

Article

Seismic Response Prediction of One-Story Bidirectionally Eccentric Structures Based on the BP Neural Network

Yi Zhang and Xiaobin Hu * 

School of Civil Engineering, Wuhan University, Wuhan 430072, China; 2023202100045@whu.edu.cn

* Correspondence: newhxb@whu.edu.cn

Abstract

Predicting a structure's seismic responses is of great importance during seismic design, especially in the preliminary stage. Hence, in this paper, a model for rapid prediction of the seismic responses of one-story bidirectionally eccentric structures based on the BP neural network is proposed. First, the equations of motion of one-story two-way eccentric structures under unidirectional seismic excitation are derived and solved through the modal response spectrum method. Factors, including eccentricity ratios and frequency ratios, are analyzed in detail to investigate their effects on these structures' seismic responses. The results show that the eccentricity ratio perpendicular to the seismic direction has a greater impact on translational responses along the seismic direction and rotational responses than the eccentricity ratio along the seismic direction. In addition, the torsional-translational frequency ratio exhibits a larger impact on translational responses along the seismic direction and rotational responses than the translational frequency ratio. Following this, the back propagation (BP) neural network model is developed, fully considering the effects of various factors. A SHAP analysis is also conducted to compare the relative importance of different factors. The outcomes show that the seismic prediction model developed in this study achieves high accuracy while adequately considering the factors influencing the seismic responses of one-story two-way eccentric structures. Finally, an example is presented to demonstrate the applicability of the proposed prediction model.

Keywords: one-story bidirectionally eccentric structure; seismic response prediction; eccentricity ratio; frequency ratio; BP neural network



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1. Introduction

As one of the most common natural disasters, earthquakes often cause severe casualties and huge economic losses to society. Post-earthquake surveys have shown that structures that undergo torsional responses are prone to damage under seismic excitations. For instance, in the 1999 Chi-Chi earthquake, a large number of masonry and reinforced concrete buildings showed significant torsional failure characteristics [1]. These structural torsional responses mainly result from plan asymmetry or eccentricity of the structure or the torsional component of ground motion [2–5]. They often result in an uneven distribution of seismic demands and inelastic deformations among structural components, thus leading to severe damage during earthquakes.

During recent decades, extensive studies have been conducted on the seismic behaviors of asymmetric or eccentric structures under unidirectional or bidirectional ground motions. For the former, researchers have mainly focused on investigating the influences of various parameters on the seismic responses of asymmetric structures, including structural

and ground motion characteristics [6–22]. For example, Goel and Chopra [8,9] systematically analyzed the influences of the stiffness and strength distribution, seismic excitation, system parameters, and yielding on the elastoplastic seismic responses of a uniaxially eccentric structure. Furthermore, Lucchini et al. [16] identified the key parameters that affect the nonlinear seismic response of planarly asymmetric buildings by evaluating the influence of different asymmetries that might characterize the building structure and exploring the influence of ground motion characteristics. Later, Eivani et al. [17] investigated the influence of diaphragm flexibility on the response of asymmetric planar structures with different uncoupled natural periods, stiffness eccentricity ratios, and torsional-to-horizontal frequency ratios under seismic loading. In addition, Ruggieri et al. [19] proposed a new practical numerical procedure to estimate floor deformability in existing RC buildings, aiming to improve the accuracy of structural response and seismic fragility assessments by avoiding the unrealistic assumption of rigid floors. In addition, Tamizharasi et al. [20] found that the torsional responses of the building are attributed to the poor planar layout of the structure, which is caused by two factors: torsional eccentricity and torsional flexibility. Recently, Kuang et al. [21,22] conducted a comprehensive parametric analysis to explore the translational–torsional coupling effect of the bidirectionally eccentric multi-story frame structure during the transition from the elastic stage to the elastoplastic stage.

In addition to the above work, researchers conducted studies on the seismic behaviors of unsymmetric structures under bidirectional ground motions [23–39]. For example, Dutta et al. [28–30] studied the variation patterns of seismic responses of the bidirectionally eccentric structure under different characteristics, such as concrete strength degradation, and different strength and stiffness eccentricity ratios caused by component cracking. Furthermore, Alam et al. [35] analyzed the relative rotational responses of flexible-edge components and rigid-edge components in order to study the influence of different earthquake directions on the nonlinear seismic response. The results show that the eccentric structure is more sensitive to the acceleration response than to the velocity and displacement responses, especially for the flexible-edge components. In addition, Hussain et al. [34,36,37] comprehensively investigated the influence of bidirectional seismic excitation on seismic effects of bidirectionally eccentric structures by varying structural parameters (including the basic lateral period, the ratio of the uncoupled torsional period to the lateral period, stiffness eccentricity, strength eccentricity, and response reduction coefficient), mass and stiffness distribution, and different seismic incidence angles. Recently, Chowdhury and Karmakar [38] conducted a study on the torsional response of eccentric structures with uneven floor mass distribution under orthogonal seismic excitations. They found that the high-order modes have a particularly significant impact on the seismic vulnerability of the structure.

In the above studies, various factors affecting the seismic responses of asymmetric structures have been thoroughly investigated in an individual manner. In these studies, one-way eccentricity is mainly studied rather than two-way eccentricity, which represents a more general situation in real structures. In addition, the conventional analytical or numerical methods, e.g., time history analysis, of obtaining seismic responses of asymmetric structures are often computationally expensive and time-demanding. There is no method or model yet proposed for the rapid response prediction of asymmetric structures under seismic excitations that adequately considers various influencing factors. To fill this gap, this study focuses on a model for predicting the seismic responses of one-story bidirectionally eccentric structures with high computational efficiency. To this end, the equations of motion of these structures are derived and solved through the modal response spectrum method. The influencing factors are analyzed in detail with emphasis on the combined effect of different factors. Then, a back propagation (BP) neural network is established to predict

the seismic response of one-story bidirectionally eccentric structures, fully considering various factors. SHAP analysis is also conducted to compare the relative importance of different parameters. Finally, an example is provided to demonstrate the applicability of the proposed prediction model.

2. Equations of Motion of One-Story Asymmetric Structures

As seen in Figure 1, the widely used idealized asymmetric system [40] is adopted to represent the actual one-story bidirectionally eccentric structure in this study, where k_{yi} is the stiffness of the i -th lateral resisting element (e.g., planar frame or shear wall) along the y direction; k_{xk} is the stiffness of the k -th lateral resisting element along the x direction; CM and CS represent the center of mass and rigidity, respectively; a_{gy} represents the ground acceleration along the y direction. Note that the origin is located at CM, and CS deviates from CM in both directions, resulting in bidirectional eccentricity, i.e., e_{sx} and e_{sy} , as shown in Figure 1.

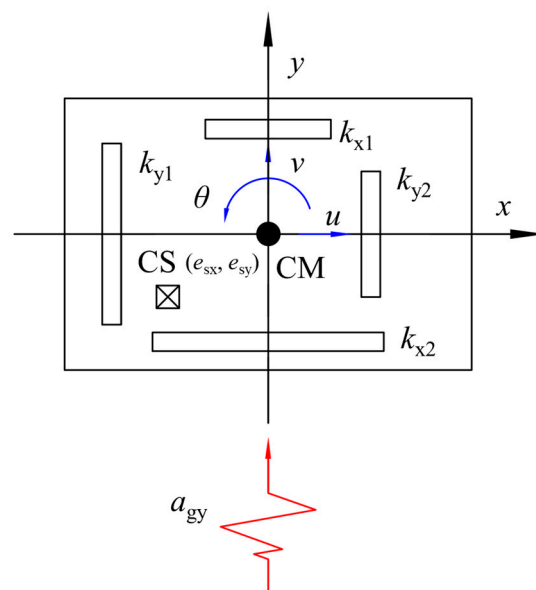


Figure 1. Idealized asymmetric system.

For the sake of simplification, the following assumptions are adopted: the floor is rigid, all elements remain elastic, and a classical damping is employed. According to d'Alembert's principle, the equations of motion of the idealized one-story asymmetric system under seismic excitation can be derived as follows:

$$\begin{bmatrix} m & & \\ & m & \\ & & J_r \end{bmatrix} \begin{Bmatrix} \ddot{u} \\ \ddot{v} + a_{gy} \\ \ddot{\theta} \end{Bmatrix} + \begin{bmatrix} c_x & & \\ & c_y & \\ & & c_\theta \end{bmatrix} \begin{Bmatrix} \dot{u} \\ \dot{v} \\ \dot{\theta} \end{Bmatrix} + \begin{bmatrix} k_x & 0 & -k_x e_{sy} \\ 0 & k_y & k_y e_{sx} \\ -k_x e_{sy} & k_y e_{sx} & k_\theta \end{bmatrix} \begin{Bmatrix} u \\ v \\ \theta \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix} \quad (1)$$

where u and v are translational displacements in the x and y directions at CM, respectively, and θ is the rotation angle; m is the total mass of the system, and J_r is the moment of inertia relative to CM as below:

$$J_r = mr^2 \quad (2a)$$

where r represents the radius of gyration; c_x and c_y are the damping coefficients in the x and y directions, respectively, and c_θ is the damping coefficient in the torsional direction;

k_x and k_y are the translational stiffness in the x and y directions of the system, respectively, and k_θ is the torsional stiffness, which are calculated as follows:

$$k_x = \sum k_{xk} \quad (2b)$$

$$k_y = \sum k_{yi} \quad (2c)$$

$$k_\theta = \sum k_{xk} y_k^2 + \sum k_{yi} x_i^2 \quad (2d)$$

where x_i is the x coordinate of the i -th lateral resisting element along the y direction, and y_k is the y coordinate of the k -th lateral resisting element along the x direction; e_{sx} and e_{sy} are the stiffness eccentricities in the x and y directions, respectively, as determined by

$$e_{sx} = \sum k_{yi} x_i / k_y \quad (2e)$$

$$e_{sy} = \sum k_{xk} y_k / k_x \quad (2f)$$

Equations (1) and (2a)–(2f) constitute the whole governing equations of an idealized one-story asymmetric system subjected to unidirectional seismic input. It is worth noting that the bidirectionally eccentric system would become a unidirectionally eccentric system when $e_{sx} = 0$ or $e_{sy} = 0$. Furthermore, for both $e_{sx} = 0$ and $e_{sy} = 0$, it turns into a symmetric system without eccentricity.

