Elasto-plastic response analysis of nuclear containment vessel structures under strong earthquakes

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Abstract. In order to ensure the earthquake-resistant safety of NPPs and avoid major equipment damage and damage of nuclear leakage, an elasto-plastic response analysis of the nuclear containment vessel structure is required to evaluate its seismic performance under strong earthquakes. Taking the CNP1000 nuclear containment vessel structure as the research object, the finite element software ABAQUS is used to establish a three-dimensional finite element model. Based on the dynamic elasto-plastic analysis theory, the influence of different earthquake intensity on the seismic response of the structure is analyzed. Through the displacement response, acceleration response and stress distribution of the structure, the characteristics of the seismic performance of the containment vessel are analyzed to obtain the structural response rules and structural damage links. The results show: the structure has an amplification effect on the acceleration response, and the amplification effect becomes more significant with the increase of the height; the structural weaknesses are the bottom of the cylinder and the vicinity of the equipment hole, and corresponding reinforcement measures should be added to improve the overall seismic performance of the structure.

1. Introduction

The nuclear containment vessel structure serves as the envelope structure for the main plant of the nuclear power plant reactor, is the last barrier to the diffusion of radioactive materials in the event of a design accident. When the structure encounters a strong earthquake, it gradually enters the elastic-plastic state from the elastic state. However, the structural anti-seismic analysis basically is established on line elasticity assumption with less research on the structural performance under the elasto-plastic state. At present, theoretical and experimental studies have been conducted at home and abroad on the earthquake response under the elasto-plastic condition of containment vessels. The seismic safety margin of the structure was assessed from the perspective of destroying seismic energy [1]. The nonlinear response of the structure was analyzed under the dual role of internal pressure and earthquake [2,3,4]. The elasto-plastic analysis method was used to compare and analyze the elastic seismic response and elasto-plastic seismic response of the structure [5,6]. These researches verify that the containment vessel structure has a large ultimate bearing capacity and seismic safety reserves, and reveal the seismic characteristics of the seismic response of the structure, but there is insufficient understanding of the elasto-plastic response laws and failures of structures under the action of strong earthquakes. Simultaneously, there is a possibility of strong earthquakes at many nuclear power plants.
sites in China. So that it is necessary to study the seismic response in the elasto-plastic state of the containment vessel structure. The dynamic elasto-plastic time history analysis method is used to study the dynamic response and stress response of the nuclear containment vessel structure. The response law of the structure under the strong earthquake is analyzed to find the relative weakness of the structure and provide a basis for design of the main powerhouse structure of the nuclear power plant.

2. Analysis model of nuclear containment vessel structure

2.1. Basic parameters of nuclear containment vessel structure
The CNP1000 nuclear containment vessel structure is mainly composed of a bottom plate, a cylindrical shell and a hemispherical shell dome. The bottom plate diameter is 50.0 m, its thickness is 6.5 m; the inner diameter of the cylindrical shell is 40.0 m, the wall thickness is 1.1 m, and the height is 48.0 m; the inner diameter of the hemispherical dome is 40.0 m and the wall thickness is 1.0 m; the total height of the containment vessel is 75.5 m. The geometric dimensions are shown in figure 1(a). There is a 7 m diameter device valve hole at a horizontal angle of 90° and a height of 25.6 m. A pedestal column is provided at each of the horizontal angles 0° and 180° for the anchoring of the circular prestressed steel bundles. The nuclear containment vessel structure is unbonded prestressed concrete structure, and the concrete strength grade is C50. The calculated elastic modulus (E_c) is 34.5 GPa, the Poisson's ratio (\nu_c) is 0.2, and the density (\rho_c) is 2500 kg/m³.

2.2. Establishment of finite element model
The finite element software ABAQUS is used to establish the nuclear containment vessel structure solid model. It is assumed that the foundation is rigid. The concrete of the bottom plate, cylindrical body and dome is mainly simulated by C3D8. The T3D2 element simulation is used for the prestressed steel strands, and the REBAR+SURFACE element simulation is used for the ordinary steel reinforcements. Steel strands and steel bars are embedded in the concrete using the Embedded command to achieve the bonding between them. The total finite element model and mesh of the nuclear containment vessel structure entity are shown in figure 1(b). There are 68513 common units and 51033 nodes divided.

