2019 SECED Conference
Earthquake risk and engineering towards a resilient world
9-10 September 2019, Greenwich, London

STRUCTURE PERFORMANCE ANALYSIS OF PRESTRESSED CONTAINMENT BY CONSIDERING TEMPERATURE AND SEISMIC EFFECT

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Abstract: *During containment accident situation, it is usually companied with high temperature and high pressure, so the temperature effect on the containment structure performance should not be neglected. Seismic effect is another important factor needed to be considered during structure performance analysis. This paper takes the measure of temperature-pressure coupling in sequence and adding pressure in step-by-step mode, by using the three-dimensional nonlinear finite element, to calculate the structure response of containment under temperature-pressure coupling. According to the calculation result of internal pressure from zero to three times design pressure and considering temperature coupling at the same time, this paper analyzes and evaluates the temperature effect influence on the containment structural performance under different containment stress state. The seismic analysis of prestressed containment is carried out through the method of floor response spectrum. The calculation results show that: When the containment is in the elastic state, the temperature effect has the influence on structural performance; When the containment is in a state of part concrete crack, temperature effect influence on structural performance reduces gradually; When the containment is in a state of complete concrete crack, the temperature has no effect on structural performance. For seismic analysis, a recommended method is proposed to calculate seismic effect for containment structure through comparing four methods. These analysis results could improve the understanding of containment structural behavior under effect of high pressure coupled with high temperature and effect of seismic.*

Key words: Prestressed containment, Temperature coupling, Seismic effect

Containment, as the last physical safety barrier of nuclear power plant, plays an important role in preventing leakage. During accident conditions, the integrity and tightness of containment structure must be guaranteed. Under the design reference pressure, the leakage rate must be less than the prescribed limit, under overpressure condition, leakage rate of containment should also be controlled. Because containment subjected to high temperature and high pressure under loss of coolant accident, it is necessary to consider not only the influence of pressure, but also the effect of temperature when studying the performance of containment structure.

Foreign scholars, such as Kanzleiter [1], have carried out the temperature and pressure tests and theoretical analysis of the 1:64 containment model under LOCA accident conditions, results show that the experimental results are in good agreement with the theoretical analysis results.

Pressure test of the containment at 1:4 was carried out by Sandia National Laboratory, and the ultimate pressure capacity of the containment and the corresponding structural response were analyzed [2]. In this paper, a detailed three-dimensional fine finite element model of a nuclear power plant containment is established by using the nonlinear finite element software ABAQUS. The temperature-pressure sequential coupling and step by step pressure method are used to evaluate the effect of temperature effect on the performance of the containment. The above research provides a reference for the design analysis of containment considering the influence of temperature under accident condition.

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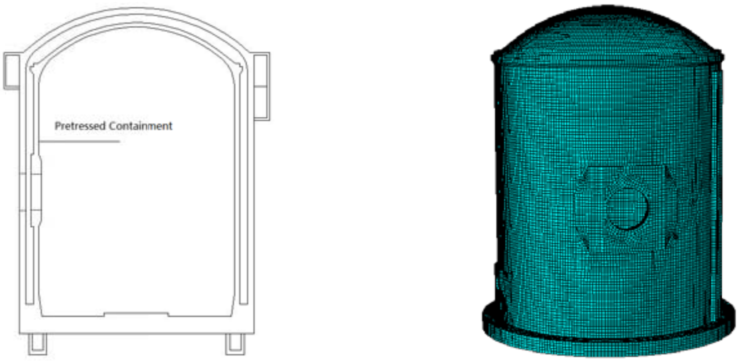
Seismic effect is another important factor for the containment design. The floor response spectrum is determined from the global seismic analysis by using global nuclear island model. The specific structural behavior analysis of seismic loading is carried out by applying the result from global seismic analysis. Simplified equivalent static method is the most common and effective way to determine seismic forces. However, since some structures geometrical conditions are complicated, high accurate seismic force analysis result is required. Based on this background, this paper demonstrates and evaluates four seismic effect calculation methods, according to which, a recommended method is proposed to calculate seismic effect for containment structure.

