DESIGN AND DYNAMIC CHARACTERISTIC ANALYSIS OF FRP COMPOSITE SUBSTATION STRUCTURE

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The Glass reinforced epoxy resin (FRP) composite material is introduced to optimize the design of the key bearing components of the substation frame. The finite element model is established, and the dynamic simulation analysis is carried out to explore the composite transformer frame's wind-sensitive characteristics and seismic performance under extreme conditions such as wind load and earthquake. The results show that: according to the modal analysis, the frequency of the first several orders of the newly designed composite transformer component is less than 1 Hz, which can eliminate the sensitivity to wind load, solve the problem that the conventional steel frame is easily affected by wind load sensitivity, and effectively improve its wind load resistance. According to the dynamic time-history analysis, the peak displacement and stress of the composite transformer frame are reduced by 71.9% and 69.1% respectively compared with the traditional steel frame under the action of frequent and rare seismic waves, which can greatly improve the seismic performance of the transformer frame. The research results have positive significance for the optimal design and safety analysis of substation components.

Keywords: Composite substation frame; Mode analysis; Dynamic time course analysis.

1. Introduction

Composite materials have the advantages of lightweight, high strength, and good insulation performance [1], which has attracted the attention of the engineering industry, especially the favor of the power transmission industry [2].

The substation frame is a flexible structure with a large span and high height, which is prone to collapse in the face of strong winds, causing great economic losses [4]. In literature [5], the Davenport spectrum was used to study the structural vibration caused by fluctuating wind loads. Literature [6] found that

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the 500 kV frame was wind-sensitive based on the modal frequency and mode characteristics of the frame, combined with the fluctuating wind speed spectrum.

The power system is closely related to people's living standards. Nowadays, earthquake disasters occur frequently. To ensure people's disaster relief work, living standards, and post-disaster reconstruction, the safety of the power transformation framework must be ensured [7]. Literature [8] takes the structure of a 220 kV standard substation as an example, selects three seismic waves, and uses time-history analysis to obtain the response results of the structure in different seismic waves. Literature [9] made a comparative analysis of the seismic response of the floor power transmission frame and the roof power transmission frame and compared the seismic response of the roof power transmission frame before and after isolation. Literature [10] compared the seismic performance of substations using isolation technology under far-field earthquakes and near-fault earthquakes.

It can be seen that the current substation structure has problems such as wind sensitivity and weak seismic performance, which leads to fatigue damage of its components, high maintenance costs, and major safety accidents such as collapse in serious cases. In this paper, FRP composite materials are introduced to redesign the power substation frame. Taking a 220 kV composite power substation frame as the research object, the finite element analysis software of the workbench is adopted. Firstly, the wind-sensitive characteristics of the composite power substation frame and steel power substation frame are compared through modal analysis and fluctuating wind speed spectrum. To improve the stability and safety of the composite and steel substation frames, the seismic response of the composite and steel substation frames is compared.

2. Project Profile

Composite power transformation frame refers to the use of composite materials to replace the traditional steel power transformation frame steel beam design type, which can replace the traditional overhang. The size comparison of the transformer frame is shown in Fig 1.

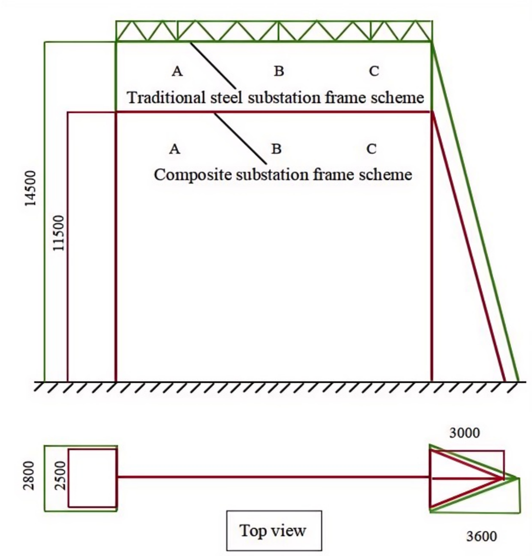


Fig 1 Transformer frame size comparison

Rigid flanges are used to connect the beams, columns, and pillar insulators of the composite power transformation frame. 220 kV composite material-based substation frame height 11.5 m, A/B phase, B/C phase flanges are separated by 4.0 m, A, C phase flanges and composite frame end flanges are separated by 2.5 m. The composite structure sketch is shown in Fig 2.

