Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division VII

SEISMICRELIABILITYASSESSMENTOF PRESTRESSEDCONCRETECONTAINMENTFOR CNP1000

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ABSTRACT

It is a good approach to apply seismic isolation devices in the containment in nuclear power plants to enhance seismic safety. A three-dimensional finite element model with the isolation bearing is established, and the seismic reliability analysis is carried out for isolated and non-isolated containment. The probability of concrete crack for base-isolated containment is shown as well as non-isolated containment with Latin hypercube sampling method. In addition, the probability of isolation devices' displacement exceeding the limit is also presented. It can be concluded that the base-isolated containment greatly improves its safety due to reasonable arrangement of isolation devices, that the failure probability of concrete crack of base-isolated containment at PGA equal to 0.3g is basically equivalent to that of non-isolated containment at 0.7g. And the failure probability of isolation devices can also be controlled within very low level.

1 INTRODUCTION

Nuclear seismic safety has been an increasingly sensitive problem during last decade.One of the most probable reasons is that nuclear power plant (NPP) may encounter beyond-design basis earthquake ground motions at any time, and seismic-induced probability of failure of nuclear structures, systems and components (SSC) cannot be denied. With continuous effort of increasing safety levelof NPP against damage initiated by earthquake events, many researchers concentrate their attention on how to mitigate effects and uncertainties of earthquake ground motions, such as isolation technique and energy dissipation technique. In 2010, (Forasassi andLoFrano, 2010)established a base-isolated three-dimensional near term reactor to investigate its influence on the reactor and prove its effectiveness and feasibility.

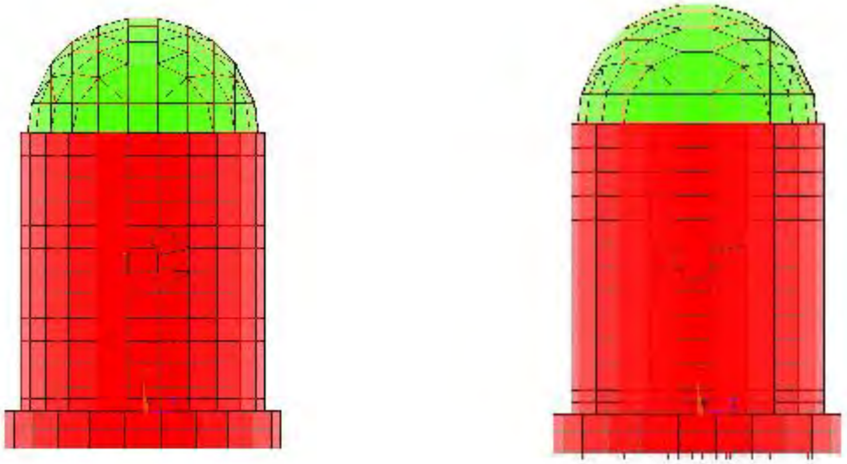
For quantification of effectiveness of base-isolated NPP, probability-based method is adopted to compare the base-isolated and non-base-isolated containment building, which is of course a better tool than deterministic assessment of structural response. The aim of this study is to present a methodology for evaluating the base-isolated containment building for CNP1000. The SSI effects is not taken into account as the containment building is assumed to be located on a stiff soil.

There are many researches focusing on the seismic reliability of containment building of NPP. (Choi et al.,2006) performed fragility analysis with a 3D cantilever beam simplified from the actual containment building, which may neglect the effects of local damage on the containment building.(Huang et al., 2011)developed fragility curves for secondary systems expressed in terms of structural response parameters, which is more rational than that in terms of ground motion parameters. In addition,(Cho et al., 2005)points out that fragility analysis results is considerably affected by site-specific ground motions selected. Therefore, in order to obtain a family of unbiased fragility curves based on the three dimensional containment model which more reflect the true seismic response, extensive dynamic time-history analysis is needed and is very time consuming. This paper develops reliability analysis based on 3D finite element model of base-isolated and non-base-isolated containment building coupled with response spectrum method. In the beginning, the containment building geometry and 3D finite element model are described.Then the paper shows the seismic response analysis and seismic capacity for base-isolated and non-base-isolated containment building. And the first principle stress is used to reflect the structural response parameter to represent the seismic capacity of the containment building. Finally, the reliability analysis results of non-base-isolated and base-isolated containment building with different total equivalent horizontal stiffness of isolation devices are compared.

