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A finite element study of the triaxial stress state around an inspection tunnel in an arch dam

Une étude avec la méthode des éléments finis de l'état de contrainte triaxiale autour d'une galérie de visite dans un barrage-voûte

Eine finite-Elemente-Analysenmethode zur Bestimmung des Dreiachsigen Spannungszustandes um einen Inspektionsgang in einer Bogenmauer

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SUMMARY

Attention is drawn on cases pertaining to particular structures or loading systems for which experimental techniques aiming at determining the triaxial stress state suffer from some limitations or difficulties.

In such cases suitable mathematical models can be used in a complementary way with respect to model (or prototype) tests.

As an example this paper illustrates the application of a F. E. mathematical model to a three-dimensional problem: the determination of the triaxial stress field around an inspection tunnel in an arch dam. This problem would entail serious experimental difficulties if its study were to be attempted by model tests.

RESUME

On montre que, pour certaines structures (ou certains cas de charge) les techniques expérimentales visant à déterminer l'état triaxial de contrainte souffrent de quelques limites ou difficultés d'application.

A titre d'exemple on illustre une analyse tridimensionnelle à Eléments Finis pour l'étude du champ de contrainte aux alentours d'une galerie de visite dans un barrage-voûte : on remarquera que ce problème poserait des difficultés très sérieuse si on voulait l'aborder par des essais sur modèle réduit.

ZUSAMMENFASSUNG

Der Beitrag zeigt wie im Falle von bestimmten Bauwerken und Lastannahmen die Versuchsmethoden nicht in der Lage sind, den Spannungszustand genau und ohne Schwierigkeiten zu bestimmen.

Unter diesen Umständen, kann die Anwendung von angepassten mathematischen Modellen die mit der Hilfe von Modellenversuchen (oder Prototypenversuchen) erreichten Ergebnisse ergänzen.

Es wird beschrieben, als Beispiel, die Anwendung einer Finite-Elemente-Analysenmethode zur Bestimmung des dreiachsigen Spannungszustandes um einen Inspektionsgang in einer Bogenmauer : dieses Problem würde grosse Schwierigkeiten bei den Versuchen, zum Beispiel auf massstäblich verkleinerten Modellen, bereiten.

1. SOME DRAWBACKS OF PHYSICAL MODELS

The role of model tests in the study of triaxially-stressed structures is undeniably of the greatest importance. However, experimental techniques meet sometimes definite limitations in the engineer's quest for a clear understanding of the stress state in said structures under various loading systems.

The origins of such limitations are manifold; among others, suffice it to mention the following :

- the difficulty (sometimes amounting to a practical impossibility) of installing instrumentation in certain points of poor accessibility, in which it is required to know the stress conditions;
- the still developing state of the art for multi-axial extensometers, whose measurements often are lacking reliability.
- the finite physical size of said multi-axial gauges, which entails a perturbation in the stress field, difficult to assess, in their proximity; such perturbations are especially troublesome in reduced-scale model tests.

If, moreover, the tests are carried out on micro-concrete models, additional difficulties can creep in due to uncertainties in separating the tensional component of the deformation tensor from the thermal, or igrometric, components.

2. USEFULNESS AND LIMITATIONS OF MATHEMATICAL MODELS

The aforesaid drawbacks of physical models can be - at least partially - overcome by suitable use of appropriate mathematical models.

The latter can yield, at least in the elastic field in the present state of the art, the stress state of any point inside the structure under study.

It goes without saying that the mathematical models suffer, in their turn, from some limitations. If, by way of example, we refer to the well-known F. E. techniques, the maximum number of nodes and/or elements in the mesh is, generally speaking, strictly tied to the memory size of the computer; the same goes for the half-bandwidth, or for the "front length", according to the type of solution technique one chooses for solving the linear equation system.

It is clear, however, that such drawbacks (themselves of a strictly practical nature, so that the use e. g. of "sub-structures", suitable numbering of nodes and elements, etc. is sometimes sufficient to circumvent them) do not detract from the value of mathematical models in themselves or, more important, as a complementary means of research.

In effect, provided that the mathematical model be able to faithfully simulate the general behaviour of the displacement and deformation fields such as given by the physical model on the accessible surfaces, we are allowed to infer that the same mathematical model will yield reliable information even for those points laying in inaccessible regions of the physical models.

3. ADVANTAGES OF A "HYBRID" PROCESS OF ANALYSIS

In the light of what above said, a design engineer confronted with a complex structure subjected to a triaxial stress state (prestressed concrete pressure vessel, underground cavity, arch dam etc.) could well avail himself of a "hybrid" research procedure, operating both on a physical and on a mathematical model. From the former he will draw direct information on the stress state of accessible points, from the latter the same kind of information both for "accessible" and "inaccessible" points : the necessary reconciliation of the two models being obviously effected by a comparison between computed and observed displacement and deformation fields on the "accessible" surfaces. Moreover, the mathematical model, if implemented before the physical model, could well yield useful suggestions concerning the optimal location of instruments or particular control tests and measurements to be carried out in the "accessible" regions of the physical model.

In effect, by suitable use of the mathematical model the choice of the physical quantities to be measured (e. g. direction of displacements and of unit elongations) could be established upon such criteria as to make more meaningful the comparison between experimental and theoretical results.

4. AN EXAMPLE OF APPLICATION OF F. E. MATHEMATICAL MODELS

The present paper concerns the study of stress concentrations induced by an inspection tunnel in an arch dam. It is hoped that it will adequately illustrate what above said.

It is well-known that on the inside surfaces of such inspection tunnels one is bound to find cracks, sooner or later in the lifetime of the prototype.

If one were to investigate this phenomenon with the sole aid of a physical model, one would meet serious difficulties. Among others, suffice it to mention the near - impossibility of installing strain-gauges capable of reading out the typically triaxial stress state around the tunnel, as well as the difficulties connected with any attempt to simulate the thermal loads, which are deemed to be influential in the formation of the aforesaid cracks.

The present analysis has been carried out by modern F. E. techniques; these allow, as the following text will show, a satisfactory "prima-facies" investigation of the question in hand.

