Finite element analysis of prestressed concrete pressure vessel

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Finite Element Analysis of Prestressed Concrete Pressure Vessel

Analyse par éléments finis de caisson en béton précontraint pour réacteurs nucléaires

Analyse Begrenzter Element von Reaktordruckbehältern aus Spannbeton

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SUMMARY

The present report is related to some studies carried out on the strain-stress behaviour of prestressed concrete pressure vessel for nuclear reactors.

At first, a finite element model is introduced in order to similate the behaviour of an equivalent physical model of the prestressed reactor vessel under examination.

Then, an average concrete elastic modulus is calculated using the information obtained by the comparison between displacements of physical and mathematical models, as well as the results from experimental tests made on concrete specimens of the same kind of the physical model.

At last, the strain-stress state of the structure is analyzed in the operating conditions under the action of fast loads. Time depending effects are not taken into account.

RESUME

Dans cette mémoire on étudie le comportement des contraintes et déformations d' un caisson en béton armé précontraint type "HTR" pour réacteur nucléaire.

On commence par la description du modèle mathématique à é-

léments finis simulant le modèle physique du caisson qu' on veut examiner.

Ensuite on effectue la détermination du module élastique du béton en se servant soit des renseignements tirés de la comparaison entre les déplacements donnés par le calcul et ceux donnés par le modèle, soit des mesures faites en laboratoire sur des éprouvettes de béton.

On termine par l' étude des champs de contrainte et de déformation dans la structure en régime d' exploitation sous l' action de changes instantanées.

ZUSAMMENFASSUNG

In diesem Bericht wird das Spannungs-und Verformungs-Verhalten eines Behälters aus Spannbeton für "HTR" Typ - Kernreaktor studiert.

Anfangs wird das mathematische Begrenzter Elemente-Modell beschrieben, welches das physikalische Modell des in Frage stehenden Kernreaktors simuliert.

Aufeinanderfolgend, wird das Betons-Elastizitätsmodul ermittelt, mit Hilfe der Auskünfte, die sich aus dem Vergleich der durch die Berechung bestimmten Verschiebungen mit den durch das Modell bestimmten Verschiebungen ergeben, sowie mit Hilfe der durch Laboratoriumsversuche auf Betonproben erhaltenen Auskünfte.

Zum Schluss, werden die Spannungen und Verformungen der Struktur unter Schnelllast-Bedingungen studiert.

1. INTRODUCTION

The problems concerning the design of PCPV for nuclear reactors show, at present, a great interest.

Some physical models on 1 : 20 scale of a tiny-walled prestressed concrete pressure vessel for Gas Reactor (1), (2), (3) have been made and tested by ISMES (Experimental Institute for Models and Structures) in Bergamo. Such models have been devised and commissioned by CPN (Nuclear Design and Construction Center) of ENEL (Italian State Electricity Board).

Also some finite element mathematical models of the same structures were made by ISMES in strict cooperation with CPN and CRIS (Hydraulic and Structural Research Center) of the R & D Dept. of ENEL with the following purposes:

- to calibrate the mathematical models on the basis of the results obtained from the physical models;
- to evaluate the stress-strain state and the local safety factor of the structure in operating conditions;

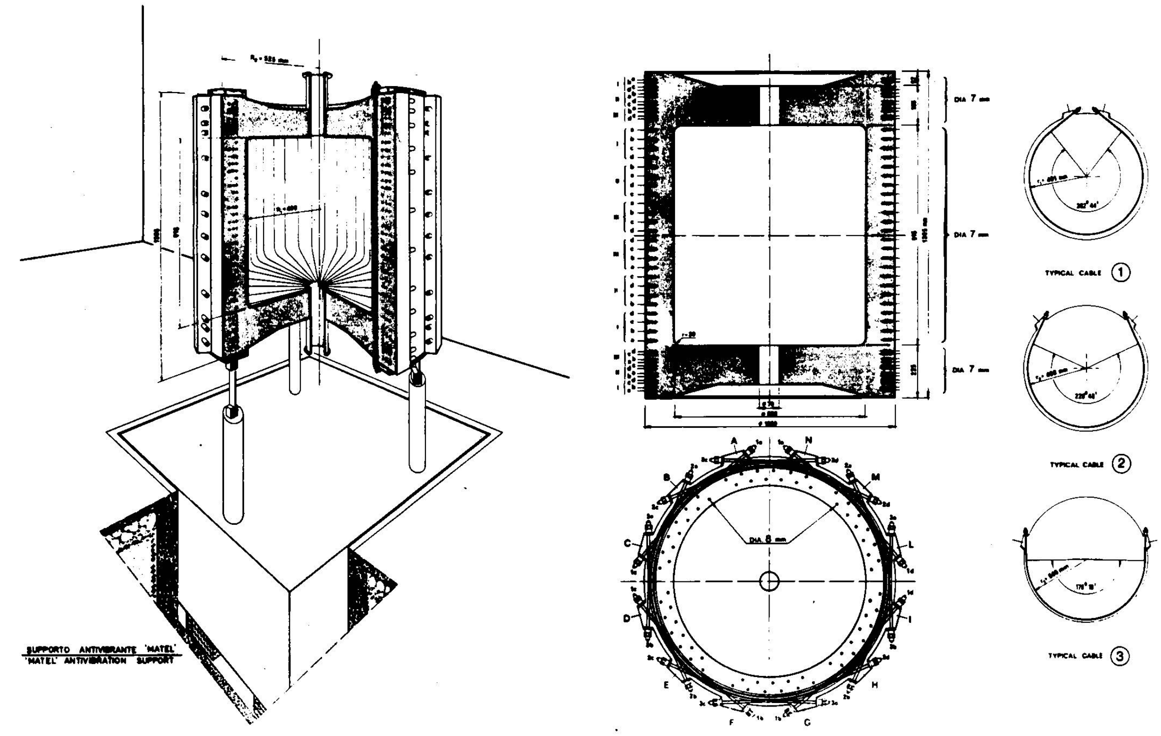

FIG. 1
Geometrical data and prestressing cables system. - Données géométriques et système des cables de précontrainte.
Geometrische Angaben und Vorspannungskalen-System.

