Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 70 (1993)

Artikel: Structural assessment of St. Mark's Basilica, Venice
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DOI: https://doi.org/10.5169/seals-53298

Structural Assessment of St. Mark's Basilica, Venice

Evaluation structurale de la Basilique de St. Marc, Venise

Tragfähigkeitsbeurteilung der Basilika von San Marco, Venedig

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SUMMARY

The diagnostic analysis to check the static conditions of the St. Mark's Basilica is presented. The wide research program, now in progress, is based on a combined experimental-numerical procedure which includes geometric survey, historical analysis, geotechnical investigation, analysis of the structural and mechanical characteristics of the masonries, monitoring system and numerical modelling.

RÉSUMÉ

On présente l'analyse diagnostique pour le contrôle des conditions statiques de la Basilique de St. Marc à Venise. L'important programme de recherche, actuellement en cours, est basé sur un ensemble de procédures expérimentales et numériques comprenant relevé géométrique, recherche historique, recherche géotechnique, analyse des caractéristiques structurales et mécaniques des maçonneries, système de surveillance et développement d'un modèle mathématique.

ZUSAMMENFASSUNG

Es wird die für die baustatische Prüfung der Basilika von San Marco in Venedig unternommene Diagnoseanalyse beschrieben. Das gegenwärtig laufende, umfangreiche Forschungsprogramm ist auf ein integriertes experimentell-numerisches Verfahren gegründet und umfasst Aktivitäten wie geometrische Aufnahme, historische Nachforschung, geotechnische Proben und Untersuchungen, Analyse des Tragverhaltens und der mechanischen Eigenschaften des Mauerwerkes, Überwachungssystem und Rechenmodelle.

1. INTRODUCTION

The Basilica of St. Mark is a structurally complex monument in which three major construction phases can be identified. The first dates from 828 A.D. when the Ducal Chapel was founded to house the body of St. Mark Evangelist which the Venetians had recovered from Alexandria in Egypt. The second phase began in 976 A.D. when the Ducal Palace and the Church were burnt by the populace to kill Doge Candiano IV; the structure was rebuilt with new decorations by Doge Pietro Orsolo the Saint. The third phase began in 1063, when Venice gave the world a fine example of its power with the construction of the grandiose building designed by the most important Byzantine architects. The Church was consecrated and dedicated to St. Mark in 1094, just two years before the ninth centenary of the life of the Saint. Built over many centuries utilising pre-existing structures as far as possible, the Basilica is showing clear signs of deformation and damage to its walls, arches, vaults and domes, as well as the flooring. Numerous earthquakes exacerbated this situation, especially those in the XII century, which shook Venice and the Basilica to their foundations, as well as several devastating fires, requiring the rebuilding of entire sections of the monument; one can also mention in this context the stylistic modifications and the increased structural weight of the domes, joined, in turn, by all the other additions made over the centuries. The longitudinal section of the Basilica in fig. 1 shows the original masonry domes and the overhanging lead domes built in the middle of the XIII century. It was only in the early XIX century, following the fall of the Venetian Republic, that the Austrian government enacted systematic restoration works based on the project developed by engineer Fustinelli, which was examined by a specially-appointed government commission. Above all, attempts were made to restore the walls, vaults and arches, and to consolidate the centuries-old structure which, under the thrust of the weight of the lead domes, was literally splitting the Basilica in two lengthways.

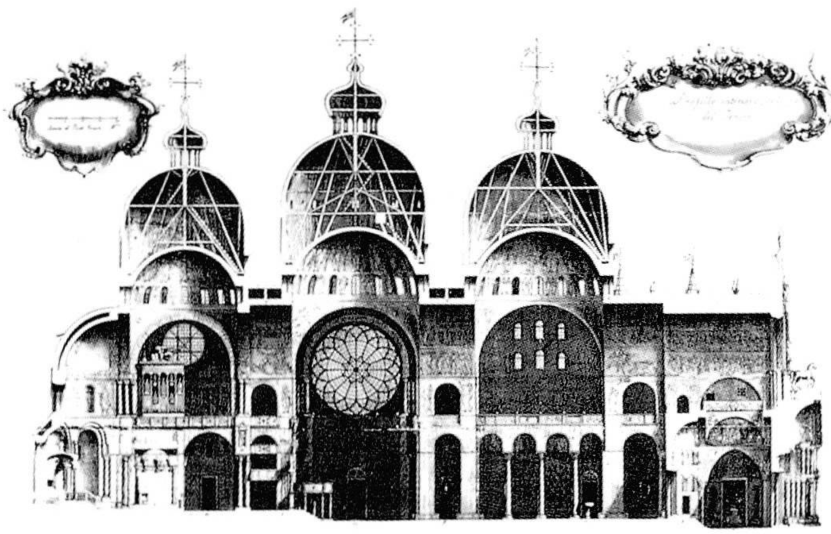

Fig. 1 - Longitudinal section (A. Visentini, XVIII century)

