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Peculiarities of a computational analysis of a prestressed concrete containment

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ANNOTATION: The specific features of the operation of a prestressed reinforced concrete containment of a nuclear power station are examined. The results of containment stress calculations are given for both the middle part of the cylinder and the stresses concentration areas (large technological penetration and joint connection of the containment cylinder with the base).

1. INTRODUCTION

An estimation of a load-carrier ability of a prestressed reinforced concrete containment of a nuclear power station exposed to an emergency load such as internal pressure is of great importance, because an exposure to internal pressure is regarded as one of the main emergency loads. The following states of a prestressed containment are analysed in the work:

1) Operation of a containment at a stage of preliminary stress;
2) Operation of a containment under internal pressure prior to a damping of preliminary stress deformations occurs;
3) Operation of a containment as a uniform elastic body when a damping of preliminary stress deformations has occurred, but preceding a concrete cracking starts;
4) Operation of a containment as an elastic body with cracks before critical cracks opening starts;
5) Operation of a containment with cracks preceding plastic deformations in the reinforcement;
6) Operation of a containment with cracks and plastic deformations in the reinforcement prior to destruction due to the reinforcement rupture.

Calculated containment models were based on geometric parameters, mechanical characteristics of used materials and type of reinforcement for standard power unit WWER-1000.

2. ESTIMATION OF CONTAINMENT STRENGTH

Primarily, calculation of stressed and deformed containment state was performed using axial symmetry approximation. There were used linear axially symmetric 4-nodes elements. Total amount of the elements was 1297 and of the nodes - 1428. It was proposed that there was sealed connection of the containment with the base along the entire lower border.

A problem of displacements, deformations and stresses calculations was solved using step by step increasing of the internal pressure load. A set of equilibrium equations was solved for each step of load increase (the method of finite elements - MFE). The model that took into account the elastic and plastic properties and analysis of plasticity threshold for both meridional and circumferential directions were used for the reinforcement layers considering the Huber-Mizes condition, when plastic deformations appeared in the steel coating.

Concrete cracking was simulated on a base of the model of orthotropic material using an iteration process. At each step of the iteration process the stresses in "concrete" elements were analysed. When stresses had reached a critical value in either meridional or circumferential direction, the concrete properties at the next iteration step were reduced in that direction in accordance with the factor of normal rigidity reduce which was equal to 0.0001. The concrete properties in radial direction were unchanged. There was used a reduced modulus of elasticity, E_{sb}', for the reinforcement elements which are neighbouring to the concrete cracked elements.

The method of successive approximations with variable elasticity parameters was used for solving the problem of elasticity and plasticity. The iteration process was applied at each step of approximation. The secant modulus of elasticity was used for the points with stresses exceeded the yield limit in accordance with obtained values of plastic deformations. For the reinforcement the meridional and circumferential directions were analysed separately. According to the components of the plastic deformation tensor the yield limit was corrected using the determined modulus of strengthening. Iteration process was stopped when stresses were less than yield limit or differed from this limit not more than by a fixed number ($\varepsilon = 0.005\ \sigma_t$) for all points.

There was also determined the lengthening of the reinforcement rods (as a result of containment geometric parameters changing), and the increase of the stresses was taken into account at the next iteration step.

The moment when stress in concrete reached the value of concrete resistance R_{bt} to the stretch was regarded as a criterion for cracking process start.

The results of the calculations showed that the destruction of the reinforcement rods started prior to the destruction of the steel coating and layer reinforcement. Thus, as a criterion for containment destruction the achievement of limits of stress values, R_{su}, and deformations, ε_{su}, in reinforcement rods was used.

The stretching force acting on the ends of the reinforcement rods was proposed to be 1000 tons. The value of the coefficient of friction of the rods on the wall of the channels was accepted to be $\mu = 0.09$. This value is one of the traditional values that has been obtained in research using full-scale constructions (Yuzhno-Ukrainskaya and Zaporozhskaya nuclear power stations [1]).

Our calculations allowed to determine the specific states of operation of a reinforced concrete prestressed containment for the middle part of the cylinder while it was under loads due to prestress and internal pressure. Primarily, the displacement of the containment in radial direction caused by prestress was determined (the 0-1 portion of the diagram). The analysis revealed that radial displacement was equal to 0.0067 m (figure 1).