1 Finite element analysis of containment

1.1 Establishment of geometric model of containment

In this paper, the prestressed concrete containment of a nuclear power plant is selected for analysis. The nuclear power station consists of a double-layer containment located on a common raft foundation. The inner containment is analyzed in this study, as shown in figure 1 (a). The inner containment is prestressed reinforced concrete containment with steel liner, which is composed of a dome, a ring beam, a cylinder, a bottom base slab and buttresses. In this paper, the three-dimensional fine finite element analysis model of containment is established. The finite element analysis model takes into account the equipment hatch penetration, personnel airlock penetration, and some typical mechanical penetrations. In order to prevent the stress and deformation concentration of the opening from causing premature failure, Local thickened area of equipment hatch and personnel airlock are established according to the actual drawing. Finite element model of the containment after meshing is shown in figure 1, (b):



(a) Containment geometry diagram *(b) Containment finite element mesh*

Figure.1. Sketch of containment structure

When modeling of containment with ABAQUS, concrete part is mainly simulated by three-dimensional solid element C3D8, in which a small number of C3D6 and C3D4 elements are used because of the complexity of the model at penetrations. The surface element is used to simulate the reinforcement in the containment, and the properties of the reinforcement rebar are assigned on the surface element to simulate the rebar layer in the containment. Steel liner and penetration assemblies are simulated by adding a layer of skin to the geometric model, S4 element is used to simulate them, and some S3 elements are used in penetration locations. At the same time, the steel liner and the inner surface of the concrete share the same node. Prestressing tendons are simulated by T3D2 element. Both rebars and prestressed tendons are embedded in concrete using the * embed command in the ABAQUS software without considering sliding effects (as shown in Fig. 2).

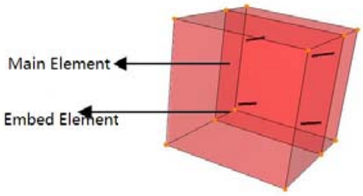
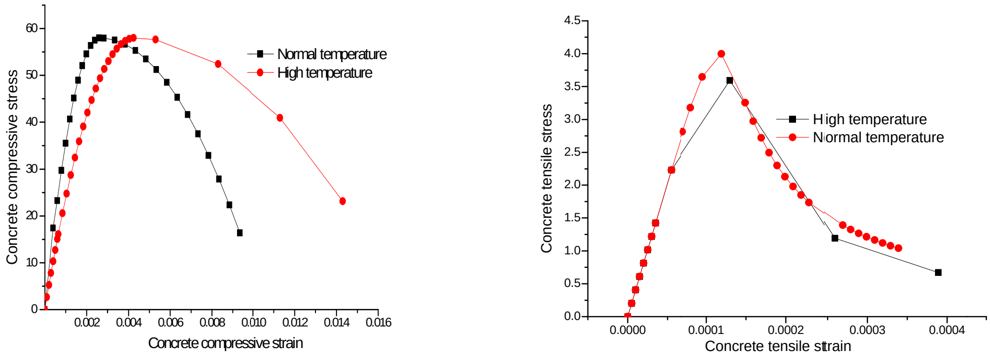


Figure 2. Embed Command Diagram

1.2 Material constitutive relationship

1.2.1 Concrete constitutive relationship

Considering the characteristics of containment structure, concrete damaged plasticity model is used in this study, which can reflect the plastic hardening and softening behavior of concrete. The concrete damaged plasticity model can take into account the tensile cracking and crushing failure of concrete, and it can also accurately reflect the damage caused by deformation of concrete materials. In order to compare the effect of temperature effect on the performance of containment structure, two kinds of compressive constitutive relations of concrete at normal temperature and high temperature are considered in this paper. The constitutive relationship recommended by concrete design code of GB50010 is used and constitutive relationship of concrete is shown in Fig. 3.

