Anti-seismic Performance Analysis of the Shielding Door in AP1000 Nuclear Power Plant

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Abstract

The shielding door is the important protective equipment of AP1000 nuclear power station. When the plant is not in the operation, it is mainly subjected to its own gravity, wind load, impact load from the heavy projectile, temperature load from the fire disaster and the seismic load from the earthquake. Taking the shielding door as the research object and using the security shut-down earthquake load as the design seismic load, the anti-seismic performance of the shielding door is analyzed and evaluated under the seismic load, respectively by two methods: static method and response spectrum method. The results show that the whole structure of the shielding door can meet the requirement of ASME; Using the static method, the worst direction of the horizontal acceleration is the direction of the angle of 45o which is the angle between one horizontal acceleration and the X axis. Spectrum analysis results show that the vertical acceleration of response spectrum contribution to seismic load, the stress and displacement is very small; Calculating results of the two methods are close, but the static method is a bit conservative.

Keywords — *AP1000; shielding door; anti-seismic performance.*

I. INTRODUCTION

AP1000 (Advanced Passive, million kilowatt) is a nuclear power technology for the advanced non-active pressurized water reactor. Its design goal is to achieve high security and good performance record. Security system design uses the natural driving force, such as pressurized gas, gravity, natural circulation, and convection, and do not use the active components, such as the pump, the fan or the diesel. It can maintain the normal operation of the function without the supply of the security level system, such as alternating current power, equipment cooling water, plant water, heating, ventilation and air-condition. Therefore, this reactor type has advantages of high security, good efficiency and high reliability[1-7]. The shielding door is an important protective equipment of AP1000 nuclear power station. When the plant is not in the operation, it is mainly subjected to its own gravity, wind load, impact load from the heavy projectile, thermal load from the fire disaster and the seismic load from the earthquake. In the design process of the shielding door, these loads should be considered. In these loads, the earthquake is an important reason to cause a nuclear power plant leakage accident[8, 9]. In order to prevent and reduce the damage caused by earthquake, the anti-seismic performance of the shielding door is of great significance for the safety, economy and reliability of AP1000 nuclear power plant.

At present, the shielding door has been widely used in general industrial, construction and civil equipment. Its design is standardization and normalization. But as protective equipment of AP1000 nuclear power plant, the manufacturing company or unit has no unified standards and specifications for the design of the shielding door. The choice of shielding door material is based on the following: First, high strength steel used in nuclear power protection can reduce the structure weight. Further, it alleviates the seismic action of the structure; Second, the steel has the uniform material and can be easy to ensure the strength and reliability of the structure; Third, the steel with good ductility can make the structure has a good ability of deformation, even if under the large deflection, it does not fall and can guarantee the anti-seismic safety of the structure. Therefore, steel is used as a good material to make the shielding door for seismic protection. However, if structural design and manufacture of the shielding door are improper, the door cannot show its various excellent performances. In addition, it does not necessarily have better seismic performance under the seismic action[10]. So the seismic design of the shielding door has important practical benefit.

II. STRUCTURE AND PARAMETERS OF THE SHIELDING DOOR

The shielding door in AP1000 Nuclear Power Plant includes six types: left open to the outside, right open to the outside, left open to the inside, right open to the inside, double open outward mother-son type and double open outward normal type. The paper takes the shielding door, which is the kind of right open to the outside, as the research object. Its structure mainly includes steel plate on the facade, shape steel with the function of reinforce in the door cavity and other parts components, such as the door closer, the hinge, the door bolt, the escape device, the handle and the lock cylinder (Fig. 1). By using the hinges, one door leaf is installed on the frame angle yards at the same side. The other side leaf is connected with door frame through door lock. When the shielding door cannot open normally, the escape device is used. Basic parameters of the door leaf structure: height of 2.25 m, width of 0.8 m, thickness of 50 mm. The steel plate thickness of the outside the door leaf is 2 mm. The rectangular steel is used in the door cavity , the total mass of the door is 85 Kg. According to the code for seismic design of nuclear power plants[10], the structure of the shielding door is seismic items for class II and body structure of the shielding door needs ensure their structural integrity under the safe shutdown earthquake load.

