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Diagnosis and Strengthening of the Brunelleschi Dome

Diagnostic et renforcement de la Coupole de Brunelleschi

Diagnose und Verstärkung der Brunelleschi-Domkuppel

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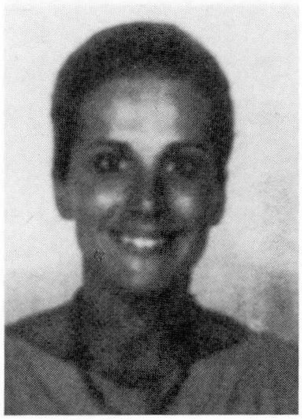

SUMMARY

The paper begins by reviewing the historical information about the different studies carried out in past centuries in order to follow the evolution of the dome's state of damage. The diagnostic evaluation advanced in 1695 is confirmed in the light of modern studies. An intervention hypothesis is then illustrated, which could be assumed as the starting point for a consolidation strategy of the monument.

RÉSUMÉ

On reprend les renseignements historiques à propos des différentes études qui, à travers les siècles, ont suivi l'évolution de l'endommagement de la Coupole. On confirme ensuite le diagnostic de 1695, et enfin on examine les effets d'une intervention de renforcement que l'on pourrait prendre comme point de départ d'une stratégie de sauvegarde du monument.

ZUSAMMENFASSUNG

Der Bericht beginnt mit einem Rückblick auf die im Laufe von Jahrhunderten über die Beschädigung der Domkuppel gemachten Studien. Die 1695 vorweggenommene diagnostische Einschätzung wird angesichts neuerer Studien bestätigt. Die Auswirkungen möglicher Verstärkungsmassnahmen werden analysiert und als Ausgangspunkt für grundlegender Sanierungsarbeiten kritisch betrachtet.

INTRODUCTION

After 1434 (the year in which Filippo Brunelleschi achieved the construction of the Dome of Santa Maria del Fiore), and after the erection of the skylight, carried out after Brunelleschi's death, no direct information is available until 1600 about mechanical problems in the Dome.
Successively, several investigation campaigns are mounted concerning the cracks observed on some of the dome's panels, especially on the sides directly above the absidal pylons, and in particular in the South-East corner, panel n° 4; see figgs. 1 and 2.
During the XVIIth century numerous studies are carried out, pointing to the conclusion - supported by reliable references - that the cracks must have been present since the beginning of XVIth century [1]. These studies are crowned by the report of a Commission, presided over by Vincenzo Viviani (a Galileo's pupil). Viviani, having carried out certain investigations, in 1695 illustrated the first diagnosis of the phenomenon, stating that the cause of damage is the dead weight of the construction, which produced a tensile-strength crisis in the masonry of some horizontal octagonal rings between the springing section of the dome and the drum apex. It is decided to proceed with a strengthening, consisting in laying down 4 iron belts, with rectangular cross-section of about 30 cm^2 each. Three of the belt should be placed externally between the springing section of the dome and the circular windows, while the fourth should be installed internally in the second walkway between the two shells.
This proposal arouses oppositions, explicit and not, as a consequence of which it is not put into effect. The diagnosis is disputed and it is requested that the number and size of the belts section be justified!
It is Father Leonardo Ximenes who resumes these contrary opinions in a study [2] published in 1757; in it we find the documentation of the cracks observed in the Dome, in the drum, in the pylons and in the rest of the Cathedral. The cause of the two main cracks (along the midline of panels 4 and 6), more or less vertical and involving the whole thickness, is attributed to an angular settlement of the pylon underlying side 4.
Only in 1937 a Commission, presided over by Pier Luigi Nervi, takes up again the problem. It is observed that the width of cracks presents also daily variations; as a consequence, a new diagnostic hypothesis is put forward, to the effect that thermal variations are the dominant damaging factor.
Last, in 1985 a new Ministerial Commission, on the basis of studies carried out by the Authors [3], concludes again that the geometry of the crack system is consistent with the expected dead-weight effect. One could almost say that three centuries were needlessly lost.
In the present work one recalls briefly the studies which led to the identification of the mechanical behaviour of the structure.
Then a possible reliabilitation scheme is considered. This is after the spirit of Freyssinet, i.e. the active consolidation by pre-stressing.
In this way the Authors evidence also the possibility of answering the question maliciously asked of Vincenzo Viviani, the Granduca's engineer.
Incidentally, it is to be remarked that the automatic on-line monitoring system existing since 5 years on the monument indicates for the time being a state of stationarity of the alteration phenomena.

