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Use of Computers for the Static Analysis of a Containment

L'utilisation des ordinateurs pour le calcul statique d'une enceinte de réacteur

Die Anwendung von Computern bei den statischen Berechnungen für einen Sicherheitsbehälter

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Summary

The paper renders a survey of the history of the static analyses of a concrete reactor containment and deals with the relation between computer calculations and conventional "by hand" calculations. The paper describes the considerations which were made for the choice of programmes and for the modelling of the structures. It ends with some conclusions gained from the project.

Résumé

Le rapport donne l' histoire du calcul statique d' une enceinte de réacteur en béton. Il traite le rapport entre des calculs sur ordinateur et des calculs conventionnels "à la main". Le rapport décrit les considérations faites pour le choix de programmes et pour le modèle de dimensionnement. Il finit par quelques conclusions tirées du projet.

Zusammenfassung

Dieser Bericht gibt eine Übersicht über die statischen Berechnungen für einen Sicherheitsbehälter und zeigt im besonderen das Verhältnis von Computerberechnungen zu konventionellen betreffs Wahl des Programms und der Berechnungsmodelle und abschliessend die bei dem Projekt gemachten Erfahrungen behandelt.

1. SCOPE

The objective of this report is to render a survey of the history of the static analysis of a concrete reactor containment. The paper deals with the relation between computer calculations and conventional "by hand" calculations in different stages of the design work and concludes with some conclusions gained form the projects.

2. BRIEF DESCRIPTION OF THE CONTAINMENTS

The nuclear power plants of TVO I and TVO II are situated at Olkiluoto on the west coast of Finland approximately 200 kilometres from Helsinki. The plants are "twin" stations and are delivered by Asea-Atom, Sweden to the Finnish company TVO. The reactor is a BWR (boiling water reactor) with a rated capacity of 660 MW_e. The reactor is enclosed by the containment, which shall protect the environment from radiation and from leakage of radioactive substances.

The main containment vessel consists mainly of a cylindrical wall of concrete, a base constructed of concrete slabs and walls, a concrete roof slab in conjunction with and stiffened by the pool structures. (The pool structures constitute accommodation for the handling and storing of reactor fuel etc.) A detachable steel lid forms the crest of the containment. The containment is founded on solid bedrock. The cylindrical wall has an inner diameter of 22.0 m, a height of 32.5 m and a thickness of 1.1 m (Figure 1).

The layout of the containment is based on the pressure suppresion (PS) principle, i.e. in case of a major pipe rupture the steam is led from the upper part, dry well, through a number of pipes to the lower part of the containment, wet well, where condensation takes place. Thanks to this principle the volume of the containment can be kept small, about one-fifth of that of a dry containment with the same design pressure. It is assumed that the pressure in the containment can rise in 10 - 20 seconds to 0.37 MPa overpressure and that the temperature in the atmosphere can go up to 175°C (Design Basis Accident, DBA).

3. DESIGN CRITERIA

The tightness of the containment is secured by the embedded steel liner, at least 5 mm thick, of carbon steel which is cast in to a depth of at least 200 mm in the concrete components.

The pressure retaining function of the containment is secured by the concrete structures. The cylindrical wall is prestressed horizontally and vertically. The longitudinal pool walls are prestressed horizontally. The design philosophy implies the following main rules as the basis for the design:

1) For all normal loading conditions, as well as for loads originating from the design basis accident situation, the design shall be carried out in accordance with applicable parts of the Finnish code. Considering allowable stresses and safety factors, the design pressure (0.37 MPa) is regarded as a normal loading condition.

2) The prestressing shall be sufficient so as not to permit any tension stress resultant forces (i.e. membrane tension) in the pressure-retaining prestressed structural parts for maximum accident design pressure loading conditions.

3) For the condition resulting from a 50 per cent exceeding of the design pressure the reinforcement and the prestressing steel shall be within 0.9 times the yield strength.

4.. LOADS AND LOAD COMBINATIONS

The main types of loads are listed as follows:

1) Dead loads from the weight of building parts and components.

2) Dead loads from storaged and transported components, water filling, etc.