3. Seismic Response Analysis

In this section, Equation (1) is solved through the modal response spectrum method to determine the seismic responses of the idealized one-story asymmetric system. To achieve this, modal analysis is performed first to determine the frequencies and modes.

3.1. Modal Analysis

For the idealized one-story asymmetric system, the following frequency parameters can be defined:

$$\omega_x = \sqrt{\frac{k_x}{m}} \quad (3a)$$

$$\omega_y = \sqrt{\frac{k_y}{m}} \quad (3b)$$

$$\omega_\theta = \sqrt{\frac{k_\theta}{J_r}} \quad (3c)$$

where ω_x and ω_y are the uncoupled translational frequencies along the x and y directions, respectively, and ω_θ is the uncoupled torsional frequency.

According to Equation (1), the corresponding undamped free vibration equation can be derived as follows:

$$\omega_y^2 \begin{bmatrix} \Omega_x^2 & 0 & -rB_y\Omega_x^2 \\ 0 & 1 & rB_x \\ -rB_y\Omega_x^2 & rB_x & r^2\Omega_\theta^2 \end{bmatrix} \begin{Bmatrix} u \\ v \\ \theta \end{Bmatrix} + \begin{bmatrix} 1 & & \\ & 1 & \\ & & r^2 \end{bmatrix} \begin{Bmatrix} \ddot{u} \\ \ddot{v} \\ \ddot{\theta} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix} \quad (4)$$

where B_x and B_y are the eccentricity ratios along the x and y directions, respectively, i.e., e_{sx}/r and e_{sy}/r ; Ω_x is the translational frequency ratio, i.e., ω_x/ω_y ; and Ω_θ is the torsional–translational frequency ratio, i.e., ω_θ/ω_y .

Based on Equation (4), the dynamic eigenvalue equation can be obtained as follows:

$$\begin{vmatrix} \Omega_x^2 - \frac{\omega^2}{\omega_y^2} & 0 & -rB_y\Omega_x^2 \\ 0 & 1 - \frac{\omega^2}{\omega_y^2} & rB_x \\ -rB_y\Omega_x^2 & rB_x & r^2\left(\Omega_\theta^2 - \frac{\omega^2}{\omega_y^2}\right) \end{vmatrix} = 0 \quad (5)$$

where ω is the natural frequency of the system to be solved. By solving Equation (5), three natural frequencies, i.e., ω_j ($j = 1 \sim 3$) in ascending order, can be obtained. Furthermore, when $\omega_j \neq \omega_x$ and $\omega_j \neq \omega_y$, the mode corresponding to each frequency can be determined as follows:

$$\begin{Bmatrix} U_j \\ V_j \\ \Theta_j \end{Bmatrix} = \begin{Bmatrix} rB_y\Omega_x^2\left(\frac{\omega_j^2}{\omega_y^2} - 1\right) \\ rB_x\left(\Omega_x^2 - \frac{\omega_j^2}{\omega_y^2}\right) \\ \left(\frac{\omega_j^2}{\omega_y^2} - 1\right)\left(\Omega_x^2 - \frac{\omega_j^2}{\omega_y^2}\right) \end{Bmatrix} \quad (6)$$

From Equation (5), it can be proven that the relative frequency (ω/ω_y) depends entirely on four dimensionless structural parameters: B_x , B_y , Ω_x , and Ω_θ . Therefore, the stiffness eccentricity ratios and frequency ratios are key parameters dominating the dynamic characteristics of the idealized one-story asymmetric system. In particular, for $B_y = 0$ and $B_x \neq 0$, i.e., the unidirectionally eccentric system, solving Equation (5) can yield one solution being equal to ω_x ; for $B_x = B_y = 0$, i.e., the symmetric system without eccentricity, the three solutions of Equation (5) are ω_x , ω_y , and ω_θ .

3.2. Seismic Response

3.2.1. Calculation Formulas

Using the modal response spectrum method [41], seismic forces of the idealized one-story asymmetric system corresponding to the j -th mode can be calculated by

$$F_{xj} = \alpha_j \gamma_{yj} U_j m g \quad (7a)$$

$$F_{yj} = \alpha_j \gamma_{yj} V_j m g \quad (7b)$$

$$F_{tj} = \alpha_j \gamma_{yj} r^2 \Theta_j m g \quad (7c)$$

where F_{xj} and F_{yj} are the j -th modal shear forces in the x and y directions, respectively, and F_{tj} is the j -th modal torque; α_j is the seismic influence coefficient corresponding to the j -th mode, which is determined using the 5% damping response spectrum [41] shown in Figure 2, where $\alpha_{\max}$ is the maximum seismic influence coefficient, and T_g is the characteristic period; γ_{yj} is the participation coefficient in the y direction corresponding to the j -th mode, as calculated by

$$\gamma_{yj} = \frac{V_j}{U_j^2 + V_j^2 + r^2 \Theta_j^2} \quad (7d)$$

Note that the reinforced concrete structures in China are mainly concerned in this study. For other cases, a different response spectrum with a different damping value can be adopted alternatively.

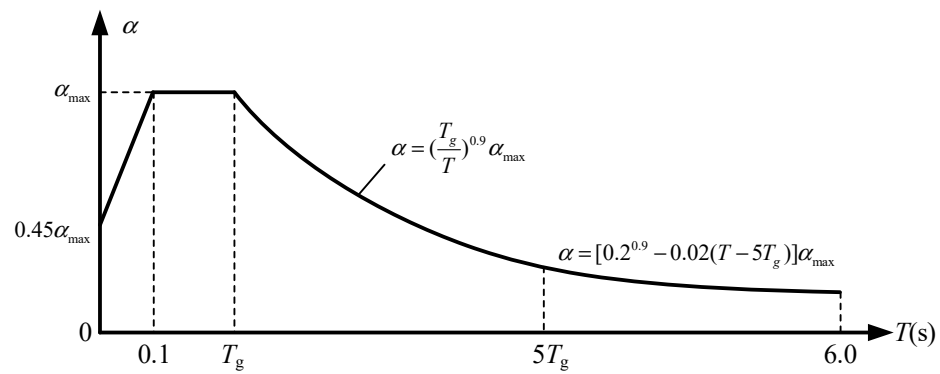


Figure 2. Response spectrum utilized in this study.

In addition, the displacements corresponding to the j -th mode can be determined by [42]

$$\Delta_{xj} = \alpha_j \gamma_{yj} g U_j / \omega_j^2 \quad (8a)$$

$$\Delta_{yj} = \alpha_j \gamma_{yj} g V_j / \omega_j^2 \quad (8b)$$

$$\Delta_{tj} = \alpha_j \gamma_{yj} g \Theta_j / \omega_j^2 \quad (8c)$$

where Δ_{xj} and Δ_{yj} are the j -th modal translational displacements in the x and y directions, respectively, and Δ_{tj} is the j -th modal rotation.

Furthermore, the CQC method [41] is used to combine different modal responses to obtain seismic responses of the idealized one-story asymmetric system as follows:

$$S = \sqrt{\sum_{j=1}^3 \sum_{k=1}^3 \rho_{jk} S_j S_k} \quad (9a)$$

where S_j represents the j -th modal response; ρ_{jk} represents the correlation coefficient between mode j and mode k , which is calculated by the following formula when the damping ratio is 0.05 [41]:

$$\rho_{jk} = \frac{0.02(1 + \lambda_T) \lambda_T^{1.5}}{(1 - \lambda_T^2)^2 + 0.01(1 + \lambda_T^2) \lambda_T + 0.02 \lambda_T^2} \quad (9b)$$

where λ_T is the natural period ratio between the k -th mode and the j -th mode.

3.2.2. Dimensionless Expression

For the symmetric system without eccentricity, i.e., $B_x = B_y = 0$, subjected to seismic excitation along the y direction, the shear force and displacement can be expressed, respectively, as follows:

$$F_0 = \alpha_0 m g \quad (10a)$$

$$\Delta_0 = \alpha_0 g / \omega_y^2 \quad (10b)$$

where α_0 is the seismic influence coefficient determined by ω_y .

Relative to the symmetric system, the dimensionless seismic responses of the idealized one-story asymmetric system can be defined as

$$f_x = \frac{F_x}{F_0}, f_y = \frac{F_y}{F_0}, f_t = \frac{F_t}{r F_0} \quad (11a)$$

$$d_x = \frac{\Delta_x}{\Delta_0}, d_y = \frac{\Delta_y}{\Delta_0}, d_t = \frac{r \Delta_t}{\Delta_0} \quad (11b)$$

where f_x and f_y represent the relative shear forces in the x and y directions, respectively, and f_t is relative torque; d_x and d_y represent the relative displacements in the x and y directions, respectively, and d_t is the relative rotation; F_x and F_y represent the shear forces in the x and y directions of the asymmetric system, respectively, and F_t is the torque; Δ_x and Δ_y represent the translational displacements in the x and y directions of the asymmetric system respectively, and Δ_t is the rotation.

From Equations (5)–(11) and Figure 2, it can be concluded that the relative seismic responses of the idealized one-story asymmetric system are totally dependent on B_x , B_y , Ω_x , Ω_θ , ω_y (or T_y), and T_g , which can be expressed generally as

$$s = f(B_x, B_y, \Omega_x, \Omega_\theta, \omega_y \text{ or } T_y, T_g) \quad (12)$$

where s represents the relative seismic response, and T_y is the uncoupled translational period along the y direction. It can be seen that, except for the uncoupled natural frequency or period of the system and the ground motion parameter, the stiffness eccentricity ratios and frequency ratios are primary parameters controlling the seismic responses of the idealized one-story asymmetric system.

4. Analysis of Influencing Factors

Using the analysis method established in the last section, the effects of various factors, including stiffness eccentricity ratios and frequency ratios, on the seismic behaviors of the one-story bidirectionally eccentric structure are thoroughly investigated in this section. The influence of individual factors is first analyzed, and that of combined factors is determined as described below. According to reference [42–44], the parameter ranges are set as follows: $B_x = 0\sim 0.5$, $B_y = 0\sim 0.5$, $\Omega_x = 0.5\sim 1$, $\Omega_\theta = 0.8\sim 2$, $T_y = 0.05\text{ s}\sim 1.9\text{ s}$.

