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Numerical study on Floor Response Spectrum of a Novel High-rise Timber-concrete Structure

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Abstract

An innovative high-rise timber-concrete hybrid structure was proposed in previous research, which is composed of the concrete frame-tube structure and the prefabricated timber modules as main structure and substructures, respectively. Considering that the timber substructures are built on the concrete floors at a different height, the floor response spectrum is more effective in estimating the seismic response of substructures. In this paper, the floor response spectra of the hybrid structure with different structural parameters were calculated using dynamic time-history analysis. Firstly, one simplified model that can well predict the seismic response of the hybrid structure was proposed and validated. Then the construction site, the mass ratio and the frequency ratio of the main-sub structure, and the damping ratio of the substructures were discussed. The results demonstrate that the peaks of the floor response spectra usually occur near the vibration periods of the whole structure, among which the first two peaks stand out; In most cases, the acceleration amplification effect on substructures tends to be more evident when the construction site is farther from the fault rupture; On the other hand, the acceleration response of substructures can be effectively reduced with an appropriate increase in the mass ratio of the main-sub structure and the damping ratio of the substructures; However, the frequency ratio of the main-sub structure has no discernible effect on the floor response spectra. This study investigates the characteristics of the floor response spectrum of the novel timber-concrete structure, which supports the future applications of such hybrid structure in high-rise buildings.

Keywords: High-rise hybrid timber structure, simplified model, main-sub structure interaction, floor response spectrum

1. Introduction

With the urbanization of the global population, over half of the people in the world lived in urban centers in 2018; that proportion is expected to increase to 68% by 2050 (UN DESA 2018). In the face of the challenge of the land shrinkage and demand, buildings tend to grow to the sky. Compared with brick, steel and concrete, wood can significantly reduce waste generated during the production, transportation and construction of the building materials, and achieve to convert carbon emissions into carbon absorption (Glover et al. 2002). The development of engineered wood products made the high-rise timber and hybrid timber construction widely constructed in Europe and North America, such as 9-story cross-laminated timber (CLT) apartment in London (Stadthaus, 2008), 10-story CLT building in Melbourne (Forte, 2012), 18-story hybrid timber apartment in Vancouver (Brock Commons, 2017), etc. (He et al. 2016).

To further promote the development of high-rise timber structures in the very dense urban area, Xiong et al. (2016) innovatively proposed a new type of high-rise hybrid timber-concrete structure as shown in Figure 1, which is composed of two parts: the concrete frame-tube structure as the main structure, and the prefabricated three-story timber modules as substructures. The main structure provides both stiffness and resistance for lateral wind load, earthquake action and vertical load, while the substruc-ture is a self-bearing system that only supports its loads of every three stories. Hence, the connection between the main structure and substructures has a significant influence on the structural performance of the whole structural system. Two kinds of connection were proposed: one is bolt connection, and the other is rubber bearing, and the feasibility of such hybrid structure was verified by numerical studies (Chen et al. 2018; Xiong 2018).

For seismic design of secondary structures, floor response spectra are commonly used as the design input. Floor response spectrum refers to the maximum responses of single-degree-of-freedom (SDOF) spring vibrators of different masses, frequencies, and damping ratios under the floor excitation. It has been a common practice to neglect the dynamic interaction between the substructures and main structure in the analyses used for generating floor response spectra (Kapur and Shao 1973; Singh 1980). In those analyses, the substructures are considered decoupled from the main structure, and the floor time-history response of the main structure in excitation of the specified ground motion is directly used as the input to

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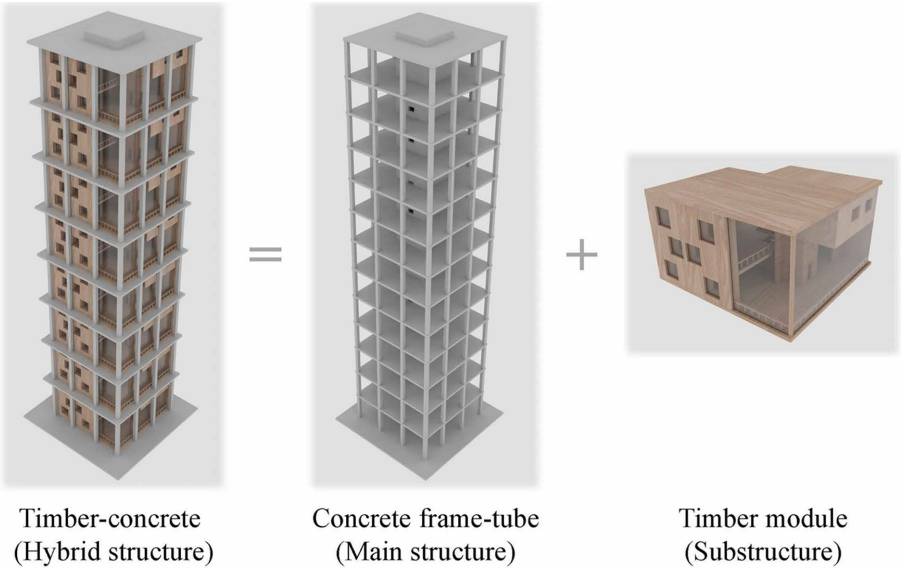


Figure 1. A novel high-rise hybrid timber-concrete structural system.

the substructure to calculate the maximum response. The decoupled analysis is manifest in theory and simple in calculation, but only acceptable when the substructure is very light. However, there are situations where the main-sub structure interaction is of great importance and needs consideration to obtain a more accurate response. Previous researches have utilized different approaches, including modal synthesis and perturbation method, to generate floor response spectra in primary-secondary system interaction form (Igusa and Kiureghin 1985; Suarez and Singh 1987; Zhang 2003).