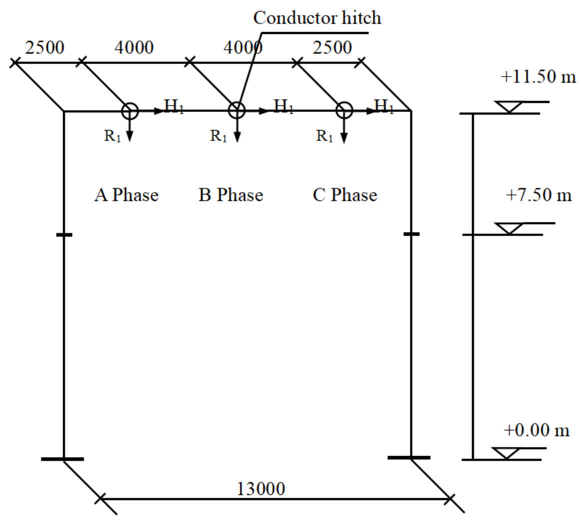


Fig 2 Composite structure sketch

This paper mainly discusses the wind-induced response in the downwind direction. The wind-induced response in the downwind direction is produced under the joint action of the average wind and the pulsating wind. The average phoenix is equivalent to the static force and does not cause structural vibration, while the fluctuating phoenix is a periodic load, so the structural vibration is mainly caused by the fluctuating wind.

According to the design data, the horizontal seismic response spectrum and basic parameters in this paper are shown in Table 1.

Table 1

Horizontal seismic response spectrum and basic parameters

Seismic intensity	6 degrees (0.05g)
Site classification	II
Design seismic grouping	The second group
Site characteristic period value	0.40
Structural damping ratio	0.05
Horizontal earthquake influencing factors	0.12

3. The establishment of a finite element model

The composite substation frame is mainly composed of pillar insulators, flanges, hanging plates, herringbone posts, and herringbone posts with end supports. The frame diagram is shown in Fig 3. The dimensions of each component are shown in Table 2. The herringbone column of the frame is made of steel pipe material, and the beam is made of Glass reinforced epoxy resin composite material by lamination method and the insulation protection is added inside and outside. To ensure the accuracy of the calculation results, to improve efficiency, the model should be simplified, including the bolt connection, the pillar insulator and the flange, the hanging plate and the flange are all fixed. To ensure that there is no relative movement between the pillar and the beam, the herringbone and the flange should also be fixed [3].The finite element model of the framework was established by using workbench finite element analysis software, which was divided by tetrahedron, with a total of 2839683 nodes and 1441973 units.

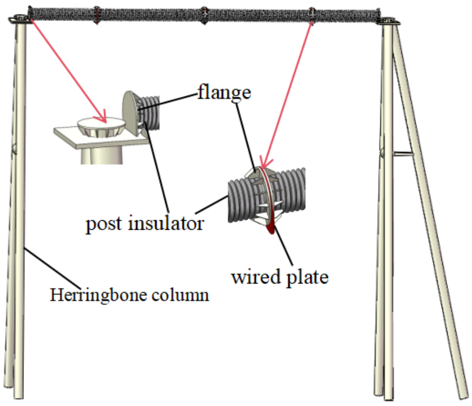


Fig 3 Structure diagram of composite substation frame

Table 2

The main component parameters of the composite substation frame

Composite substation frame	Herringbone column	Herringbone column end brace	Composite beam
Sectional dimension (mm)	Ø325×8	Ø325×8	Ø351×8

4. Wind load response analysis of substation frame

4.1 Principles of modal analysis

Modal analysis is a method to study the dynamic characteristics of a structure. By defining the characteristics of the main modes of the structure in a certain frequency range, the actual vibration response of the structure under the action of various vibration sources inside and outside the frequency can be judged. The significance of modal analysis is that it can find the direction of the small stiffness of the structure and whether the structure is prone to resonance in the future working state. The general equation of structural dynamics is defined as formula (1).