4.1. Effect of Individual Factors

4.1.1. Effect of the Eccentricity Ratio Perpendicular to Seismic Direction

In order to investigate the influence of the eccentricity perpendicular to seismic input on the seismic responses of the one-story bidirectionally eccentric structure, the values of B_x are changed from 0 to 0.5 with an interval of 0.1, while other parameters are kept constant as follows: $B_y = 0.5$, $\Omega_x = 0.8$, $\Omega_\theta = 1.4$, $T_y = 0.3\text{ s}$, and $T_g = 0.4\text{ s}$. Note that $B_x = 0$ corresponds to a structure only with unidirectional eccentricity along the seismic direction.

The calculated seismic responses of the one-story bidirectionally eccentric structure for different values of B_x are shown in Figure 3, where s_f denotes the dimensionless shear force or torque, and s_d refers to the dimensionless translational displacement or rotation. It can be seen that $f_y = d_y = 1$ and $f_x = f_t = d_x = d_t = 0$ for $B_x = 0$, meaning that the shear force and horizontal deformation only emerge along the seismic direction without the torque and rotation incurred. This shows that a one-story unsymmetric structure with single eccentricity along seismic direction behaves like a single-degree-of-freedom (SDOF) system translating along seismic direction. This holds as the inertia force passes through the center of rigidity and thus incurs no rotation in the structure. In addition, as B_x increases from 0 to 0.5, f_y and d_y decrease by 20.7% and 5.3%, respectively, while the rest of the responses increase in a monotonic way, indicating that the structure transforms from an SDOF system to a 3DOF (three-degree-of-freedom) system. In addition, the rise in eccentricity perpendicular to the seismic direction decreases the translational responses along seismic direction, while increasing the translational responses perpendicular to the seismic direction as well as torsional responses.

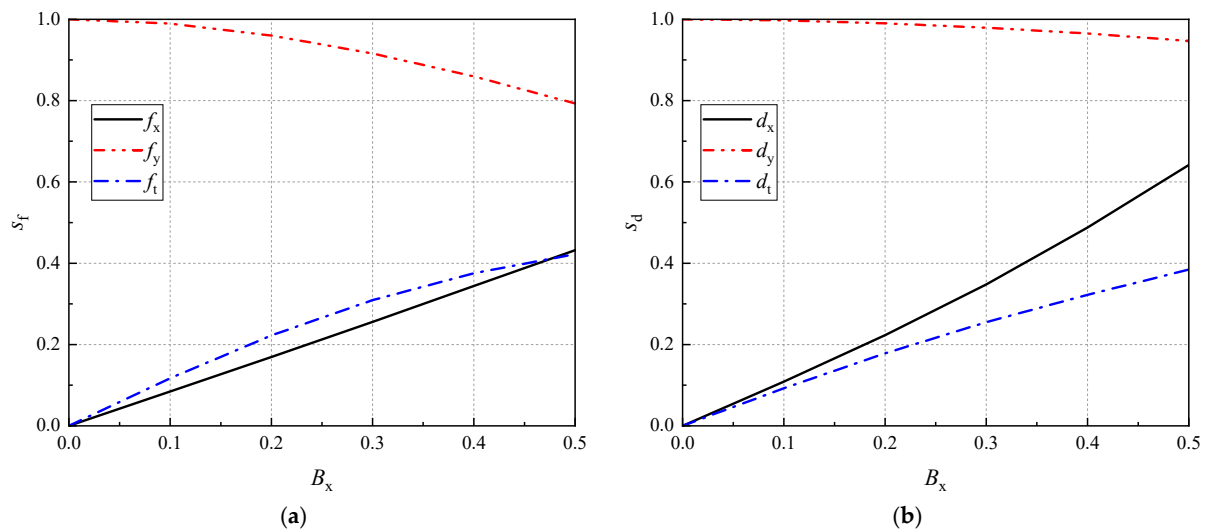


Figure 3. Seismic responses for different values of B_x : (a) relative force and torque; (b) relative displacement and rotation.

4.1.2. Effect of the Eccentricity Ratio Along the Seismic Direction

In order to investigate the influence of the eccentricity along the seismic direction on the seismic responses of the one-story bidirectionally eccentric structure, the values of B_y are varied from 0 to 0.5 with an interval of 0.1. The remaining parameters have the following constant values: $B_x = 0.5$, $\Omega_x = 0.8$, $\Omega_\theta = 1.4$, $T_y = 0.3$ s, and $T_g = 0.4$ s. Note that $B_y = 0$ corresponds to a structure only with unidirectional eccentricity perpendicular to the seismic direction.

The computed seismic responses as a function of B_y are plotted in Figure 4. As shown, $f_x = d_x = 0$ for $B_y = 0$, indicating that no force and displacement are generated orthogonal to the seismic direction. This shows that a one-story unsymmetric structure with unidirectional eccentricity perpendicular to the seismic direction acts as a 2DOF (two-degree-of-freedom) system. Moreover, as B_y increases from 0 to 0.5, f_y and d_y decrease by 8.4% and 12.4%, respectively, and f_t and d_t decrease by 15.7% and 20.2%, respectively, while f_x and d_x increase monotonically, indicating that the system changes from a 2DOF system to a 3DOF system. In addition, the increase in eccentricity along the seismic direction reduces translational responses along this direction as well as the torsional responses, while significantly enhancing seismic responses perpendicular to the seismic direction.

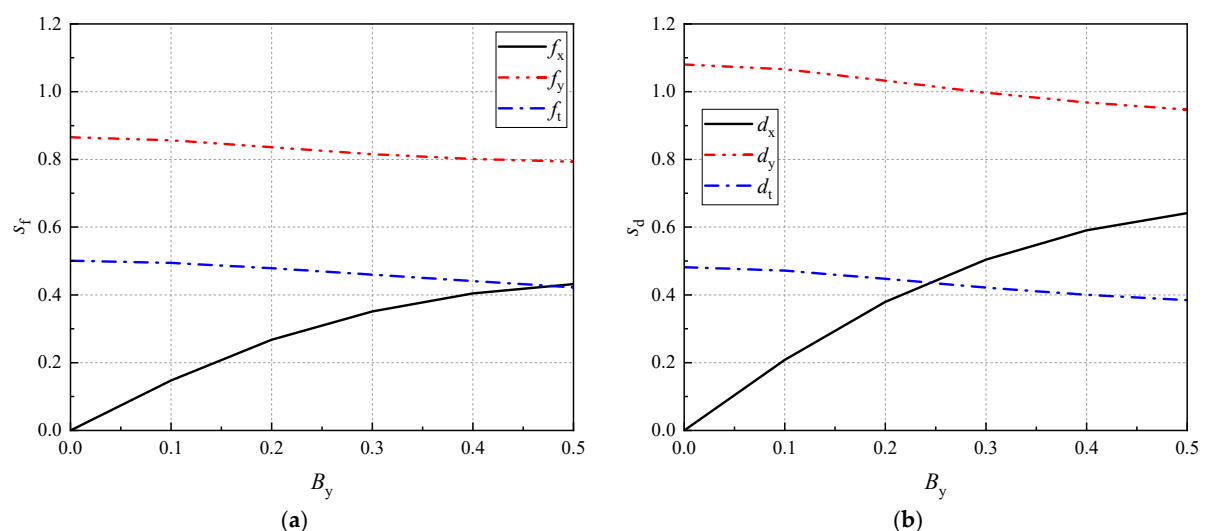


Figure 4. Seismic responses for different values of B_y : (a) relative force and torque; (b) relative displacement and rotation.

By combining Figures 3 and 4, it can be further summarized that translational responses along the seismic direction can be effectively reduced by increasing the eccentricity in both directions. However, the translational responses perpendicular to the seismic direction are always larger, while the rotational responses can be larger or smaller depending on the eccentricity direction.

4.1.3. Effect of the Translational Frequency Ratio

In order to study the influence of the translational frequency ratio on the seismic responses of the one-story bidirectionally eccentric structure, the values of Ω_x are set between 0.5 and 1.0 with an interval of 0.1, while the values of the remaining parameters are taken as follows: $B_x = 0.5$, $B_y = 0.5$, $\Omega_\theta = 1.4$, $T_y = 0.3$ s, and $T_g = 0.4$ s.

The calculated seismic responses for various values of Ω_x are shown in Figure 5. It can be seen that, when Ω_x increases from 0.5 to 1.0, f_y and d_y decrease by 19.7% and 19.8%, respectively, while f_x and d_x increase by 544.4% and 282.3%, respectively, and changes in f_t and d_t are relatively small. It indicates that improving the stiffness perpendicular to the seismic direction can remarkably reduce translational responses along the seismic direction while significantly increasing the translational responses orthogonal to the seismic direction.

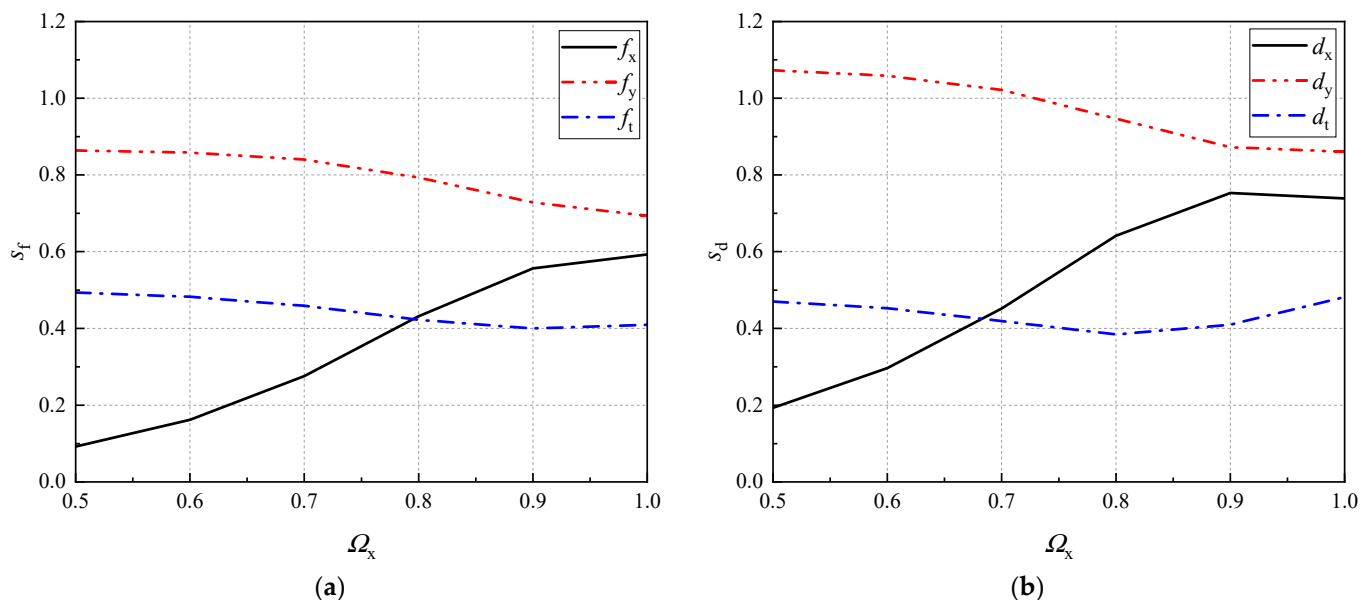


Figure 5. Seismic responses for different values of Ω_x : (a) relative force and torque; (b) relative displacement and rotation.