In order to make a comparison between the physical and the mathematical models and to evaluate the stress-strain state in working conditions, a physical model without penetrations and an axysimmetric mathematical model in linear-elastic behaviour have been studied. Fig. 1 shows the geometric data of the model and the prestressing cable system pattern.

2. FINITE ELEMENT SIMULATION OF PCPV

Prestressed concrete pressure vessels are usually structures of relevant complexity because of the presence of penetrations, steel reinforcements, prestressing cables, anchoring plates, cable ribs, etc.

The elastic stress-strain analysis of such structures, based on finite element method, has not shown conceptual differences with respect to the analysis made for homogeneous continua (4), (5).

In fact, for a given finite element mesh, the stiffness matrix of each element "i" is defined as follows:

$$\left[K_i\right] = \int_{Vol} \left[B\right]^T \left[D\right] \left[B\right] \, dvol$$

where the matrix $[B]$, which represents the link between the strain and the nodal displacements depends on the type and the geometric shape of the element, while the matrix $[D]$ represents the elastic properties of the material.

Once known the stiffness of each element, the stiffness matrix $[K]$ of the whole structure is built assembling the stiffness matrixes of each element. The $[K]$ matrix relates the external forces acting at the nodes to the nodal displacements.

In order to study the behaviour of the model under consideration, it was necessary to define the stiffness matrix $[K_i]$ of the different types of elements, as shown in fig. 2, that is:

- quadrangular and triangular axisymmetric isoparametric solid elements capable of simulating concrete behaviour. All the basic expressions are indicated in (6);
- quadrangular and triangular isoparametric elements capable of simulating the anchoring cable ribs. Due to the presence of the ribs, the structure cannot be considered perfectly axisymmetric. In order to restore the axial-symmetry, special elements with a meridian stiffness equivalent to that of the ribs have been defined, having suitable thickness ΔR and "fictitious" elastic modulus E_r. Since the ribs did not present circumferential deformation ε_θ, the stiffness matrix $[D]$ has been adequately modified;
- Hoop bars able to simulate the action of circunferential cables on barrel and slabs. The bars are schematized with a point, and they

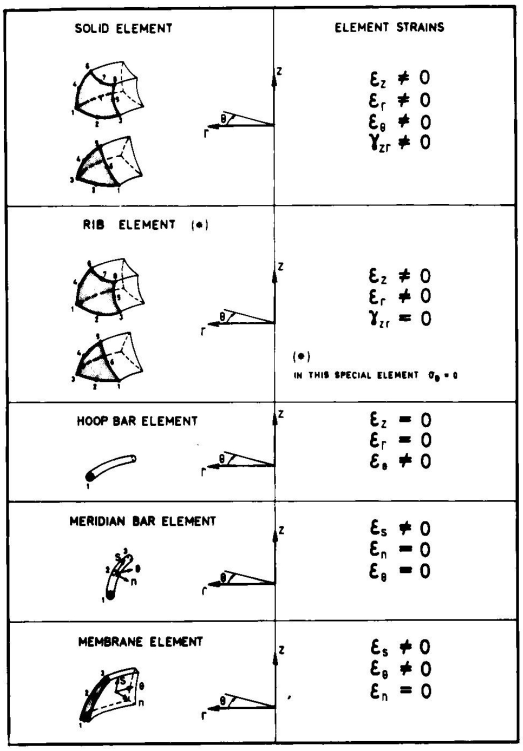

FIG. 2
Finite elements used for axisymmetric PCPV analysis.
Eléments utilisés pour l' analyse statique du caisson.
Begrenzte Elemente zur statischen Analysis von Behältern.

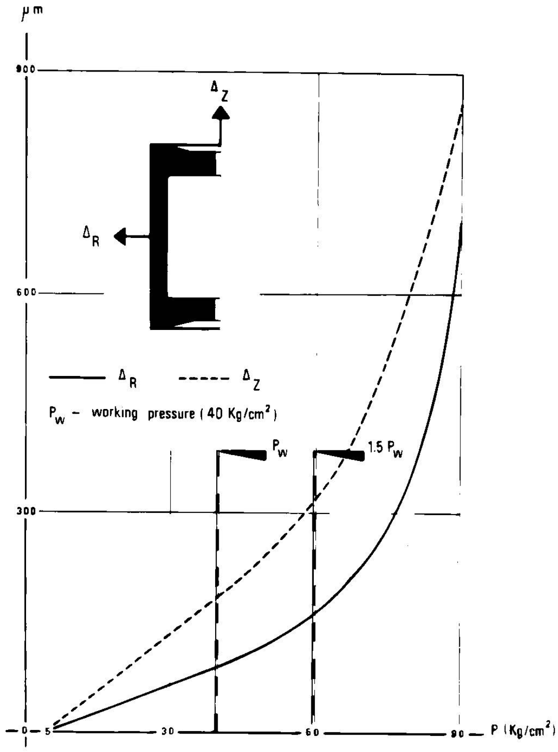

FIG. 3
Equatorial and top cap deflections versus pressure.
Déplacements de la section équatorielle et de la plaque d' extrémité en fonction de la pression.
Aequatorschnittes-und Plattenvershiebungen in Hinsicht auf den Innendruck.

have stiffness only in the circunferential direction. Their strain is defined as: $\varepsilon_\theta = u/r$. The determination of the strain matrix $[B]$ is, in thiscase, immediate;

- meridian bars capable of simulating the action of the cables lying on the meridian plane. They are schematized as a continuous line and have stiffness in the s direction tangent to the bars. The strain matrix $[B]$ links, in this case, the strain ε_s, defined in local axis, to the nodal displacements defined in global axis;
- membrane elements capable of simulating a liner of assigned thickness. These elements have stiffness in the circunferential direction and in s direction, tangential to the membrane in the meridian plane. The strain matrix $[B]$ links, in this case, ε_s and $\varepsilon_\theta$strains, defined in local axis, to the nodal displacements defined in global axis.