2 THE CONTAINMENTGEOMETRYAND 3D FINITEELEMENTMODEL

CNP1000 is a PWR nuclear power plant designed independently by China and has a power rating of 1000MW. The containment is a prestressed concrete structure and composed of a cylindrical part and a hemispherical dome (Wang et al., 2008;Xia et al., 2002).The inside diameter of the cylinder is 40.0 m, wall thickness 1.1m and height 48.0m. The inside radius of the dome is 20 m,dome thickness 0.9 m, and the total height of the containment is 68.9 m. Two buttresses are set up in the horizontal angle of 0 degree and 180 degree in order to anchor the horizontal hoop tendons which surround the entire circumference of the containment. On the containment building there is a 7 m diameter orifice in the horizontal angle of 90 degree and the height of 25.6 m.

The containment building model was established with finite element modeling code (ANSYS software, 2009): the solid elements (solid65) were chosen to represent the concrete walls of cylindrical part and the foundation, the shell elements (shell63) for the dome, and the horizontal hoop tendons and vertical tendons were set up through truss elements (link8). For base-isolated containment model, spring-damper elements (combin14) were chosen to simulate the isolation devices. According to the proposed modeling method above, the base-isolated and non-base-isolated containment building were set up as shown in Fig.1. Fig.2 and Fig.3 show the scheme of distribution of hoop and vertical tendons and layout of isolation devices, respectively.



(a) (b)

Fig.1.Non-base-isolated (a) and base-isolated containment building (b)

3 THESEISMICRESPONSEANALYSIS

Conventional seismic response analysis for fragility analysis was carried out through dynamic time history analysis. However, extensive dynamic time history analysis is time-consuming and may have a biased analysis results if the quantities of the ground motion selected or generated from referenced response spectrum are not enough to obtain an unbiased results. It is important to note that response spectrum in nature represents the ground motions and the ground motions can be replaced by the response spectrum for the containment building fragility analysis. Moreover, the modified response spectrum

(NUREG/CR-0098, 1978) developed by Newmark and Hall is not only a probability-based response spectrum that the control point corresponds to a logarithmic distribution but also have a range of damping values from 0.5 percent critical to 20 percent critical, as shown in Table 1. And the vertical motions will be achieved based on the horizontal direction spectrum values multiplied by 2/3 across the entire frequency range due to Newmark and Hall's recommendation.