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F(t)\} \tag{1}$$

where $[M]$ is the mass matrix; $\{\ddot{u}\}$ is the acceleration response vectors; $[C]$ is the damping matrix; $\{\dot{u}\}$ is the velocity response vectors; $[K]$ is the stiffness matrix; $\{u\}$ is the displacement response vectors; $\{F(t)\}$ is the external load matrix.

4.2 Modal analysis

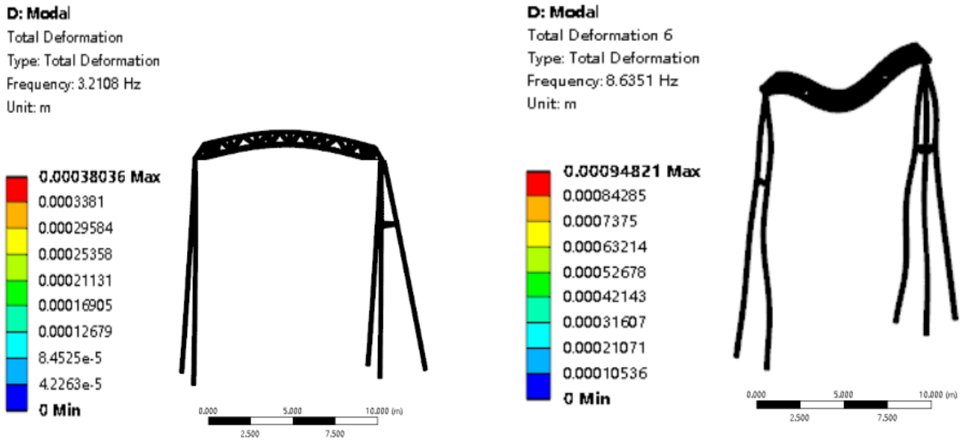
4.2.1 Modal analysis of traditional steel substation frame

The modal analysis of the traditional steel substation frame is carried out. The first 10 frequencies and vibration mode characteristics of the structure are shown in Table 3, and some vibration modes are shown in Fig 4.

Table 3

Frequency and mode characteristics of the first 10 orders of steel substation frame

<table>
<tr><td>Order</td><td>Frequency/ Hz</td><td>Mode characteristics</td></tr>
<tr><td>1</td><td>3.211</td><td>The beam is arched +Y curved</td></tr>
<tr><td>2</td><td>3.549</td><td>The herringbone column is Z-bending</td></tr>
<tr><td>3</td><td>5.133</td><td rowspan="2">Beam bending in Y direction + herringbone column bending in Z direction</td></tr>
<tr><td>4</td><td>6.664</td></tr>
<tr><td>5</td><td>7.665</td><td>The herringbone column with end brace is bent along the Z direction</td></tr>
<tr><td>6</td><td>8.653</td><td>The beam is "~ shape" +Y curved</td></tr>
<tr><td>7</td><td>8.943</td><td>The herringbone column and the herringbone column with end brace is bent along the Z direction</td></tr>
<tr><td>8</td><td>11.088</td><td>The beam is arched +Y curved, and the herringbone column and the herringbone column with end brace is bent along the Z direction</td></tr>
<tr><td>9</td><td>16.241</td><td rowspan="2">The beam presents a "~ shape" +X bending, Z-bending herringbone column with end brace, and the overall torsion of the herringbone column</td></tr>
<tr><td>10</td><td>18.038</td></tr>
</table>



