and measuring equipment for the calibration of flat-jack tests.

Borehole dilatometer

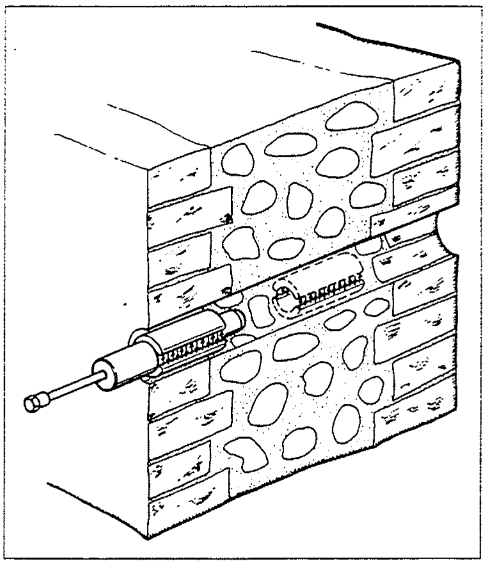

Fig. 20 - Scheme of borehole dilatometric test that determines the deformability characteristics of the surface and inner layers.

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 carry out dilatometric tests using boreholes made by coring. A special probe about 25 cm long applies uniform hydrostatic pressure on the borehole surface, and the measurement of the consequent deformation determines the modulus of deformability (Fig. 20). 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 21 shows the testing scheme used on the foundation ring of the Tower of Pisa. Several dilatometric tests were carried out in radial boreholes together with sonic logs and cross-hole measurements. The values of deformability modulus are shown in the histogram in Figure 21. 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.

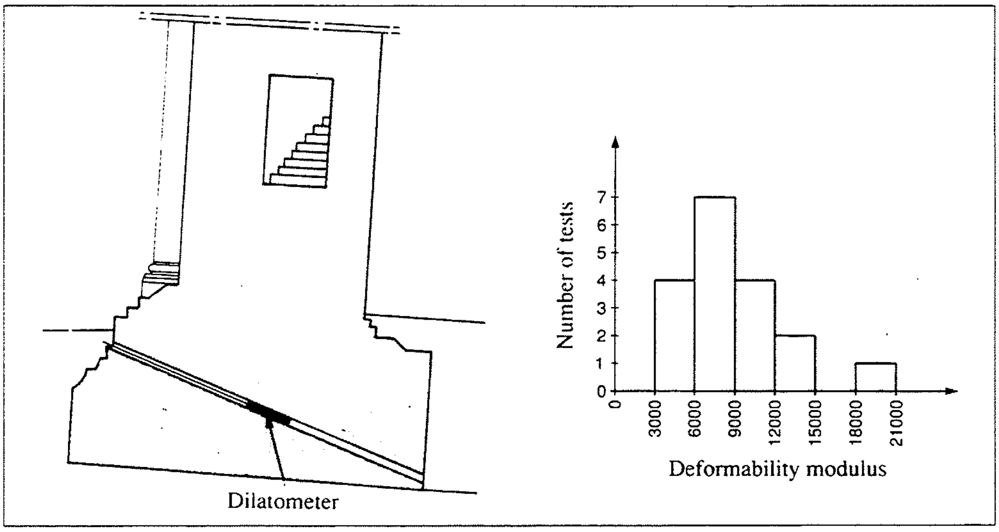

Fig. 21 - Use of the borehole dilatometer for analyzing the deformability characteristics of the foundation of the Tower of Pisa - Histogram of the deformability moduli.

4. NUMERICAL MODELLING

A significant contribution to the knowledge of the static conditions of a structure is provided by the mathematical model which utilise all the data obtained through in-situ and laboratory investigations and the information coming from the monitoring system. As concerns the mechanical parameters of the masonry, the input data for the mathematical model are obtained by flat-jacks deformability tests and the validation of the model is carried out through the comparison between the calculated values of the state of stress and those measured in situ by flat-jack tests. Different loading conditions are
applied to the model: (dead load, thermal effect, differential settlements of the foundation structures and dynamic loadings) and the deformation behaviour of the structure is analyzed with great attention in order to obtained a better understanding and a more meaningful interpretation of the data provided by the monitoring system.
In Fig. 22 a view of the mathematical model of St. Mark's Basilica in Venice, is presented. The high degree of complexity of the structure suggested the opportunity of considering the whole Basilica as the sum of suitable substructures. It seemed advisable to devide the structure into 9 substructures in order to analyze separately the pillars, the lateral walls and the domes; the boundary conditions of each single substructure reproduce correctly the stiffness of the adjacent substructures. The complexity of this model is clearly shown by the very high number of degrees of freedom (about 250.000).