Thanks to the admirable attention of the "Procuratoria" (ancient name of the Surveyor Board of the Basilica) in the eighties a scientifically advanced restoration programme was planned by the Technical Department of the Basilica. A first programme of structural investigations, including the monitoring system, was financed by ISMES and ENEL in 1990. Then ISMES was commissioned by the Venice Water Board of the Ministry of Public Works to carry out a wide-ranging programme of surveys for the evaluation of the static conditions of the Basilica. This research programme, which is now in progress, is based on a combined experimental numerical procedure consisting of the following major steps:
– topographic and photogrammetric survey; – historical analysis; – detailed crack pattern survey; – geotechnical investigation and foundation survey; – analysis of the mechanical characteristics of the masonry structures by sonic tomography, radar, coring and video camera survey and flat-jack tests; – monitoring system; – numerical modelling

2. HISTORICAL SURVEY

The works performed on the Basilica in the past are documented up to the fall of the Venetian Republic in the Venice State Archives and subsequently through documents filed for the most part in the Historical Archives of the "Procuratoria" of St. Mark. These documents comprise texts, drawings and photographs. This material is extremely important and provides the essential basis for properly targeted restoration work; moreover, the Technical Department of the Basilica is well-informed of the works performed over the last 20-30 years. This material has to be organised in a manner which integrates knowledge of written documents with graphics and photographs and, especially, coordinated in a chronological and topographical fashion in order to provide rapid access, with the aid of computers, to the information concerning the various fields of intervention. Work therefore involves cataloguing these documents, in order to prepare report cards detailing the major restoration tasks implemented in the past.

3. TOPOGRAPHICAL AND PHOTOGRAMMETRICAL SURVEY

Unfortunately, no full-scale geometric survey of St. Mark's Basilica presently exists. Ferdinando Forlati, the famous Surveyor - Architect, indeed hoped that one would be able to conduct a scientific geometrical survey of the Basilica in his book on the Restoration of the Basilica (1974). Various attempts to survey the Basilica are extant, some of considerable prestige, such as those carried out by Antonio Visentini in the mid-1700s and later by the Surveyor - Architect Scattolin. The structure of the Basilica, however, is of such spatial complexity - dominated by curved surfaces embellished by figurative and decorative low reliefs and mosaics - that it cannot be reproduced faithfully without a careful survey of forms, dimensions, measurements and alignments which alone will make it possible to evaluate static conditions and verify historical hypotheses in order to target restoration work and conservation methods appropriately. In the case of St. Mark's Basilica, architectural photogrammetry is especially meaningful and pertinent, since it is the only means of ensuring absolute correspondence between graphic reproduction and actual architectural-spatial placement. The photogrammetric study, already begun in 1983, now requires the elaboration of all the photographs taken, in close relationship with the reference topographic map in order to ensure the dimensional accuracy of the drawings and provide structural analysis with definitive information concerning the deformation of the monument. The project envisages numerical data acquisition for the survey, so that this information can then be used for restoration work. By converting historical drawings into computer graphics, it will also be possible to compare manual surveys of past work with the current status of the building. By overlapping these visual elements, further information will be gained in order to complete the graphic reproduction of the Basilica.

