Static Analysis of Factory Structures in the Reactor Device Area in a Nuclear Power Plant

Qingwu Shao\textsuperscript{1}, Yibo Fan\textsuperscript{1}, Xiaohai Qi\textsuperscript{1} and Yanqiang Bai\textsuperscript{1}

\textsuperscript{1} China Nuclear Power Technology Research Institute, Shenzhen, Guangdong, 518124, China

Abstract. To inspect the static response of the factory structures in reactor device area in a nuclear power plant in design and construction stage, a numeral model of the structures is set and the effect of different combinations of dead load, live load, wind load, seismic action and temperature effect are considered. It is considered that the combination of dead load, live load and seismic action has the control action and the spallation target factory is the most unfavorable part.

1. Introduction
The reactor device area, including the reactor factory, the spallation target factory, the electric and ancillary factory and the auxiliary factory, is the core and a critical sensitive area in a nuclear power plant. In the construction stage, the factories in the reactor device area will bear different kinds of combined effects consisting of dead load, live load, wind load, seismic action, temperature effect, etc. Since the structure forms of the factories are quite different from each other, considerable internal force of deformation will possibly appear in some part of certain factory under these combined effects, which will badly affect the safety performance of the structure. To investigate responses under combined effects and find out the most unfavorable load-bearing part of each factory, thus to take measures to reinforce the structures and take control of the construction quality to insure the safety of the factories, numerical models of the factories are built in the design stage to help analyze.

2. Principle of modeling

2.1 Model input
The numerical models of the factories in the reactor device area by ANSYS are shown as Figure 1-1. For a simpler analysis and a proper proportion to real factories, the sizes of the models are set as follows: the reactor factory is a 25m-long and 18m-wide cuboid with the bottom elevation of -10.000m and the top elevation of +15.000m (i.e. 25m high); the electric and ancillary factory is 55m-long and concave-shaped with the bottom elevation of -5.000 m and the top elevation of +15.000m (i.e. 20m high), and its widest side is 30m wide and the other side 22m wide; the auxiliary factory is rectangle-shaped with the bottom elevation of -10.000m and the top elevation of +15.000m (i.e. 25m high), and its longest side is 40m long and the other side 35.75m; the spallation target factory is a 25m-long and 20m-wide cuboid with the bottom elevation of -35.000m and the top elevation of +25.000m (i.e. 60m high); the elevation of the ground is ±0.000 m. All factories consist of roof sheathings, floors and load-bearing walls, and the thickness of all floors, roof sheathings, exterior walls and retaining walls is 0.5m and the other walls 0.3m, and all walls share the same material. The foundations of all factories are raft foundations with the heightness of 1.5m. All walls and floors are...
built by SHELL181, and the materials used in modeling include steel (HRB400) and concrete (C30).

2.2 Material Parameters

(1) Concrete (C30)

- Density: \( \rho = 2.5 \times 10^3 \text{ kg/m}^3 \)
- Design value of strength: \( f_c = 14.3 \text{ N/mm}^2, \ f_t = 1.43 \text{ N/mm}^2 \)
- Elasticity modulus: \( E_c = 3.0 \times 10^4 \text{ N/mm}^2 \)
- Poisson’s ratio: \( v = 0.3 \)
- Coefficient of linear expansion of all directions: \( \alpha = 1 \times 10^{-5} \text{ /}^\circ \text{C} \)

(2) Steel (HRB400)

- Density: \( \rho = 7.89 \times 10^3 \text{ kg/m}^3 \)
- Design value of strength: \( f_y = 360 \text{ N/mm}^2 \)
- Elasticity modulus: \( E_c = 2.0 \times 10^5 \text{ N/mm}^2 \)

3. Load input

3.1 Analysis method

5 kinds of load, including dead load (D), live load (L), wind load (W), seismic action (E_0, Ess) and temperature effect (T), are taken into consideration and selected to make different combinations according to the codes for structural design and nuclear design, thus to investigate the maximum deformation values and maximum stress values in X directions and Y directions of the roof sheathings, floors and walls and the entire cloud pictures for deformation and stress of each factory under different combinations listed.

