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Remarkable case histories regarding S. Vitale church, Ravenna, Italy

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Abstract

The article presents a critical analysis of the results achieved in the study regarding the properties of the subsoil, the foundations and the evolution of the cracking phenomena occurring on the monument, enabling us to make plans concerning possible consolidation measures.

1 Introduction

The complex dedicated to S. Vitale consists of several buildings more or less closely surrounding the basilica. This paper provides an analysis and describes the situation of the basilica alone.

The basilica of S. Vitale was designed by Giuliano Argentario and consecrated in 547 A.D.. It is octagonal in shape, with sides measuring 15 metres (Fig.1), composed of two main bodies: the taller internal section, which includes the cupola, and the outer part comprising an ambulatory on the ground floor and a women's gallery on the first floor (Fig.2). Along the outside perimeter are two chapels on each side of the apse and an arcade between the stair tower leading to the women's gallery and the bell tower.

Like many other ancient buildings, over the centuries this church has undergone several alterations (i.e. extensions, other structures built adjacent to it, partial demolition, restoration, etc.) that have more or less changed its original layout.

Since its erection, S. Vitale has undergone several large-scale construction works, such as the building of the chapels and chantries along the outer perimeter, making it necessary to remove part of the outer walls of the basilica to provide openings; the building of passage-ways to adjacent buildings (e.g. sacristy) by means of openings made through the outer walls; and the further upward extension of the southern stair tower, transforming it into a bell tower standing 43 metres above the present ground level.

By the end of the year 1700, the basilica was practically surrounded by buildings constructed in earlier centuries.

Work on sediment removal started in the 1880s, much of which was carried out between 1898 and 1906, at first under the direct supervision of Corrado Ricci, Superintendent of Monuments in Ravenna, and later through his diligent collaborators when his higher duties kept him away from Ravenna. In actual fact, except for the demolition of the vestibule and boundary walls, which was commissioned by the Regional Office for Monumental Conservation of Emilia around the year 1880, all the other works that brought the S. Vitale basilica to its present state were carried out either directly or indirectly under Corrado Ricci's supervision in these eight years alone (1898 - 1906).

Of all the sediment removal operations carried out on the basilica, two were of particular significance for their scale. First, the great Sacrament (or S. Benedetto) chapel was demolished in the summer of 1899, followed by restoration of the walls of the basilica (on the side where the chapel had been erected against it in the 16th century); then works to separate the "old" sacristy were started in winter 1900. Considerable difficulties were encountered right from the start. Sturdy, provisional underpinning structures were set up and the pillar of the basilica that had been incorporated as part of the "old" sacristy had to be reconstructed. Extensive restoration work was also carried out along the outer perimeter of S. Vitale to remove materials left behind in the 16th and 17th centuries. But during inspection of the building in autumn 1904, evidence was found that the pillar was still shifting. Domenico Majoli, an architect of the Superintendency of Monuments, found that the cracks in the roof vault of the women's gallery, which had been sealed only two weeks earlier, were again starting to open up. A bracing system was installed, involving chains and steel bars tied to the corners of the pillar and then incorporated into the walls. By the end of 1906, the "old" sacristy had been demolished and a new one (currently the offices of the Superintendency) had taken its place, whereas all that remained of the structures that were originally attached to the basilica (shown in the floor plan, Fig.1) were the two buttresses on the left- and right-hand sides of the Sacramento chapel and the counterthrusting north and north-east pillars (the latter on the side of the Galla Placidia mausoleum) on the outer wall of the basilica.

The main purpose of the works ordered by Corrado Ricci was to restore S. Vitale to its original appearance. With regard to the outer face of the building, it may be said that this intent has been achieved, except for the arcade, bell tower, and two buttresses mentioned earlier. However, although the original door and window openings in the outer walls have been restored, this is definitely not the case with the alterations made to the internal structures of the building, although they do not involve any fundamental part, except for the original wooden counterlaths that have been substituted by cross-vaults on the floor level of the women's gallery.