Several examples of the novel high-rise timber structure showed that the total gravity of the substructures could reach 20%~40% of that of the main structure (Wu 2016; Chen et al. 2018). Hence, the main-sub structure interaction is significant and should not be ignored in generation of floor response spectrum. Meanwhile, the frequency of substructures may be close to that of the whole structure, which may result in resonance with the building. Timber substructures should be subjected to a careful and rational seismic design to reduce economic loss and to avoid threats to life safety as well as what concerns substructures. Therefore, the study on the floor response spectrum of the whole structure could be conducted to reveal further the interaction between the main structure and the sub-structure, and make it conducive for the establishment of the design method of the structure system.

Previous researches on the novel high-rise timber structure were all based on specified examples. These are, however, far from enough for analyses of structural parameters for the structural system, such as the mass ratio and the frequency ratio of main-sub structure, etc. Therefore, this paper firstly developed and validated one simplified model that can well predict the seismic response of the hybrid structure, and then discussed the characteristics of floor response spectra of the simplified model with different structural parameters under a series of ground motions. The target of the research is to lay a foundation for future applications of such hybrid structures in high-rise buildings.

2. Simplified Model

In the estimation of the lateral deformation and natural frequencies, etc. of tall buildings, a coupled shear-flexural continuous model (CSFCM) as shown in Figure 2(a) was proposed, which was proved to be able to efficiently represent intermediate modes of lateral deformation in seismic response of shear wall-frame buildings (Miranda 1999; Miranda and Reyes 2002; Miranda and Akkar 2006). The tuned mass damper (TMD) is widely attached to a structure, especially a high-rise building, to reduce dynamic response in seismic or wind response of the structure. The attachment of TMDs leads to the mathematical complexity of the problem and thus hinders the use of the CSFCM. To settle the problem of simplifying the tall building model with TMDs, Huergo and Hernandez (2019) developed an equivalent coupled shear-flexural discrete model (CSFDM) as Figure 2(b) shown, which can be used for dynamic analysis of high-rise shear-wall frame buildings carrying any number of TMDs accurately.

2.1. Coupled Shear-flexural Discrete Model with Sub-structures

Up to now, there has been no such simplified model that can predict the seismic response of the novel high-rise hybrid timber-concrete structure. This hybrid structure can form a mega-sub structure control system, in which the substructure mass is relatively small, and the control mechanism is worked as a TMD mechanism (Tan et al.

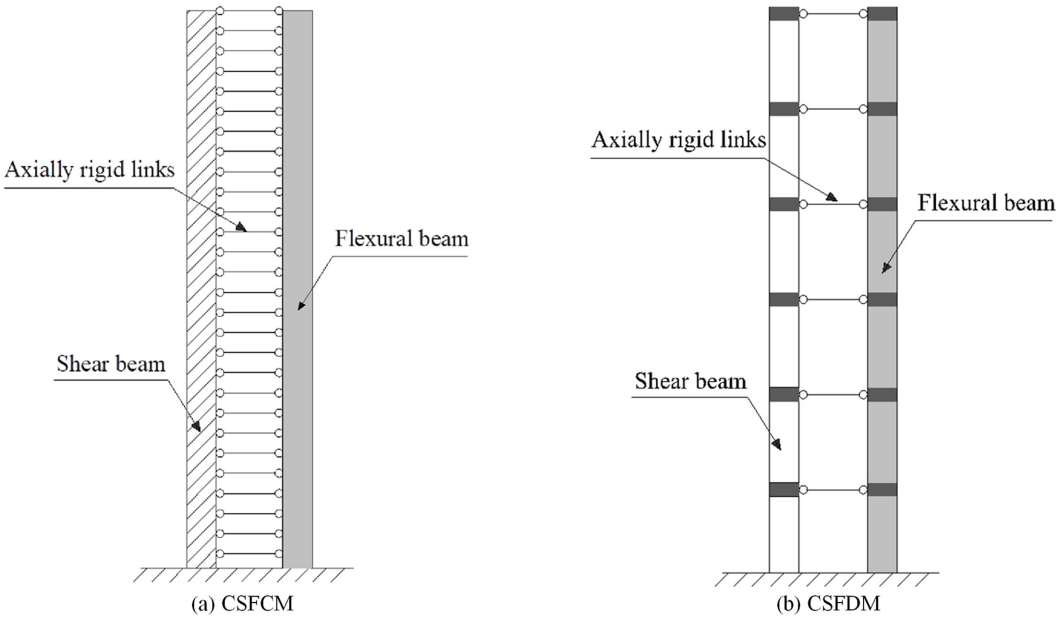


Figure 2. Coupled shear-flexural models for a fix-base tall building.

2014). Hence, based on CSFDM, this paper proposed a simplified model of the whole structure composed of *N*-floor main structure and *n*-floor substructures, considering the substructures are fixed to the floors of the main structure (see Figure 3).

