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STRUCTURAL CAPACITY ASSESSMENT OF WWER-1000 MW REACTOR CONTAINMENT

IAEA Coordinated Research Programme
"Benchmark Study for Seismic Analysis and Testing of WWER-Type Nuclear Power Plants"

PROGRESS REPORT

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BENCHMARK STUDY FOR SEISMIC ANALYSIS AND TESTING OF WWER-TYPE NPPs

IAEA Coordinated Research Programme

STRUCTURAL CAPACITY ASSESSMENT OF WWER-1000 MW REACTOR CONTAINMENT

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PROGRESS REPORT

TITLE OF PROJECT

Structural Capacity Assessment of WWER-1000 MW Reactor Containment

RESEARCH INSTITUTE

EQE-Bulgaria

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1. SCIENTIFIC BACKGROUND AND SCOPE OF THE STUDY

The objective of the project is to provide assessment of the structural behaviour and safety capacity of the WWER-1000 MW Reactor Building Containment at Kozloduy NPP under critical combination of loads according to the current international requirements. The analysis is focused on a realistic assessment of the Containment taking into account the non-linear shell behaviour of the pre-stressed reinforced concrete structure. Previous assessments of the status of pre-stressing cables pointed out that the efficiency of the Containment as a final defence barrier for internal and external events depends on their reliability. Due to this, the experimental data obtained from embedded sensors (gauges) at pre-stressed shell structure is to be compared with the results from analytical investigations. The reliability of the WWER-1000 MW accident prevention system is under evaluation in the project.

The Soviet standard design WWER-1000 MW type units installed in Kozloduy NPP were originally designed for a Safe Shutdown Earthquake (SSE) with a peak groud acceleration (PGA) of 0.1g. The new site seismicity studies revealed that the seismic hazard for the site significantly exceeds the originally estimated and a Review Level Earthquake (RLE) anchored to PGA=0.20g was proposed for re-assessment of the structures and equipment at Kozloduy NPP [1].

The scope of the study is a re-assessment of the Containment structure under critical combination of loads according to the current safety and reliability requirements, including comparison between the Russian design requirements and the international regulations. Additionally, an investigation of the pre-stressing technology and the annual control of the cables' pre-stressing of the Containment is to be made. The crane influence on the dynamic behaviour of the Containment will be done as well as a study of the integrity of the Containment as a final defence barrier.

2. DESCRIPTION OF THE STUDY AND THE EXPERIMENTAL METHODS USED

To fulfil the scope of the study EQE-Bulgaria undertook the following activities:

- Finite element modeling of the WWER-1000 MW Reactor Containment of Kozloduy NPP;
- Static and dynamic analyses including soil-structure interaction assessment;
- Strength and failure mode analyses of the Reactor Containment including reliability assessment of cable pre-stressing technology.

These activities are aimed at efficient analyses of its structural behaviour and integrity of the Containment as well as at assessment of the reliability of the cables pre-stressing. The analyses will give a deeper insight of the Reactor Containment safety.

2.1 Description of the Containment Structure

The Containment structure of the Reactor Building is made of a pre-stressed concrete shell with a steel liner. The post tension cables (tendons) are anchored in a stiff ring girder at the junction of the cylinder shell with the spherical dome. The wall thickness is variable for the different zones of the cylinder and the dome. The heavy polar crane is located close to the upper part of the shell. The general cross-section and layout of the WWER-1000 MW Reactor Building are shown in Figures 2.1 and 2.2 , respectively.

2.2 Development of the Containment Structure 3-D Models

Two finite element models have been developed to study the structural behaviour of the Containment:

- A preliminary 3-D shell model of the Containment using SAP90 program for linear analyses;
- A detailed 3-D coupled model of the Reactor Building using COSMOS/M program for non-linear analyses.

The first one was used for preliminary static loads analyses of the Containment for an assessment of the loading conditions effects on the structure integrity. The second one is a detailed finite element coupled shell and stick model of the Reactor Building. It is used for studying of linear and non-linear static and dynamic responses of the Containment to the loads due to normal operation, additional loads due to the anticipated operational occurrences and some additional loads due to accident conditions. The intention is to assess the bearing capacity of the structure, as well as failure modes in critical loading combinations, and hence, to assess the vulnerability of the Containment.

2.3 Static and Dynamic Analyses Including the Soil-Structure Interaction

The static and dynamic analyses should result in finding the margins of the Containment behaviour, including its preserving capabilities as a final defence barrier of the environment according to the current requirements and regulations. The evaluation of the pre-stressing of the Containment has to be made by investigating the pre-stressing technology, as well as the on-line scanning of the pre-stressing using embedded sensors and annual verification of cables pre-stressing of the unit. Comparison of this evaluations with the finite element model analyses results will help to tune the model and assess the reliability of the non-destructive control and monitoring system of the Containment.

The seismic response analyses will be based on both response spectrum method and time history response analyses. The seismic response analyses will include the soil-structure interaction effects, obtained by the substructure method incorporated in the CLASSI chain of computer programs [2].

The combination of the loading conditions will follow the recommendations of the corresponding codes and guidelines.

2.4 Strength and Failure Mode Analyses of the Reactor Containment

The capacity check of the Containment shell will be done in accordance with the current concrete design codes. Pre-stressed reinforced concrete Containment structures have large seismic margins above the SSE level because they have been designed for a combined SSE and loss of coolant accident. Shear, flexural and bond failure modes have been postulated and analysed in previous studies. The breakage of one pre-stressing cable is not critical for the Confinement. This study will concentrate on concrete cracks development and flexural failure modes analyses. The calculation of the fragility curves will be done if necessary.

