NON-LINEAR ANALYSIS OF THE IGNALINA NPP ACCIDENT LOCALIZATION SYSTEM STRUCTURAL INTEGRITY

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ABSTRACT

Numerical analyses are carried out by using the NEPTUNE finite element program to predict the ultimate pressure capacity and the failure mode of the RBMK-1500 reinforced compartments 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 was used reinforced concrete element for analysis of reinforced concrete structures. Material nonlinearity such as concrete tension and compression, yielding of reinforcing steel are simulated with proper constitutive models. The code determines what layers are applied with tension and what are applied with compression and performs calculations up to the limit for tension and limit for compression. Calculations for tension are performed in all the places of concrete and the possibility of element failure is verified. The results of the structural integrity analysis of the Accident Localization System are presented in the analysis. In the analysis the testing characteristics of concrete and rebar steel applied.

INTRODUCTION

The nuclear reactors of the Ignalina Nuclear Power Plant (NPP) belong to the RBMK class of reactors designed and constructed in 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 (Fig. 1). The ALS towers are interconnected through a system of the leak-tight compartments designed for steam discharge in case of rupture primary coolant circuit. The leak-tight compartments 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.

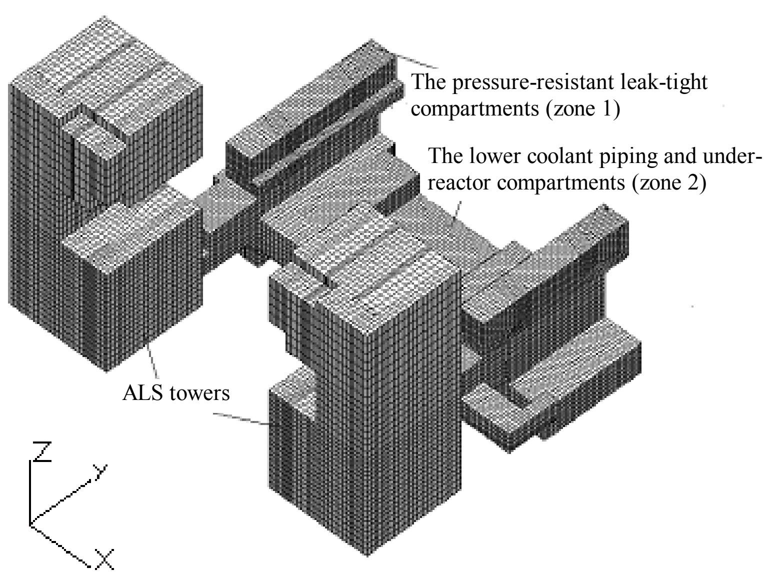

Fig. 1: General layout of ALS

The objective of non-linear analysis is to evaluate strength limit of ALS building structures and the failure mode of the RBMK-1500 reinforced containment at Ignalina Nuclear Power Plant. The structural analysis of the ALS is very important due to the fact that design pressure testing was conducted neither during their operational life, nor before the commissioning of Ignalina NPP units.

Finite Element Method (NEPTUNE code) has been used for ALS structural non-linear analysis. NEPTUNE code is a three-dimensional finite element program developed to simulate the response of reactor components in three-dimensional space for beyond-design-basis loads. An important feature of NEPTUNE code is its ability to handle non-linear problems. The element formulations can properly treat large deformations (geometric nonlinearities) and the rate - type material models can handle large material strains (material nonlinearities).

Evaluations of building structures were performed using as-built reinforcement concrete data. For verification purpose of the as-built situation, non-destructive testing was used for monitoring of reinforced concrete. Measured mechanical properties of concrete and reinforcement bars have been used for evaluation of the walls and slabs strength. The stress analysis and cracks analysis in concrete of the ALS structures was performed.

DATA FOR STRUCTURAL INTEGRITY FEA OF THE ALS

Geometrical Models

Due to symmetry of the ALS geometry, only half of the actual building was chosen for the analysis (Fig. 2). The basic philosophy of 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 and the special program from the ALGOR software package for combining of models [1]. ALGOR/NEPTUNE interface program was made to transform all input variables (nodal coordinates as well as element properties) from ALGOR input to NEPTUNE input. The ALGOR models are presented in reference [2]. Comparison of ALGOR and NEPTUNE solutions was made [3].

