FINITE ELEMENT STRUCTURAL ANALYSIS OF A P.C.P.V. FOR A B.W.R.

R. RICCIONI and G. ROBUTTI
Mathematical Models Department,
ISMES, Istituto Sperimentale Modelli e Strutture, I-24100 Bergamo, Italy

F.L. SCOTTO
ENEL, Centro Progettazione e Costruzione per gli Impianti Nucleari, I-00198 Rome, Italy.

SUMMARY

An interactive method has been adopted at I.S.M.E.S. in undertaking a design of a Prestressed Concrete Pressure Vessel for a Boiling Water Reactor. (Research sponsored by ENEL-D.S.R., Studies and Research Direction, on behalf of ENEL-C.P.N., Nuclear Design and Construction Centre, Rome).

By means of an immediate and continuous reading of automatic graphic outputs (displacements, stresses, local safety factors, etc.), such a procedure has made it possible to identify the necessary improvements for the optimization of the structure under consideration. The structure involved consists mainly of a cylinder of constant thickness closed at the lower end with a bottom slab, and at the upper end with a removable lid slab.

The interactive method was adopted for the optimization of:

- The design of the bottom slab using a linear elastic finite element program.
- The design of the lid slab using a non-linear finite element model which takes into account the lid-barrel contact. Different hypotheses on the friction coefficient, defining the physical behaviour of the contact, were analyzed.

On the structure involved, the following operating conditions have been taken into account:

- Prestressing of the barrel vertical cables;
- Prestressing of the circumferential barrel and bottom slab cables;
- Prestressing of the lid slab cables;
- Anchorage of the lid slab to the barrel;
- Condition in which total prestressing and internal design pressure (85 kp/cm^2) are combined.

1. INTRODUCTION

The so-called "interactive man-computer" procedures for the purpose of optimizing computerized projecting of complex structures are up to now well known. Such a procedure has been utilized at I. S. M. E. S. for the application of the P. C. P. V. concept to BWR. The research programme involves a study of the behaviour of a "thin-wall" vessel having an original type top closure, in succesive stages. The first stage concerns optimization of the prestressed concrete main structure then of the removable lid and finally of the whole structure.

The design philosophy, the geometrical data and the prestressing cable system are illustrated in reference [1] and [2] .

The structure involved was designed for the following conditions:

- Prestressing of the lid and of the main structure.
- Mutual effects due to the connection of the two above mentioned structures.
- Effect due to design pressure (85 Kg/cm^2) acting on the prestressed structures.
- Thermal effects.

Under such design conditions the structure must have the basic requirement to be in a "fully compressive" stress state. The static behaviour of the cylindrical barrel did not involve excessive problems to size, while difficulties arise to correct size determination of slabs.

2. PROJECTING OF CONTINUOUS STRUCTURES

The process of optimizing projecting finds a considerable obstacle in the high cost of utilization and in the difficulty of standardization. For this reason the codes directed toward automation of the problem are of highly complex order and a large number of variables must be taken into account, which might jeopardize its handiness. The optimal structure is therefore often determined by man-computer interactive methods. [3] . The procedure followed at I. S. M. E. S. to establish the size of the lower slab and the lid structure is, in fact, of this type and, as such, is not of a general but of a contingent and empirical nature. It therefore has the features of a research specific to transitional periods which do not lead to unchangeable and general laws, but do help to attain such laws, besides making it possible to reach the goal, i. e ., results.

The interactive method used in the examined case may be sinthetized as follows;

- Devising of a single finite-element model whose mesh is such as to cover different structure geometries simultaneously.
- Evaluation of the stress-strain state of different structure geometries. This phase was completely automatized by the computer programme facilities.
- Analysis of the obtained stress-strain state.
- Perfecting of the geometry by applying suitable considerations experienced. It is this stage that involves man most, since experience and personal intuition are necessary in order to act.

- Detailed feasibility analysis of the solution achieved by perfecting the geometry.

3. DESCRIPTION OF THE INTERACTIVE PROCESS ADOPTED FOR BOTTOM SLAB DESIGN

3.1. Finite-Element Calculation.

A finite element mesh (fig. 1) was built, such as to allow different slab thicknesses (from 200 cm. to 300 cm.) and a barrel of constant thickness of 240 cm.

