Non destructive investigations on the church of S. Maria di Castello, Alessandria

Giuseppe Pistone
Department of Structural
Engineering - Turin Politecnico

Born in 1948, graduated in civil engineering from the Politecnico of Turin in 1971; is on the faculty of Construction Laboratory, at the School of Architecture of the Turin Politecnico. His interests focus on building restoration and consolidation.

Pier Paolo Rossi
Engineer
ISMES S.p.A. Bergamo, Italy

Born in 1942, received his engineering degree from the University of Bologna. Manager at ISMES, he is involved in monumental restoration and rock mechanics engineering.

Summary

Following a restoration program commenced in the Seventies, the Church of S. Maria di Castello of Alessandria (Piedmont, Italy) is not plastered and its foundations are bare: this makes it possible to appreciate the severity of the damages to the building. This paper describes a non destructive testing campaign (core drilling and inspection to the brickwork, flat jack tests, monitoring system) which is currently underway.

1. Introduction

The Church of S. Maria di Castello is one of the most important monuments in the city of Alessandria (Piedmont, Italy): its present-day configuration dates back to the second half of the 15th century, but the archaeological excavations performed in the 1970's uncovered the remnants of two paleo-Christian basilicas presumably dating back to the 8th and 10th centuries.
The building, (Fig. 1) with a nave and two aisles, has a transept of the same width as the nave, and ends in a polygonal apse behind the presbytery. The 1970's saw the on-start of a restoration program which, however, was soon interrupted for lack of funds and could not be resumed until 1989. Since then, minor interventions have been carried out in several stages till the present day, without, however, being able to provide a viable solution to the problem of an overall restoration of the building. At present, the church walls are unplastered, and the foundations, laid bare by the excavations of the Seventies, can be clearly seen in the huge underground environment that was formed by covering the digs with a concrete block slab which now serves as the walking floor of the church. For such reasons, it now proves possible to discern the structural layout and, above all, to appreciate the wealth of lesions that threaten the stability of the building.

Recently, sufficient funds have become available to finance a definitive consolidation program and get the initial phase of the restoration works underway. To this end, a non-destructive testing campaign has been planned out and implemented, including core drilling from the masonry followed by inspection through the holes by means of television probes. Tests by means of flat jacks have been performed on the big stone columns belonging to the primitive configuration of the church (13th century) and on the transept columns. Furthermore, the most significant displacements of the structure along the two main directions of the building are being monitored by means of wire-type extensometers, and the relative data are recorded continuously. The facade and on of the transept columns have been equipped with high-precision pendulums to ascertain the presence of irreversible displacements of the structures and to verify the data obtained by means of the extensometers.

DIA

Fig. 1 Interior of the Church of S. Maria di Castello of Alessandria

2. Study of the behaviour of the church

Since 1989 the church has been studied on an-going basis to evaluate its materials, damages and static conditions. Until a short time ago, however, the shortage of funds had made it impossible to conduct a number of sophisticated analyses, which have now been undertaken.
The analyses conducted in the past include:

- geognostic investigations into the foundation soil, which have revealed that the building rises on a layer of sandy silt in a clay matrix, displaying appreciable variations in terms of consolidation; at a lower depth, we find alluvia with better mechanical characteristics;
- survey of the foundations which, at any rate, have been largely laid bare by the archaeological digs conducted in the Seventies;
- detailed geometrical survey of the bearing structures of the building;
- determination of the cracking conditions and the vertical alignment of the right hand side aisle;
- core drilling from the brickwork to identify the nature and consistence of the masonry works;
- study of the displacements by means of No. 38 strain gauges located astride the most significant lesions, whose readings are checked periodically by means of a mechanical extensometer (Mayes, accuracy of 1/500 mm);
- numerical analysis of the structure through finite elements models.

These analysis and, above all, observations spanning over a non negligible period of time, have made it possible to formulate founded hypotheses as to the causes of the damages; such hypotheses have already been presented in earlier works, see especially [1].
The most significant aspects that are seen to characterise the behaviour of the building and its damages are:

- the cross-section of the building tends to open outward, owing to the thrust of the vaults which is not adequately counteracted by the vertical bearings; the numerical analyses reveal an a-symmetrical behaviour with a more marked misalignment on the western side, probably due to the confinement action afforded on the opposite side by the structures of an ancient cloister.