3. DESCRIPTION OF THE PCPV PHYSICAL AND MATHEMATICAL MODEL

The tests carried out on the physical PCPV model have been performed in the elastic and non-elastic fields up to the model collapse (3). These tests have practically defined up to the working pressure (40 Kg/ /cm^2) an internal "pressure-displacements" relationship (fig. 3) of a linear elastic type, while the first cortical microcracks were detected at a pressure of about 70 Kg/cm^2.

The purpose of the mathematical model was the investigation of the stress-strain state in working conditions. With the results obtained from the behaviour of the physical model it was possible to schematize, with a good approximation, the behaviour of concrete, as linear elastic.

The geometrical symmetries of the structure were taken into account in building up the finite element mesh shown in fig. 4. The mesh consisted of:

- 269 second order isoparametric elements to simulate the concrete;
- 29 second order isoparametric elements to simulate the ribs;
- 39 elements to simulate the radial prestressing cables;
- 21 elements to simulate the meridian prestressing cables;
- 36 elements to simulate the internal copper liner.

The computer programs used for the mathematical model and available at ISMES, were:

- GEOTAV 2 to set up and draw the finite element mesh on plotter
- AXITEN 3 to evaluate the stress-strain state
- BICAMP 3 to evaluate the temperature distribution
- DIPLA 13 to draw the results automatically on plotter.

4. ESTIMATE OF THE CONCRETE ELASTICITY MODULUS

In this phase of calculation, attempt was made to give an estimation of the average elastic modulus of the concrete by a comparison between measured and calculated displacements.

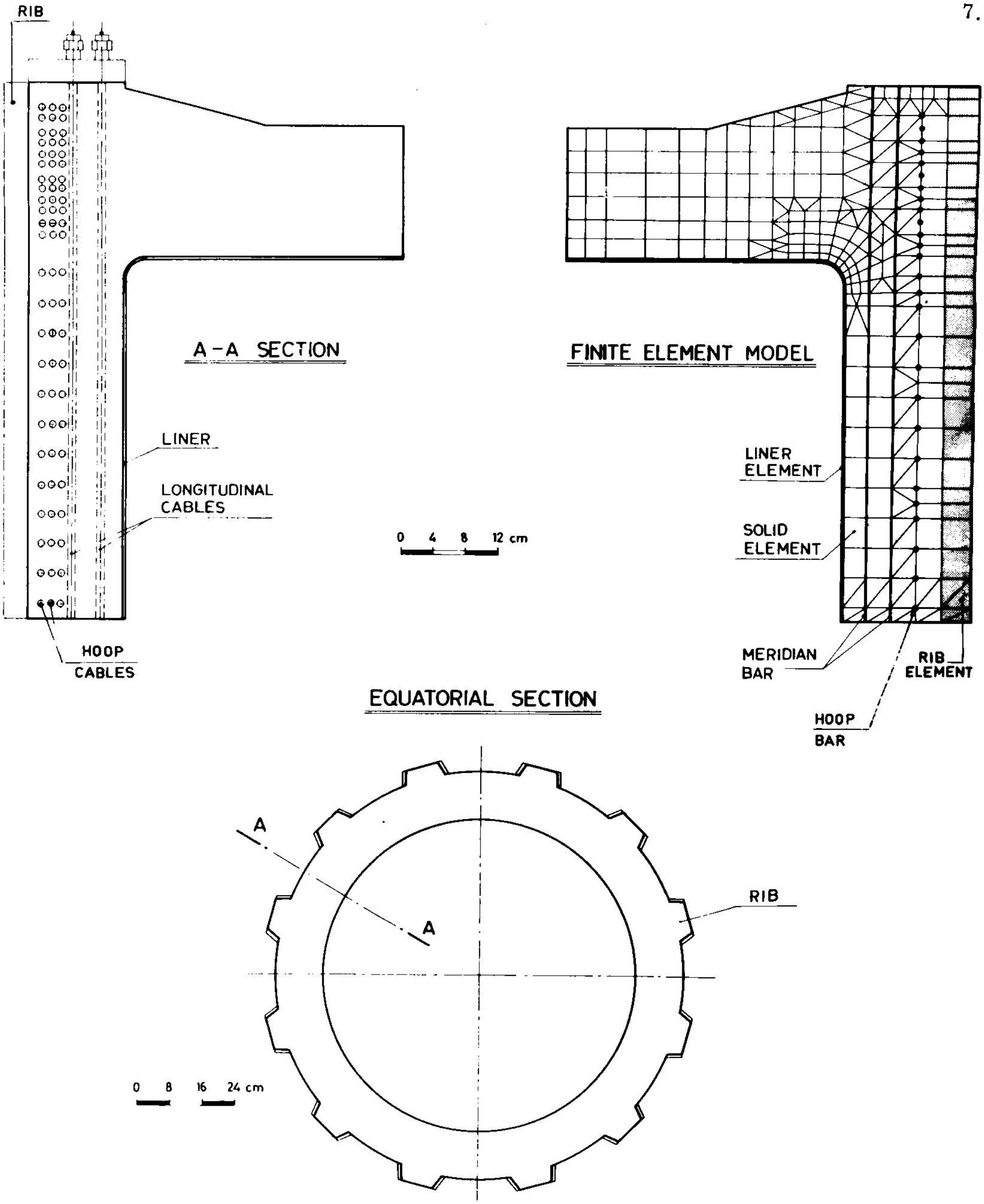

FIG. 4

Equatorial and meridian sections of the vessel and finite element mesh.

Sections équatorielles et méridiennes du caisson, avec réseau d' éléments finis.

Meridian-und Aequatorschnitte des Behälters mit Begrenzter Elemente-Masche.

Such value has been subsequently verified by the results of uni axial compression tests performed on same samples of the same concrete utilized for the physical model.

The logical scheme of this calculation phase is briefly outlined in fig. 5.

Practically, reference was made to the measured displacements at some points of particular interest on the vessel, relative to an internal pressure variation $\Delta_p = 10\ Kg/cm^2$.