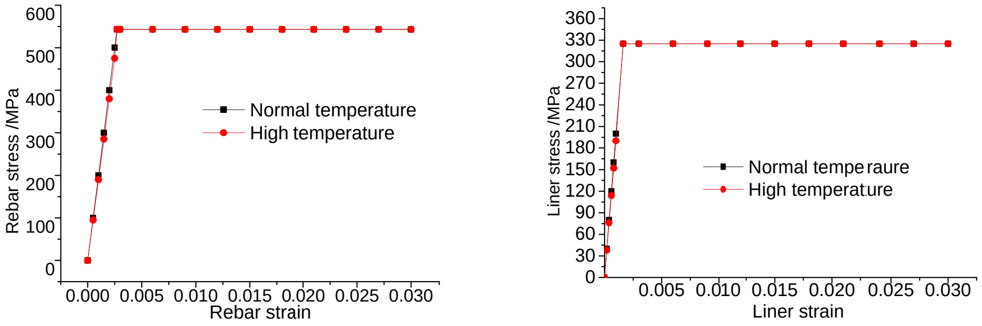


(a)Compressive constitution of concrete *(b)Tensile constitution of concrete*

Figure 3. constitution of concrete

1.2.2 Constitution of rebar and steel liner

The ideal elasto-plastic model is adopted in the finite element model for the constitutive relationship of rebar and steel liner. The elastic modulus of rebar and steel liner material is 200 000MPa, and the steel bar is made from HRB500. Because the maximum temperature is about 150 ℃ in the severe accident condition, the temperature has minor effects on the constitutive relation of steel bar and steel liner. Rebar, steel liner constitutive relationship as shown in Fig. 4.



(a) Constitution of rebar *(b) Constitution of steel liner*

Figure 4. Constitution of rebar and steel liner

1.2.3 Constitution of prestressed tendons

Since the prestressed tendons are made of steel strands without obvious yield point, the strain hardening constitutive relation of the prestressed tendons should be considered according to reference [2]. The yield strength of the prestressed tendons is 1860 MPa, and the elastic modulus of the prestressed tendons is 195 000 MPa. As shown in Fig. 5, the constitutive relation of prestressed tendons is basically consistent with the constitutive relation of rebar and steel liner, the constitutive relation of prestressed tendons at normal temperature and at high temperature is almost the same.

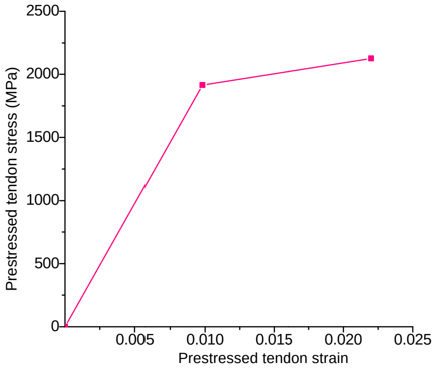


Figure 5. Constitution of prestressed tendons

1.3 Temperature-Coupling simulation

When the temperature of the object changes, the object will cause strain due to expansion. If the thermal deformation of each part of the object is not constrained, the deformation will not cause thermal stress. However, if the temperature of each part of the object is not uniform, or connected to other objects, that is, under constraints, the thermal deformation cannot be released freely, and then the thermal stress is induced. Under accident condition, the environmental temperature in the containment is higher, and the temperature difference between the inside and outside of the containment will inevitably induce the thermal stress.

In this paper, the thermal stress of containment shell is analyzed by sequential coupling method. The assumptions of the calculation are as follows:

1) Considering the small deformation of the structure, the temperature load is applied by the sequential coupling method, that is, firstly, the heat transfer calculation is carried out , the temperature distribution of the concrete is obtained, and then the calculated results are applied to the concrete.(Under LOCA accident, the time-history curve of temperature in the containment is shown in Fig. 6);
2) Using an approximate method to consider the thermal effects on rebar and prestressed tendons, that is to say, when calculating the temperature of concrete, the influence of rebar is not taken into account (the thermal resistance of concrete is much greater than the thermal resistance of steel bars, which is reasonable). Then the temperature of the prestressed tendons is obtained by interpolation method according to the position of the prestressed tendons in the concrete.
3) Thermal and mechanical properties of the materials are in accordance with the relevant Codes and taken into account during the analysis. The constitutive relation of the materials is shown in Fig. 3-Fig. 5.