These hypotheses are born out by the measurements of the vertical alignments, taken on the west aisle, and by the presence of a series of lesions, on the same side, which are fully consistent with the transverse displacements in question;

- the facade tends to project out towards the square;
- the stresses in the masonry - according to the numerical analyses - reach relatively high values at various points. Though their size is considerable, the masonry blocks are discontinuous and heterogeneous, not firmly packed together;
- the pillars of the nave, which play a decisive role in the building's static equilibrium, consist of stone columns laterally confined by brickwork reinforcements added at a later time (fig. 2): these raise much perplexity as to the distributions of the stresses inside them, due to the heterogeneity of the materials and repeated tampering over the years;

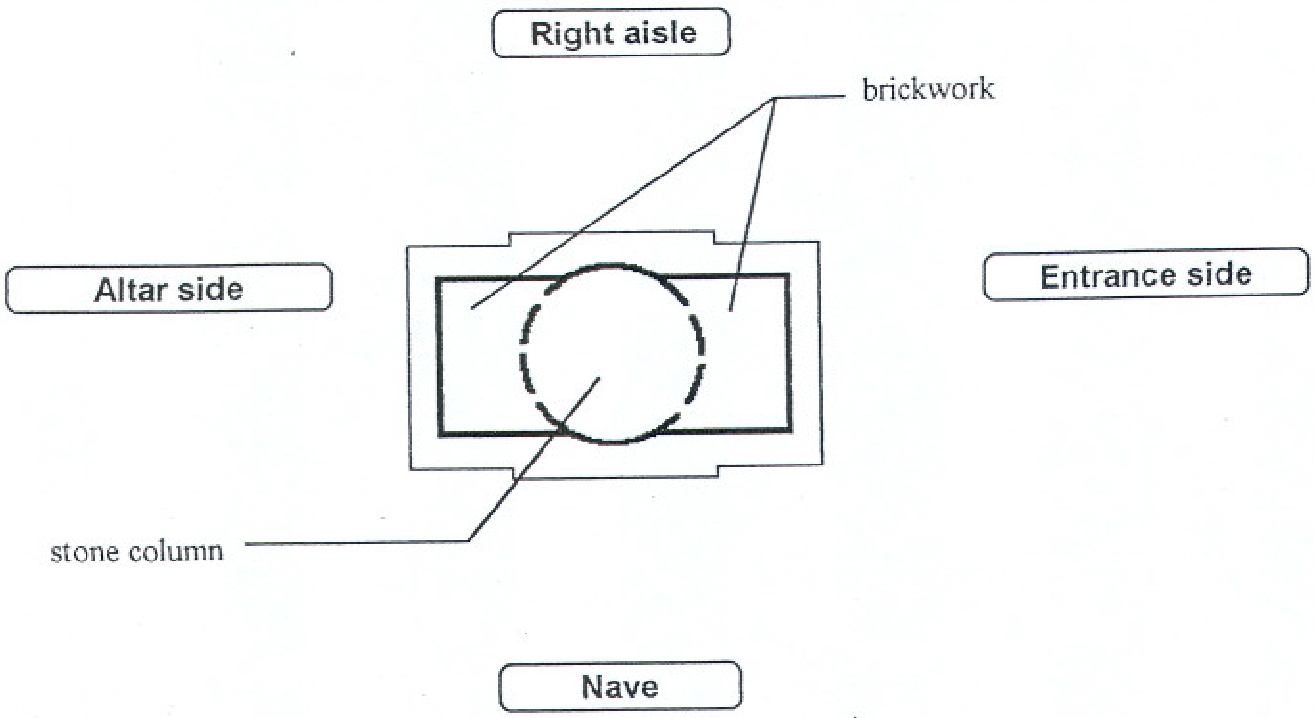

Fig. 2 Horizontal cross-section of the first composite pillar on the right starting from the entrance

- where the damages are concerned, some of the lesions now seem to be quiescent, especially the ones arising from settlements of the foundations (save for the right aisle chapels, that have very shallow foundations); other lesions instead seem to be still evolving, especially those associated with the tendency to open out of the building's cross-section and with the displacement of the facade towards the square.

3. The investigation campaign underway

The series of investigations illustrated in this paper was prompted precisely by these uncertainties concerning fundamental aspects of the building's static conditions.
In particular, the campaign focused on the following aspects:

- nature and consistency of the masonry fabric in the areas not yet examined;

- level of the stresses in structural members having a major static role, such as the nave columns;
- measurement of the significant movements of the building over time, to supplement previous measurements of displacements in damaged zones.