The F.E.M. programme performed in single step the calculation for geometries where slab thickness attained values equal to 200, 260, 300 cm. For each of these geometries, the calculation was performed in linear elastic hypothesis under the following load conditions:

- Total prestressing (varied for each thickness on the base of feasibility criteria).
- Internal design pressure of 85 Kg/cm^2.

3.2. Detailed Analysis of Results.

Fig. 2 shows the value of radial σ_r and circumferential σ_θ stresses on the slab's axis of symmetry for the slab geometries analyzed. With regards to the thicknesses involved, it can be seen that prestressing yelds a higher stress value at the inner than at the outer slab border. This is in contrast with the fact that, with respect to the bottom border, the compressive stress arising from prestressing alone must exceed, in terms of absolute value, the tensile stress due to internal pressure alone. As concerns the effects due to pressure alone, a graph has been plotted (fig. 3) which shows the value of radial and circumferential stresses at point B at the bottom border of the slab on the axis of symmetry, as thickness varies. In order to achieve a state of total compression, at the lower slab border (point B) a compression value of at least 20 Kg/cm^2 must be had from the resulting diagram of prestressing and pressure; in fact, the effect of temperature has been estimated around 20 Kg/cm^2 of tension on the outer surface of the slab. As it can be seen in fig. 2, this condition has not been met.

3.3. Perfecting of Geometry.

The project condition has therefore not been met. Remedies were therefore devised to improve the static behaviour of the structure. Possible remedies consisted in:

- Suitably altering the geometry.
- Altering loads arising from the prestressing system.

Both points were acted on. With respect to alterations on the geometry, it was decided to add a 30 cm. high ring base to the structure. This made it possible to increase, to a considerable extent, the eccentricity arising from prestressing on the slab; and to cause the diagram of stresses, arising from prestressing to become rectangular (fig. 2). With respect to loads, pull was increased at the prestressing cables of the slab alone. The study was carried out with slab thicknesses s=260 cm. and s=280 cm. Results of these two cases are again shown on fig. 2.

The structure with 280 cm. thick slab was considered as meeting the requisite of "fully compression". Comparisons among the five structures involved, have been carried out when total prestressing and internal pressure are combined. Contours of the structures' local safety factor [4] referred to the 'Mohr-Caquot' intrinsic curve are shown on fig. 4.

The analysis of results extended to the behaviour of the whole structure shows in all situations examined the presence of a critical area at the point of internal connection between slab and barrel. A suitable mild steel reinforcement should be provided for this area which is, however, restricted on the reference solution.

3.4. Detailed Analysis of the Structure.

For the purpose of analysing the behaviour of the structure with ring base having a 280 cm. thick slab, separate anlyses were performed of the following effects:

- Effect due to every vertical and hooping prestressing cable group.
- Effect due to internal pressure of 85 Kg/cm^2.

A detailed analysis of results confirms the lack of mutual influence among the slabs, and suggests a reduction to a 20% extent in initial power of the prestressing cables in the 5th group of barrel cables.

4. DESCRIPTION OF THE INTERACTIVE PROCESS ADOPTED FOR LID SLAB DESIGN

Also as regards the lid, a procedure of the interactive man-computer type was set up for the purpose of optimal definition of its size. In this instance, the problem was complicated further with respect to the study on the lower slab size, owing to:

- The presence in the operative working phase of the effect of anchoring cables between lid and barrel.
- The need to simulate contact between lid and barrel with special elements called "joints" whose behaviour is of the non-linear type.
- Simultaneous presence of two critical areas: the area at the lid' s axis of symmetry on the outer surface and the lid-barrel contact area.

4.1. Joint Elements to Simulate Lid-Barrel Contact.

The study on lid size determination was performed by means of non-linear type calculation with a view to correctly simulating behaviour of the lid-barrel contact. Contact behaviour was described by means of special "joints" element. Within the joint element, the stress state is characterized by the normal and shear stresses σ_n and τ . Whenever the value of normal stress within the joint exceeds limit tension σ_ℓ the joint opens as a consequence. Whenever the value of the shear stress exceeds the limit value σ_ℓ obtained by the relation $\tau_\ell = C + \sigma_n \, Tg \, \varphi$ where C is cohesion and φ is angle of internal friction of the contact surfaces, failure occurs as a consequence. For the structure here involved, no cohesion between contact surfaces was considered. As regards the technique adoptedto solve the non-linear problem a mixed method was utilized making use of direct iterative technique (elastic moduli E and G functions of total strain) combined with the incremental "initial stress" technique, so as not to extent calculation time excessively. By operating with the "initial stress" tecnique, as a matter of fact, no need arises to redifine elastic characteristics and consequently the stiffness matrix at each stage. This makesit to cut costs. The behaviour of the joint element is described on the logical scheme shown on fig. 5.

