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Structural response of the ACS in the ignalina NPP due to design pressure

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ABSTRACT: A mathematical model of the structural confinement or the Accident Confinement System (ACS) of the RBMK-1500 reactors is presented. The system is required to prevent the release of radioactive materials from reaching the atmosphere in case of rupture of the coolant piping, including the design base accident. Thus far the mathematical model of the structure is subjected to the specified design pressures. The results a analyzed with respect to wall deflections and maximum stresses in the reinforcing bars which maintain the integrity of the ACS walls. They indicate exessive deflections of the walls and high stresses in the reinforcement in certain areas of the ACS.

1. INTRODUCTION

The nuclear reactors of the Ignalina nuclear power plant (NPP) belongs 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 which 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 confinement system (ACS) or the accident localization system (ALS). The ACS 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). For the Ignalina RBMK-1500 reactors theACS is made up of a large number of separate and interconnected rectilinear compartments, uses ten separate pools of water for steam condensation and possesses a clean air venting system.

The ACS guards the release of radioactive materials from reaching the atmosphere in case of rupture of the coolant piping, including the design base accident. It is important to ascertain that the ACS is sufficiently effective to hold the maximum pressure that can be hypothesized in the RBMK-1500 accident.

Even though the original ACS design is based on assumed static loading, the resultant pressurization in the LOCA is in fact of dynamic nature. The pressure first rises during water vapor expulsion from the ruptured piping and then drops when the steam condensation becomes effective. Thus, under the resultant hypothetically postulated accidental events of pressure as well as thermal loading, the pressure boundary must not be breached and therefore the response of the structure needs to be evaluated. The integrity of the ACS must be maintained during the excursion process, the analysis of which will be the object of this paper.

2 GEOMETRIC MODELING ASPECTS

By far the most time-consuming effort of evaluating the response of the ACS was the geometrical representation of the analytical model. This was because of the structural complexity of the ACS, which is composed of a maze of box-like rectilinear interconnected compartments. The modeling was even more involved by the anticipated compatibility requirement of the finite element nodes of the adjacent 3-D compartment walls. The structural drawings of the second unit of the Ignalina NPP were used as the basis for the model.

The geometrical modeling was realized by the ALGOR computer program graphics program. This graphics program enabled a rather realistic display of the ACS structure and provided a reassuring check of the analytical model. A periodic transformation of the geometrical configuration to a finite element plate model of the ALGOR program ensured visual compatibility of the model. The complete configuration of the ACS structure is depicted in Figure1.

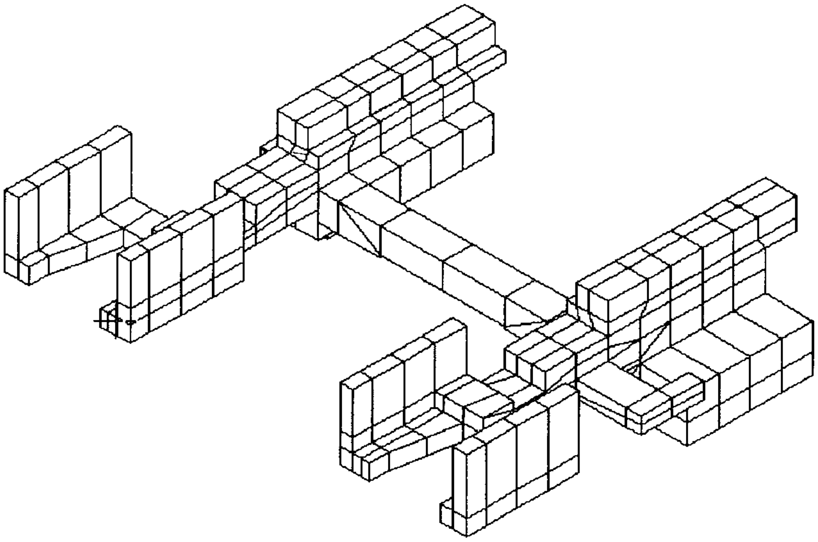


Figure 1. Configuration of the Entire ACS

3 FINITE ELEMENT REPRESENTATION

The finite element chosen to represent the reinforced concrete walls was the sandwich element of the ALGOR element library. This is a composite element based on Mindlin plate theory made up of different orthotropic layers. The concrete reinforcement was represented by two smeared uniaxial layers of steel adjacent and orthogonal to each other. Transverse wall reinforcement was neglected in the analytical model.

The presence of heavily steel-reinforced columns, to carry the weight of the structure, and mounted inside the walls of the structure, must contribute to the response of such walls to inside pressure of the containment. The contribution of these heavily steel-reinforced columns is modeled by separate beam elements. The compatibility of the position of these beams is accomplished by locating the beam nodes geometrically identical to those in the composite plate model. Extensive information about this modelling aspects was presented in (Petkevicius).