(a) First order mode (b) Sixth order mode

Fig 4 Part mode diagram of steel substation frame

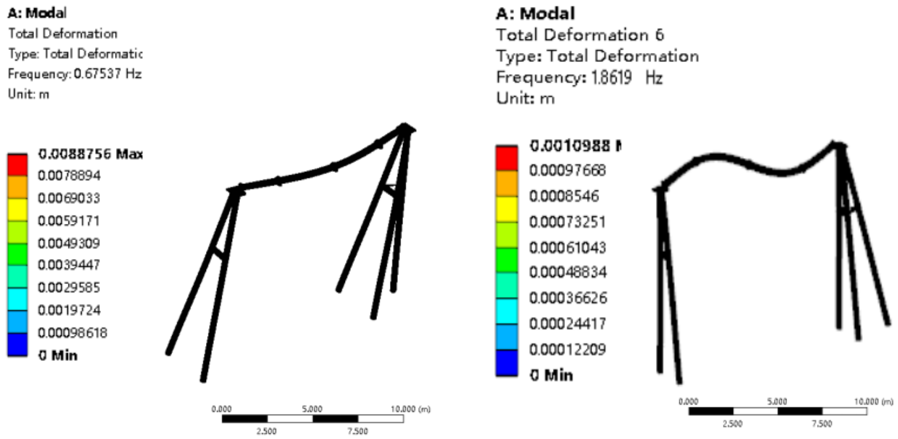
4.2.2 Modal analysis of composite substation frame

The modal analysis of the composite substation frame with steel tube for the frame column and glass reinforced epoxy resin for the beam is carried out. The first 10 natural frequencies and modal characteristics of the structure are shown in Table 4, and some modal characteristics are shown in Fig 5.

Table 4

Frequency and mode characteristics of the first 10 orders of the composite substation frame

Order	Frequency/Hz	Mode characteristics
1	0.675	The beam is curved in a bow +Y direction
2	0.818	The beam is arched +Y curved
3	1.217	Beam bending in Y direction + herringbone column with end brace bending in Z direction
4	1.43	
5	1.838	Z-bend herringbone column with end braces
6	1.862	The beam presents a "~ shape" +Y bend
7	1.883	The herringbone column is curved in the Z direction
8	2.331	The beam presents arch +Y direction bending, and the herringbone column Z-direction bending
9	3.558	The beam presents a "~ shape" +X bending, and the whole herringbone column is twisted
10	4.299	



(a) First order mode (b) Sixth order mode

Fig 5 Composite substation frame part mode mode diagram

4.3 Effect of fluctuating wind speed on vibration of substation frame

Currently, the calculation method of the wind-induced response of the structure is generally based on Davenport of Canada in the 1960s and has been developed and improved.

Davenport [6] analyzed the spectra of more than 90 strong wind records measured in different regions and at different heights in the world and summarized the expression of the pulsating wind power spectrum as equation (2).

$$S_v(f) = 4k(v_{10})^2 \cdot \frac{x^2}{(1+x^2)^{4/3}} \tag{2}$$

where $x = 1200f/v_{10}$; v_{10} is the average wind speed of 10 meters; f is the pulsating wind frequency; k is the surface roughness coefficient.

According to the wind power grade distribution table, this paper selects $v = 25$, 30, 40 m/s, and calculates the power spectrum of pulsating wind speed, as shown in Fig 6.

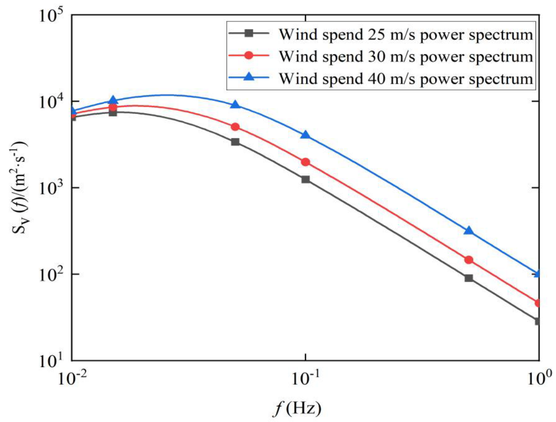


Fig 6 Power spectra at different wind speeds

Modal analysis can obtain natural frequencies and modes of different orders. However, it is the first modes that play a dominant role in motion. By comparing Table 3、4 and Fig 6, we can see that the frequency of the first several stages of the composite substation frame is greater than 1.0 Hz, the frequency of the first several stages of the steel substation frame is less than 1.0 Hz, but the energy of the wind load is mainly concentrated in (0-1.0) Hz. Hence, the 220 kV composite power transformation frame is not a wind-sensitive structure, and the steel power transformation frame is a wind-sensitive structure.