4.2.Choice of Finite-Element Mesh for Lid Size Calculation.

The mesh utilized for lid analysis is shown on fig. 6. Three separate parts are identified:

- The first represents the sub-structure.
  The substructure mesh and its calculation were performed only once. Stiffness matrix and forces due to sub-structure were determined at the nodes common to structure and sub-structure.and then applied to the structure.
- The second part represents the mesh of the residual barrel portion. This mesh was retained without alterations for the subsequent stages of calculation.
- The third part is the lid mesh. This mesh had to be altered repeatedly whenever analysis of the results supplied suggestions for improvements.

4.3. Lid Calculation - Detailed Analysis of Results.

When optimizing the lid size a special attemption was given to the outer surface around the axis of symmetry and the contact area between lid and barrel.

As regards the outer surface, it was deemed advisable to resort, by analogy , to results for the lower slab, A parametric study was then carried out to evaluate the effect of boundary conditions on the stress state, defining three different values of the internal friction coefficient f between lid and barrel:

- f = 0 . Simulates simple laying.
- f = ∞ Simulates continuity and compatibility between lid and barrel.
- f = 0. 2. A realistic intermediate value.

The initial study was performed by means of the structure having thickness s=170cm shown on fig. 7. The same figure also shows the stress states $\sigma_\theta = \sigma_r$ at the axis of sym metry outer surface corresponding to load conditions:

- Total prestressing.
- Internal design pressure (85 Kg/cm^2) and lid anchorage.

The stress diagram obtained by superimposing the two diagrams obtained for load conditions of above, shows a large area under tension therefore the structure was considered as no longer meeting project conditions. With a view to define a lid thickness such as to meet project conditions, information obtained for the above analysis were utilized. Fig. 8a) shows the radial stress at point B versus lid thickness for the conditions due to internal pressure and lid anchoring only. This curve was carried out starting from the stress value obtained for slab thickness of 170 cm, assuming that the law describing the variation of stress versus thickness was similar to the one obtained for bottom slab. This hypothesis, though not complying in full with fact, made it however possible to define the presumable range within which the optimal slab thickness is to be found. Fig. 8b) shows, instead, the stress value at point B versus friction coefficient. It may be seen that the curve declines rapidly and already at values of f = 0.5 approaches asymptotic values ($f = \infty$).

4.3. Refining of the Geometry.

On the basis of results achieved at this early stage of calculation, it was deemed advisable to perform the following alterations:

- Attempt to increase lid thickness without increasing the weight to a considerable extent.
- Increase eccentricity of the lid cable prestressing system.
- Increase the pull of the lid prestressing cables.

The calculation was thus performed with a lid geometry having a thickness s = 250 cm shown on fig. 7.

The stress state for lid structure having thickness s = 250 cm is shown on the same figure. The analysis of results reveals the structure was not meeting the required conditions along the axis of symmetry. In fact, the diagram resulting from prestressing and internal pressure shows a tensile stress value $\sigma_\theta = \sigma_r = 15\ Kg/cm^2$ at point B; The structure displacements also show a large area of detachment at the contact between lid and main structure (fig. 9). For this reason it was decided to incline the surface of contact between lid and barrel. The results achieved for this geometry (fig. 7) are satisfactory on the axis of symmetry. On the lid, near the contact, a restricted tensile area is present.

It is therefore necessary to provide this area with a suitable mild steel reinforcement. The weight of the lid structure was restricted to 456 tons.

4.4. Results for Operating Conditions.

The following operating conditions were examined on the structure involved:

- Total prestressing.
- Total prestressing and lid anchorage.
- Total prestresing, lid anchorage and internal pressure (85 Kg/cm^2).

The stress state due to total prestressing is shown on fig. 10 by means of main stresses pattern and main stresses contours.

Fig. 11 shows stress state for the situation in which total prestressing and lid anchorage are combined. Vertical stresses acting on different horizontal sections of the barrel are represented. This makes it possible to study in detail the effect due to anchorage.