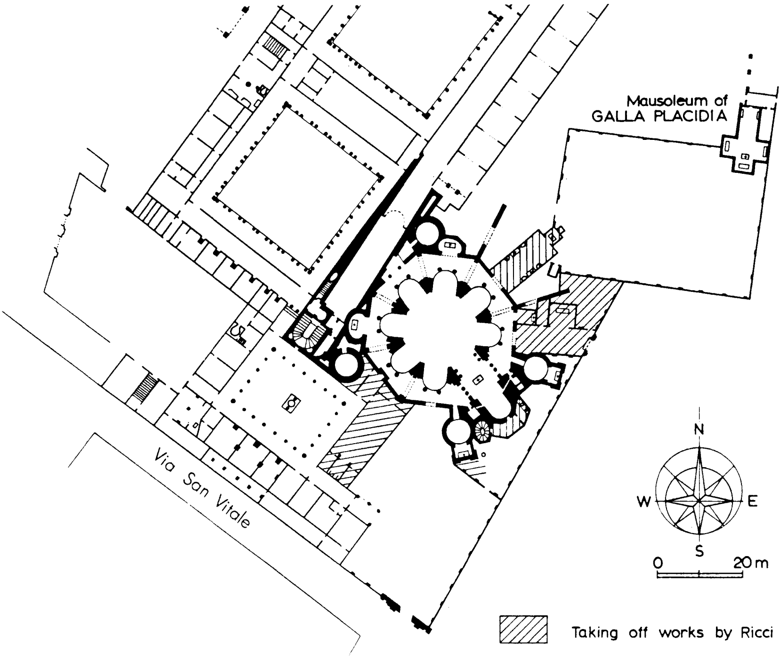

Fig. 1 - Plan by Fiandrini (1798) showing buildings erected against S. Vitale basilica

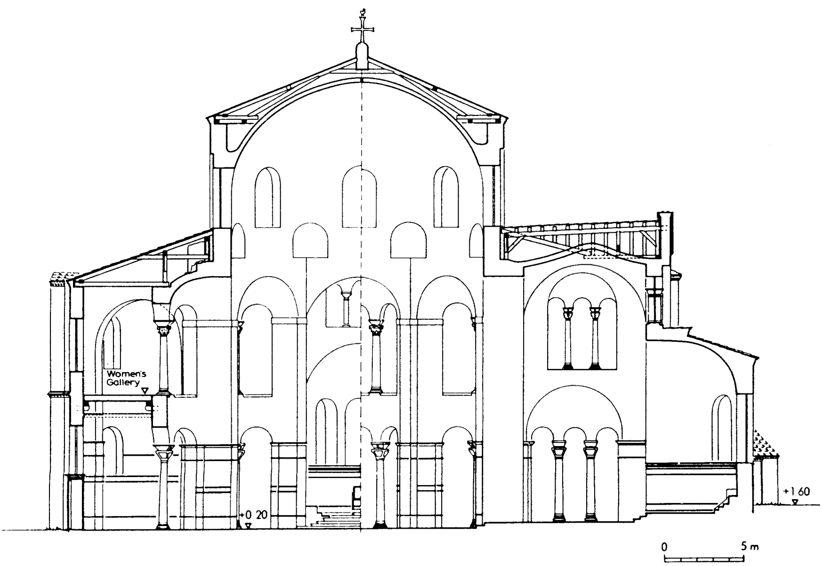

Fig. 2 - Cross-Section of S.Vitale Basilica

2 Subsidence

The whole Ravenna district and the city itself are well-known to be seriously affected by large-scale subsidence.

The term subsidence is used to describe gradual sinking of the level of the soil over a large area, a phenomenon which normally originates from either natural or anthropic processes.

Natural subsidence is basically of geological origin. Soil sinking is generally caused by tectonic movements of the deep rocky substrate or magma, and also by the natural decrease of loose top soil volume by compaction under its own weight. Unlike seismic activity or magma movements, which may in some cases cause sudden and considerable subsidence, deep underground tectonic compaction processes are normally very slow, taking up to tens or even hundreds of thousands of years.