2. THE GENERAL SCHEME OF CRACKS

Recent surveys evidence [4] a prevalent systems of cracks, formed by:

- "type A" cracks, subvertical, through the whole thickness. (panels with even numbering);
- "type B" cracks, subvertical, through the whole thickness, in the panels with odd numbering;
- "type C" cracks, penetrating only to a partial depth in the thickness, in the edges between adjoining panels;

- "type D" cracks, also penetrating only to a partial depth in the thickness, along the midline of the panels with odd numbering (see figgs. 1 and 2).

The time evolution of cracks is known too, insofar as in 1757 only "type A" cracks were observable, and then only on sides 4 and 6, whereas nowadays cracks are observable in all four sides above the pylons.

3. THE FIRST VIRTUAL MODEL

In the process of mechanical identification of the structure a first virtual numerical model was built up, formed only by the following members,: pylons, drum, dome. In this virtual F.E. model, 15 and 20 nodes isoparametric elements were used, with the same linear elastic constitutive law-throughout the structure. The first numerical analysis concerned the original (undamaged) virtual model under gravitational loads (deadweight).

A perusal of results clearly shows that the "parallels" just above the circular windows on the even-numbered panels undergo high levels of tensile stresses. Horizontal tensile stresses are found also in the drum, above the keystone of arches on the odd-numbered sides (see fig. 3 a, b, c, d).

4. THE "FIRST-IDENTIFICATION" MODEL

The results of the "continuous monitoring" yielded by the crack disposition allows to introduce cracks type A and B in the virtual model according to the dead-weight effects,. Thus the first-identification model is defined.

The results of the analysis carried out on this second model confirm the indications of the crack pattern, explaining in particular the origin of the cracks "type C and D". It is observed also that the external shell on the odd-numbered sides is subjected to vertical tensile stresses, whereas the highest level of vertical compressive stresses is found in the internal corners of cracks "type A".

This distribution of vertical stresses has been confirmed experimentally through another "continuous monitoring" operation using the flat jack technique (fig. 4 a, b, c, d; fig. 5 a, b, c).

5. ANALYSIS OF THE EFFECTS OF A STRENGTHENING HYPOTHESIS

By using the identified model one can simulate, starting from the present situation, the effects of the installation of horizontal belts.

The strengthening intervention could be effected through harmonic-steel cables placed at floor level in the first walking. The shape of these belts, pulled on at the midpoint of each side, would be octagonal; thus the interaction with the existing structure (apart from local effect) could be schematized by a system of radial forces, applied in the edges at the springing section of the dome.

Perusing the numerical simulation of this strengthening carried out on the "first-identification" model, one is surprised by the close- fitting antagonistic effect brought about by the intervention as against the dead-weight stress pattern (fig. 6 a, b, c, d).

One can remark that, according to the Betti theorem, the mutual work of the two force systems (dead-weight and prestressed belts) is obviously negative. However, one can moreover generally recognize that "almost everywhere" is negative also the local function which expressed the density of mutual work at every point of the structure.

It seems, thus, right to state that the intervention proposed in 1695 was a qualitatively correct therapy ensuing from a realistic evaluation of the main damaging factor.

Such an intervention, if carried out, would undoubtedly have produced positive effects, considering how far the phenomenon has advanced in the last 3 centuries.

