ULTIMATE ANALYSIS OF IGNALINA NPP REINFORCED CONCRETE CONTAINMENT SUBJECTED TO INTERNAL PRESSURE

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ABSTRACT

Numerical analysis are carried out using the NEPTUNE finite element program to predict the ultimate pressure capacity and the failure mode of the RBMK-1500 reinforced containment at Ignalina Nuclear Power Plant. NEPTUNE is a three-dimensional finite element program developed to simulate the response of reactor components in three-dimensional space to design basis and beyond-design-basis loads. It uses reinforced concrete element for analysis of reinforced concrete structures. Material nonlinearity such as concrete tension and compression, yielding of reinforcing steel are simulated with appropriate constitutive models. Calculations for concrete rupture are performed in all the layers of the elements. The results of the analysis for the determination of the Accident Localization System (ALS) failure start with the leakage mode presented in the analysis. Calculations are performed until the appearance of the first crack, which propagates through the all layers of the concrete wall.

KEYWORDS

Finite elements, nonlinear analysis, concrete cracking, stress

INTRODUCTION

The nuclear reactors of the Ignalina nuclear power plant (NPP) belong to the RBMK class of reactors designed and constructed by the Ministry of Nuclear Power Construction of the former Soviet Union. These reactors do not possess the conventional Western containment structure that could confine the radioactive products of a severe nuclear accident. Instead, the Ignalina NPP has a suppression type containment which, for Soviet built reactors, is referred to as the Accident Localization System (ALS) or sometimes as the Accident Confinement System (ACS). The ALS encloses about 65% of the entire cooling circuit, the most dangerous sections of piping to rupture in case of the so-called Loss-Of-Coolant Accident (LOCA).
The ALS reinforced concrete building of the RBMK-1500 reactors is comprised of two (similar in design) towers adjacent to the reactor unit (Figure 1). The ALS towers are interconnected through a system of the leak-tight compartments designed for steam discharge in case of rupture of the primary coolant circuit. The leak-tight compartment system is divided in to following zones: Zone 1 - the pressure-resistant leak-tight compartments, and Zone 2 - compartments of the reactor fuel channel feeder pipes and group distribution headers.