3) Prestressing force loads before and after time-dependent losses.

4) Pressure loads (in accident situation).

5) Test pressure loads.

6) Temperature loads (internal forces originating from temperature differences within structural parts) during operating conditions.

7) Temperature loads from accident, test and construction cases.

8) Static and dynamic pipe rupture loads (reaction and jet impingement forces).

9) Water pressure in flooding situations.

10) Pressure oscillations in the suppression pool.

The above listed elementary loading cases can be combined in quite a number of load combinations (approximately 50) which, of course, implies aggravating circumstances for the design analysis.

The TVO containments are not calculated for seismic loads.

5. PRELIMINARY DESIGN CALCULATIONS

The first phase of the design work was carried out when the layout of the plant was decided. The main structural drawings with the concrete dimensions had to be available at an early stage of the project.

During this period of the design work rather extensive calculations were made but no large computer models were used. The different structural elements (slabs, walls, shells) were analysed by "hand" calculations or by minor time-sharing programmes with conservative approximations regarding boundary conditions etc. For each member only the most important load combinations were considered. With this approach we could judge that the concrete dimensions were sufficient to carry the applied loads with respect to bending compression and shear and that the bedrock stresses were within acceptable limits. As mentioned before, this was the main objective of the preliminary design calculations but we could as well define a first-step arrangement of the prestressing tendons. Moreover, we could judge that the necessary reinforcement areas (for membrane tension, bending tension and shear) were in any case reasonable with respect to available spaces within the concrete members. After we had carried out the preliminary design calculations, our remaining design problems could be listed as follows:

1) To calculate concrete shear and bending stresses with greater accuracy so that the calculations could be presented to scrutinizing authorities.

2) To calculate the necessary reinforcement areas in every section. On the one hand a considerable amount of loads had to be taken into consideration, on the other hand an excessive conservatism would result in important cost increases.

3) To check and possibly adjust the distribution of the prestressing forces.

6. FINAL DESIGN CALCULATIONS

6.1 General considerations

In order to solve the remaining design problems according to the preceding chapter, we judged it necessary to make the final design calculations by means of finite element models (FEM). On the one hand we felt that a model comprising the whole containment would be too difficult to survey and too expensive, on the other hand the models had to embrace a considerable number of concrete members if the FEM-calculations were to be more accurate than the preliminary calculations already made. Moreover, different parts of the containment could be approximated with different conditions of symmetry. On the FEM-programme we had the following special requirements:

1) The radial shear forces had to be listed if it were to be possible to calculate the shear reinforcement areas (if shear reinforcement was necessary). Many FEM-programmes cannot fulfil this requirement.

2) The output should be listed in a user-orientated manner so that the FEM-calculated forces and moments could easily be taken for the stress calculations. The format of the output paper should preferably be the same as the format used for the hand calculations as all the calculations of the project had to be copied and distributed to all the partners involved. The requirement on user-orientated printing of the output data was further underlined by the restricted time available for the design work after the FEM-calculations had been carried out.

   On the contrary we could simplify the FEM-models as the models were primarily made for the reinforcement dimensioning. We judged it adequate to approximate all the members as thin elements. The influence of the member thickness was of minor importance and could be neglected. If the members were to be modelled in transversal direction as well, the calculations would be more expensive and it would be difficult to use the output data directly for the dimensioning of the reinforcement.

   Moreover, the static loads were in most cases dimensioning compared to the dynamic loads. The latter ones could in many cases be approximated as static loads. Therefore the main FEM-models were made only for static analysis.

The programme chosen for the analyses was STRIP STEP S developed by the Swedish company Nordisk ADB.

The containment was divided in two FEM-models, one for the base and one for the roof part of the containment.

6.2 FEM-model of the base part of the containment

The model of the base part comprises the bottom and ring slabs together with the cylindrical and radial walls between the slabs, as well as the lower parts of the inner and outer containment walls and the bedrock foundation (Figure 2). The bedrock is simulated by means of a system of vertical walls coupled to each other and to the containment base and given such properties as to simulate "elastic halfspace" of the bedrock below the containment. Due to the symmetries of the structures and of the loads, the model is limited to include only a 22.5°-segment of the base part. Deviations from the symmetry are analysed by manual calculations.