4.1.4. Effect of the Torsional–Translational Frequency Ratio

In order to investigate the effect of the torsional–translational frequency ratio on the seismic responses of the one-story bidirectionally eccentric structure, the values of Ω_θ are altered from 0.8 to 2.0 with an interval of 0.2, while the remaining parameters are kept constant as follows: $B_x = 0.5$, $B_y = 0.5$, $\Omega_x = 0.8$, $T_y = 0.3$ s, and $T_g = 0.4$ s.

The computed seismic responses for various values of Ω_θ are shown in Figure 6. It can be seen that as Ω_θ increases from 0.8 to 2.0, f_y and d_y increase by 48.6% and 13.2%, respectively, while, on the whole, f_x and d_x decrease by 57.4% and 73.1%, respectively, and f_t and d_t decrease by 57.7% and 87.7%, respectively. Therefore, for the parameter values considered here, the increase in the torsional stiffness results in an increase in translational responses along the seismic direction and a significant decrease in translational responses perpendicular to the seismic direction and rotational responses. This is consistent, since the torsional stiffness helps to mitigate rotational responses of asymmetric structures.

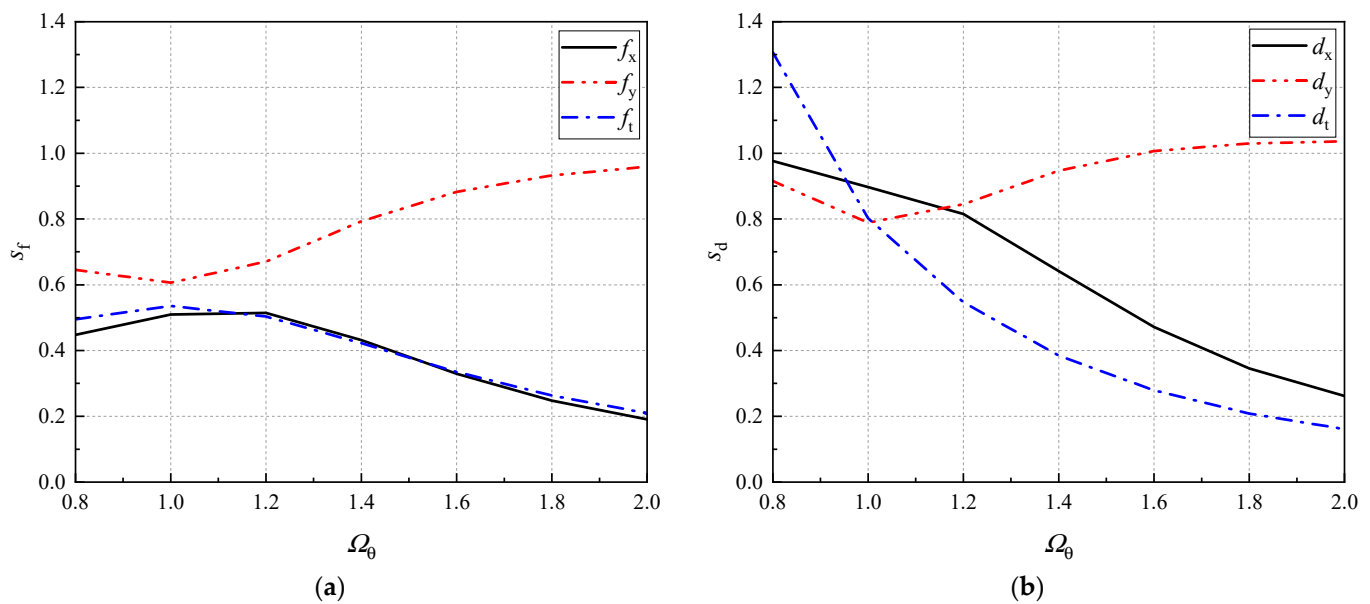


Figure 6. Seismic responses for different values of Ω_0 : (a) relative force and torque; (b) relative displacement and rotation.

4.2. Combined Effect of Factors

Considering the similarities in the physical implications of the above factors, they are divided into two groups to explore their combined influence on the seismic responses of the one-story bidirectionally eccentric structure: the influences of the eccentricities in two directions are combined, as are the influences of the translational frequency and torsional–translational frequency ratios.

4.2.1. Effect of Eccentricity Ratios in Two Directions

In order to investigate the influence of eccentricities in two directions, combining the seismic responses of the one-story bidirectionally eccentric structure, the values of B_x and B_y are both changed from 0 to 0.5 with an interval of 0.1. The remaining parameter values are set as follows: $\Omega_x = 0.8$, $\Omega_0 = 1.4$, $T_y = 0.3$ s, and $T_g = 0.4$ s.

The computed seismic responses for various values of the B_x and B_y combinations are shown in Figure 7. On the whole, it can be seen that the translational responses perpendicular to the seismic direction (f_x and d_x) and rotational responses (f_t and d_t) both display monotonic variation trends as B_x and B_y change. However, the translational responses along the seismic direction (f_y and d_y) exhibit a more complex changing tendency, especially for the displacement response. Specifically, both f_x and d_x increase continuously as B_x and B_y increase, finally reaching maximum values of 0.432 and 0.642, respectively,

Both B_x and B_y are equal to 0.5. However, both f_t and d_t increase as B_x increases and B_y decreases.

In addition, as shown in Figure 7c–f, the partial derivatives of f_y , d_y , f_t , and d_t with respect to B_x are generally larger than those with respect to B_y , showing that the eccentricity perpendicular to the seismic direction has a greater impact on the translational responses along the seismic direction and rotational responses than the eccentricity along the seismic direction. However, as observed in Figure 7a,b, partial derivatives of f_x and d_x , with respect to B_x and B_y , are similar, suggesting that the eccentricities in the two directions have comparable effects on the translational responses perpendicular to the seismic direction.

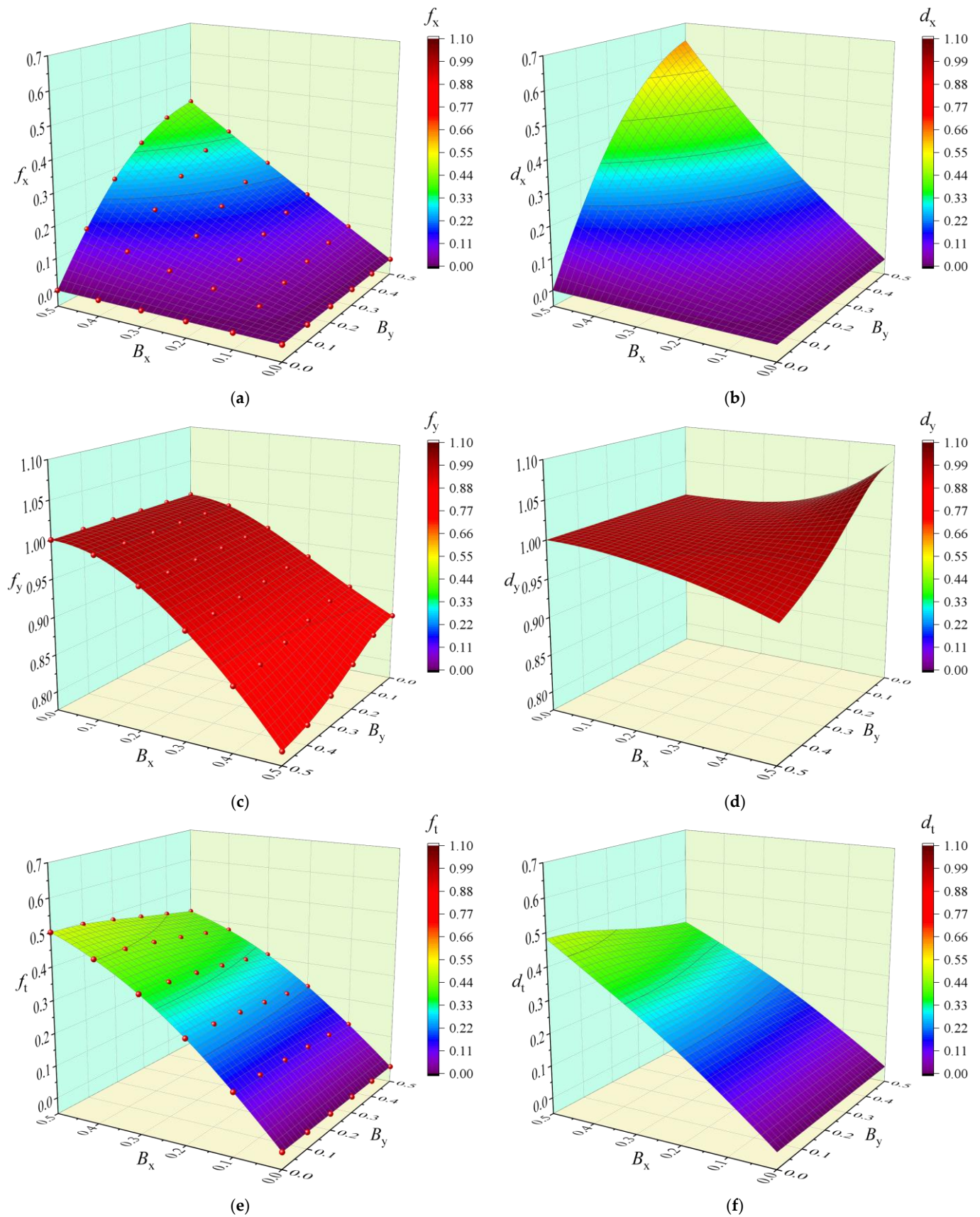


Figure 7. Seismic responses for different values of eccentricity ratios in two directions combined: (a) relative shear force in the x direction; (b) relative displacement in the x direction; (c) relative shear force in the y direction; (d) relative displacement in the y direction; (e) relative torque; (f) relative rotation.