The geometrical data of compartments (dimension 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 steps of laying out of the reinforcement bars in the walls and slabs, dimensions, laying out and design of metallic frame, type of reinforcements bars, concrete and elements of metallic frames) were obtained from reinforced concrete drawings.

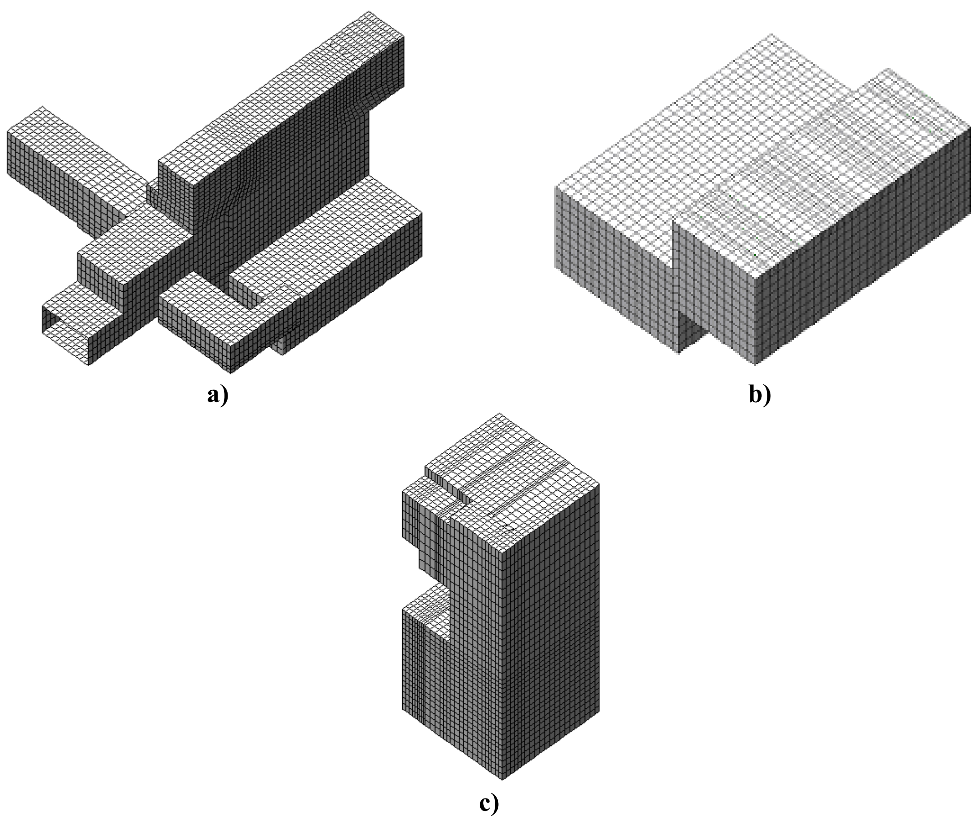

Fig. 2: Finite element models of zone 1(a), zone 2 (b) and ALS tower (c)

Most loaded places (according to preliminary calculations) were selected for carry out non-destructive testing of reinforced concrete structure performed by Force Institute (Denmark). It was determinate the location and depth of reinforcement bars, geometrical characteristics, connection of reinforcement bars, quality of reinforcement bars and concrete. The results of non-destructive testing were used for development of as-built ALS structural model.

Modelling of Reinforced Concrete Walls by Finite Elements

The NEPTUNE code model uses four-node quadrilateral plate element developed by Belytschko (Fig. 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.