Subsidence of anthropic origin is due to mining, tunnelling or pumping of water, either for drinking, agricultural or industrial purposes. Although similar soil sinking phenomena have been reported in many other parts of the world, at Ravenna the greatest reason for concern consists in the incomparable artistic value of its monuments and the fact that the city is so close to the sea.

The most serious soil depression measured in Ravenna is about 130 cm, a considerably alarming value if we consider that the entire area of the city and the coastline only averages about 1.00 metre above sea level.

Considering more specifically the situation of the sites of S. Vitale and Galla Placidia, it can be estimated that, from the date of their construction up to the present day, the ground level has sunk approximately 150 cm due to natural subsidence. If we also take eustatic processes into account, by estimating an average rise in sea level of approximately the same order (within a certain degree of error), we find that the level of the original foundation plane with respect to sea level has sunk by about 3.00 metres. These natural subsidence effects have been accentuated even more by the extraction of underground water and natural gas in the Ravenna district which started in the 1950s. The sites of these deposits suggest that the phenomenon that is still taking place in the historical centre of the city, where the soil sank an average of 90 cm between 1950 and 1985, is due exclusively to extraction of natural gas and water.

In conclusion, the resulting situation clearly demonstrates that subsidence has brought about two different actions, both producing negative effects on the integrity of the S. Vitale buildings.

In some cases, there has been a shifting of ground water deposits, producing flooding of the foundations or sometimes even the flooring of the buildings. In other cases, the soil has sunk unevenly, due to the different characteristics of the subsoil. As a consequence, quite serious angular distortions have been generated, adding to the effects of strains commonly found in most ancient buildings and worsening cracks, thus further impairing their endurance to other strains.

Measures taken to lower the level of the ground water artificially and dry out the foundations of the buildings proved to be utterly inefficient, as they only worsened the situation by adding to the general sinking of the soil. In particular, a drainage system installed under the pavement of the basilica facilitated access to the building.

3 Geotechnical characteristics of soil

A geotechnical survey was planned and conducted in order to analyse the nature and characteristics of the soil at the site of the church, which is located north of the historical town centre of Ravenna. The survey involved the execution of five borings with collection of soil samples and five Dutch cone penetration tests (CPT). The surrounding countryside is about 0.6 to 2.50 metres above sea level. The boreholes were then used to install double-pipe piezometers (Casagrande type).

Section C-C' (Fig.3), which runs approximately NE - SW, yielded many on-site and laboratory test data and provided the best picture of the stratigraphic situation under S. Vitale. Analysis of the stratigraphic columns allows certain hypotheses regarding the nature and configuration of the underlying formations.

From the planimetric and altimetric points of view, all the main formations show continuity within the survey area, although their thickness varies. The separation planes between the various layers are essentially horizontal or only slightly tilted. Starting from ground level, the surveys revealed a top layer consisting of alluvial soil mixed with highly anthropic materials and remains of brick and clay pots going down several metres (from 3.80 m to 6.30 m). Underneath this rather heterogeneous layer are four main homogeneous formations, with alternating granular and cohesive layers.

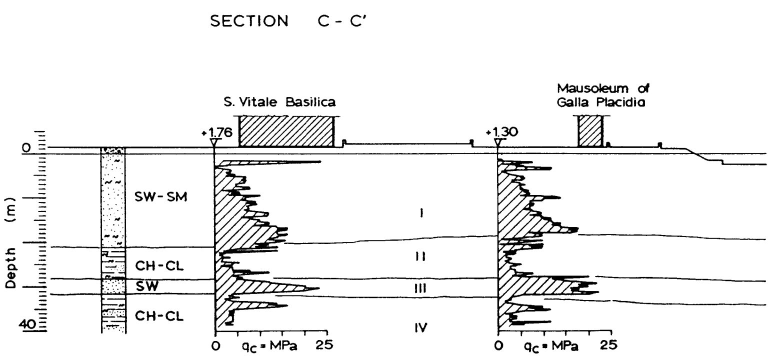

Fig. 3 - Geotechnical cross-sections of the soil, obtained from survey data and static penetration tests.