The lateral deformation of the high-rise frame-tube structure should be considered as the coupling of shear and bending deformation, and hence the core tube of the main structure is simplified as the flexural beam which only contributes to bending deformation while the outer frame as the shear beam contributing to only shear deformation. The two cantilever beams are connected in parallel by a finite number of axially rigid members k_j^l, which ensured the deformation coordination of the beams. The shear beam and flexural beam are divided into N finite elements, s_j and f_j respectively, where j = 1, 2, 3, …, N, according to the floors of the main structure. The total mass of the main structure is divided into two equal parts for each beam. Assuming that the mass is distributed evenly along the building height H and the mass per unit length of the building is defined as $\overline{m}$, the mass of the shear beam and flexural beam are both equal to $\overline{m}H/2$. Similarly, the mass of each finite element of both beams is divided into two proportional parts of each node.

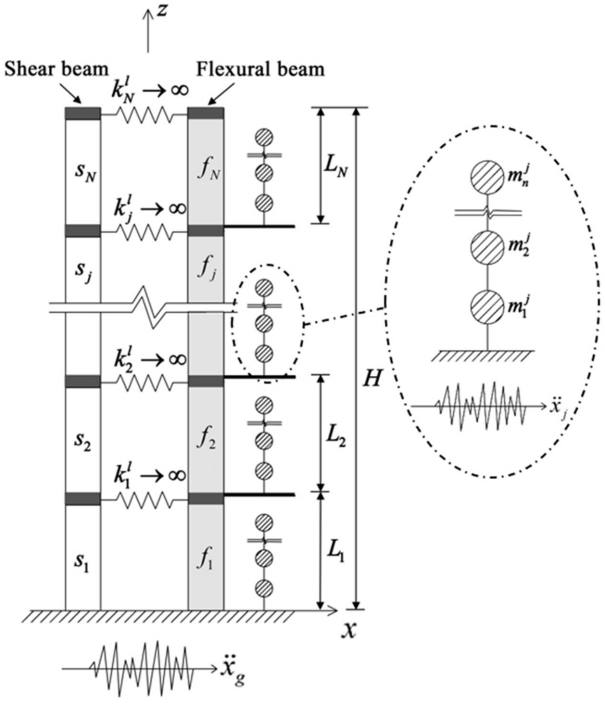


Figure 3. The simplified model of the high-rise timber-concrete hybrid structure.

The lateral deformations under floor excitation of all substructures on the same floor of the main structure are supposed the same, and all substructures on the floor are idealized as a multistory shear building, namely multi-particle model (MPM), by assuming that the mass is lumped at the floor and roof diaphragms. The ith lumped mass of the substructure on the jth floor of the main structure is defined as m_i^j, where i = 1, 2, 3, …, n.

The shear stiffness GA of the frame and frame-wall in a plane can be solved by equation (1) and (2), respectively, while the bending stiffness can be solved by equation (6) (Smith 1986).

$$GA = \frac{12E}{h\left[\frac{1}{\sum\frac{I_c}{h}} + \frac{1}{\sum\frac{I_b}{l}}\right]} \tag{1}$$

$$GA=\frac{6EI_b}{lh}[(1+r)(1+2r+s)] \tag{2}$$

$$r=\frac{b}{l} \tag{3}$$

$$s=\frac{\alpha-3r-1}{\beta+2} \tag{4}$$

$$\alpha=\frac{6EI_c}{EI_b}\cdot\frac{l}{h} \tag{5}$$

$$EI=\sum(EI_c+EI_w) \tag{6}$$

where E is Young's modulus of elasticity; h is the height of the frame column, and I_c is the moment of inertia of the column section; l is the span of the frame beam, and I_b is the moment of inertia of the beam section; I_w is the bending stiffness of the shear wall; b is the distance from the center of the shear wall to the edge.

If the shear and bending stiffness of each floor of the main structure are not the same along the height and yet the change is not that large, the equivalent stiffness GA_{eq} and EI_{eq} can be calculated by using the weighted average method as equation (7) and (8), respectively. The subscript i distinguishes the original values of different floors.

$$GA_{eq}=\frac{\sum h_i(GA)_i}{\sum h_i} \tag{7}$$

$$EI_{eq}=\frac{\sum h_i(EI)_i}{\sum h_i} \tag{8}$$

2.2. Verification and Validation

The proposed simplified model (SM) was validated by a specific refined model (RM), a typical 30-story office building in Shanghai, which was selected to redesigned as the timber-concrete hybrid structure by Chen et al. (2018). OpenSees, an open-source and object-oriented software program for earthquake engineering simulation, was utilized to conduct elastic time-history analysis on RM and SM to validate the accuracy of the simplified model.

2.2.1. Model Information

In Chen et al.'s redesigned hybrid structure, the height between slabs of the 10-story concrete main structure is 9.2 m, and eight timber modules, whose typical story height is 2.9 m, are fixed to every concrete slab. According to the simplification rules in Section 2.1, the node mass of each beam of CSFDM is $M_j^S = M_j^F = 5.72 \times 10^5$ kg, where j = 1, 2, 3, …, 9, while the mass of the top node is by half. The shear stiffness of flexural beam $(GA)^S$ and the flexural stiffness of shear beam $(EI)^F$ are calculated to be $(GA)^S = 2.46\times10^9$ N and $(EI)^F = 1.17 \times 10^{18}$ N·mm^2, respectively. All values of k_j^l stay constant and large enough to guarantee the coupling of two beams, considered to be $k_j^l = 1.0 \times 10^{15}$ N/mm. The node mass of all MPMs is $m_i^j = 1.10 \times 10^5$ kg, where i = 1, 2, and the mass of top nodes is by half. The lateral stiffness of every story of MPMs is calculated to be $K = 8.97 \times 10^4$ N/mm. A structural damping ratio of 0.05 was considered for the whole structure.

