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The crypt of St. Carlo alle Quattro Fontane in Rome

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Abstract

The Church of "St. Carlo alle Quattro Fontane", designed by Francesco Borromini, is a masterpiece of the Italian Baroque. The appearance of deformations and cracks in the vault of the crypt called for the insertion of props. Historical research was carried out to ascertain the original shape and compare it with the deformations visible today. Investigations revealed that the vault was built in good quality pozzolanic concrete mixed with irregular tuff stone blocks. Structural analyses were carried out using finite element models, taking into account the non-linear behaviour of the vault's material.

The results show how the peculiar shape of the vault reduces the safety margins with partializations of sections; cracks have expanded slowly over the years, probably also in relation with the high sensitivity to horizontal displacement produced by little soil settlements. Interventions were designed taking into account also the high artistic and historical value of the building, respecting Borromini's original concept. It as therefore decided to use a system of prestressed tie bars, placed along the radius through the vault, anchored at the edges and connected, in the central area, by a stainless steel elliptical ring placed at the intrados of the vault itself.

1 Introduction

The Church (figure 1) was built between 1634 and 1636 on a quasi-elliptical plan, generated by the joining of four secondary ellipses to a principal and central ellipse (figure 2). This complex form of the nave rises to the cornice and is then covered by an elliptical dome base on four pendentives and four semi-elliptical domes.

The vault of the crypt is based on the same plan as the nave above and it is very flattened with an upward longitudinal concavity in the central zone. If on the one hand this design gives exceptionally plastic results, on the other it penalizes the bearing capacity, which can only develop along the low diagonal arches (figure 3); this is the main reason for the static problems that have arisen since its construction. In effect, the hollow structure implies very high thrusts, which are extremely sensitive to even small horizontal movements of the supports, so that substantial bending moments are generated and as a result an extended pattern of cracks has developed.

figure 1: facade of the Church

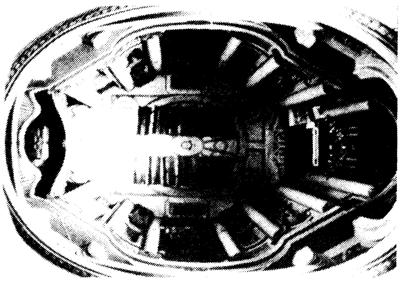

figure 2: view from above

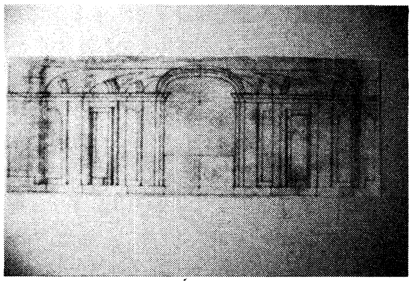

figure 3: longitudinal section of the vault

2 Historical analysis and description of the vault

Borromini began work on the church, which is part of a larger complex for the Trinitarians, in 1634 and the crypt was completed almost immediately.
Here the formally unitary treatment of space is matched by the composition of the vault which, as endoscopic tests have shown, was built from a massive casting of pozzolanic concrete mixed with tuff stones and brick

figure 4: endoscopy of the thickness of the vault

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fragments (figure 4); the resulting structure is highly compact, has no cavities and mortar is extremely cohesive.

3 Description of the damage

The vault has extended cracks (figure 5), consisting of a principal longitudinal lesion on the intrados of the vault and several cracks on the extrados of the springings (figure 6). There are also a number of probably transient transversal lesions near to the apse and a settlement of about 3 cm. in the central part of the vault.