5. Seismic impact analysis of substation frame

5.1 The selection of seismic waves

In earthquake engineering, the peak acceleration spectrum is usually used to analyze the vibration of structures in earthquakes and determine the design parameters of structures According to China's [13] Technical Regulations for Substation Building Structure Design (GB50011-2010) and [14] Code for Seismic Design of Power Facilities (GB50260-2013): When the dynamic time-history component is used for seismic design, the actual strong earthquake record or artificial ground motion can be used as the input time-history of ground motion. Input ground motion time history should not be less than three, at least one manually composite ground motion time history, and the total duration of the time history should not be less than 12 s.

In this paper, three acceleration time history curves are used for time history analysis, namely, PAKRKF_C12DWN seismic wave, SFERN_PVEO65 seismic wave, and artificial wave, which are selected from [11] (Pacific Earthquake Engineering Research Center, PEER) Strong earthquake record database.

The following factors should be considered in selecting the input seismic wave: peak value, spectral characteristics, and ground motion duration.

1. Peak adjustment

The peak value of the seismic wave input to the structure should be comparable to the peak value of the multiple or rare earthquakes required by the fortification intensity, otherwise, it should be adjusted, according to Code for Seismic Design of Electric Power Facilities (GB50260-2013): e.g., Table 5 is the maximum value of the seismic acceleration timescale used for the time-range analysis (mm·s^{-2}).

Table 5

Maximum seismic acceleration for time history analysis (mm·s^{-2})

Earthquake effect	6 degrees (0.05g)	7 degree (0.10g)	8 degree (0.15g)	9 degree (0.40g)
Frequent earthquake	180	350	700	1400
Rare occurrence earthquake	1250	220	4100	6200

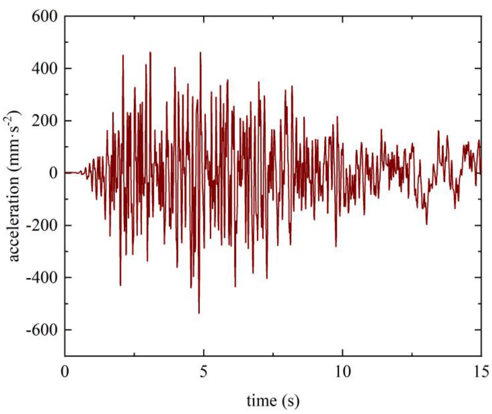
2. Spectral characterization

Spectrum refers to the frequency components of ground motion and the degree of influence of each frequency. It is closely related to the distance of earthquake propagation and the soil properties of the site where the medium-level structure is located in the propagation area.

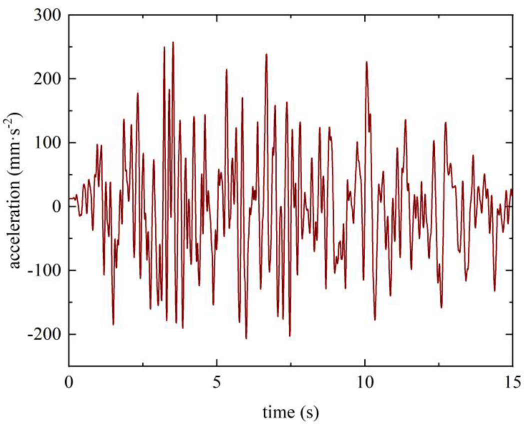
3. Ground motion duration

Under seismic waves, the structure only deforms and does not collapse, but under the influence of subsequent seismic waves, the structure is destroyed and collapses, which indicates that the earthquake response is different due to the duration of the vibration. Generally, the duration can be considered as 5-10 times the basic period of the structure.