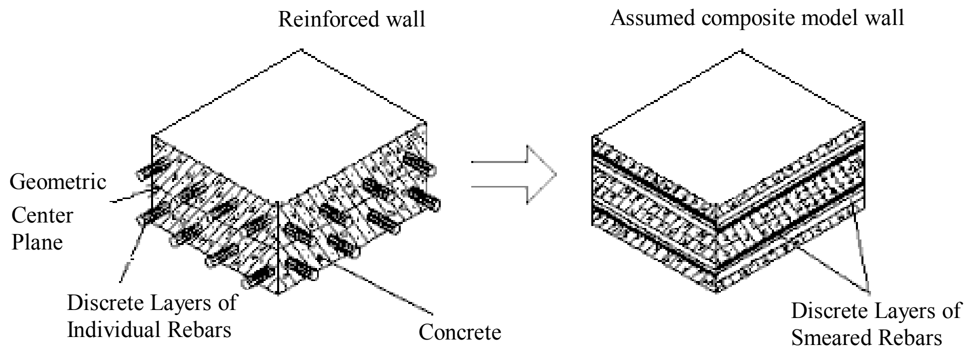

Fig. 3: Section through wall/slab and equivalent finite element model with distinct layers of smeared reinforcing bars

The concrete failure model used is the Hsieh-Ting-Chen four –parameter model, so that the represent the following four failure states [5]:

1. Uniaxial compressive strength,
2. Uniaxial tensile strength,
3. Equal biaxial compressive strength,
4. Combined triaxial compression.

NEPTUNE calculates stresses on central axis of element in five integration points for concrete and in each rebar layer.

The certain parts of walls and slabs has metallic frame in reinforced concrete. The bar elements were used for analysis of metallic frame. The bar (truss) elements are using two nodded element. This element is based upon a velocity strain formulation. The element can only treat tension/compression loads along the line, which connects the two nodes. The bending loads cannot be handled.

Boundary Conditions and Material Properties

The outside surface of the main ALS is shown in Fig. 1. When pressurized, the deformation of this structure is resisted by the outside structure, which is not shown in Fig. 1. The outside constraints consist of walls, 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 constraint would be primarily resisting the ALS deformation in the tension-compression mode, their stiffness would be very large. For simplicity, therefore, the locations of the external nodes, which would be in fact connected to adjacent structures, are assumed in the first approximation to be completely fixed in translation.

The nonlinear analysis of the ALS was performed using actual material properties obtained from the testing results. The concrete properties are presented in Table 1.

Table 1. Material properties

Material	Young's modulus, MPa	Poisson's ratio	Yield stress, MPa	Compressive stress, MPa	Ultimate strain, %
Concrete	1.95e4	0.184	25.8	51.6	0.47

The reinforcing steel class AIII (GOST 5.1459-72 –[6, 7]) was used for building structures of the ALS. Measured mechanical properties of reinforcement bars have been used for evaluation of the walls and slabs strength. The experimental data of strain-stress curves are presented in Fig. 4. The worst true strain-stress curve of the reinforcing steel used for nonlinear analysis of the ALS structural integrity.

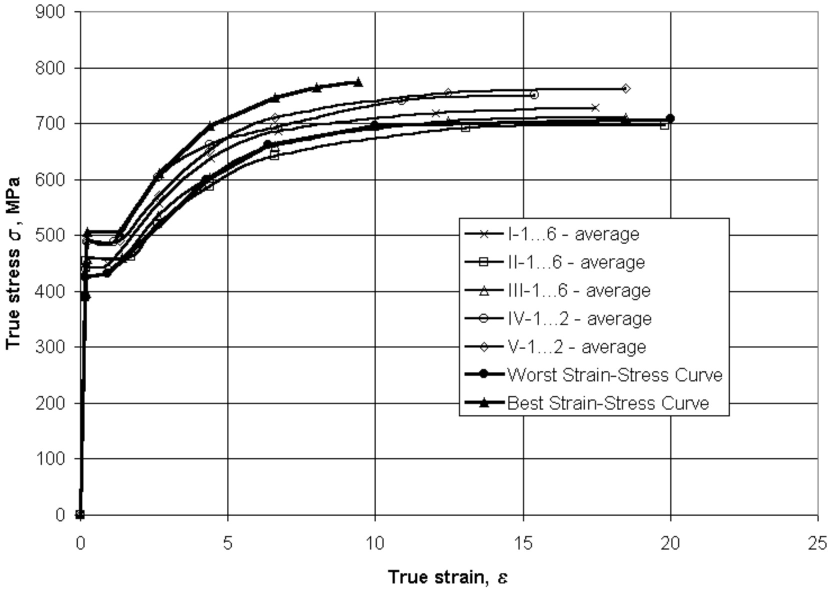

Fig. 4 Stress-strain curves of reinforcing steel class AIII (35 GS)

