Calculation of seismic performance of nuclear containment vessel structure under design base earthquake

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Abstract. To study dynamic response of the nuclear containment vessel structure under the action of design basis earthquake and evaluate the seismic performance of structure, the elastic time history analysis of nuclear containment vessel structure is performed to determine the most unfavorable displacement and stress distribution. A 3D nuclear containment vessel structure was modelled in FE package tool ABAQUS to perform time analysis. The maximum displacement in X direction occurred at the top of the structure dome under the excitation of three different seismic records; the time at which the top response acceleration peak of the structure does not coincide with the time of the base input seismic wave peak, and it is mainly related to the relation between the period of natural vibration and the period of seismic waves; Under the different seismic waves’ excitation of 0.2 g peak acceleration, the tensile stress around the equipment hole and near connection between the bottom plate and the cylinder body is large, while the maximum tensile stress appears around the hole of the device. In the design of nuclear containment vessel structure, the displacement of the top should be controlled and the reinforcement ratio around equipment hole should be increased.

1. Introduction

Nuclear energy as a new energy source is indispensable in modern society. China will increase nuclear power plant construction on the basis of improving the safety of nuclear power. Nuclear power plant containment vessel is an extremely important structure for ensuring the safe operation of nuclear reactions. The destruction of containment vessel structure caused by earthquakes and the destruction of humans caused by nuclear leakage will be extremely tragic. Therefore, to ensure the safe operation of the nuclear reaction, the design of the nuclear containment vessel structure should be highly valued in its anti-seismic performance. At present, scholars at home and abroad have systematically studied the determination of seismic fortification of nuclear power plants, the analysis of nuclear containment vessel structure 3D seismic response, and nuclear containment vessel structure model tests, achieved certain research results. Pekka Iivonen [1], T.Kobayashi [2] and Pentti Varpasuo et al. [3] established the finite element analysis model of the containment vessel structure, combined with the seismic design code of china to carry out dynamic time-history analysis of the containment vessel structure to obtain the displacement of the structure. According to the displacement response, acceleration response and floor response spectrum of the structure, it provides a theoretical basis for evaluating the
seismic capability of nuclear power plant. China has also done a lot of research work on the seismic performance of nuclear containment vessel structure. Shen Xiaobai [4] and Wang Xiaolei et al.[5] established a 1:15 scale model of nuclear containment vessel, conducted shaking table tests, and tested experimental values and theories. The results obtained by derivation are close to each other. Tests show that the containment vessel structure is still within the elastic deformation range under the action of the design reference earthquake. The containment vessel structure has a large enough seismic storage capacity. In summary, analyzing the seismic performance of nuclear safety shell structures under earthquake is the basic guarantee for ensuring the normal operation of nuclear reactions. At the same time, it provides theoretical support for the design of nuclear containment vessel structures and evaluation of seismic margin.

2. Dynamic time history analysis theory

Time history analysis method is an iterative calculation method for seismic calculation by establishing system mechanical equations. The basic principle is: the ground motion time is divided into a series of small time intervals $\Delta t$ according to a fixed time interval and quantity, calculate the reaction of the structure at each moment by step integration. The vibration equation is

$$\left[ M \right] \ddot{u} + \left[ C \right] \dot{u} + \left[ K \right] u = - \left[ M \right] \ddot{u}_s$$  \hspace{1cm} (2.1)

Where $[M]$ is mass matrices; $[C]$ is damping matrices; $[K]$ is stiffness Matrices; $\ddot{u}_s$ is input seismic acceleration of each moment. Damping matrix calculation formula

$$[c] = a[M] + b[K]$$  \hspace{1cm} (2.2)

Where $a$ and $b$ are matrix damping coefficient, it is determined by the mode decomposition method

$$a = \frac{2\omega_0 \epsilon \omega_i \left( \omega_i - \epsilon \omega_0 \right)}{\omega_i^2 - \epsilon^2 \omega_0^2}$$  \hspace{1cm} (2.3)

$$b = \frac{2\epsilon \omega_0 \left( \omega_i - \epsilon \omega_0 \right)}{\omega_i^2 - \epsilon^2 \omega_0^2}$$  \hspace{1cm} (2.4)

Where equation 2.1, the change quantity is large and the real-time change frequency is fast, the seismic response of the structure can not be obtained by mathematical solution. The numerical method can solve the above problems. The Newmark $- B$ [6] method is used as a numerical method to solve this problem.

3. Model establishment and ground motion input

3.1. Establish the containment vessel structure finite element model

A prestressed concrete containment vessel structure consists of a hemispherical dome, a cylindrical body, and a base slab. Hemispherical dome with inner diameter of 40 m and dome wall thickness of 0.9 m; The inner diameter of the cylindrical cylinder is 40 m, the height of the cylinder is 48 m, and the wall thickness of the cylinder is 1.1 m; The basic floor thickness is 6.5 m; and the total height of the containment vessel structure is 68.9 m; The concrete strength grade is C50, elasticity modulus of concrete is 34.5 GPa, poisson ratio is 0.2 and density is 2500 kg/m³. Geometry of the nuclear containment vessel structure is shown in figure 1(a).

In the analysis, the solid model of nuclear containment vessel structure was established by finite element analysis software ABAQUS. It is assumed that the bottom plate of the nuclear safety shell is fixed on the foundation, and R3D4 ELEMENT is chosen to simulate the foundation, which is regarded as rigid; C3D8R ELEMENT is used to simulate the nuclear containment vessel structure bottom plate, dome and cylinder adopts unit simulation; Both the circumferential and vertical prestressed steel bars are all modelled by T3D2 ELEMENT, and ordinary steel bars are simulated by REBAR+SURFACE methods. Cooling method is used to simulate the application of prestressed. Ordinary steel bars and prestressed steel bars are embedded in concrete units using the ABAQUS built-in Embedded
command. The employed mesh consists of 68513 elements and 51033 nodes in the following analysis. As shown in figure 1(b).