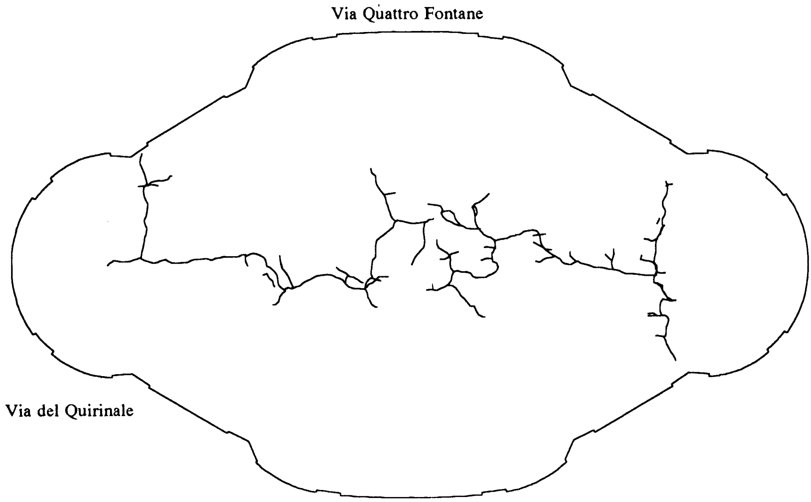

figure 5: crack pattern of the vault

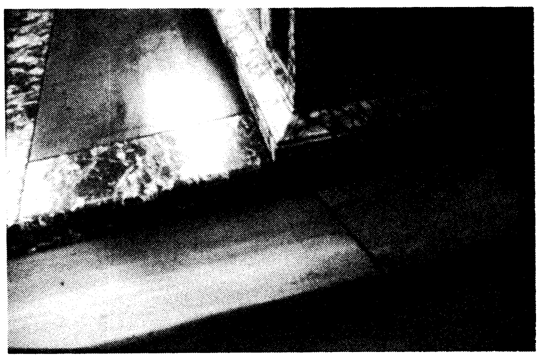

figure 6: cracks in the extrados near the altar

It is not possible to determine the precise development over time of these lesions. It is, however, probable that the central longitudinal crack in the intrados and the cracks in the springings of the extrados had already been caused by the weight of the structure when the scaffolding was removed. The fact that the lesions on the intrados are clearly visible even after the plastering and painting operations carried out in recent years, suggests that the phenomenon continues.

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4 Structural Analysis

4.1 General

Finite element mathematical models were used for the dual purpose of identifying the principal causes of the above damage and providing a qualitative and quantitative evaluation of the measures needed to restore the necessary levels of safety.

4.2 Overall original condition

The study envisaged first of all a three-dimensional model aimed at analysing the whole vault in an elastic field. The results showed that the weight of the structure alone causes high levels of traction both on the intrados of the keystone (30 t/sq.m., figure 7) and on the extrados near to the side altars (43 t/sq.m., figure 8).

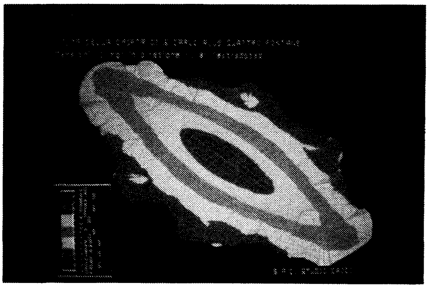

figure 7: 3D model - transversal stresses in the extrados

figure 8: 3D model - transversal stresses in the intrados

The model also revealed that, on account of the little curvature and high ratio between the major and minor axes, the central band of the vault behaves essentially like a flattened arch, for a width of about 4 metres. A second two-dimensional finite element model was thus prepared and both a linear and a non-linear elastic analysis carried out.

4.3 Damaged condition

The non-linear analysis was carried out in stages, submitting the vault to increasing loads. At each increase of the load, a post-processor reduced the rigidity of all the elements for which the points representative of the state of tension were outside the strength dominion, redistributing the corresponding tensions to the adjacent elements. The first breaking finite elements were reached on the intrados, in the centre-line, with 63% of dead weight (formation of the longitudinal crack in the keystone of the vault); the structure then achieved a new configuration of equilibrium until at 93% of the load, further cracks occurred and the diagram tent to an horizontal line.
When all the dead weight was applied other cracks were formed in the extrados near to the side altars (figure 9).

Further increases in the load leaded to rapidly increasing deformations, making it possible to identify an ultimate load corresponding to a value of the order of 25-30% over the working load (figure 10). The safety margin was thus extremely narrow and the calculation amply explained the actual damage situation.