4.2.2. Influence of Two Frequency Ratios

In order to examine the influence of the two frequency ratios on the seismic responses of the one-story bidirectionally eccentric structure, the values of Ω_x are varied between 0.5 and 1.0 with an interval of 0.1, and those of Ω_θ are changed between 0.8 and 2.0 with an interval of 0.2. The other parameter values are taken as follows: $B_x = 0.5$, $B_y = 0.5$, $T_y = 0.3$ s, and $T_g = 0.4$ s.

The calculated seismic responses for various Ω_x and Ω_θ values are shown in Figure 8. The results show that clear fluctuations are present on the plotted surfaces, especially in Figure 8c–e. By comparing Figures 7 and 8, it can be inferred that, in general, the frequency ratios have a more complex impact on the seismic responses of the one-story bidirectionally eccentric structure than the eccentricity ratios.

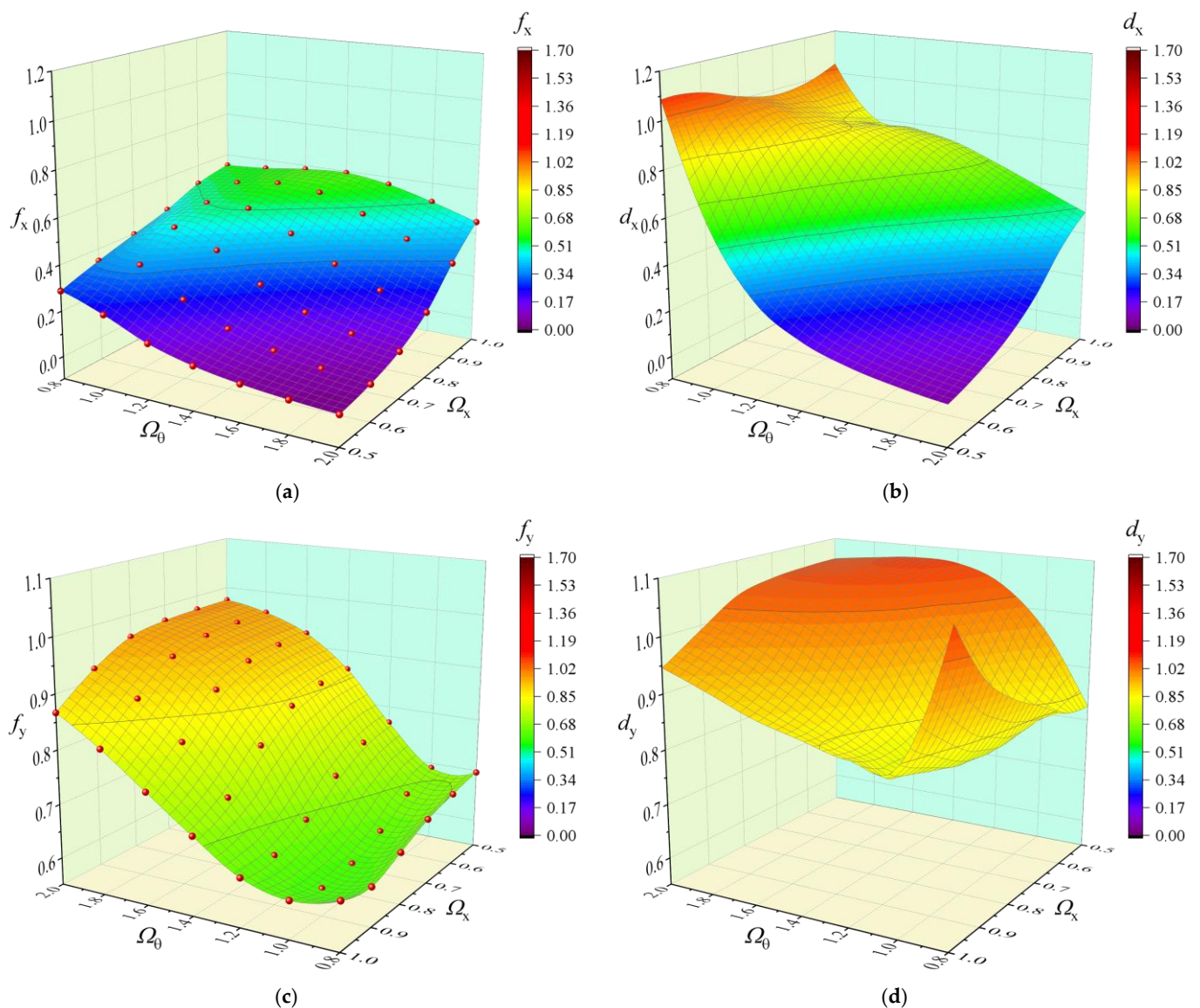


Figure 8. Cont.

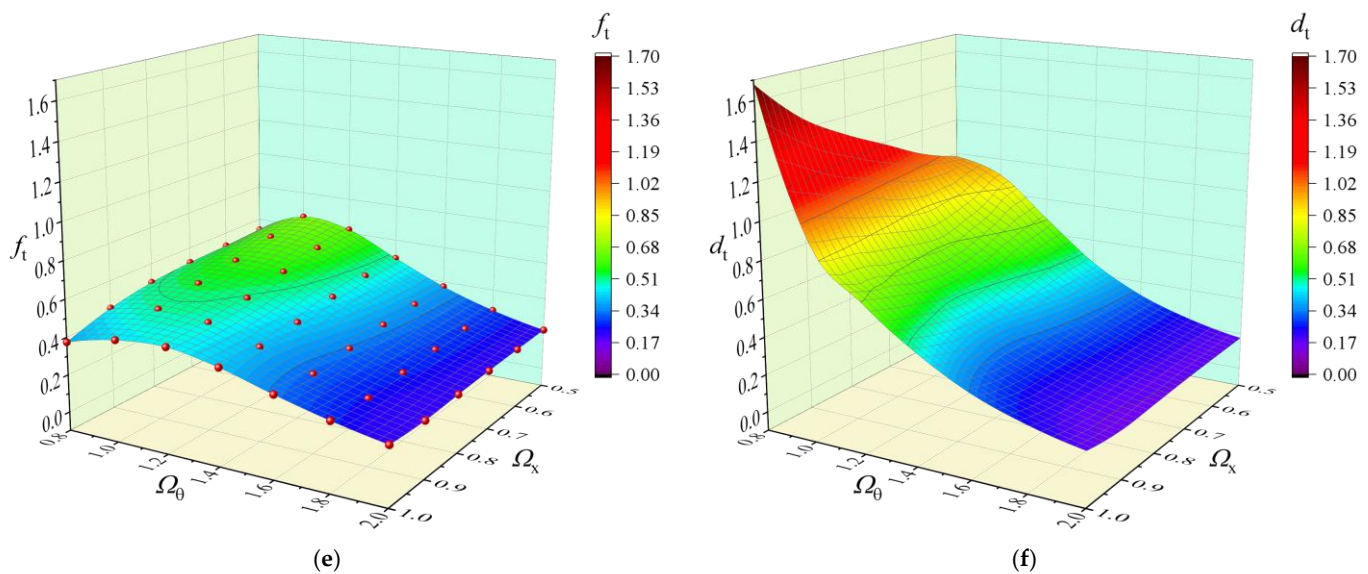


Figure 8. Seismic responses for different values of two frequency ratios combined: (a) relative shear force in the x direction; (b) relative displacement in the x direction; (c) relative shear force in the y direction; (d) relative displacement in the y direction; (e) relative torque; (f) relative rotation.

In addition, as shown in Figure 8c–f, partial derivatives of f_y , d_y , f_t , and d_t , with respect to Ω_θ , are generally larger than those for Ω_x , indicating that the torsional–translational frequency ratio exhibits a greater impact on the translational responses along the seismic direction and rotational responses than the translational frequency ratio. However, as shown in Figure 8a,b, partial derivatives of f_x and d_x with respect to Ω_x and Ω_θ are similar, demonstrating that the two frequency ratios have similar impacts on translational responses perpendicular to the seismic direction.

5. Seismic Response Prediction

In this section, the prediction model is established, taking into account all the influencing factors, to estimate the seismic responses of the one-story bidirectionally eccentric structure. According to Equation (12), a total of six factors are involved in the prediction model, which have complex influences on the seismic responses of this structure, as seen in Figures 7 and 8, making it complex to determine a mathematical model simply by fitting. To tackle this problem, a widely used machine learning model, i.e., the BP neural network, is utilized to develop the prediction model due to its strong nonlinear mapping capacity.

5.1. Dataset Construction

As mentioned above, a total of six features or attributes are considered in the dataset, namely B_x , B_y , Ω_x , Ω_θ , T_y , and T_g . In order to generate sufficient samples in the dataset, the values of these features are set, as listed in Table 1. Note that the values pertaining to B_x , B_y , Ω_x , and Ω_θ are the same as those in Section 4. Regarding T_y and T_g , 11 and 7 different values are considered, respectively [45]. Based on these values, a total of 116,424 samples are generated.