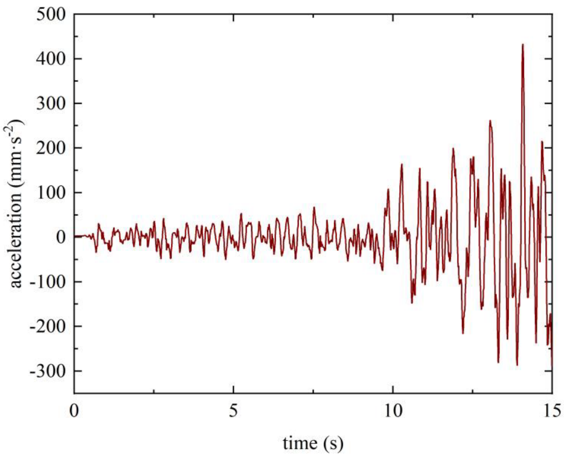
In this paper, the PAKRKF_CN wave (named P-wave), SFERN_65 wave (named S-wave), and artificial wave (named R-wave) are selected, and the acceleration curve of the first 15s time history is shown in Fig 7.



(a) Time history of P-wave acceleration



(b) Time history of S-wave acceleration



(c) Time history of S-wave acceleration

Fig 7 The acceleration curve of the first 15 s time history

Among them, the peak acceleration of the P-wave was 540 mm·s^{-2} which appeared at 4.83 s, the peak acceleration of the S-wave was 260 mm·s^{-2} which appeared at 3.52 s as well and the peak acceleration of the R-wave was 430 mm·s^{-2} which appeared at 14.08 s. According to the requirements of China's Code for Seismic Design of Power Facilities (GB50260-2013), the peak acceleration of 6-degree earthquakes is 180 mm·s^{-2}, and that of rare earthquakes is 1250 mm·s^{-2}. The adjusted coefficients are shown in Table 6.

Table 6

Earthquake acceleration adjustment factor

earthquake wave	The peak is 180 mm·s^{-2} adjustment factor	The peak is 1250 mm·s^{-2} adjustment factor
P-wave	0.33	2.31
S-wave	0.69	4.81
R-wave	0.42	2.91

According to the requirement of seismic wave selection, the three seismic wave acceleration response spectra and the standard response spectra are compared. As shown in Fig 10. As can be seen from Fig 8, the three seismic spectra basically conform to the standard response spectra.

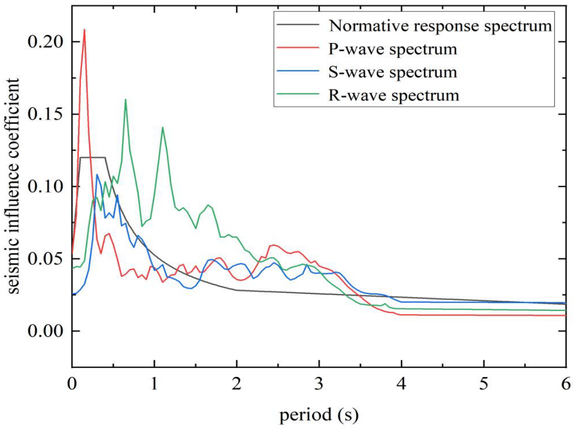


Fig 8 Comparison between the selected seismic wave and the standard response spectrum

5.2 Seismic response analysis of substation frame

The selection of time step size is a key problem in the calculation of transient dynamics, which directly affects the accuracy of the solution. Generally speaking, the smaller the step size, the higher the calculation accuracy. However, too small a step size will increase the burden of the computer, and too large a step size will cause a high-order mode response error, so it is vital to choose the appropriate time step size. According to the above factors, the time step taken in this paper is Δt=0.01 s.

5.2.1 Seismic response analysis of traditional steel substation frame

According to the results of the modal analysis, the stiffness of the steel substation frame is the weakest in the Y-axis direction, so the adjusted seismic wave is added in the Y-axis direction during seismic response analysis. P wave, S wave, and R wave are applied to the steel substation frame to analyze the stress and deformation of the structure under earthquake action. The results show that the steel substation frame's peak displacement appears on the structure's beam, so the joint displacement in the middle of the beam is taken as the research object. The results also show that the maximum plastic deformation occurs in the end brace of the steel substation frame, so the stress element in the middle of the end brace is taken as the research object. The response results of the steel substation frame are listed below, as shown in Table 7.