The first of these is granular, featuring sporadic silt and clay bodies in some cases. From visual inspection, this formation was found to be a fine sand, somewhat silty in certain points, dark grey to greenish-grey in colour. Its thickness varies from 16.40 to 20.00 metres. The Dutch cone strength q_c varies between 2 MPa at the shallowest point and 15 MPa at the deepest. The variation, which shows a generally linear increase with depth, is mainly due to increasing geostatic stresses in the soil.

The second formation is of cohesive nature and consists of a silty, dark-grey or greenish-grey clay. Thickness ranges from 3.60 to 6.50 metres. Strength q_c varies from 2 to 3 MPa.

The third formation is granular and consists of a medium-fine grey sand. Strength q_c ranges from 13 to 23 MPa, and thickness from 3.55 to 6.25 metres. The fourth formation consists of a silty, greenish-grey clay with inclusions of sandy and silty bodies. The top of this formation, which extends down to the maximum depth reached by this survey, ranges from -33 to -34 metres; strength q_c ranges from 2.5 to 4.0 MPa.

Table 1 summarises the physical and mechanical properties of the formations in the soil under the buildings.

4 Survey of the current state of the structure

Survey of the structural situation of the foundations of S. Vitale started in 1983 (Ricceri [1]), with a series of measurements both near and within its load-bearing structures. The 1.50-metre wide wall foundations consist of limestone elements and trachyte blocks bound together by lime mortar. The intrados is approximately 3.00 metres below the floor level of the church, which is in turn 0.20 metres above sea level. The foundation elements are supported by upright oak piles whose tips reach -3.00 metres, embedded in the sandy silt found at these depths.

This was the situation observed in the foundation structures of all the internal walls and pillars, whereas there was no evidence of oak piles under the outer walls. Fig.4 shows the characteristic dimensions of the foundations.

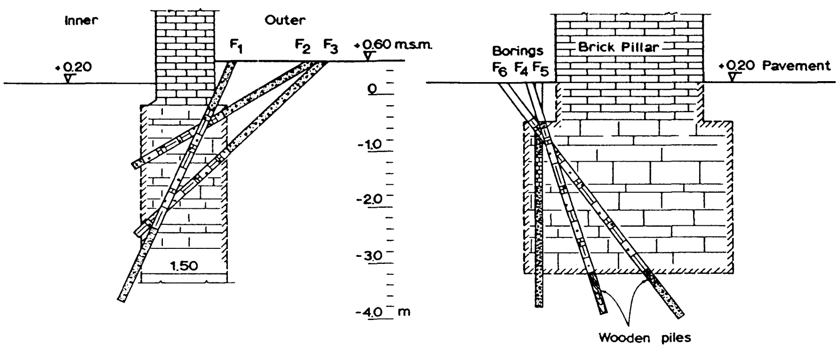

Fig. 4 - a) Cross-section of external wall foundations.
b) Internal pillar foundations.

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TABLE 1

FORMATION 1
THICKNESS: 16.45 - 20.00 metres
NATURE OF LAYER: alluvial, fine and slightly silty sand.
$\gamma = 19.5$ kN/m^3
w = 23%
$\phi' = 40°$ from drained triaxial compression tests C.I.D.
E = (1.7 - 2.4)z + 12.75 (MPa) determined with CPT tests

FORMATION 2
THICKNESS: 3.65 - 6.5 metres
NATURE OF LAYER: alluvial, silty clay.
$\gamma = 18.8$ kN/m^3
w = 32.9% $w_L = 55.1\%$ $I_p = 26.5\%$
$c_u = 55$ kPa $\phi' = 24\text{-}29°$ from undrained triaxial compression tests C.I.U.
$E_{oed} = 2.8 - 7.1$ (MPa) from oedometric tests

FORMATION 3
THICKNESS: 3.55 - 6.25 metres
NATURE OF LAYER: medium-fine, silty sand
$\gamma = 19.9$ kN/m^3
w = 21.4%
$\phi' = 32° - 35°$ from C.P.T. data
E = (1.8 - 2.0)z + 12.70 (MPa).