When modelling the structure (collaboration between the design engineer and the computer engineer) the different members were modelled primarily as thin shell elements. At connections between the base part and the cylindrical walls above the base part we thought it suitable to use rigid links.

The FEM-calculations were carried out in two stages. In the first stage the stiffness matrix was decomposed. The decomposed matrix was saved for later needs (if any). At the same time the different types of loads were analysed but no load combinations were made. The structural behaviour was studied and the results were compared with the results of the preliminary design calculations. The results gave no surprises. The conclusions after the preliminary design calculations were still valid.

Having made this scrutiny (including scrutiny of the FEM-model of the roof part of the containment), we found it suitable to make minor adjustments of the prestressing force distribution. The calculations were then made regarding the influence of the load combinations.

For the base part model we could restrict the number of load combinations to 17 but with the addition of manual corrections. The output data with corrections were used for the reinforcement dimensioning of the different structural members including checks of concrete bending and shear stresses. The reinforcement was dimensioned not only for tension and bending but also for the twisting moment and for the tangential shear. The calculations were made "by hand" and were rather time-consuming.

6.3 FEM-model of the roof part of the containment

The model of the roof part of the containment comprises the roof slab, all the pool walls and the bottom slabs of the fuel pools. The upper part of the outer containment wall is included in this model. Due to the (approximate) symmetries of the structures and of the loads the model was limited to include a 90°-segment of the roof part. Deviations from the symmetry were analysed by manual calculations. The model is shown in Figures 3-5. The structure was modelled according to the same principles as for the base part.

The FEM-calculations were carried out in two stages in the same way as for the base part model. For the roof part model the number of load combinations were of the magnitude of 30. The experience gained from the dimensioning of the base part indicated that these calculations would be time-consuming and difficult to survey for the roof part. For these reasons we decided to make the reinforcement dimensioning by means of computers. At that time there was no such programme available in Sweden. After discussions with the computer engineers of Nordisk ADB we engaged them to develop such a programme based upon the output data from the programme STRIP STEP S. The programme also calculates concrete bending compression stresses and concrete shear stresses with the theory of cracked concrete (stage II).

7. CONCLUSIONS

The experience gained from the projects TVO I and TVO II regarding the use of computers for the design of a reactor containment in concrete can be summarized as follows:

1) The FEM-calculations shall be preceded by rather detailed preliminary design calculations. The design engineer ought to be sure that the concrete dimensions are thick enough before the FEM-models are made.

2) The computer calculation of the FEM-models shall be made step by step. The design engineer ought to control the results at least for the most important loads before any load combinations are made.

3) The decomposed stiffness matrix ought to be saved for possible future demand (i.e. additional loads).

4) The dimensioning of the reinforcement and the checks of concrete bending stresses and shear stresses ought to be made by means of computer programmes linked to the FEM-programme.

5) In most FEM-programmes there are routines for checking the geometry (for example by plots). For a containment analysis it is almost just as important to have routines for checking the loads. This was not carried out for the TVO I and TVO II projects.

For containments to be designed later on we have asked the computer engineers to attach summation control of the loads. The coordinates of the load resultant are calculated as well. The design engineer can then make an easy check that the loads have been applied correctly or with only small errors (if there are any).