RESULTS OF NON-LINEAR STRUCTURAL ANALYSIS

The non-linear structural analysis of the ALS model was performed using NEPTUNE code with tested nonlinear material data of concrete and rebar. The NEPTUNE code determines what layers are subjected to tension and what are subjected to compression and performs calculations up to the tension and compression limits. Calculations for tension are performed in all elements of concrete and the possibility of element failure is verified. 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;
- Crashing of boundary element – element reaches ultimate strength for compression and looses resistance for any loading;
- Rebar failure – the structure looses its integrity.

The calculations are performed up to the pressure at which the strength limit of building ALS zone 1, zone 2 and ALS tower is exceeded

ALS Zone 1 Analysis

It was calculated that at pressure of 0.476 MPa the reinforcing bars begin to fail. The NEPTUNE analysis results using experimental concrete and reinforcing bars material properties are presented in Fig. 5. The maximum normal stress is 460 MPa (tension) and 426 MPa (compression) under over-pressure of 0.475 MPa. This over pressure is last available before reinforcing bars failure condition. The failure of ALS zone 1 begins in compartment Nr. 1 (Fig. 5). The strain in rebars of this wall reaches 5 % (460 MPa).

ALS Zone 2 Analysis

The ALS zone 2 was designed to 0.08 MPa. To ensure protection of related the compartments against an overpressure above the design value of 0.08 MPa, eighteen 700-mm diameter burst disks are fixed in the compartment walls. They open at an overpressure of 0.02 MPa. The structural integrity analysis was performed up to failure of building using the testing concrete data and rebar data for confirmation of sufficient strength of ALS zone 2 in case of burst disks disoperation. The failure of slab Nr. 2 (Fig. 6) of a compartment this zone begins at pressure 0.121 MPa, i.e. cracks opening in concrete begins. The NEPTUNE analysis results using testing concrete and reinforcing bars material properties are presented in Fig. 6. The maximum normal stress is 233 MPa (tension) and 82 MPa (compression) under over-pressure of 0.12 MPa. The yield stress of reinforcing bars is not achieved, i.e. the failure of bars will not occur. It means, that the structures at this compartment will not be destroyed. The maximum normal stress in concrete is 5.1 MPa (tension) and 24.3 MPa (compression) under overpressure of 0.12 MPa (see Fig. 6). It means, that in concrete of slab Nr. 2 ultimate strength to tension is achieved and cracks opening begins (such cracks are presented by asterisks - * - see Fig. 7).

From the presented results it is visible, that using testing data concrete and rebar at pressure 0.121 MPa the failure of of ALS zone 2 structures will not occur (reinforcing bars and metallic frames). The concrete will be destroyed, i.e. the integrity of these compartments will be violated.

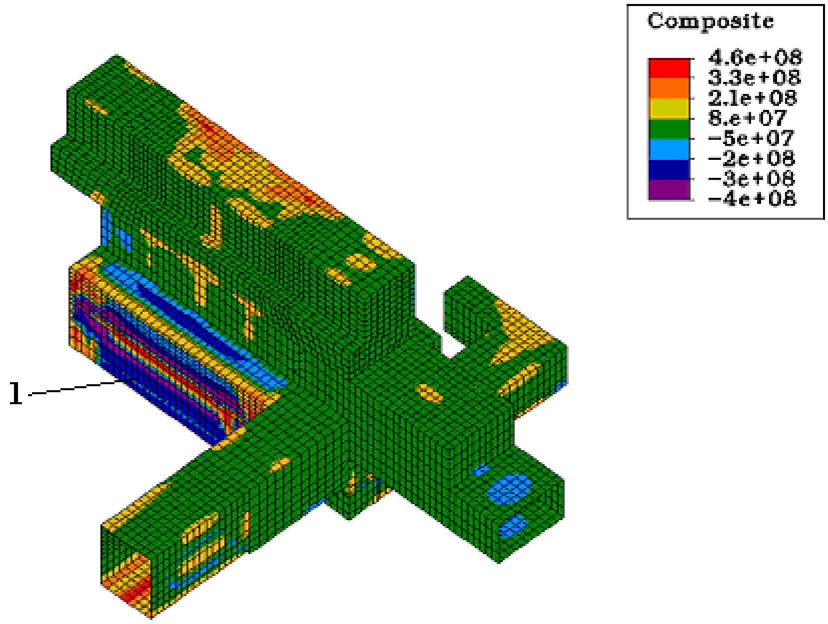

Fig. 5 Maximum principal stress (Pa) distribution in ALS zone 1 at pressure 0.475 MPa

