STRENGTHENING INTERVENTIONS OF THE ROMANESQUE TEMPLE OF SAN TOME' IN BERGAMO

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ABSTRACT:
The Temple of San Tomè near Bergamo is one of the most singular Romanesque structure. The church has a circular plan and it was built in the first centuries of the Christian Era. A diagnostic investigations campaign was carried out in 1980 in order to analyse the structural characteristics of the stones masonry and to check the property of the soil foundation. In the same period a monitoring system was installed to observe the deformation behaviour of the walls interested by important vertical cracks. During the observation period of about 27 years (from 1984 to 2012) a progressive opening of the cracks was observed. A strengthening intervention was designed in order to restrain the radial deformations of the structure. The effect of the strengthening interventions was analysed by means of a finite element mathematical model of the whole structure. The paper describes the design criteria and the execution of the strengthening interventions that were completely covered by the stone slabs of the roof.

INTRODUCTION:
San Tomè is a Romanesque temple with a circular plan, located in Almenno San Bartolomeo, near Bergamo. It is made up of three cylinders, one on the top of the other, with decreasing diameter from the bottom up. The construction of the actual temple started in 1150 (or thereabouts) when the Bishop decided to build it on the foundations of a previous circular structure. The works continued for some years and the presbytery and the abse were completed in 1180. During the same period, a convent was built on the southern side adjacent to the church.
The monument underwent many repairs; the most consistent structural intervention dates back to the end of 19th century and was realized by the engineer Elia Fornoni.
The Temple was built with squared stones of local origin (pink-white limestone, for the most part, as well as a typical conglomerate from the river Brembo called "ceppo", and grey-green sandstone). The larger cylinder is decorated with thin semi-columns which end with carved capitals joined together by small hanging arches. The second cylinder is decorated with pilasters, with rectangular section, arranged at regular intervals. The third cylinder (the lantern) has four double lancet windows which emphasize its lightness (figure 1).
In figure 1 the inside of the Temple is shown, with the central room including eigth monolithic columns (with beautiful carved capitels) and the surrounding women's gallery (Matroneo). There are two staircases with opposite entrance leading to the women's gallery, carved unto the thickness of the perimetral wall.
The longitudinal section of the Temple is shown in the same figure 1.

Figure 1. The Temple of San Tomè: external and internal view and longitudinal section

DIAGNOSTIC INVESTIGATIONS

In 1984, several signs of decay of the masonry and the presence of many cracks, advised the execution of a wide diagnostic investigation in order to analyse the structural conditions of the Temple.

At first, a geotechnical investigation was carried to define the stratigraphy and the mechanical characteristics of the different layers of the soil foundation. By using a continuous borehole 15 m deep and several static penetrometric tests, it was found, under the foundations of the temple, a formation of glacial and fluvial origin , which is resting on a layer of conglomerate (“ceppo”). The scheme of the testing points is shown in Figure 2. The mechanical characteristics of the soil foundations are satisfactory excluding a small portion near the head of the slope where a softer soil was found up to a depth of about 3 m.

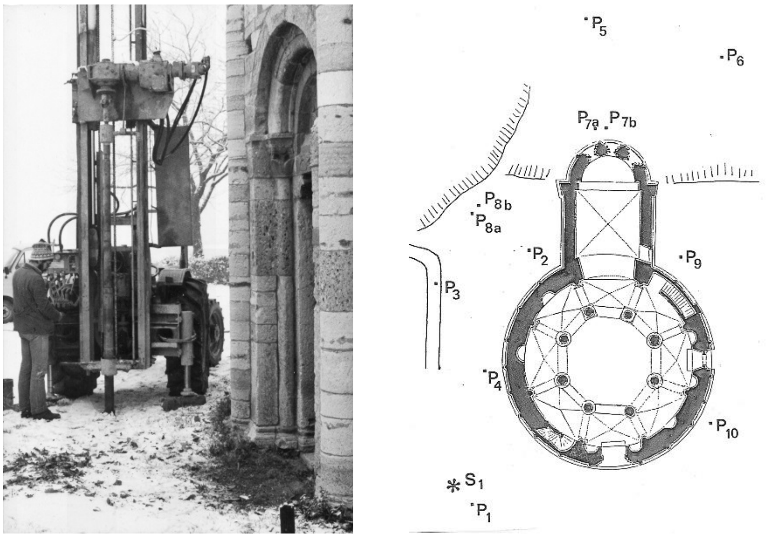

Figure 2. Geotechnical investigation and lay-out of the testing points.