3.1 Inspection to the masonry fabric

The masonry structures were evaluated by drilling cores and inspecting the holes with a television probe so as to identify their conditions at the level of the foundations of the nave columns, for which the extent and nature of the underpinning works performed in the Seventies was not known, and to examine the brickwork of the composite section angular pillars of the transept.

The diagnostic program was organised according to the following program:
- continuous mechanical core drilling from the left pillar of the transept followed by the inspection of the holes by means of colour television probes;
- continuous mechanical core drilling from the foundations and vertical masonry structures located in the basement, and inspection by means of colour television probes.

The water-cooled manual feed core drilling machine employed had a thin walled diamond crown, with OD of 63 mm and ID of 56 mm. The holes were inspected with a colour television probe to supplement the information already acquired from the material drilled out, especially as concerns the presence and size of possible discontinuities and cavities enclosed in the masonry structure.

3.2 Tests with flat jacks

The tests with flat jacks were aimed at evaluating the static conditions of the central part of the church, especially the nave columns which - as mentioned before - involved considerable uncertainties as to their states of stress and, therefore, raised doubts as to the safety of a portion of the building of decisive importance. Such tests were therefore performed on all the interior columns of the church and several continuous walls, according to the scheme depicted in fig. 3, which also gives the stresses measured at the testing points.

In addition to the primary goal, i.e., the assessment of the state of stress, these tests were also aimed at determining the stress-strain curves, of special significance for the evaluation of brickwork structures. In this connection it should be noted that since four pillars have a composite stone and masonry section (see pillars Nos. 1, 2, 4 and 5 in fig. 3), numerous tests were also performed on the stone columns, by fitting the flat jack into the horizontal joints between the circular stone elements. The testing campaign used flat jacks of different shapes and sizes; in particular:
- semi-circular flat jacks, sized 255x345x4 mm
- square flat jacks, sized 150x150x8 mm.

3.3 Monitoring system

The monitoring system (fig. 4) installed was aimed at documenting the movements of the building in the transverse and longitudinal directions so as to be able to determine whether the lesions observed in these directions have evolved, or are likely to continue evolving over time even after the consolidation works already performed or about to be performed.

The static structural monitoring system adopted for the control of displacements as a function of time and temperature variations included both automatic and manual data acquisition instruments. The automatic acquisition system uses Invar wire extensometers and heat probes managed by a data logger (which measures and stores the values acquired). The manual section consists of removal pendulums, with a coordinometer for the readings.