These studies can also form the basis for the definition of a safety system to be put into action if the evolutionary phenomena should, for causes now not ascertainable, start to increase again.

Further studies are under development in order to define a "second-identification" virtual model, taking into account also the presence of the external chapels.

ACKNOWLEDGEMENTS

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REFERENCES

1. BARBI L., DI TEODORO F., Le lesioni della Cupola di S. Maria del Fiore: una proposta di datazione. Bollettino degli Ingegneri 1983 n. 9.
2. XIMENES L., Del vecchio e nuovo gnomone fiorentino e delle osservazioni astronomiche, fisiche ed architettoniche fatte nel verificare la costruzione. Firenze, 1757, Nella Stamperia Imperiale Libro II°.
3. CHIARUGI A., FANELLI M., GIUSEPPETTI G., Analysis of Brunelleschi - Type Dome Including Thermal Loads. IABSE SYMPOSIUM, Venezia, 1983.
4. MINISTERO PER I BENI CULTURALI ED AMBIENTALI, Rapporto sulla situazione del complesso strutturale cupola-basamento della Cattedrale di S. Maria del Fiore in Firenze. Marzo 1985.

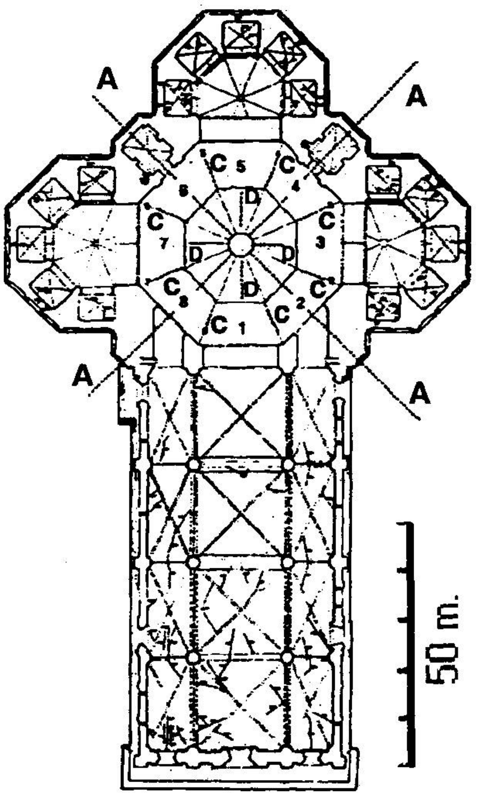


Fig. 1 Sides numbering and planar position of type "A, B, C and D" cracks.

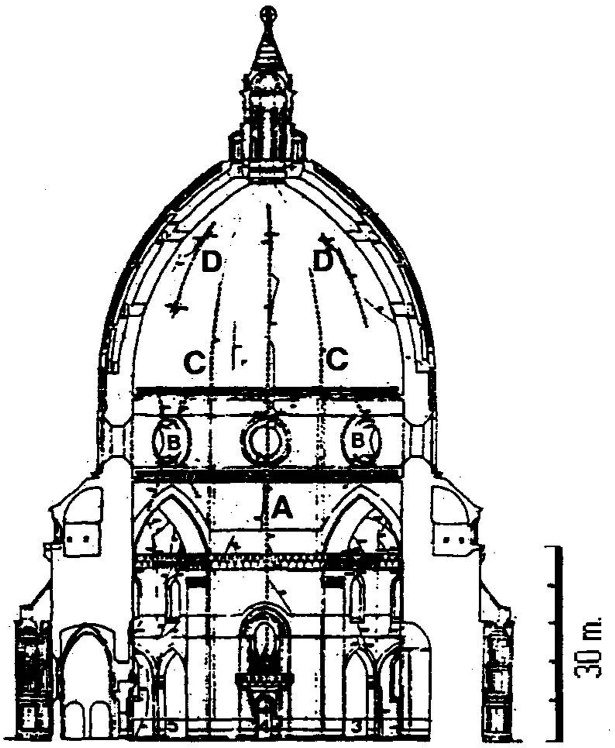
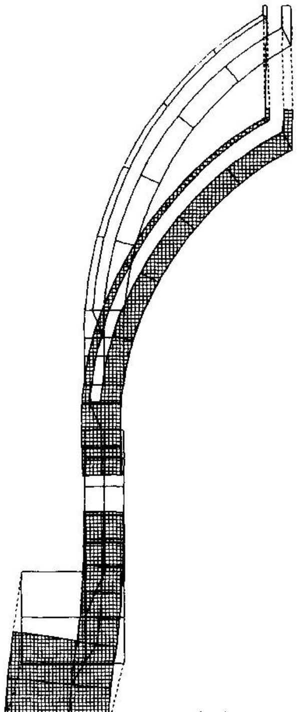
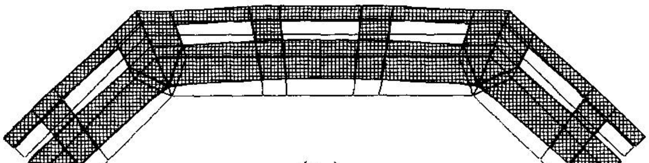