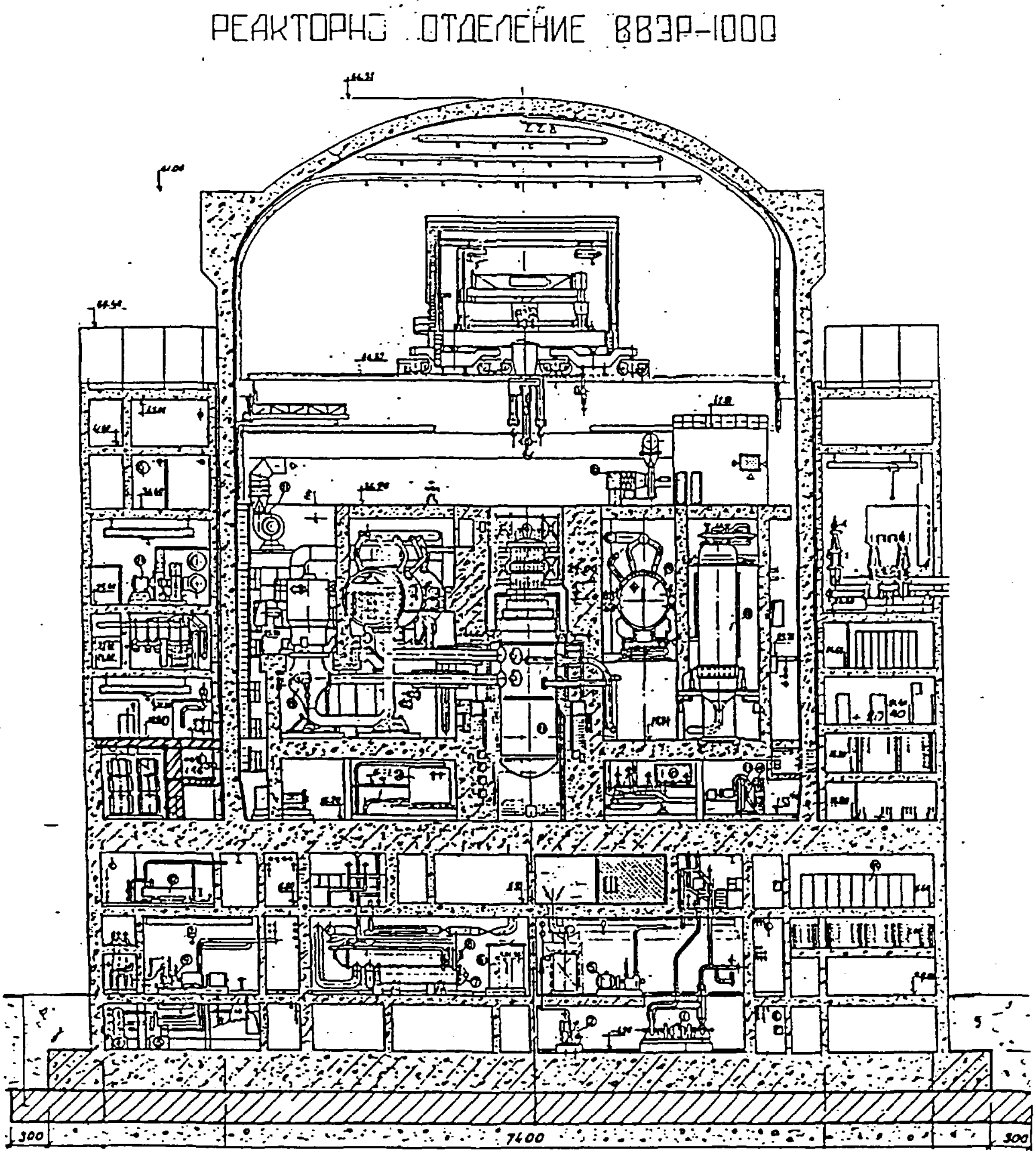


Figure 2.1 WWER-1000 MW Reactor Building Cross Section

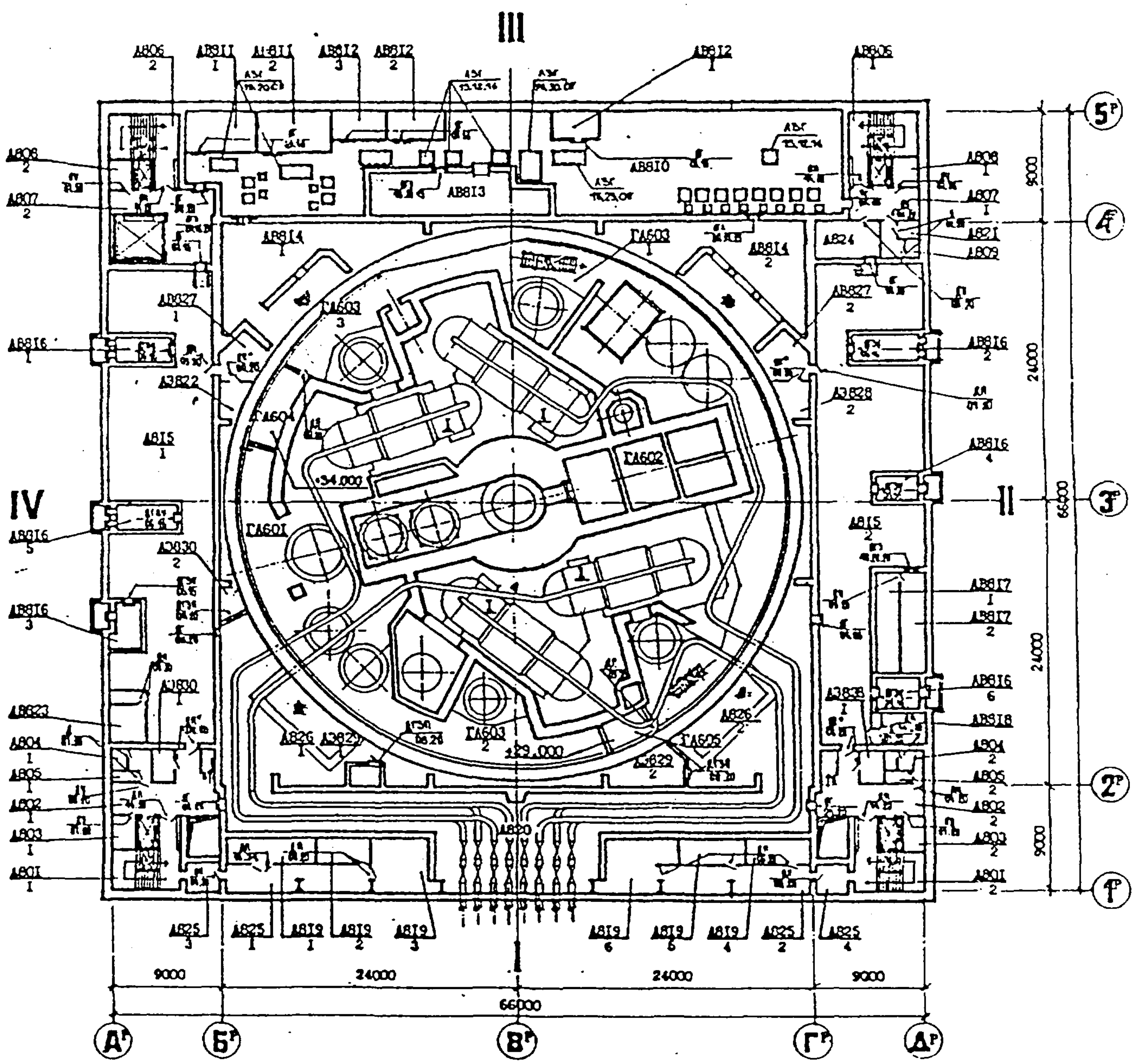


Figure 2.2 Plan View of WWER-1000 MW Reactor Building

3. WORK CARRIED OUT

3.1 Data Collection

The following information has been collected for the modeling and the analyses of the Containment:

- Detailed drawings of the Containment structure;
- Embedded gauges records for a long time period;
- Data from the annual checks of the cables pre-stressing.

3.2 General Assumptions

The following assumptions were accepted for the preliminary linear response analysis study:

The Containment is a separate structure, lying on the thick plate at Elevation +13.20m, and it has independent dynamic behaviour for seismic loading.

For other loading conditions (dead load, temperature, pre-stressing, etc.) the study of the Containment as a separate structure is accurate enough.

The seismic analysis is based on the floor response spectrum technique, obtained from previous investigations of EQE-Bulgaria [3]. The floor response spectra at Elevation+13.20m are used for seismic response analysis of the Containment.

The soil-structure interaction effects are taken into account in the input floor response spectra.

3.3 Containment Modeling and Analyses

The following activities were carried out in the preliminary study:

A detail 3-D model of the Containment structure was developed using SAP90 program. A general view of the model is shown in Figure 3.1. Due to the axial symmetry of the structure and loading conditions, and symmetry of the seismic loading about vertical plane, only half of the

Containment is modeled. The model is composed of 4-node shell elements with 6 DOF per node. The elements have both membrane and bending characteristics. The model consists of 784 shell elements and 813 nodes. The appropriate boundary conditions (restraints) were applied on the nodes of symmetry plane. The horizontal thick plate at Elevation +13.20m is modeled by means of appropriate elastic springs. The modulus of elasticity of the pre-stressed reinforced concrete is assumed to be E=30000 MPa and Poisson's coefficient is ν=0.2.

The loading conditions considered in the study are: dead load, pre-stressing, break of the pre-stressing cable, and LOCA. The LOCA is modeled by means of internal pressure with intensity of 46 kN/m^2. The forces in hoop and longitudinal directions due to the LOCA pressure are shown in Figures 3.2 and 3.3. The pre-stressing of the Containment is modeled by equivalent uniform pressure, varying in value in different locations, on the middle surface of the shell model. However, the pre-stressing forces of the cables can not cover the design requirements. The recommended value of 10000 kN pre-stressing force can not be reached during the annual pre-stressing checks. The mean values of the pre-stressing forces vary from 8500 kN to 9000 kN. A new system of pre-stressing cables is under development for changing of the existing cables. A cable break during service period or during annual cables checks is considered as anticipated loading occurrence. This event may cause a shock impact on the Containment structure. A static loading by a cable break has been considered in the preliminary study. The forces in hoop and longitudinal directions due to the cable break are shown in Figure 3.4 and Figure 3.5.

The eigen values and mode shapes extraction analysis is carried out for the 3-D shell model of the Containment. The first 20 natural modes are obtained and few of them are shown in Figures 3.6 to 3.9. Mode shape frequencies and mass participation coefficients are presented in Table 3.1.