The first analytical model of the reiforced concrete wall is made utilizing the sandwich element of the ALGOR element library. In this model the layers of individual rebars of are represented by smeared uniformly distributed layers of steel. The thickness of these layers is determined by assuming that the cross-sectional areas of the rebars are spread along the respective pitch of the layers. The direction of reinforcement is specified in the sandwich element model.

In order to use the elastic response of the sandwich element, certain simplifying assumptions are made regarding concrete strength in tension. Because concrete is weak in tension, it is completely neglected in strength evaluation. This assumption permits the use of element layers without having to take cracking into consideration. Nevertheless, the extent of cracking within the wall, which corresponds to the tensile range, must be predicted at the start.

By assuming the tensile range to be at an arbitrary distance x a summation of forces normal to that cross-section must equal zero. In this force calculation a linear strain distribution is assumed and only compressive forces in concrete exist. The calculation results in the following expression for locating the neutral surface

$$x = x_1(\sqrt{1+t_0/x_1}-1),$$

where $x_1=2hE_s/E_c$, t_0 is the distance between row of reinforcement; h is the reinforcement layer thickness and E_s, E_c are the module of elasticity of steel and concrete, respectively.

With the location of the neutral surface known, the construction of the composite element can be formulated. The layers of the element are made up of reinforcement and compressive parts of the concrete, arranged in geometrically accurate position with respect to the neutral surface. The correct location of respective layers from the neutral surface is important even in the tensile range of the concrete wall. For this purpose an artificial layer is introduced, spanning the neutral surface and the reinforcing layer in the tensile range. This layer holds the reinforcement in its proper location but does not possess any strength.

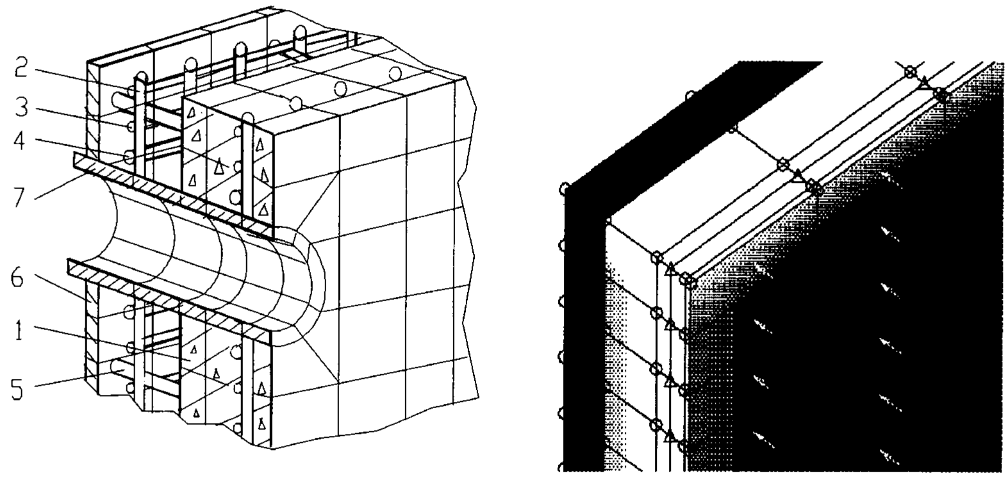
The configuration of the main ACS is shown in Figure1. When pressurized, the deformation of this structure is resisted by the outside structure, which is not shown in Figure1. The outside constraints consist of walls, floor-ceiling slabs of the adjacent structure. Most of the outside nodes of the ACS model are common with those of the external constraints. Because the external constraint would be primarily resisting the ACS deformation in tension and compression, 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 thus assumed to be completely fixed in translation.

The design of the ACS was based on a temperature of 143°C, so those material properties to be used in the analytical model need to be adjusted (Bajkov). Concrete wall thicknesses ranged from 0.4 m through 1.2 m for the ACS analyzed. The diameter of the reinforcing bars varied from 8 mm to 40 mm.

The reinforced leaktight compartments (the location of the circulation pumps and high pressure piping), the steam receiving channel, the connecting channels of the ACS are subjected to 0.3 MPa, the design pressure of this part of the ACS (Almenas). The steam reception chambers (the location of the condensing pools) were designed for a pressure of 0.1 MPa. The two parts of the ACS with different design pressure are in fact interconnected and separated by a rather tight opening. The steam reception chamber also located at the far end of the ACS from the source of the hypothesized accident.

For the sake of consistency, a nearly concentrated load, simulating the weights of the four circulating pumps, is imposed in the reinforced leaktight compartments. The individual weight of 1.04 MN (Almenas) is distributed in a circular area configuration.

The second part of the analysis involved the investigation of that part of the first analytical model which was shown to be stressed the most. This part was the wall of ACS separating the rooms which locate the pressure collectors of the main circulation pumps and the distribution collectors. A 3-D stress analysis model was made of this wall where the concrete layers (1)* in compression were modeled by brick elements, and the cross- (2) and longitudinal- steel (3) reinforcement layers were modeled beam elements. The outside metallic liner (6) was modelled by shell elements. A fragment of this model can is given in Figure2-a.



a b

Figure 2. Structure of Wall ALS

A 4mm thick plate extends 300 mm down along the wall surface. It is attached to steel pipes (5), which pass through the wall (1). These pipes were modeled by beam elements. Other 20 drain pipes, which pass trough this wall, bushings (7) fixed to the wall. This welded piping construction to the bushings limits deformation of the wall to 45 mm. This effect of the bushings is not accounted for in the calculation. A fragment of the model, which makes use of the ALGOR program, is depicted Figure2-b.