Fig. 2 Crack description summary with type "A, B, C and D" cracks.



(a)



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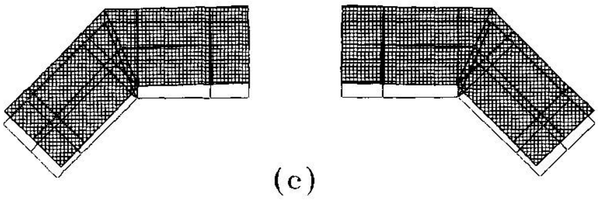

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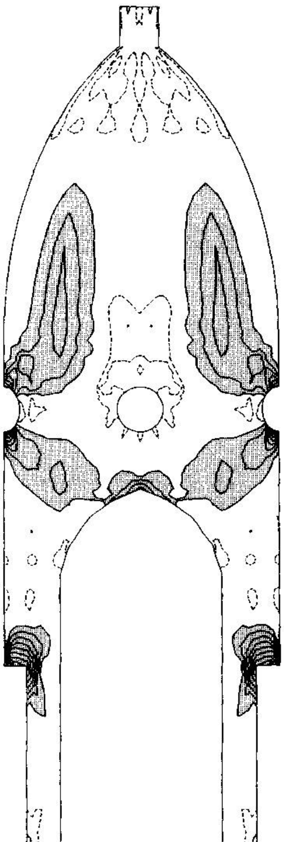


(d)

Fig. 3 "First virtual model" undamaged structure:

(a) deformed line of vertical section in centerline on even-numbered panel;
(b) deformed line of section 3-3 at 66 m level;
(c) deformed line of horizontal section on circular centerline window (note ovalization of opening on even-numbered panel);
(d) stress distribution σ horizontal on intrados face (note tension increase around the circular windows of even numbered panel and above the keystone of arch). Tension zone shaded.

- "First virtual model" characteristic:
  n° nodes 3286
  n° elements 569
- Elements characteristic:
  isoparametric hexahedrons with 20 nodes
  isoparametric pentahedrons with 15 nodes
- Material characteristic:

modulus of elasticity:		50000 kg/cm^2
Poisson's ratio	:	0.1
Density	:	0.0018 kg/cm^3