3.2 Load setting

3.2.1 Dead load (D). The dead load includes the dead load of structures, the load of immobile equipment on each floor and the backfill lateral pressure between the elevation of ±0.000m and -10m. The dead load of structures is set as the acceleration of gravity with the value of 9.8m/s^2; the load of immobile equipment on each floor is equivalent to a uniform load with the value of 4kN/m^2 according to practical engineering; the backfill is set as sand so that the coefficient of active earth pressure is 0.3 and the gravity density is 16.17kN/m^3. The load setting is shown as Figure 2-1 (the blue area) and Figure 2-2 (the middle area).

3.2.2 Live load (L). The live load includes the roof live load with the value of 2kN/m^2 and roof live load with the value of 5kN/m^2 according to the Load Code for the Design of Building Structures (GB
50009-2012). The load setting is shown as Figure 2-3 (the blue area).

3.2.3 Wind load \((W)\). The value of basic wind pressure is set as 0.75kN/m\(^2\) according to the Load Code for the Design of Building Structures (GB 50009-2012), and positive wind and negative wind in X direction and Y direction (4 working conditions in total) are taken into consideration for the analysis. The load setting is shown as Figure 2-4 and Figure 2-5, where the uniform wind load (with the unit of Pa) in different windward and leeside are shown respectively by arrows with different colors. The area below the elevation of ±0.000m is the underground area without wind load.

3.2.4 Seismic action \((E_0, E_{ss})\). The seismic action includes frequent earthquake \((E_0)\) and rare earthquake \((E_{ss})\), and the acceleration in rare earthquake is 2 times of that in frequent earthquake. For seismic response spectrum analysis, 4 frequency points are selected and the calibration value is set as 0.15g. Each of seismic action is analyzed under horizontal condition (including X direction and Y
direction) and vertical condition (Z direction) i.e. 3 working conditions in total. The dead load of immobile equipment and floor live load are put in as added mass. The frequencies and the corresponding accelerations of frequent earthquake are shown as Table 2-1, and allowing for the complication of modeling, the top 50 natural frequencies of vibration in modal analysis are selected.

3.2.5 Temperature effect (T). According to practical engineering, the temperature inside the factories ranges from 15°C to 40°C and the construction temperature is 20°C, in this paper the value of the temperature inside the factories is set as 20°C. The temperature outside the factories above the elevation of ±0.000m is set as 35°C in correspondence with the local maximum temperature, and that below the elevation of ±0.000m is set as 10°C. The load setting is shown as Figure 2-6.

| Frequency (Hz) | 0.25 | 2.5 | 9 | 33 |
|----------------|------|-----|---|----|
| Horizontal acceleration (g) | 0.225 | 1.565 | 1.305 | 0.5 |
| Vertical acceleration (g) | 0.15 | 1.49 | 1.305 | 0.5 |

Figure 2-6. Load setting for temperature effect

3.3 Load combination

For wind load, 4 working conditions, including positive wind and negative wind in X direction, positive wind and negative wind in Y direction, are taken into consideration. For frequent earthquake and rare earthquake, the seismic actions in X direction, Y direction and Z direction are taken into calculation respectively and combined under NEW_MARK Method shown as below, thus to work out the standard value of seismic action in each direction for load combination.

\[
\begin{align*}
E_x &= ±[|R_x| + 0.4|R_y| + 0.4|R_z|]; \\
E_y &= ±[0.4|R_x| + |R_y| + 0.4|R_z|]; \\
E_z &= ±[0.4|R_x| + 0.4|R_y| + |R_z|].
\end{align*}
\]

According to the ASME Boiler and Pressure Vessel Code (ACI 359-13), 9 kinds of load combinations (25 load combinations in total) are taken into consideration for analysis, and the coefficients of combinations are shown as Table 2-2.

| Combinations | D | L | T | W | E_s | E_sss |
|---------------|---|---|---|---|-----|-------|
| 1             | 1.4 | 1.7 |   |   | 1.7  |       |
| 2             | 1.4 | 1.7 |   |   | 1.7  |       |
| 3             | 1.4 | 1.7 | 1.0|   | 1.0  |       |
| 4             | 1.0 | 1.0 | 1.0|   | 1.15 |       |
| 5             | 1.0 | 1.0 |   |   | 1.0  |       |
| 6             | 1.0 | 1.0 |   |   | 1.0  |       |
| 7             | 1.05| 1.3 | 1.05| | 1.3  |       |
| 8             | 1.05| 1.3 | 1.05| | 1.3  |       |
| 9             | 1.05| 1.3 | 1.05| | 1.3  |       |
4. Result analysis

4.1 Deformation analysis

According to the combinations listed in Table 2-2, the maximum deformation values of each factory are shown as Table 3-1, and the deformation pictures are shown from Figure 3-1 to Figure 3-4.