Then, the structural characteristics of the foundation masonries were examined by means of small excavations around the perimeter of the temple. These excavations, included in the program of the archeological surveys, showed the structural characteristics of the foundation masonry which is composed by an upper layer (80 cm thick) made with squared stones well cemented with mortar, which is resting on a lower layer (about 70 cm thick) of masonry built with irregular stones with some mortar. The total thickness of the foundation masonry is about 1.50 m, as is shown in Figure 3

Figure 3. View of the foundation masonry discovered during the archeological survey

The structural characteristics of the masonries which compose the Temple, were than examined. The external and internal abutments of the masonries were built with squared stones blocks arranged in regular layers. Between the two abutments, an irregular masonry was inserted by using irregular stone blocks with some mortar. The total thickness of the wall of the lower cylinder is about 1.30 m.

A detailed mapping of the different stones used for the construction of the masonries was made. The stones are of local origin: pink-white limestone, for the most part, as well as a typical conglomerate from the river Brembo called “ceppo” and grey-green sandstone.

Particular attention was devoted to the crack-pattern survey. Several cracks were observed in the lower cylindrical structure. These cracks are mainly due to the shape of the structure and seem less dependent from differential settlements of the soil foundations. Their direction is generally vertical and some of them cut the whole thickness of the masonry. In figure 4 the two main vertical cracks are shown, The crack number **1** is located in the northern side while the crack number **2** is located in the western side and crosses the main entrance door and the overhanging windows. Both cracks have a great structural importance because they cross the whole thickness of the wall up to the top of the main cylindrical structure

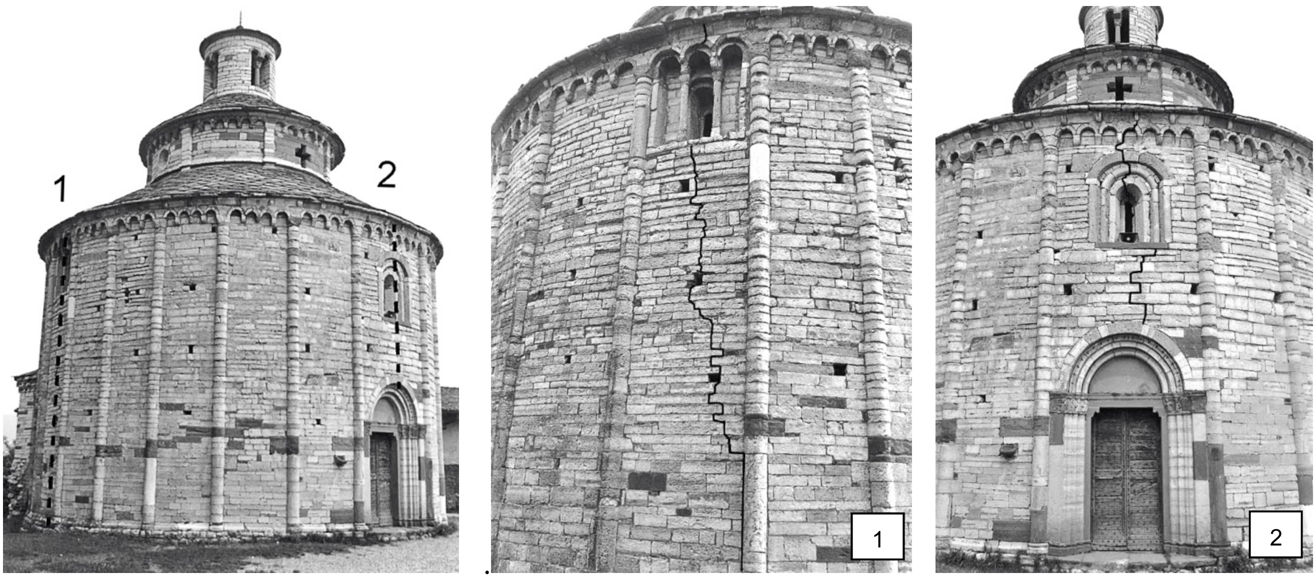

Figure 4. Crack-pattern survey – the two main vertical cracks

MONITORING SYSTEM

In 1984, several measuring points were installed on the main cracks of the Temple. A removable mechanical crack-gauge was used with a measuring base of 200 mm and the based were composed by a couple of circular steel plates with a diameter of 5 mm. In the figure 5 , the removable crack-gauge with high precision, is shown together with the scheme of the measuring points.

