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Damage and Repair of the St. Charles Basilica in Rome

Dommages et réparations à la Basilique de Saint Charles à Rome

Schäden und Eingriffsmöglichkeiten für die St.-Karls-Basilika in Rom

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SUMMARY

The paper reports on studies of damage and solutions proposed for the restoration of the dome of the St. Charles Basilica in Rome. The study is based on the results of an indepth program of investigation on the soil conditions, the building materials and the analysis of the behaviour during this period. The data has been recorded by a computer connected to a monitoring system. The assessment of the safety levels was performed with the support of mathematical models, by studying historical information and a permanent analysis and comparison of theoretical results with reality.

RÉSUMÉ

L'article présente l'étude des problèmes structuraux et des propositions pour la restauration de la coupole de la Basilique de Saint Charles à Rome. L'étude a utilisé les résultats d'un programme de recherches sur les caractéristiques du sol et de la maçonnerie, et l'enregistrement de la variation de l'ouverture des fissures, grâce à un réseau d'instruments connectés à un ordinateur. L'estimation des niveaux de sécurité a été effectuée au moyen de différents modèles mathématiques, tenant compte des renseignements historiques et comparant les résultats théoriques avec la réalité.

ZUSAMMENFASSUNG

Der Bericht handelt von einer Studie über Schäden und Lösungsvorschläge für den Umbau der Kuppel der St.-Karls-Basilika. Die Studie gründet auf Ergebnissen eines Forschungsprogrammes über Bodenbedingungen, Baustoffe und Analyse des Verhaltens der Basilika, die von einem mit dem Computer verbundenen Beobachtungssystem während dieser Zeit aufgenommen wurden. Die Ermittlung des Sicherheitsfaktors erfolgte mit Hilfe von Computermodellen, dem Studium historischer Berichte und der Analyse und konstanten Vergleichen der theoretischen Ergebnisse mit der Wirklichkeit.

1. INTRODUCTION

The research and studies that will be discussed in the following paper, report on the results of an interdisciplinary operation between the Sovrintendenza of Rome and the consulting engineering of Prof. Ing. Giorgio Croci, with the cooperation of Ing. Giuseppe Carluccio. The construction works were carried out by Impresa Castelli Spa, the monitoring system and investigation were carried out by Società Tecnocontrolli Srl. This approach made it possible to investigate the globality of the problem with mutual exchange and enrichment of imformation from the historical survey, the archeological and geotechnical research, the architectural and artistic aspects (including statues, plasterwork, decoration, colour,....), the structural analysis, etc.
The interdisciplinary approach, which is appropriate for all restoration projects, allowed us to fully understand the problems and phenomena that have occurred and to identify a solution.

2. HISTORICAL SURVEY

The construction of the church began in 1612, after Pope Paul V canonised St. Charles Borromeo. It was finished in 1684 with the completion of the façade (fig. 1).
The builder and director of works was Onorio Longhi who must have also constructed the foundations, the basementwalls of the three naves, the presbitery and the tribune.
At the death of Onorio the project continued under the guidance of his son, Mario Longhi, with successive interuptions due to lack of funding, the most important being the interuption which occurred from 1625 to 1642, during which the central vault was absent; this probably lead to large deformations of the columns in the central nave that are now out of plumb by about 10cm (fig. 2).

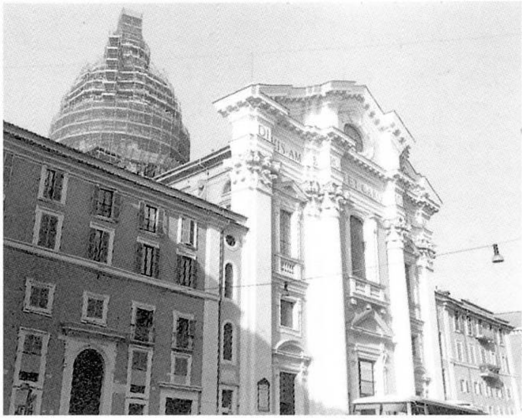

Fig. 1

The drum and dome were built in 1668 and 1669 under the direction of Pietro Berrettini (known as "il Cortona") (fig. 3). By the time Rome was affected by the strong earthquake, which caused damage and failures in the Colosseum, in 1703, the building was completed.
An interesting collection of architects were consulted as problems emerged during construction, including Carlo Rainaldi, Giovanni De Rossi and Borromini himself.

