

Analysis of the 3-D response of RC frame-bent structures subjected to multi-dimensional earthquakes

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Abstract. Under the two-dimensional components of seismic action, the seismic response spectrum method was applied to irregular structures that were constructed in order to replicate the main powerhouse of a large thermal power plant with a frame-bent in the transverse direction and a frame-shear wall in the longitudinal direction. An elastic-plastic time history analysis of the model, subjected to the one- and two-dimensional components of ground motion, was performed. A practical value and theoretical significance were obtained by modifying the combination formula of the seismic response in Chinese seismic codes based on the calculated ratios of the seismic effect of a one- or two-dimensional earthquake.

Introduction

In theory, ground motions and structural responses during earthquakes are multidirectional. In fact, a complete representation of the ground motion induced by earthquakes consists of not only three translational components of motion, but also three rotational components of motion. In general, most buildings are space structures with three-dimensional load transmission components, which can bear loads from different directions. Thus, the seismic responses of these space structures are expected to be multidimensional as well.

In order to meet the requirements of the manufacturing process, factory buildings are designed to be spacious structures composed of multi-storey and mono-storey structures. As such, transverse frame-bent structures and longitudinal frame-shear walls are commonly used in the main powerhouse buildings of thermal power plants. The non-uniform distribution of the mass and stiffness on the sides of the frame and bent creates a bidirectional, eccentric, irregular space structure with a level difference, an asymmetric distribution of anti-seismic members, and an inconsistency between the center of mass and center of stiffness. Such a structure, if subjected to an earthquake, would have a significant torsional effect and a combination of longitudinal and transverse vibrations. Therefore, the translation-torsion coupling earthquake response of a structure under bidirectional horizontal seismic excitation should be analyzed.

In this paper, UPFs (User Programmable Features) were used with ANSYS for secondary development. Using the FORTRAN programming language, an elastoplastic model of concrete material was modified and a subroutine of a beam column element was compiled. A user customized element could be added to the ANSYS element library through compilation and linkage. The assembly of a global stiffness matrix was implemented using the default function of ANSYS. In current engineering practice, the modal superposition response spectrum method is usually applied to the analysis of one-dimensional seismic responses. However, since the elastoplastic time-history analysis method was expected to have a higher accuracy, it was used to calculate the response of the

irregular space structure under bidirectional seismic excitation. Then, the calculated result was compared to the actual structural response of one-dimensional seismic excitation.

Structural response under bidirectional horizontal seismic excitation

Since the irregular space structure exhibits bidirectional eccentricity, the horizontal earthquake action can be obtained with the modal superposition response spectrum method, which considers the translation-torsion coupling. The motion of the irregular structure subjected to horizontal earthquake action can be expressed as the differential equation^[1].

$$[M] \begin{Bmatrix} \ddot{u}_x \\ \ddot{u}_y \\ \ddot{\phi} \end{Bmatrix} + [C] \begin{Bmatrix} \dot{u}_x \\ \dot{u}_y \\ \dot{\phi} \end{Bmatrix} + [K] \begin{Bmatrix} u_x \\ u_y \\ \phi \end{Bmatrix} = -[M] \begin{Bmatrix} \ddot{x}_g \\ \ddot{y}_g \\ 0 \end{Bmatrix} \quad (1)$$

The earthquake action of a structure at any time is the sum of the earthquake action for each mode shape at that time. The following equations from seismic design code of China were used for this calculation^[2]. In this way, the translation-torsion coupling seismic effect of spatial structure (S_{EK}) under bidirectional horizontal seismic excitation was developed.

$$S_{EK} = \sqrt{S_x^2 + (0.85S_y)^2} \text{ or } S_{EK} = \sqrt{S_y^2 + (0.85S_x)^2} \quad (2)$$

In practice, the equation that yielded the larger S_{EK} value was used. The in-plane internal force combination was then used for checking section bearing capacity based on the seismic effect of the controlling section and the gravity load.

Time history analysis of the spatial frame-bent structure under bidirectional horizontal seismic excitation

The existing seismic codes for structures of China only roughly consider the effect of bidirectional ground motion on the structure, ignoring the correlation of multidimensional ground motion. Equation (2) was used to consider the effect of the combination of the horizontal bidirectional earthquake actions based on the statistical analysis of the observations and records of strong earthquakes. This analysis yielded a ratio of 1: 0.85 for the maximum value of two horizontal earthquake equations, which were not necessarily achieved simultaneously. As such, the *SRSS* (square root of the sum of the squares) in Equation (2) was used to express the combination of the horizontal bidirectional seismic effect. Although the code for seismic design of buildings of China considered the effects of structural torsion in different directions, they ignored the effect of the incident angle of a seismic wave on the structural response^[3] and lacked a basis on theory. Currently, the two axes of the global coordinate system of the structure are usually chosen to calculate the incident directions of seismic waves for simple and regular structures, such as a structure with one or two symmetric planes. However, for complex structures, the maximum value of each response for the different components is associated with the corresponding incident direction of a seismic wave for calculations, resulting in an unsafe design.