For the same pressure variation, displacements at the same points were calculated assuming that the elastic concrete modulus E_c is respectively 400,000 - 410,000 - 430,000 Kg/cm^2, and the steel modulus E_f equal to 2,100,000 Kg/cm^2.

In each particular case a concrete modulus $E'_c = E_c/K'$ was evaluated by means of the least square method in order to have calculated displacements as close as possible to the measured ones.

If δ_{ic} and δ_{im} are the calculated and measured displacements at point "i", the value K' was determined in order to minimize the function:

$$\phi(K) = \sum_{i=1}^{N} (K\ \delta_{ic} - \delta_{im})^2$$

where, the above summation has been extended to the N points at which displacements were measured. The following values were found:

- for $E_c = 400,000\ Kg/cm^2$; $K' = 0.932739$; $E'_c = 428,834\ Kg/cm^2$;
- for $E_c = 410,000\ Kg/cm^2$; $K' = 0.955781$; $E'_c = 428,968\ Kg/cm^2$;
- for $E_c = 430,000\ Kg/cm^2$; $K' = 1.0005$; $E'_c = 429,934\ Kg/cm^2$.

Finally, at the third attempt it was found that the concrete mo dulus definying a value $K' = 1$ is about 430,000 Kg/cm^2. The comparison between displacements evaluated by finite element model and those measur ed on the physical model is shown in fig. 6.

To evaluate the reliability of this kind of procedure, the values so found were verified by means of other experimental data.

At the Niguarda Laboratories of CRIS in Milan, some uniaxial compression tests were carried out on samples of the concrete used for the physical model. It was thus possible to evaluate the variation of the secant modulus versus the uniaxial stress.

With the finite element model previously used it was possible to calculate at every nodal point the triaxial state of stress for the loading combinations of total prestress with a gas pressure variation $\Delta_p = 10\ Kg/cm^2$.

Among the three principal nodal stresses, the one of maximum compression was selected, assuming that in this direction, the stress state can roughly be considered the closest to the uniaxial one.

On the basis of such compression value, the modulus has been

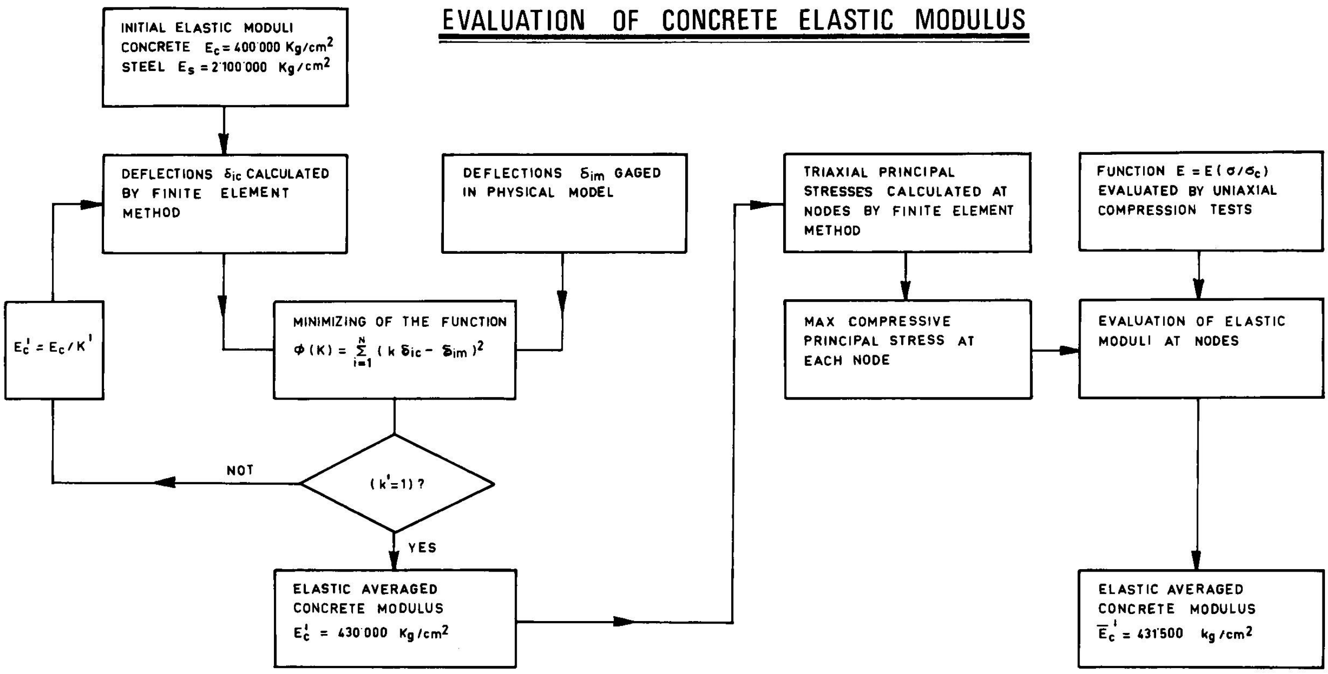

FIG. 5

Logical scheme to evaluate the concrete modulus.

Schème logique pour évaluer le module élastique du béton.

Logisches Schema zur Berechnung des Betons-Elastizitätmoduls.