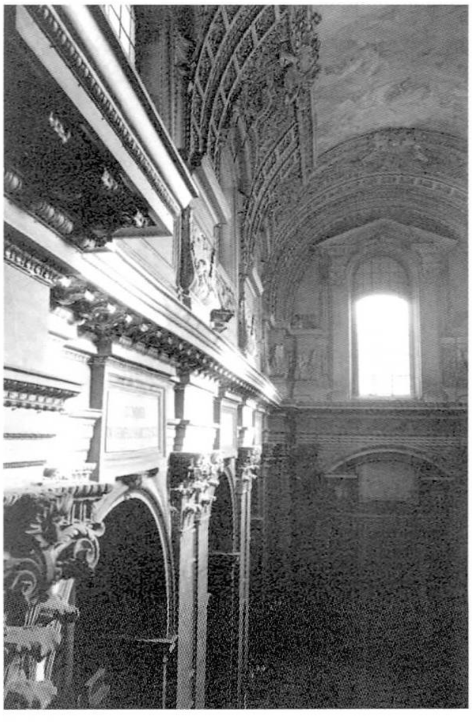

Fig.2

Fig. 3

3. CURRENT STATE AND INVESTIGATIONS

The church has suffered from large scale cracking present in the dome, the vaults of the lateral naves and the vaults of the preambulatory (in general they are diagonal and symmetrical about the longitudinal axis of the church), some cracks are also present in the walls, the crypt, the paving and in the floor above. The cracks in the dome are rather serious, being of the amplitude of a few centimeters (fig. 4); they follow the meridian curves and are concentrated around the ribs, where the architectural requirement of emphasing the ribs lead to a reduction of the dome section immediately next to them, they continue along the drum and also affect the fan arches connected to the drum.

Fig. 4

In the apse area the crack pattern present at the vault level is repeated at the level of the vault of the crypt and at the upper levels; the cracks are almost symmetrical about the longitudinal axis of the church.

Longitudinal cracks are present along the lateral nave in the keys of the vaults, these are associated with a pronounced deformation of the columns along the central nave and a macroscopic deformation of the cornice (fig. 2).

In the course of the study, a series of tests and controls were carried out in order to ascertain the the structural characteristics of the basilica and to evaluate, as accurately as possible, the existing margins of safety.

An important part of this investigation was the monitoring system set up to automatically survey the opening and closing of the cracks over time, in relation to the variation of temperature and other phenomena (fig. 5).

During the control period, which took place, with interuptions, for over three years, no sign of evolutionary phenomena linked to the cracking was observed; however the longitudinal cracks showed a high sensibility to both the daily and seasonal temperature cycles, probably caused by the fact that these cracks represent a hinge which runs along the centre of the basilica and along which the thermal deformations take place (fig. 6).

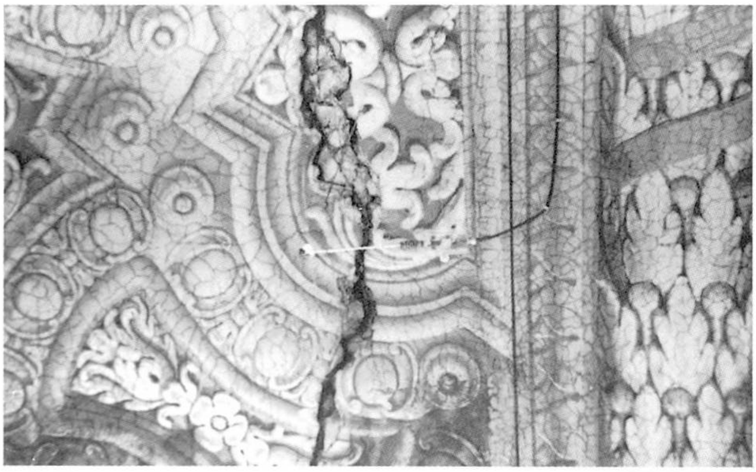

Fig. 5

A series of tests were carried out in order to ascertain the nature of the stuctural constituents:

- traditional geognostic tests and inspection of the soil strata and foundations with a miniture telecamera;
- observation of the composition and condition of the masonry by means of an endoscope placed in small drilled holes, the presence of deep cracks or cavities could also be ascertained (fig. 7);
- sonic tests to determine the homogeneity and compaction of the masonry;
- in-situ flat-jack and pull-out tests, to determine both the strength and the existing stress levels of the masonry to a reasonable approximation (fig. 8);
- measurement of the verticality of the columns in the nave.

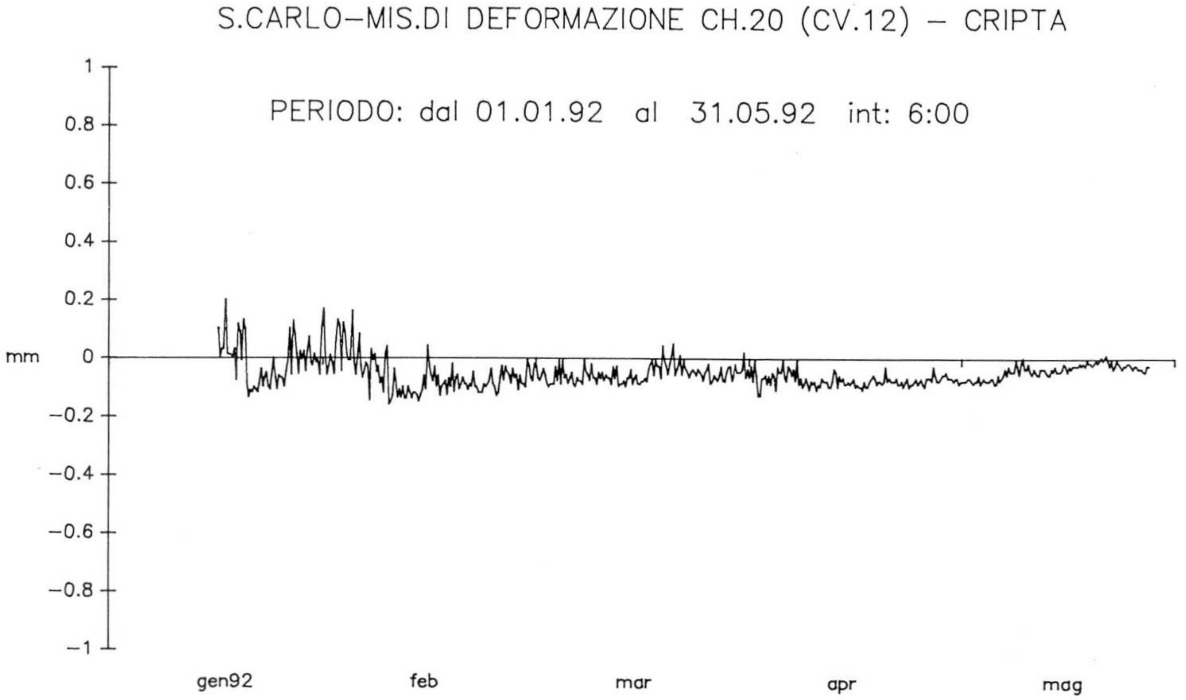

Fig. 6

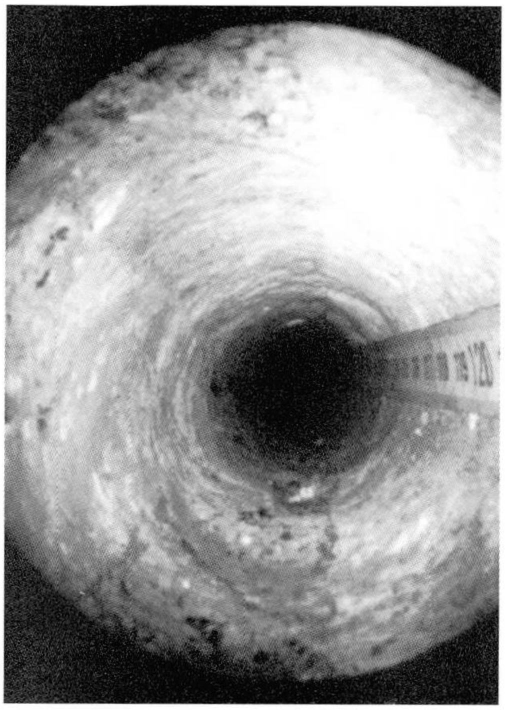

Fig. 7

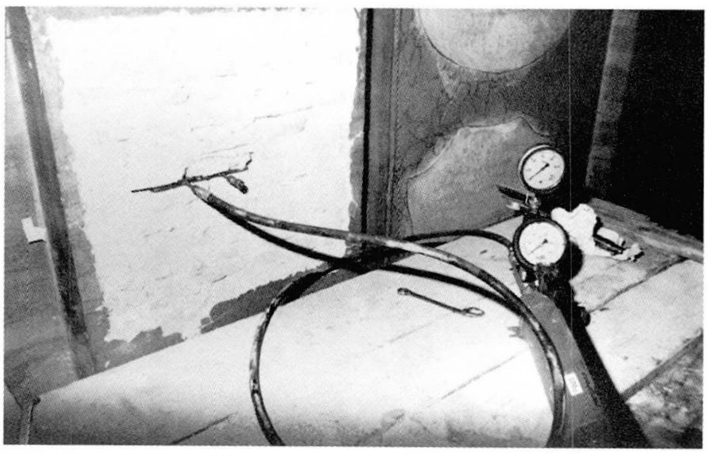

Fig. 8

4. ANALYSIS OF THE STRUCTURAL BEHAVIOUR

The theoretical analyses of the behaviour of the monument used the information obtained during the series of checks, and were carried out by means of different finite element mathematical models of the structure; the global model took into account the real three-dimensional distribution of the mass and rigidity of the basilica and of the adjacent buildings, closely connected to the walls of the lateral chapel (fig. 9).

Three different analyses were calculated by means of these models: the first considering the dead load only, the second taking account of seismic actions coresponding to the earthquake of 1703, the third considering the effects of temperature. In particular, the models took account of the entire form of the dome disregarding the presence of cracks in order to discover what caused them.

Regarding the central part of the basilica, the levels of tensile stress in the parallels of the dome were analized to find the correlation between them and the existing cracks. The maximum values obtained were:

- for dead load: $0.7 t/m^2$
- dead load + seismic load: $0.8 t/m^2$
- dead load + seasonal variation in temperature (summer to winter) + seismic action: $1.1 t/m^2$.

The maximum tension was verified as being adjacent to the ribs of the dome, due to the reduction of the section at this point, corresponding perfectly to the existing crack pattern; however the low values of tensile stress do not justify the presence of cracks in otherwise strong masonry.

It thus appeared necessary to investigate other possible phenomena, and in particular the role of soil movements; a finite element model was then used to specifically study the interaction between structure and soil, and to evaluate the influence of soil movements on the formation of the cracks (fig. 10). This model took into account the mechanical characteristics of the soil gleaned from the series of tests carried out.