The response of high-rise building structures induced by bidirectional horizontal seismic excitation has been reported to be approximately 1.2 to 1.6 times larger than the response induced by unidirectional horizontal seismic excitation^[4]. In this paper, in order to prove the necessity of the analysis of the response of irregular space structures with bidirectional eccentricity (such as frame-bent structures) to bidirectional horizontal ground motion and the comparison of the combination method to the bidirectional earthquake method adopted in the existing codes, the following were analyzed: (1) the maximum effect of the combined action of bidirectional ground motion components and two separate unidirectional horizontal ground motions, which are orthogonal to each other; (2) the maximum effect of the combined action of bidirectional ground motion components and the combination of the seismic response adopted in engineering practice (derived from the *SRSS* expression); and (3) the ratio of the maximum effect under two separate horizontal

ground motion components, which are orthogonal to each other, and the connections and rules associated with the maximum effect^[5].

Structure calculation model

A model of eight full-scale, three-span, frame-bent structures with turbine halls, deaerator bays, and coal bunker bays was developed for analysis using the main power house of a thermal plant with a unit capacity of 600 MW as a prototype. A diagram of this structural analysis is shown in Figure 1. The main power house was designed for a seismic intensity of seven and an earthquake resistance degree of eight based on the detailing requirement. Due to the complexity of the structure type, the prototype of the structure required simplification^[6].

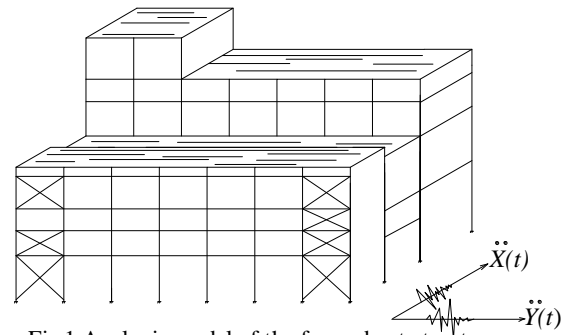


Fig.1 Analysis model of the frame-bent structure

Considering the widespread use of such structures in China, a site condition of class II or III was used when selecting a seismic wave. Numerous ground motion records were selected from the seismic wave incidences listed in the *Code for Seismic Design of buildings (GB50011-2010)* (China) for comparative analysis, including El-Centro (1940), Taft (1952), EMC-Fairview (1987), and the horizontal acceleration time histories measured at the Beijing Hotel and the Tianjin Hospital during the Tangshan Earthquake of 1976 (hereinafter referred to as the “Tangshan wave” and “Tianjin wave”). The selected seismic wave, with strong ground motion lasting up to 10 seconds in duration and a peak ground acceleration (PGA) reduced to 300 gal in an equal-ratio, maintained its wave shape. For comparison, the internal force and displacement of the structure with a PGA of 220 gal decreased as the acceleration increased under different peak accelerations, meaning the structure had reached the elastoplastic phases.

The two orthogonal components of the seismic wave acted on the entire structure simultaneously. The incident direction of the seismic wave changed once every 30 degrees. The maximum of the time-history in all incident direction of the seismic wave was identified around the structure. According to the principle of structural mechanics and experimental observation, the external force applied to the frame was more than 20 times the external force applied to the bent when both met the same deformation requirement. When the deformation of both structures was compatible, the frame essentially supported the horizontal earthquake movement acting on the frame-bent structure. Moreover, the lateral system exhibited the most weakness, and the damage to the columns was more serious than that to the beams. Due to their short columns, colonnades B and C always compensated for most of the seismic load, which put those columns at risk of local collapse in the case of a strong earthquake; this resulted in a sudden change of local stiffness. Therefore, the seismic effects of the side frame (axis-①) and beam-column components at the setback of the structure (axis-③), such as the bending moment, torque, axial force, shear force, and displacement, were selected as the focus of this research, as shown in Figure 2. In this paper, the seismic effects of each component subjected to earthquake wave were calculated for statistical analysis^[6]. Due to the length of this paper, the calculation results of contrastive values of certain representative earthquake waves which were concentrated were selected; the results are shown in the figures below.