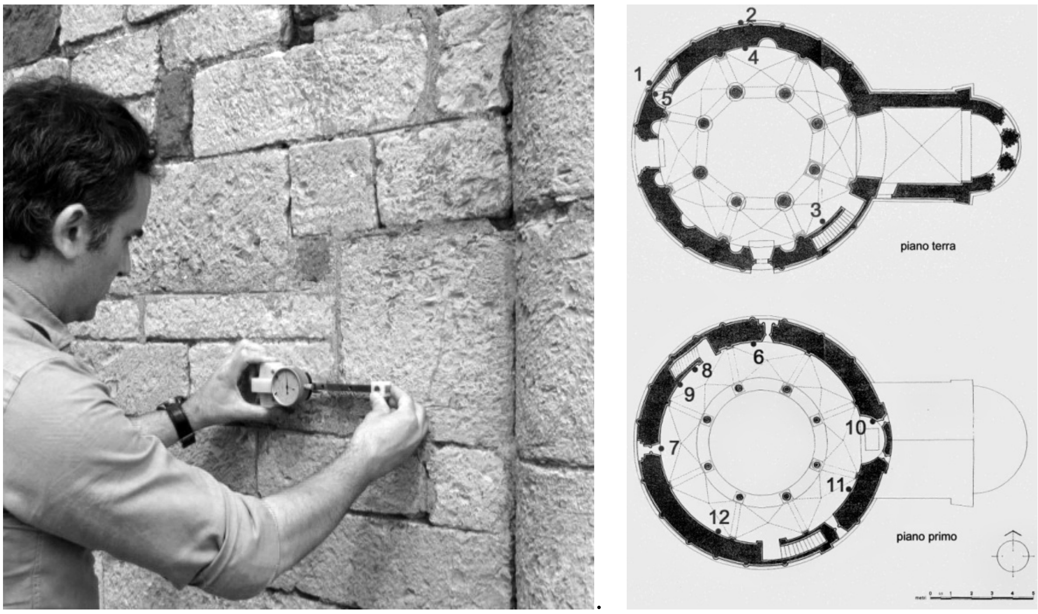

Figure 5. Mechanical removable crack-gauge and lay-out of the measuring points.

A first period of observation of about 6 years, from 1984 to 1990, allowed the analysis of the opening of the cracks during the seasonal thermal cycles, as function of time and temperature. The diagrams of the opening variations of the cracks are shown in figure 6. The diagrams show a significant influence of temperature on the openings of the cracks. Some permanent deformations were observed on the measuring points installed on the main cracks (1 and 2), with an opening trend of about 0.05 mm/year.