Table 7

Response result of steel substation frame

	Peak displacement in the middle of the beam (mm)			Peak stress in the middle of the end brace (MPa)		
	P-wave	S-wave	R-wave	P-wave	S-wave	R-wave
Frequent earthquake	1.23	1.46	0.82	12.37	18.11	7.24
Rare occurrence earthquake	11.46	15.34	8.09	41.16	58.53	32.23

5.2.2 Seismic response analysis of composite substation frame

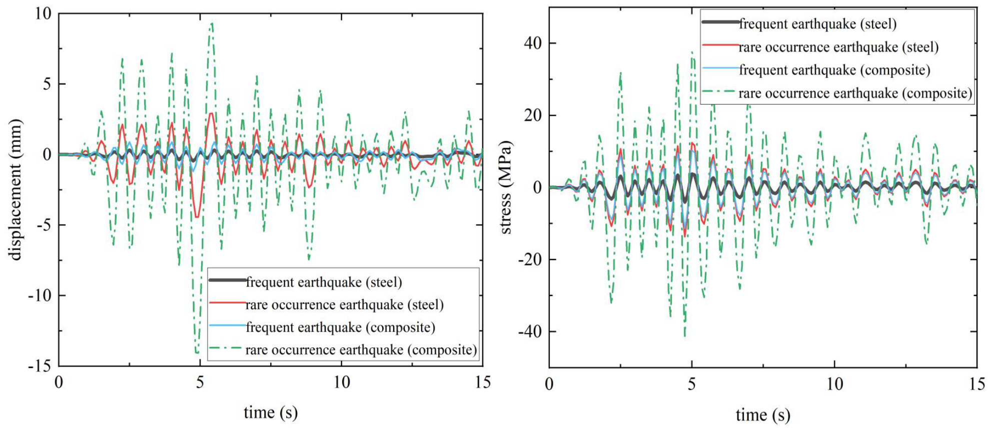
Seismic waves are still applied along the Y-axis to the composite substation frame compared to the conventional steel substation frame. The research object of the structure is the same as that of the steel substation frame. The response results of the composite substation frame are listed below, as shown in Table 8.

Table 8

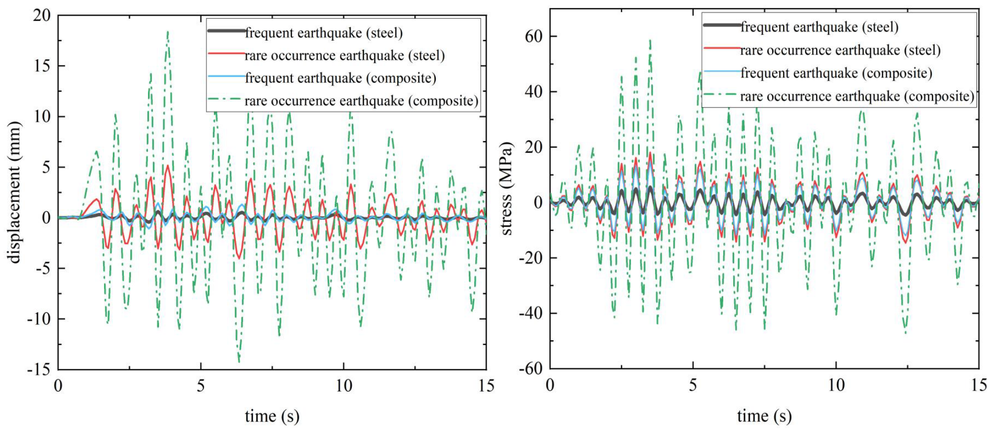
Response result of composite substation frame

	Peak displacement in the middle of the beam (mm)			Peak stress in the middle of the end brace (MPa)		
	P-wave	S-wave	R-wave	P-wave	S-wave	R-wave
Frequent earthquake	0.45	0.61	0.31	4.09	5.61	2.25
Rare occurrence earthquake	3.62	4.33	2.56	13.65	18.18	10.71