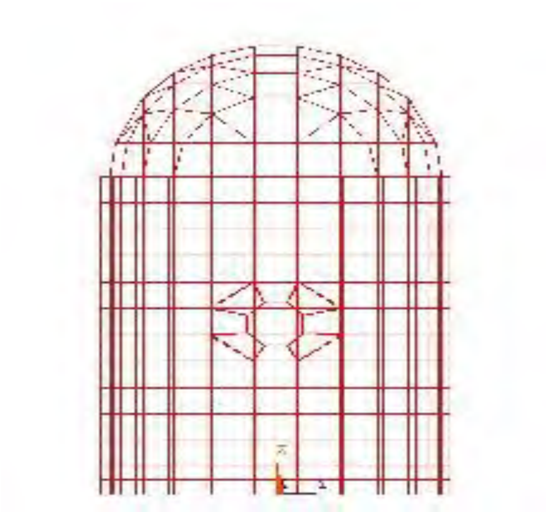


Fig.2. Distribution of hoop and vertical tendons

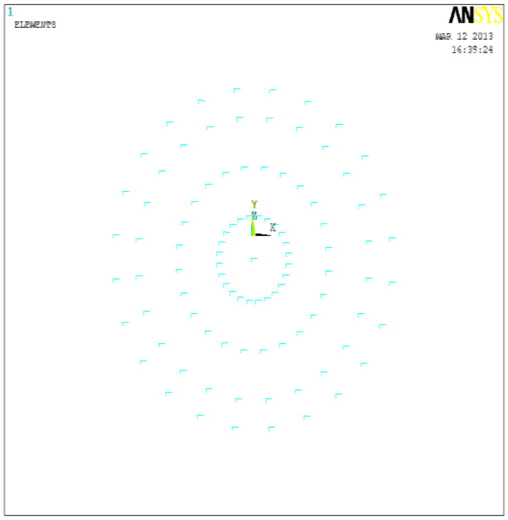


Fig.3. Layout of isolation devices

Table 1 Spectrum amplification factors for horizontal elastic response

Damping %critical	One sigma (84.1%)			Median (50%)		
	α_A	α_V	α_D	α_A	α_V	α_D
0.5%	5.10	3.84	3.04	3.68	2.59	2.01
1%	4.38	3.38	2.73	3.21	2.31	1.82
2%	3.66	2.92	2.42	2.74	2.03	1.63
3%	3.24	2.64	2.24	2.46	1.86	1.52
5%	2.71	2.30	2.01	2.12	1.65	1.39
7%	2.36	2.08	1.85	1.89	1.51	1.29
10%	1.99	1.84	1.69	1.64	1.37	1.20
20%	1.26	1.37	1.38	1.17	1.08	1.01

Before the development of the response spectrum analysis of base-isolated and non-base-isolated containment building, damping values were first assumed to representthe dynamic characteristics of the structure and the energy absorbed by the structure under earthquake excitations. It is important to stress that base-isolated structures have non-classical damping characteristics, and as the damping values of the isolation devices increase, the non-classical damping characteristics will be more evident that may affect the response of the structure greatly. Instead of assuming classical damping values, material-dependent dampingsupported by (ANSYS software, 2009)was used, as shown in equation (1).

$$\xi_i = \frac{\sum_{j=1}^{N_m} \beta_j^m E_j^s}{\sum_{j=1}^{N_m} E_j^s} \qquad (1)$$

Where: ξ_i is the effective damping ratio for mode i; β_j^m is the damping constant stiffness matrix multiplier for material j; and E_j^s is given by:

$$E_j^s = \frac{1}{2}\{\phi_i\}^T\left[K_j\right]\{\phi_i\} \tag{2}$$

Where: E_j^s is the strain energy for material j in mode i; $\{\phi_i\}$ is the displacement vector for mode i; $\left[K_j\right]$ is the stiffness matrix of part of structure of material j.

Assuming that the damping ratio of superstructure was 0.05 and the isolation devices 0.2, the effective mode damping ratio calculated by (ANSYS software, 2009) can be derived from Table 2. Therefore, as the damping ratio of the isolation devices varies, the effective mode damping ratio will be changed.

Table 2 Effective modal damping ratio calculated by ANSYS

Mode	Damping ratio	Mode	Damping ratio	Mode	Damping ratio	Mode	Damping ratio	Mode	Damping ratio
1	0.199	5	0.05	9	0.049	13	0	17	0
2	0.199	6	0.049	10	0.048	14	0	18	0
3	0.199	7	0.049	11	0	15	0	19	0.049
4	0	8	0	12	0.05	16	0.049	20	0

Afterwards, the uncertainty of structural properties were also taken into account to obtain the probability-based response. The structural properties selected to be random variables are density of concrete, density of prestressed steel, poisson's ratio of concrete, poisson's ratio of steel, thickness of dome, elastic modulus of concrete, elastic modulus of steel, tensile stress of concrete, thickness of cylindrical wall. The statistical characteristics of random variables assumed to be normal and the mean values and standard deviation are given in table 3 according to code for design of concrete structures of Chinese and (Jiang et al., 1995).

Table 3Statistical characteristics of random variables of nuclear containment

Random variables	Distribution type	Mean	Standard deviation
Density of concrete[Kg/m^3]	Normal	2500	50
Density of prestressed steel[Kg/m^3]	Normal	7850	157
Poisson's ratio of Concrete	Normal	0.2	0.12
Poisson's ratio of steel	Normal	0.3	0.18
Thickness of dome[m]	Normal	0.9	0.009
Elastic modulus of concrete[N/m^2]	Normal	3.6e10	0.36e10
Elastic modulus of steel[N/m^2]	Normal	1.95e11	0.195e11
Tensile stress for concrete[N/m^2]	Normal	3.238e6	0.4857e6
Thickness of wall[m]	Normal	1.1	0.011

According to the information above, the response of base-isolated and non-base-isolated containment building were performed not only account for the uncertainty of ground motion referred to as aleatoric uncertainty but also the containment properties referred to as epistemic uncertainty. In thecarried out analysis, extensive groups of response spectrum curves based on different damping ratios and structural properties generated with Latin hypercube sampling method (Iman, 1980)were combined, resulting in a combination of random models with different structural properties andrandom seismic demand. Andnote thatthe three directional response spectrum excitation are applied to the containment building.