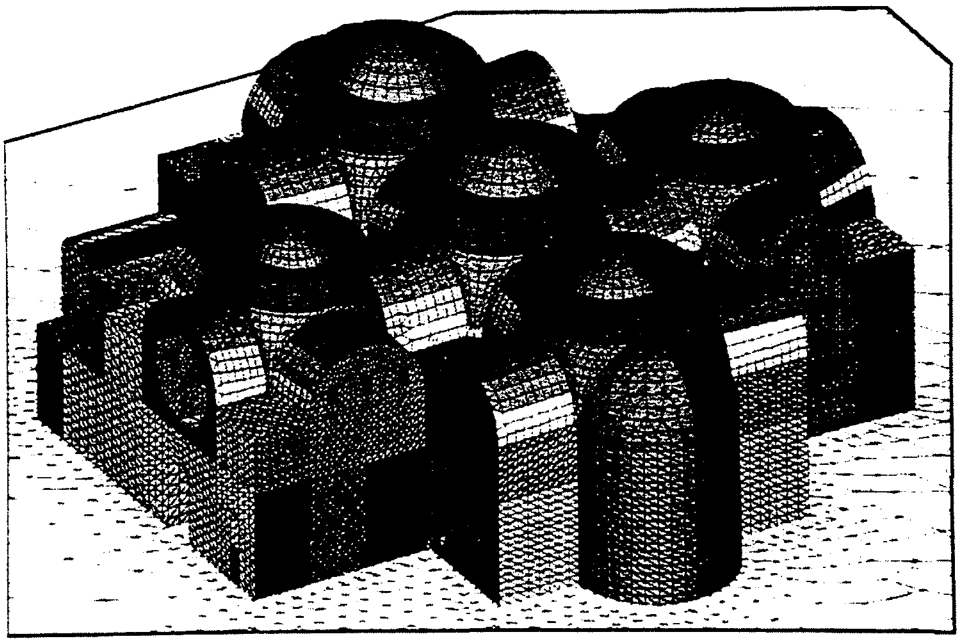

Fig. 22 - Numerical modelling of St. Mark's Basilica in Venice.

5. 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 content.

Fig. 23 - Dynamic analysis in a corner of the "Terme di Caracalla" in Rome, to assess the effect of the road traffic on the structure.

Through spectral analysis techniques it is then possible to evaluate the dynamic model parameters. As an example, Figure 23 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.

The forced vibration technique using a vibrodyne was recently used by ISMES to analyse the structural condition of several towers in the town of Pavia Fig. 24.

6. MONITORING

Installing measuring instruments to monitor the structural behaviour of a building can be considered a reliable method for the 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 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;

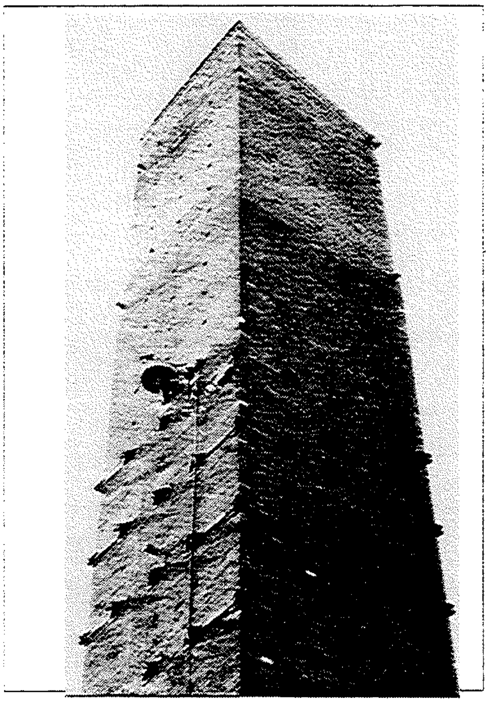

Fig. 24 - Forced vibration test carried out by a vibrodyne on the tower "Fraccaro" in Pavia.

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 25 an extensometer, recently installed by ISMES in a pillar of St. Mark's Basilica in Venice is shown.

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. Figure 26 shows the installation of these long base extensometers on the internal wall of the Pisa tower.

