Comparative Analysis of Torsion Resistance Performance between Traditional Support Structure System and Structure with Diagonal Brace

Jian Wu¹, Guo-liang Bai², Ke-wu Kang³ and Hui-juan Dai⁴

¹Shaanxi Key Laboratory of Safety and Durability of Concrete Structures, Xijing University, Xi’an, China, wujian2085@126.com
²College of Civil Engineering, Xi’an University of Architecture and Technology, Xi’an, China, guoliangbai@126.com
³Chian Mobile Group Design Institute Co., Ltd., China
⁴College of Architecture and Civil Engineering, Xi’an University of Science and Technology, Xi’an, China, dailuijuan1985@163.com

Abstract. Traditional support structure system of air-cooled condense adopts hybrid structure system of steel truss and reinforced concrete pipe column, and this type of structure has a remarkable torsion effect because that the quality and rigidity is badly non-uniform at the vertical direction. In order to study the natural vibration period, vibration type and dynamic response under multidimensional ground motions, this paper chooses the support structure system with diagonal brace to analysis the dynamic characteristic and lateral-torsional coupled seismic response of the structure, and compares the results with the traditional structures to study the reasons of these changes so as to make recommendations on the designing of structure. The results show that this new-type structure could reduce the torsional effect, lateral displacement and strengthen overall seismic capacity.

1. Introduction

According to provisions of 《Outline of the National Program for Long-and Medium-Term Scientific and Technological Development (2006-2020)》 [1], Power industry of China will develop in the direction of large capacity, high parameters, energy conservation and emission reduction, and adopt policies to limit the development of small power plants. Air-cooled technology is an effective way to achieve this goal, for comparing with the same grade of wet cooling unit, air-cooled technology could save about 2/3 of water, which is suitable for the development in the coal-rich and water-scarce northwest region.

The traditional air-cooled support structure adopts a vertical mixing arrangement of steel truss and reinforced concrete pipe columns, which results in uneven distribution of structural mass and stiffness along the vertical direction. Pipe columns are the main lateral forces resisting member, so the damage of the columns has a serious impact on the structural security. In view of this structural system, many studies have been carried out. Liu [2] analysed the basic seismic performance of 600MW air-cooled unit, and obtained the dynamic characteristics of the structure. Zhao [3] gave the parameters of the wind load of the air-cooled support structural system through wind tunnel tests. Jiang [4] studied the influence of the uneven settlement on the structural deformation and internal force redistribution so as
to ensure the normal use of the structure. Jia [5] introduced the influence of temperature on the support structure. These studies provide theoretical basis for the promotion and application of air-cooled support structure in China. However, the torsional effect of this type of structure is obvious, and special studies on the torsional properties of support structure of large capacity air-cooled unit are relatively few. Therefore, this paper mainly analyses the seismic effect of the air-cooled support structure of a 1000MW unit, and studies the effect of diagonal brace on torsional performance of support structure to promote the development of this type of structure.

The finite element models of two structures are shown in Figure 1. The number of reinforced concrete pipe columns is 25, height is 50.00m, section dimension is 4.0m×0.4m (diameter×thickness); the upper and lower strings of steel truss platform and web member use section steel, circular steel tube, respectively; square steel tube is used as diagonal brace, whose dimension is 450mm×450mm×30mm (length×width×thickness); height of A-frame is 11.00m, and the cantilever length of steel truss platform are 11.18m (along the direction of A-frame) and 11.39m (perpendicular to the direction of A-frame); the height of the windshield is 11.00m.

2. Analysis of dynamic characteristics
The dynamic characteristics of two kinds of structural systems are shown in Table 1. It could be concluded that the first order mode shows the characteristics of torsion, while the second and third order modes are the translational motion of the Y axis and X axis with torsion, respectively. The natural vibration period of the structure with diagonal brace is less than that of the traditional structure, meaning that the presence of diagonal brace increases the overall stiffness of the structure. The first three order modes of the structure could be seen in Figure 2.
Table 1 Dynamic characteristics of support structure system

| Structure               | Vibration mode | Natural vibration period/s | Participation coefficient of X direction/% | Participation coefficient of Y direction/% | Participation coefficient of Rz direction/% |
|------------------------|----------------|---------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|
| Support structure      | 1              | 1.293                     | 0.046                                     | 0                                         | 20.55                                     |
| with diagonal brace    | 2              | 1.263                     | 0.046                                     | 84.56                                     | 52.67                                     |
|                        | 3              | 1.260                     | 84.89                                     | 84.56                                     | 84.99                                     |
| Traditional structure  | 1              | 2.252                     | 0.025                                     | 0                                         | 19.63                                     |
|                        | 2              | 2.181                     | 0.025                                     | 79.70                                     | 49.93                                     |
|                        | 3              | 2.165                     | 79.97                                     | 79.70                                     | 80.10                                     |

According to the relevant regulations of Industry Standard JGJ 3-2010 (Code of China [6]), for A-level high-rise buildings, the ratio of the first vibration period (T<sub>i</sub>) dominated by the structure twisting to the first vibration period (T<sub>1</sub>) dominated by translation should not be larger than 0.9, while for B-level high-rise buildings and complex high-rise buildings with mixed structure exceeding A-level height, the ratio is 0.85. From Table 1, it could be known that the ratios of the two structures are 1.024 and 1.033, respectively. Both of the ratio are larger than the specification, meaning that the torsional stiffness of the structure is small.