4 THESEISMICCAPACITYOFCONTAINMENTBUILDING

According to (Han etal., 1998), since crack failure is an important index for the design of reinforced concrete containment structures to protect the radioactive materials from emission, the cracking of concrete is defined as a limit state based on the first strength theory, and the limit state equation is given by:

$$Z = R(x) - S(x) = f_t - \sigma_1 \tag{3}$$

in which $R(x)$ and $S(x)$ are the expression of the structural capacity and response respectively; f_t and σ_1 are the tensile strength of concrete and first principle stress, respectively.

Also for the isolation devices, the failure of the isolation devices is served as another limit state, which is written as:

$$Z = R(x) - S(x) = d_L - d_R \tag{4}$$

in which d_R is the displacement of isolation devices under earthquake excitation, d_L the maximum allowable displacement.

5 RELIABILITYANALYSIS

5.1 The Sampling Number

In reliability analysis, sampling number affects not only the accuracy of the obtained analysis results but also the time for analysis. Before the performed reliability analysis, the sampling number was first defined in order to reach the unbiased results and also to save time. Fig.4 shows the tendency for the mean of first principle stress versus the sampling number, and Fig.5 for the coefficient of variation, which demonstrates that 5000 sample size is enough to reach the unbiased results.

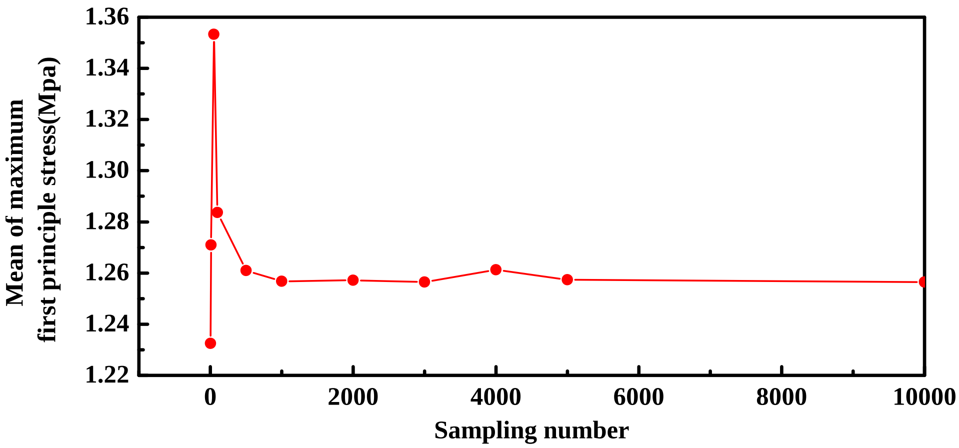


Fig.4.Tendency for the mean of first principle stress

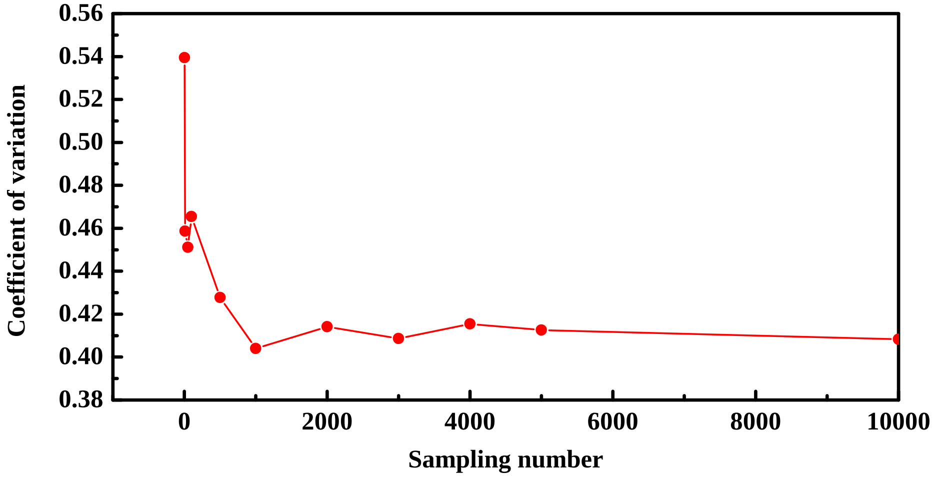


Fig.4.Tendency for the coefficient of variation

5.2 Analysis Results

5000 sampling analysis were performed for non-base-isolated and base-isolated containment building with different total equivalent horizontal stiffness for isolation devices, and the obtained results are summarized in table 4, table 5, table 6, table 7. Note that the damping ratio of isolation devices were assumed to be 0.2 in order to investigate the effects of horizontal stiffness of isolation devices on the containment building.

Table 4 Reliability of nuclear containment without isolation under different PGA

PGA	0.3g	0.4g	0.5g	0.6g	0.7g	0.8g
Cracking of concrete	3.08×10^{-2}	2.66×10^{-1}	6.12×10^{-1}	7.84×10^{-1}	9.21×10^{-1}	9.99×10^{-1}

Table 5 Reliability with total *equivalent* horizontal *stiffness* of4.11e8N/mforisolation layerunder different PGA

PGA	0.3g	0.4g	0.5g	0.6g	0.7g	0.8g
Cracking of concrete	0	0	0	1×10^{-3}	2×10^{-3}	2.45×10^{-1}
Failure of isolation layer	1×10^{-3}	1×10^{-2}	2×10^{-2}	4.8×10^{-2}	9.2×10^{-2}	1.46×10^{-1}

Table 6 Reliability with total *equivalent* horizontal *stiffness* of7.88e8N/mforisolation layerunder different PGA