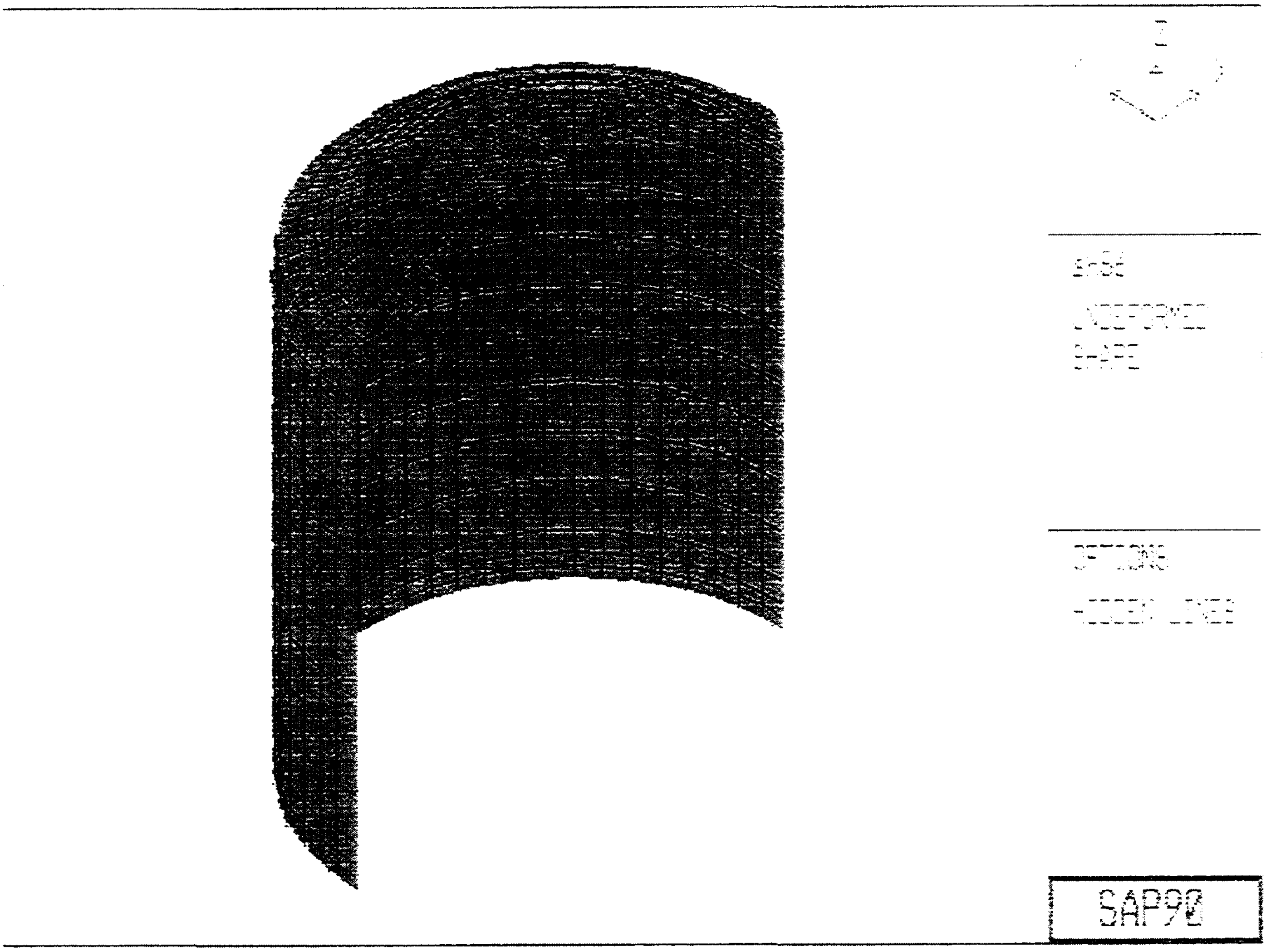


Figure 3.1 3-D Shell Model of the Containment Structure

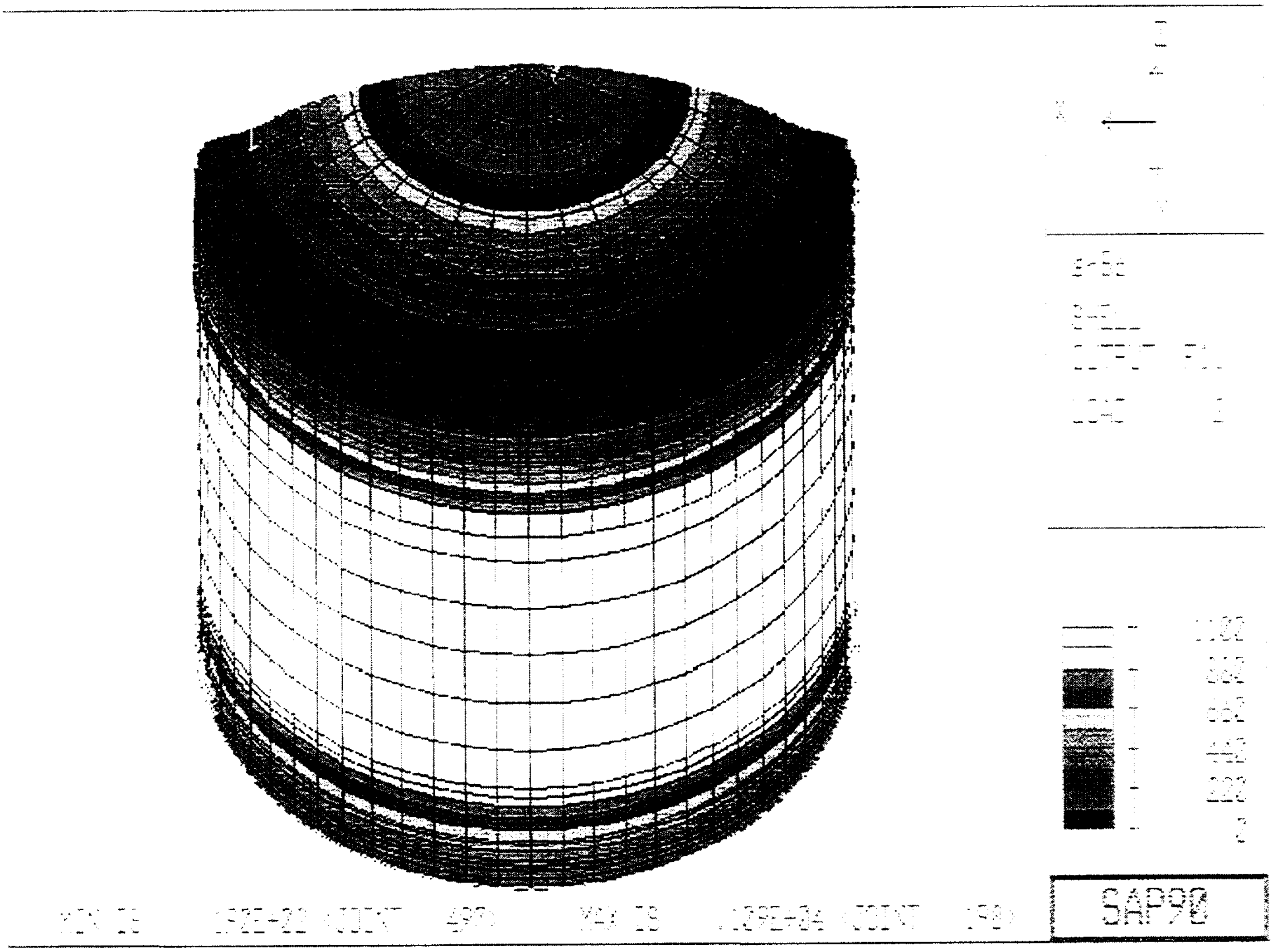


Figure 3.2 Hoop Forces Diagram at the Containment Shell Due to LOCA

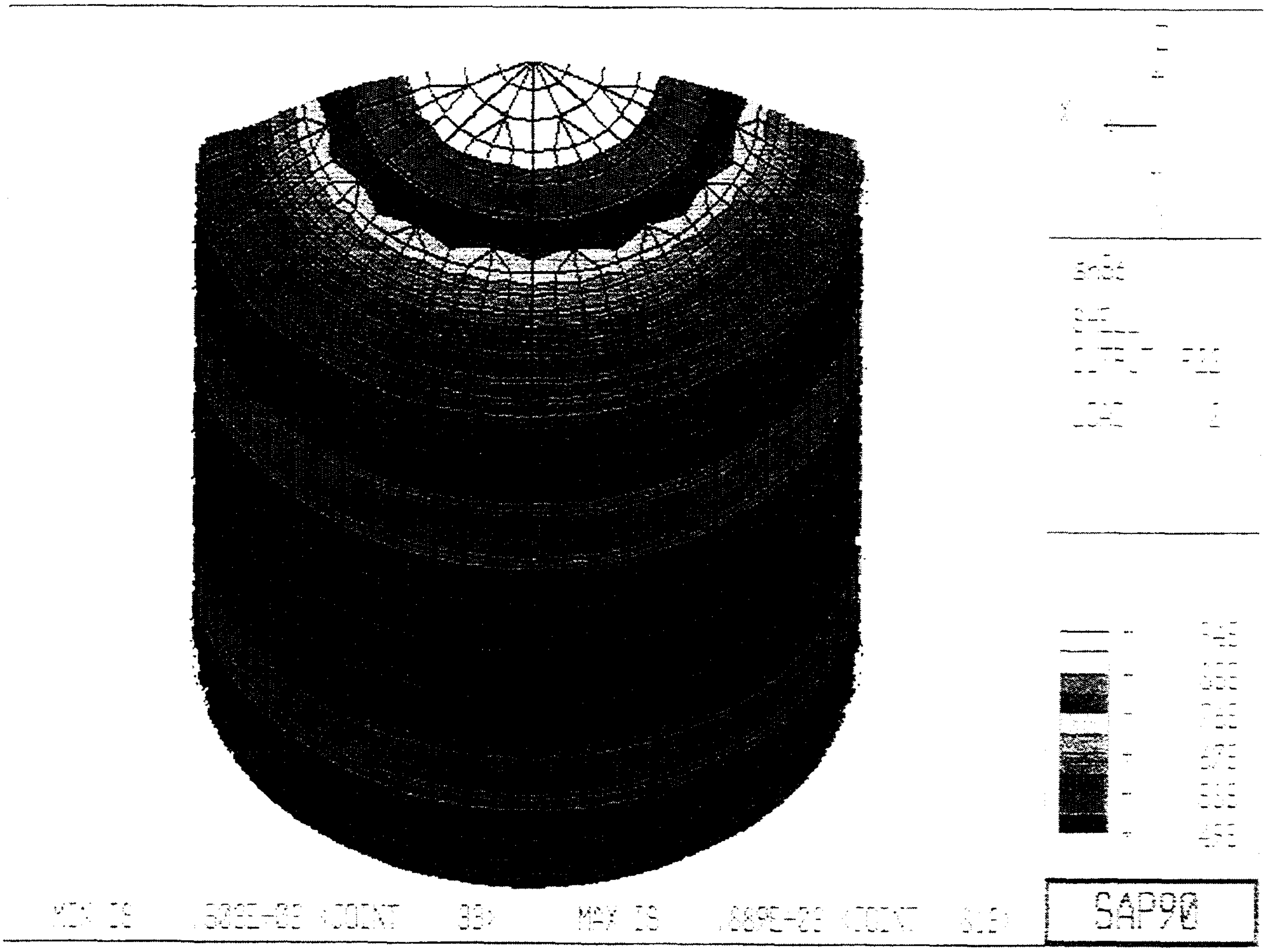


Figure 3.3 Longitudinal Forces Diagram at the Containment Shell Due to LOCA

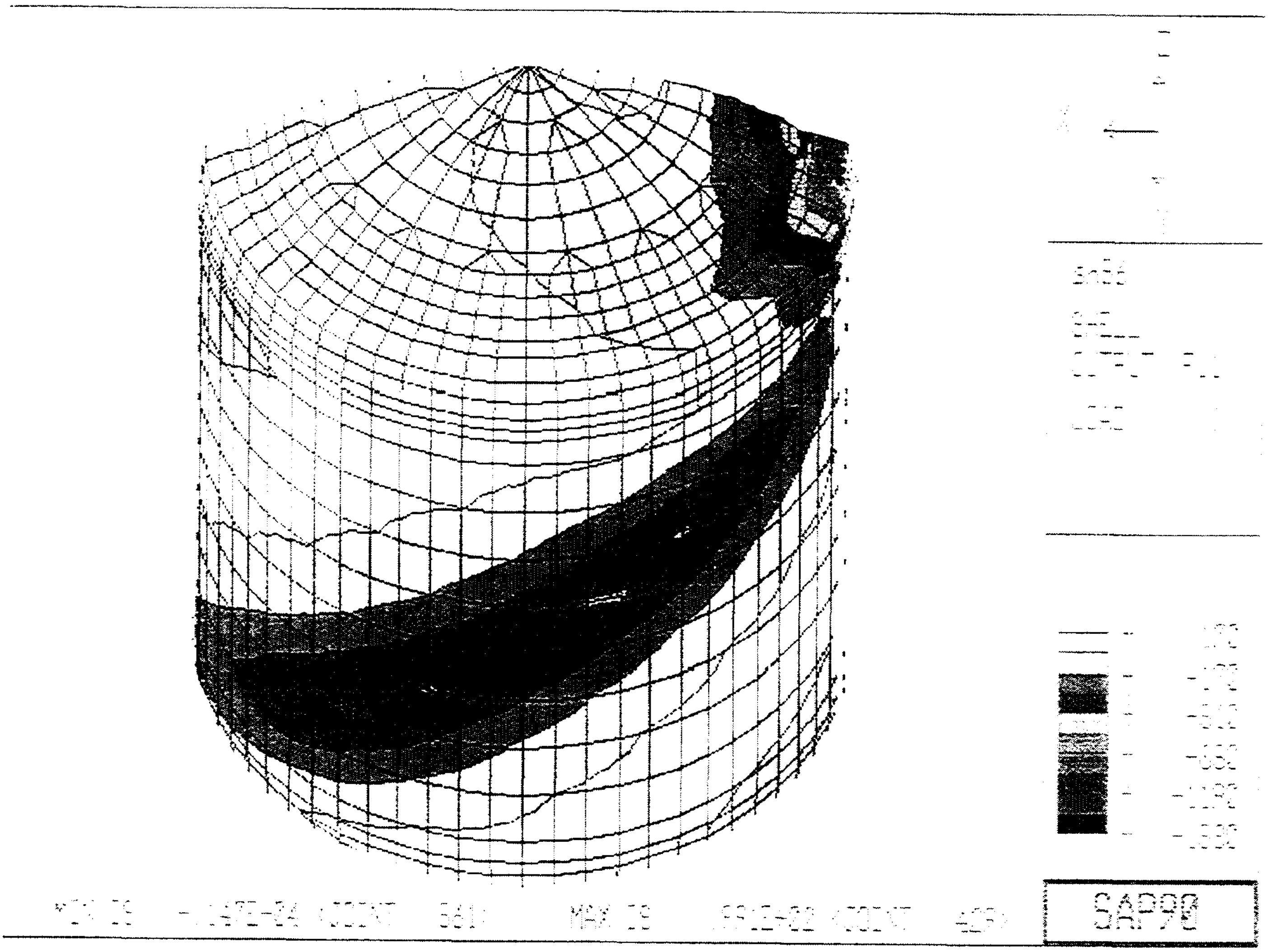


Figure 3.4 Hoop Forces Diagram at the Containment Shell Due to Pre-stressing Cable Break