FORMATION 4
THICKNESS: cannot be determined on basis of maximum depth reached by boring operations.
NATURE OF LAYER: alluvial, silty clay.
$\gamma = 18.9$ kN/m^3
w = 29.0% $w_L = 52.0\%$ $I_p = 25.2\%$
c_u=78.5 kPa $\phi' = 24\text{-}26°$ from undrained triaxial compression tests C.I.U.
$E_{oed} = 4.3 - 10.4$ (MPa) from oedometric tests

As the original flooring of S. Vitale is currently 0.20 metres above sea level, and as the total subsidence since the church was built is approximately 3.00 metres, we can deduce that the foundations were originally laid at +0.00 metres and that the floors of S. Vitale and Galla Placidia were probably 2.50 to 3.00 metres above sea level.

Results of stress tests show a rather wide range of variability. Strength values range from 150 to 230 MPa, with elasticity moduli of 48,500 to 62,500 MPa for limestone, from 63.9 to 106.7 MPa with elasticity moduli of 22,000 to 30,000 MPa for trachyte, from 7.7 to 11.1 MPa, with elasticity moduli of 2,860 to 5,400 MPa for the conglomerate, and from 10.3 to 22.0 MPa, with elasticity moduli of 1,000 to 1,200 MPa for the bricks.

A very thorough and accurate survey on S. Vitale was carried out by F.W. Deichmann [2], revealing that the outer walls have a constant thickness of 1.00 metre, whereas the thickness of the eight internal pillars is irregular, as can be seen in Fig.1.

In particular, the walls consist of an outer layer of brick about 60 cm thick, enclosing an inner wall of mixed filling material bound with lime mortar.

The tholobate which supports the cupola is 1.2 metres thick. The cupola itself was made of a layer of hollow brick pipes approximately 5 cm in diameter, bound together by lime mortar to form a total thickness of 20 cm. The floor and roof of the women's gallery are two bricks thick.

5 Stress state and recording of the strain situation

Section 1 provided the historical background of the events that affected S. Vitale in the course of its lifetime. Most probably the original complex consisted of the outer walls and the central nucleus connected by means of the radial arches reaching the pillars at the corners of the octagon. The static function of these connections was not only to reduce the free length of the outer walls, but also to provide support for the wooden beams which originally formed the floor and roof of the women's gallery. The cupola, which may be considered as a membrane with a force acting at the edge of 22 kN/m, has an average stress value of 110 kPa.

Loads on the central pillars range from 2510 to 2930 kN and the average pressure at the foundation level is 426 to 528 kPa. The outer walls are exposed to loads of 230 kN, corresponding to average pressures of 220 kPa. The static range is of special interest at those points where the radial arches are connected to the outer walls and are enlarged on the outer side by buttresses, where the pressure increases from 250 to 800 kPa (taking into account the horizontal action of the radial arches as well).

Considerable alterations in static conditions took place at these points in the year 1700, when the floor and roof of the women's gallery were substituted with brick cross-vaults. This work brought about a general improvement in the static conditions of the central nucleus by balancing horizontal forces, but it generated considerable movement in the outer walls. This made it necessary to install auxiliary metal supports in 1898, when Corrado Ricci eliminated the various other buildings that had been attached to the main body of S. Vitale in previous centuries. Building-to-soil contact pressures vary considerably between outer walls (220 kPa) and central nucleus (550 kPa), mainly because the architects who designed the building complex were afraid that excessively high strains would take place at the edges, due to the fact that the outer walls were rather isolated from the nucleus, thus generating sinking and rotation of the bases of the pillars.

The upright oak piles found beneath the pillars (taking into account stress levels) were introduced mainly for the purpose of compacting the sandy silt and sand.