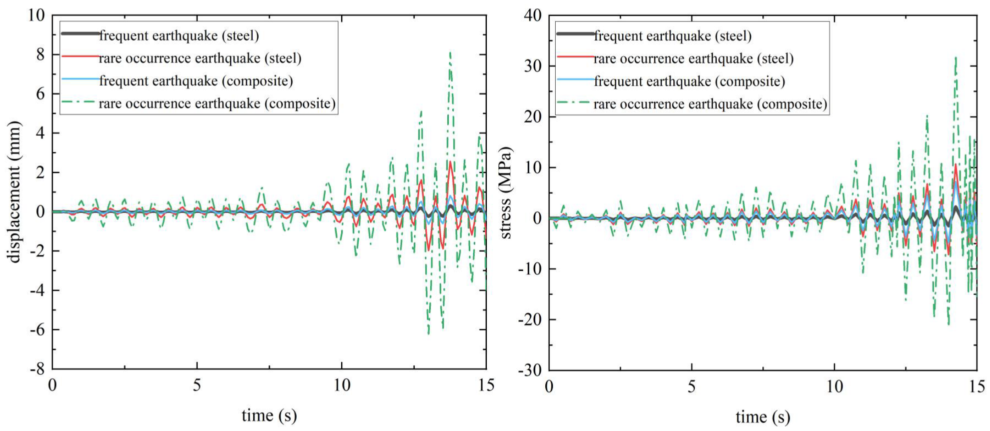
The following is the time history curve of the observation point comparison between the composite substation frame and the traditional steel power transformation frame, as shown in Fig 9.



(a) Time history response curve of P-wave



(b) Time history response curve of S-wave



(c) Time history response curve of R-wave

Fig 9 Comparison of time history curves of composite substation frames and steel substation frames

According to the simulation analysis: (1) It can be seen from Fig 9 that the seismic response of the structure is good, and the time history curve of the observation point is consistent with the acceleration time history curve of Fig 7. (2) Under the earthquake, the peak displacement of the traditional steel transformer frame and the composite substation frame in the middle of the beam is 4.33 mm and 15.43 mm, respectively. According to the "Substation Frame Design Manual" [12], the ratio of the limit value of the deflection of the beam to the span of the beam is $\Delta = \frac{\mu_{\max}}{l} < \frac{1}{43}$, which meets the requirements. (3) Under frequent earthquakes, the peak displacement and stress of the steel substation frame are 1.46 mm and 18.11 MPa, respectively, and the peak displacement and stress of the composite substation frame are 0.61 mm and 5.61 MPa, respectively, which decreased by 58.2% and 69.1% year-on-year. (4) Under rare earthquakes, the peak displacements and stresses of steel substation frames were 15.34 mm and 58.53 MPa, respectively, and those of composite substation frames were 4.33 mm and 18.18 MPa, respectively, which were 71.9% and 68.9% lower year-on-year.

6. Conclusion

In this paper, the dynamic characteristics of the 220 kV composite substation frame are analyzed by finite element simulation. Through the modal analysis of the structure, the wind sensitivity of the structure is analyzed with the pulsating wind speed power spectrum; The dynamic time-history analysis of the structure obtains the peak response of the structure. There are the following conclusions:

(1) The frequency of the first several stages of the composite power transformation frame is greater than 1.0 Hz, the frequency of the first several stages of the steel power transformation frame is less than 1.0 Hz, and the energy of the wind load is mainly concentrated in (0-1.0) Hz, hence, the 220 kV composite power transformation frame is not a wind sensitive structure, and the steel power

(2) By applying three seismic waves in frequent and rare occurrences to the substation frame, all meet the requirements of the code. Under frequent earthquakes, the peak displacement and stress of the composite power substation frame decrease by 58.2% and 69.1%, respectively, compared with that of the steel substation frame. Under rare earthquakes, the peak displacement and stress of composite substation frame decrease by 71.9% and 69.1% respectively compared with that of steel substation frame. The seismic performance of the composite substation frame is better.

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