The analysis of the deformations caused by loads transmitted to the soil from the structure (fig. 11), showed a large settlement in the area of the crypt

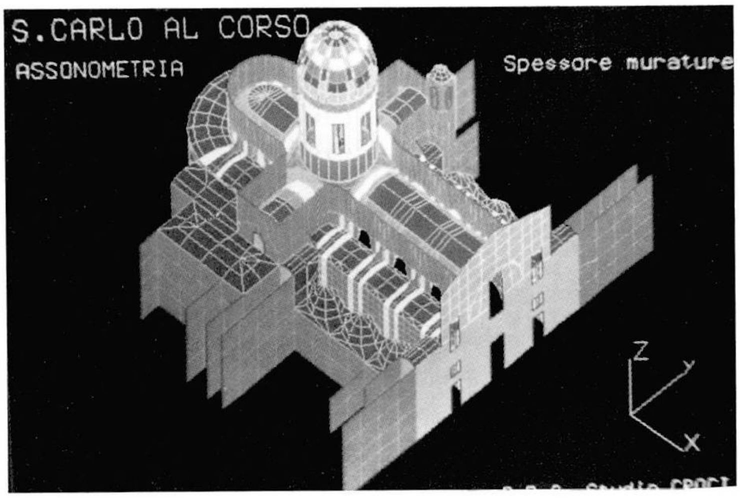

Fig. 9

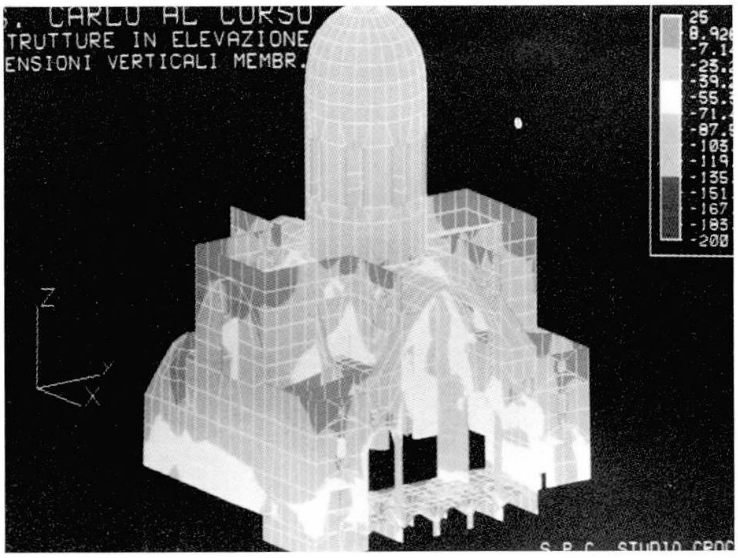

Fig. 10

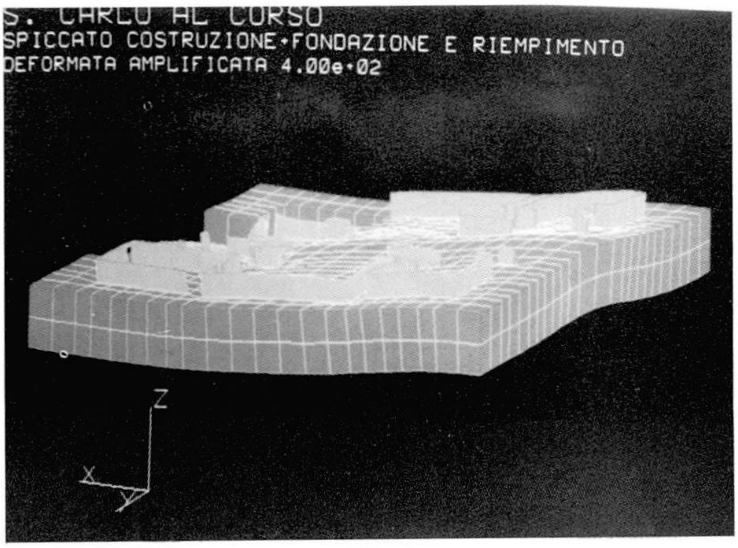

Fig. 11

and apse with respect to the lateral nave. The deformations of the transepts, with respect to the central part of the basilica, produce a rotation around the outer columns of the dome (fig. 12), and additional stresses in the rings of the drum and the dome itself.
As the drum is affected by four windows, which, for architectural motives of symmetry, occupy the principal axes of the basilica, the load of the dome is transmitted in the lower arches with an eccentricity in relation to the columns; this leads to a further increase in stress that is suoerimposed onto those generatedby load, temperature and seismic actions, overcoming the strength of the material thereby causing the distribution of cracks visible today (fig. 13).
The study of the soil - structure interaction also justified the lateral deformation of the columns in the nave and the curvature of the cornice, probably produced during construction due to the delay in the construction of the central nave which left the thrust from the vaults of the lateral naves unresisted for decades.