At the end for the last operating condition the stress state and safety factor calculated locally by means of the intrinsic 'Mohr-Caquot' curve are shown on fig. 12. Analysis of the stress state shows two limited areas where tension is present. Also the local safety factors show these two critical areas at the lower haunch of the vessel and at the lid contact surface area. Here suitable mild steel reinforcements are necessary.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

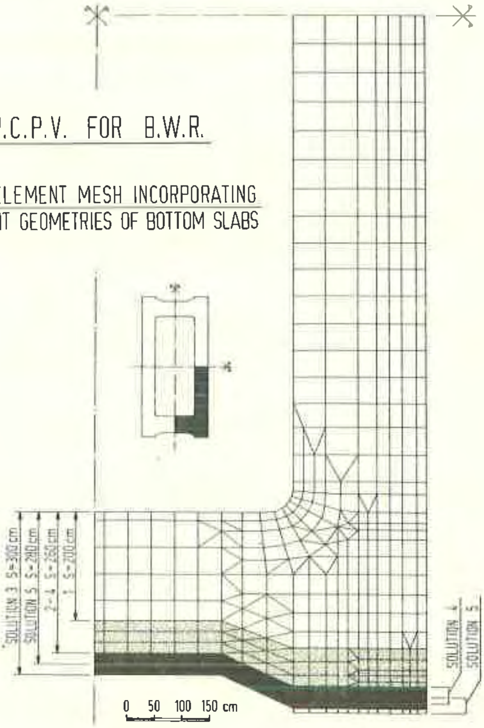
This study has made it possible to attain a more then satisfactory solution for a P. C. P. V. structure for BWR affording highly complex characteristics. To achieve this, an operating method was employed, connected with computer facilities. Once a general computerwise criterion was set up, the attempt was made to operate within its frame as accurately as possible, so as to limit dispersal of human energy and waste of cost. The road opened by this study was not free from difficulties and obliged the Authors to considerably extend their experience in a field - that of automated projecting - affording ample development. Subsequent improvements of this study will involve both perfection of automation of the procedure adopted and a detailed study on the same structure taking into account the stiffness of prestressing cables, the inner steel liner and the anchorage ribs. The study will be carried out as far as collapse conditions and compared with the physical model results.

[1] FUMAGALLI, E., VERDELLI, G., "Research on P. C. P. V. for BWR - Physical Model as Design Tool. Main Results", 3rd Intl. Conf. on Structural Mechanics in Reactor Technology, London, England, September 1 - 5, 1975.

[2] SCOTTO, F. L., "Thin Walled Concept and a New Top Lid applied to BW Scandinavian P. C. P. V.", 3rd Intl. Conf. on Structural Mechanics in Reactor Technology, London, England, September 1 - 5, 1975.

[3] FANELLI, M., "A General Review of Structural Mechanics Applications", International Symposium on "Discrete Methods in Engineering", Cise, Segrate, Milan - Italy, September 1974.

[4] FANELLI, M;, RICCIONI, R., ROBUTTI, G., "Finite Element Analysis of P. C. P. V.", IABSE Seminar, Bergamo, Italy, May 17 - 19, 1974.

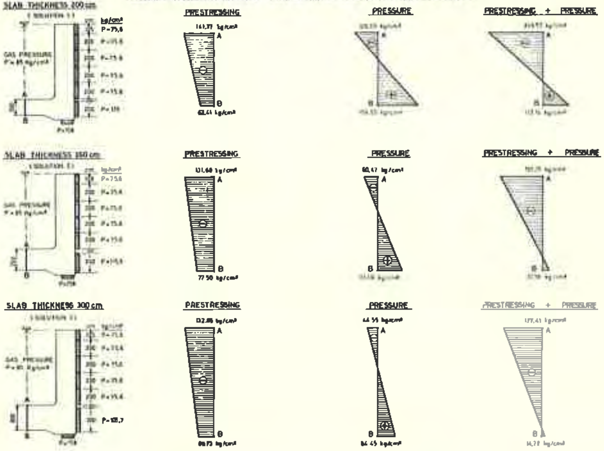


P.C.P.V. FOR B.W.R.