4 a). Features of the arch dam under analysis

The main physical and geometric features of the double curvature, thin, non-symmetrical arch dam chosen for the present study are hereunder summarized :

- Young modulus for concrete	E_c	=	300,000 $kg\ cm^{-2}$
- " " for the rock	E_r	=	150,000 "
- Poisson's ratio	ν	=	.2
- maximum dam height	H	=	94 m
- maximum dam thickness	s_m	=	14.2 m
- minimum " "	s_n	=	2.25 m
- developed length at crest	L	=	238 m .

The numerical analysis of the entire dam with the inspection tunnel would require a mesh sufficiently "densely packed" around the tunnel. Such a mesh would have such a number of nodes and elements as to exceed the present limits of the computer used for applying the F. E. programme.

Recourse was consequently made to a particular trick which, even if not completely rigorous, allows one to obtain valid results (see further on).

4 b) . Scheme followed in the numerical analysis

In a first stage the entire dam was subjected to analysis, without inspection tunnel, which fact allowed one to use a simple mesh. A sufficiently extended region of foundation rock was included in the mesh (fig. 1), which was formed by 3-dimensional hexaedric or pentaedric "isoparametric" elements (having either 20 or 15 nodes). The nodes totalled 871 and the elements 114.
(The displacements obtained for hydrostatic and thermal loads with this first - stage model compared extremely well with those measured on the prototype, so that the mathematical model was considered as satisfactorily validated).

For a first, rough appraisal of the overall (integral) effect of the presence of the inspection tunnel on the displacements, a second-stage analysis was carried out by altering the Young modulus of the elements through which the tunnel runs in proportion to the ratio of actual cross--section (with tunnel) to full cross-section (without tunnel).
It was immediately evident that the effect of the tunnel on the displacements was negligible.

This ascertained, a third stage analysis was carried out by isolating a central portion of the first mesh, within which a finer mesh was fitted, the latter including the tunnel surfaces.

Fig. 2 shows position and size of said tunnel in the crown section.

Figgs. 3 and 4 show - in a perspective view - the 3-dimensional mesh, respectively from upstream and from downstream, from which the central region was isolated for the more detailed investigation.

Fig. 5 shows the new mesh for said central region; this latter mesh includes 521 nodes and 86 iso-parametric elements either with 20 (hexaedric) or 15 (pentaedric) nodes.

For this central region there remained to be assigned the boundary conditions, i. e. the displacement or the force values at all nodes lying on the cutaway surfaces, so as to simulate the action exerted on this region by all the rest of the dam.

The only practical way to achieve this, due to the lack of a symmetry plane in the structure, was to assign to every such node the displacements obtained in the first-stage analysis.

It is evident that in this way one introduces an error, because the assigned displacements were obtained for a structure geometrically and physically different (without tunnel) from the one to be presently

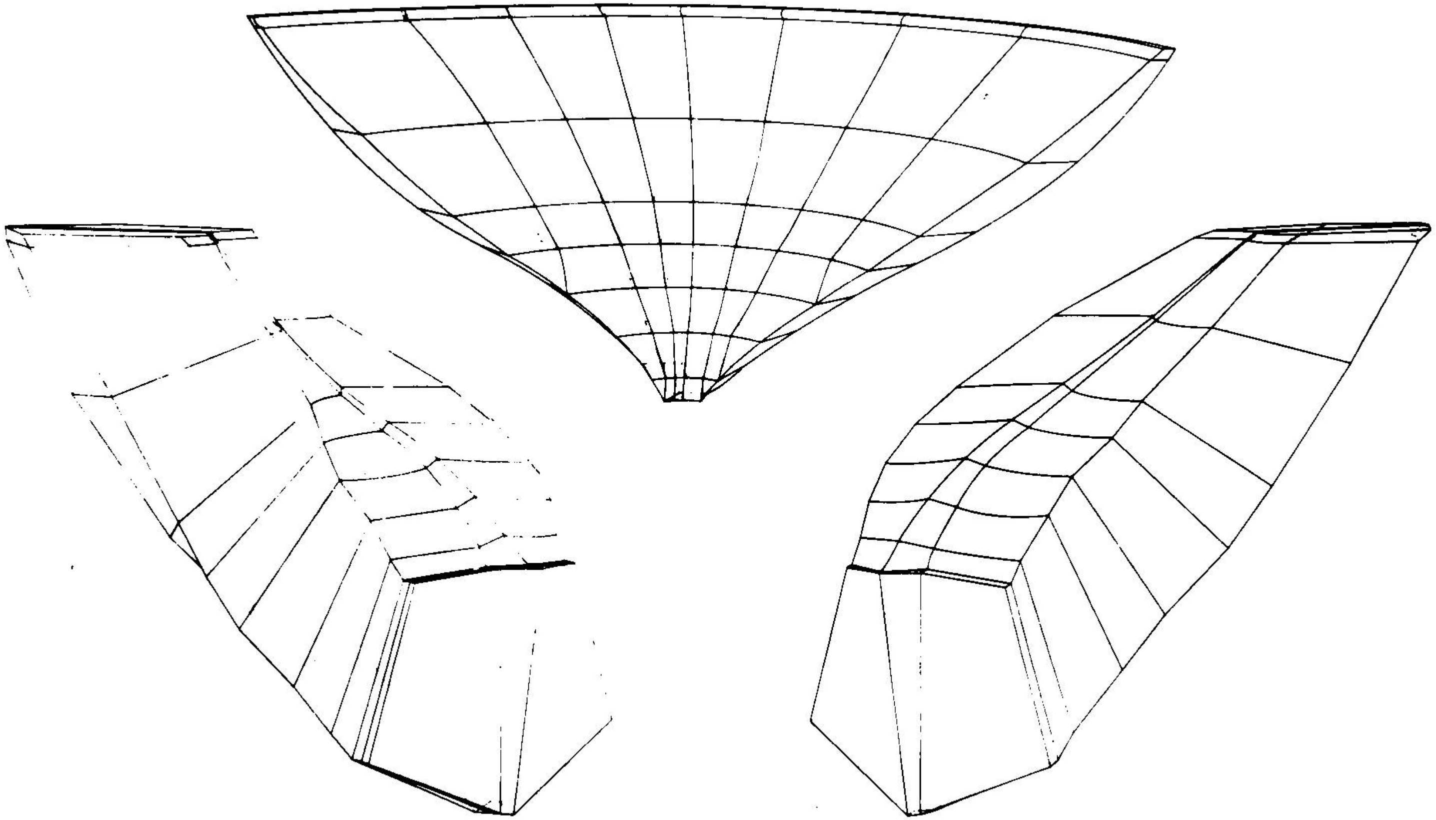

Fig. 1 - Total mesh of the arch dam and the foundation rock.
Maillage complète du barrage et du rocher de foundations.
Masche der gesamten Staumauer und des Felsuntergrundes.