2.2.2. Dynamic Response

El Centro wave, whose duration time is 40.0 s, was selected for an elastic time-history analysis. According to the Chinese *Code for seismic design of buildings* (GB50011-2010), the peak ground acceleration (PGA) of the wave was adjusted to 55 gal, the characteristic value for the frequently occurred earthquake with an exceedance probability of 63.2% in 50 years.

Table 1 shows the natural vibration periods T_i and modal participating mass ratios $m_{eff,i}$ of the first four modes of vibration computed for *yz* plane by the SM and the RM. The difference between the two models is minimal (the relative error of $\Sigma m_{eff,i}$ is only -1.0%), which proves the accuracy of the SM for simulating the high-rise timber-concrete hybrid structure.

The peak values of floor displacements, accelerations and inter-story drift ratios of the main structure are shown in Figure 4 for SM and RM, respectively, and it could be seen that the peak values of the two models have high consistency in the dynamic analysis, especially the maximum floor displacements. Figure 5 shows how the floor displacement and acceleration developed as the time went under earthquake, which is practically identical between SM and RM (the relative error is less than 5%).

The periods of vibration, modal participating mass ratios, peak displacements and acceleration of the main structure, etc. were compared between SM and RM to identify the validation of the SM. Meanwhile, running time for both numerical models in OpenSees software were recorded (SM for 17 seconds while RM for 2.5 hours), which proves the exceptional efficiency of elastic dynamic analysis by SM.

Table 1. Periods of vibration and modal participating mass ratios of the models: *yz* plane

i	Refined model (RM)		Simplified model (SM)	
	T_i (s)	$m_{eff,i}$ (%)	T_i (s)	$m_{eff,i}$ (%)
1	2.24	71.0	2.24	73.2
2	0.68	15.7	0.66	11.9
3	0.49	1.9	0.48	1.9
4	0.47	0.0	0.47	0.7
$\Sigma m_{eff,i}$		88.6		87.7

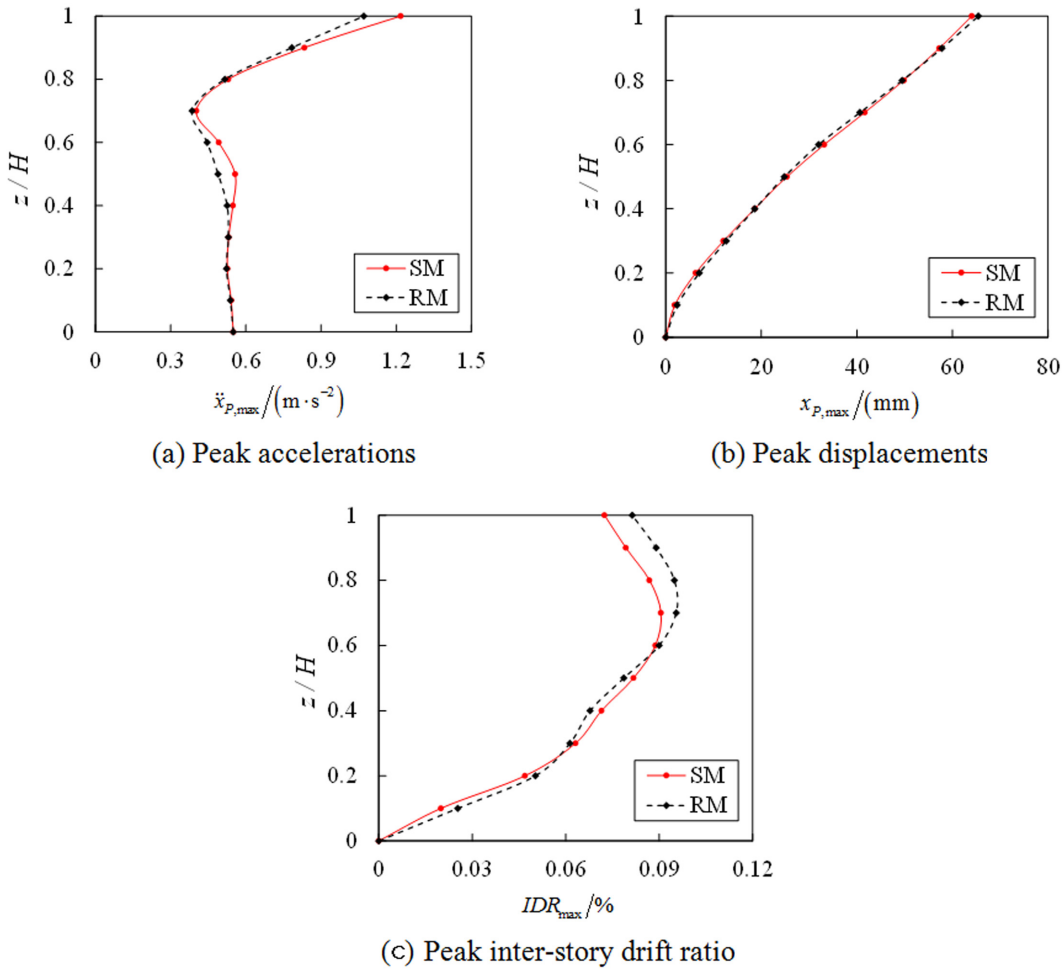


Figure 4. Seismic elastic response of the main structure: *yz* plane.