![Figure 1. Geometrical dimensions and finite element model of containment vessel structure.](image)

2.3. Selection of constitutive model
In the simulation of concrete materials, the ABAQUS damage plasticity model is used. It is a continuous damage model based on plasticity, which can describe the irrecoverable damage occurring in the process of concrete crushing. The model is suitable for structural dynamic elasto-plastic analysis and has good convergence. Prestressed tendons and ordinary steels follow the von Mises elasto-plastic yield criterion and use a bi-break line model [6].

3. Modal analysis
In order to reasonably select seismic waves and understand the basic characteristics of the nuclear
containment vessel structure, the linear perturbation analysis step is established by using the finite element software ABAQUS. The modal analysis of the structure is performed based on the block Lanczos method to obtain the natural frequency and mode shape of the structure. The first and second order natural frequencies of the model are 4.165 Hz and 4.183 Hz respectively; the third order natural vibration frequency is 6.842 Hz and the mode shape is a cylinder triangle.

4. Ground motion input
The design earthquake level of CNP1000 nuclear power plant containment vessel is SL-2, equivalent to the United States SEE (Safety Shutdown Earthquake) level, the maximum acceleration is 0.4 g. According to the principle of seismic wave selection [7], the classical EL Centro wave is selected for dynamic time history analysis. The step length of the wave input is 0.02 s. The holding time is 20 s, which is generally 5-10 times of the natural period of the structure. The original seismic records are amplitude-modulated so that the peak accelerations of 0.3 g, 0.4 g and 0.5 g meet the requirements of strong earthquakes and their adjusted specific values are 2.94 m/s², 3.92 m/s² and 4.90 m/s². Based on the results of the modal analysis of the nuclear containment vessel structure, the main vibration mode of the structure is dominated by translational motion and the coupling between the modes is not obvious so that the elastic-plastic time history analysis still uses one-way seismic excitation.

5. Time history analysis results

5.1. Structural displacement response
The displacement time histories of the apex of the structure in the X-direction is subtracted from the time displacement histories at the bottom of the foundation to obtain the relative displacement time of the dome, as shown in figure 2(a)~(c). Figure 2(a), (b) and (c) correspond to the seismic intensity of 0.3 g, 0.4 g and 0.5 g. The relative displacement time-history curves under three kinds of ground motion intensity changes similarly with the magnitude of the input earthquake acceleration. When the acceleration reaches the peak point in 5.53 s, the maximum relative displacement of the dome will reach the maximum, and values of the displacement are 6.67 mm, 9.18 mm and 11.72 mm respectively.

![Figure 2. Relative displacement of the structure vertex in X-direction.](image)

Based on the time history of nuclear containment vessel structure displacement, the maximum relative displacement curve along the height distribution of the structure is shown in figure 3. The reason why the overall lateral displacement amplitude of the containment vessel structure is smaller is that the lateral stiffness is larger. The displacement of the structural apex relative to the base of the foundation is the largest, which means that the nuclear containment vessel structure has a certain amplification effect on the displacement response to earthquake; under the influence of earthquakes with different intensities, the relative displacements along the height distribution of the structure are basically the same, which shows that the stiffness along the height of the nuclear containment vessel structure changes uniformly and there is no abrupt change; under the effect of the three seismic intensities, the story drifts of the bottom layer are relatively large, indicating that the structural weakness is near the bottom of the structure.
5.2. Structure acceleration response

The acceleration of the vertex acceleration of the nuclear containment vessel structure is output to obtain the acceleration time history of the X-direction output of the dome under the three types of ground motion intensity in figure 4(a)–(c). Figure 4(a), (b) and (c) correspond to the seismic intensity of 0.3 g, 0.4 g and 0.5 g. It can be seen from the figure that the acceleration time histories of the vertex output and the input acceleration of the structure have similar waveform. The acceleration response amplitude also increases as increasing of the ground motion intensity. In the three types of ground motions, the absolute acceleration responses of the dome are 12.17 m/s², 16.22 m/s² and 19.79 m/s² and the corresponding time of occurrence are 2.65 s, 2.44 s and 2.41 s. So that it can be seen that the maximum acceleration time of the dome is relatively close.