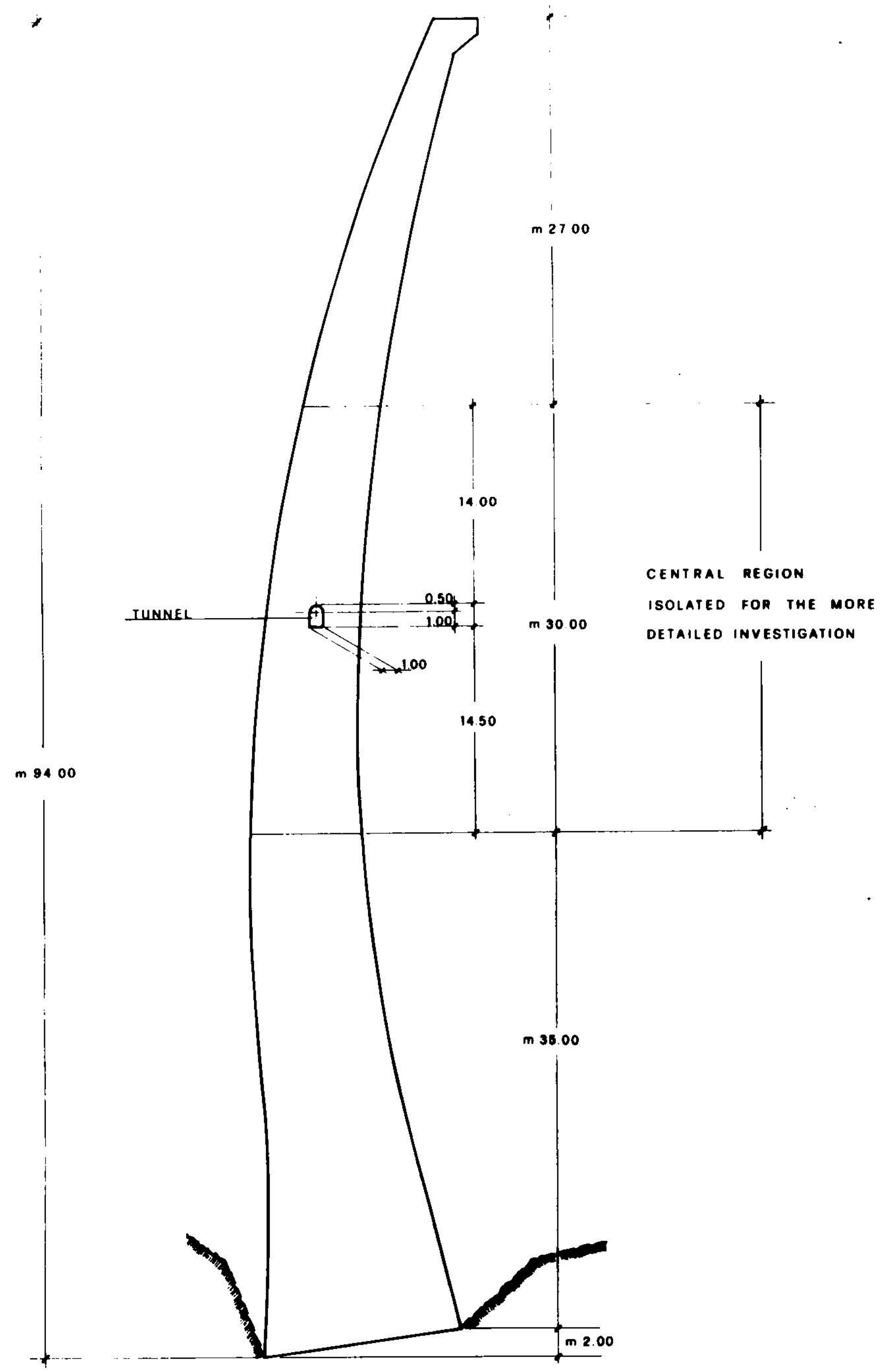

Fig. 2 - Crown section with the inspection tunnel.
Coupe en clé avec la galerie de visite.
Scheitelschnitt mit Inspektionsgang.