Effect of the internal pressure was taken into consideration at the next step of calculations. The pressure of 0.025 MPa was used as an increment of the load. Damping of deformations caused by prestress of the containment begins at the internal pressure 0.650 MPa (point 2 in the diagram). In the period between damping of prestressed deformations and beginning of the cracking process the containment is still working as a uniform elastic body. Cracking starts at the internal pressure 0.725 MPa (point 3 in the diagram).

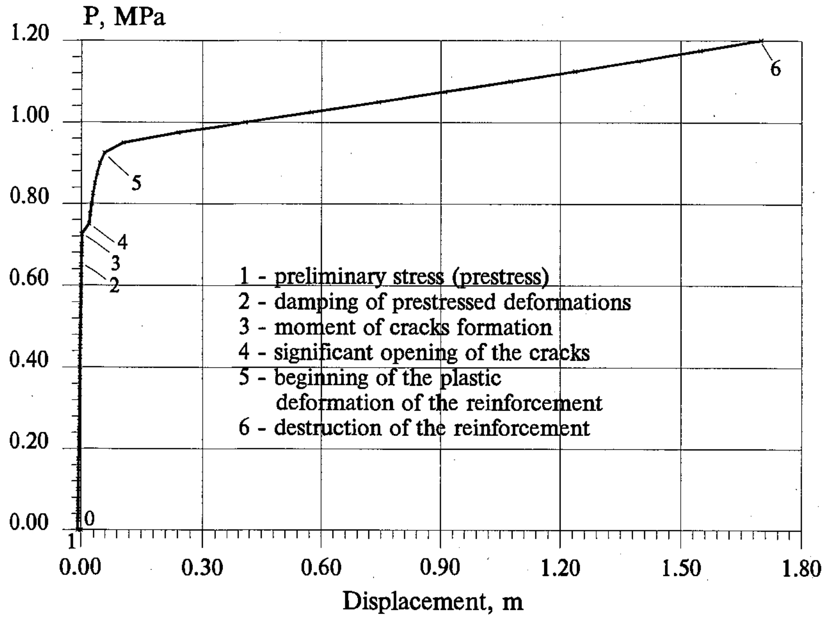


Figure 1. Diagram of operation of containment affected by internal pressure.

The next step of the load increasing showed that at the internal pressure 0.750 MPa the cracking process greatly enhanced (point 4 in the diagram). Plastic deformations of the reinforcement occurred beginning with the internal pressure 0.925 MPa (point 5 in the diagram).

Destruction of the containment occurs in the middle part of the cylinder due to the rupture of the reinforcement at the internal pressure 1.2 MPa (point 6 in the diagram). Radial displacements in the middle part of the cylinder preceding its destruction are 1.6994 m.

The diagram of the stress changing in the reinforcement rods depending on the internal pressure is given in figure 2. It shows that the major increase of stresses is observed for 0-1 portion of the diagram (64.6 % of the maximal values). The minimal increase of stresses was detected for the 1-3 portion preceding the cracks formation in the concrete and is only 3.4 %, while the internal pressure rise is 60.4 % of the maximal pressure, acting on the containment before its destruction.

The dependencies of meridional and circular stresses in the steel coating and layer reinforcement on the internal pressure are shown in figure 3. It is seen that at the internal pressure 0 to 0.725 MPa diagrams of stresses in the steel coating

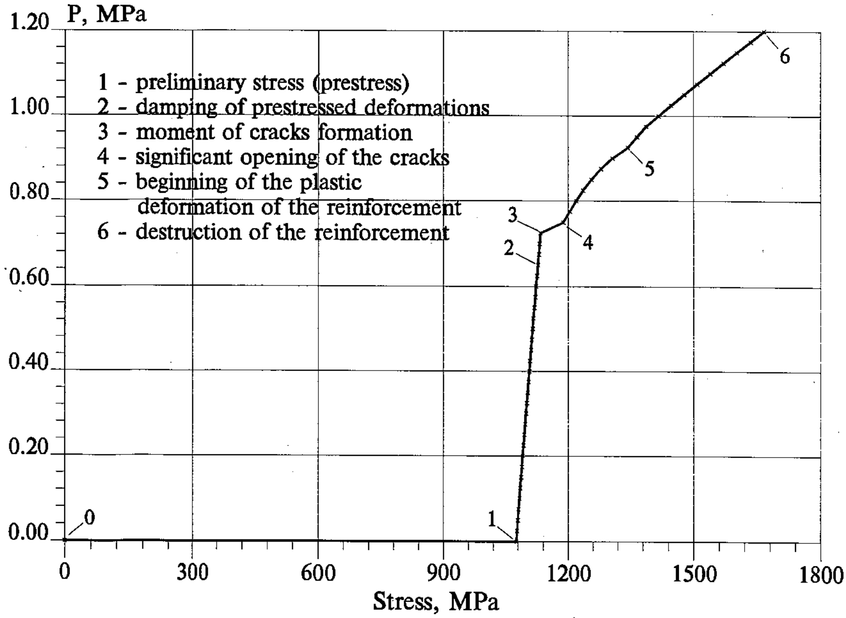


Figure 2. Dependence of stress changing in the stressed reinforcement on internal pressure