For each sample, the label corresponding to the six response quantities, i.e., f_x , f_y , f_t , d_x , d_y , and d_t , can be calculated using the method presented in Section 2. To facilitate this process, the program is developed using MATLAB R2016b [46], and a dataset with a total of 116,424 samples is finally constructed. According to the hold-out method [47,48], the dataset is further randomly divided into training, validation, and testing sets with a ratio of 8:1:1, resulting in 93,140 samples in the training set and 11,642 samples in the validation and testing sets, respectively.

Table 1. Values of features.

Feature	Number of Values	Values
B_x	6	0, 0.1, 0.2, 0.3, 0.4, 0.5
B_y	6	0, 0.1, 0.2, 0.3, 0.4, 0.5
Ω_x	6	0.5, 0.6, 0.7, 0.8, 0.9, 1
Ω_θ	7	0.8, 1, 1.2, 1.4, 1.6, 1.8, 2
T_y (s)	11	0.05, 0.1, 0.3, 0.5, 0.7, 0.9, 1.1, 1.3, 1.5, 1.7, 1.9
T_g (s)	7	0.2, 0.3, 0.4, 0.55, 0.65, 0.75, 0.9

Furthermore, the input features are normalized using the Min–Max method [49] to eliminate the influence of dimension and order of magnitude, which is expressed as

$$x_{\text{new}} = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \quad (13)$$

where x_{new} is the normalized value, x is the original value, and $x_{\min}$ and $x_{\max}$ are the minimum and maximum values in the dataset, respectively.

5.2. Model Training

Based on the above dataset, the BP network is established to predict the seismic responses of the one-story bidirectionally eccentric structure. The BP model consists of an input layer, hidden layers, and an output layer. The input layer contains six neurons, corresponding to six features: B_x , B_y , Ω_x , Ω_θ , T_y , and T_g . The output layer contains six neurons, corresponding to six response quantities: f_x , f_y , f_t , d_x , d_y , and d_t .

The following functions are chosen as activation functions for the hidden layer and output layer, respectively:

$$f_1(x) = \max(0, x) \quad (14a)$$

$$f_2(x) = x \quad (14b)$$

In addition, the mean squared error (MSE) is adopted as the loss function as described below:

$$L_{\text{MSE}} = \frac{1}{N} \sum_{i=1}^N (\|y_i - \hat{y}_i\|_2)^2 \quad (15)$$

where N represents the number of samples, and y_i and $\hat{y}_i$ represent the true value and predicted value corresponding to the i -th sample, respectively.

Using the MATLAB R2024a deep learning toolbox [50], the above BP model is trained using the Levenberg–Marquardt algorithm. The maximum number of iterations is set to 1000, and the error threshold is 1×10^{-6} . Given the relatively simple structure of the network, the model hyperparameters are determined through repeated trials and adjustments, which have the final optimal values as follows: two hidden layers are adopted with 40 and 20 neurons, respectively, and the learning rate is 0.01. Note that alternative methods, such as grid search [51] and Bayesian optimization [51], can be used to fulfill the above task. Figure 9 shows the architecture of the proposed BP model to estimate seismic responses of one-story bidirectionally eccentric structures, where m and n are the numbers of neurons contained in the two hidden layers, respectively.

Figure 10 shows the loss curves of the proposed BP model obtained from the training and validation sets. As shown, L_{MSE} gradually decreases as the number of epochs increases until it approaches a stable value. When the number of epochs reaches 163, L_{MSE} drops to 9.77×10^{-5} . Following this, the learnable parameters, including the weights and biases, are updated, and the proposed BP model is complete.

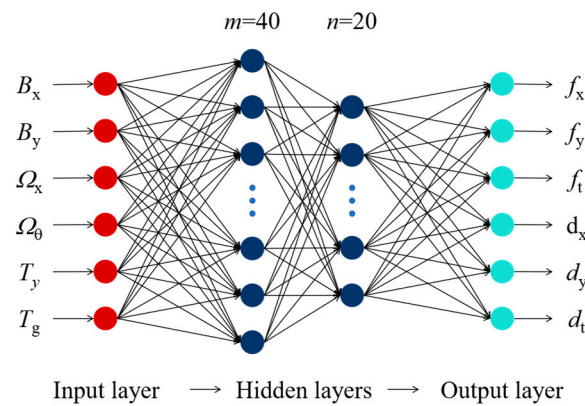


Figure 9. Architecture of the proposed BP model.

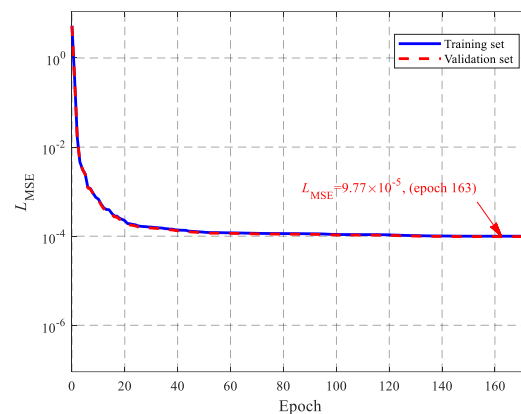


Figure 10. Loss curves of the proposed BP network.

5.3. Model Testing

Based on the testing set, the actual values and predicted results using the BP model established in the last section are shown in Figure 11. Further, the residual plots are given in Figure 12. In addition, various performance indicators, including the coefficient of mean squared error (MSE), mean absolute error (MAE), and determination (R^2), are listed in Table 2. It can be seen that all the fitting curves corresponding to different seismic responses are close to the curve line $y = x$ on the whole, indicating that the model proposed in this study has a high accuracy and good generality. In addition, the proposed model has better accuracy in predicting the relative force and torque than in predicting the relative displacement and rotation. This may be due to the fact that relative displacement and rotation have a more complex dependency on the input features compared to the relative force and torque, as seen in Equations (7a)–(7c) and (8a)–(8c).

Furthermore, the relative error between the predicted value and the actual value is defined as follows:

$$\delta = \frac{x_t - x_p}{x_t} \quad (16)$$

where x_t is the true value and x_p is the predicted value. Note that, in very rare cases, the actual values may be zero, such as f_x and d_x , as seen in Figure 3, which will result in numerical problems in the above equation. Therefore, these cases are excluded in the above error analysis.

Figure 13 shows the distributions of the relative error obtained from the proposed BP model in terms of different seismic responses. It can be found that the probabilities of relative error between $\pm 10\%$ pertaining to f_x , f_y , f_t , d_x , d_y , and d_t are 91.6%, 100%, 99.8%, 82.9%, 99.6%, and 99.5%, respectively. These outcomes are consistent with the findings from Figure 11, demonstrating again that the proposed model has an excellent performance of

predicting the seismic responses of one-story two-way eccentric structures while adequately considering the influencing factors.

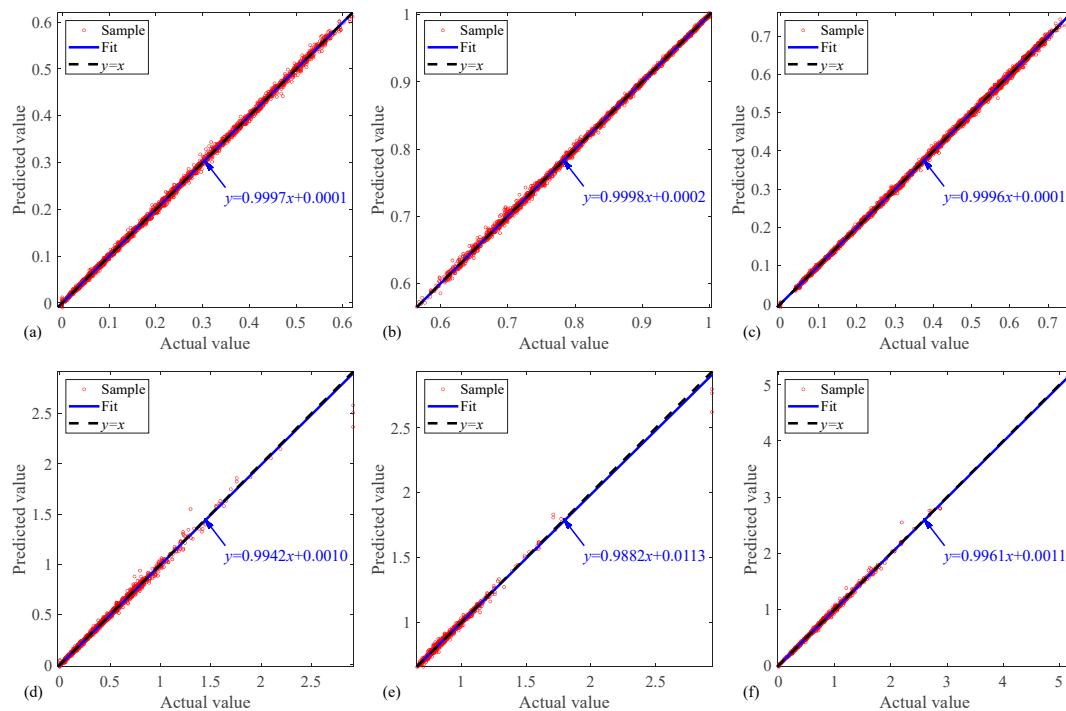


Figure 11. Comparison between the predicted and actual values: (a) relative shear force in the x direction; (b) relative shear force in the y direction; (c) relative torque; (d) relative displacement in the x direction; (e) relative displacement in the y direction; (f) relative rotation.