4. SUBSOIL AND FOUNDATION SURVEY

A detailed survey of the subsoil of the Cathedral was carried out in order to define the stratigraphy of the soil as well as the mechanical characteristics of the different soil layers. Seven boreholes (30 m deep) were drilled around the perimeter of the Basilica and many undisturbed samples were taken for carrying out physical and mechanical laboratory tests. Static cone penetration tests were also carried out in three testing points, using a digital cone, in order to identify the mechanical characteristics of the different layers of soil. On the basis of in situ and laboratory tests, the stratigraphy of the soil was identified. As an example, fig. 2 shows the stratigraphic profile obtained by correlating the results of three boreholes drilled on the North side of the Cathedral. Under a surface layer of filling material, a silty-clay layer (about 5 m thick) has been observed. A

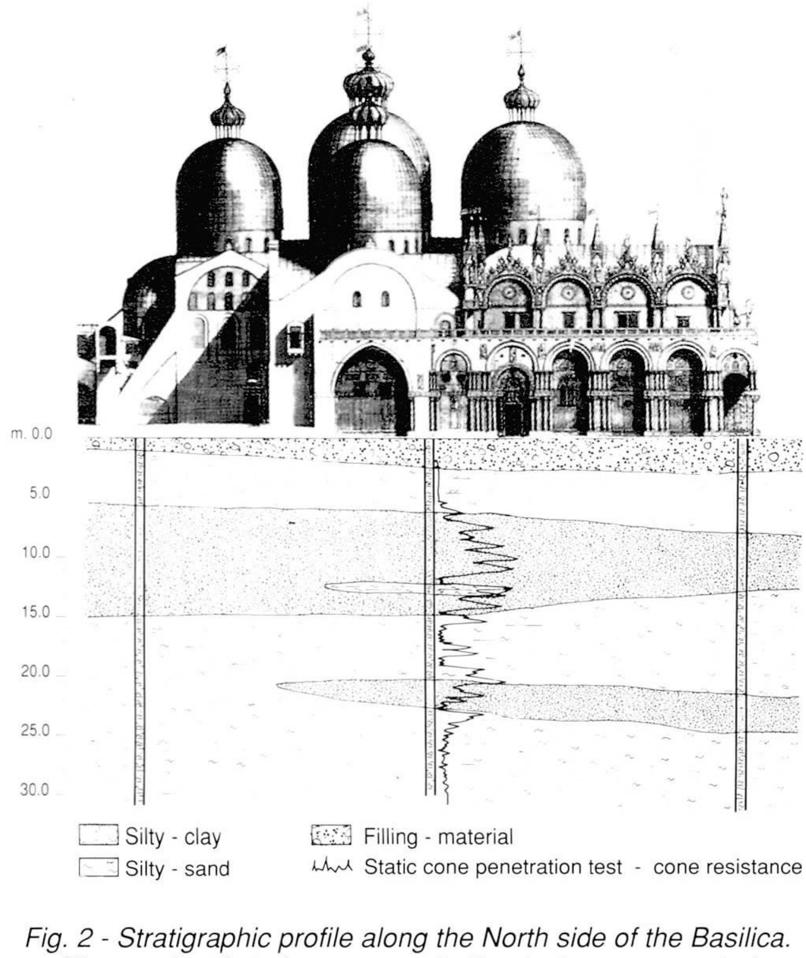

Fig. 2 - Stratigraphic profile along the North side of the Basilica. The results of static cone penetration tests are presented

silty-sand layer with higher mechanical characteristics is also present with a thickness varying between 5 and 10 m. Under the sand layer, silty-clay material was found. The presence of local lenses of sand inside the silty-clay material was observed as usual in lagoon-side environments. Three boreholes were equipped with electric piezometers and three with long base settlement-gauges connected to an automatic reading unit. This monitoring system will allow the settlement of the perimeter of the Cathedral to be controlled as a function of time and water-table variations.

An in-depth investigation was also carried out to analyze the geometric and structural characteristics of the foundation masonry of the perimeter walls and of the pillars. Several small boreholes (diameter 62 mm) were cored by using a light diamond saw and the lateral surface of the boreholes was surveyed by means of a colour video camera. Fig. 3 shows the drilling equipment installed at the base of a pillar for coring the foundation masonry. More than 50 subvertical boreholes were drilled to investigate the structural characteristics of the foundation masonries. In order to obtain qualitative information concerning the mechanical characteristics of the masonry structures, a sonic-log survey was carried out as well as cross-hole measurements by using two parallel boreholes. As a result of the coring and video camera survey, the typical structural scheme of the foundation masonry was determined (Fig. 4). At a depth of about 70-90 cm from floor level, a stone basement made with large blocks of sandstone is present with a thickness of about 2 m. Underneath this stone basement there is a wood plate (10 cm thick) which is about 3.0 m below the floor. This wood plate rests on short wooden piles which are very poorly preserved.