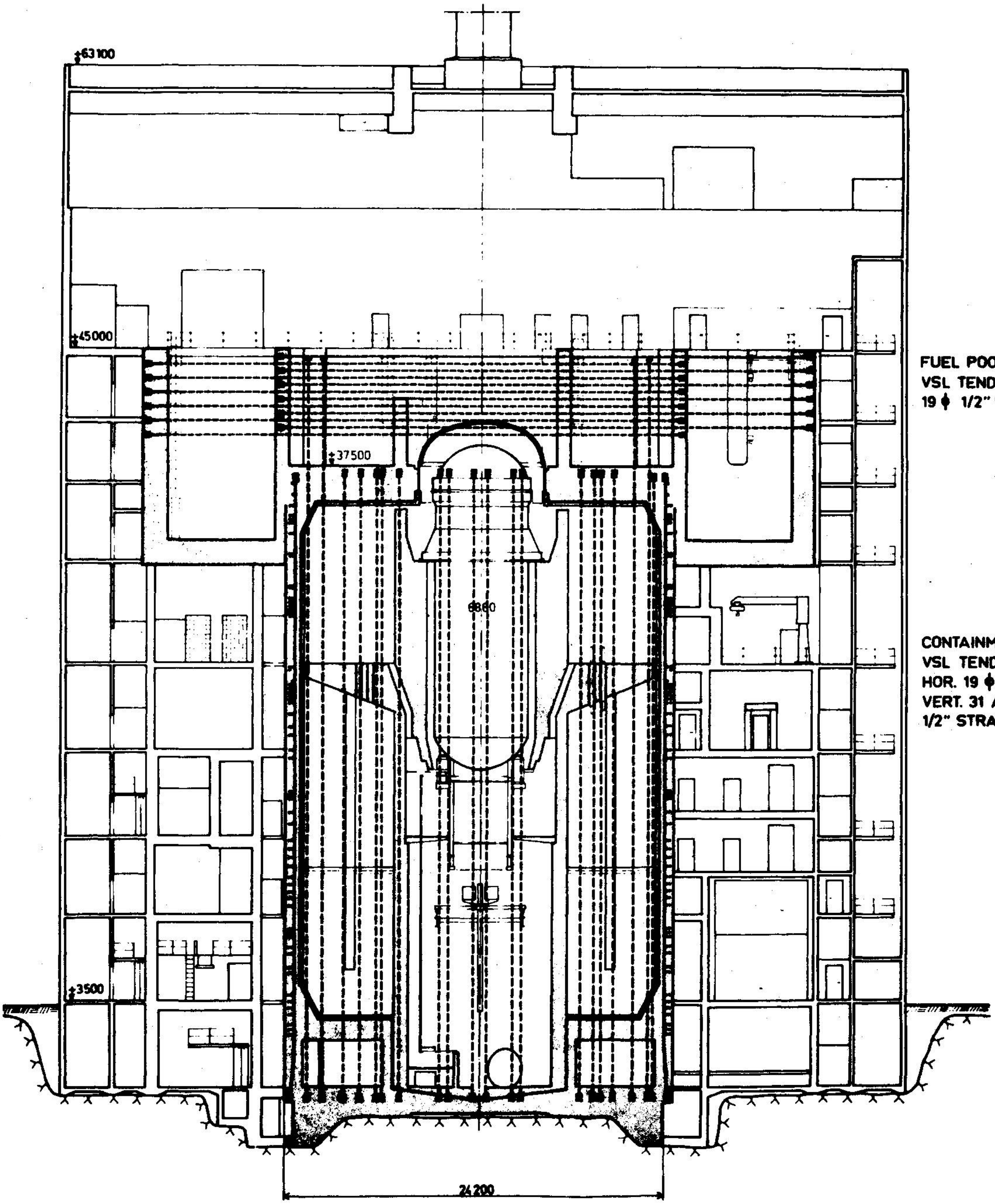
6) Most FEM-programmes print the results loading case after loading case. For calculations with tenths of load combinations, it is convenient to print the results node after node (with all load combinations for one node) as a supplement to the normal output.

7) The computer programme ought to be well known to the computer engineer, who must be competent and allowed to make adjustments and supplements to the programme in order to meet certain demands from the design engineer.

8) The preceding remarks indicate that there must be a close cooperation between the design engineer and the computer engineer. They must talk the same language. For that reason it is suitable if the computer engineer has a structural engineering background (preferably civil engineer). On the other hand, the design engineer must be wholly responsible for the safety of the structure. He must be skilled enough to judge the computer data correctly. If there are any errors in a certain computer programme, he can blame the computer engineers for that, but he cannot get away from the responsibility for the structure.