Through the comparison of the substrate input seismic acceleration curve and the containment vessel vertex acceleration response curve, the acceleration magnifications under different ground motion intensities are obtained in figure 5. Acceleration magnification times of the peak accelerations of 0.3 g, 0.4 g and 0.5 g are 5.22, 5.48 and 5.13 respectively, which increases with the increasing of the structural height and changes non-linearly, revealing that the structural height of the nuclear containment vessel structure has a significant effect on the acceleration amplification effect.

Under different earthquake intensity, when the acceleration of the vertex of the nuclear containment vessel structure reaches the maximum, the acceleration distribution along the structure height is shown in figure 6. The X-directional acceleration distribution along the height is consistent with the basic characteristics of the X-direction first-order vibration mode. At the elevation of the structure between 0 m and 5 m, the acceleration value changes from a negative value to a positive value, which leads to a larger shear force at the structure, reflecting that the junction between the
bottom plate and the barrel of the structure is a weak part of the structure.

Figure 5. Acceleration magnification of the structure.

Figure 6. The acceleration distribution along the height at the moment of the maximum acceleration of the structure vertex.

5.3. Structural stress response

According to the nonlinear elasto-plastic analysis of the nuclear containment vessel structure, the distribution of the first principal stress of the structure at the maximum input acceleration (2.1 s) is shown in figure 7(a)–(c). When the input ground motion peak acceleration is 0.3 g, the maximum tensile stress of the nuclear containment vessel structure appears at the bottom of the cylinder as shown in figure 7(a), its value is 2.074 MPa, exceeds the tensile strength of the concrete. A small amount of cracking appears in the concrete at the bottom of the cylinder, and the stress centered around the cracking position is distributed in a circular direction. Four areas of tensile stress concentration occurred around the equipment hole, but the stress value have not reached the tensile strength of the concrete so that cracking do not occur.

![Figure 7](image)

(a) (b) (c)

Figure 7. The first principal stress contours of the structure at 2.1 s.

When the peak acceleration reaches 0.4 g, the maximum tensile stress of the nuclear containment vessel structure at the bottom of the cylinder reaches 2.396 MPa and the cracking area at the bottom of the cylinder further expands upward as shown in figure 7(b); the area where the tensile stress exceeds the tensile strength of the concrete first appeared on the lower side of the equipment hole, which also brings about the cracking phenomenon on the left and right sides of it.

When the peak acceleration reaches 0.5 g, the maximum tensile stress at the bottom of the nuclear containment vessel structure reaches 2.651 MPa as shown in figure 7(c), cracks occur in more concrete units, and cracks are more severe in the bottom part of the area; the area of high stress around the device hole of the nuclear containment vessel structure gradually expands, and the scope of cracking gradually simultaneously expands.
Therefore, under strong earthquakes, the nuclear containment vessel structure begins to crack from the point where the tensile stress is largest with the increase of seismic input intensity, and the cracking range gradually expands along the stress distribution direction until failure of the structure. According to the stress distribution and cracking of the structure under the action of the earthquake, weak parts of the structure are places at the bottom of the nuclear containment vessel structure cylinder and around the equipment hole, which are the key positions of the seismic design and need to be considered.

6. Conclusions
The main conclusions are as follows:
(1) Under earthquake action, the acceleration magnification of the nuclear containment vessel structure increases with the increasing of the height, reflecting that structural height has a significant influence on the acceleration amplification effect.
(2) At the elevation of the structure between 0 m and 5 m, the acceleration value changes from a negative value to a positive value, which causes the structure to generate a large shear force at this point, revealing that the junction between the bottom plate and the cylinder of the structure is a weak part of the structure.
(3) Under earthquake action with different strengths, the stress concentration zone appears near the weakness of the structure and equipment hole, where the stress is distributed in a ring shape around the cracking point of the structure.

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