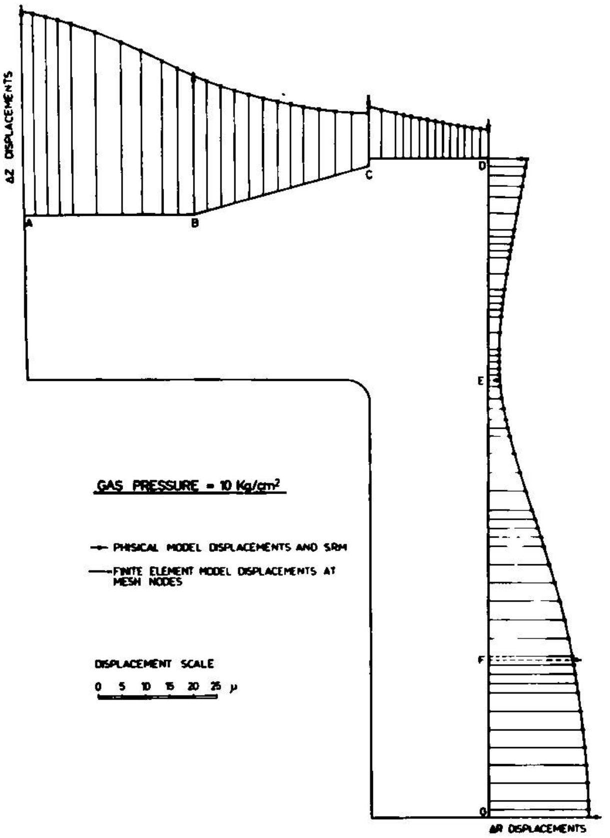

FIG. 6

Finite element and physical model displacements.

Déplacements du modèle à éléments finis et du modèle physique.

Verschiebungen des Begrenzter Elemente-und physikalischen Modelles.

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determinated at each nodal point through the experimental relationship as shown in fig. 7 a.

By averaging the nodal values, an elastic modulus $\overline{E'}_c = 431{,}500$ Kg/cm^2 was found. This value fairly agrees with the value $E'_c = 430{,}000$ Kg/cm^2 previously obtained.

Contour lines of the elastic modulus, obtained by plotting the above-mentioned nodal values, are shown in fig. 7 b.

5. ANALYSIS OF THE STRESS - STRAIN STATE OF THE STRUCTURE IN WORKING CONDITIONS

Further analysis consisted in studying the stress-strain behaviour of the structure in the working conditions under the action of fast loads. Therefore, the typical time-dependent phenomena of concrete like shrinkage and creep, were not considered.

The structural loading conditions are the following:

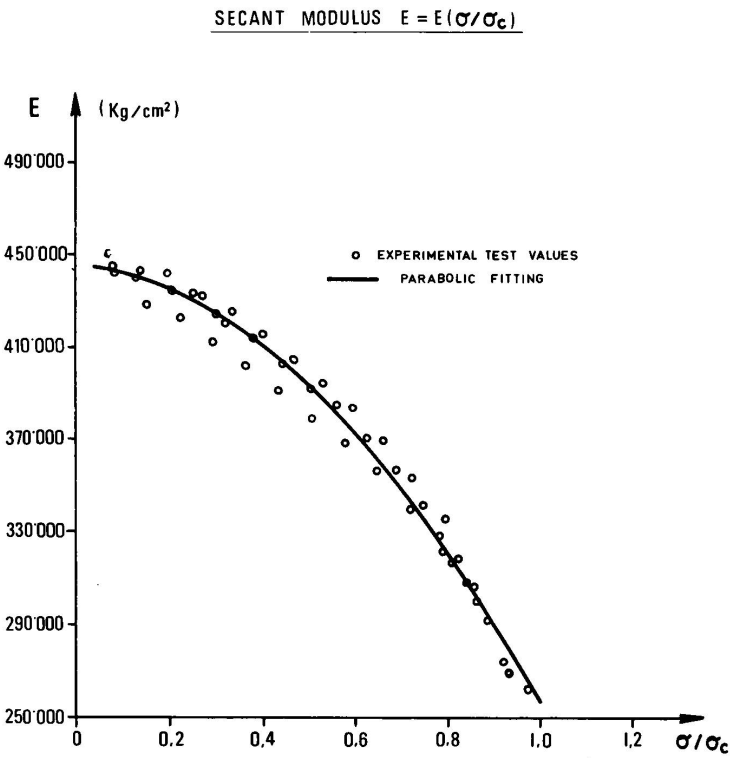

FIG. 7 a

Function E = E (σ / σ_c)

Fonction E = E (σ / σ_c)

Funktion E = E (σ / σ_c)

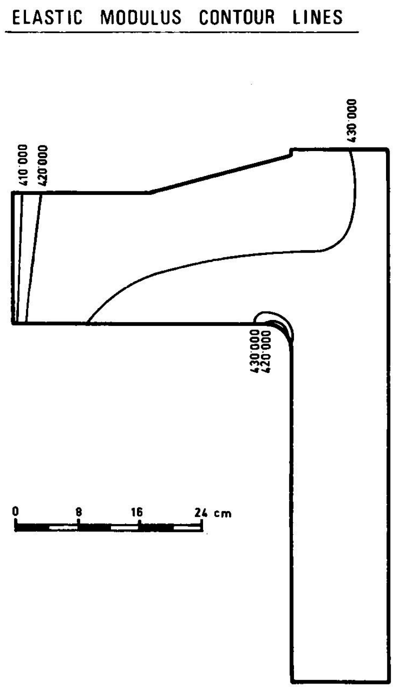

FIG. 7 b

Elastic modulus contour lines for the structure.

Lignes d' égale valeur pour le module élastique dans la structure.

Elastizitätlmoduls-Niveaulinien im der Struktur.

a) The cable pulling sequences up to total prestress.

By means of computer calculations, it was possible to evaluate the optimum cable pulling sequence, i.e., the sequence avoiding tensile stresses acting locally in the structure, during an intermediate stage of prestressing.
Fig. 8 shows the prestressing sequences for the structure and the contour lines of the safety factor for the subsequent stages of prestress until the total pulling is over. In order to calculate the local safety factor, the Mohr - Caquot theory (7) has been taken into account. The intrinsic curve shown in fig. 9 was determined on the basis of the values of the tensile ultimate strength $\sigma_{rt} = 32$ Kg/cm^2 and the compressive ultimate strength $\sigma_{rc} = 525$ Kg/cm^2 derived from uniaxial tests.
Fig. 10 shows the principal stress patterns acting on the meridian plane, and the contour lines for the three principal stresses for the total prestress.

b) The operating conditions where the following actions are combined:

- Total prestress
- Gas pressure (40 Kg/cm^2)
- Temperature difference between inner and outer wall assumed as $T_i - T_o = 10^oC$.