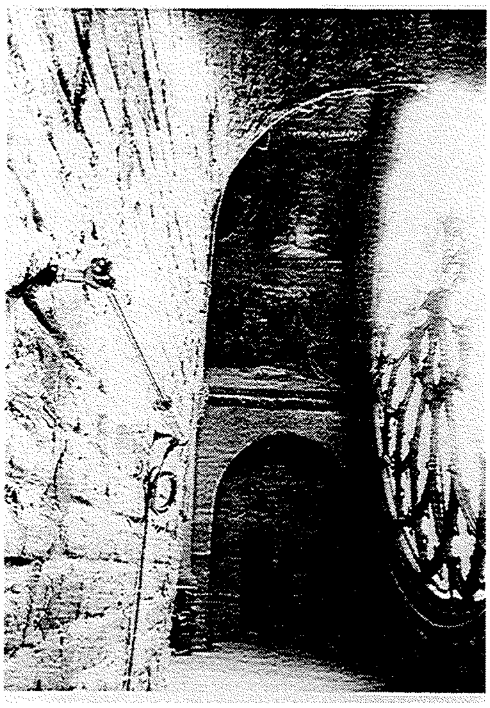

Fig. 25 - Extensometer for measuring the opening of a crack in a pillars of St. Mark's in Venice.

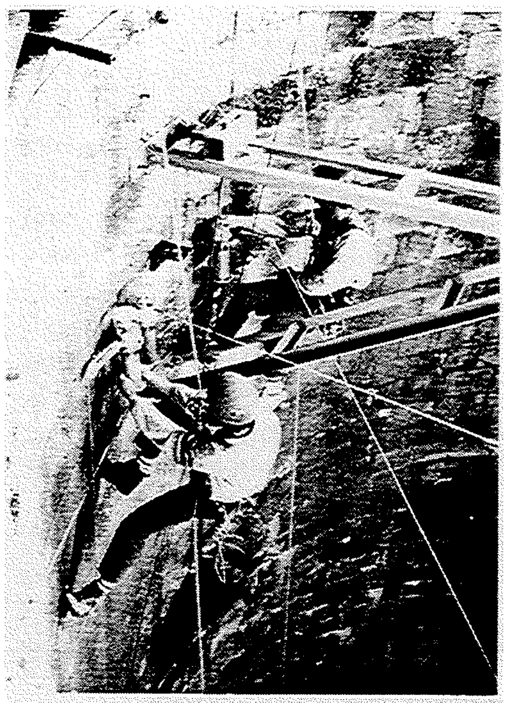

Fig. 26 - Installation of long-base extensometers on the internal wall of the Pisa tower.

Fig. 27 shows the diagrams of the relative displacements between the pillars of St. Mark's Basilica in Venice, measured by long-base extensometer in a period of about 3 years. In the figure the diagram of the temperature of the air inside the Basilica (T4) is also shown.

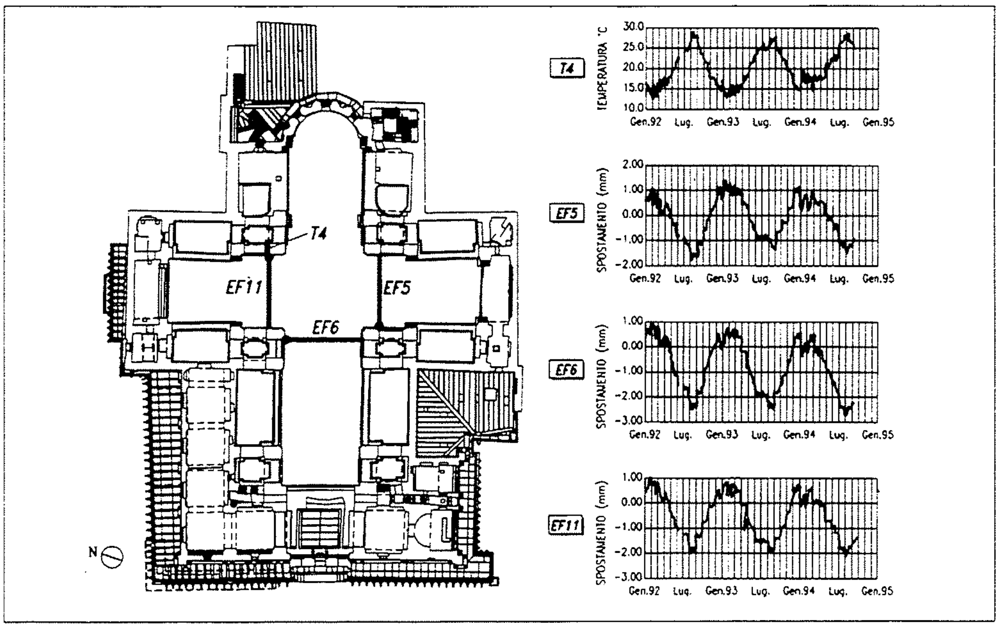

Fig. 27 - Diagrams of the relative displacements between the pillars of St. Mark's Basilica (Venice) measured by long-base extensometers.

Rotation changes of vertical or horizontal elements can be measured by installing either fixed or removable clinometers.

In constructions of great historical or monumental interest, the instruments are usually connected to automatic collecting and recording systems which can quickly indicate possible irregularities in the structural behavior.