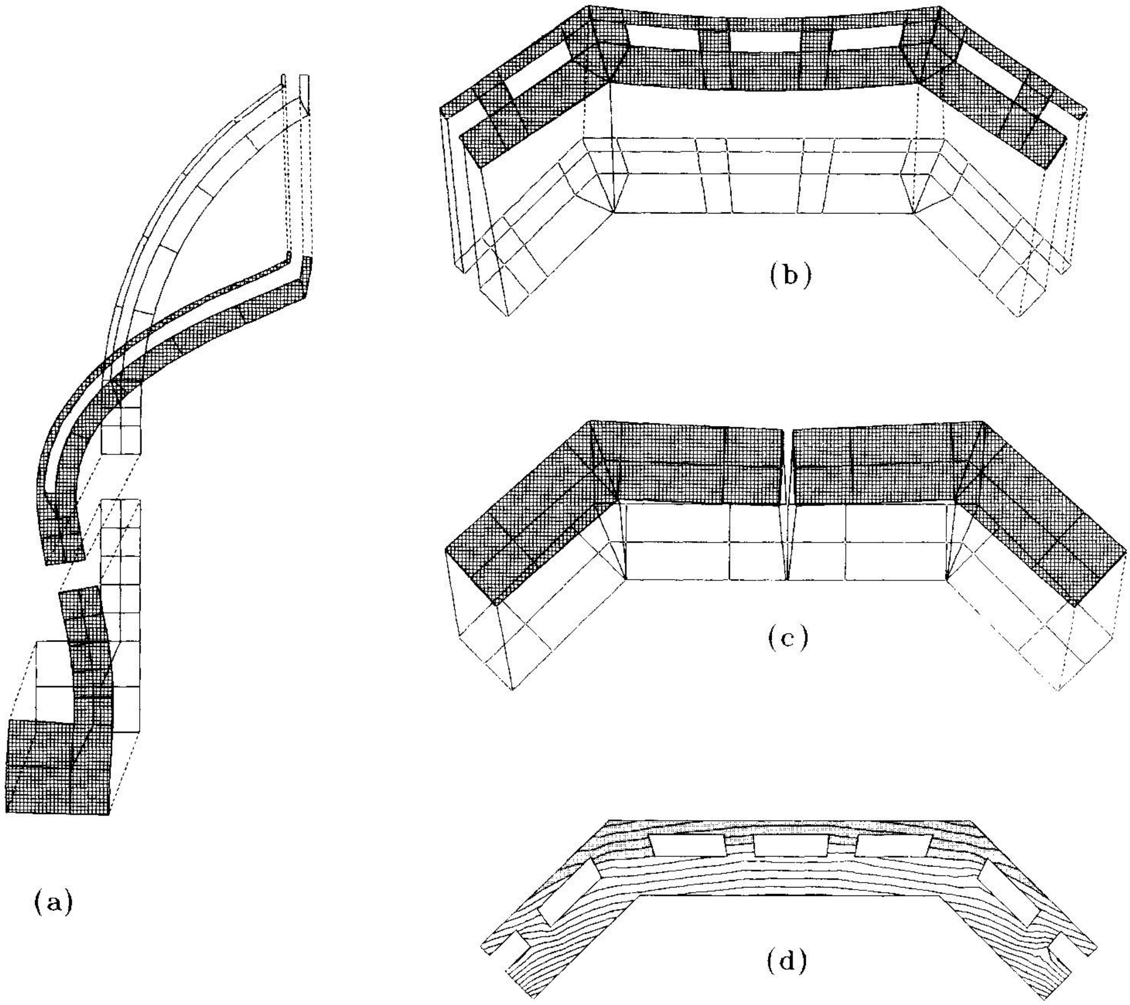


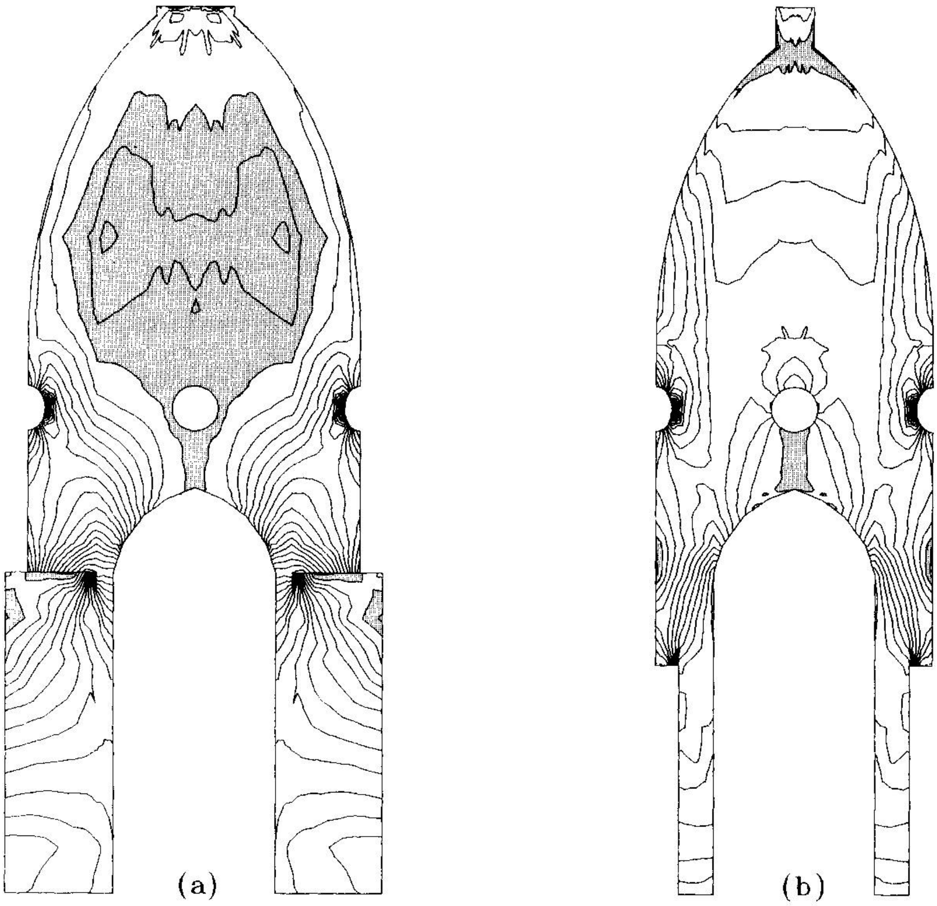
Fig. 4 "First identification model" with type A and B cracks:

(a) deformed line of vertical section;

(b) deformed line of section 3-3 at 66 m level (note inflexion on the section plane);

(c) deformed line of section under circular window (note opening crack B);

(d) stress distribution σ z vertical in section 3-3 (note effects of bending with vertical tension localized in external panels with odd numbering). Tension zone shaded.