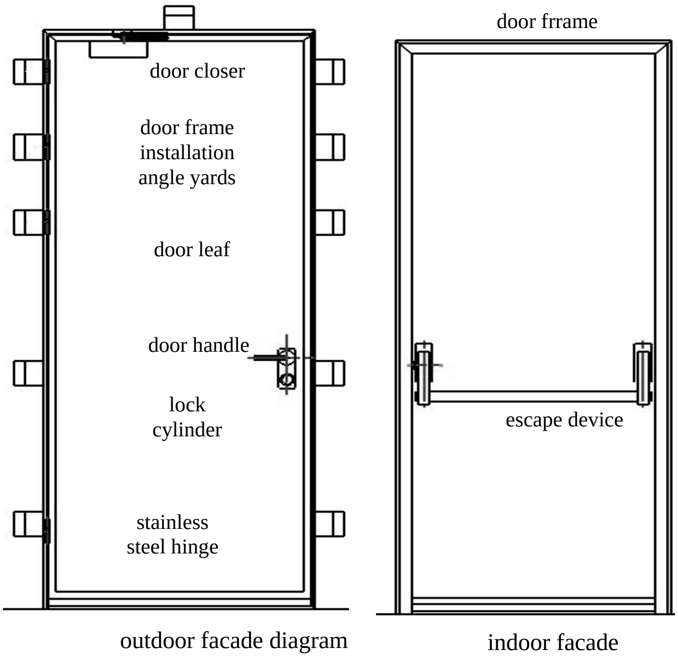


Fig.1 Structure of Shielding Door With Opening to the Right of its Outside

III. THE METHOD AND MODEL OF ANTI-SEISMIC ANALYSIS

A. The Method of Anti-Seismic Analysis

There are three analysis methods in nuclear power equipment seismic analysis, such as the static method, the spectrum analysis and the time history analysis method[11-13]. When the static method is used to estimate seismic force, the dynamic characteristics of structure and dynamic properties of earthquake (deformation and damping) are not considered. It is assumed that the structure was rigid and the horizontal earthquake force acted on the center of the mass of the structure, the size of the force was equivalent to the weight of the structure multiplied by a constant proportion. The spectrum analysis method develop based on the ground motion acceleration, the nature of the earthquake ground motion and the response characteristics of the structural dynamic. Based on the elastic response spectrum, the theory combines the response spectrum with structural vibration mode decomposition method. The total inner force of the structure is obtained by combining the forces of different vibration mode. It has a major breakthrough on the calculating method. At present, the spectrum analysis method is widely used in the seismic design of many countries after constantly improvement. The time history analysis method thinks the earthquake as a process of time, chooses typical earthquake acceleration time history as the ground motion input, simplifies the structure as the multiple degree system, gets the seismic response of the structure at each moment through calculation and completes the anti-seismic design work.

In the application of nuclear power engineering, the static method and spectrum analysis method are usually used. The anti-seismic performance of the steel door is analyzed and evaluated respectively by the two methods.

B. The Finite Element Model

According to the structural characteristics of shielding door, the finite element model is built by using the Shell181 and Beam188, as shown in Fig. 2. Because the mass of the hinge, the door handles, the escape device, the door closer and other hardware device relative to the mass of the door is very small, the effect of these components on anti-seismic performance of shielding door is not considered. The hinge in the model restrains three moving degrees of freedom and two rotational degrees of freedom. The handle restraints all degrees of freedom.