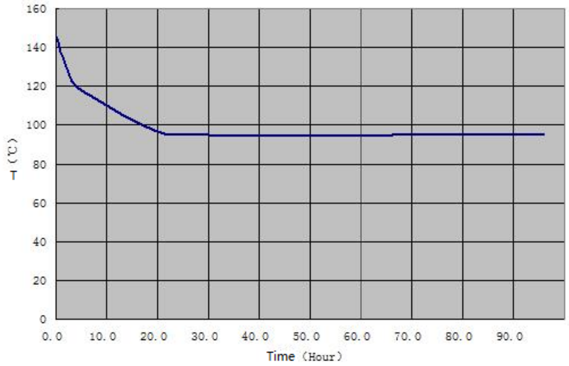


Figure 6. Time-history curve of temperature in the containment under LOCA accident

The thermal conduction analysis module of ABAQUS is used to obtain the temperature field of the containment under LOCA condition. The distribution of the temperature field inside the containment is obtained as shown in Fig. 7. From 0 to 20 hours, due to the large variation of temperature, the temperature decreases from inside to outside along the wall thickness of the containment and presents a parabolic gradient distribution. After 20 hours, the change of temperature tends to be smooth, and the temperature field along the direction of the thickness of the containment presents a linear gradient distribution.

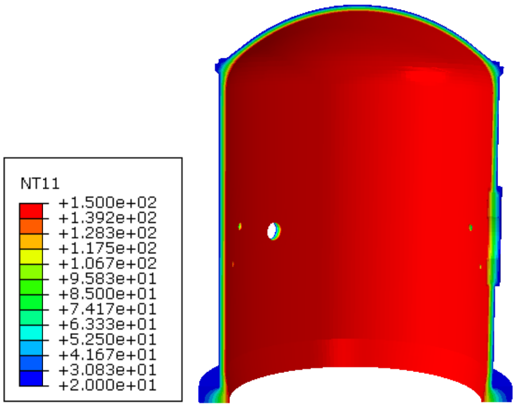


Figure 7. Temperature distribution inside the containment

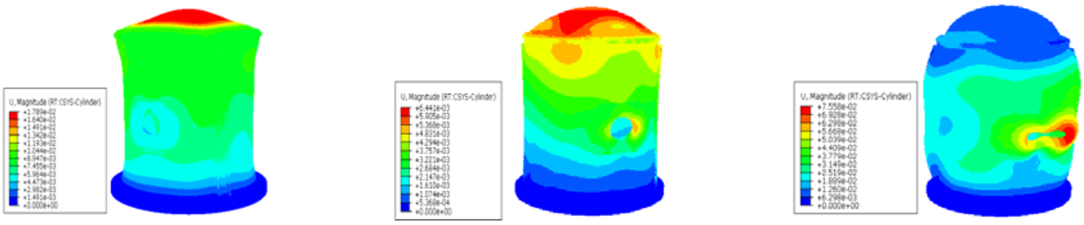
Combined with the study of temperature loading mode, the following analysis steps are established in ABAQUS simulation to perform the structural analysis under pressure and thermal effect:

- Applying self-weight
- Applying prestressing load
- Applying temperature load
- Applying pressure through step-by-step increase to 3 times design pressure (design internal pressure is 0.42MPa).

2 Temperature Effect Analysis Results

2.1 Nonlinear finite element results of containment considering temperature effect

The nephogram of the displacement distribution of the containment at different loading stages is shown in figure 8. From figure 8 (a), it can be seen that after prestressing loading, the whole cylinder wall of the containment occurs inwardly deformation, and the dome presents mainly outward deformation. At the same time, the deformation of the dome under prestressing effect is greater than that of the cylinder wall. When the containment is in the counter-prestressing stage, the deformation of the containment under prestresing effect decreases and the redistribute of displacement appears (as shown in fig. 8 (b). The containment is dominated by outward deformation from the end of counter-prestressing stage to ultimate capacity stage, as shown in Fig. 8 (c).