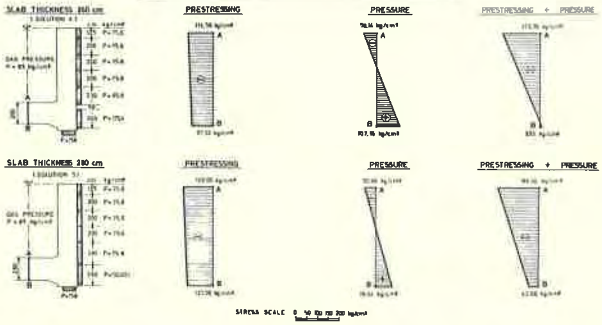
FINITE ELEMENT MESH INCORPORATING DIFFERENT GEOMETRIES OF BOTTOM SLABS

STRESS PATTERN AT THE SLAB SIMMETRY AXIS

SOLUTIONS WITHOUT THE BASE-1st STEP CALCULATION



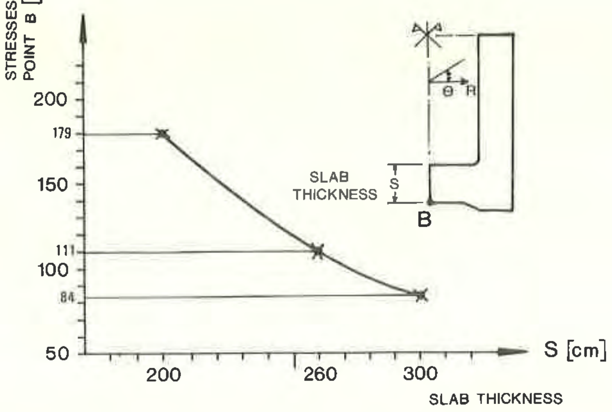
SOLUTIONS WITH THE BASE-2nd STEP CALCULATION



INTERNAL PRESSURE (85 Kg/cm^2)

$\sigma_\theta = \sigma_R$ STRESSES AT POINT B

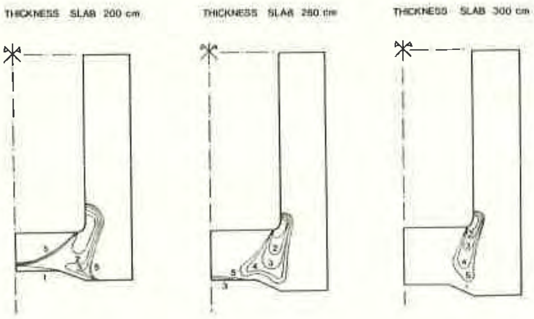
VERSUS BOTTOM SLAB THICKNESS



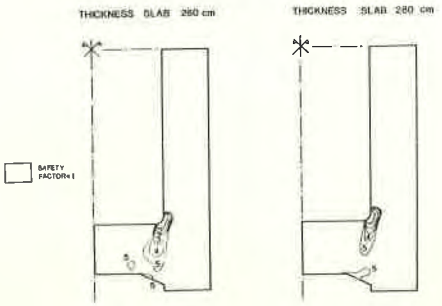
DIFFERENT GEOMETRIES-SAFETY FACTOR

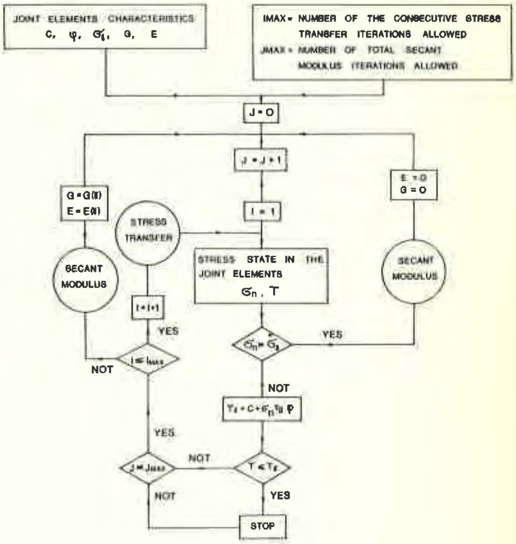
PRESTRESSING + PRESSURE (85 Kg/cm^2)