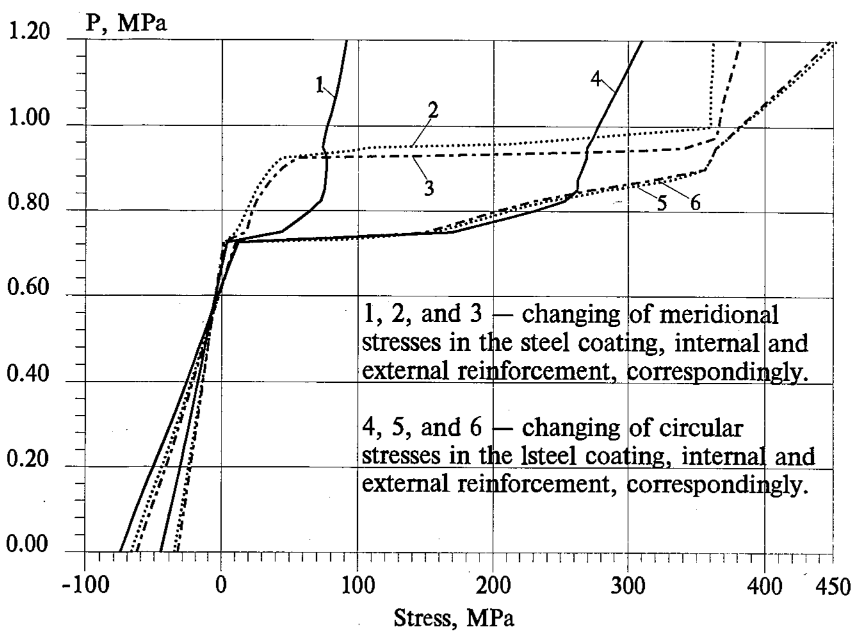


Figure 3. Dependencies of stresses in the steel coating and unstressed reinforcement on internal pressure

and reinforcement exhibit a linear behaviour. Then, after the cracks formation in the circular direction a significant rise of stretch in the steel coating and reinforcement is observed for this direction. The coating material reaches the yield limit in circular direction at the internal pressure 0.825 MPa, the reinforcement - at 0.925 MPa. Increase of circular stress in the coating after beginning of cracking in the concrete affects its meridional stress. However, while meridional load is increasing, there are no significant stresses in the coating. It could be explained by the fact that meridional stresses have instant, character leading to the decrease of stretch on the internal surface of the wall. A great rise of meridional stresses is observed after beginning of the wall cracking in the perpendicular direction (P = 0.950 MPa), and at the internal pressure of about 0.975 MPa stresses reache the yield limit.

3. ESTIMATION OF PRESTRESSED CONTAINMENT STRENGTH IN THE STRESSES CONCENTRATION AREAS

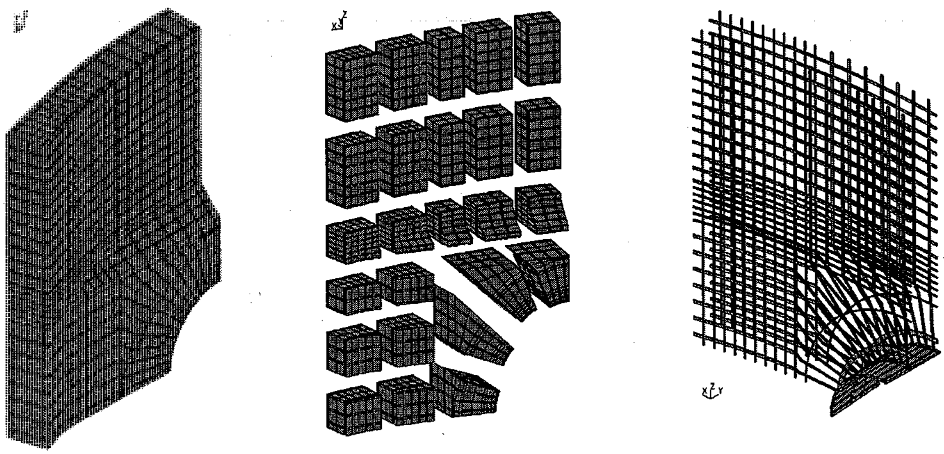
Estimation of the containment strength in the volumetric approximation was performed for the stresses concentration areas (large technological penetration of 4 m diameter and joint connection of the cylinder of the containment with the base).