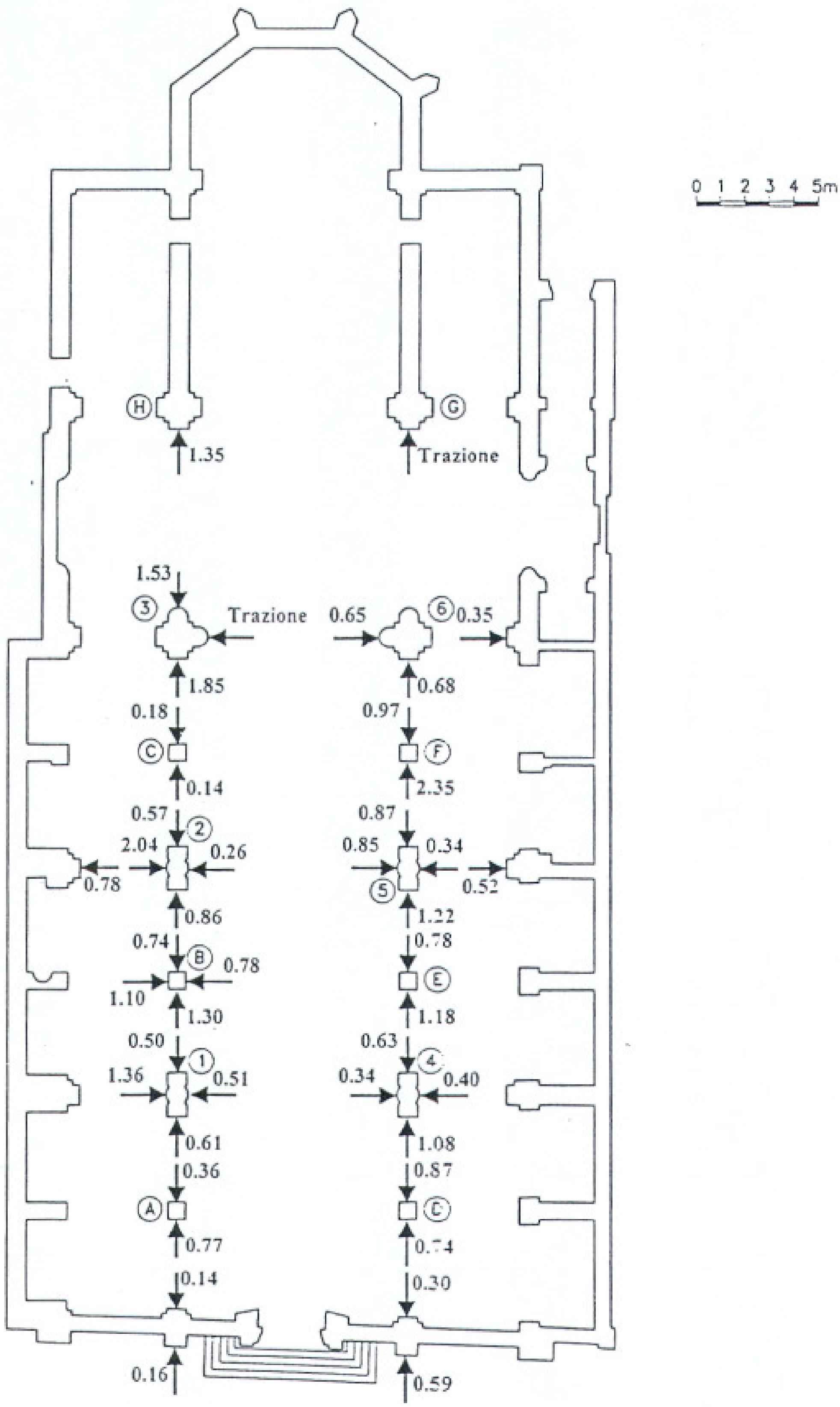

Fig. 3 Plan view of the church with the results of the flat jack tests; the results are expressed in N/mm^2