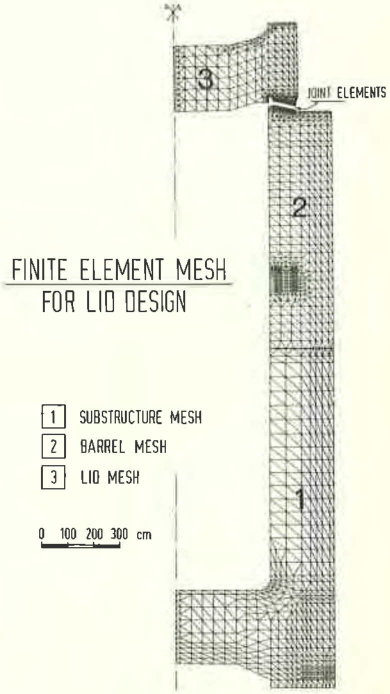
SOLUTIONS WITHOUT THE RING BASE



SOLUTIONS WITH THE RING BASE

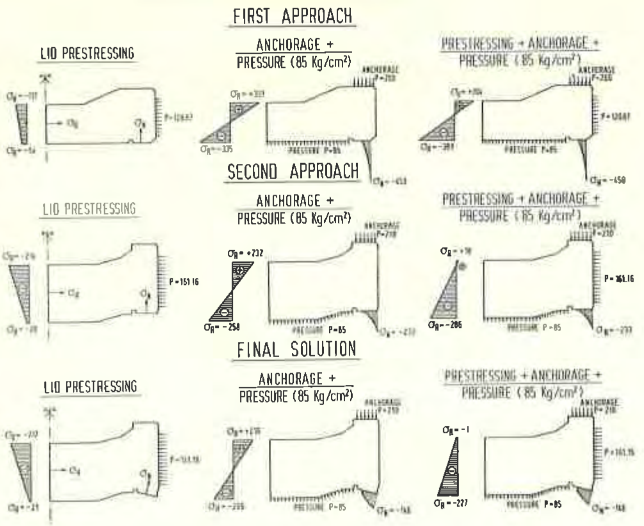






FINITE ELEMENT MESH FOR LID DESIGN

DIFFERENT GEOMETRIES RESULTS

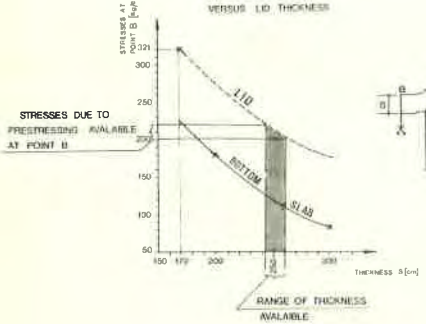


UNIT OF MEASURE FOR STRESSES AND PRESSURE = Kg/cm²
+ TENSILE STRESSES
— COMPRESSION STRESSES

ANALYSIS OF THE LID RESULTS

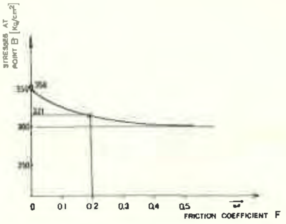
(a)

STRESSES AT POINT B VERSUS LID THICKNESS

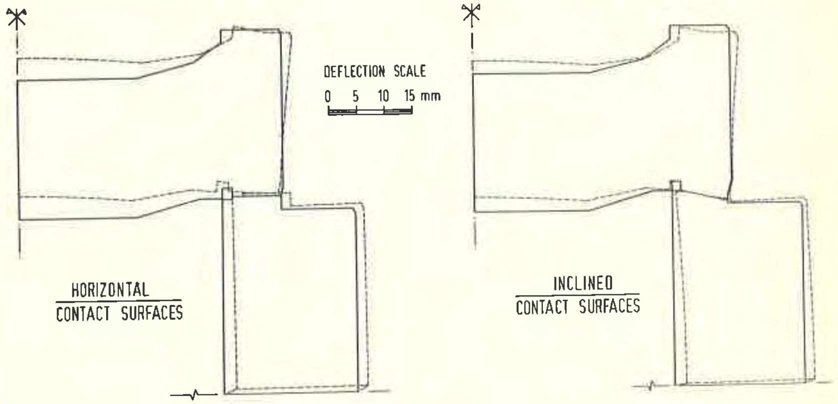


(b)