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6 Movements of the complex

In order to check the movements of the buildings, a thorough analysis of cracking was performed. On the basis of the results, a certain number of cracks were chosen as sites for installing 27 strain bases, two hygrothermographs, eight level measurement devices and two deformation measurement rods set in place from the floor to the roof of the women's gallery (Fig.5). Deformation measurements were taken once a month. Temperature, relative humidity and sinking values were checked during the week in which the above deformation tests were performed.

DAG 10 level measurement devices were installed on the floor of the women's gallery and connected to the expansion vessels in order to measure relative variations in floor level at the points of installation with an accuracy of 1/100 mm. Fig.6 lists recordings of the opening and closing of cracks.

Fracture movement trends on the various structural components ranged from 0.20 to 0.58 mm for the cross-arches, from 0.20 to 0.25 mm for the windows, from 0.10 to 0.20 mm for the cross-vault, and from 0.25 to 0.45 mm for the arches supporting the vaults between the central pillars.

Fig.7 shows temperature and relative humidity trends in the survey period, revealing considerable thermal inertia of the building with respect to daily and seasonal variations.

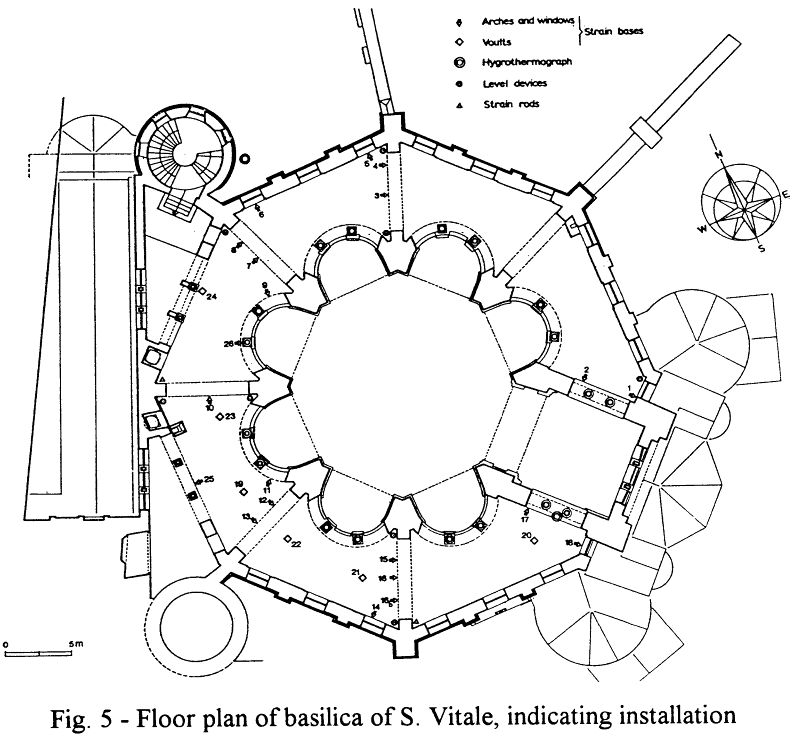

Fig. 5 - Floor plan of basilica of S. Vitale, indicating installation sites of survey instruments.