In Fig. 28 the automatic data acquisition and recording system installed in the Cathedral in Milan in order to control the effect of the consolidation works carried out on the pillars.

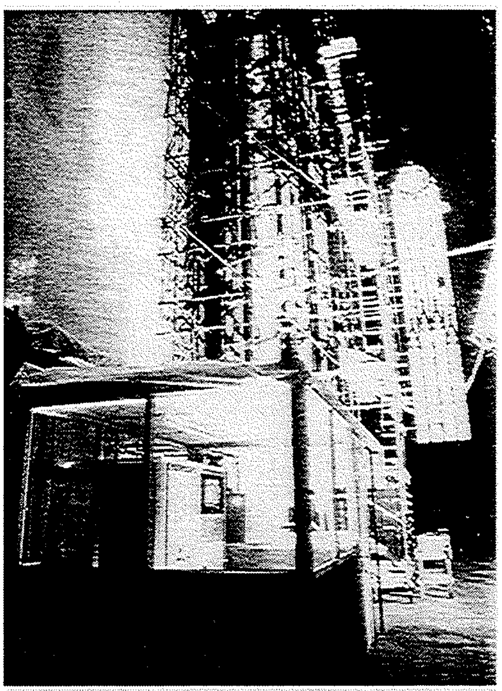

Fig. 28 - Automatic data acquisition and recording system installed to monitor the consolidation work on the pillars of the Cathedral in Milan.

REFERENCES

BONALDI P., JURINA L., ROSSI P.P., *"Indagini sperimentali e numeriche sui dissesti del Palazzo della Regione di Milano"*, Comunicazione presentata al Congresso Nazionale di Geotecnica, Firenze, Ottobre 1980, Ismes Bull. n. 156.

SACCHI LANDRIANI G., RICCIONI R., *"Comportamento statico e sismico delle strutture murarie"*, Clup, Milano (1982).

ROSSI, P.P. *"Analysis of mechanical characteristics of brick masonry tested by means of non-destructive in situ tests"*. 6th Int. Brick Masonry Conference - Rome 1982.

ROSSI P.P. *"Determination experimental des caracteristique mecanique des maçonnerie"* Restauration des Ouvrages et des Structures - Pont et Chaussees - Paris 1983.

BINDA, L., ROSSI, P.P., SACCHI, G. *"Diagnostic analysis of masonry buildings"* IABSE Symposium - Venice 1983.

BARLA, G., ROSSI, P.P. *"Stress measurement in tunnel lining"* Int. Symp. Field Measurement in Geomechanics - Zurich 1983.

ROSSI, P.P. *"Flat jack test for the analysis of mechanical behaviour of brick masonry structures"* 7th Int. Brick Masonry Conference - Melbourne 1985.

ROSSI, P.P. *"Recent development of the flat-jack test on masonry structures"* U.S.A. - ITALY workshop on evaluation and retrofit of masonry structure, August 1987.

BLASI, C., ROSSI, P.P. *"Indagini sulle strutture murarie del tempio cosidetto di Romolo nel Foro Romano"* Int. Confer. Non Destructive tests. Perugia, April, 1988.

GIANI, G.P., DEL GRECO, O., ASTORI, B. - ROSSI, P.P. *"Analysis and control of the static behaviour of the Consolazione Church in Todi, Italy"* Int. Symposium *"The Engineering Geology of Ancient Works, Monumental and Historical Sites"*, Athens, September 1988.

ASTORI, B. - GIANI, G.P. - ROSSI, P.P. *"Control measurement and stability analysis of the Cathedral of Orvieto, Italy"* Int. Symposium *"The Engineering Geology of Anciement Works, Monuments and Historical Sites"* Athens September 1988.

RICCIONI, R., ROSSI P.P. *"Restauro edilizio e monumentale. Diagnosi e consolidamento"* Editrice il Cigno, Galileo Galilei, Roma 1989.

ROSSI, P.P. *"Non destructive evaluation of mechanical characteristics of masonry buildings, Conference on "Non Destructive Evaluation of Civil Structures and Materials"*, University of Colorado, Boulder, USA October 1989.

BLASI C., CONFORTO M.L. - ROSSI P.P. *"Analysis of the statical behaviour of the Costantino's arch in Rome"* Int. Techn. Conference Structural *"Conservation of Stone Masonry"* Athens 1989.

MODENA, C., ROSSI, P.P. *"In situ investigations, structural analysis and strengthening of a stone masonry bell tower,"* I Int. Congress on Restoration of the Architectural Heritage and Building, Canarias, July 1992.

ROSSI P.P., VENTRUCCI F., VIO E., *"Structural Assessment of St. Mark's Basilica, Venice"*, IABSE Symposium *"Structural Preservation of the Architectural Heritage"* Roma 1993.