3. Floor Response Spectrum Calculation

Based on the simplified model validated in Section 2.2, this paper adopted the advanced method considering the coupling effect between the main structure and sub-structures to calculate the floor response spectrum. The mass ratio and the frequency ratio of the main-sub structure, etc. were changed to build couples of models, and ground motion data were input for elastic time-history analysis to obtain the floor acceleration of the main structure, which then was used to excite an SDOF spring vibrator for maximum response.

3.1. Ground Motion Records

To fully consider the random nature of ground motions, 22 far-field and 28 near-field ground motion records recommended by FEMA P695 (2009) were used as excitation in this study. The PGA of every record was adjusted to 55 gal.

3.2. Definition of Floor Response Spectrum

To better present the amplification effect of substructures, this paper defines the floor acceleration dynamic coefficient β of the hybrid structure as the ratio of the maximum absolute acceleration S_a of an SDOF spring vibrator on the concrete floor to the maximum ground acceleration $|\ddot{x}_g|_{\max}$, as the equation (9) shown.

$$\beta=\frac{S_a}{|\ddot{x}_g|_{\max}} \tag{9}$$

Different simplified models of the hybrid structure were excited by the selected ground motion records to obtain the relationship curves corresponding to the β of every concrete floor and the vibration period T of SDOF spring vibrator as Figure 6 shown. The β-T curve was studied as the floor response spectrum in this paper.

Therefore, for an SDOF elastic system on the floor of the main structure, the horizontal seismic action F can be determined by formula (10), where k is the seismic coefficient that reflects the intensity of the earthquake, and G is the particle gravity of the SDOF system.

$$F=mS_a=mg\left(\frac{|\ddot{x}_g|_{\max}}{g}\right)\left(\frac{S_a}{|\ddot{x}_g|_{\max}}\right)=Gk\beta \tag{10}$$

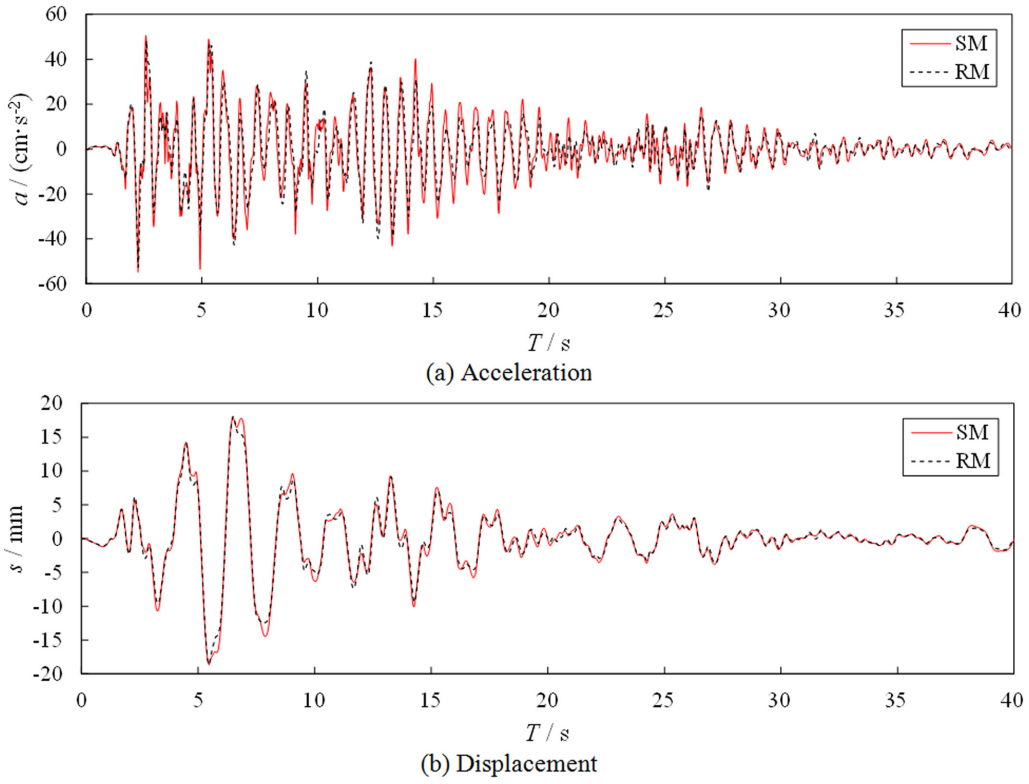


Figure 5. Time-history curve of response on the fifth floor of the main structure: *yz* plane.

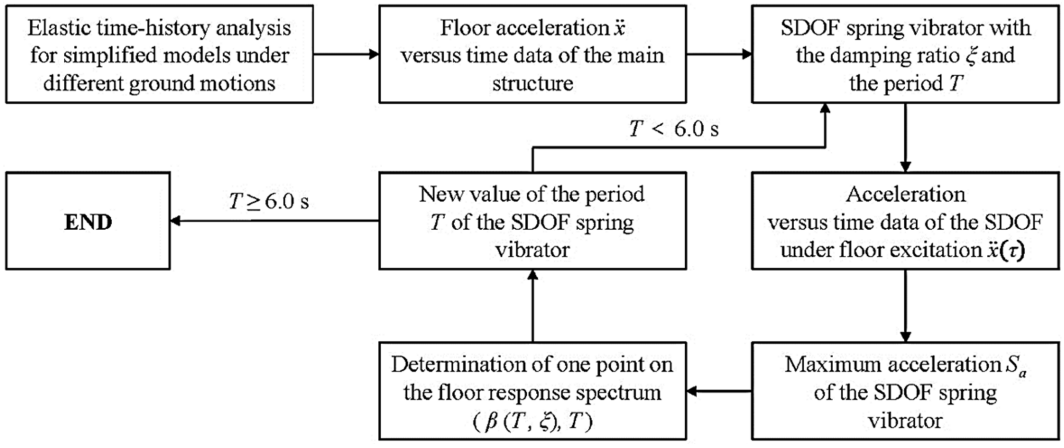


Figure 6. The calculation process of the floor response spectrum "β-T curve".