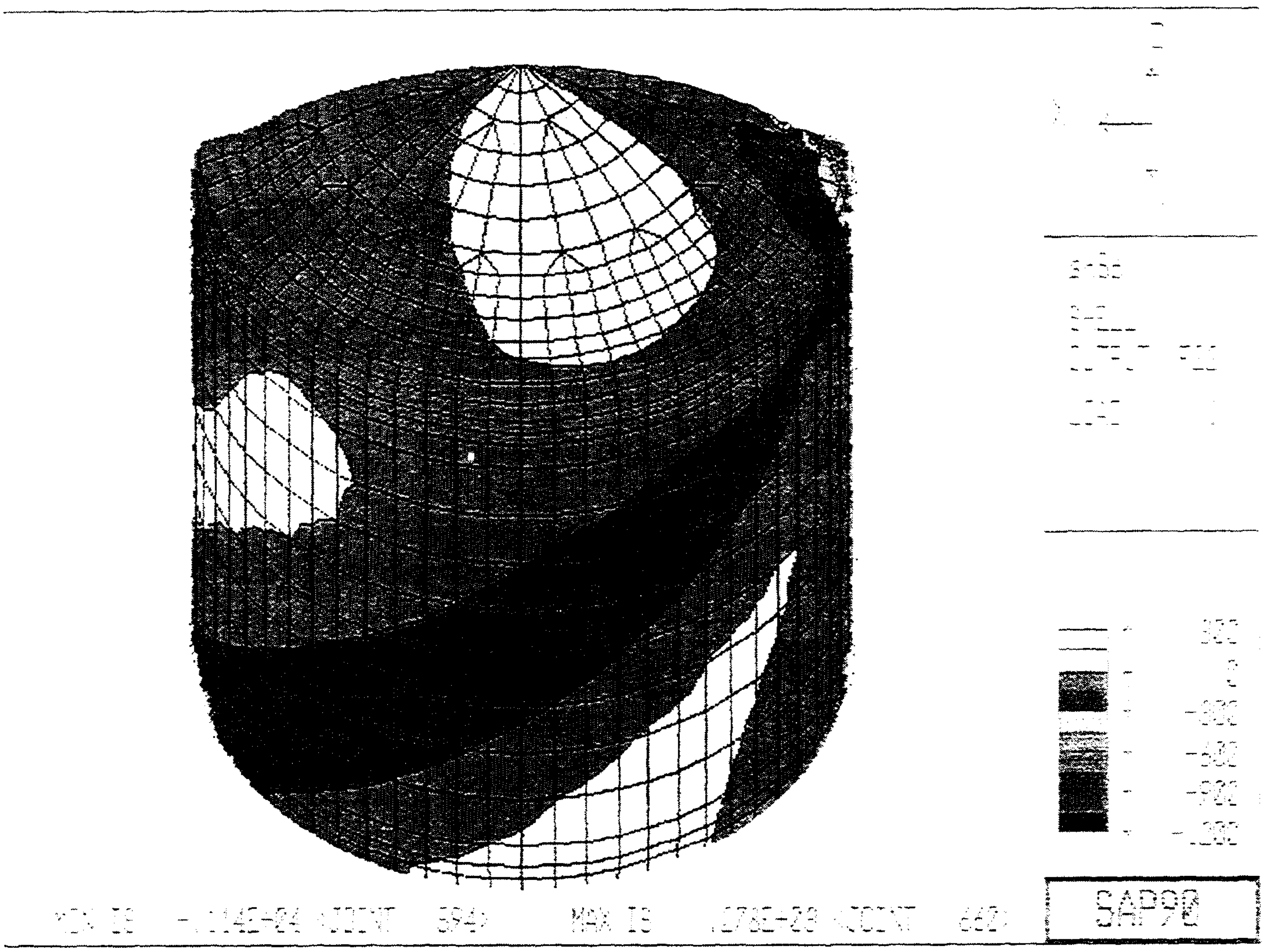


Figure 3.5 Longitudinal Forces Diagram at the Containment Due to Pre-stressing Cable Break