For the evaluation of the thermal stress state generated in the structure, temperature values at mesh nodes were obtained with a finite element program solving field problems governed by Laplace's equation.
Fig. 11 shows the isothermal contour lines for the structure. In fig. 12 are shown the patterns of the principal stresses acting on the meridian plane and the contour lines of the three principal stresses for the operating conditions. The local safety factors shown in the same figure are quite satisfactory.

6. CONCLUSIONS

The main purpose of the present study was the evaluation of the stress-strain state and the local safety factor of the structure during the construction phase and in the working conditions, assuming an elastic behaviour for the materials. To this end it was necessary to define the elastic moduli of the materials under consideration which being the input data of the problem conditioned all the calculation results. Information on the rheological behaviour was at hand both for the physical model and concrete samples. Thus, it was deemed advisable to utilize this kind of information to evaluate the elastic modulus values of concrete and then compare the obtained values.

The study, which in its preliminary phase, was a study of con

SAFETY FACTORS IN PRESTRESSING SEQUENCE

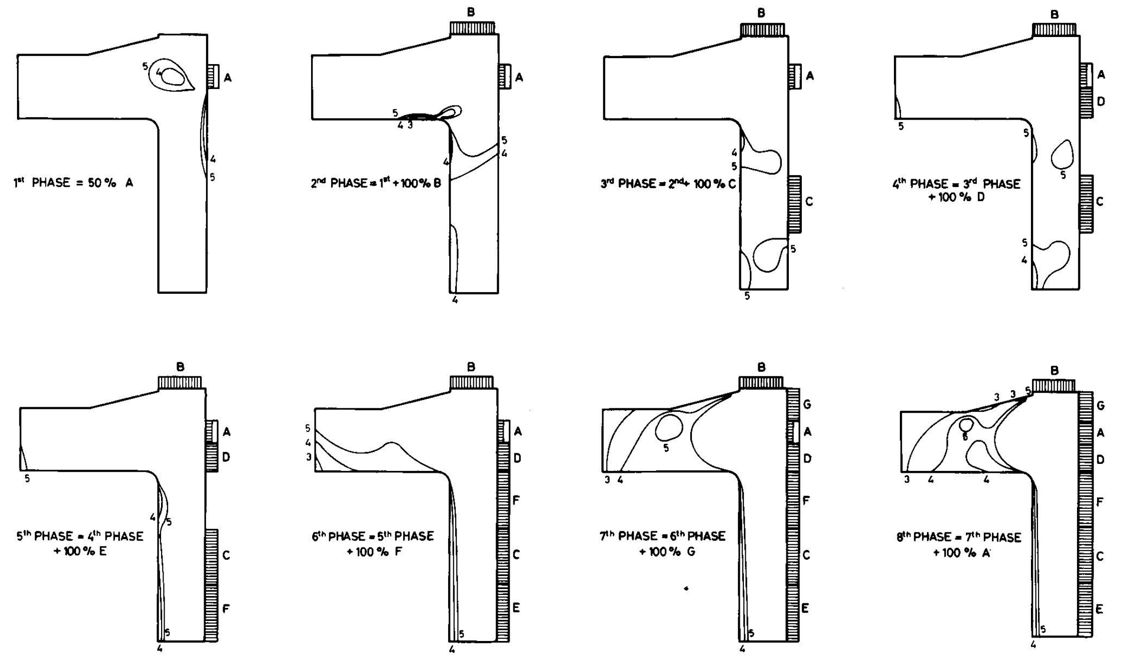

FIG. 8
Safety factor contour lines in prestressing sequence. - Lignes d' égale valeur pour le coéfficient de sécurité pendant les opérations de précontrainte. - Sicherheitskoeffizients-Niveaulinien während der Vorspannung.

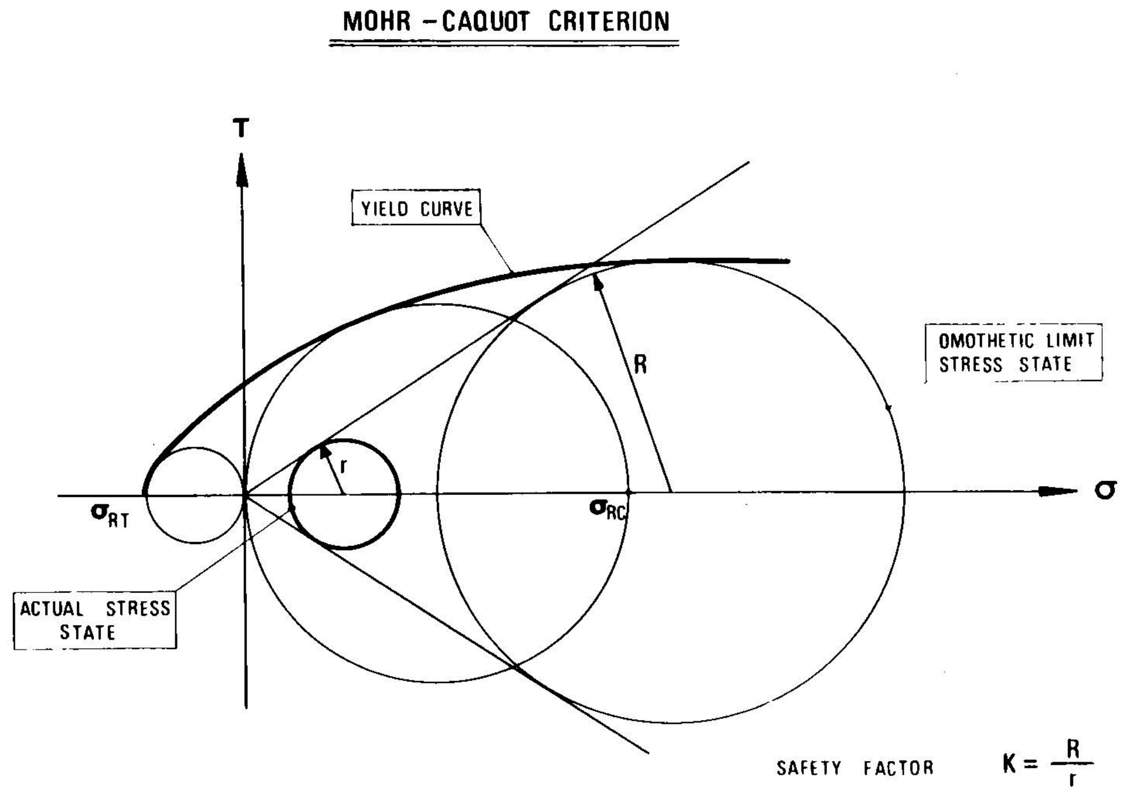

FIG. 9

Mohr-Caquot criterion and safety factor definition.