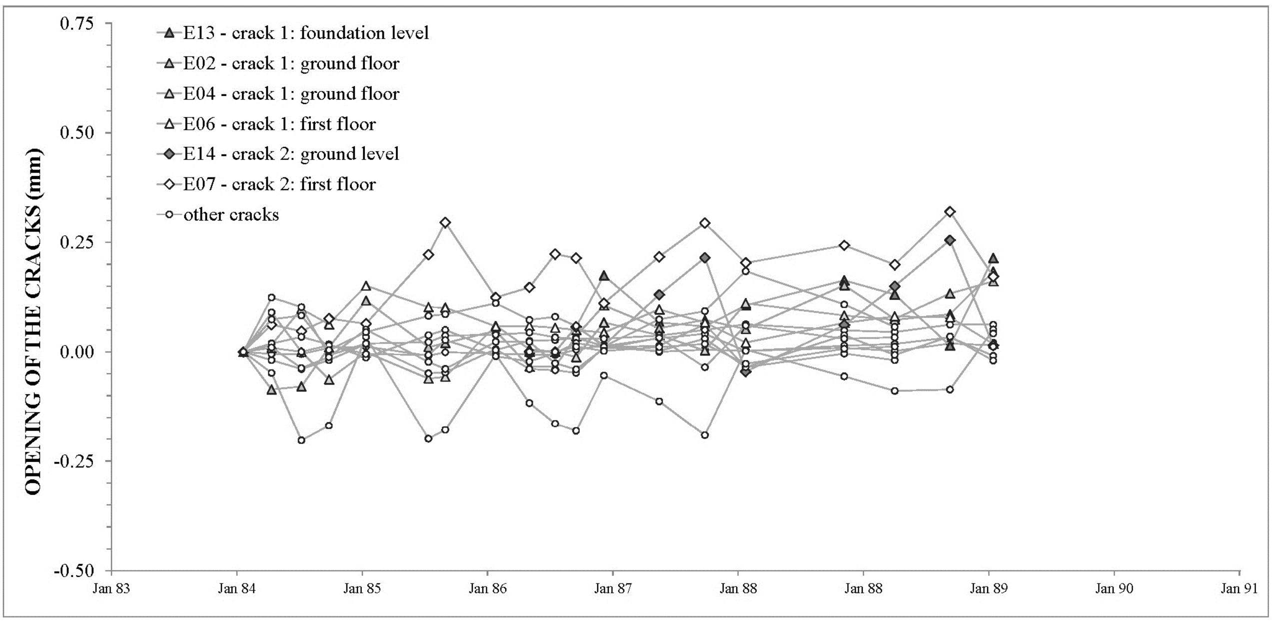

Figure 6. Diagrams of the opening variations of the cracks in the first period 1984-1990.

At the beginning of 2010, about 20 years after the end of the first measuring cycle, the authors realized that the measuring bases installed on the main cracks of the Temple were still in order. By using the same removable mechanical crack-gauge of the previous measuring cycle, a new reading of the opening variations of the main cracks was made. The results of this control is shown in the diagrams of figure 7. It can be observed that the measuring bases installed on the main cracks 1 and 2 (see figure 4) show significant permanent opening of the cracks with values up to 1.20 mm. This opening value, divided for the whole measuring period of about 26 years, means an opening trend of about 0.046 mm/year. The measuring bases installed in the other cracks show not significant opening variations.
The progressive openings of the cracks 1 and 2, clearly show that the main cylindrical structure of the Temple is involved by radial deformations due to the height and shape of the structure and to the absence of an efficient structural confining system.