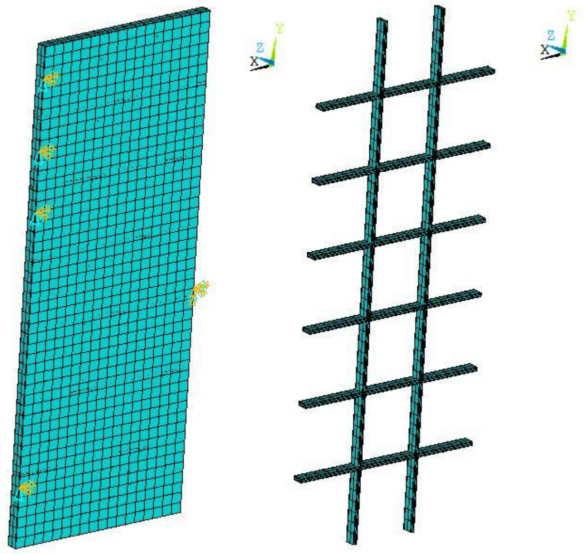


Fig.2 Finite Element Model of Steel Door

C. Static Analysis Method

The maximum acceleration of shielding door floor in the earthquake in each direction is selected as the acceleration of static method. The coordinate system is shown in Fig. 2. The first horizontal acceleration inputs along the X axis and the second horizontal acceleration inputs along the Z axis. Then, the first horizontal acceleration rotates around the Y axis to the positive direction of the Z axis. At the same time, two horizontal accelerations maintain the angle of 90o. Assuming that the angle of the first horizontal acceleration to the X axis is θ, value range of 0o ~ 360o and make one calculation every 45o. The computational load is the acceleration of gravity under the weight, the safety shutdown earthquake load is the superposition of the gravitational acceleration and the earthquake acceleration, as shown in Table I. The gravity and safety shutdown earthquake loads are applied to the shielding door to calculate. The relationship between the max tresca stress and the angle of horizontal acceleration is obtained by computing, as shown in Fig. 3. The results show that the max tresca stress change with the increase of the angle in the trend of approximate sine function. When θ equals 315o, the maximum tresca stress has a minimum value. When θ equals 45o, the max tresca stress has a max value. Therefore, the horizontal earthquake acceleration of θ=45o is used for seismic performance analysis and evaluation of shielding door.

Fig. 4 and 5 show the tresca stress and displacement of the shielding door under the gravity and seismic load. The maximum tresca stress appears at the door lock, because the incoming points of the earthquake force at the lock side are less than the other side. The biggest membrane stress Pm and the sum of the maximum membrane stress and the maximum bending stress (Pm + Pb) under various operating conditions are extracted, as shown in Table II. The force Fx and Fz of the earthquake acceleration in horizontal direction are equal and are greater than the force Fy in the vertical direction. This is in conformity with the size of the acceleration in different directions.

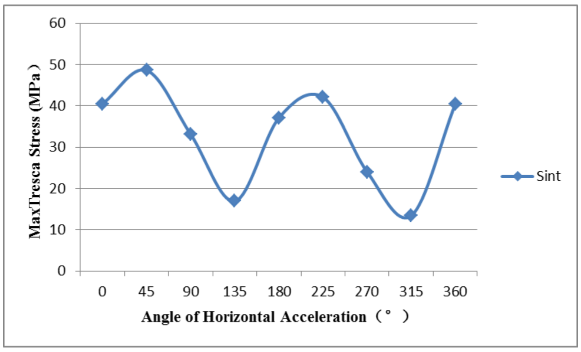


Fig.3 The Relationship Between The Max Tresca Stress And The Angle Of Horizontal Acceleration

TABLE I : GRAVITY AND SEISMIC ACCELERATION

Load	ax [m/s2]	ay [m/s2]	az [m/s2]
Gravity	0	9.80	0
Earthquake	60.48	48.90	60.48

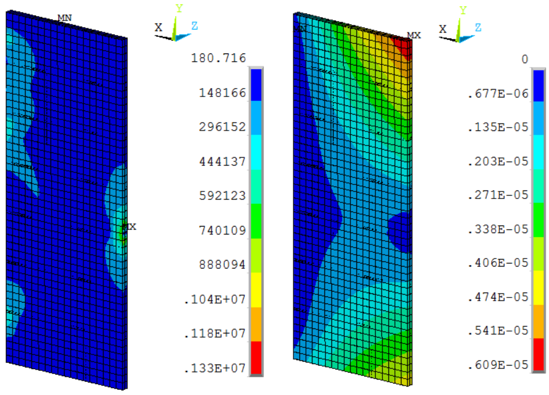
IV. SPECTRUM ANALYSIS

A. Modal Analysis

The modal analysis to the shielding door needs to be carried out before the spectral analysis. Modal analysis requires that the effective mass of the shielding door in each order natural frequency is greater than the 90 percent of the total mass of the finite element model. The effective mass and the proportion of participation of the shielding door under different order natural frequency can be obtained by calculating the front 10, 20 and 30 order natural frequency, as shown in Table III. The results shows that the sum of the effective mass and the proportion of participation in each direction are greater than 95% (more than 90%), meeting the 90% mass participation principle[15]. Therefore, the modal analysis uses the front 30 order natural frequency of the shielding door to calculate. The modal extraction method uses Block lanczos method.