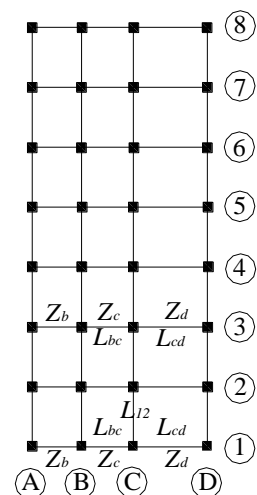


Fig.2 Chart of calculation members

Compared to the other three types of seismic waves, the effect of the bidirectional seismic effect on the Taft wave was much more significant than that of the unidirectional seismic effect. This was primarily subject to the slight difference of the waveform between the two horizontal components of

the Taft wave and whether or not the position or time corresponding to the occurrence of the positive or negative acceleration peaks were close. The superposition of the accelerations in the same direction could clearly increase the result. Therefore, although there was no pronounced difference between the waveform of the combined bidirectional seismic acceleration time-history curve and the unidirectional seismic acceleration time-history curve, the difference between the combined bidirectional and original unidirectional seismic effect, which indicate the effect of earthquake wave, was significant.

The ratio of the maximum effect induced by bidirectional horizontal seismic excitation to the maximum effect induced by unidirectional seismic excitation (XY/X)

As shown in Figures 3 and 4, the changing curve of the ratio of maximum seismic action effect (XY/X) under the action of various seismic waves was regulated well. The majority of the ratios varied from 1.1 to 1.4, with some outliers greater than 1.4. For these irregular structures, the consideration of only the unidirectional effect of seismic waves yielded unsafe results, and the multiplication of only the magnification factor when considering the seismic effect of the components of the side span yielded inaccurate results.

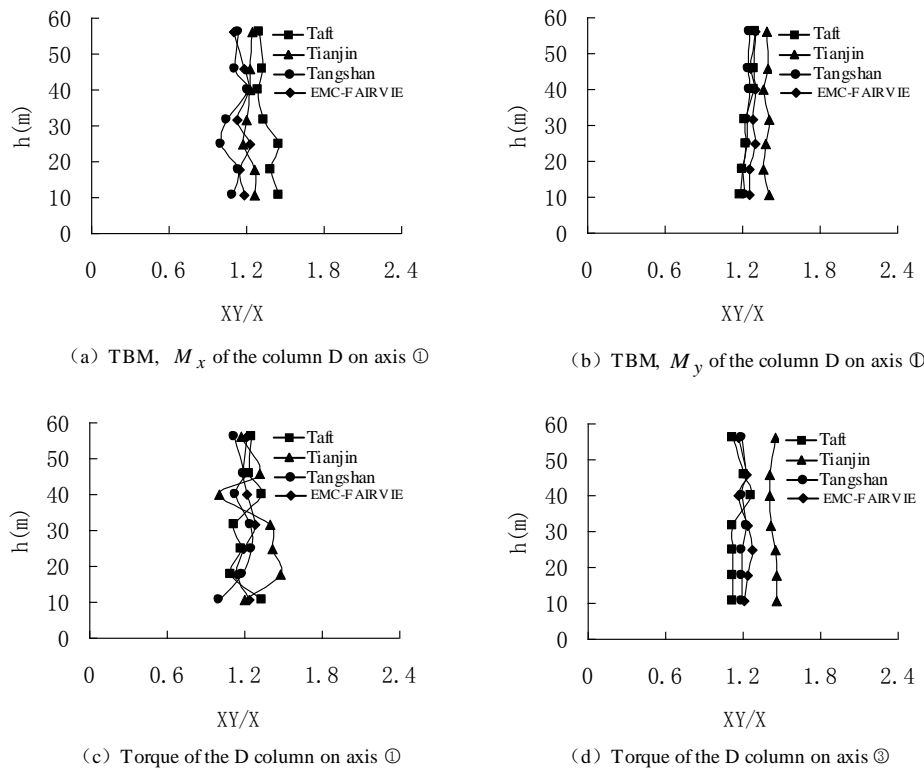


Fig.3 Earthquake effect ratio of column D on axes ①&③
(TBM=transverse bending moment; LBM=longitudinal bending moment)