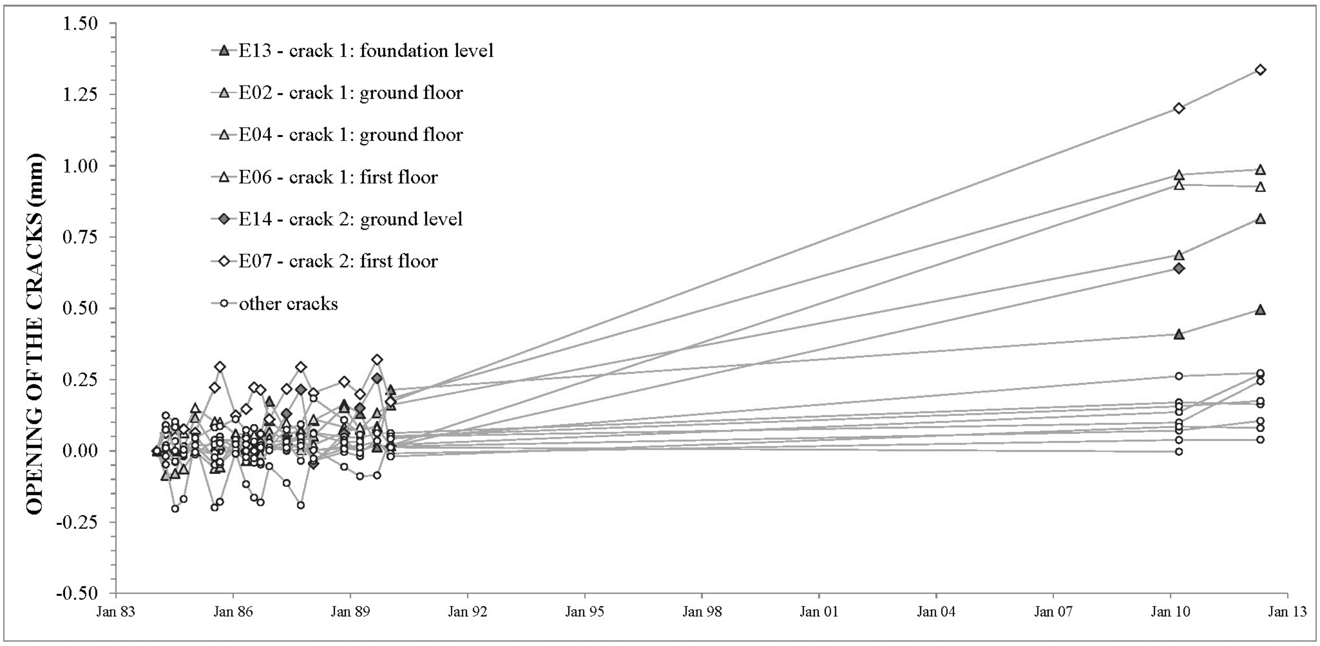

Figure 7. Diagrams of the opening variations of the cracks in the whole period from 1984 to 2012.

STRENGTHENING INTERVENTION

Two years ago, the Municipality of Almenno San Bartolomeo promoted a restoration intervention of the Temple, including the removal and the restoration of the roof, made of slate slabs, and the restoration of the external walls. The complete removal of the roof slabs, allowed the installation of a strengthening structure able to reduce the radial movements of the main cylindrical masonry. The design and the direction of the works were carried out by the authors, for the structural interventions, and by the architects Cesare Rota Nodari and Bruno Cassinelli, for the restoration of roof and walls.
The structural intervention proposed by the authors, aimed at introducing an efficient confining effect at the top of the cylindrical masonry which is able to reduce the radial movements of the Temple. It must be pointed out that the strengthening intervention has no visual impact because all the structures are hidden under the slabs of the roof.
The strengthening intervention is shown in figure 8. The main confining structure is a steel ring (300 mm large and 30 mm thick) which is installed on the top of the perimetral wall by means of stainless steel anchors (diameter 20 mm and length 1000 mm) grouted with special lime mortar. The ring is made with 12 sectors connected each other by bolts. In order to increase the mechanical characteristics of the masonry involved by the anchoring system of the steel ring, the upper layer of the perimetral wall has been grouted by lime mortar injected inside boreholes 1.0 m long.