TABLE II : STRESS AND REACTION FORCE RESULTS BY EQUIVALENT STATIC METHOD

Load	Gravity	Earthquake
Pm [MPa]	1.08	23.27
Sm [MPa]	Sm=125	2Sm=250
Pm + Pb [MPa]	1.33	38.05
Sm [MPa]	1.5Sm=187	2*1.5Sm=375
Fx [N]	0	5143
Fy [N]	833	4159
Fz [N]	0	5143

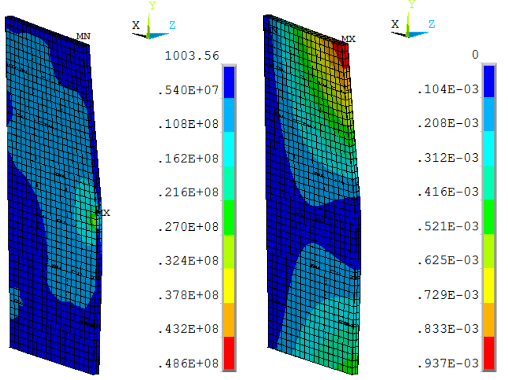


（a）Tresca stress [Pa] （b）displacement [m]

Fig.4 Tresca Stress and Displacement of the Steel Door Under the Gravity Load

The front 30 order natural frequency of the door are obtained by calculation, as shown in Table IV. The front 4 order vibration mode of the shielding door is shown in Fig. 6.

The front 4 order vibration modes are based on the bending vibration of the shielding door. The first order vibration mode focuses on the flexural vibrations of the upper of door lock. The second order vibration mode focuses on the flexural vibrations of the lower of door lock. The third order vibration mode focuses on the flexural vibration of the center of the hinge. The fourth order vibration mode focuses on the flexural vibration of the center of the hinge, the upper and lower of door lock. Because the vibrant area are unconstrained, improving the stiffness of these area can enhance the seismic intensity of the shielding door.



（a）Tresca stress [Pa] （b）displacement [m]

Fig.5 Tresca Stress And Displacement Of The Steel Door Under The Seismic Load

TABLE III : SUM OF MASS FOR THE FREQUENCIES IN DIFFERENT STEPS

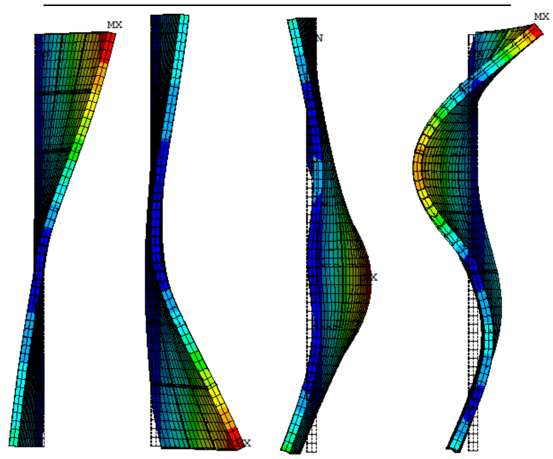
Order	Direction	X	Y	Z
10	Total effective mass/kg	51.22	11.32	51.22
	Percent of total mass /%	60.23	13.31	60.23
20	Total effective mass /kg	84.15	74.19	84.15
	Percent of total mass /%	98.95	87.24	98.95
30	Total effective mass /kg	84.21	81.2	84.21
	Percent of total mass /%	99	95.48	99

B. Spectrum analysis

The front 30 order natural frequency is used to perform the spectrum analysis. The model is applying the acceleration response spectrum in the horizontal directions (X and Z) and the horizontal and vertical directions (X, Y and Z). The stress distribution of the shielding door under different incentive is shown in Fig. 7 and 8. The max membrane stress Pm and the sum of the maximum membrane stress and the maximum bending stress (Pm + Pb) and the reaction force at the constraint under various loads are shown in Table V. The results show that: (1) the shielding door is able to withstand the load of safe shutdown earthquake and satisfies the requirement of anti-seismic design; (2) the vertical acceleration response spectrum makes little contribution to the seismic load, the stress and displacement.