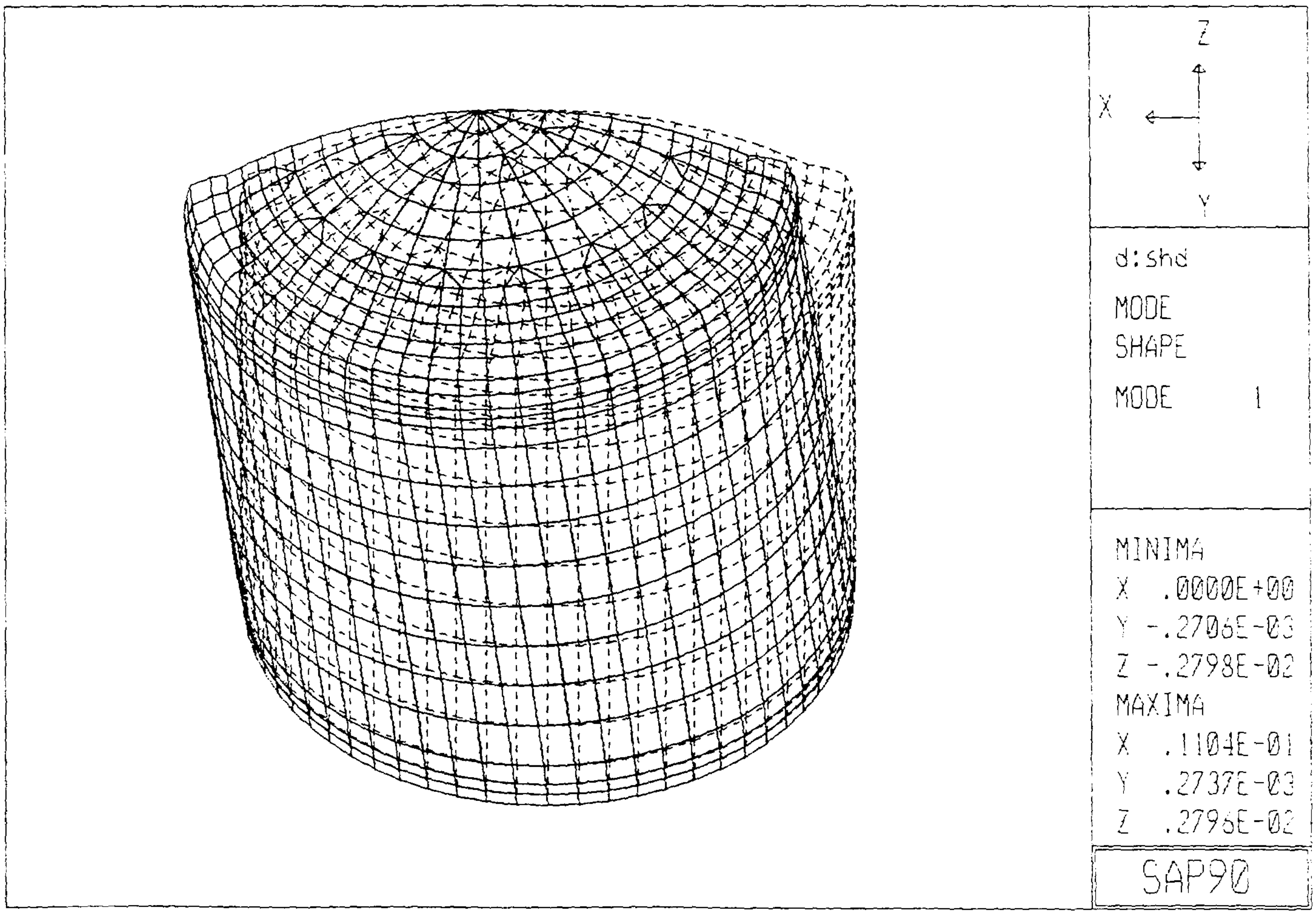


Figure 3.6 Mode Shape 1, F1=4.59 Hz

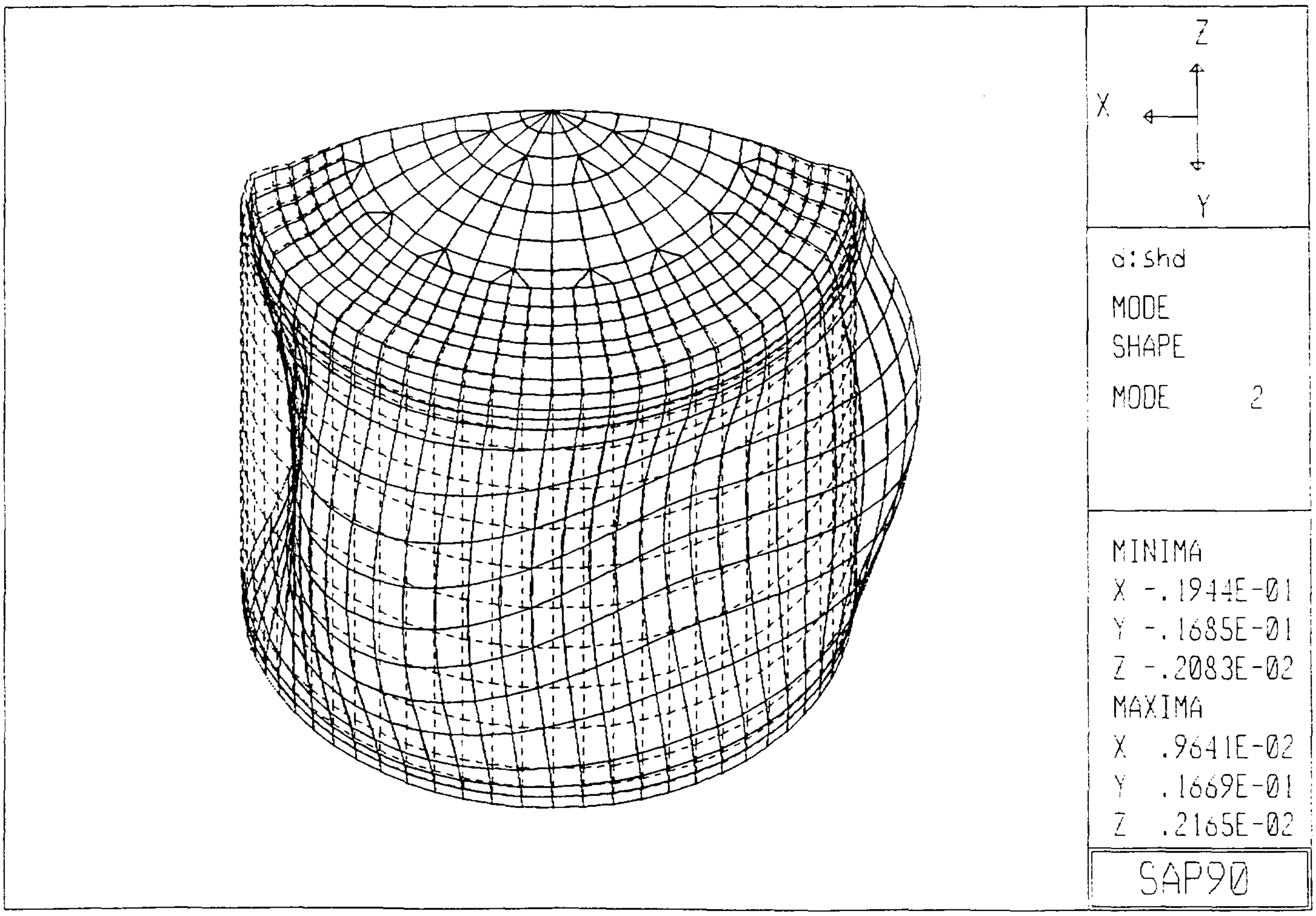


Figure 3.7 Mode Shape 2, F2=7.73 Hz

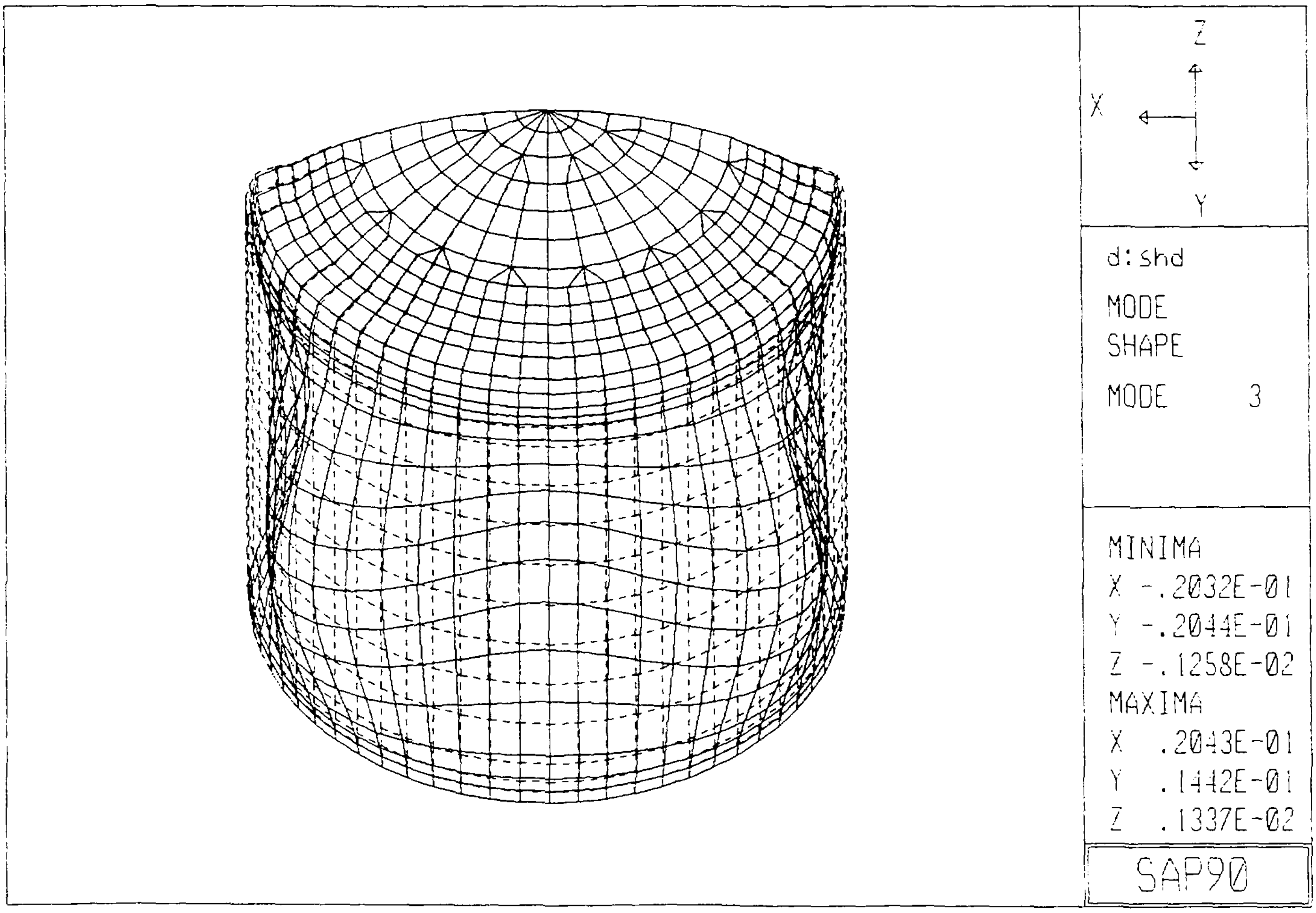


Figure 3.8 Mode Shape 3, F3=8.55 Hz

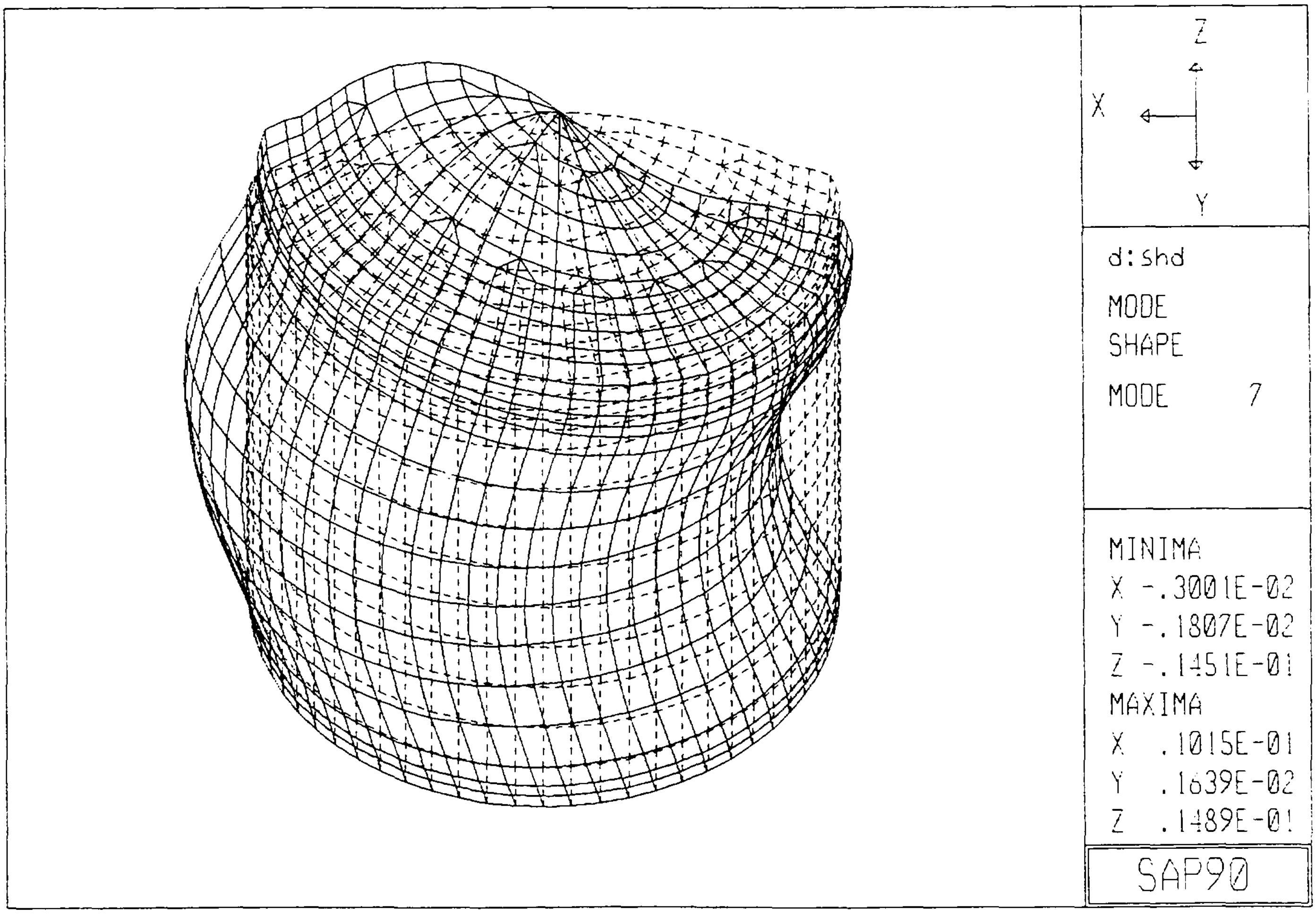


Figure 3.9 Mode Shape 7, F7=14.29 Hz

TABLE 3.1 Natural Frequencies and Mass Participation Coefficients

E I G E N V A L U E S   A N D   F R E Q U E N C I E S

MODE NUMBER	FREQUENCY (CYCLES/SEC)	PERIOD (SEC)
1	4.585902	.218060
2	7.725597	.129440
3	8.545570	.117020
4	9.170468	.109046
5	11.172483	.089506
6	11.506520	.086907
7	14.294334	.069958
8	15.044120	.066471
9	15.333074	.065218
10	15.778994	.063375
11	16.006338	.062475
12	16.769103	.059633
13	16.925143	.059084
14	17.299805	.057804
15	19.686235	.050797
16	19.787643	.050537
17	19.854797	.050366
18	20.325288	.049200
19	21.076812	.047446
20	21.706561	.046069