FIGURE 1

TVO OLKILUOTO NUCLEAR POWER PLANT I
ASEA-ATOM BWR 660 MW$_e$
REACTOR CONTAINMENT PRESTRESSING



FUEL POOLS:
VSL TENDONS
19 ϕ 1/2" STRANDS

CONTAINMENT VESSEL:
VSL TENDONS
HOR. 19 ϕ 1/2" STRANDS
VERT. 31 AND 19 ϕ
1/2" STRANDS

FIG. 2

TVO I

FEM-MODEL OF THE BASE PART OF THE CONTAINMENT

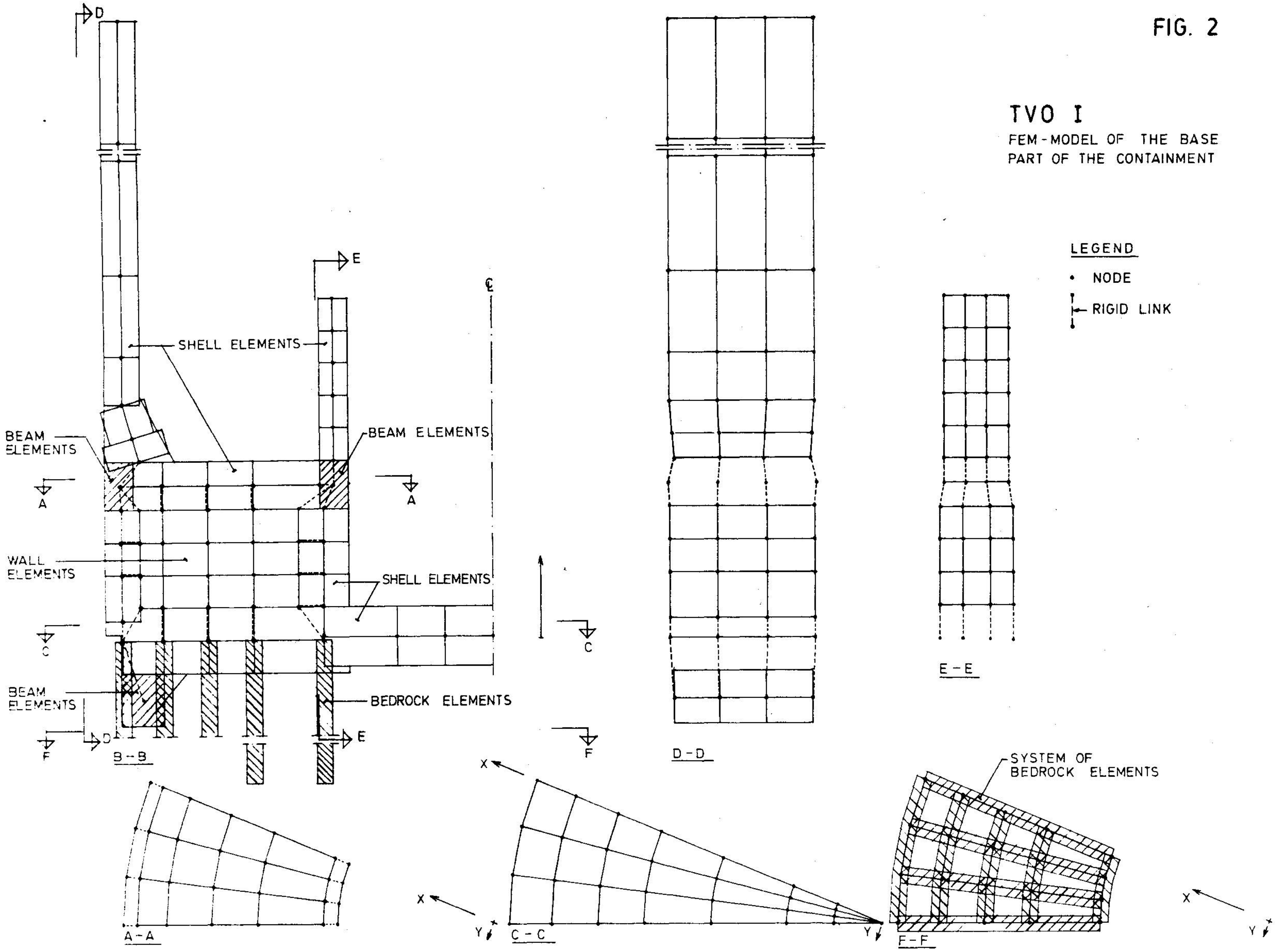


FIG. 3

TVO I