4. Floor Response Spectrum Characteristics Analysis

The characteristics of the floor response spectrum are represented by spectrum form and spectrum value. The simplified model in section 2.2 was used to analyze the spectrum shape characteristics. The mass ratio and the frequency ratio of main-sub structure, and the damping ratio of the substructures were changed to establish 15 simplified models to analyze how these factors influence the spectrum value.

4.1. Spectrum Form

Figure 7 shows the floor response spectra of the main structure in seismic response of El Centro wave with the PGA of 55 gal, and revealed the characteristics of the spectrum shape as follows:

(1) There are peaks near the vibration periods of the whole structure, among which the first two peaks stand out ($T_1 = 2.24$ s, $T_2 = 0.66$ s), because of the resonance between the substructures and the whole structure with close frequency.

(2) As the floor height increases, the spectrum value

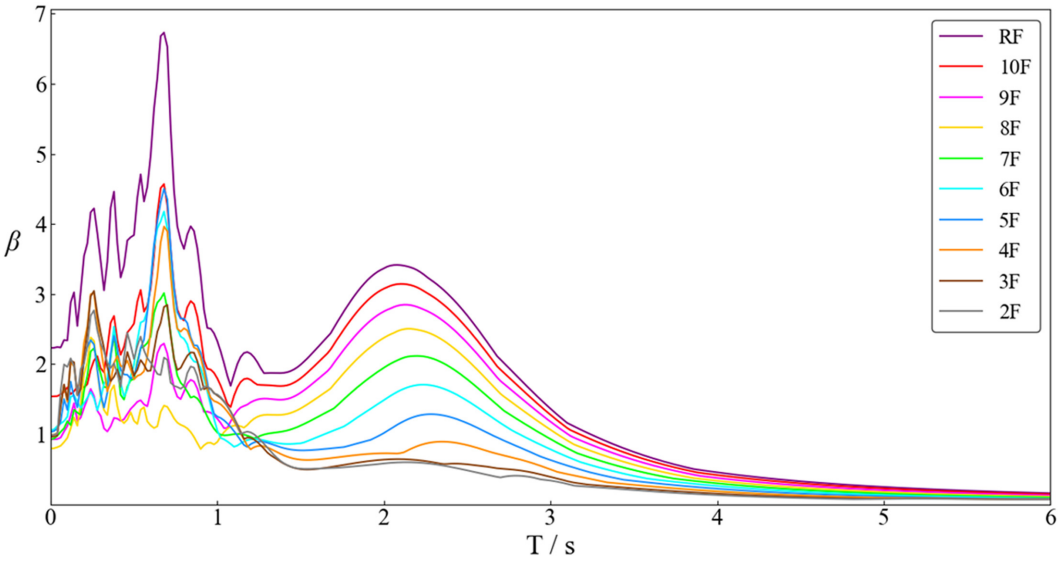


Figure 7. The floor response spectrum of each main structure floor.

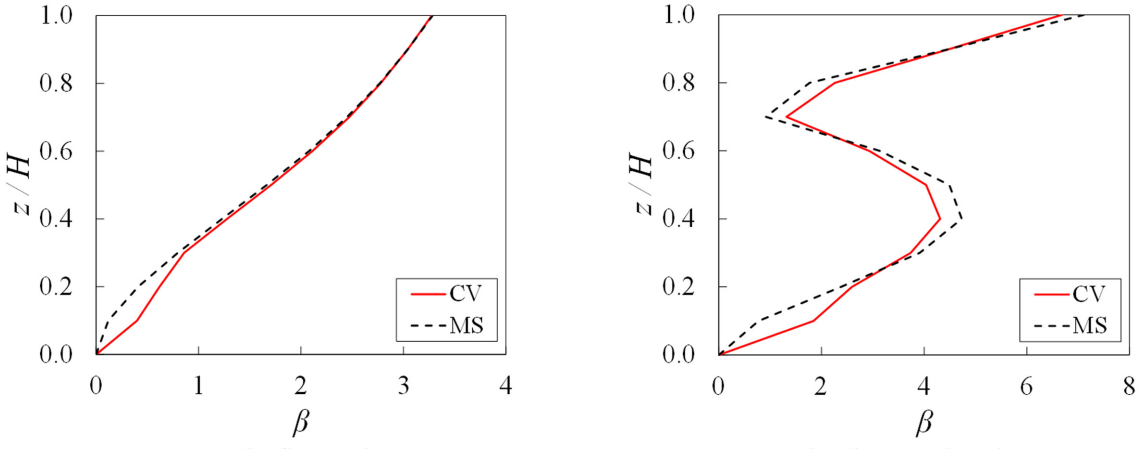
corresponding to the fundamental period of the whole structure increases, since the whiplash effect becomes prominent on the higher floor. However, the spectrum values corresponding to the period of higher vibration modes gradually disappear due to the offset of the damping force.