Critère de Mohr-Caquot et définition du coefficient de sécurité.

Mohr-Caquot-Kriterium und Sicherheitskoeffizients-Bezeichnung.

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catenation and interaction between the mathematical model and the experimental results, evidences the limits and possibilities of the various types of information and therefore, the necessity of complementaring of physical, rheological and mathematical models one with each others. The results confirm the validity of the linear elastic approach for the structure for the operating conditions.

In the above mentioned conditions, for all the points of the structure the safety factor values are satisfactory, confirming what experienced on the physical model, that is, no crushing, cracking or sliding are to be expected in the bulk of the structure.

As far as the safety factor is concerned, the Mohr - Caquot theory was adopted, whose limitations are well known. In fact, that theory neglects the principal intermediate stress. More recent studies (8), (9), (10) give results more in agreement with the concrete behaviour under triaxial state of stresses, considering also the effect of the principal intermediate stress and the two different collapse modes (brittle and shear failure).

PRESTRESSING ONLY

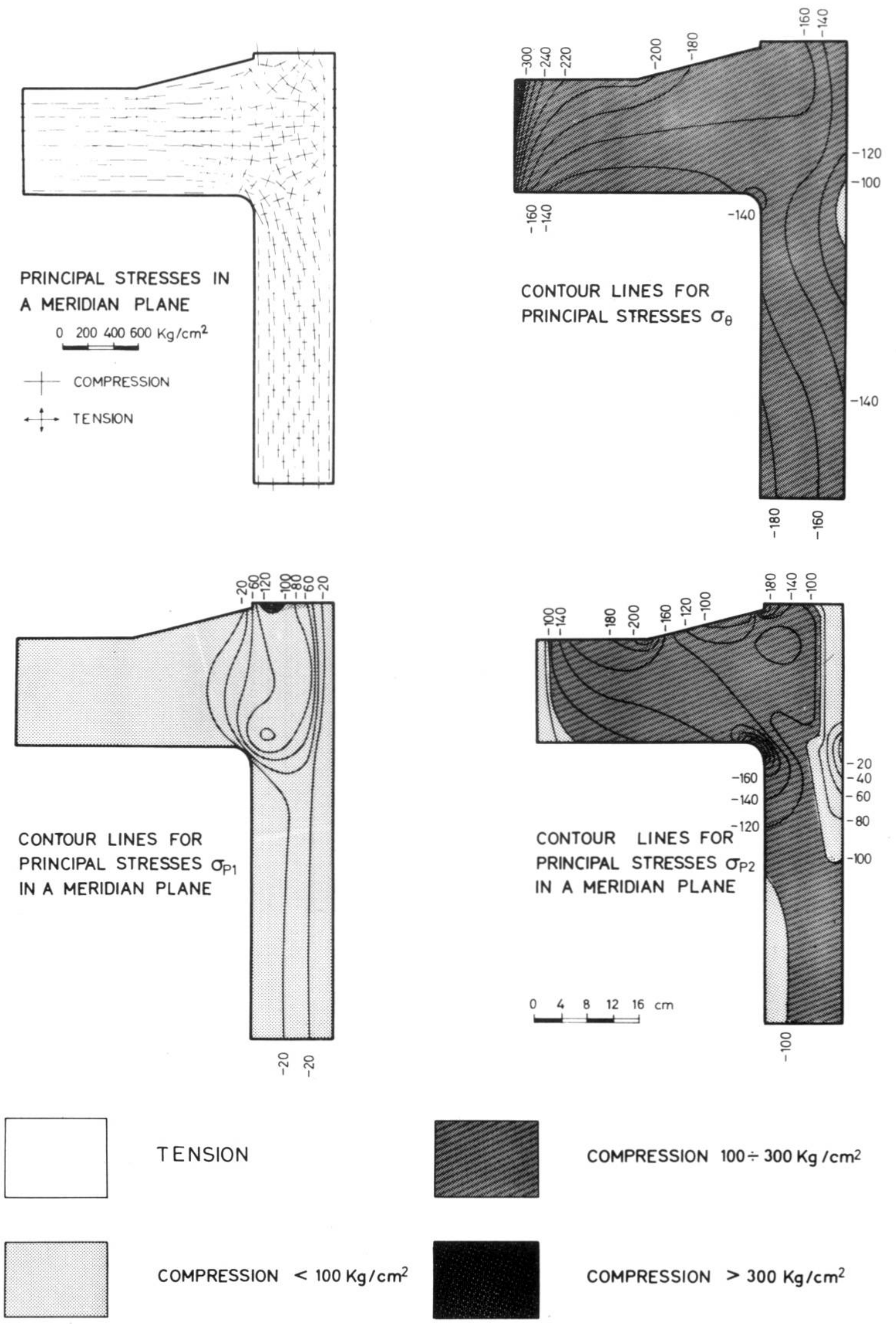

FIG. 10

Principal stress patterns and contour lines of the principal stresses for prestressing only.

Croix et lignes d' égale valeur pour les contraintes principales en régime de seule précontrainte.

Hauptspannungs trajektorien-Schema und Hauptspannungs Niveaulinien nur unter Vorspannungs- Bedingungen.