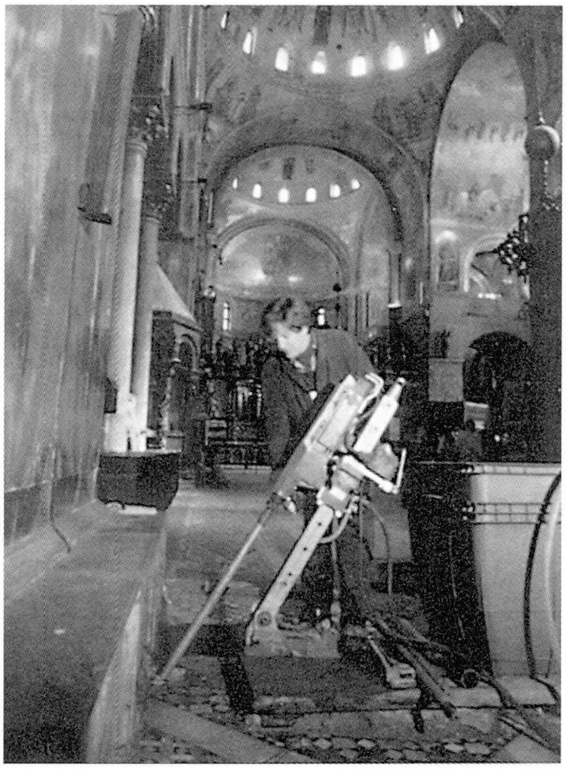

Fig. 3 - Drilling equipment for coring the foundation masonry

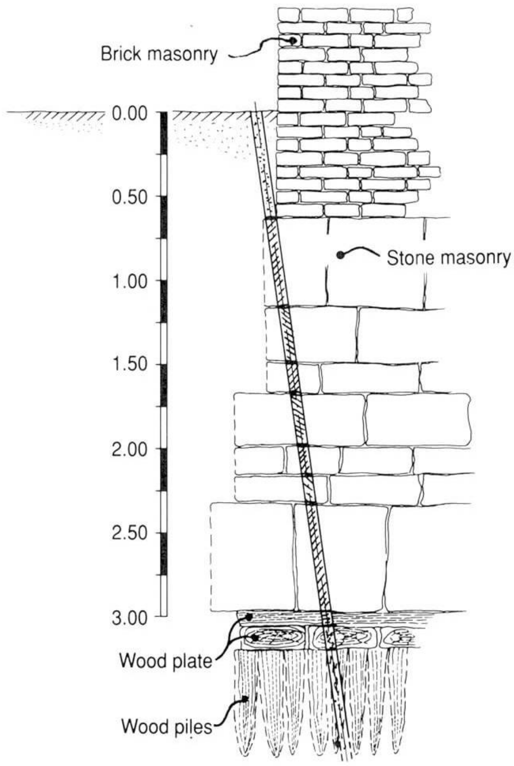

Fig. 4 - Structural scheme of the foundation masonry

5. ANALYSIS OF THE MECHANICAL CHARACTERISTICS OF THE MASONRY STRUCTURES

The pillars and the perimeter walls of the Basilica were intensively investigated by using both non-destructive and slightly-destructive tests. Special attention was devoted to the pillars which were investigated in the only unlined portion (about 1 m high) along the women's gallery. Under this layer, the pillars are lined with marble and over this layer the surfaces are covered by mosaics.

5.1 Sonic tomography and radar survey

At first a non-destructive investigation was carried by using sonic tomography and radar survey in order to check the presence of possible anomalies. The most significant results were obtained from the sonic tomography survey which provided a clear mapping of the different velocity zones. As an example, fig. 5