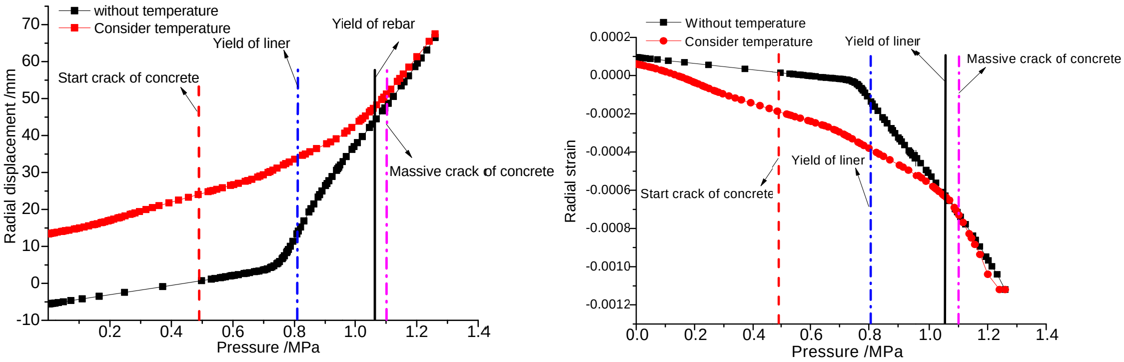


(a) After prestressing loading *(b) Counter-prestressing stage* *(c) Failure limit states*

Figure 8. Displacement distribution at different loading stages

2.2 Comparative analysis of containment considering temperature effect

The calculated results of the displacement and strain of the containment under severe accident temperature conditions and normal operational temperature conditions are shown in Fig.9. Current zone is selected for comparison, and the displacement and strain corresponding to the zero pressure point in the figure include the self-weight and the response of the initial prestressing load. It can be seen in Fig.9 (a) that, the temperature has the greatest influence on the radial displacement of the containment before the crack of the concrete; the effect of the temperature on the radial displacement of the containment is gradually reduced from the beginning of the concrete crack to the massive crack of concrete, and after the concrete is cracked massively, The temperature has small effect on the radial displacement of the containment. It can be seen in Fig.9 (b) that, the effect of temperature on the strain is similar to that of displacement.



(a) Comparison of radial displacement *(b) Compairison of radial strain*

Figure 9. Comparative diagram of temperature effect on containment structural nonlinear behavior

As analysis result showed, after considering the effect of temperature, thermal strain produced by temperature effects in containment leads to additional tensile strain in concrete. Before the cracking of concrete, the containment is under elastic condition without degradation of rigidity, the thermal stress is continuously applied on the containment. Therefore, temperature will cause great influence on the structural performance of containment. Comparing the tensile constitutive law of concrete under normal and high temperature can also lead to the conclusion that strength is decreased under high temperature, see figure 3 (b). Starting from the initial cracking of concrete until the massive cracking of concrete, in this stage, containment occurs partial crack, the rigidity is initially degraded due to the stress redistribution of concrete. The temperature effect on containment structure is decreased at this stage. After the complete cracking of concrete (massive crack), the rigidity of containment is basically degraded meanwhile material performance of reinforcement and liner has almost no degradation under this temperature condition (see figure 4a and b), thus containment nonlinear response has no obvious variation considering temperature effects at this stage.

3 Seismic Effect Analysis

The containment is positioned on the common raft. The geometrical conditions of containment are very complicated. These bring difficulties for seismic effect calculation. This paper analyzed the seismic effect through four methods.

3.1 Simplified equivalent static method, mass point-beam model

Applying uniform floor peak acceleration to the identical floor in equivalent static method is not prudent to calculate seismic effect. It can cause massive tolerance for complicated 3D finite element model calculation. Thus, this method is not recommended for calculating seismic effect of containment.

3.2 Improved equivalent static method

The improved equivalent static method applies the similar approach as equivalent static method. Instead of directly applying the uniform absolute acceleration a_I for each floor, a_I is distributed to each node by following rules, a_{iX} is the absolute acceleration of i node in X direction.

$$a_{iX} = \frac{X_i}{\sum_{i=1}^{N} |X_i| \Big/ N} a_{IX} \qquad (1)$$

In the equation, X_i is the displacement of i node in X direction.

a_{iY}, a_{iZ} is similarly described as a_{iX}.