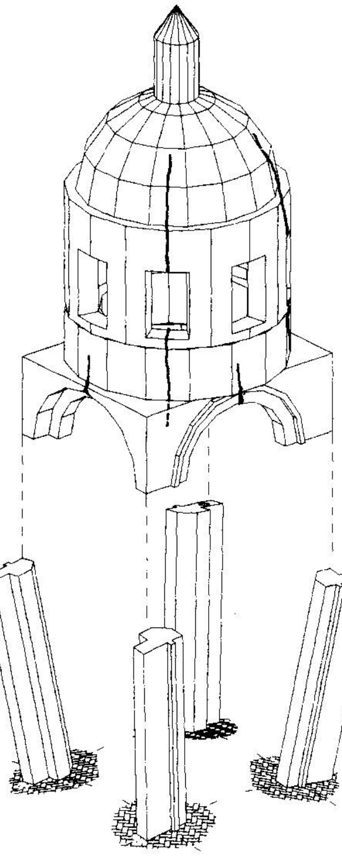

Fig. 12

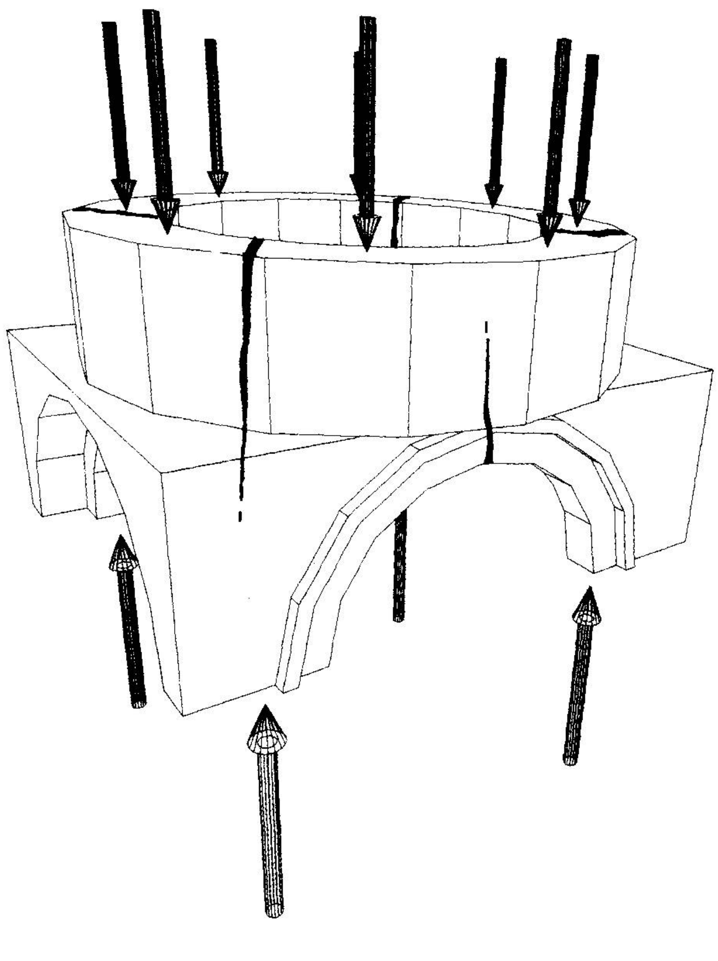

Fig. 13

5. INTERVENTIONS

Thus having understood the origin of the cracks in the dome and the drum a new model has been made to verify the present safety level. The results show important bending moments in the "arches" created along the meridians by the cracks themselves (fig. 13). In order to eliminate this unfavourable situation a system of hoops, using metal cables placed at different levels on the outer surface of the dome, was proposed; the cables are not visible as they are placed beneath the lead sheeting which will be replaced and re-anchored.