On the basis of National Standard GB 50010-2010 (Code of China [7]), if the first three modes of vibration have two horizontal mode participation coefficients that are of the same order of magnitude, it means that there is a clear torsional effect in the structure. Therefore, the twisting effect should be considered in the two structural systems, and the twisting characteristics could be obtained through seismic response analysis of lateral-torsional coupling.

3. Calculation of torsional component

It is difficult to pick up the torsional components of seismic waves in practical engineering, so theoretical analysis is often used to obtain the torsional components. Commonly used calculation methods mainly include travelling wave method proposed by Newmark [8] and frequency domain method proposed by Trifunac [9]. Considering the generality of the method [10], frequency domain method is chosen in this paper to analysis the seismic wave calculations.

Table 2 The amplitude of acceleration earthquake wave

| Earthquake wave | Horizontal component amplitude/ (10<sup>2</sup>m·s<sup>-2</sup>) | Torsional component amplitude/ (10<sup>-2</sup>rad·s<sup>-2</sup>) |
|-----------------|-------------------------------------------------------------|-------------------------------------------------------------|
|                 | Positive direction/ Negative direction                      | Positive direction/ Negative direction                      |
| EL-Centro       | 341.7/0.413                                                 | -1.25/0.235                                                 |
| Taft            | 175.9/0.248                                                 | -0.235/0.271                                                |
| Chihuahua       | 265.0/0.266                                                 | -0.271/0.266                                                |

This paper selects the recording of the translational components of the time records of three seismic waves of EL-Centro, Taft, and Chihuahua that are suitable for medium-hard sites. Based on the elastic wave theory, the torsion component is calculated by using Matlab software: (1) Determining the apparent velocity of seismic wave (γ<sub>y(f)</sub>) based on the dispersion curve of seismic wave group velocity;

(2) The horizontal component of ground motion (v<sub>t(f)</sub>) is transformed into the frequency spectrum line (v<sub>t(ω)</sub>) through Fourier transform (FFT); (3) Substituting v<sub>t</sub> and γ<sub>y(f)</sub> into Φ<sub>g(ω)</sub> = iωv<sub>t(ω)</sub>/2γ<sub>y(f)</sub> to obtain the frequency spectrum of the torsional component; (4) Fourier inverse transform is applied to the frequency spectrum of torsional components, and takes the real part as the final torsional
component time history record. The amplitude of the torsional wave of seismic waves are shown in Table 2, and the torsion time curve could be seen in Figure 3.

![Graph showing torsional acceleration over time for different earthquake waves.](attachment:image.png)

(a) EL-Centro earthquake wave  
(b) Taft earthquake wave  
(c) Chihuahua earthquake wave

Figure 3. Acceleration time history curve of torsional component

4. Elastic time history analysis of two structural systems

When analysing the elastic time history of the structure subjected to 8 degree frequent earthquake, seismic wave peak needs to be amplitude modulated: the horizontal peak value is adjusted to 70gal (cm/s²) [7], while the torsional component is adjusted to 0.0054 rad·s⁻² [11].

The time history analysis of bidirectional translational component with or without torsion component is carried out. In order to consider the maximum adverse effects of the torsional component, the seismic response of a structure subjected to multi-dimensional earthquake uses the sum of the absolute value of the horizontal component and the torsional component response value (\( S_{u,2} \) and \( S_{\phi} \)), which is \( S = |S_{u,2}| + |S_{\phi}| \). Through the model analysis, it could be concluded that the new type of air-cooled support structure has increased the overall stiffness of the structure due to the diagonal brace, and comparing with the traditional structure, the total base shear force has been greatly improved, the increasing range is about 40% to 120%; the total base shear force of support structure with diagonal brace under multi-dimensional earthquake is about 5%~20% higher than the value under bidirectional earthquake, the torsional effects of the two structures are relatively obvious, but the torsional effect of structure with diagonal brace is about 1/3 lower than that of traditional structure, as shown in Table 3, in which 1 indicates the response of the structure under bidirectional seismic action, 2 indicates the response of the structure under multi-dimensional earthquake.