According to Table 3-1, Combination 3 is the most unfavorable working condition where the deformation of each factory reaches the maximum value, and according to Fig.3-2, the maximum deformation appears in the roof sheathing or floors of each factory, and the maximum deformation value of the spallation target factory has reached 103mm. Compared to Combination 3, the response under Combination 1 is quite close to the maximum value, which shows that dead load and live load have control action on response of structures while wind load has little effect. According to Combination 1 and Combination 2, seismic action also has obvious effect on the vertical deformation of each factory and weakens the effect of dead load and live load to some extent. According to Combination 4 and Combination 6, the electric and ancillary factory and the auxiliary factory show strong response to temperature effect while others show little.

Besides, the spallation target factory shows obvious vertical deformation under each combination, and the ratio of deformation to span under each combination is not less than 1/350 and the maximum value even reaches 1/190 which has exceeded significantly the deflection limiting value (1/300) of floor on the load code, which needs reinforcement measures such as using concrete with higher strong grade, changing the sizes of floors, adding more constrains on components, etc.

Table 3-1. Maximum deformation values of each factory / mm

| Combinations | Reactor factory | Spallation target factory | Electric and ancillary factory | Auxiliary factory |
|--------------|-----------------|---------------------------|--------------------------------|-------------------|
|              | Value           | Deformation /Span         | Value                          | Deformation /Span |
| 1            | 62.8            | 1/280                     | 103                            | 1/190             |
| 2            | 55.6            | 1/320                     | 89.2                           | 1/220             |
| 3            | 62.9            | 1/280                     | 103                            | 1/190             |
| 4            | 39.6            | 1/450                     | 59.9                           | 1/330             |
| 5            | 39.7            | 1/450                     | 60.0                           | 1/330             |
| 6            | 39.7            | 1/450                     | 60.0                           | 1/330             |
| 7            | 47.3            | 1/380                     | 77.8                           | 1/250             |
| 8            | 41.6            | 1/430                     | 67.1                           | 1/290             |
| 9            | 47.3            | 1/380                     | 77.8                           | 1/250             |
| Maximum      | 62.9            | 1/280                     | 103                            | 1/190             |

Figure 3-1. General deformation picture under Combination 3 (D + L + W)
Figure 3-2. Structural deformation picture for each factory under Combination 3

Figure 3-3. General deformation picture under Combination 8 (D + L + T + E₀)
4.2 Stress analysis

The maximum stresses of each factory under different combinations are shown as Table 3-2 and the structural stress pictures are shown from Figure 3-5 to Figure 3-8.

According to Table 3-2, the combination where the maximum stress appears for one factory is not totally correspondence to that for each other, that is, the response under certain combination is different for different factories. According to Combination 1 and Combination 3, dead load and live load have strong effect while wind load has little. According to Combination 1 and Combination 2, seismic action has the strongest effect on the spallation target factory and the maximum stress with the value of 44MPa appears on the edge of the floor under Combination 2, and the floors have much stronger response to rare earthquake according to Combination 5 and Combination 6. According to Fig.3-8, temperature effect makes the stress distribution in each factory more complicated and scattered and the maximum stress appears mostly on the edge of the structure or the cross of components. The electric and ancillary factory has the strongest response to temperature effect and the maximum stress with the value of -8.99MPa appears on the edge of the structure under Combination 9.

Table 3-2. Maximum stress values of each factory / MPa (+/tensile stress, -/compress stress)