FEM-MODEL OF THE ROOF PART OF THE CONTAINMENT

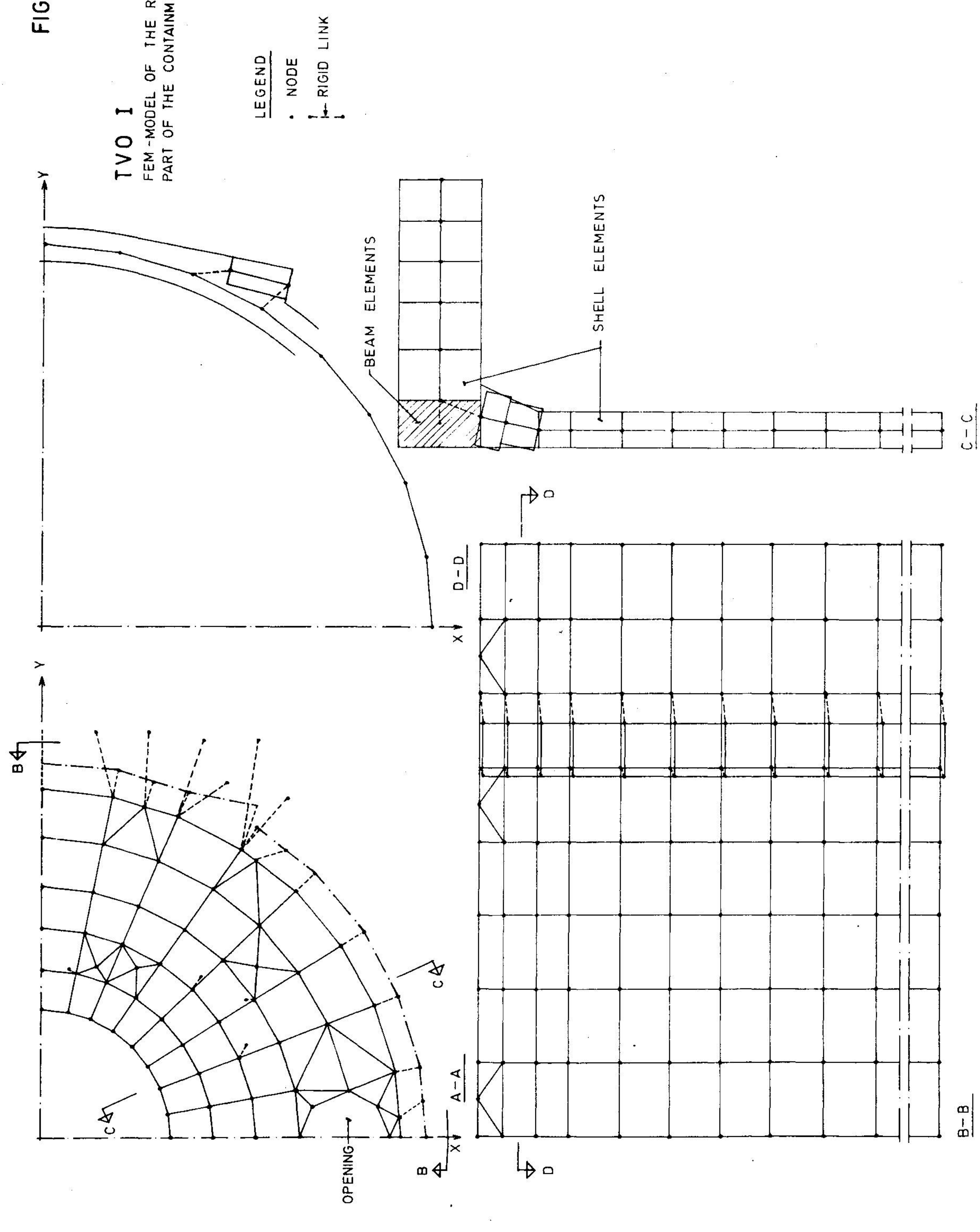


FIG. 4

TVO I

FEM-MODEL OF THE ROOF
PART OF THE CONTAINMENT

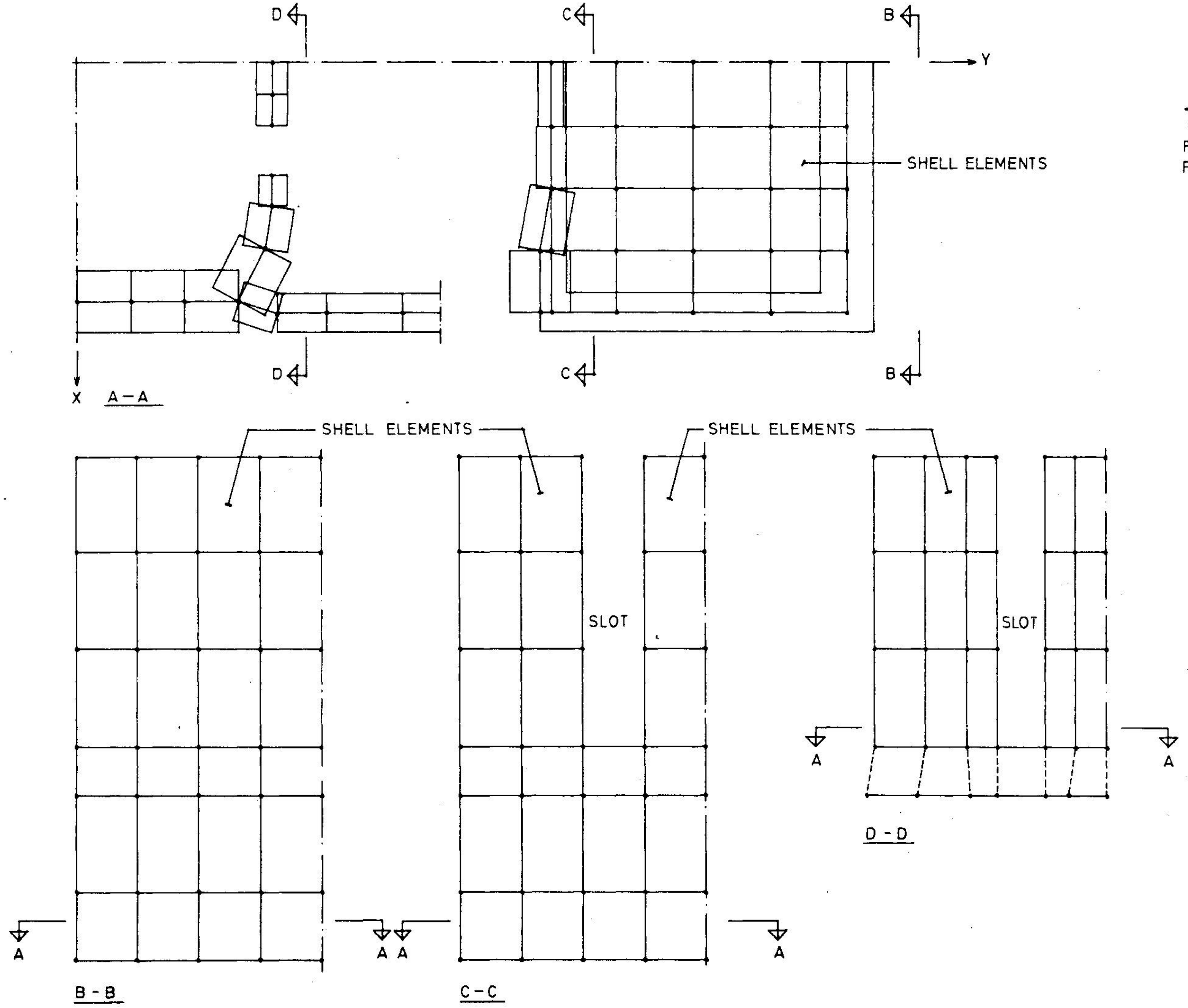