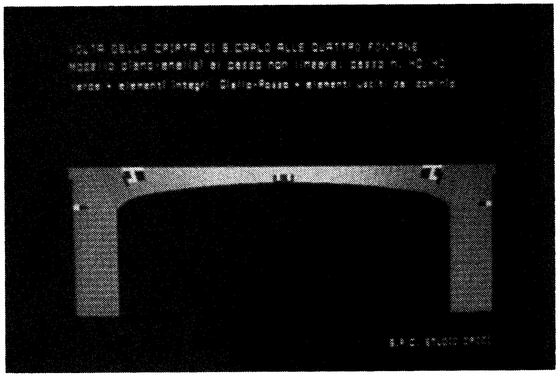

figure 9: 2D model - non linear analysis

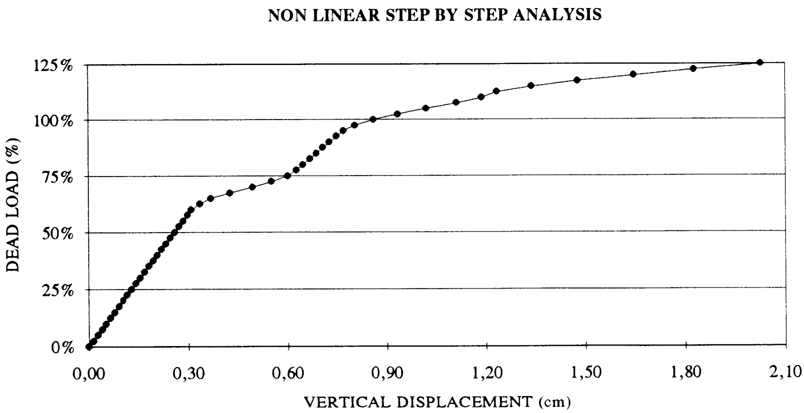

figure 10: load - vertical displacement curve

In order to check the safety levels found, a second type of calculation was carried out using a three-dimensional elastic model in which the actual cracks were directly inserted; this showed high level of tensile stresses (figure 11) confirming that the vault has essentially come to the end of its bearing capacity. It was therefore judged absolutely necessary to proceed with the planned reinforcement measures described below.

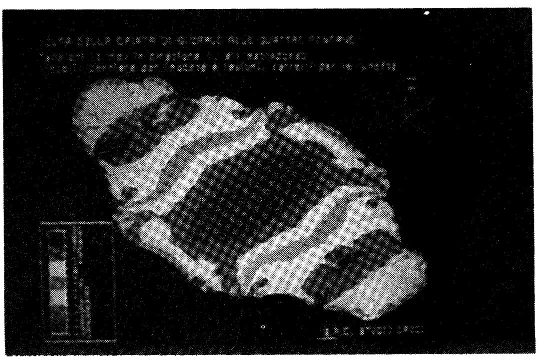

figure 11: 3D model with cracks longitudinal stresses

4.4 Situation after intervention

The reinforced structure was analysed by applying to the vault forces equivalent to the prestressing supplied by the tie bars. The effectiveness and advantages of the measures adopted can be seen in the results obtained by both the three-dimensional and two-dimensional models (figures 12-13-14). In both cases there is a noticeable reduction in stress peaks. The pressure falls from 60 to 38 t/sq.m. and the traction from 45 to 14 t/sq.m. on the extrados near to the side altars and from 30 to 5 t/sq.m. on the keystone of the intrados.

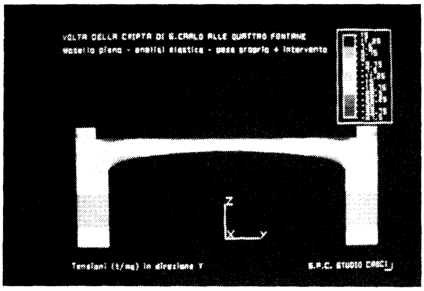

figure 12: 2D model - situation after intervention

figure 13: 3D model - the extrados after intervention

figure 14: 3D model - the intrados after intervention

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5 Criteria for intervention

The reinforcement measures were designed so as to assure the necessary safety levels while keeping to a minimum any alterations to the original design. It was therefore decided that the best solution was to adopt a radial system of tie bars inserted in holes made through the thickness of the vault (figure 15).

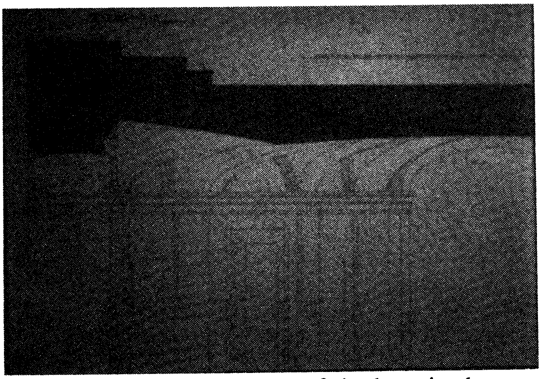

figure 15: arrangement of the bars in the thickness of the vault

The bars are connected in the central part by a stainless steel ring (figures 16-17) and anchored at the ends at the level of the floor of the premises adjacent to the chapel.