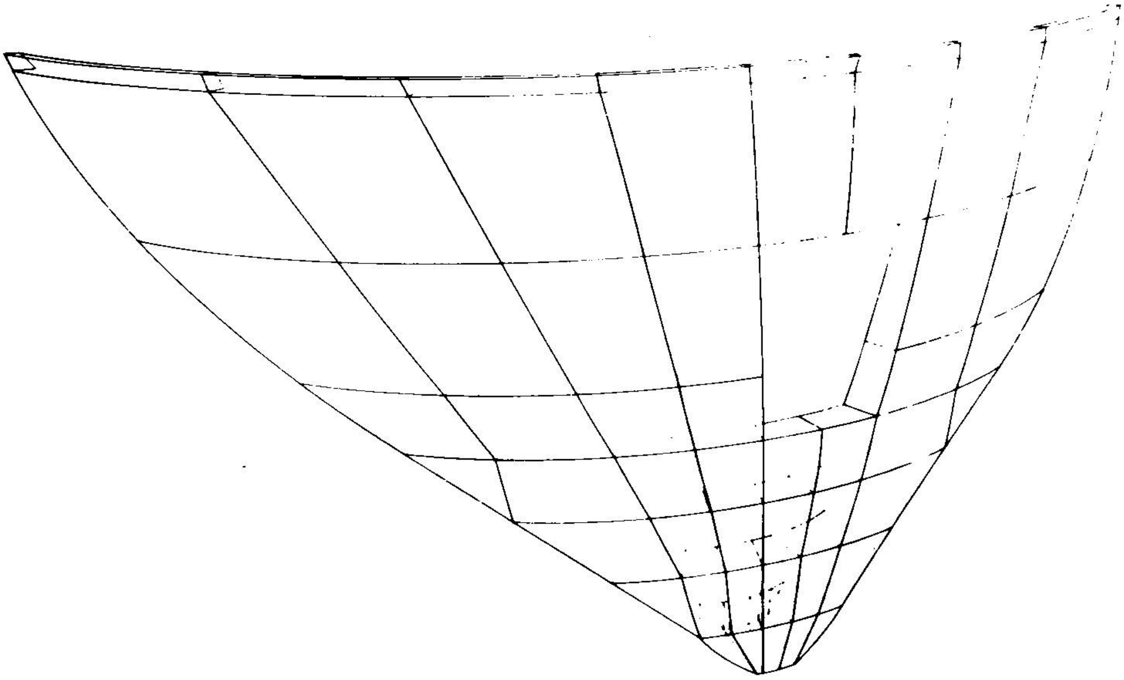

Fig. 3 - Upstream view of the 3-dimensional mesh without the central region. Vue d'en amont du maillage tridimensionnel sans la partie centrale. Wasserseitige Ansicht der dreidimensionalen Masche, der Mittelteil ausgeschlossen.

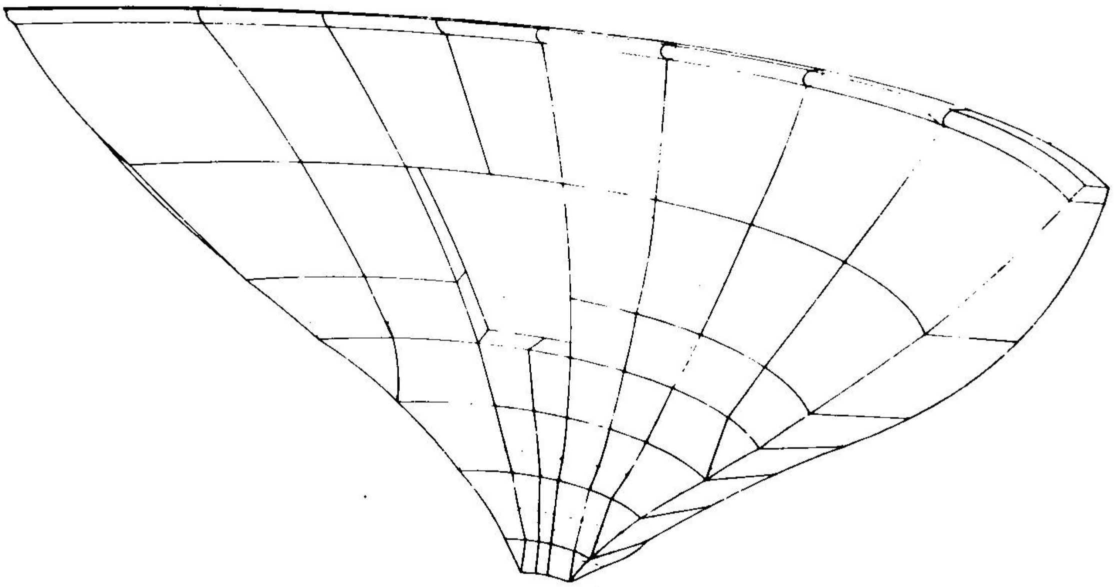

Fig. 4 - Downstream view of the 3-dimensional mesh without the central region. Vue d'en aval du maillage tridimensionnel sans la partie centrale. Luftseitige Ansicht der dreidimensionalen Masche, der Mittelteil ausgeschlossen.

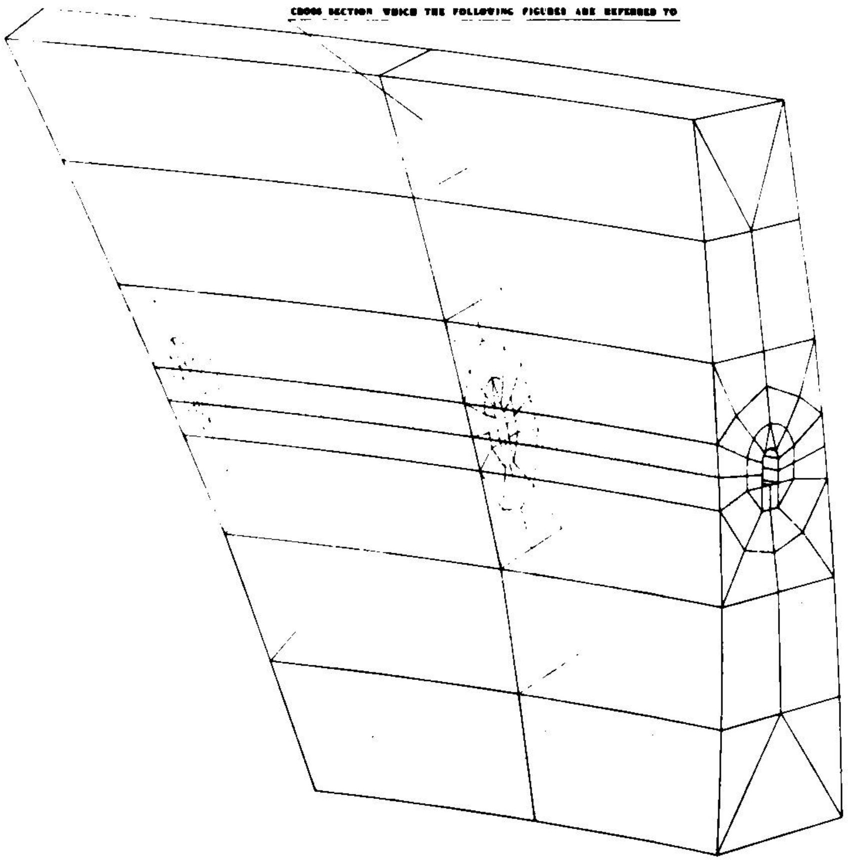

Fig. 5 - Tridimensional mesh of the central region with the inspection tunnel. Maillage tridimensionnel de la partie centrale avec la galerie de visite. Dreidimensionale Masche des Scheitelschnittes mit Inspektionsgang.