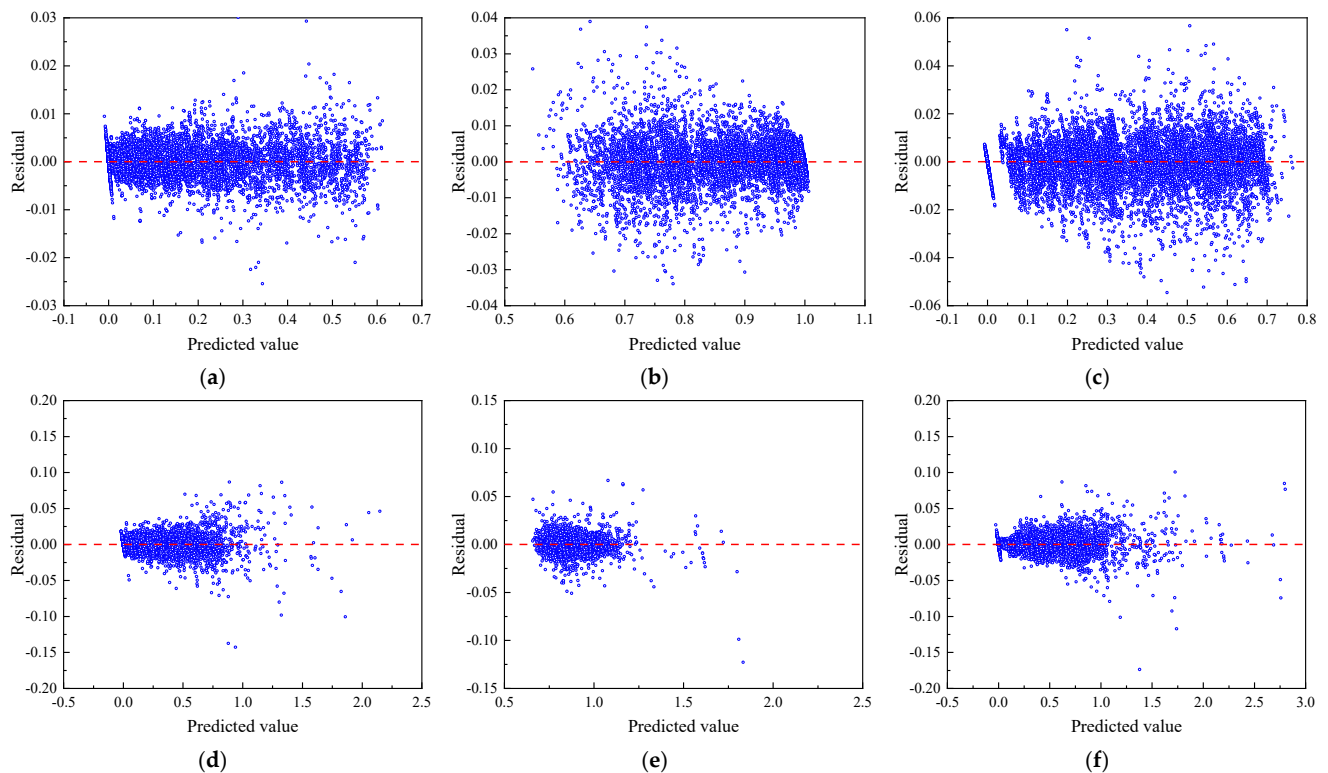
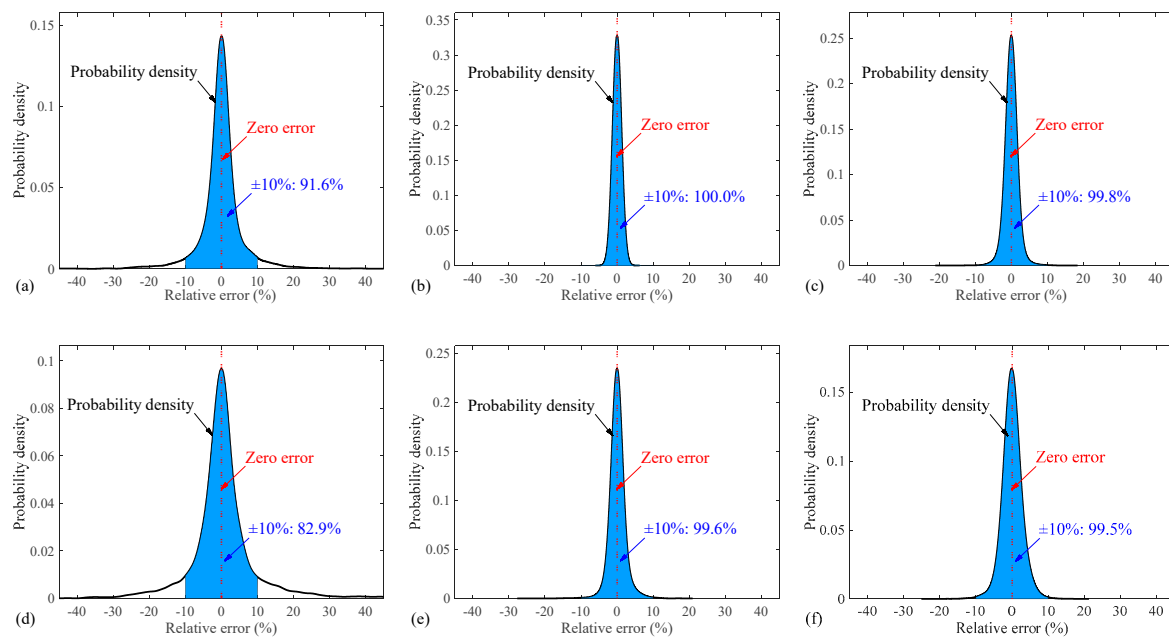


Figure 12. Residual plots: (a) relative shear force in the x direction; (b) relative shear force in the y direction; (c) relative torque; (d) relative displacement in the x direction; (e) relative displacement in the y direction; (f) relative rotation.

Table 2. Values of various performance indicators.

Response	MSE ($\times 10^{-5}$)	MAE ($\times 10^{-5}$)	R ²
f_x	4.78	5.09	0.9979
f_y	2.76	3.72	0.9976
f_t	8.57	7.12	0.9982
d_x	62.99	15.05	0.9887
d_y	41.49	11.96	0.9566
d_t	152.20	20.65	0.9853

**Figure 13.** Distributions of relative errors: (a) relative shear force in the x direction; (b) relative shear force in the y direction; (c) relative torque; (d) relative displacement in the x direction; (e) relative displacement in the y direction; (f) relative rotation.

5.4. SHAP Analysis

Based on the BP model proposed in this study, a SHAP analysis, which often serves as a tool to explain machine learning models [52], was further carried out to investigate the contribution of each feature to different output quantities in this section.

Figure 14 shows the average absolute SHAP value of each feature, i.e., B_x , B_y , Ω_x , Ω_θ , T_y , and T_g , with respect to each seismic response, i.e., f_x , f_y , f_t , d_x , d_y , and d_t . It can be seen that the average absolute SHAP values of B_x , B_y , Ω_x , and Ω_θ are generally much larger than those of T_y and T_g , meaning that the latter two features have the lowest influence on the seismic responses of the one-story bidirectionally eccentric structure. This is evident as relative or dimensionless seismic responses are adopted in this study, as shown in Equations (11a) and (11b). In particular, the average absolute SHAP values of B_x , B_y , Ω_x , and Ω_θ for f_x and d_x are relatively close, indicating that the seismic responses perpendicular to the ground motion are equally governed by the four structural parameters, as evidenced by Figures 7a,b and 8a,b. Nevertheless, for the other responses, Ω_θ and B_x have the greatest impacts.

Figure 15 plots the distributions of SHAP values for each feature pertaining to each seismic response to visually identify the correlation between them. For example, according to Figure 15c, B_x , B_y , and Ω_x are negatively correlated with f_y , while Ω_θ is positively correlated with f_y . These observations are in line with those made from Figures 7c and 8c.

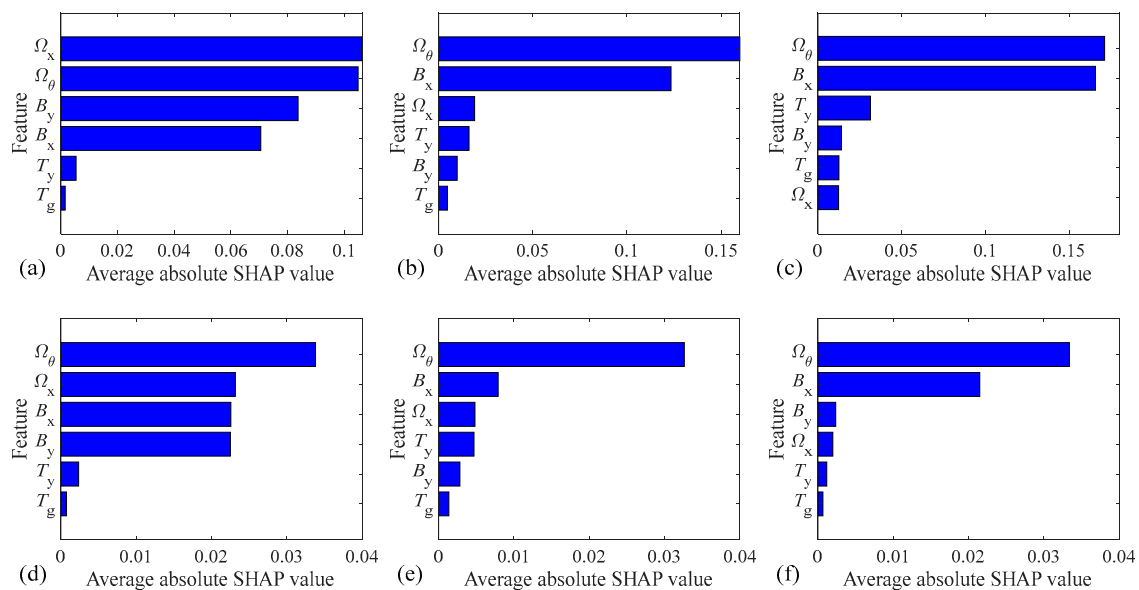


Figure 14. Average absolute SHAP value of each feature: (a) relative shear force in the x direction; (b) relative shear force in the y direction; (c) relative torque; (d) relative displacement in the x direction; (e) relative displacement in the y direction; (f) relative rotation.