Below comments are arised from this method:

The absolute acceleration of node is determined by displacements while ignoring the damping. The equivalent static force (elastic force) is expressed as below:

$$f_S = ku(t) = -m\ddot{u}^t(t) \quad \ddot{u}^t(t) = -\frac{k}{m}u(t) \qquad (2)$$

The direction is expressed by this method. The direction of absolute acceleration $\ddot{u}^t(t)$ is opposite to that of elastic force f_S, so as displacement u(t).

The challenge of this method is to identify the node displacement X_i, Y_i, Z_i of each floor. One option is to apply main vibration mode to determine displacement.

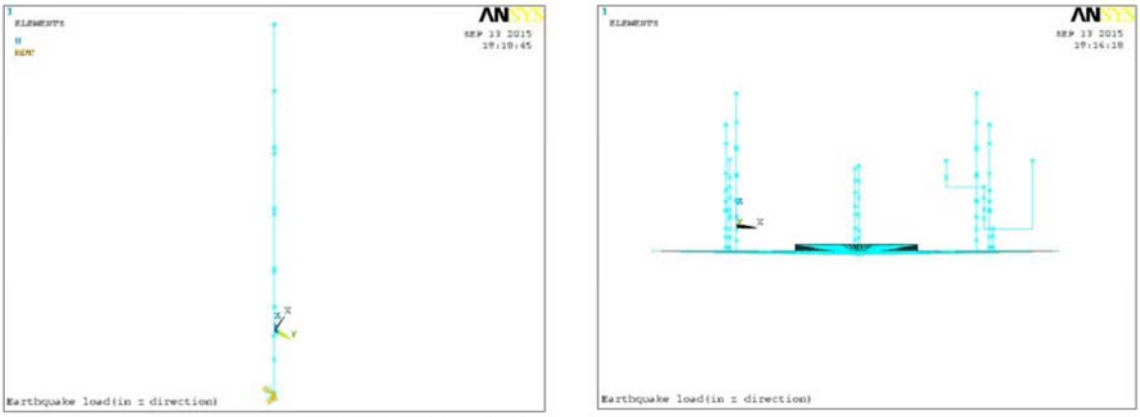
Due to complexity of finite element model with multiple vibration modes, the identification of main vibration mode is difficult. In addition, since there are many local vibrations, calculating absolute acceleration of node by main vibration mode might lead to a large tolerance.

3.3 Improved equivalent static method considering influence of vibration mode

To solve the shortness of only considering main vibration mode in chapter 3.2 by using improved equivalent static method, the contribution of each vibration mode is considered in this method by using the whole floor response spectrum. This method can ameliorate the disadvantage of improved equivalent method, however, the whole floor response spectrum would cause a large calculation work and lose the meaning of equivalent static method.

3.4 Mode-superposition response spectrum method

By considering floor response spectrum at the base of raft as design spectrum for containment finite element model, the mode-superposition response spectrum method is applied to calculate seismic effect and behavior of containment. Basement shear is compared through independent containment model and the global nuclear power plant model to justify its safety. The two models are described as below.



(a) Containment mass point-beam model

(b) Nuclear island plant mass point - beam model + common raft base

Figure10. Model diagram

3.5 Comparison of basement shear

The shear of containment basement through global model calculated by ground spectrum is around 3.5E8(N).

The shear of containment basement through independent containment model calculated by common raft floor response spectrum is around 3.6E8(N).

3.6 Conclusion of seismic effect analysis

Comparing the shear of containment basement through global model calculated by ground spectrum and that through independent containment model calculated by common raft floor response spectrum, the former is less than later, thus the seismic effect calculation by this method can be considered to be conservative and acceptable.

4 Conclusions

Through nonlinear finite element analysis of containment by considering the temperature effect, it shows that the temperature has a large influence on containment structural performance under elastic condition, this impact decreases with the development of crack. Therefore, in case of analysis and evaluation of prestressed concrete, temperature effect needs to be considered when evaluating the leak-tightness of containment; temperature effect can be neglected when analyzing ultimate capacity.

According to the comparison result of multiple seismic effect calculation methods, the mode-superposition response spectrum method is recommended to calculate seismic effect, by applying raft floor response spectrum as design spectrum of containment for the finite element model. However, since the containment structure is not so complex, other methods are also available for calculating seismic effect for the efficiency purpose, though they are more conservative in some cases.

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