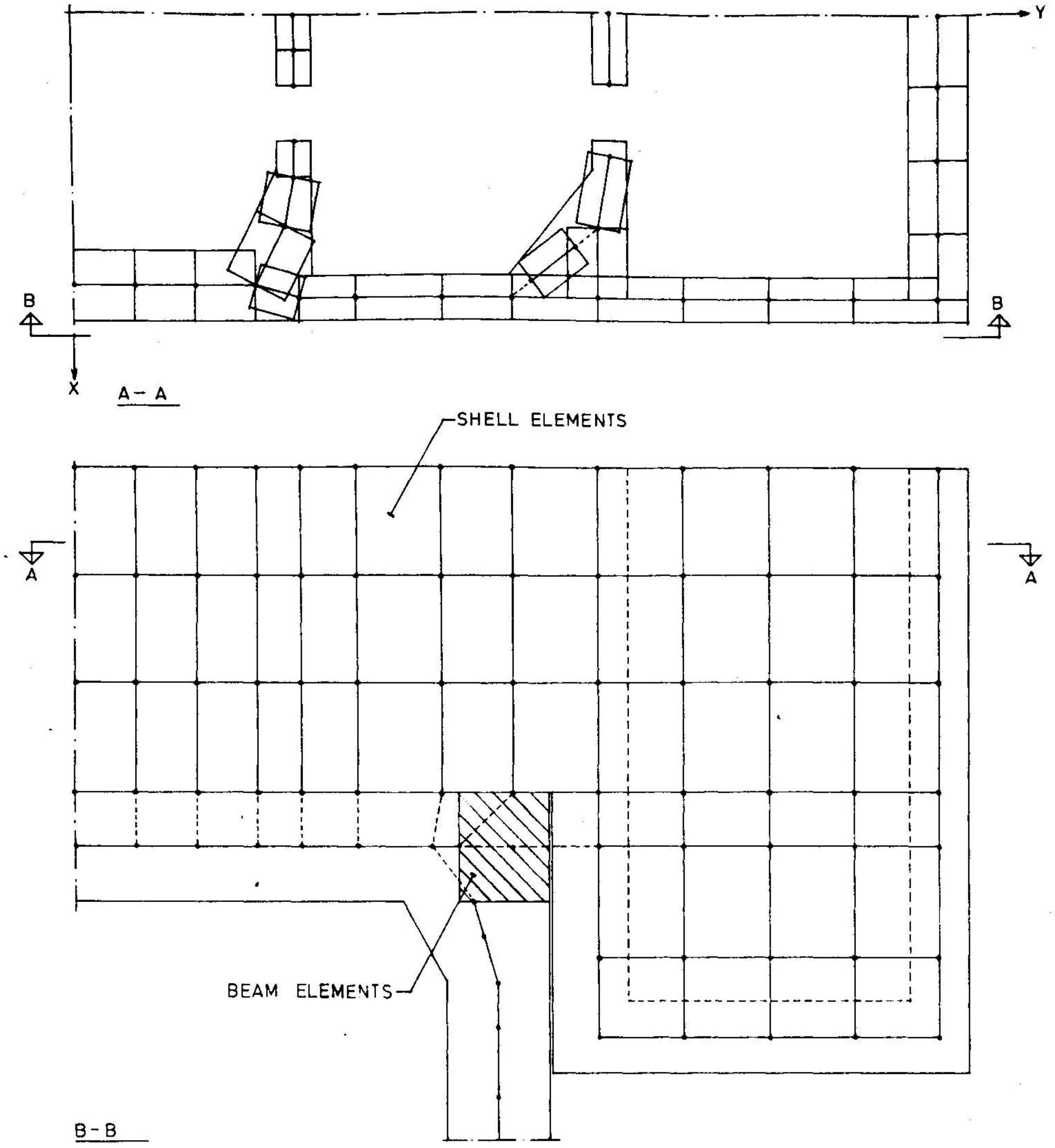


FIG. 5

TVO I

FEM-MODEL OF THE ROOF
PART OF THE CONTAINMENT



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