P A R T I C I P A T I N G   M A S S - (percent)

MODE	X-DIR	Y-DIR	Z-DIR	X-SUM	Y-SUM	Z-SUM
1	76.765	.000	.000	76.765	.000	.000
2	.000	.001	.001	76.765	.001	.001
3	.000	.656	.002	76.765	.656	.003
4	.000	18.330	.001	76.765	18.987	.003
5	.001	.000	.000	76.765	18.987	.003
6	.001	1.226	69.127	76.766	20.213	69.131
7	10.995	.003	.015	87.762	20.216	69.146
8	.000	.161	.002	87.762	20.377	69.148
9	.000	.001	.002	87.762	20.378	69.150
10	.007	.001	.000	87.769	20.379	69.150
11	.000	.715	7.334	87.770	21.093	76.484
12	.015	.001	.000	87.784	21.094	76.484
13	2.427	.001	.005	90.211	21.095	76.488
14	.001	2.059	.001	90.212	23.154	76.489
15	.438	.002	.001	90.650	23.156	76.491
16	.000	.012	.002	90.650	23.169	76.492
17	.033	.002	.003	90.683	23.171	76.495
18	.001	1.792	.002	90.685	24.963	76.497
19	.000	.810	5.523	90.685	25.773	82.020
20	.005	4.517	.027	90.690	30.289	82.047

3.4 Experimental Data

An evaluation of the Containment pre-stressing has been made by investigation of the pre-stressing technology and by on-line scanning of the pre-stressing, using embedded sensors and annual verification of the pre-stressing during unit operation by the control of tendon stresses. The design value of the cable force should be 10000 kN. According to the Soviet documents [4], [5] a maximum decrease of 15% of this value is allowed. The pre-stressing forces are re-evaluated each 2-3 years. A monitoring system operates on-line using embedded gauges for prevention of unexpected occurrences. The reliability of this system is under discussion. The appropriate way to tune the gauges data is to compare the Containment stresses obtained from them with those calculated analytically using annual cables checks data, read directly from the monitoring system. The stresses in the concrete due to cables pre-stressing and from the preliminary results of the analytical study are given in Figures 3.10 to Figure 3.13.

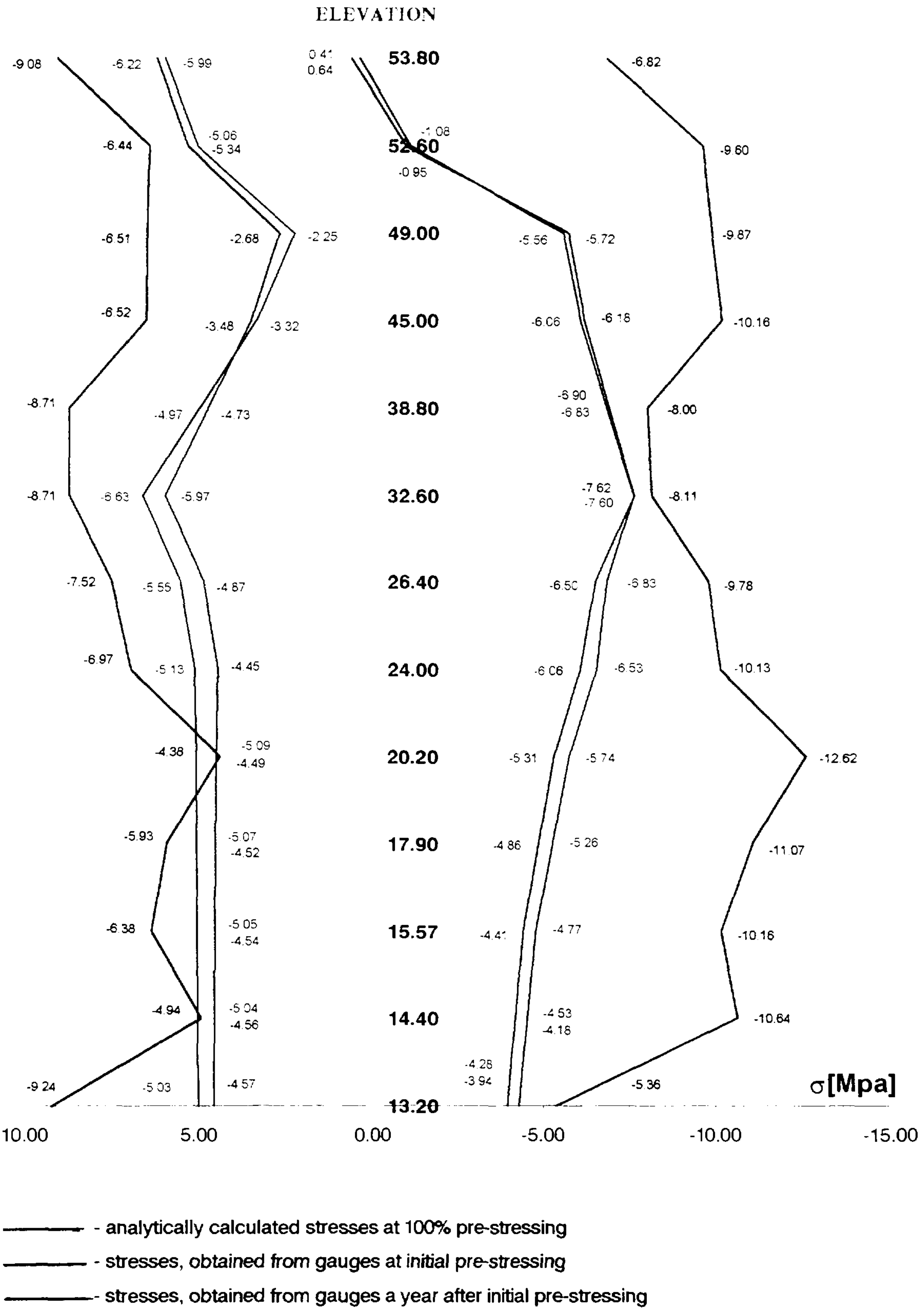
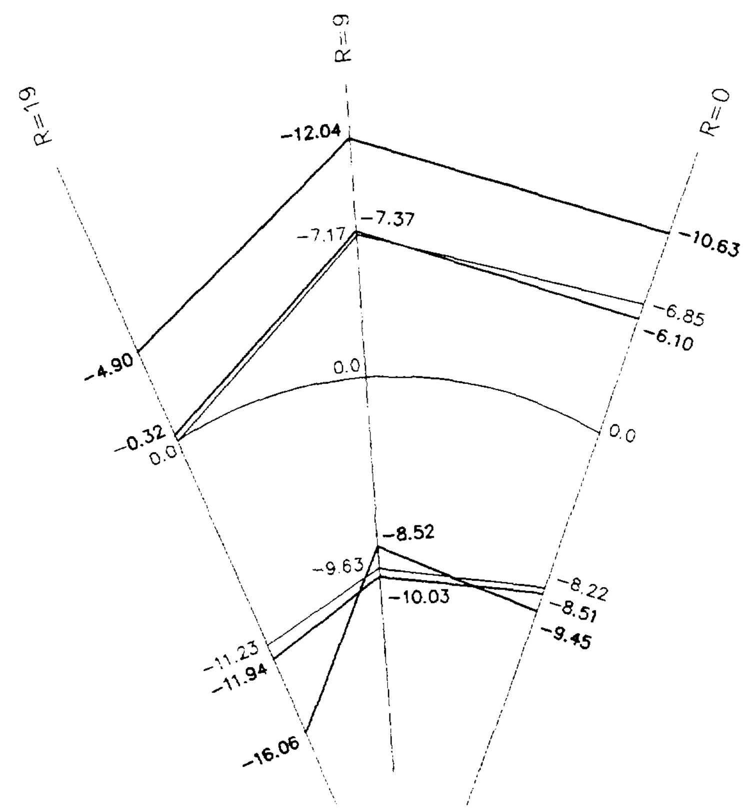


Figure 3.10 Longitudinal Stresses Diagrams in the Concrete of the Cylindrical Shell at Inner and Outer Surface Due to the Pre-stressing