PGA	0.3g	0.4g	0.5g	0.6g	0.7g	0.8g
Cracking of concrete	0	0	1×10^{-3}	1.3×10^{-3}	4×10^{-3}	3.08×10^{-1}
Failure of isolation layer	0	0	0	1×10^{-3}	4×10^{-3}	1×10^{-2}

Table 7 Reliability with total *equivalent* horizontal *stiffness* of1.58e9N/mforisolation layerunder different PGA

PGA	0.3g	0.4g	0.5g	0.6g	0.7g	0.8g
Cracking of concrete	0	0	1.36×10^{-3}	3×10^{-3}	1.1×10^{-2}	4.45×10^{-1}
Failure of isolation layer	0	0	0	0	0	0

It can be read from the table above that as the total equivalent horizontal stiffness for the isolation devices increases, the failure probability of isolation layer decreases while the cracking of concrete is increased; also from the table 6 and table 7, the criterion for seismic precaution of NPP at least increase from 0.3g (SSE) to 0.4g on the condition that the superstructure and the isolation layer remains excellent without damage. It also should be noted that as the peak ground acceleration reaches 0.7g, the cracking of concrete can be kept within an allowable range and the isolation layers remain intact owing to reasonable arrangement of isolation devices (through changing the horizontal stiffness of the isolation devices). Observing the response of base-isolated containment under 0.8g earthquake excitation, the cracking of concrete increases rapidly and is larger than that of non-base-isolated containment by an order of magnitude.

5 CONCLUSION

This paper shows the evaluation of base-isolated and non-base-isolated containment building based on three-dimensional finite element model established by ANSYS and the response spectrum method coupled with Latin Hypercube sampling method. The probability of concrete crack and isolation devices' displacement exceeding the limit are presented indicating that the safety of containment building can be significantly improved if base-isolated. Compared with the non-base-isolated containment building, the probability of concrete crack for base-isolated containment under 0.7g seismic excitation is basically equivalent to that under 0.3g due to reasonable arrangement of isolation devices, and the failure probability of isolation devices can also be controlled within very low level.

ACKNOWLEDGEMENT

This research has been supported by the Seismic Industry Special Funds for Scientific Research (No. 201208013),the National Science and Technology Major Project (2011ZX06002-010-15), the National Natural Science Foundation of China (No. 51238012, 91215301), the Program for International Science and Technology Cooperation Projects of China (No. 2012DFA70810) and the Program for New Century Excellent Talents in University of Ministry of Education of China (No. NCET-11-0813).

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