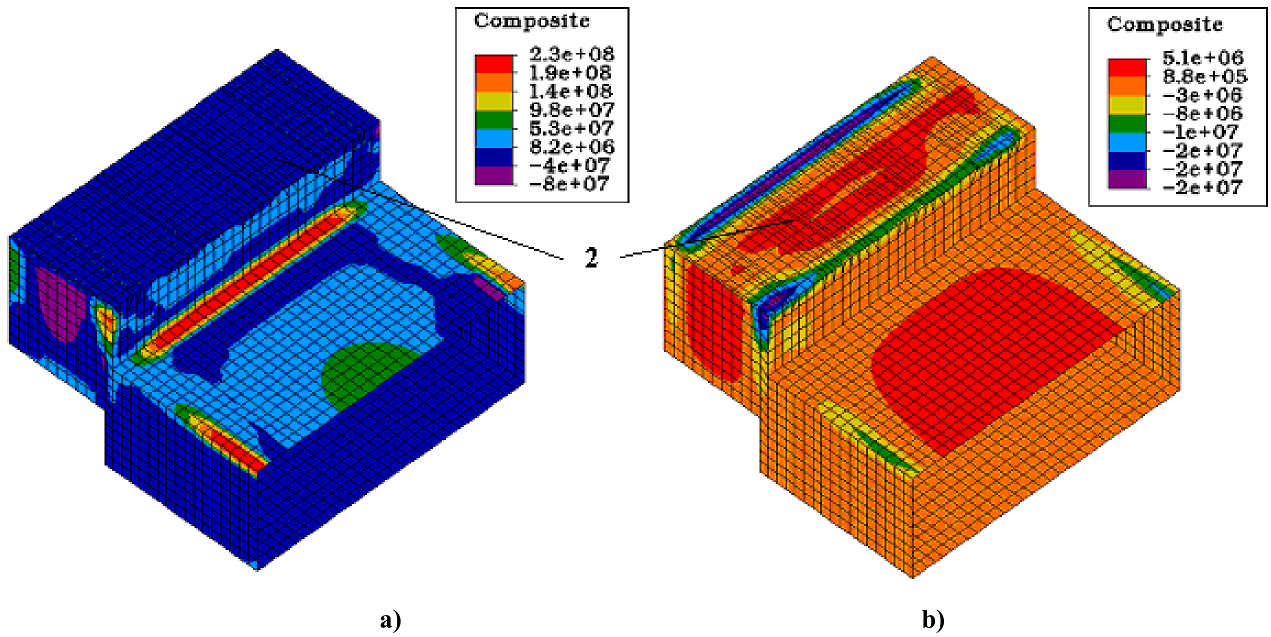

Fig. 6 Maximum principal stress (Pa) distribution in walls (a) and in concrete (b) of the ALS zone 2 at pressure 0.12 MPa