| Combinations | Reactor factory | Spallation target factory | Electric and ancillary factory | Auxiliary factory |
|--------------|-----------------|---------------------------|--------------------------------|-------------------|
|              | Floor/ Roof sheathing | Wall | Floor/ Roof sheathing | Wall | Floor/ Roof sheathing | Wall | Floor/ Roof sheathing | Wall |
| 1            | 25.4             | -16.6 | 33.4             | -16.6 | 4.78                | -5.41 | 6.36                | -4.22 |
| 2            | 22.2             | -12.8 | 44.0             | -14.3 | 3.61                | -5.00 | 4.69                | -4.33 |
| 3            | 25.4             | -16.6 | 33.5             | -16.6 | 4.77                | -5.56 | 6.36                | -4.29 |
| 4            | 17.7             | -8.44 | 32.5             | 12.3  | -8.05               | -8.44 | 5.97                | -5.57 |
| 5            | 15.8             | -9.11 | 29.2             | -9.68 | 2.58                | -3.54 | 3.34                | -3.07 |
| 6            | 15.8             | -9.11 | 33.4             | -9.67 | 2.58                | -3.54 | 3.34                | -3.07 |
| 7            | 21.2             | -11.2 | 26.4             | 14.8  | -8.98               | -8.98 | 7.16                | -6.07 |
| 8            | 18.6             | -8.87 | 32.4             | 13.4  | -8.46               | -8.87 | 6.28                | -5.85 |
| 9            | 21.2             | -11.2 | 26.4             | 14.8  | -8.99               | -8.99 | 7.16                | -6.08 |
| Maximum      | 25.4             | -16.6 | 44.0             | -16.6 | -8.99               | -8.99 | 7.16                | -6.08 |
Figure 3-5. General stress picture under Combination 3 (D + L + W)

Figure 3-6. Structural stress picture for each factory under Combination 3

Figure 3-7. General stress picture under Combination 8 (D + L + T + E₀)
5. Conclusion

This paper investigates the most unfavorable deformations and stresses of the factories in the reactor device area under 9 kinds of load combinations in the design stage and preliminarily assesses the load bearing performance of all structures. The conclusions are as follow:

1) Dead load, live load and seismic action have control action among load combinations, and the combination of them becomes the most unfavorable working condition for each factory.

2) The spallation target factory has the strongest response under every load combination thus becomes the most unfavorable part among the structures, which needs reinforcement measures such as using concrete with higher strong grade, changing the sizes of floors, adding more constrains on components, etc.

3) Some edge parts of the electric and ancillary factory has strong response to temperature effect, which needs local reinforcement measures.

4) Except the spallation target factory, the structural design and construction materials of the factories in the reactor target area meet the requirement for deformation and load bearing, but more structure optimizations on the sizes of components and materials etc. are needed to enhance the load bearing performance of factory structures and become much more cost-effective.

Acknowledgments

This paper was supported by the research and development of nuclear power plant safety management platform based on Building Information Model (BIM) technology of Shenzhen Science and Technology Commission (Grant No. AN2017001).

References

[1] Zhang, N., Sun, Y., Gong, J. (2018) Design method study of in-plane shear resistance of reinforced concrete walls of nuclear power plant. Building Structure, 48: 59-64.

[2] Wang, F., Yang Y. (2015) Integral analysis of the pumping station in a nuclear power plant. Special Structures, 32: 65-68.

[3] Li, P., Li, Z. (2011) Thermal effects analysis of containment structure of pressurized water reactor
nuclear power plants. Industrial Construction, 41: 140-144.

[4] Zhou, X., Zhang, L., Zhou, L., Liang, S., Zou, Y. (2011) Wind tunnel test and wind-induced dynamic response evaluation on main powerhouse structure of EPR nuclear power plant. Journal of Vibration and Shock, 30: 142-147.

[5] Wang, L., Zhu, H., Pan, R., Yang, Y. (2016) Discussion about the evaluation of the fundamental wind pressure of anti-seismic I constructions in nuclear power plant. In: 1st China International Forum on Reliability and Seismic Performance Evaluation Techniques of NPP Civil Structures, Beijing, pp: 83-85.

[6] Pan, R., Luan, H., Zhu, X., Hou, C. (2016) Static Elastoplastic response analysis of nuclear island building under excess design basis earthquake. Industrial Construction, 46: 13-16.

[7] Wang, X. (2007) Engineering Structural Numerical Analysis with ANSYS. China Communications Press, Beijing.

[8] Wang, X. (2011) Structural Analysis Units and Application with ANSYS. China Communications Press, Beijing.

[9] Code for Design of Concrete Structures (GB 50010-2010). China Architecture & Building Press, Beijing.

[10] Code for Seismic Design of Buildings (GB 50011-2010). China Architecture & Building Press, Beijing.

[11] Load Code for the Design of Building Structures (GB 50009-2012). China Architecture & Building Press, Beijing.

[12] 2013 ASME Boiler and Pressure Vessel Code (ACI Standard 359-13) III Rules for Construction of Nuclear Facility Components Division 2 Code for Concrete Containments. The American Society of Mechanical Engineers, New York.

[13] Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary (ACI 349-13). American Concrete Institute.