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

3.2. Ground motion input
When the nuclear containment vessel structure is subjected to time history analysis, the self-weight and the prestress are applied by multiple cooling. The El-Centro wave, Taft wave and Nanjing wave were respectively input in the X direction of the structural base to obtain displacement response, acceleration response, and stress response of nuclear containment vessel structure. Before the wave is input, it is necessary to adjust the spectrum of the seismic wave, the peak value of the acceleration, and the time of the ground motion. To meet the seismic parameters of most nuclear power plants in China, the design of the nuclear plant containment vessel structure is based on a seismic intensity of 0.2 g, various seismic waves take the first 20 s, the time interval takes 0.02 s, corresponding seismic wave horizontal peak acceleration is adjusted to 1.96 m/s². As shown in figure 2.

![Figure 2. Earthquake wave after adjusting the peak acceleration.](image)

4. Calculation of elastic time history of structure

4.1. Displacement response calculation
In the entire time history analysis, the maximum displacement in X direction occurred at the top of the structural dome of the nuclear containment vessel structure under the excitation of three different seismic records. The maximum displacement is 4.84 mm, 4.66 mm and 4.37 mm, the corresponding time of occurrence is t=2.79 s, t=6.9 s and t=10.6 s respectively. Figure 3(a) ~ (b) gives the overall structure of the displacement of the structure at the moment of their maximum displacement.

As shown in figure 4(a) ~ (c), the X - direction maximum displacement of the containment vessel structure along the height distribution under different seismic waves. The El-Centro wave has the greatest effect on the structural deformation, and its maximum displacement is 4.84 mm, displacement is littler, which indicates that the rigidity of the structure is large; under the different seismic waves’
excitation of 0.2g peak acceleration, horizontal maximum displacement of the structure increases gradually from bottom to top, which is basically linear. The overall lateral shift amplitude of the structure is small, indicating uniform changes in the stiffness of the nuclear containment vessel structure; the bottom layer displacement of the containment vessel structure is greater than other layers, indicating that the bottom layer of the nuclear containment vessel structure is subjected to a large force, and the bottom is a weak part.

Figure 3. Displacement deformation of the nuclear containment vessel structure.

Figure 4. The X direction maximum displacement along the height.

4.2. Acceleration response calculation

Time history analysis is performed to obtain the acceleration of nuclear containment vessel structure, at different height under three different seismic waves. Comparing with the input acceleration of the structural substrate, it can get the height magnification of each height position. As shown in figure 5(a) ~ (c).

Figure 5. Acceleration magnification factor of the containment vessel structure.
Figure 6(a) ~ (c) gives the acceleration time history curve of the vertex of the dome of the nuclear containment vessel structure in the X direction. The figure shows the acceleration time history at the top of the nuclear containment vessel structure and the acceleration time history at the base position have a consistent change trend under different seismic waves. The maximum output acceleration during the entire analysis reached 8.82 m/s², 7.70 m/s² and 6.87 m/s². The corresponding moment is 5.0 s, 4.5 s and 3.9 s. The time of the structure’s the top-level response acceleration peak does not coincide with the time of the base-input seismic wave peak, which causes the periodic lag, mainly related to the relative relationship between the natural period and the seismic wave cycle of the structure.

![Figure 6](image)

**Figure 6.** The acceleration time history of the containment vessel structure vertex.

### 4.3. Stress response calculation

Considering the complexity and importance of the nuclear containment vessel structure, it is necessary to analysis the seismic response of the whole structure. Figure 7(a) ~ (c) give the first principal stress distribution cloud diagram of the nuclear containment vessel structure at different earthquake excitations.

![Figure 7](image)

**Figure 7.** The first principal stress contours of the containment vessel structure.

As shown in figure above, under the different seismic waves’ excitation of 0.2g peak acceleration, the tensile stress around the equipment hole of the structure and around the connection between the bottom plate and the cylinder body is large. The maximum tensile stress appears around the equipment hole, the values are 0.638 MPa, 0.627 MPa and 0.606MPa. It shows the maximum tensile stress of concrete in the nuclear containment structure did not achieve the tensile strength of C50 concrete under the excitation of different seismic waves’ 0.2 g peak acceleration. Concrete elements do not crack in the structure. It is shown that the nuclear containment structure maintains its elastic condition, while the structure has a large seismic storage and meets the seismic requirements.
5. Conclusions
In this paper, a 3D nuclear containment structure was modelled in FE package tool ABAQUS to perform time analysis. The conclusions can be drawn as following:

(1) The bottom layer displacement of the containment vessel structure is greater than other layers, and the bottom of the containment vessel structure is a weak part. In the design of the structure, it is necessary to appropriately increase the reinforcement ratio and enhance the structural stability;

(2) The X-axis maximum acceleration response of the dome is inconsistent with the time of the peak of the input seismic wave, which is mainly related to the relative relationship between the natural period and the seismic wave cycle of the structure;

(3) Under the different seismic waves’ excitation of 0.2 g peak acceleration, the maximum tensile stress of the concrete in the nuclear containment vessel structure is 0.638 MPa. The tensile strength of C50 concrete is not reached, and the nuclear containment vessel structure maintains its elasticity. The structure has a large seismic margin and meets seismic requirements.

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