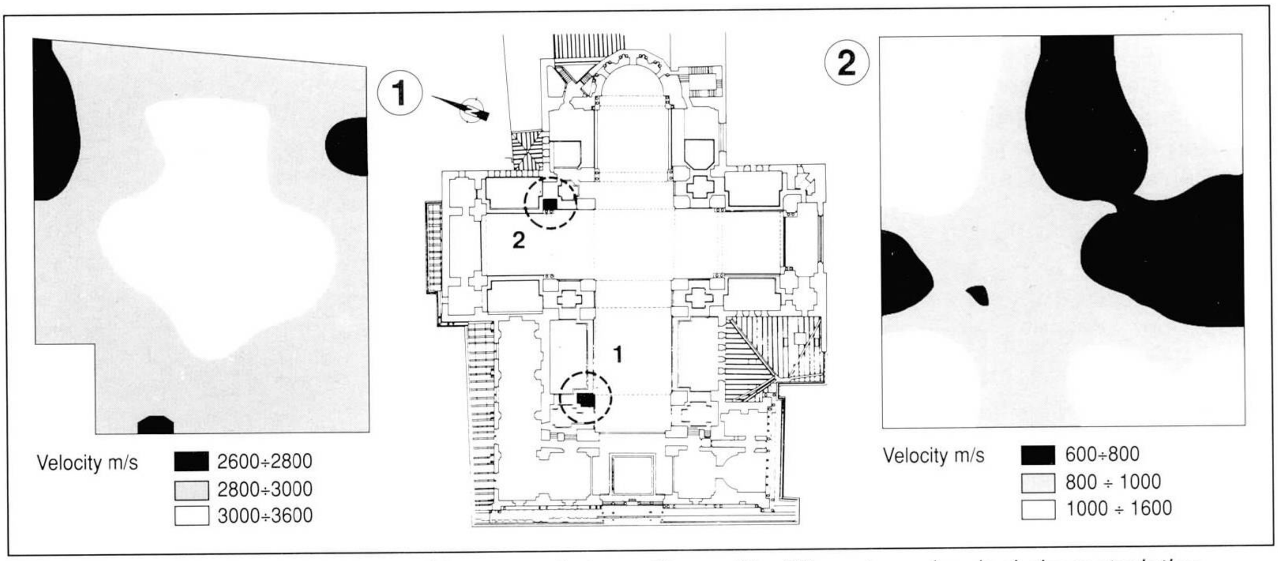

Fig. 5 - Results of tomographic survey in two pillars with different mechanical characteristics

shows the results for pillars 1 and 2. It can be clearly observed that pillar 1, which was consolidated by grouting about 30 years ago, clearly 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).

5.2 Coring and borehole video camera survey

In every pillar, horizontal and vertical boreholes (more than 60) were drilled by using light drilling equipment. Then a video camera survey was performed with a detailed description of the surface of the boreholes. Fig. 6 shows the equipment used for the video camera survey and the results of the inspection into the horizontal borehole of the pillar 2 indicated in fig. 5. A large number of voids can be observed inside the masonry, which confirms the results obtained by sonic tomography. By drilling subvertical boreholes (about 4 m long) starting from the level of the women's gallery, it was possible to investigate the lower part of the pillars lined with marble plates. Several boreholes were also carried out along the perimeter walls of the Basilica.

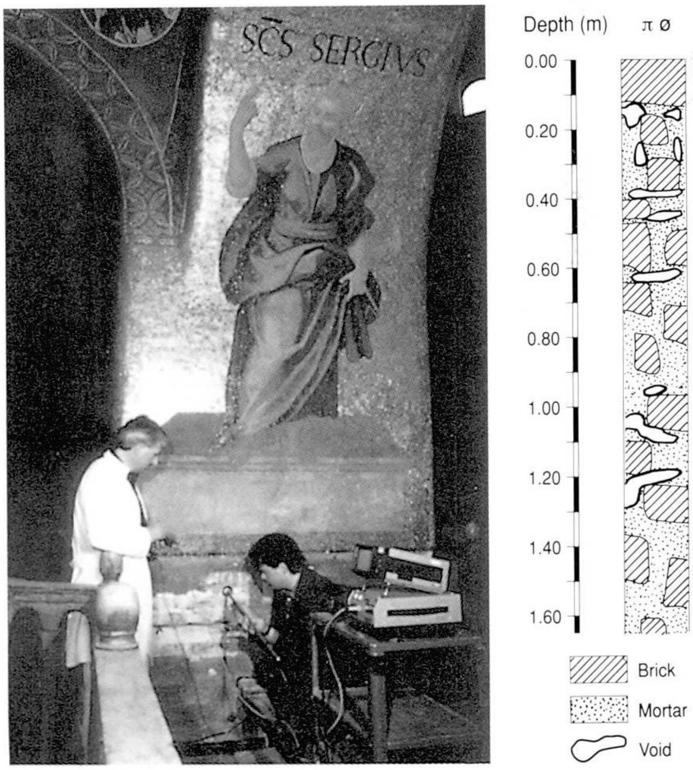

Fig. 6 - Video-camera survey equipment and result of the inspection into the horizontal borehole drilled in the pillar n. 2