- analytically calculated stresses at 100% pre-stressing
- stresses, obtained from gauges at initial pre-stressing
- stresses, obtained from gauges a year after initial pre-stressing

Figure 3.11 Longitudinal Stresses Diagrams in the Concrete of the Spherical Dome at Inner and Outer Surface Due to the Pre-stressing

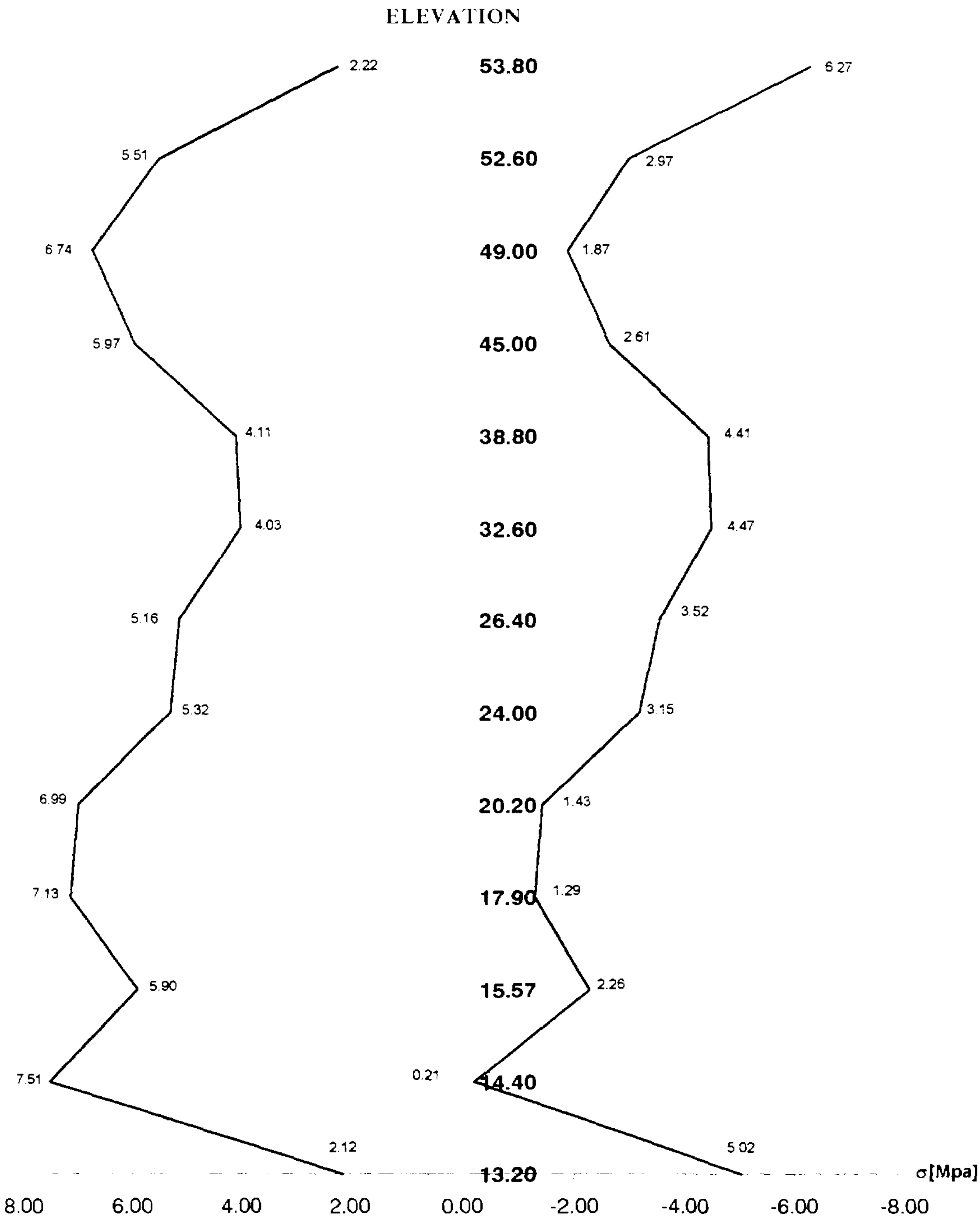


Figure 3.12 Longitudinal Stresses Diagrams in the Concrete of the Cylindrical Shell at Inner and Outer Surface Due to the LOCA

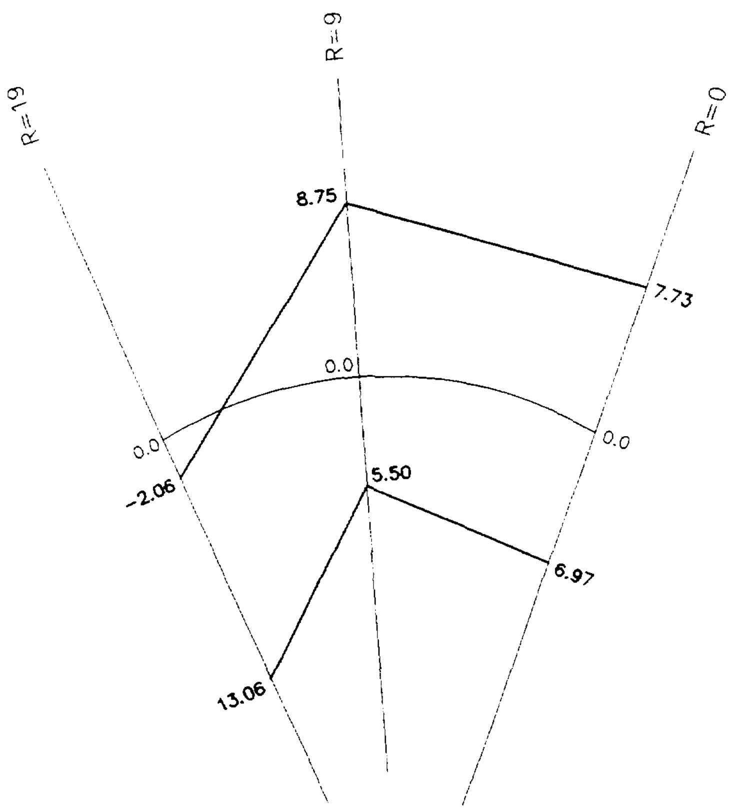


Figure 3.13 Longitudinal Stresses Diagrams in the Concrete of the Spherical Dome at Inner and Outer Surface Due to the LOCA

4. WORK PLAN

A new detailed 3-D model of the Reactor Building is under development with the COSMOS/M program. The available 3-D stick model of the WWER-1000 MW unit from a previous Benchmark study of EQE-Bulgaria [3] and the shell model of the Containment from the preliminary study with the SAP90 program are used. The new 3-D model is necessary for non-linear analysis of the Containment.

The model is composed of a 3-D shell model for the Containment and equivalent stick models for the Substructure, Internal Structure and Outer Building Structure of the Reactor Building. The Containment model is created by 8-node shell elements with 6 DOF per node. The elements have both membrane and bending capabilities. Isotropic elements with constant thickness are utilized. They are arranged on the middle surfaces of the cylindrical shell and the spherical dome, inclined on the first one and orthogonal on the second one, following the pre-stressing cables arrangement on both surfaces. The Containment model is constrained at the upper thick mat of the Substructure. Material nonlinearity is considered. The characteristic curves are approximate by bilinear curves. The non-linear behaviour of the model is controlled by displacements.

The polar crane is modeled using a simplified equivalent beam model. It is aimed at assessing of the crane influence on the important parameters of the dynamic behaviour of the Containment. The crane model also helps to determine various loadings, which the crane imposes on the Containment under different loading conditions. One of the additional loadings is due to the non-symmetry of the crane path caused by the Containment deformation resulting from unequal pre-stressing of the cables.

The detailed model will be studied for normal operation loads (dead loads, pre-stressing, crane loads, snow, live loads), additional loads from the anticipated operational occurrences (internal pressure and temperature due to design bases accident, asymmetrically prestressing of the structure, sunshine influence), and additional loads due to accident conditions (loss of coolant accident, impact of pre-stressing tendon break). A fixed-base linear-elastic modal extraction analysis will be performed to determine the eigenvalues and eigenvectors of the combined model. The model will be analysed for seismic loading using available envelop response spectra for the Foundation Reference Point (FRP) or corresponding time histories for different soil conditions. The time histories at FRP have been obtained by SSI analysis of the Reactor Building for the site specific seismic input motion. The envelop response spectra have been generated by enveloping and broadening of FRP response spectra for three different soil conditions: median estimate, lower and upper boundaries. The combination of loading conditions according to the current requirements and a bearing capacity assessment of the Containment will be made. Finally, the assessment of the critical points of the Containment and the possible failure modes under critical conditions will be done.

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