A fragment of the calculated model showing the internal part of the containment in the area of the large technological penetration is given in figure 4 (a). The model includes 15360 linear 8-nodes finite elements, 18171 nodes and 54513 degrees of freedom.

Considering the difficulty of the geometric shape of the containment and specific features of the used materials, the new code "CONT" - "CONT_SE" used for calculations has been worked out. The code uses the effective algorithm of the method of superelements (MSE). This method is based on the main equations of traditional method of finite elements and represents an expansion of the method. The method requires to consider the construction as a combination of subconstructions of different levels, connected to each other at boundary points. Using a special equation allows one to eliminate internal nodes at each step of the calculations that leads to significant reduce of the equations dimension. There is given a superelemental fragment of the containment wall at the bore area in figure 4 (b).

The peculiarities of the concrete reinforcement at the bore area have been considered in the calculated model. Figure 4 (c) represents the diagram of the reinforcement modelling using the reinforcement arrangement in the area of the large technological penetration that is closely reproduced a full-scale construction.

The finite elements model of a fragment of the connection of the containment cylinder with the base was constructed using the same approach. The model includes 3675 linear 8-nodes finite elements, 5348 nodes and 16044 degrees of freedom. In the transient area the increment of the reinforcement both in radial and axial directions was accepted to be 200 mm at its thickness determined in the model of square 30×30 mm^2 section rod that is close enough to the real reinforcement construction. While moving out of the transient area the increment of the reinforcement and section size were doubled and quadrupled in the appropriate direction.



a) b) c)

Figure 4. A fragment of the calculated model of the containment wall at the bore area. a) - a fragment showing the internal surface of the wall; b) - superelemental fragment of the wall; c) - modelling of a reinforcement arrangement in the bore area.

Primarily, the calculations for the bore area were performed in elastic approximation. The stresses distributions due to the preliminary stress were obtained. Then the load due to the internal pressure with increment 0.05 MPa was taken into account. At the internal pressure 0.6 MPa stresses in concrete reach the value of concrete strength to the stretch both in meridional and circular directions. Beginning from this point concrete cracking was taken into consideration.

Concrete cracking was simulated using an iteration process. At each step of the iteration process all components of the stresses in concrete were analysed. When one of the components had reached the value of concrete resistance to the stretch in either finite element, the cracked concrete properties were used for the calculations (modulus of elasticity E = 330 MPa, Poisson coefficient $\mu = 0.2$) and the iteration process was started again for this value of load. The iteration process was carried out until stresses in all finite concrete elements of the model became lower the strength limit.

The concrete cracking character for the bore area is illustrated in figure 5, where the elements with cracks are not shown. The figure shows the state of the bore area at the initial and final stages of the cracking process at internal pressure 0.6 MPa.

So, the results of the calculations showed that at internal pressure 0.6 MPa the through cracks appeared at the bore area.

Analysis of the stressed state of the connection area showed that while increasing the internal pressure up to 0.65 MPa stresses in concrete did not exceed the concrete strength limit to a stretch. Further increasing of the internal pressure, as the calculations revealed, leaded to the cracking of the reinforced concrete.

Figure 6 illustrates the concrete cracking process depending on increase of the internal pressure. Increasing the pressure up to 0.70 MPa causes the increasing of circular stresses in the cylindrical part of the containment so that they exceed the concrete strength limit to a stretch. At this stage cracking of this part of the containment spreads into the entire section depth. Also, a small area of cracking is observed for the place of connection of the cylinder and the base. However, because of meridional stresses in this section do not exceed the circular stresses and possess an instant character, i.e. change their sign along the depth of the wall, the cracking of the entire wall section does not take place.

Further increasing of the load leads to the gradual concrete cracking in the area of connection of the cylinder and the base. At pressure P = 0.95 MPa concrete is practically cracked over the entire section.

4. CONCLUSIONS

1) The results of the containment calculations, performed both in axial symmetric and volumetric approximations, showed that up to the value of internal pressure 0.6 MPa the construction operates as an elastic body and its analysis can be done in the elastic approximation.