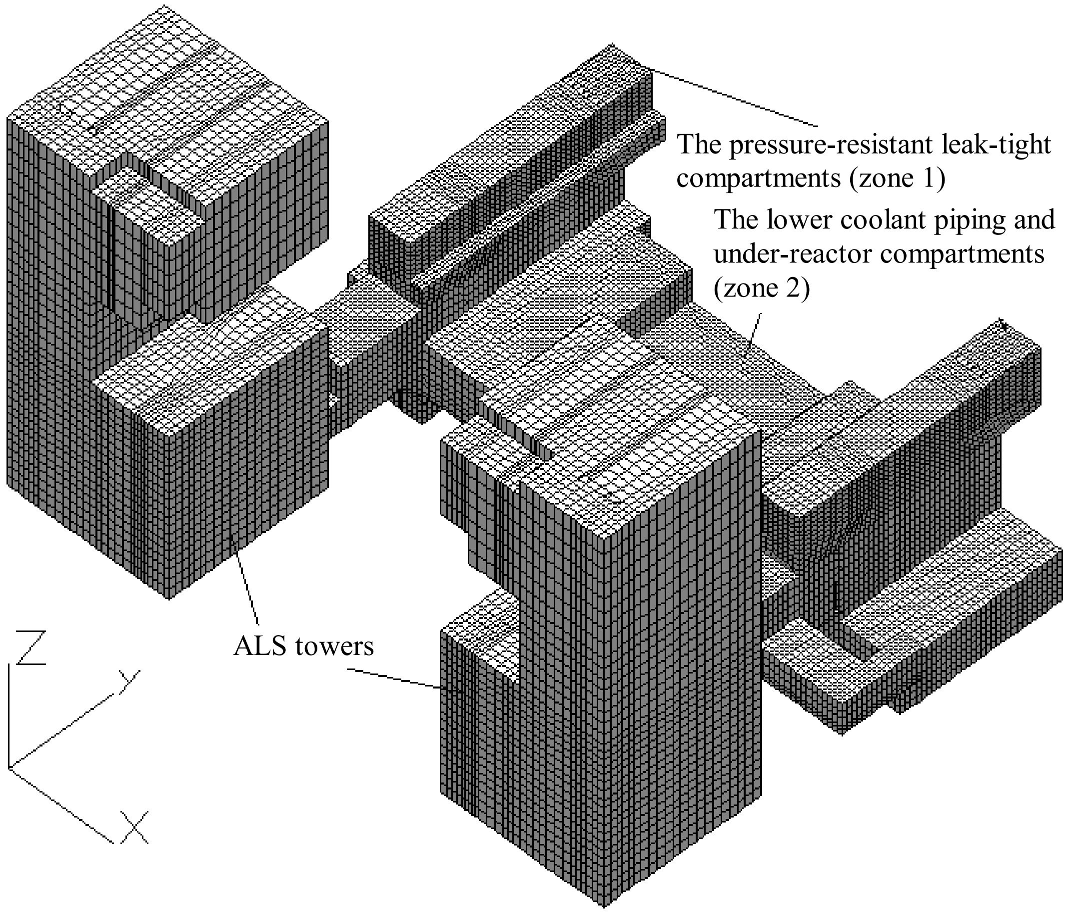

Figure 1: General layout of ALS

In structural integrity analysis of ALS it is important to evaluate strength limit of ALS building structures as well as to establish load at which first through-wall crack appear in the outer wall of ALS. Therefore, it is very important, that available leak-tightness of ALS in case of an accident would not be exceeded and would not release radioactive materials to the atmosphere. In the analysis the standard properties of concrete and rebar steel are applied. The calculations are performed until the appearance of the first crack, which passes through all layers of the concrete wall. The analysis results of the ALS failure (zone 1), when the first through-wall crack appears in the outer wall of ALS, are presented in this paper.

GEOMETRICAL MODEL

Due to symmetry of the ALS (Zone 1) geometry, only one half of the actual building was chosen for the analysis. The basic philosophy creating these models was, at first step, to model separate compartments and then combine the individual models into the entire composite model. This was performed by employing the features of the ALGOR preprocessor [1]. ALGOR/NEPTUNE interface program was created to transform all input variables (nodal coordinates as well as element properties) from ALGOR input to NEPTUNE input [2]. Comparison of ALGOR and NEPTUNE solutions was made [3] for validation.

The geometrical data of compartments (dimensions of the walls and slabs and location of the compartments) were obtained from architectural drawings. The data of reinforced concrete (thickness of walls and slabs, diameters and location of reinforcement bars in the walls and slabs, dimensions and positioning of metallic frames, type of reinforcement bars, concrete and elements of metallic frames) were obtained from reinforced concrete drawings.

The finite element model of the ALS zone 1 is presented in a Figure 2.