STRESSES AT POINT B VERSUS CONTACT SURFACES FRICTION COEFFICIENT

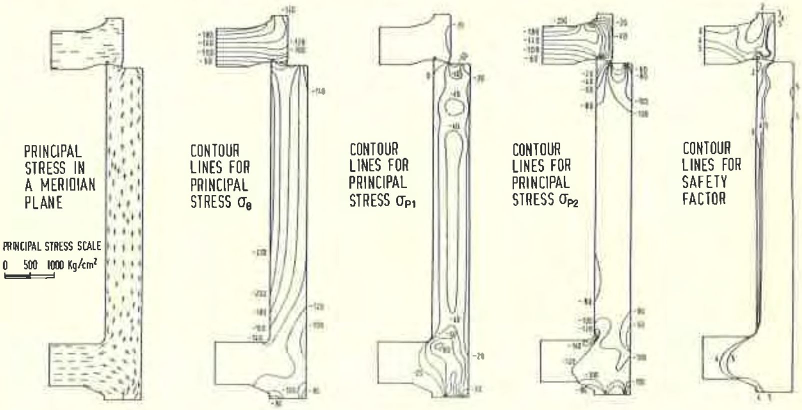


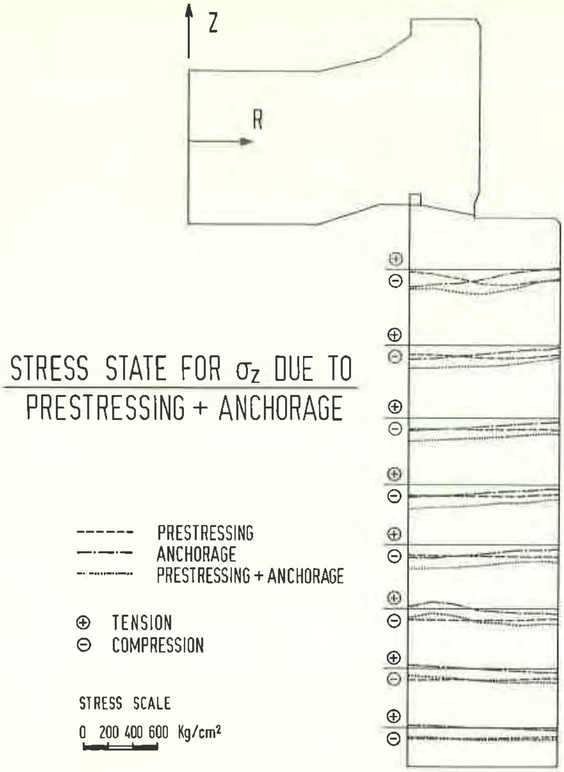
DEFLECTIONS DUE TO ANCHORAGE + PRESSURE (85 Kg/cm²)



TOTAL PRESTRESSING

TRIAXIAL STATE OF STRESS AND SAFETY FACTOR

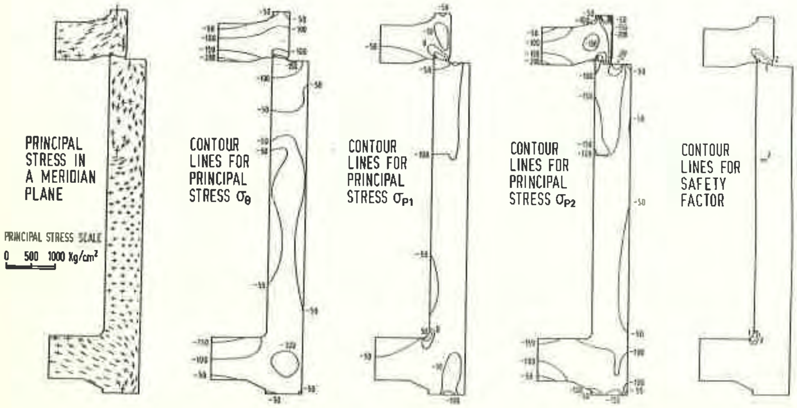




STRESS STATE FOR σ_Z DUE TO PRESTRESSING + ANCHORAGE

PRESTRESSING + ANCHORAGE + INTERNAL PRESSURE (85 Kg/cm²)

TRIAXIAL STATE OF STRESS AND SAFETY FACTOR



PRINCIPAL STRESS IN A MERIDIAN PLANE

CONTOUR LINES FOR PRINCIPAL STRESS σ_θ

CONTOUR LINES FOR PRINCIPAL STRESS σ_{P1}

CONTOUR LINES FOR PRINCIPAL STRESS σ_{P2}

CONTOUR LINES FOR SAFETY FACTOR