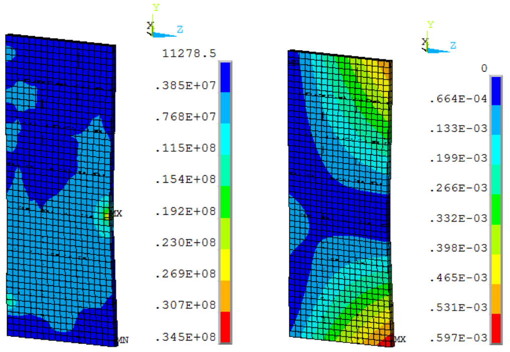
TABLE IV : FIRST 30 NATURAL FREQUENCIES OF THE STEEL DOOR

Order	Frequency	Order	Frequency
1	63.65	16	880.65
2	82.57	17	923.32
3	178.17	18	994.10
4	249.23	19	1034.07
5	324.26	20	1052.19
6	357.67	21	1123.04
7	403.31	22	1228.65
8	493.15	23	1285.49
9	526.94	24	1316.21
10	586.26	25	1362.16
11	602.19	26	1423.14
12	637.47	27	1448.98
13	721.25	28	1481.22
14	728.00	29	1555.06
15	788.73	30	1653.19



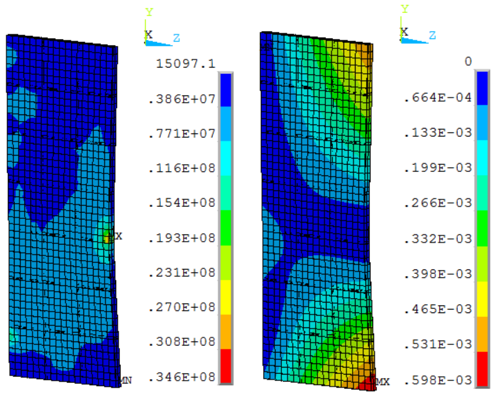
(a)First order （b）Second order （c）Third order（d）Fourth order

Fig.6 First, Second, Third, Fourth Order Model Shape



（a）Tresca stress [Pa] （b）displacement [m]

Fig.7 Tresca Stress And Displacement of the Steel Door Under The Horizontal Acceleration



（a）Tresca stress [Pa] （b）displacement [m]

Fig.8 Tresca Stress And Displacement of the Steel Door Under The Horizontal and Vertical Acceleration

TABLE V : STRESS AND REACTION FORCE RESULTS BY SPECTRAL ANALYZING METHOD

Direction	Horizontal direction	Direction X/Y/Z
Pm [MPa]	21.12	21.14
2Sm [MPa]	250	250
Pm + Pb [MPa]	36.07	36.53
3Sm [MPa]	375	375
Fx [N]	4003	4252
Fy [N]	4481	4900
Fz [N]	4822	5040

Results comparison is shown in Table VI. The vertical direction reacting force Fy in the static method is less than Fy in spectral analysis method. The horizontal reacting force Fx in the static method is greater than Fx in the spectrum analysis method. The horizontal reacting force Fz in two methods are close. And the stress results show that the static method is little conservative than spectral analyzing method.

TABLE VI : RESULTS COMPARISON

Analysis method	Pm [MPa]	Pm + Pb [MPa]	Fx [N]	Fy [N]	Fz [N]
Static	23.27	38.05	5143	4159	5143
Spectral analysis	21.14	36.53	4252	4900	5040
Ratio	0.91	0.96	0.83	1.18	0.98

V. CONCLUSIONS

According to the structural characteristics of the shielding door, the finite element model is built and the static method and response spectrum method are used to analyze and evaluate the anti-seismic performance. The results show that:

(1) The whole structure of the shielding door can meet the requirement of ASME.

(2) Using the static method, the worst direction of the horizontal acceleration is the direction of θ=45o.

(3) When the spectral analysis method is used, applying the 90% mass participation principle ensure the front 30 order natural frequency of the shielding door. Spectrum analysis results show that the vertical acceleration of response spectrum contribution to seismic load, the stress and displacement is very small.

(4) By comparing the results, the static method is simple, smaller amount of calculation and the acceleration and direction needs to be determined. This method is a bit conservative. The results of the spectrum analysis method are closed to the result of static method. Spectrum analysis method needs to compute natural frequencies and vibration mode. It is complex and larger amount of calculation, but the calculating results is more accurate.

ACKNOWLEDGMENT

The authors acknowledge the support of the Province Postdoctoral Foundation of Jiangsu (1501164B) and the Technical Innovation Nurturing Foundation of Yangzhou University (2015CXJ016).

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