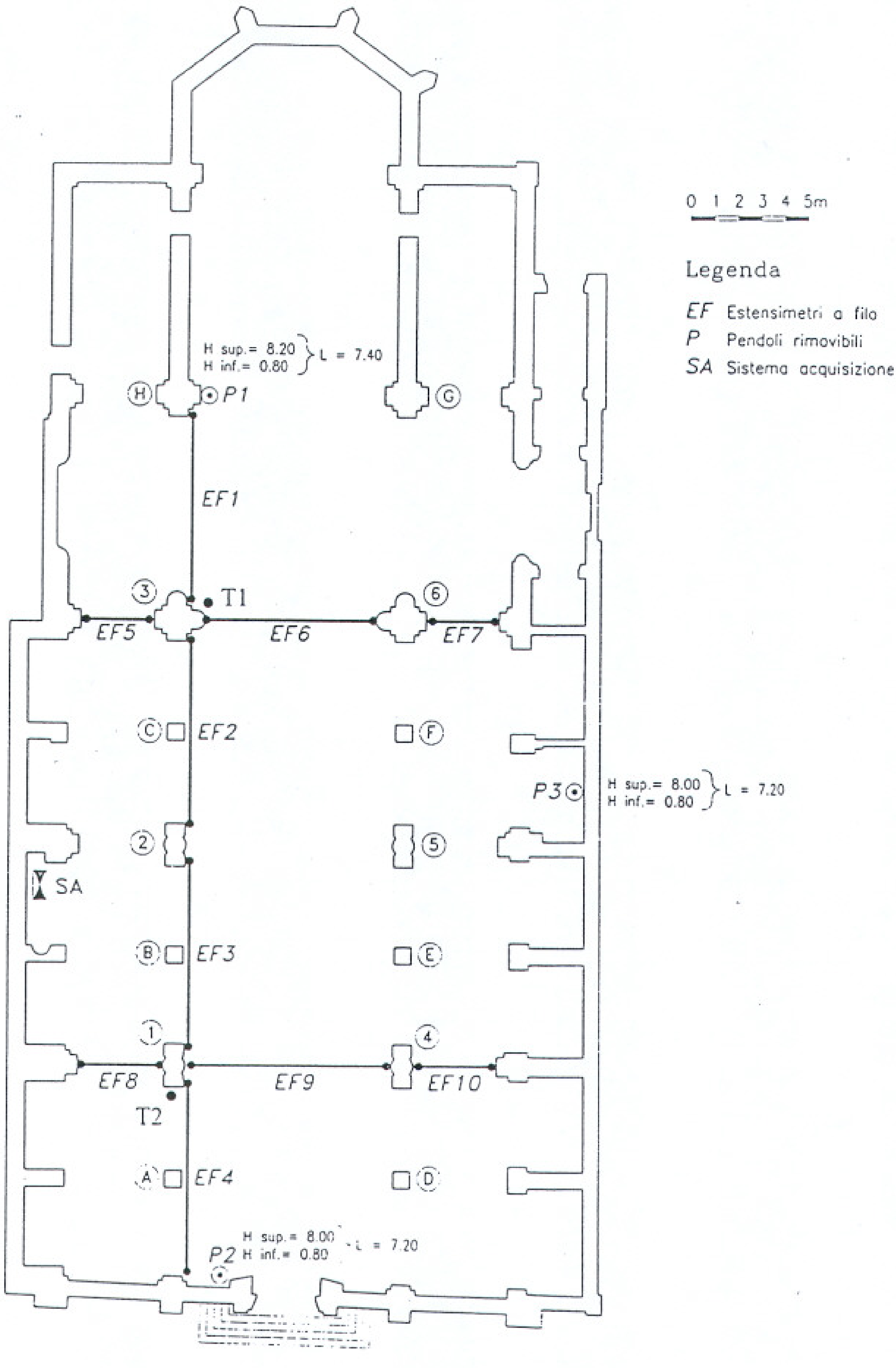

Fig.4 Plan view of the church showing the arrangement of the monitoring system

All in all the system consists of:
- No. 10 long range Invar wire extensometers
- No. 2 heat probes
- No. 3 removable pendulums to detect possible departures from the vertical of the structures and to measure the changes in their inclination over time
- No. 1 acquisition system.

The system was inaugurated in September 1996; the data acquisition timing was set at 6 hour intervals.

4. Results of the investigation

The results of the testing campaign turned out to be very significant, especially for the diagnostic part, and made it possible to clear up several aspects of the building's static conditions. As for the monitoring process, a longer time period will obviously be necessary to take full advantage of the observations made.

4.1 Core drilling tests

The holes drilled, in the present-day basement of the church, into the masonry substructure of the central nave columns revealed that during the archaeological digs of the Seventies the impost plane of the foundations was lowered through the addition of brickwork reinforcements along the perimeters of the existing pillars; this underpinning and the lowest parts of the pre-existing foundations were then enshrouded, albeit only partly, with r.c. castings from 10 to 15 cm thick.

Of special interest proved the inspection conducted by core drilling in the left hand side pillar of the transept, which brought to light the brickwork of the element and the construction methods adopted for its realisation (fig. 5).