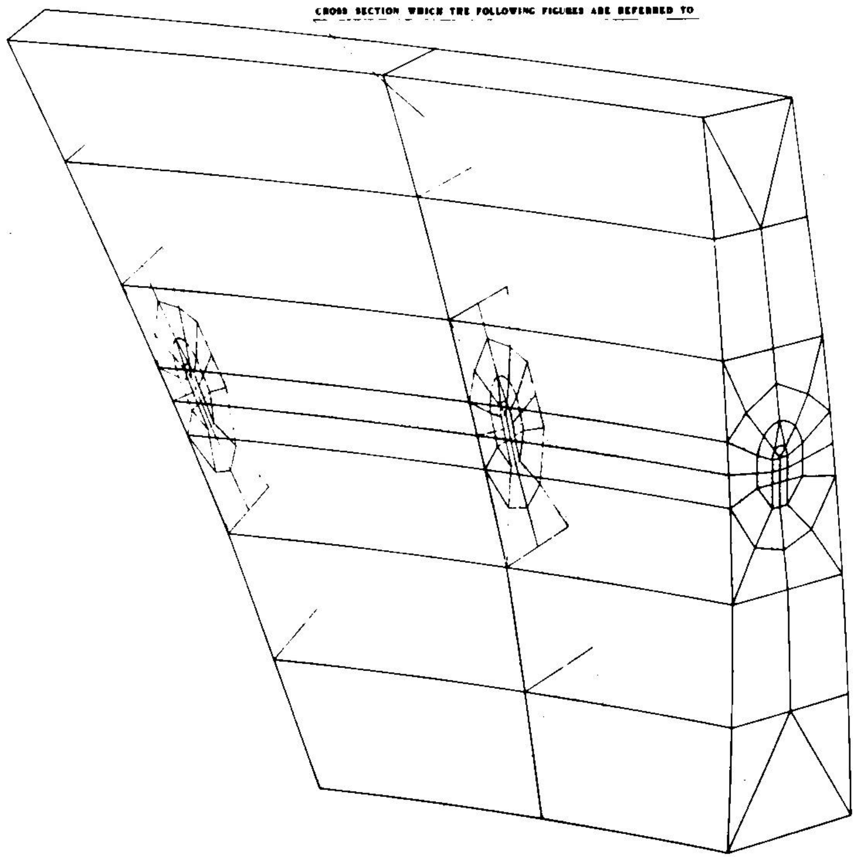

Fig. 6 - Tridimensional mesh of the central region without the inspection tunnel. Maillage tridimensionnel de la partie centrale sans la galerie de visite. Dreidimensionale Masche des Scheitelschnittes ohne Inspektionsgang.

analysed (with the tunnel). Nevertheless, the error is deemed to be negligible for the points sufficiently remote from the "cutaway" surfaces.

The results hereunder presented pertain, indeed, to points lying on an intermediate section plane sufficiently far from the cuts.

A second point to be considered is the following : in the finer mesh, on the cutaway surfaces, there are many more nodes than on the corresponding faces of the coarser mesh. The problem thus arises of finding "consistent" displacement values to assign to these new nodes.

This problem was solved with a sub program which starts from the global coordinates of the "new" nodes, computes the local normalized coordinates and from these, via the shape functions, the required displacements as functions of the nodal displacements obtained in the first - stage analysis.

For the 3-dimensional analysis of the entire dam and of its central region containing the inspection tunnel, use was made of the F. E. programme TRITEN 1 ; all the graphic outputs (see further on) were obtained by means of the plotting programme DIPLA 13 ; the perspective drawings of the meshes were obtained via the programme DI TRI Ø1 . (°)

The computer used was an IBM 360/65.

The final comparison was made between the stress states corresponding to the finer mesh with and without the inspection tunnel; to this end the finer mesh was further modified (fig. 6) by adding 14 3-dimensional isoparametric elements filling the tunnel, and the stress analysis was repeated under the same boundary conditions.

The analyses were all carried out for external loads corresponding to hydrostatic pressures such as given by maximum impounding level on the upstream face of the dam.

4 c) . Graphic presentation of results

In figgs. 7 to 18 the results of the above illustrated analyses are presented, via the automatic plotting of iso-curves for the two cases considered (central region with and without inspection gallery), at a plane cross-section lying about half-way between the cuts.

(°) All the above-cited programmes were developed within the CRIS (Centro Ricerca Idraulica e Strutturale) of ENEL by a joint-venture team ENEL-ISMES (Istituto Sperimentale Modelli e Strutture). These programmes are available trough ISMES in Bergamo (Italy).

From this comparison one can infer that the perturbations induced by the tunnel in the stress regime due to hydrostatic loads are not very conspicuous. It seems, thus, probable that the cracks sometimes found around such tunnels are not due to static loads as much as to thermal loads (and perhaps shrinkage).

A study of thermal stress states would not be outside the pale of possibilities with the F. E. methods here used; however, in order to yield meaningful results, such a study would require a detailed knowledge of the temperature field in the prototype in presence of the tunnel; lacking which, this second part of the investigation could not proceed.

5. CONCLUSIONS

It is reasonable to conclude that, in the present state of the art, the physical as well as the mathematical models suffer from some limitations.

Whenever the design engineer is confronted with problems of great complexity, careful consideration should be given, in our opinion, to the possibility of a "parallel" use of both investigation means.
By adopting suitable comparisons and cross-checks, it is possible to compose a unified picture from these double-source informations.

Such mutual integration appears particularly fruitful in the regions subjected to a triaxial stress state, where the need for detail is, generally speaking, more acutely felt.

6. AKNOWLEDGEMENTS

The Authors express here their sincere thanks to Messrs. Franco Pari, who cared after the data preparation, execution of computational and plotting phases, etc. and John Cadei, who cooperated in the initial phase of the study.