* Numbers in parentheses refer to components shown in Figure2

4 RESULTS

The present analysis yields results of the ACS structure response due to the static design pressure. The ALGOR graphics program provides a detailed visual display of the resultant deformations as well as the stress distribution through all the seven layers of the model of the reinforced concrete walls. Color graphics displays the variations of stresses throughout the model.

Maximum deflection is shown to be 32 mm and corresponds to the largest unsupported wall area of the ACS. The deflection plot of that wall is given in Figure3. The corresponding tensile stresses of the wall reinforcement are 386 MPa and 303 MPa along the long and the short side of the wall orientation, respectively. Concrete compressive stress in the same wall is 20 MPa.

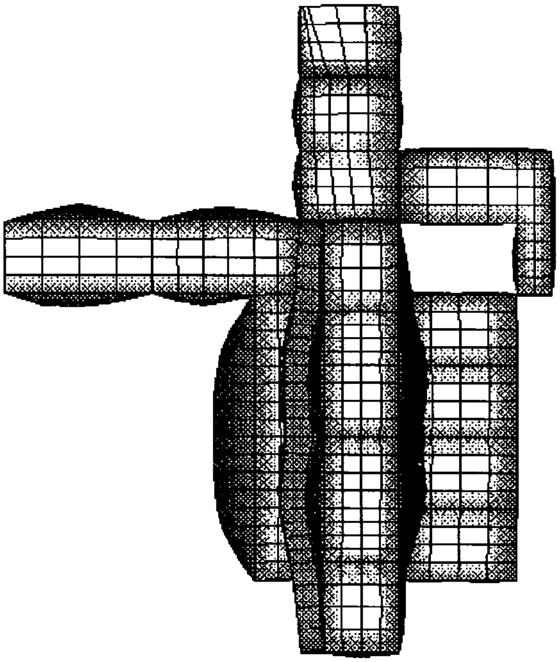


Figure 3. Top View of the Analytical Model

In second part of the analysis calculations were provided for a model with an outside liner and without he. The results without the liner yield a maximum tensile stress in concrete of 14 MPa, and in the reinforcement 160 MPa. The maximum tensile stresses in wall with an outside liner are determined to be 10 MPa in the concrete, and 130 MPa in the reinforcement. A stress of 105 MPa was calculated in the outside steel liner. The local zones with maximum tensile stresses are located close to the intersection of the wall with the horizontal ceilings. The compression limit of concrete is about 30-35 MPa, and in tension the limit is about 2-4 MPa (Bajkov), therefore, it is reasonable to expect cracking in this area. Consequently, a crack through concrete layer whould not necessarily affect the airtightness of the ACS.

5 CONCLUDING REMARKS

The results of this study provide a good understanding of the response of ACS due to the design pressure. In general, the design pressure causes the reinforcement bars to be close to the yield strength of the material. The effect of yielding of the bars in tension enables concrete cracking to emanate through the walls of the containment. However, this does not mean that the pressure barrier has been breached, which, after all, is of primary concern. The liner, which is on the inside of the ACS surface could remain intact until the membrane mode of loading would come into play. And this mode of loading would be initiated only if the tensile reinforcing bars would rupture. Thus, the mode of failure of the ACS would be the ultimate strength of the reinforcing bars, rather than their yield strength. This seems to be the appropriate mode of failure for the Ignalina reactor structural confinement systems.

The yield stress of the reinforcing bars can be associated with local failure of the confinement system. Keeping in mind the large volume of the ACS and the measured leakage of the system (Almenas), local failure of the ACS would change the leakage to a relatively minor degree. The rupture of the reinforcing bars, and consequently the liner of the inside wall, would constitute global failure thus significantly altering the containment integrity. The latter, global failure of containment, thus seems to justify this mode of failure for the ACS confinement system.

An analysis done by Kulak et al. (1989) of the response of Soviet VVER-440 ACS does shed some light on the ultimate capacity of a similar type of structure. Using nonlinear structural analysis programs they analized the response to design pressure and also obtained an ultimate capacity of the ACS limited by the rupture of the reinforcing bars. Their design pressure was 0.15 MPa and it was found that the rupture of the reinforcing occured at a pressure of 0.4 MPa. The study showed the large difference between the design pressure and the ultimate destructive failure of the confinement system. While direct analogy of that system and that of the Ignalina NPP can not be made, the analysis would seem to imply a significant reserve of the Ignalina ACS to ultimate failure. An inelastic analysis, nevertheless, would be needed to find the global failure of the Ignalina ACS.

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