(3) The spectrum value corresponding to the period of zero, which represents the ratio of the peak floor acceleration of the main structure to the peak ground acceleration, can be less than 1.0 and is not proportional to the height of the building.

(4) The spectrum values of different floors corresponding to the periods of the whole structure are related to the mode shape of the main structure. The red line in Figure 8 represents the calculated values (CV) of the first two spectrum peaks (from right to left) along the building height, while the black line is the mode shape (MS) of the main structure, whose value on the top floor is equated with the CV and values are all taken absolute. Figure 8 shows that within the resonance region, the change of the spectrum value of the main structure along the building height is nearly consistent with the mode shape, especially for the first two modes.

4.2. Parameter Analysis

The floor response spectrum is related to many factors such as site conditions, and the dynamic characteristics of the main structure and substructures, etc., which mostly affect the spectrum. The analyses of such factors are conducted as follows. Numerical study shows that the influence on spectra of different concrete floors is similar, and therefore the response of the fifth floor is taken as an example for analyses.



(a) The first mode (b) The second mode

Figure 8. The spectrum peak values versus the mode shapes of the main structure.

4.2.1. The construction site

With the input of 22 far-field and 28 near-field accelerograms, the average response spectra of the fifth floor of the main structure were calculated, respectively. Figure 9 shows that the distance from the construction site to the fault rupture will affect the spectrum value; the spectrum value corresponding to the far-field earthquake is smaller than that of the near-field earthquake in the range of long period, while the relationship changes to be opposite when the period is short owing to the filter effect of the site soil and the structure.

4.2.2. The mass ratio of the main-sub structure

In this paper, the mass ratio of the main-sub structure δ_m refers to the ratio of the sum of the floor masses of the substructures on a particular concrete floor to the mass of the main structure floor, as shown in equation (11). Simplified models with different mass ratios and the same frequency ratio of the main-sub structure were excited by 28 near-field ground motions. Figure 10 shows that as the mass ratio of the main-sub structure increases, the average response spectrum values of the fifth floor corresponding to the periods of the whole structure decrease, and the periods of substructures corresponding to the peaks increase.

$$\delta_m = \frac{\sum_{i=1}^{n} m_i^j}{\frac{M_j^F + M_{j+1}^F}{2} + \frac{M_j^S + M_{j+1}^S}{2}} \tag{11}$$

4.2.3. The frequency ratio of the main-sub structure

The frequency ratio of the main-sub structure δ_f was defined as the ratio of the fundamental frequency of substructures to that of the main structure. The frequency ratio of the main-sub structure was changed in simplified models with the same mass ratio of the main-sub structure. Figure 11 shows that in seismic response of 28 near-field

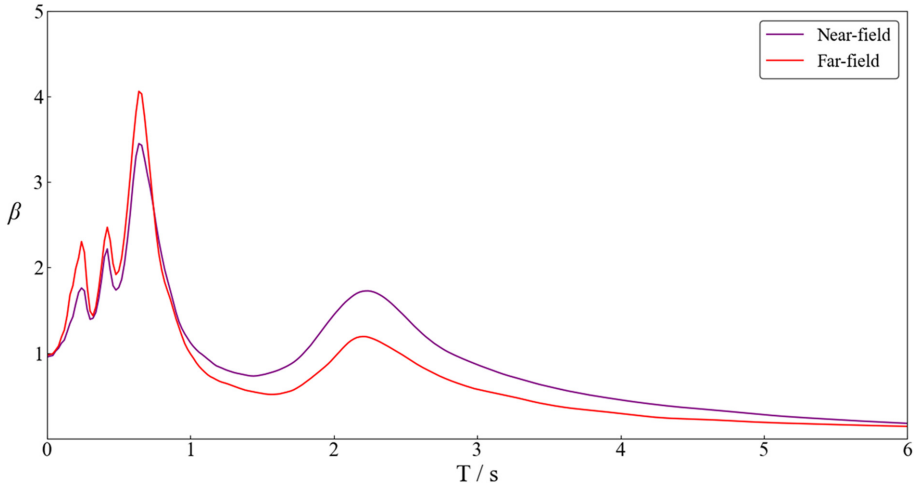


Figure 9. The response spectra of the fifth floor under near-field and far-field earthquake.

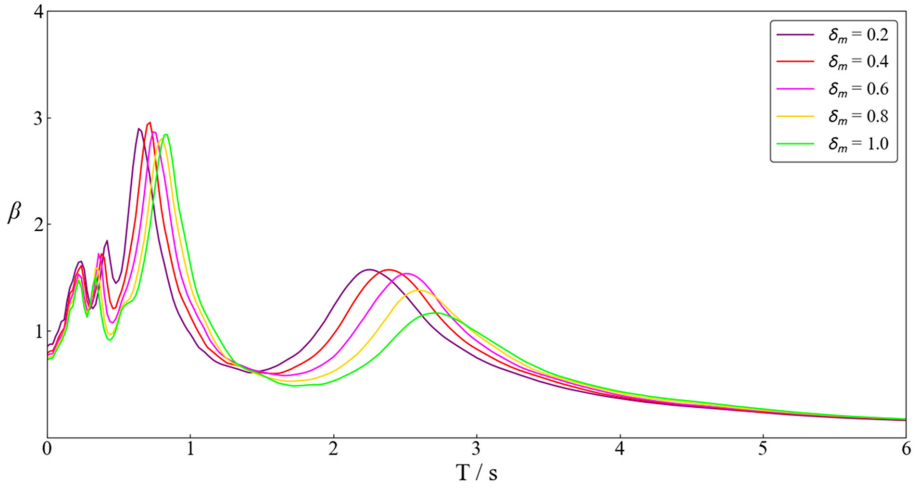


Figure 10. The floor response spectra with different mass ratios of the main-sub structure.