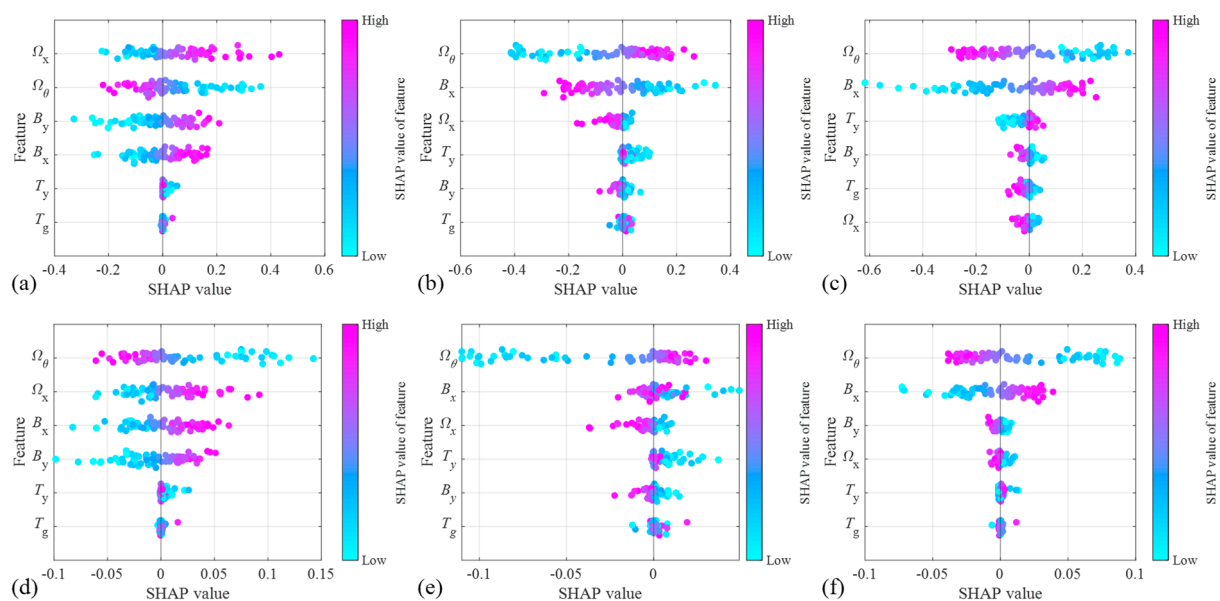


Figure 15. Distributions of SHAP values of each feature: (a) relative shear force in the x direction; (b) relative shear force in the y direction; (c) relative torque; (d) relative displacement in the x direction; (e) relative displacement in the y direction; (f) relative rotation.

6. Application Example

In this section, an example is offered to illustrate the applicability of the proposed BP model for predicting seismic responses of the one-story two-way eccentric structure. As shown in Figure 16, the structure comprises one slab with the mass $m = 90$ kips/g (4.082×10^4 kg) and four columns with different lateral stiffness ($k = 1.5$ kips/in or 262.695 kN/m) [53].

For the given condition, the following parameters pertaining to the system can be obtained: $B_x = 0.245$, $B_y = 0.245$, $\Omega_x = 1$, $\Omega_\theta = 1.732$, and $T_y = 1.108$ s. In addition, it is assumed that T_g has four different values as follows: 0.2 s, 0.4 s, 0.65 s, and 0.75 s. Using the method given in Section 2 and the BP model proposed in Section 4, the actual and

predicted seismic responses can be determined, respectively, as shown in Figure 17, where the number represents the relative error between the actual and predicted values. It can be seen that the proposed BP model achieves a satisfactory accuracy in predicting the seismic responses of the one-story asymmetric structure.

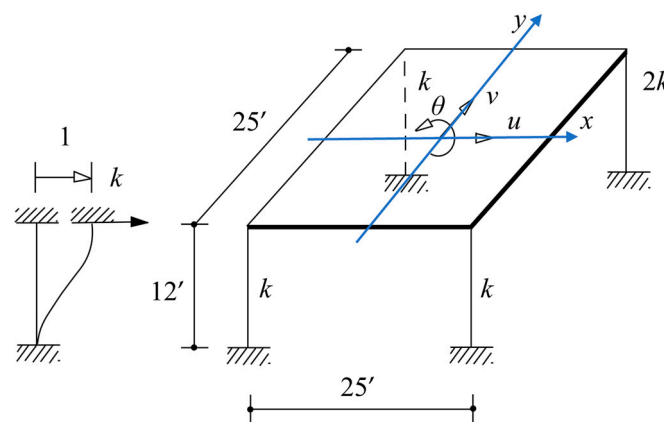


Figure 16. Overview of the one-story asymmetric structure analyzed.

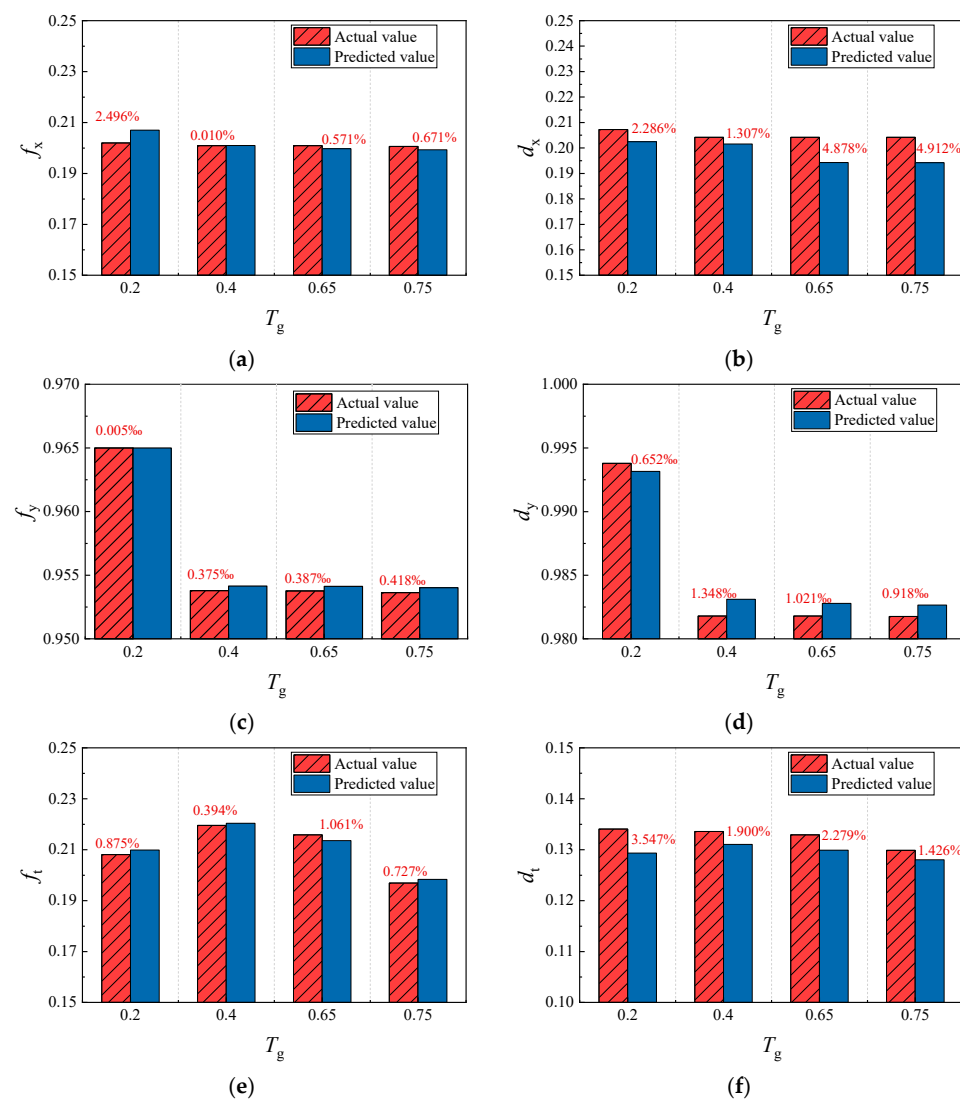


Figure 17. Comparison between the predicted and actual values: (a) relative shear force in the x direction; (b) relative displacement in the x direction; (c) relative shear force in the y direction; (d) relative displacement in the y direction; (e) relative torque; (f) relative rotation.

7. Conclusions

In this paper, the equations of motion of a one-story two-way eccentric structure under unidirectional seismic excitation are first derived. The modal response spectrum method is utilized to determine its seismic responses to investigate the influences of various factors, with an emphasis on the combined effect of different factors. Subsequently, a BP neural network is developed to predict the seismic responses of this structure, fully incorporating various influencing factors. SHAP analysis is then conducted to compare the relative importance of different parameters. Finally, an example is presented to examine the applicability of the proposed model. Based on the results presented in this paper, the following main conclusions can be drawn:

- (1) By increasing the eccentricity in both directions, the translational response along the earthquake direction can be effectively reduced. However, the translational response perpendicular to the earthquake direction will always increase, while the rotational response will increase with the eccentricity perpendicular to the earthquake direction but decrease with the one along the earthquake direction.
- (2) Increasing the stiffness in the direction perpendicular to the earthquake can significantly reduce the translational response along the earthquake direction, while the translational response in the direction perpendicular to the earthquake direction increases. An increase in the torsional stiffness of the system leads to an increase in the translational response along the earthquake direction, while the translational response perpendicular to the earthquake direction and the rotational response decrease significantly.
- (3) The eccentricity perpendicular to the earthquake direction has a greater impact on translational responses along the seismic direction and rotational responses than the eccentricity along the earthquake direction. In addition, the eccentricities in both directions have comparable effects on translational responses perpendicular to the seismic direction.
- (4) The torsional–translation frequency ratio exhibits a greater impact on translational responses along the seismic direction and rotational responses than the translation frequency ratio. Moreover, this ratio has a similar impact on the translational responses perpendicular to the seismic direction to that of the translation frequency ratio.
- (5) Using the BP neural network, the model is trained and tested to predict the seismic responses of the one-story bidirectionally eccentric structure taking various factors into account. It is further used in an example to demonstrate its application value. The results show that the seismic prediction model developed in this study has a fairly high accuracy while fully considering the factors influencing the structure's seismic responses.

The prediction model can be used for scheme comparison, for parameter sensitivity analysis, or as a supplement to existing code-based methods. In particular, during the preliminary design stage, the designer can quickly compare different structural layouts with the help of the proposed model. However, it is worth noting that some assumptions are adopted when establishing the motion equations dominating the seismic responses of the asymmetric system in this study, such as the rigid floor, unidirectional horizontal seismic excitation, and a classical damping. Future studies can be directed to consider more realistic conditions. In addition, the BP model proposed in this study is only applicable for the parameter ranges considered in this study.

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Y.Z.; supervision, X.H.; project administration, X.H.; funding acquisition, X.H. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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