2) In the area of the large technological penetration the concrete strength limit to a stretch is reached at the load 0.6 MPa and containment begins to work as nonlinear elastic body with cracks. In the area of connection of the cylinder with the base the concrete strength limit to a stretch is reached at internal pressure 0.70 MPa and in the middle part of the cylinder - at internal pressure 0.725 MPa. So, we conclude that for the analysis of containment strength for the loads exceeding 0.6 MPa it is necessary to use calculated models considering the concrete cracking.

3) The containment destruction will occur at internal pressure ~1.2 MPa because of the exceeding the strength limit of the reinforced rods that are the basic carrier elements of the construction.

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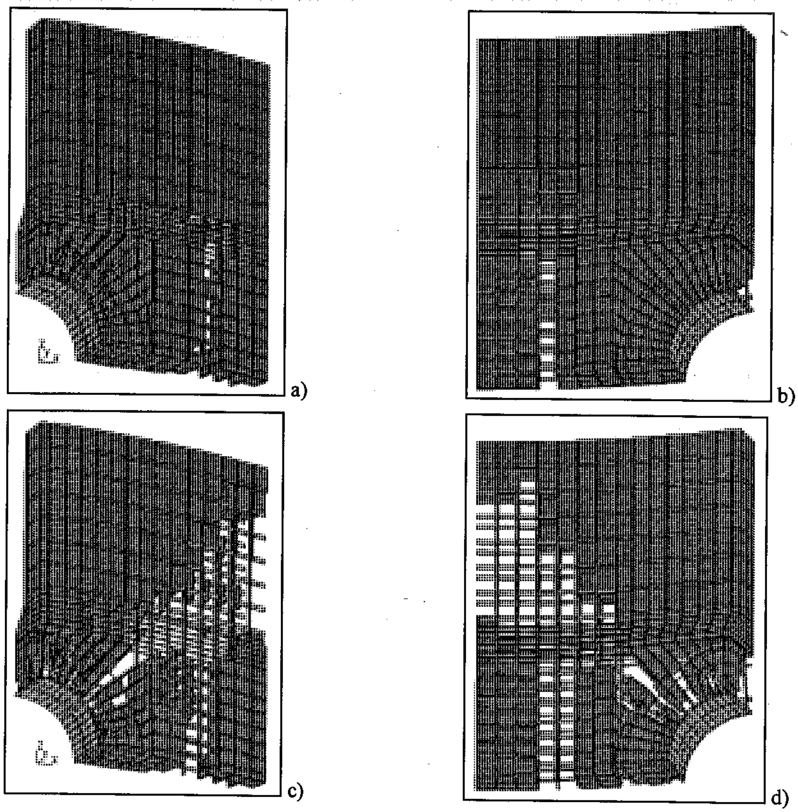

Figure 5. States of the bore area at the initial and final stages of the cracking process at internal pressure 0.6 MPa

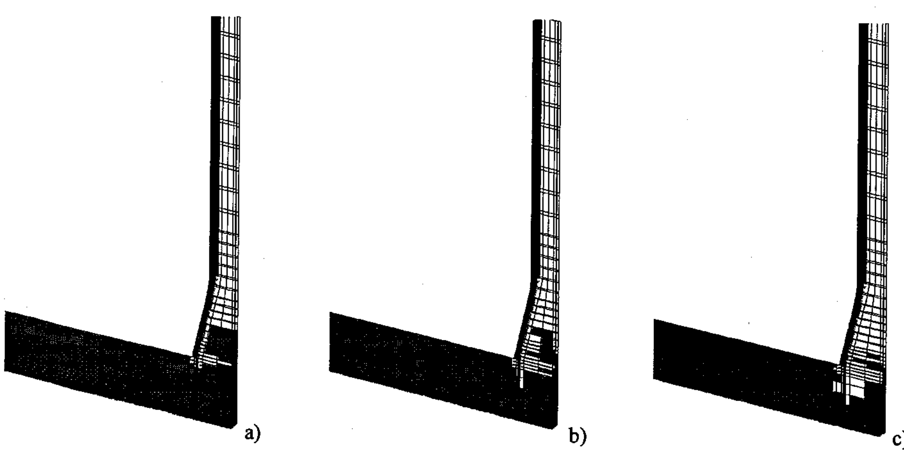

Figure 6. Concrete cracking process at the connection area depending on internal pressure (a - P=0.70 MPa, b - P=0.85 MPa, c- P=0.95 MPa)