figure 16: the anchor ring

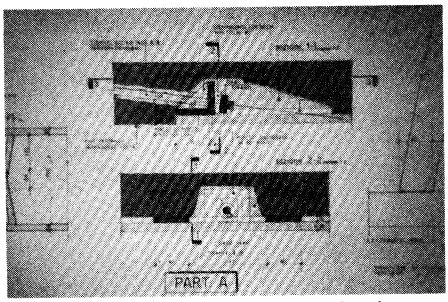

figure 17: detail of the anchoring arrangement

The effect of the bars is not only to provide vertical forces which, as already noted, are directed upwards in the region of the central ring, lightening the load on the vault, but also thanks to the radial arrangement, to encircle and connect the springings and perimeter walls so as to counter all lateral movements to which the vault is particularly susceptible on account of its extremely flattened design.

The stages of intervention can be summarised as follows: plastering and injection of structural mortar into the main cracks; precision drilling with a diamond-headed core barrel placed radially and inclined into the thickness of

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the vault (figure 18); insertion of 22 stainless steel bars with a diameter of 18 mm; prestressing to a value of approximately 6 t (figures 19-20).

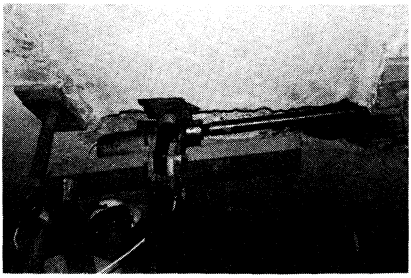
figure 18: perforation of the vault

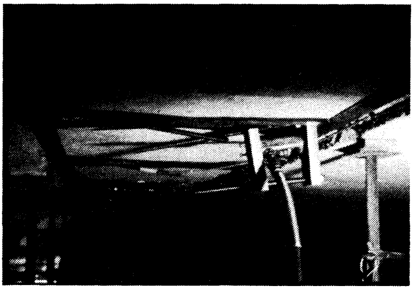
figure 19: anchor ring during prestressing

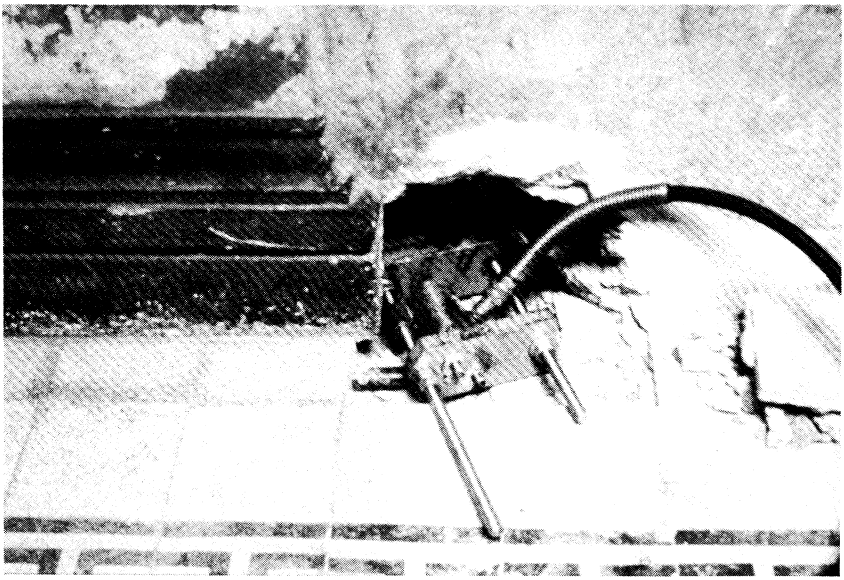
figure 20: detail of prestressing mechanism

To keep the structure under control, both during the prestressing and later during the first stage of the works, a series of strain gauges were connected to a data recording unit able to monitor the stressing values continuously (figure 21).

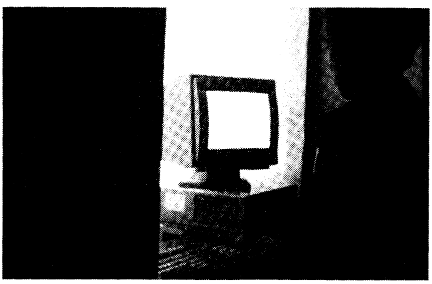
figure 21: data recording unit

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