The hooping cables, made of high strength stainless steel, (the type normally used for sailing boats) are lightly prestressed, in order to provide immediatly the optimum radial action and reestabilish a bidimensional "meridians-parallels" membrane behaviour. This solution incorporates economy, ease of construction, favourable structural behaviour anddurability.

To find the most appropriate positioning of the hoops, which consist of three separate pairs of cables, to determine the level of prestressing required in order to minimize the bending stresses in the meridians that developed as a result of the cracking and to assume appropriate safety levels, a final mathematical model was created (figg. 14 and 15).

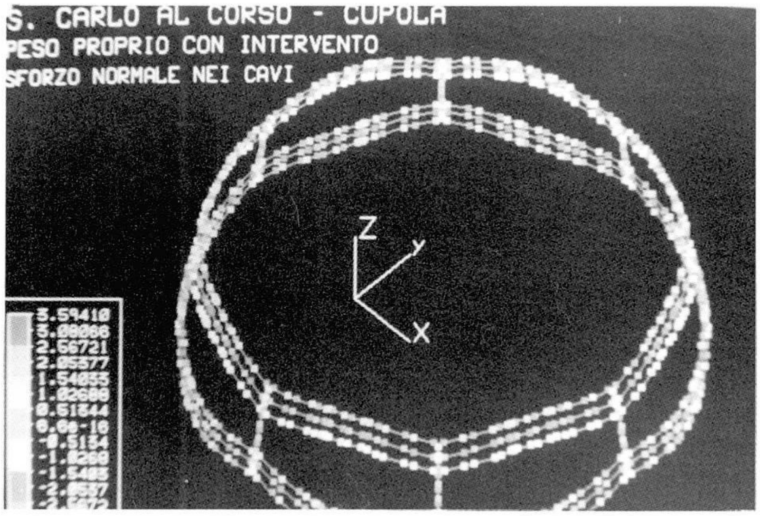

Fig. 14

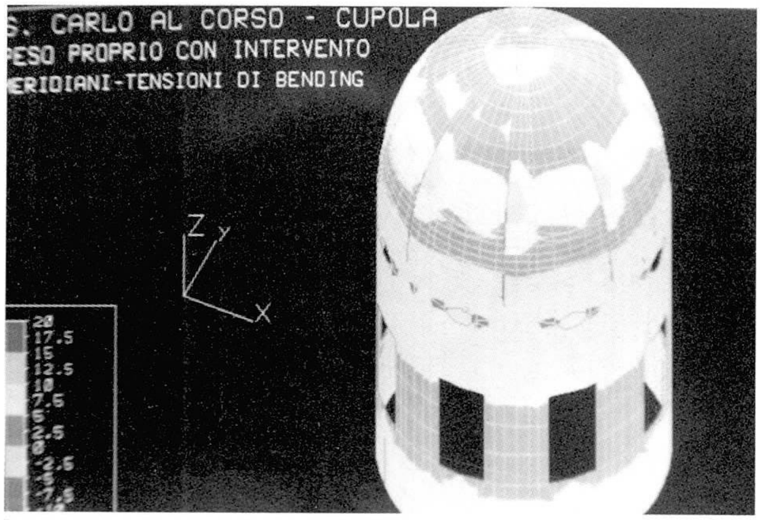

Fig. 15

This type of intervention is really a modern version of an ancient method for reinforcing domes, that used to involve chains built around the base of the dome. It is reversible and does not alter the architectural aspect of the dome; from the structural point of view moreover, notwithstanding the modest stresses directly applied to the masonry as shown by the mathematical model, it guarantees the survival of the monument even in the evet of future earthquakes.

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