5.3 Measurement of the state of stress and analysis of the deformability characteristics

For the evaluation of the static conditions of the Basilica it seemed advisable to measure the actual state of stress on the main supporting structures with special attention to the pillars. For this purpose the well-known flat-jack test was used. This non-destructive test, developed by ISMES about 15 years ago, is based on the release of the state of stress by making a small slot in a mortar layer and then reloading by means of a thin flat-jack inserted into the slot. This test is very simple and reliable, as proven by calibration tests carried out in the laboratory. More than 80 flat-jack tests were carried out (about 65 on the pillars and 20 on the perimeter walls). Fig. 7 shows the view of a flat-jack test on a pillar.

The stress values measured on the pillars are shown in fig. 8. A certain heterogeneity of the state of stress in the pillars can be observed, which is related not only to the position and size of the pillars but also to the type and extent of the consolidation works which some pillars have undergone in the past. High stress values (up to 1.1 MPa) were measured in some pillars. Furthermore, in the above-mentioned pillar 2 (the south-east pillar of the St. John's Dome), a state of stress of 0.95 MPa was measured. This value was considered very high in relation to the results obtained by sonic tomography, coring and video camera survey.

By using two parallel flat-jacks the deformability characteristics of the masonry were determined for the pillars and along the perimeter walls. Two flat-jacks were inserted in the masonry in order to delimit a specimen of appreciable size (40 x 50 cm) on which a uniaxial state of stress was applied. During the loading phase, the axial and transversal deformation of the specimen was plotted as a function of the applied load. This simple testing technique allowed the deformability moduli of the different types of masonries analyzed to be determined. These values have been used as input data for the finite element model.

Fig. 7 - Measurement of the state of stress in a pillar by means of the flat-jack technique

The deformability characteristics of the pillars are a function of the type of consolidation works performed on the masonry. The tests carried out on the original unconsolidated masonry show values for Young's modulus varying between 800 and 2000 MPa (for a stress range of 0.4 ÷ 0.8 MPa). The values determined on the masonry consolidated by grouting are higher (between 1600 and 4000 MPa) in the same stress range. In some pillars, where the masonry was completely rebuilt about 30 years ago, Young's modulus has an average value of about 5000 MPa.

5.4 Supplementary investigation on the south-east pillar of St. John's Dome

The combined analysis of the results obtained by flat-jack test, sonic tomography, coring and video camera survey clearly shows that the pillar n. 2 (sout-east pillar of St. John's Dome) has to withstand very severe loading conditions in comparison with the poor mechanical characteristics of the masonry. For this reason, it was decided to carry out a more detailed investigation in the lower part of the pillar after removing the marble lining. At first a detailed