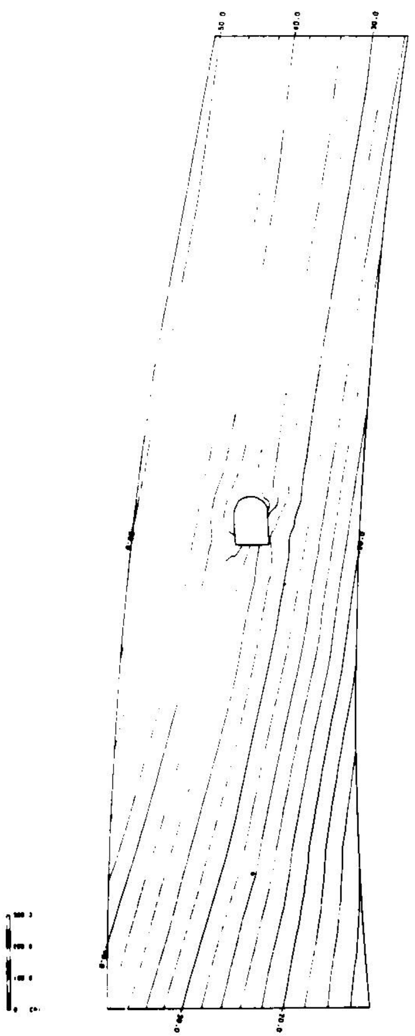

Fig. 7 - Contour-lines of the first principal stress in the cross section shown in fig. 5.
Lignes de niveau de la première contrainte principale dans la section transversale montrée en fig. 5. Niveaulinien der ersten Hauptspannung im in Abb. 5 dargestellten Querschnitt.

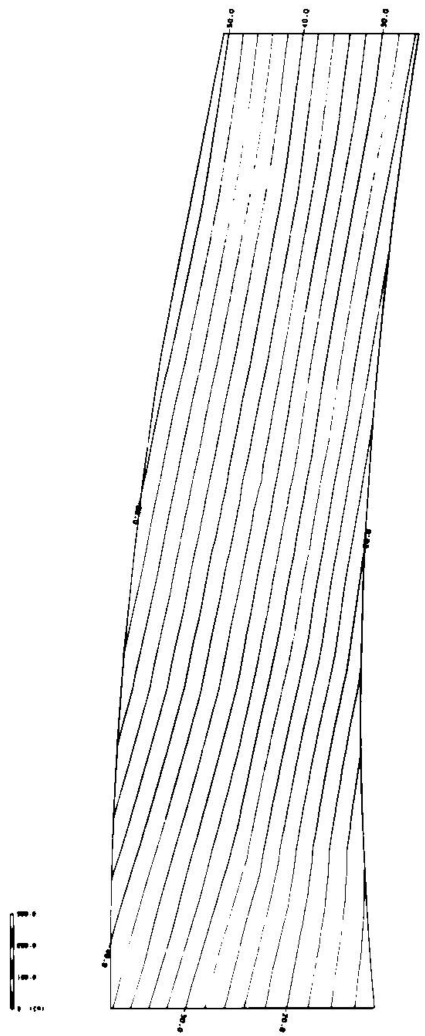

Fig. 8 - Contour-lines of the first principal stress in the cross section shown in fig. 6.
Lignes de niveau de la première contrainte principale dans la section transversale montrée en fig. 6. Niveaulinien der ersten Hauptspannung im in Abb. 6 dargestellten Querschnitt.

Fig. 9 - Contour-lines of the second principal stress in the cross section shown in fig. 5. Lignes de niveau de la deuxième contrainte princi pale dans la section transversale montrée en fig. 5. Niveaulinien der zweiten Hauptspannung im in Abb. 5 dargestellten Querschnitt.

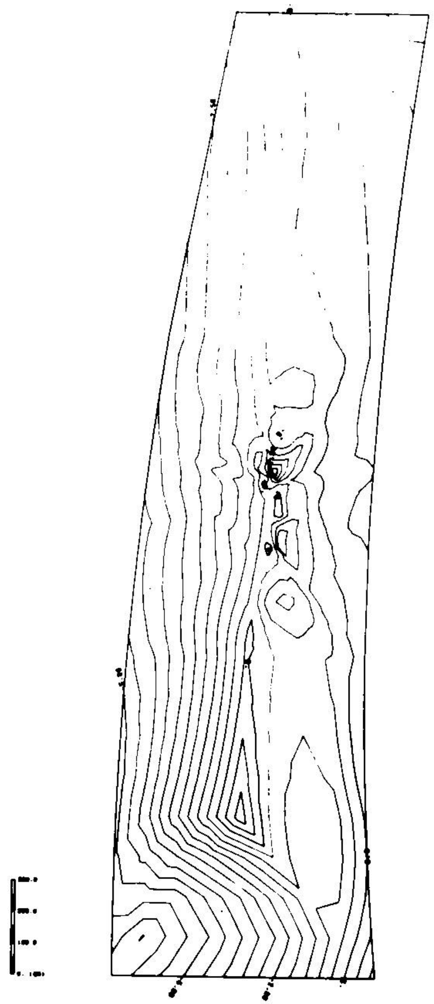

Fig. 10 - Contour-lines of the second principal stress in the cross section shown in fig. 6. Lignes de niveau de la deuxième contrainte princi pale dans la section transversale montrée en fig. 6. Niveaulinien der zweiten Hauptspannung im in Abb. 6 dargestellten Querschnitt.

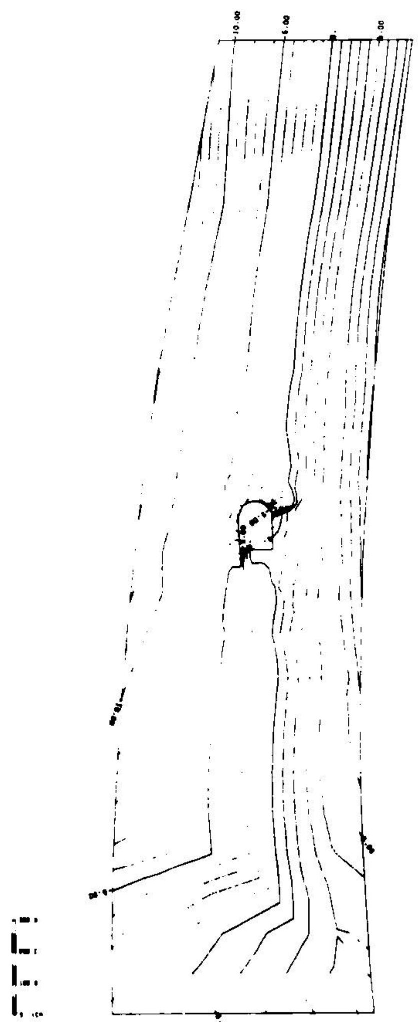

Fig. 11 - Contour-lines of the third principal stress in the cross section shown in fig. 5. Lignes de niveau de la troisième contrainte principale dans la section transversale montrée en fig. 5. Niveaulinien der dritten Hauptspannung im in Abb. 5 dargestellten Querschnitt.