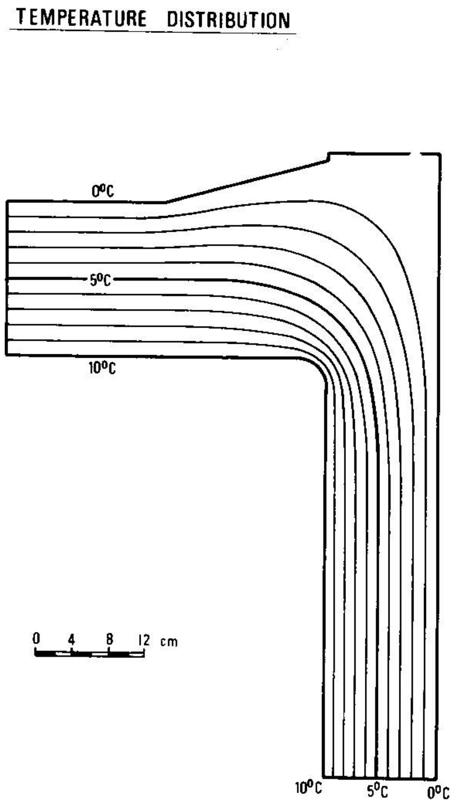

FIG. 11

Contour lines of the temperature distribution.

Lignes isothermes pour la distribution de températures.

Niveaulinien für die Temperaturverteilung.

For the structure under consideration, it is felt that the safety factor should be defined.on the basis of a more realistic rheological model, taking into account as well the fact that the external actions (pressure and temperature) act on a prestressed structure subjected to a triaxial state of stresses.

The logical development of the present work will be the studies of the structure in non-linear conditions up to the collapse limits, taking care of the viscous-elastic characteristics of the concrete in such conditions.

PRESTRESSING + GAS PRESSURE (40 kg/cm2) + TEMPERATURE VARIATION ΔT=10°C

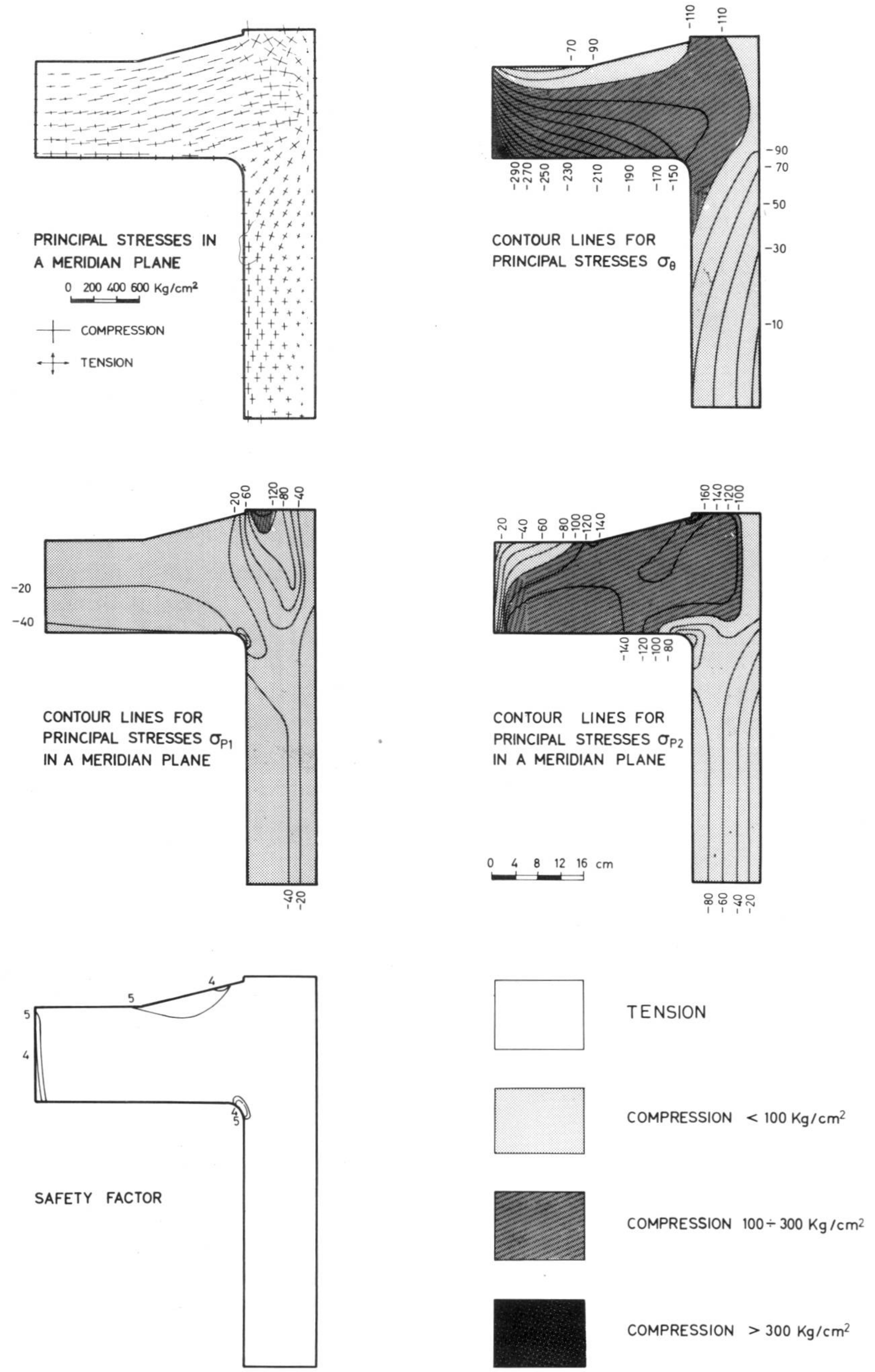

FIG. 12

Principal stress patterns and contour lines of the principal stresses and safety factor in working condition. - Croix et lignes d' égale valeur pour les contraintes principales et le coéfficient de sécurité en régime d' exploitation. - Hauptspannungs trajektorien- und Hauptspannungs und Sicherheitskoeffizients Niveaulinien im Betriebszustande.

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