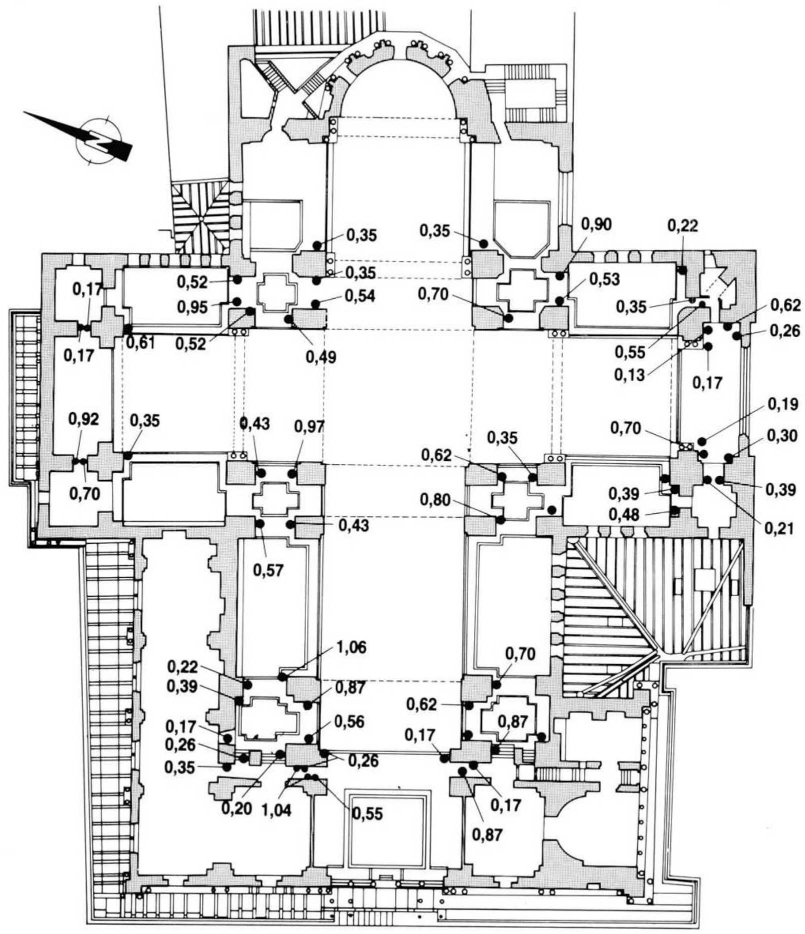

Fig. 8 - General lay-out of the flat-jack testing point with the indication of the measured states of stress

crack pattern survey was carried out which showed the presence of several vertical small cracks, especially near the corners. Sonic tomography was performed at three sections of the pillar at different heights from the floor and the results obtained confirmed the low velocity values presented in fig. 5. In several points of the pillar, the state of stress was measured by flat-jack test and an average value of 0.85 MPa was found. Then, in two points, the deformability characteristics were determined by two parallel flat-jacks. The typical stress-strain curve of the masonry is shown in fig. 9, where axial and transversal strain values are presented as functions of axial stress. The average value of the measured state of stress is also indicated. It can be observed that the masonry presents a linear behaviour up to a stress level of about 0.8 MPa with a value of Young's modulus of about 2.000 MPa. For higher stress levels, up to 1.2 MPa, Young's modulus decreases to a value of about 900 MPa and for the stress range between 1.2 and 1.5 MPa the modulus is lower than 300 MPa. It can be observed that the average state of stress measured in the pillar exceeds the limit between elastic and plastic behaviour. This supplementary investigation clearly confirmed that the static conditions of the pillar are not satisfactory and for this reason it was decided to carry out urgent consolidation works which are now in the design phase.

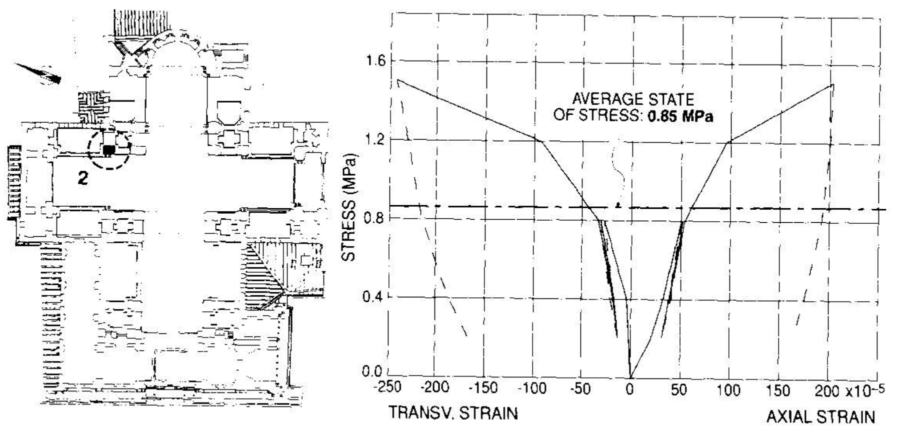

Fig. 9 - Stress-strain diagrams obtained by flat-jack tests on the pillar n. 2 with the indication of the measured state of stress

6. MONITORING SYSTEM

In order to obtain a continuous control of the static behaviour of the Basilica, in 1991 a monitoring system was installed by ISMES. The principal features which are monitored are as follows:

- opening of the main cracks in the pillars (8 extensometers)
- relative horizontal movements of the pillars (11 long base extensometers)
- tilting of the vertical structure (4 inclinometers)
- internal and external temperature (5 temperature-gauges)
- vertical settlement of the soil foundation (3 long base settlement gauges)
- water-table variations (3 piezometers).