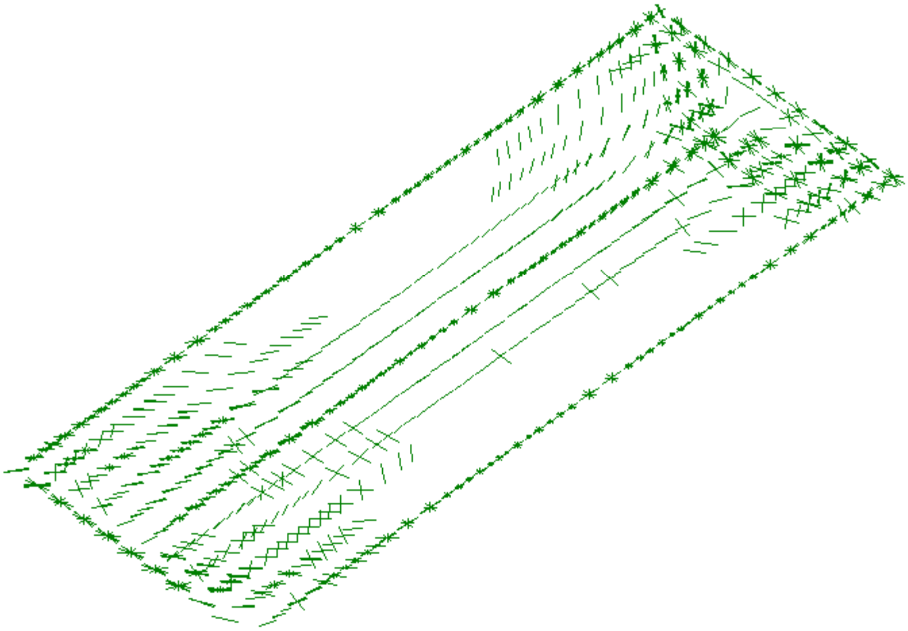

Fig. 7 Cracking pattern in slab Nr. 2 (pressure – 0.12 MPa)

ALS Tower Analysis

It was calculated that at pressure of 0.1715 MPa begins the failure of the metallic frames, with which the wall of compartment 3 (Fig. 8) fastens to walls of adjacent compartments. The NEPTUNE analysis results using experimental concrete and reinforcing bars material properties are presented in Fig. 8. The maximum normal stress is 499 MPa (tension) and 281 MPa (compression) under over-pressure of 0.1714 MPa. This over-pressure is last available before reinforcing bars failure condition.

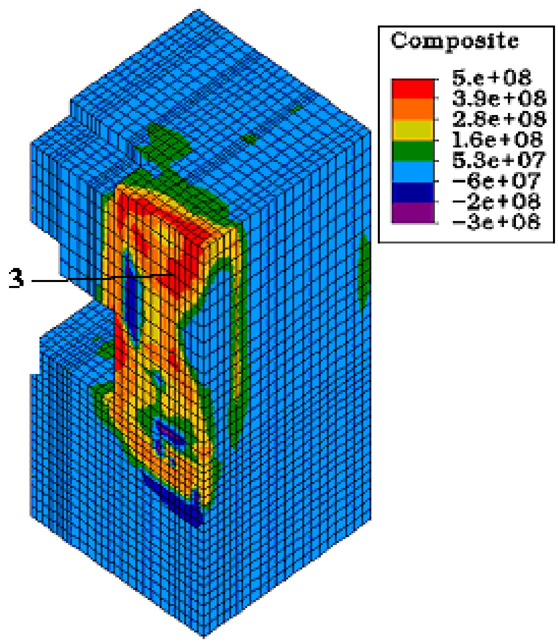

Fig. 8 Maximum principal stress (Pa) distribution in ALS tower at pressure 0.1714 MPa

SUMMARY AND CONCLUSION

Numerical analyses are carried out by using the NEPTUNE finite element program to predict the ultimate pressure capacity and the failure mode of the RBMK-1500 reinforced compartments at Ignalina Nuclear Power Plant. The paper presents the results of ultimate strength of the ALS zones 1 and 2 as well as ALS towers. It is calculated, that:

- The failure of ALS zone 1 begins at pressure 0.476 MPa;
- The failure of ALS zone 2 begins at pressure 0.121 MPa (will be destroyed concrete, i.e. cracks opening in concrete), but the failure of building will not take place, i.e. failure of reinforcing bars and metal frames will not faill;
- The failure of ALS tower begins at pressure 0.1715 MPa.

The ALS zone 1 was designed to 0.3 MPa, and the ALS zone 2 and ALS towers was designed to 0.08 MPa. Thermo-hydraulic analysis showed, that maximum pressure in case of design basis accidents reaches 0.180 MPa in ALS zone 1, 0.041 MPa in ALS zone 2 and 0.08 MPa in ALS tower [8]. In all the cases calculated that ALS failure starts at the pressure higher than design pressure of ALS and maximal calculated excess pressure. This means, that safety margin exists before ultimate strength is reached.

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