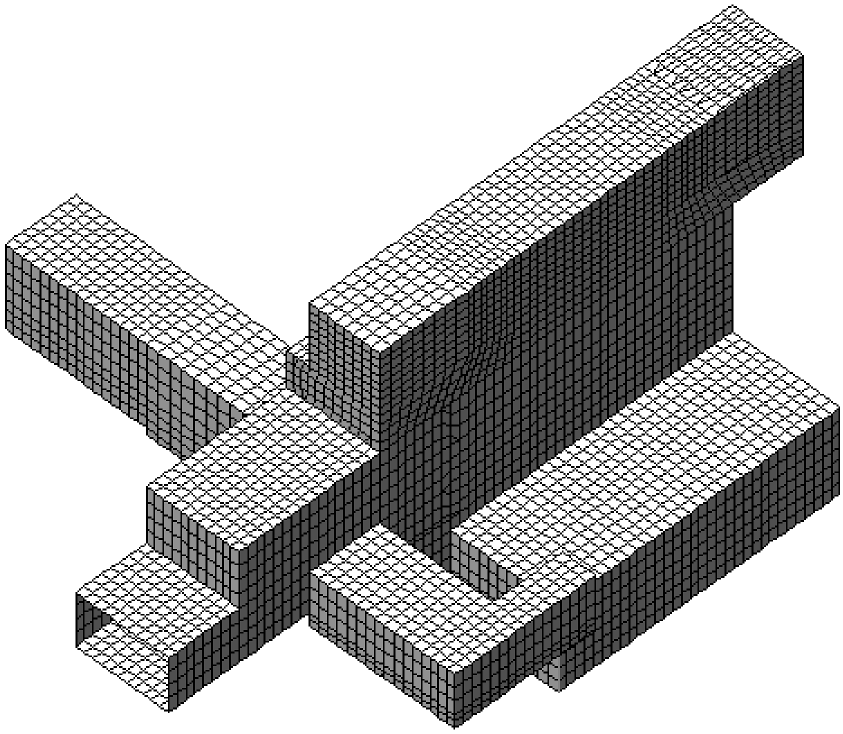

Figure 2: Finite element model of zone 1

MODELLING OF REINFORCED CONCRETE WALLS USING FINITE ELEMENTS

The NEPTUNE code model uses four-node quadrilateral plate element developed by Belytschko (Figure 3) [4]. The formulation of this element is based on the Mindlin theory of plates and uses a velocity strain formulation. Kulak and Fiala further developed the element by incorporating the features to represent concrete and reinforcing steel [5]. Subsequently, additional failure criteria were added and this enabled the modified elements to model concrete cracking, reinforcing bar failure and gross transverse failure.

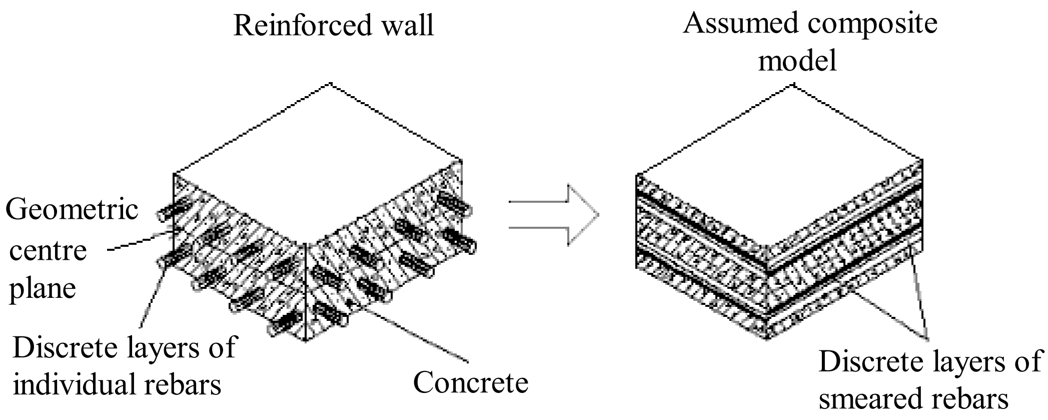

Figure 3: Section through wall/slab and equivalent finite element model with distinct layers of smeared reinforcing bars

The concrete failure model used is the Hsieh-Ting-Chen four–parameter model. The model uses the following four-parameter criterion involving the stress invariants I_1, J_2 and the maximum principal stress σ_1 [5]:

$$f(I_1, J_2, \sigma_1) = a\frac{J_2}{f_c^2} + b\frac{\sqrt{J_2}}{f_c} + c\frac{\sigma_1}{f_c} + d\frac{I_1}{f_c} - 1 = 0 \qquad (1)$$

The four failure parameters (a, b, c, d) are determined so that they represent the following four failure states:

1. Uniaxial compressive strength, f_c;
2. Uniaxial tensile strength, f_t=0.1 f_c;
3. Equal biaxial compressive strength, f_{bc}=1.15 f_c;
4. Combined triaxial compression, f_{pc}=0.8 f_c, f_{cc}=4.2 f_c.

The transverse shear failure of a reinforced concrete slab is considered by an empirical formula [5]:

$$\tau_u = \left(0.05\left(pf_y - \sigma_v\right) + 0.5\right)\sqrt{f_c};\cdots where \cdots 0.5\sqrt{f_c} \le \tau_u \le 4.5\sqrt{f_c} \quad (2)$$

Terms of equation (1) are the following: σ_y is the normal stress, f_y is the yield strength of reinforcement, p is the reinforcement ratio, f_c is the compressive strength of concrete.