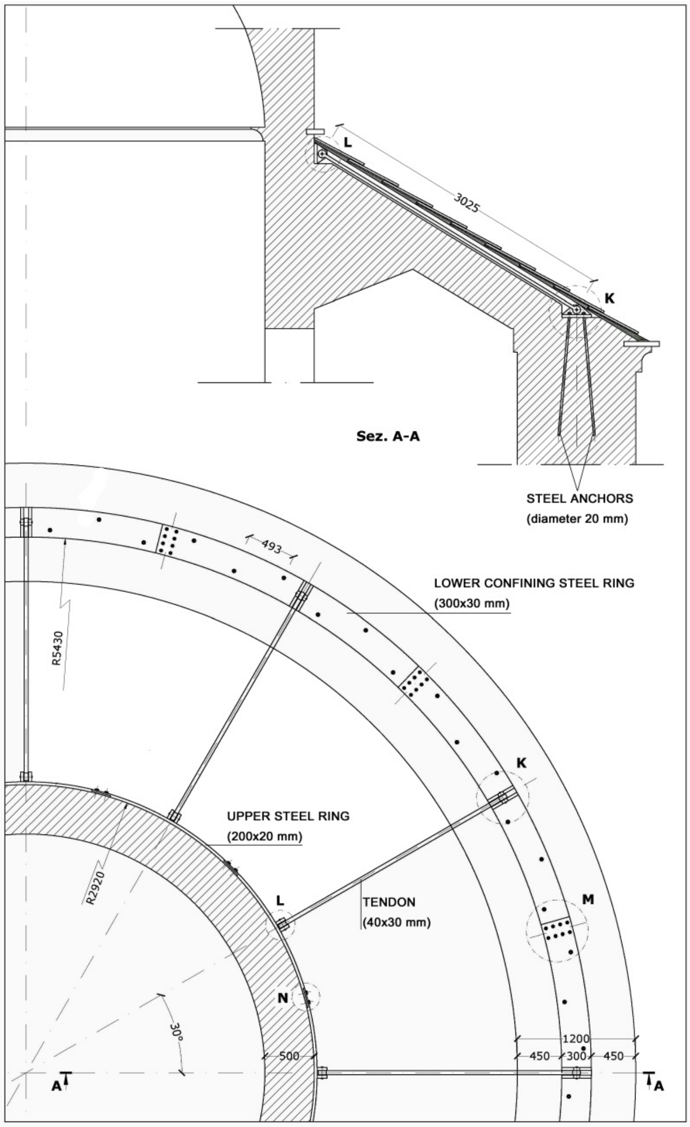

Figure 8. Scheme of the strengthening intervention.

A second steel ring (200 mm high, 20 mm thick) is set around the base of the upper cylindrical structure. Also this second ring is composed by 12 sectores connected by bolts.
The lower ring is connected to the upper one by means of 12 steel tendons with hendge at both sides. All the strengthening structures are made with COR-TEN steel.
The main characteristic of this strengthening system are the following:

- confining effect with satisfactory reduction of the radial deformations, as shown by the result of numerical analysis
- no visual impact because all the structures are covered by the roof slabs
- complete reversibility, because all the steel structures can be easily removed

STRUCTURAL ANALYSIS WITH MATHEMATICAL MODEL

The analysis of the strengthening solution has been carried out with the aid of a finite elements mathematical model of the whole structure where the steel confining structures have been reproduced. Also the effect of the consolidation of the masonry by grouting in the upper layer of the wall, has been reproduced in the model trough an increase of the elastic modulus.

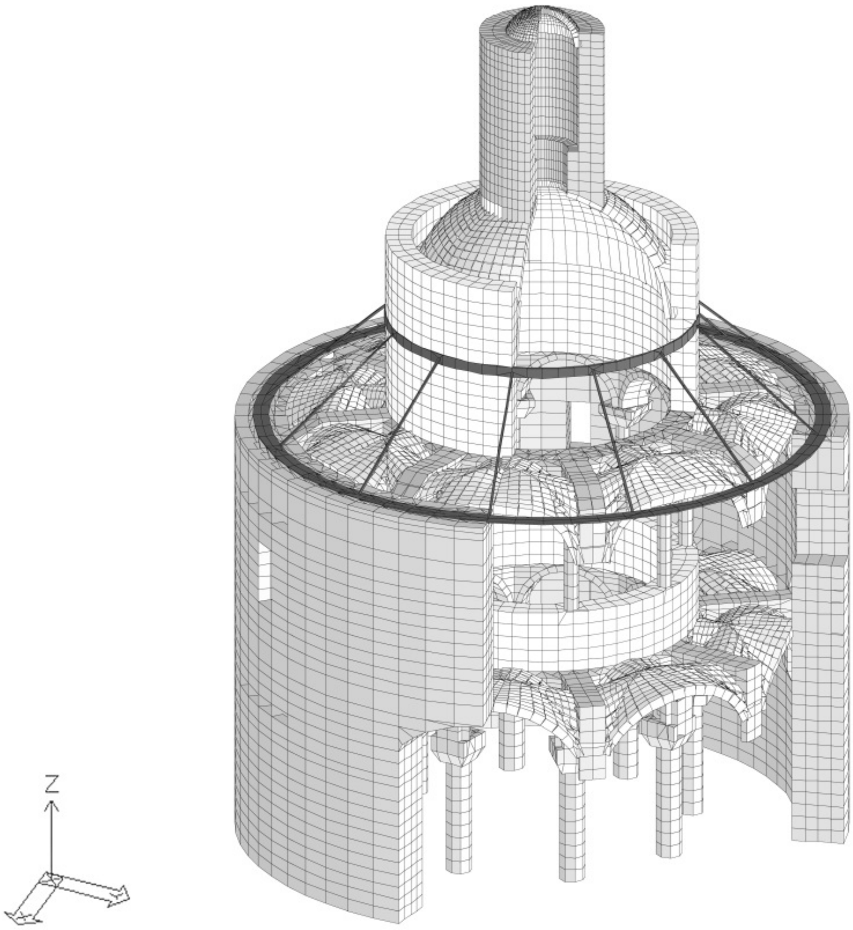

Figure 9. Finite elements mathematical model

Three different cases have been examined:

- Case A - Complete structure without cracks
- Case B - Presence of the main cracks (1 and 2) in the perimetral wall
- Case C - Reproduction of the steel strengthening structures

The deformation behaviour of the structure has been analyzed for the most severe combination of static and dynamic load. The comparison between the results of the cases A and B clearly shows the effect of the main cracks on the radial displacements of the perimetral wall. The increasing of the radial displacement in the zone involved by the crack 1 is 94% in comparison with the case A , while in the zone of crack 2, the increase of the radial displacement is 104%.

The comparison between the cases B and C is particularly significant because it let us to evaluate the effect of the strengthening works under the most severe combination of static and dynamic load. A remarkable reduction of the radial displacements was observed due to the confining steel structures. In the zone of crack 1, the reduction of the radial displacements was about 33% in comparison with the case B, while, in the zone of crack 2, the decrease of the radial displacements was 28%.

EXECUTION OF THE STRENGTHENING WORKS

During the removal of the stone slabs from the roof, it was observed, under the slabs, the presence of a masonry made of irregular stones cemented with lime mortar in several areas of the roof (see figure 10a). In some areas cohesionless material was found, with irregular stones and earth, without mortar (see figure 10b). The presence of this heterogeneous filling material under the roof slabs, advised to cover it with a layer of lime mortar (from 50 to 80 mm thick) reinforced with a stainless steel mesh (50 x 50 mm).

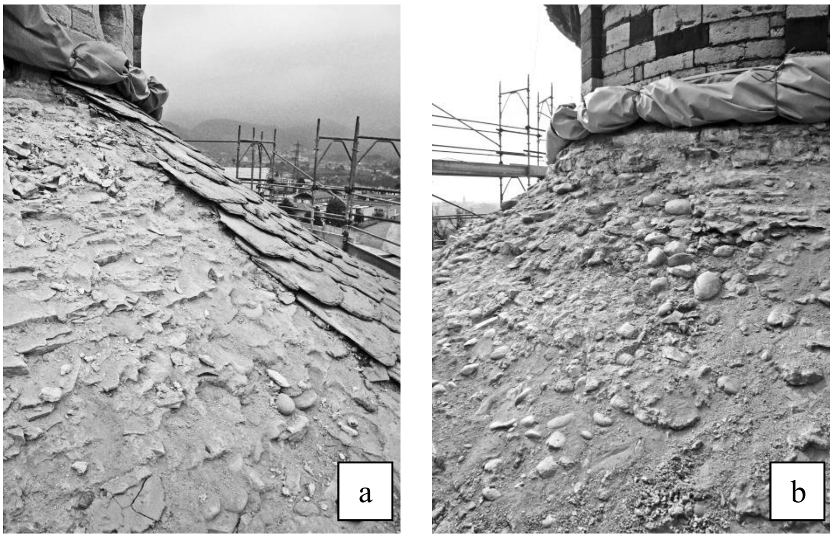

Figure 10. Removal of the stone slabs from the roof and analysis of underlying masonry:
a- Irregular masonry cemented with lime mortar
b- Cohesionless material

To allow the installation of the lower confining ring, the surface layer of lime mortar was cut, as shown in figure 11. Before the installation of the ring, the upper layer of the masonry was consolidated by grouting lime mortar with low pressure into boreholes 1.0 m deep, as shown in figure 11.
The sectors of the lower steel ring were then installed and connected each other in order to obtain a rigid structure which was connected to the masonry beneath by means of stainless steel anchors (1.0 m long).