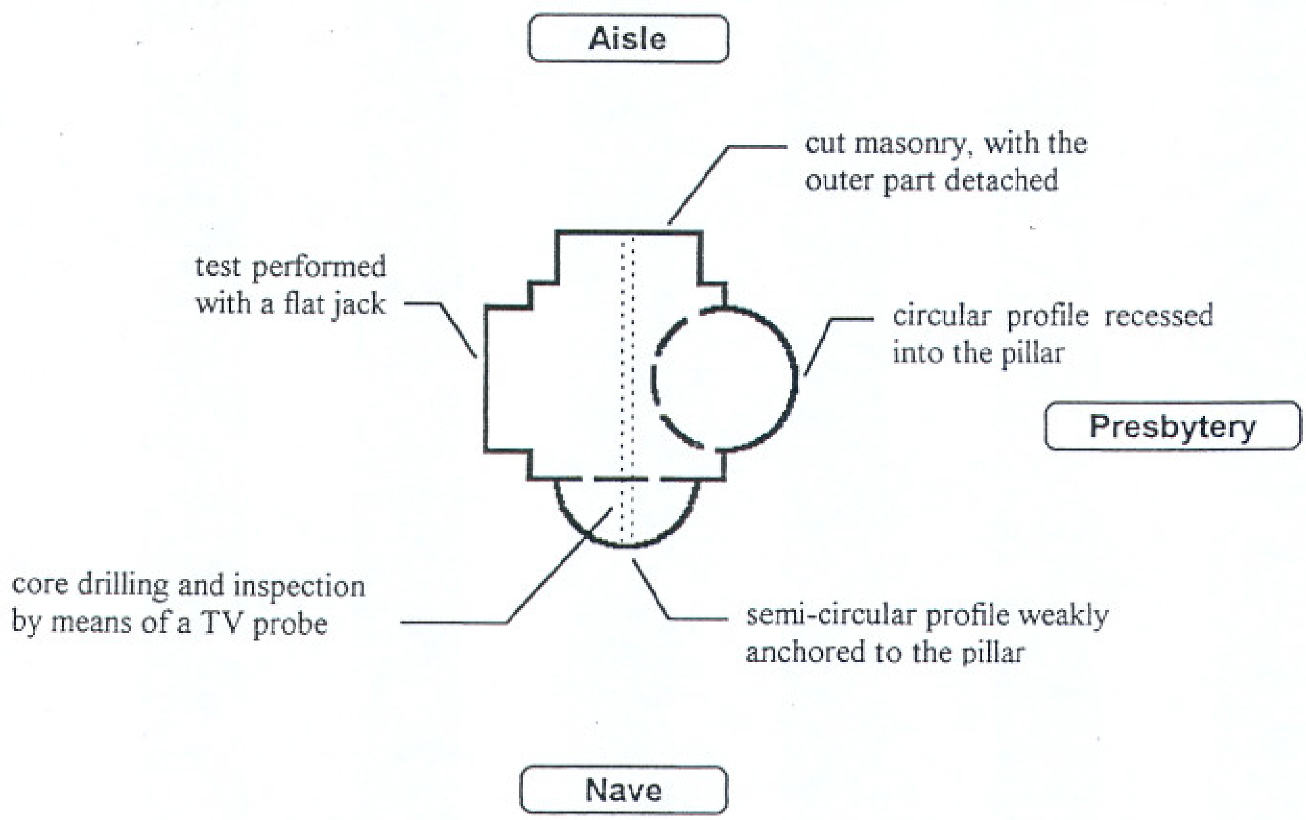

Fig. 5 Horizontal cross-section of the left pillar of the transept showing the configuration of the masonry and the position of the tests performed in July 1996 (by ISMES S.p.A. of Bergamo)

In particular, it can be seen that the multi-lobed section is composite and is the outcome of subsequent interventions over time: the portion facing the aisle looks as if it had been cut out of a pre-existing wall, it is badly cracked and displays a loose fabric. The semi-circular section facing the nave is merely "applied" to the rest of the pillar, whist the portion facing the presbytery is part of a veritable circular column lodged into the masonry (as demonstrated by the visual examination of a small breakage at the connection with the straight section of the pillar); the masonry of the half-column facing the nave is tightly packed, whilst the inner portion at its back displays small empty zones; the fabric of the portion of the pillar facing the facade is presumably good, according to the results of a test performed with a flat jack, revealing high stress values and, hence, presumably, considerable stiffness.

4.2 Tests by means of flat jacks

The systematic inspection of the nave pillars has shown first of all that in general they are subjected to considerable compression and bending stresses, which in some cases are very high. Fig. 3 concerning the overall situation of the state of stress determined from the measurements shows numerous values of over 1 N/mm^2, even in the masonry parts, with a peak of 2.04 N/mm^2 in the stone portion of the first composite element on the left, starting from the transept.
Of even greater significance is another aspect that emerges from the data: contrary to the results of the numerical analyses and the phenomena recorded historically, the building now seems definitely "attracted" to the side involved in the archaeological digs and the underpinning works performed in the Seventies. The earlier static equilibrium was reversed by such interventions on the foundations, which caused settlements throughout the eastern part of the church, i.e. the part subjected to the underpinning works. As a result of these settlements, the building has been displaced towards the cloister, with considerable bending and compression phenomena affecting the near totality of the pillars.

The tendency of the building to "reach out" in the perpendicular direction towards the facade was confirmed, however. Save for the zone adjacent to the transept, all the pillars are seen to be subjected to compression and bending towards the facade, fortunately with stress values lower than those recorded in the transverse direction of the building.

Finally it should be noted that some tests, continued until the masonry reached the plastic stage, have revealed stress levels of the same order of magnitude as those observed in service conditions in several masonry structures.

5. Conclusions

The non destructive tests conducted in recent years on the Church of S. Maria di Castello of Alessandria made it possible to shed much light of aspects as yet unknown of the building's static set-up. The most significant fact is that the digs carried out in the Seventies altered to a substantial extent the static equilibrium of the building, also on account of the type of underpinning adopted, which resulted in marked settlements of the foundations.

In particular, the building's historically documented tendency to lean out towards the west has been reversed, and the building now appears to be "reaching out" in the opposite direction, with appreciable bending and compression phenomena affecting the masonry of the columns.

References

[1] Pistone, G., "La conoscenza della struttura", in *S. Maria di Castello*, Cassa di Risparmio di Alessandria S.p.A., Alessandria, 1996.