Table 4 shows the total shear force values and comparisons of bi-directional seismic action and multi-dimensional seismic action at the installation of the diagonal brace. After considering the torsion effect, the total reaction force of the base increases by 10~20%; as the main load transfer member in the structural system, diagonal brace takes up 70~80% of the total shear force of the basement. The meaning of 1 and 2 in Table 4 is the same as in Table 3.
Table 3 Base reaction

| Earthquake wave  | New type structure/kN | Traditional structure/kN |
|------------------|-----------------------|-------------------------|
|                  | X direction | Y direction | X direction | Y direction | X direction | Y direction |
| El-Centro        | 14149    | 14913     | 13920     | 14706     | 8166      | 9093     |
| Taft             | 12451    | 14967     | 12731     | 15230     | 8269      | 10727    |
| Chihuahua        | 14004    | 15189     | 14283     | 15485     | 6209      | 7487     |

Table 4 Total shear force at the setting department of diagonal brace

| Shear force | El-Centro earthquake wave | Taft earthquake wave | Chihuahua earthquake wave |
|-------------|---------------------------|----------------------|---------------------------|
|             | 1/kN  | 2/kN | Change range/% | 1/kN | 2/kN | Change range/% | 1/kN | 2/kN | Change range/% |
| X direction | 11333 | 13729 | 21.14 | 10235 | 11942 | 16.67 | 12212 | 13767 | 12.73 |
| Y direction | 11165 | 13509 | 21.00 | 9915 | 11676 | 17.76 | 12296 | 13882 | 12.90 |

The lateral displacement of the support structure with diagonal brace is smaller than that of the traditional structure, and the displacement at the height of 40m (Where the diagonal brace is stalled) increases slowly, which indicates that the existence of the diagonal brace effectively restricts the lateral displacement of the tube column, as shown in Figure 4.

![Fig.4 Displacement of pipe column under multidimensional ground motions](image)

5. Conclusions

In this paper, a new type support structure for air-cooled equipment is studied, and also the comparison with traditional structure under the action of earthquake is introduced. Based on the analysis results, the following conclusions could be drawn:

1. The basic period of the new air-cooled support structure with diagonal brace is about 1.3s, while the basic period of the traditional structure is about 2.3s, meaning that the diagonal brace has improved the lateral stiffness and the overall stiffness of reinforced concrete pipe columns.
2. The first vibration modes of the two structural systems are torsion, and the second and third orders are the Y direction and X direction translational motions with torsional effect, respectively. The coupling of the first several modes of the structure is obvious, and the mode shape is complicated.

3. Both structural systems should consider the effect of torsion. In seismic design of the structure, if the influence of the torsional component is not taken into account, it is recommended that the seismic response obtained by bidirectional seismic action of the new type structure and the traditional structure should be multiplied by a magnification factor of 1.3 and 1.2, respectively.

4. The diagonal brace is the key research object in the structure seismic design, and the length ratio, the stress of the component should be strictly controlled. The force at the connection of diagonal brace and the pipe column is complicated, so reasonable structural measures should be adopted in the design.

5. The air-cooled equipment supported on the upper part of the support structure is expensive, and the damage of the equipment caused by the structural damage and the maintenance of the equipment after the earthquake must be considered. In performance-based seismic design, reasonable determination of its performance objectives needs further study.

Acknowledgments
The study was supported by the Scientific Research Foundation for High-level Talents (XJ17T08) and the Special Scientific Research Project of Shaanxi Provincial Education Department-“Application Feasibility Study of Prefabricated Recycled Concrete Column in Shale fired Heat-Insulation Block Wall”.

References
[1] Ministry of Science and Technology of the People’s Republic of China. Outline of the National Program for Long-and Medium-Term Scientific and Technological Development (2006-2020), 2006.
[2] Lin Liu. Study on the performance and earthquake response of the support structure system for air cooled condenser (Master thesis), Xi’an University of Architecture and Technology, 2007.
[3] Gengqi Zhao. Research on effect of wind load and wind-parameters of the air-cooled structure (Master thesis), Xi’an University of Architecture and Technology, 2009.
[4] Wenbo Jiang. Analysis on responses of 1000MW air cooled condenser structure under settlement (Master thesis), Xi’an University of Architecture and Technology, 2008.
[5] Jinyan Jia. Studies on the supporting structure system for air cooled condenser of big power plant under the temperature action (Master thesis), Xi’an University of Architecture and Technology, 2007.
[6] JGJ 3-2010. Technical specification for concrete structures of tall building, China Architecture and Building Press. Beijing, China.
[7] GB 50010-2010. Code for Code for seismic design of buildings, China Architecture and Building Press. Beijing, China.
[8] N.M. Newmark, E. Rosenblueth. Principle of earthquake, China Architecture and Building Press. Beijing, China.
[9] M.D. Trifunac. A note on rotational components of earthquake motions on ground surface for incident body waves, Soil Dynamics and Earthquake Engineering. 1(1)(1982) 11-19.
[10] Huipeng Huang. Torsional effect of structres of tall building, Guangdong Building Materials. 27(1)(2011) 75-76.
[11] Shijun Sun, Xingguo Chen. Standard response spectrum of ground motion rotational components, Journal of Nanjing Architectural and Civil Engineering in Institute. (04)(1999) 12-16+25.