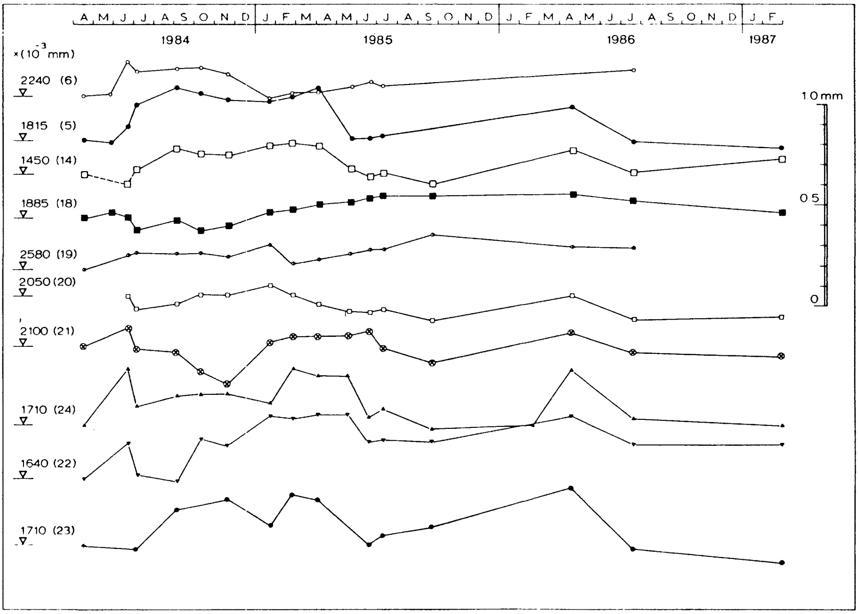

Fig. 6 - Deformation recordings of S. Vitale basilica

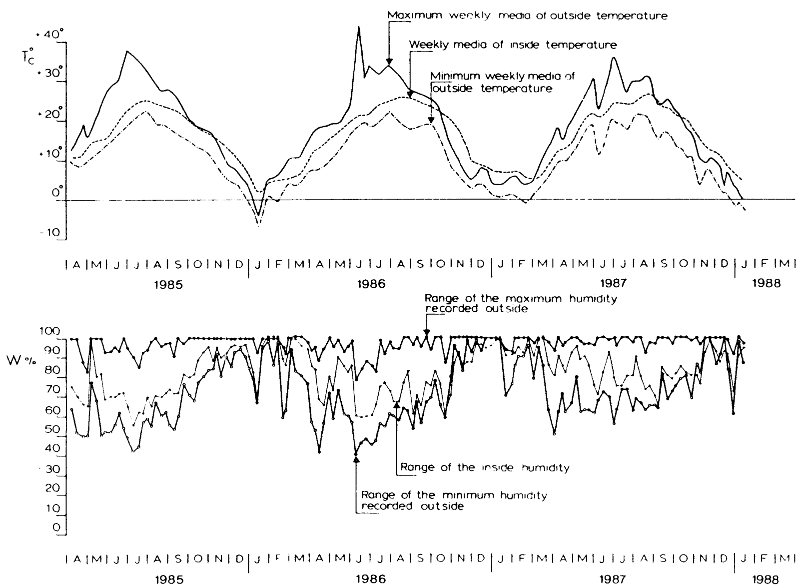

Fig. 7 - Variations in temperature and relative humidity at S. Vitale basilica

Comparison of these figures shows that the opening and closing of cracks follow seasonal variations in temperature, with a certain delay in response. Measurements of daily variations reveal that temperature only moderately affects cracking.

The opening of cracks was found to follow seasonal temperature trends with practically no relative residual movements.
Fig.8 reports values recorded by the level measurement devices from April 1984 to July 1986. Fig.9 illustrates the variations in height of the women's gallery, detected by the varying length of the deformation rods connecting the floor with the vaults overhead.

Measurements of uneven structural sinking indicate moderate values, within a range of less than 1 mm. Sinking exhibits seasonal oscillations, correlated basically to variations in temperature and ground water movements.

7 Conclusive observations

The research results presented here allow the following conclusions to be drawn:

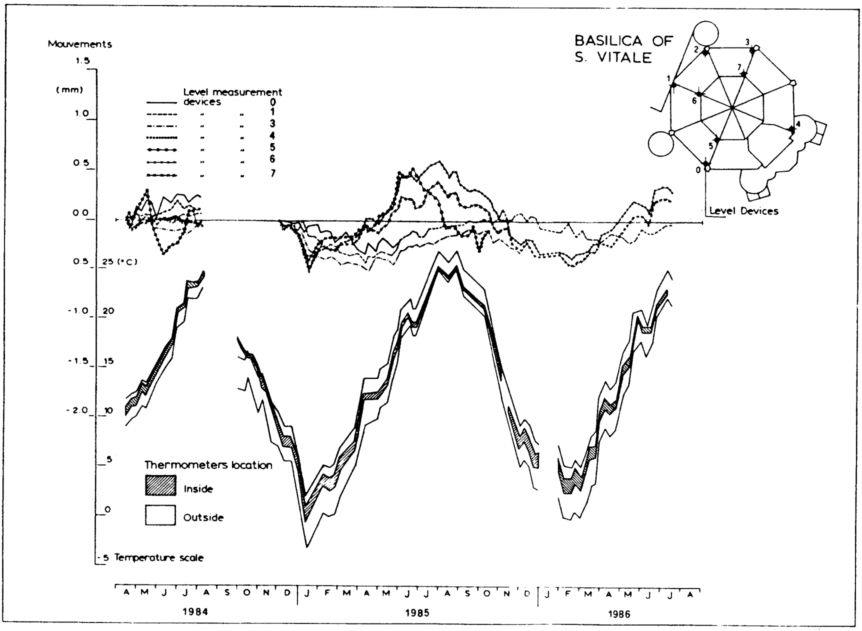

Fig. 8 - Vertical displacements at S. Vitale basilica recorded by level measurement devices.

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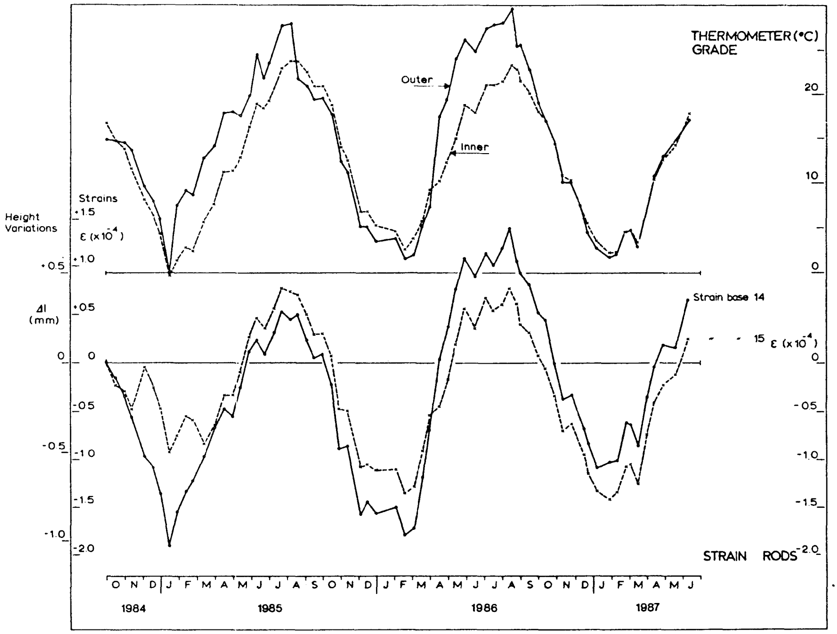

Fig. 9 - Measurements obtained with strain rods installed between floor and roof of the women's gallery at S. Vitale basilica.

- correct diagnosis of the stress-strain behaviour of this ancient monument requires a monitoring system not merely designed to collect data to be compared with questionable models of behaviour, but also planned with the intent to follow and represent the building as a whole, after careful analysis of its various structural elements and of the soil. Such a system is of particular significance and perhaps the only one capable of highlighting the most important variables identified, in buildings which the passing of time renders especially vulnerable;
- analysis of such a model would not only yield reference parameters on which to base possible consolidation and restoration works, but also to take the necessary actions without altering the natural development of strains;
- a monitoring system and continual analysis of its recordings must be incorporated into all preservation and restoration works;
- critical analysis of data collected over a period of three years reveals the effects of constant water pumping, necessary to keep the interior of the basilica accessible and to arrange for small-scale work on the tholobate and radial ties in the floor and roof of the women's gallery.

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