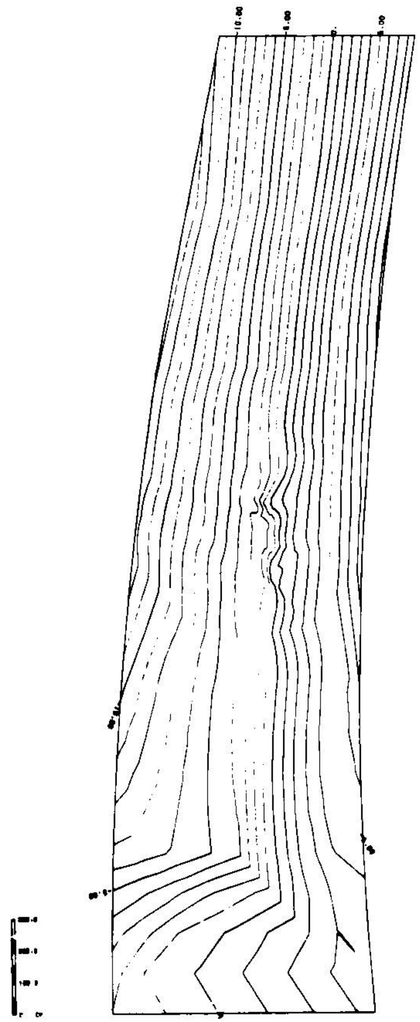

Fig. 12 - Contour-lines of the third principal stress in the cross section shown in fig. 6 . Lignes de niveau de la troisième contrainte principale dans la section transversale montrée en fig. 6. Niveaulinien der dritten Hauptspannung im in Abb. 6 dargestellten Querschnitt.

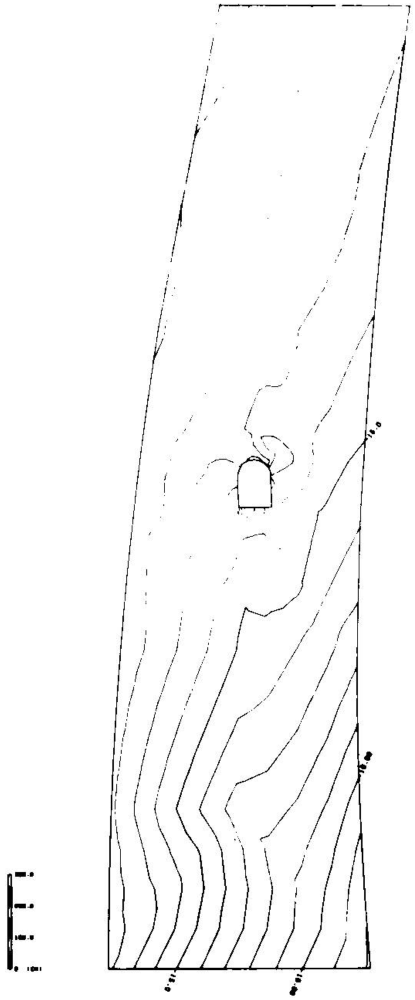

Fig. 13 - Contour-lines of the maximum shear stress in the cross section shown in fig. 5. Lignes de niveau de la contrainte maximale de cisaillement dans la section transversale montrée en fig. 5. Niveaulinien der maximalen Scherspannung im in Abb. 5 dargestellten Querschnitt.

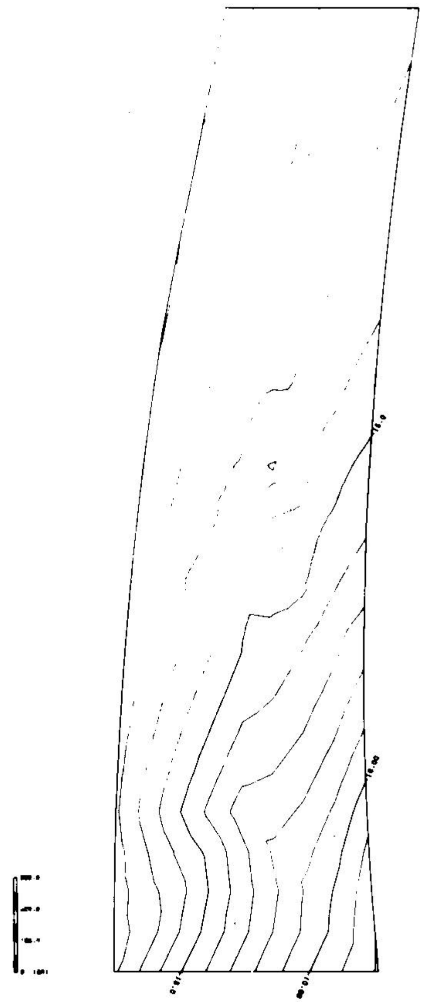

Fig. 14 - Contour-lines of the maximum shear stress in the cross section shown in fig. 6. Lignes de niveau de la contrainte maximale de cisaillement dans la section transversale montrée en fig. 6. Niveaulinien der maximalen Scherspannung im in Abb. 6 dargestellten Querschnitt.

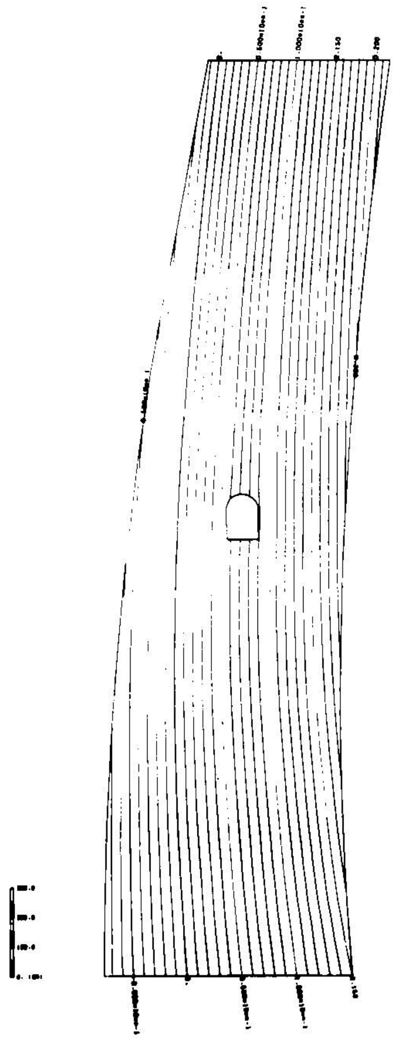

Fig. 15 - Contour-lines of the normal component of the displacement in the cross section shown in fig. 5. Lignes de niveau de la composante normale du déplacement dans la section montrée en fig. 5. Niveaulinien der Verschiebungen-Normalkomponente im in Abb. 5 dargestellten Querschnitt.