BOUNDARY CONDITIONS OF MODEL AND MECHANICAL PROPERTIES OF MATERIALS

The outside surface of the main ALS is shown in Figure 1. When pressurized, the deformation of this structure is resisted by the outside structures, which are not shown in Figure 1. The outside constraints consist of walls and floor-ceiling slabs of the adjacent structure. Most of the outside nodes of the ALS model are common with those of the external constraints. Because the external constraints should be primarily resisting the ALS deformation in the tension-compression mode, their stiffness should be very large. Therefore, for simplicity, the locations of the external nodes, which in fact are connected to adjacent structures, for the first approximation are assumed completely fixed in translation.
The structural integrity analysis of the ALS was performed using standard material properties the concrete and steel properties of which are presented in Table 1 [6, 7].

TABLE 1
MATERIAL PROPERTIES

Material	Type	Young's modulus, MPa	Poisson's ratio	Yield stress, MPa	Compressive stress (concrete)/ Ultimate stress (steel), MPa	Ultimate strain, %
Concrete	M300	2.7e4	0.2	8.5	17	0.35
Steel	A III	20.5 e4	0.3	392	590	14

THE STRUCTURAL INTEGRITY ANALYSIS OF ALS

The layer element shown in Figure 3 is used in performing calculations by the NEPTUNE code. Five (5) layers are applied in the ALS models for the modelling of concrete. The code determines what layers are subjected to tension and what are subjected to compression and performs calculations subject to the failure surface of the constitutive model. Calculations for tension are performed in all elements of concrete and the possibility of element failure is considered. The code gives the following messages about the element failure:

- Failure surface reached – limit for tension is reached, the concrete cracking begins;
- Completed softening – tension evaluation is completed and the crack in concrete starts to open;
- Crushing of boundary element – element reaches ultimate strength in compression and looses resistance for any loading;
- Rebar failure – the structure looses its integrity.

Rebar failure is assumed not at the ultimate strength but when 5 % of strain is reached. This is related to the ultimate load capacity of two-rebar connector that fails at the specified deformation.
The first event of element failure (failure surface reached) means that tension limit is reached but the leakage is improbable. The calculations are performed up to the pressure at which the ultimate tension strength is

exceeded and the crack opens in all 5 layers of one concrete element (information “completed softening” in all layers of one element is recorded), i.e. the through-wall crack appears in the ALS wall.

The strength calculation of the building structures of ALS zone 1 was performed up to the pressure at which the first through-wall crack in the concrete of the outer ALS wall appears. The stress-strain curve of the reinforcing bar is assumed to be elastic-perfectly plastic, i.e. up to the limit of elasticity of the rebar steel.

The results of the stress state in zone 1 employing code NEPTUNE are presented in Figure 4. The maximum normal stresses at the pressure of 0.284 MPa are 392 MPa for tension and 355 MPa for compression. It is calculated that at this pressure one through-wall crack appears in concrete of the slab in compartment 1 (Figure 5). This picture shows the outside layer of zone 1 and it is assumed that the leakage is possible through this crack.