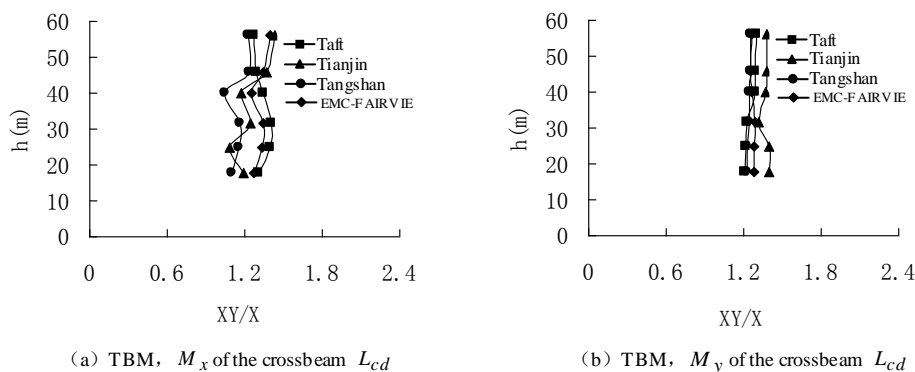


Fig.4 Earthquake effect ratio of the cross beam

The ratio of the maximum effect induced by bidirectional horizontal seismic excitation to the maximum effect combination induced by unidirectional seismic excitation (XY/R)

The seismic effect of a structure subjected to two orthogonal, unidirectional horizontal seismic components was unable to achieve the maximum simultaneously. Furthermore, the structural response of the combined action of two horizontal seismic components was not equal to the superposition of the structural response resulting from either of the two unidirectional seismic components. Currently, the *SRSS* adopted in the seismic code for the combination of seismic effects has a certain degree of approximation. Extensive statistics based on numerous computations have modified these *SRSS* results; some of these results are shown in Figures 5 and 6. The changing curve of the ratio of the maximum seismic effect of different seismic waves (XY/R , where R represents the combination of seismic effect) exhibited a certain regularity; the ratio XY/R ranged, for the most part, from approximately 0.8 to 1, but some differences were apparent for different seismic waves.

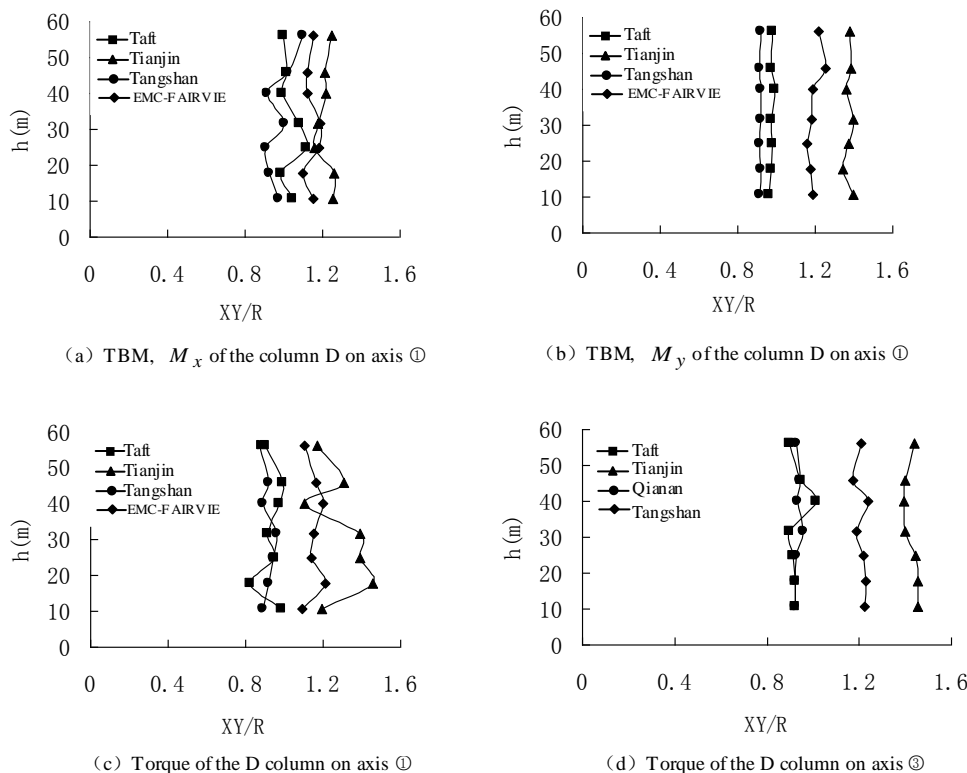


Fig.5 Earthquake effect ratio of column D on axes ①&③
(TBM=transverse bending moment; LBM=longitudinal bending moment)