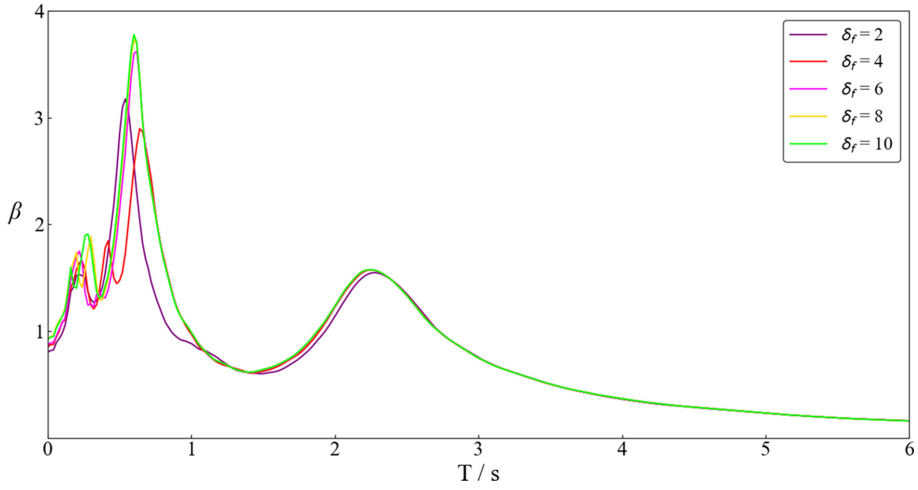


Figure 11. The floor response spectra with different frequency ratios of the main-sub structure.

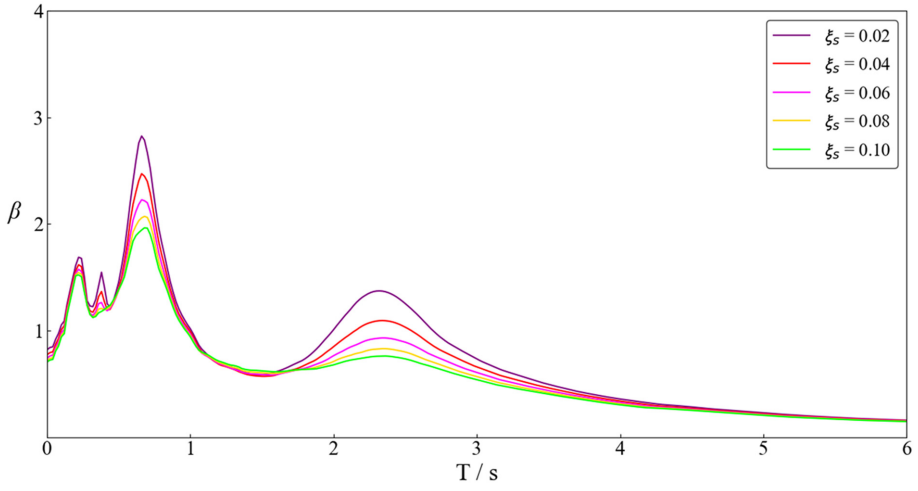


Figure 12. The floor response spectra with different damping ratios of substructures.

ground motions, the average spectrum values of the fifth floor are nearly the same with the change of the frequency ratio of the main-sub structure, though fluctuate corresponding to the periods of higher vibration modes of the whole structure.

4.2.4. The damping ratio of substructures

This paper adopted the Rayleigh damping theory and determined the damping ratio of the main structure as 0.05. With the change of the damping ratio of substructures, several simplified models were built and excited by 28 near-field ground motions to obtain the average response spectra of the fifth floor of the main structure. Figure 12 shows that as the damping ratio of substructure increases, the spectrum value decreases, especially at the peaks, and the vibration periods of the whole structure are nearly the same.

5. Conclusions

To efficiently analyze the elastic floor response spectrum characteristics of the innovative high-rise timber-concrete hybrid structure in seismic response, OpenSees software was utilized to build multiple elastic simplified finite element models, whose structural parameters were changed to analyze the influence of the floor response spectrum. The following conclusions and recommendations can be drawn from the analysis of the results:

1. The floor response spectrum has peaks corresponding to the vibration periods of the whole structure, which reminds that in the design of the hybrid structure, the vibration periods of substructures should be avoided close to that of the whole structure as far as possible, especially for the first two periods. In the preliminary design of substructures, if the main structure has been designed, the vibration periods of substructures should not go near 1.1~1.3 times that of the main structure. If not, the application of dampers on substructures can reduce the acceleration amplification effect.

2. The influence of factors on the floor response

spectrum includes: 1) Compared with far-field earthquakes, near-field earthquakes are more unfavorable to the resistance of substructures; 2) The position of the main structure floor has little impact on the spectrum value outside the resonance region. It is safe to replace the floor response spectrum of lower floors with that of the top floor, and the change of the spectrum values at peaks along the building height is nearly consistent with the vibration mode shapes of the main structure; 3) Increasing the mass ratio of the main-sub structure appropriately decreases the spectrum value; 4) If the damping ratio of substructures is increased, the spectrum value will decrease, especially at the peaks; 5) The change the frequency ratio of the main-sub structure has little impact on the floor response spectra.

6. Acknowledgments

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