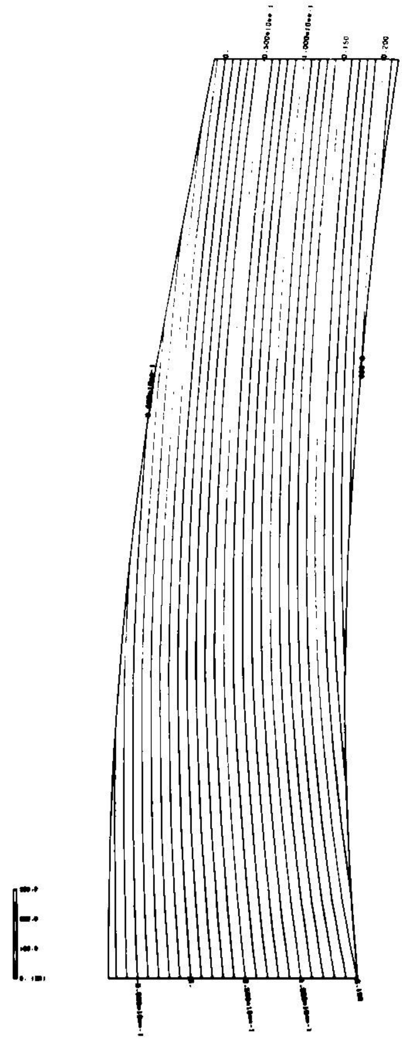

Fig. 16 - Contour-lines of the normal component of the displacement in the cross section shown in fig. 6. Lignes de niveau de la composante normale du déplacement dans la section montrée en fig. 6. Niveaulinien der Verschiebungen-Normalkomponente im in Abb. 6 dargestellten Querschnitt.

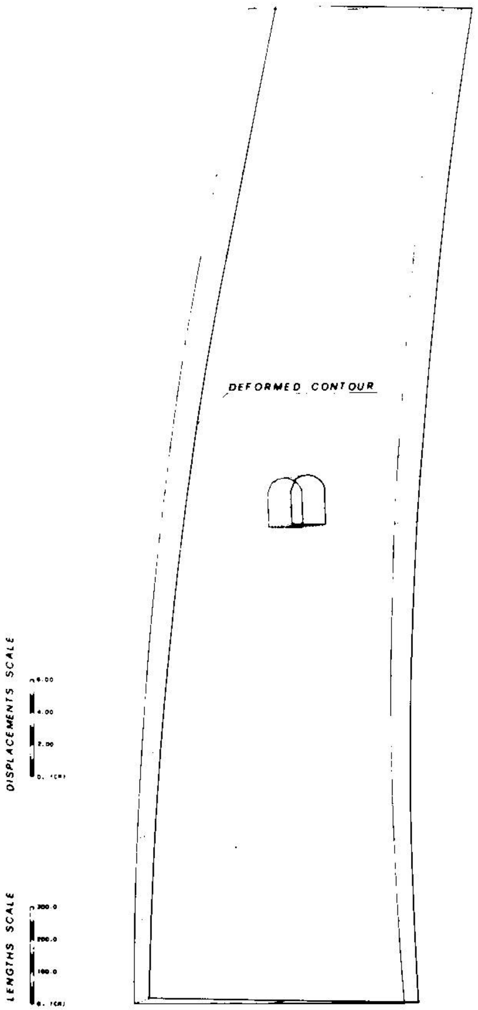

Fig. 17 - Deformed contour of the cross section shown in fig. 5.
Contour deformé de la section transversale montrée en fig. 5.
Verformter Umriss des in Abb. 5 dargestellten Querschnittes.

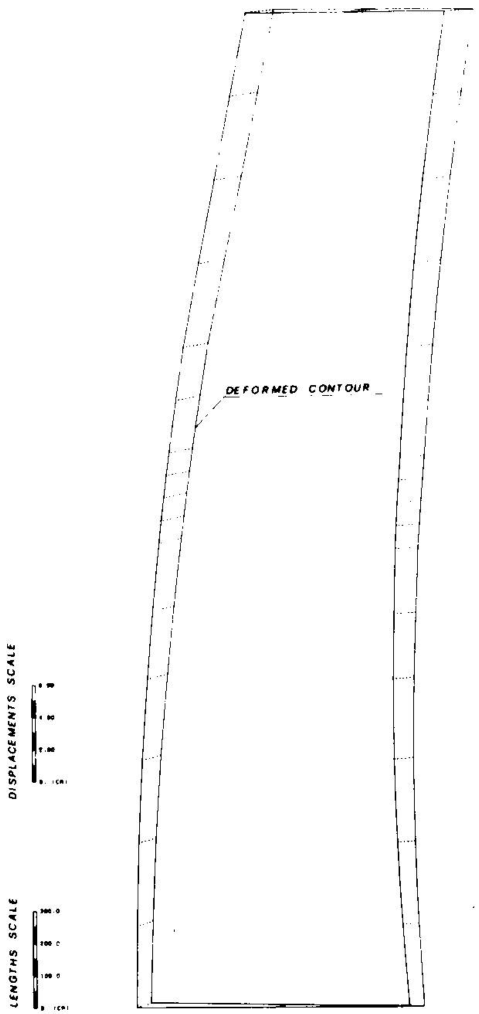

Fig. 18 - Deformed contour of the cross section shown in fig. 6.
Contour deformé de la section transversale montrée en fig. 6.
Verformter Umriss des in Abb. 6 dargestellten Querschnittes.

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