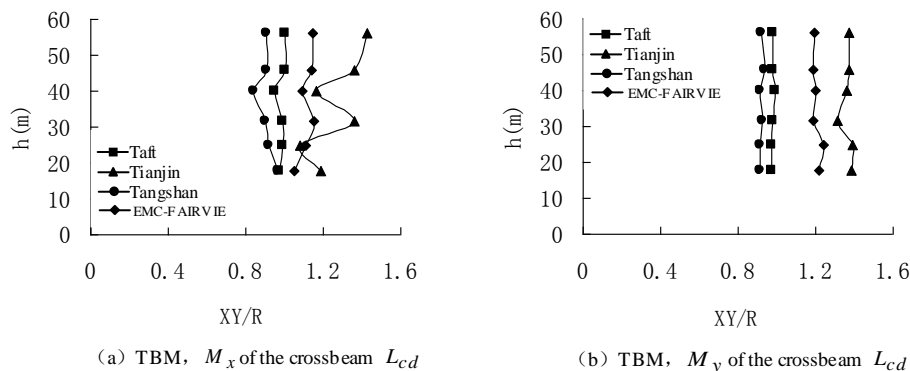


Fig.6 Earthquake effect ratio of the crossbeam

The ratio of the maximum seismic effects between two unidirectional earthquake actions (X/Y)

The ratio of the seismic effect induced by two horizontal components of earthquake component, which were applied separately to the structure, is shown in Figures 7. The ratio of the earthquake effect for different components of the structure was different from the ratio of the corresponding seismic acceleration. The results of numerous statistics demonstrated that the ratio of earthquake effect exhibited a certain regularity for different seismic waves or different structural components. The ratio mostly ranged from 0.75 and 1, with a ratio of 0.9 for the type of structure studied in this paper.

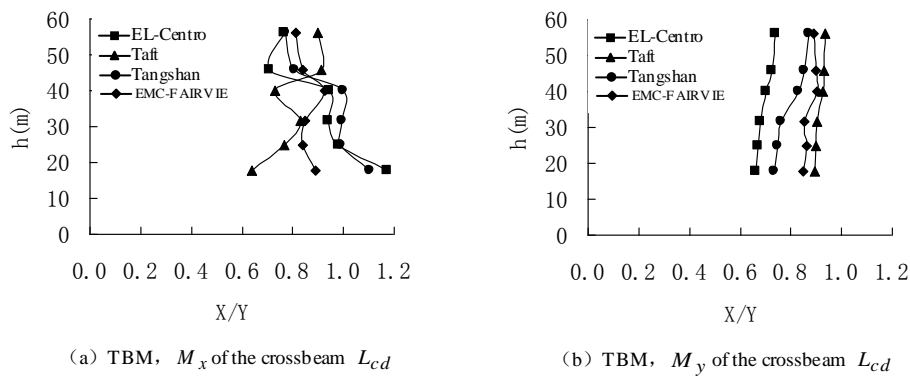


Fig.7 Earthquake effect ratio of the cross beam

As shown in Figures 3 through 7, the ratio of the longitudinal earthquake effect for the different components varied more uniformly with height than the ratio of the transverse earthquake effect, primarily due to the more uniform distribution of the longitudinal mass and stiffness of the structure. Thus, in such a spatial frame-bent structural system, the weakest aspect was located along the transverse direction. During structural design, the position of a sudden change in structure stiffness and mass should be monitored closely. As shown in this analysis, the combination formula of the seismic effect of bidirectional horizontal earthquake action, as required by the seismic code, should consider coefficient modification in eccentric irregular structures.

$$S_{EK} = \alpha \sqrt{S_x^2 + (\beta S_y)^2}$$

$$S_{EK} = \alpha \sqrt{S_y^2 + (\beta S_x)^2}$$
(3)

Where α is the adjustment coefficient, which ranges from 0.8 to 1 and β is the proportion of the seismic effect between two unidirectional earthquake actions, equal to 0.9 in this calculation.

Conclusions

(1) The use of unidirectional ground motion input as a calculation method was only suitable for simple structures. However, for irregular complex structures, if the seismic responses of structures under bidirectional horizontal earthquake actions are not considered, the calculations will yield unreasonable results.

(2) The solid structure of a three-dimensional space is subjected to loads from different directions, and different incident angles of seismic waves produce different seismic effects. Thus, the incident angle of seismic waves must be considered in the performance analysis of space structures under multidimensional ground motions.

(3) Although the *SRSS* adopted in the seismic code considers the twisting coupling effect of the structure in all directions, it ignores the influence of the incident angles of seismic waves on the structural response, making it unreasonable for complex structures. Based on the numerical calculations performed in this paper, the coefficient adjustment was applied to the formula used in the

seismic code; the result could be used as a reference for the formulation of relevant industrial specifications.

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