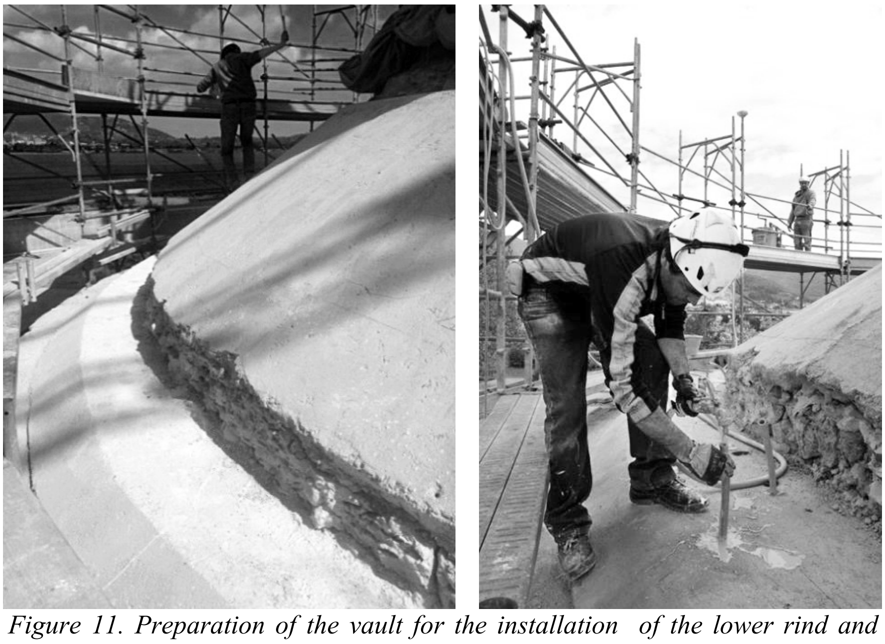

Figure 11. Preparation of the vault for the installation of the lower rind and consolidation of the upper layer of the perimetral masonry by grouting with lime mortar

In figure 12 , the grouting of the steel anchors, by using special lime mortar, is shown. Before the installation of the steel bars, the boreholes were investigated by video-camera survey in order to check the effect of the grouting intervention which was carried out before the installation of the ring to improve the mechanical characteristics of the masonry.

Figure 12. Grouting with lime mortar of the steel anchors which connect the steel ring to the masonry and investigation of the boreholes with video-camera

Then, the upper ring was installed at the base of the upper cylindrical structure and the two rings were connected by 12 steel tendons, as shown in the particular of figure 13. For the installation of the tendons, cuts were made in the mortar layer which was cast over the roof.
A general view of the complete installation of the steel strengthening system is shown in figure 14. It can be observed that also the lower ring has been covered by lime mortar and now the surface of the roof is ready for the installation of the stone slabs.

Figure 13. Connection between the upper ring to the lower and detail of the connection of the tendon to the lower ring.

Figure 14. General view of the complete installation of the steel strengthening system

The placing of the stone slabs, which are connected to the mortar layer by means of nails, represents the last phase of the structural intervention, as shown in figure 15.
It can be clearly observed that roof slabs are completely covering all the strengthening steel structures.
After the end of the replacing of the roof slabs, the restoration of the walls of the Temple was completed.

Figure 15. Final step of the straightening intervention: the placing of the stone slabs on the roof.

A second strengthening intervention should be necessary to complete the confining effect on the main cylindrical structure and to increase the reduction of the radial deformations. This intervention should be carried out at the level of the women's gallery, as shown in the scheme of figure 16. Before the reconstruction of the floor of the women's gallery, a new steel confining system should be designed to connect the perimetral wall to the inner one.

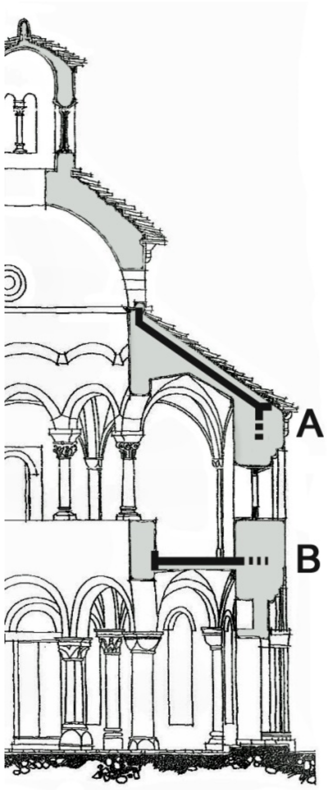

Figure 16. Strengthening confining interventions:
A- Intervention described in the paper
B-Future confining intervention at the level of women's gallery

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