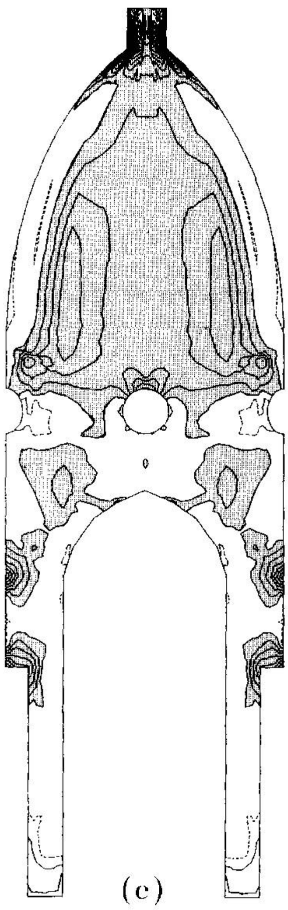


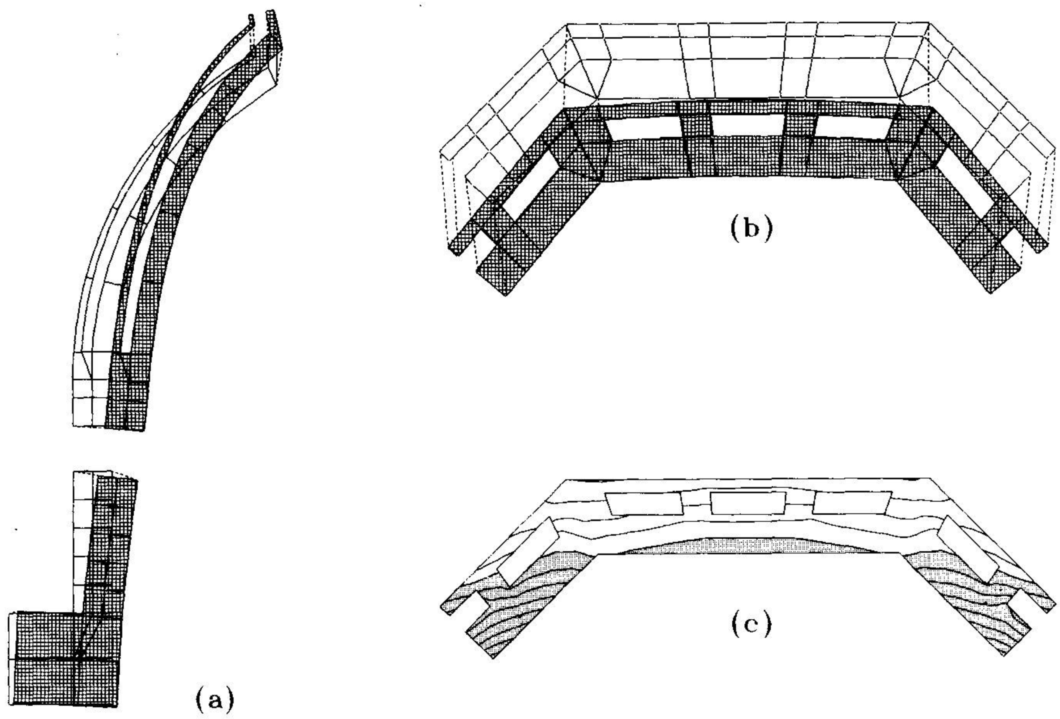
Fig. 5 "First-identification" model with type A and B cracks:

(a) stress distribution σz vertical on extrados face;

(b) stress distribution σz vertical intrados face;

(c) stress distribution σ horizontal on intrados face (note tension in the corner and in the central zone of the panels with odd numbering, corresponding at type C and D cracks).

Tension zone shaded.



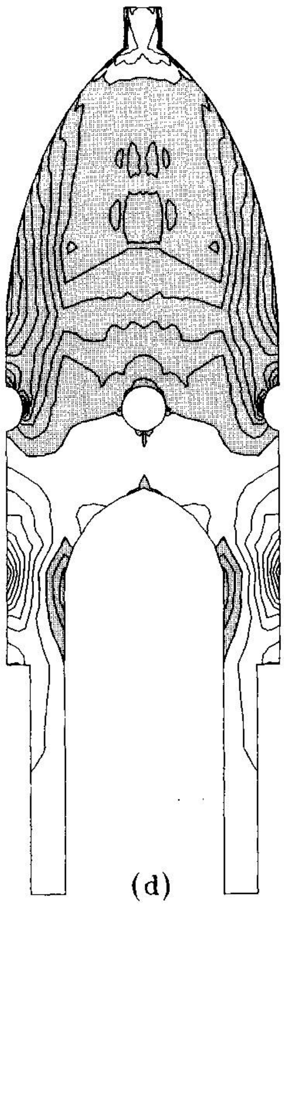


Fig. 6 "First identification model" under only strengthening effect:

(a) deformed line of vertical section;
(b) deformed line of section 3-3 at 66 m level;
(c) stress distribution σz vertical in the section 3-3; with opponent distribution with espect to the dead-weight;
(d) stress distribution σz vertical on intrados face;

Tension zone shaded.