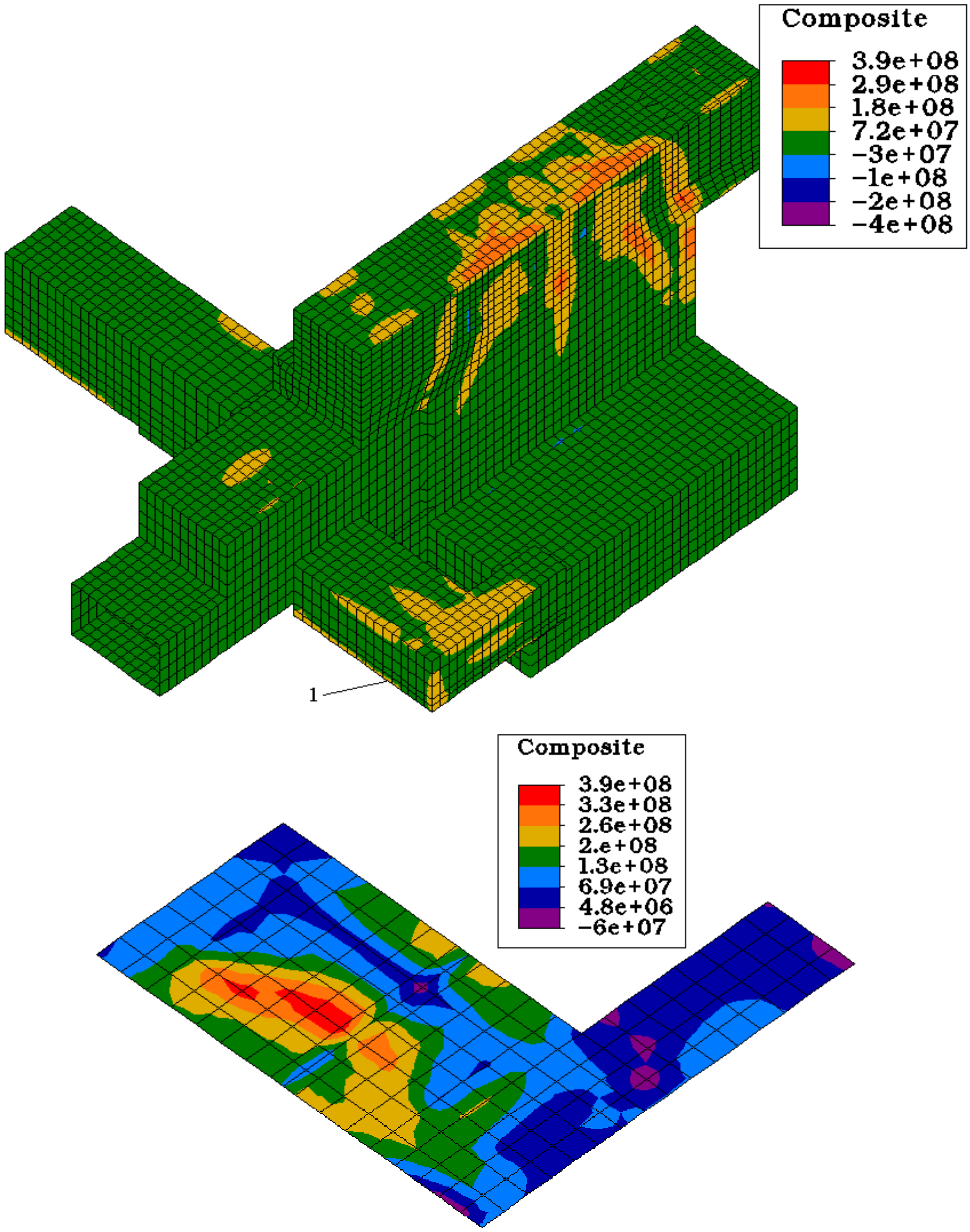

Figure 4: Distribution of the maximum principal stress (Pa) in the outside walls of zone 1 and the slab of compartment 1 (pressure – 0.284 MPa)

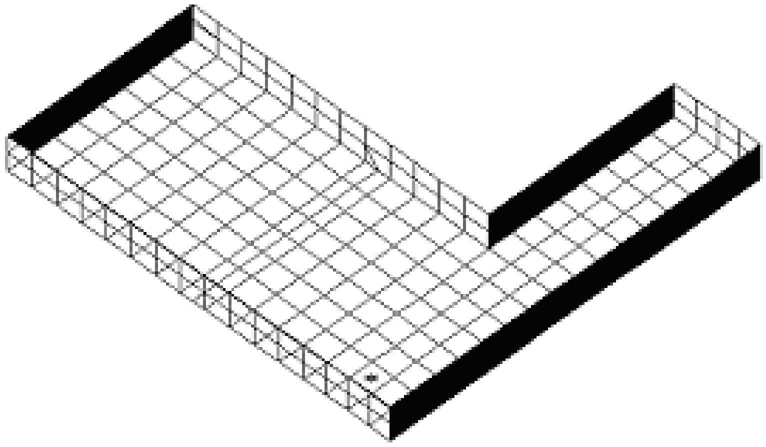

Figure 5: Location of the first through-crack in the slab of compartment 1 (star)

CONCLUSIONS

Analysis of ALS building showed that the first through-wall crack in concrete appears in the slab of compartment 1 (Figure 5) at pressure 0.284 MPa. This slab shows the outer layer of zone 1 and the leakage through this crack is possible. Thermo-hydraulic analysis showed that pressure in case of maximum design basis accident reaches 0.180 MPa. Thus, pressure safety margin exists before the first through-wall crack in the outer walls of ALS appears.

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