All the instruments are connected to an automatic data acquisition and recording unit which can quickly indicate possible anomalies in the structural behaviour. The analysis of the deformations as a function of time and temperature makes it possible to separate thermal effect from the deformations arising from other structural causes. As an example, fig. 10 shows the diagrams of the relative horizontal movements between some pillars measured by three long base extensometers during the first period of observation. It can be clearly

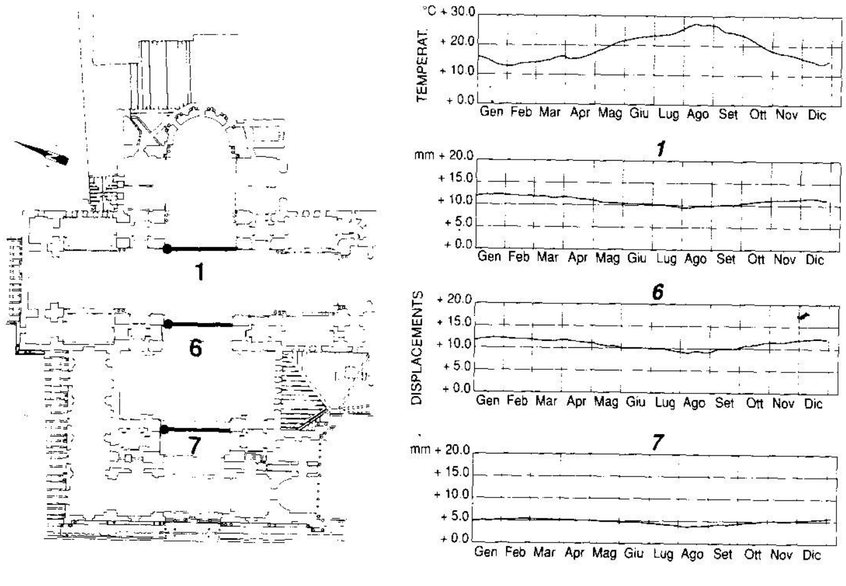

Fig. 10 - Diagrams of the relative horizontal displacements of some pillars during the first year of observation

seen that the deformation diagrams follow temperature changes and no permanent deformation is noticed at the end of the first yearly cycle.

7. NUMERICAL MODELLING

A significant contribution to the knowledge of the static conditions of the Basilica will be provided by the mathematical model which will utilise all the data and information obtained through in-situ investigations. This mathematical analysis, which is now in progress, has the following aims:

- to set up a mathematical model capable of providing a reasonable picture of the present stress distribution due to dead loads; the validity of the model in achieving this aim will be tested by comparing experimental stress measurements with analytical results in certain points of the structure;
- to estimate the effect that a reduction of stiffness in some structural elements could produce in terms of displacement and stress redistribution;
- to forecast the displacement trend under cyclic loads, such as thermal loads, in order to obtain a better understanding and a more meaningful interpretation of data provided by the monitoring system.

The high degree of complexity of the structure suggested the opportunity of considering the whole building as the sum of suitable substructures. Several analyses on simplified models have been performed in order to identify the most significant substructures. It now appears evident that a good representation of the global behaviour of the Basilica can be achieved by isolating five parts, each containing one dome; the boundary conditions of each single substructure will reproduce correctly the stiffness of the adjacent substructures.

8. CONCLUSIONS

The diagnostic analyses illustrated here represent an exhaustive example of the methodological approach which should be followed when studying the static behaviour of an important monument. This combined experimental and numerical procedure is effectively the only research tool for the study and design of restoration and consolidation work. The results of the experimental investigations (flat-jack tests, coring and video camera survey, sonic tomography, radar, etc.) have been used to evaluate the strength, the deformability and the composition of the masonry, as required for the construction of the numerical model, and to determine the present state of stress, which can than be used for safety checks and for calibrating the numerical models. This study is not yet completed, but a first important result has been obtained; the existence of a weak point in the structure has been established (the south-east pillar of St. John's Dome) where consolidation work is now in progress.

It may also be mentioned that once cataloguing is completed of the enormous quantity of written and graphic material detailing the Basilica, together with the data obtained from the present analysis and research work, an invaluable tool will be at our disposal to ensure historical and technical continuity in restoration procedures.

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