# Seismic interaction between a reticular structure and a multi-supported secondary structure

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## ABSTRACT

In this study, shake table experiments on a large-scale reticular shell structure were conducted. The steel structure has an equal width and length of 4.5 m and a height of 1.5 m. The existence of secondary structures can determine the behaviour of the spatial flexure response of the shell structure. The influence of the interrelation between the dynamic properties of the ground motions and the structural properties on the response of primary and secondary structures was revealed. The results show that the commonly applied floor response spectrum can lead to unrealistic estimates and, thus, an inadequate design of secondary structures.

## 1 INTRODUCTION

Secondary structures, also known as non-structural components, such as ceilings, pipelines, façades, and equipment in a building, are often essential for ensuring the functionality of the building but are not part of the main load-bearing system. Since the seismic design is usually performed, focusing mainly on the primary structure, secondary structures are treated neglectfully. They often become vulnerable to earthquakes (Chen and Soong, 1988; Chouw, 1995; Lim and Chouw, 2015).

The response of secondary and primary structures during earthquakes is complex because their responses depend on each other. Several experimental and numerical studies have been conducted (e.g. Lim and Chouw, 2018; Li et al., 2025). However, many influencing factors are still not well understood. In multi-storey buildings, the support locations of an advertisement board, for example, Fig. 1, can extend over a few floors. Consequently, the response is significantly influenced by the earthquake-induced vibrations at those floors. In the current state of knowledge, for simplicity, the intertwining relationship between primary and secondary structures is often neglected. Instead, it is assumed that the response of the secondary structures can be determined by using the acceleration at the supporting floors, which is described by their floor response spectrum (FRS). In this assumption, the response of the primary structure is solely used to calculate the FRS. However, this simplification may lead to an unrealistic estimation of the response of secondary structures.

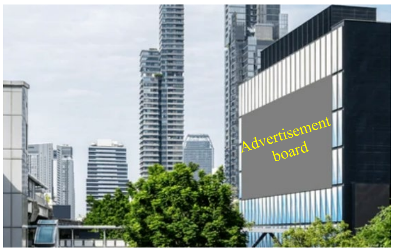


*Fig. 1 Example of a secondary structure attached to the different floors of a multi-storey building*

Several researchers (e.g. Igusa and Kiureghian, 1985) categorized the dynamic interaction between secondary and main structures into (1) Tuning effect: the coincidence of the natural frequency of primary and secondary structures, which gives rise to resonant-like responses of the secondary structure; (2) Feedback effect: the interaction due to the relative movements between primary and secondary structures and mostly tends to reduce the response of secondary structures; (3) Non-classical damping: the difference in the damping of both main and secondary structures, which renders classical damping assumption inapplicable; and (4) Spatial coupling effect due to multiple support excitations of the secondary structure.

It is common to consider the first three influencing factors on the response of the primary structure, while the spatial coupling effect is only considered one-sided on secondary structures. However, there were experiments showing that in multi-storey buildings, the spatial coupling effect has a significant influence on the response of the primary structure, especially during vertical excitation when the soil is incorporated (Malligarjunan et al., 2015; Lim et al., 2017).

To the authors' knowledge, existing research on the interaction between primary and secondary structures focuses predominately on multi-storey buildings. For other frequently used public buildings, such as large-span spatial structures, the research is rare. In this paper, shake table experiments on a reticular shell structure were conducted. The secondary structure was a steel frame with three supports. Horizontal and vertical excitations were considered to investigate the influence of spatial coupling between main and secondary structures.

## 2 EXPERIMENTAL SETUP

### 2.1 Model development

The experimental model is a single-layer reticular structure, which is a commonly used large-span spatial structure like a train station or airport. The secondary structure had three supports attached in the middle area of the primary structure. Because of the limited size of the shake table, the size of the structure needs to be scaled down. Due to the selected scale for the length, the time and the mass need to be scaled correspondingly. The scale factor of the model is given in Table 1, and the model is shown in Fig. 2.

*Table 1: Scale factors*

| **Parameter** | Length | Density | Time | Acceleration | Mass |
|---|---|---|---|---|---|
| **Scale factors** | 1/6 | 1 | $(1/6)^{1/2}$ | 1 | $(1/6)^{2}$ |

## 2.2 Properties of the primary structure

The model has a rise-span ratio is 1/3. The equal total length in the X- and Y-directions is 4500 mm, with a height of 1500 mm. To incorporate the activated inertial forces adequately, the mass effect of the shell needs to be considered according to the similitude law. An additional mass of 38 kg is added to each joint. The shell is fixed at 14 solid hemisphere supports. The fundamental frequency of the primary structure in the X-, Y-, and Z-direction is 2.74 Hz, 1.22 Hz and 2.81 Hz, respectively.

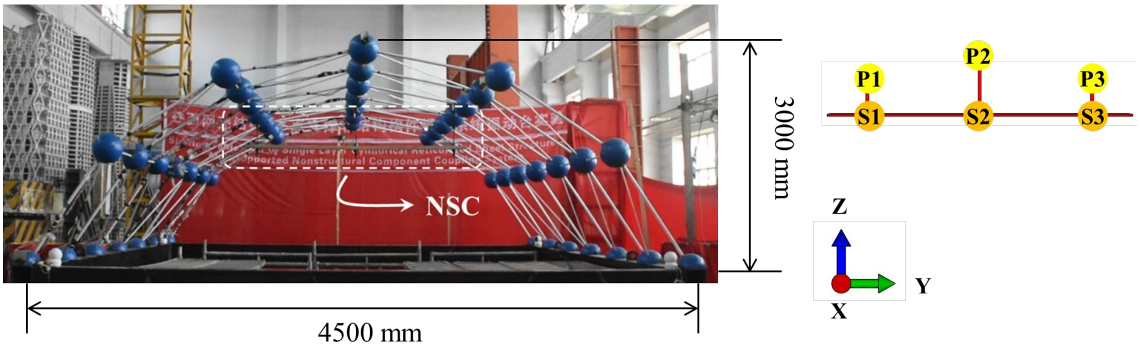


*Fig. 2 Experimental modal*

## 2.3 Properties of the secondary structure

The secondary structure was a frame structure with a distributed mass supported by three columns. The circular cross-section had a diameter of 10 mm. The length of the column connecting P1, P2 and P3 with the secondary structure was 115 mm, 300 mm and 115 mm, respectively. The dimensions of the secondary structure were 2100 mm × 80 mm × 27.5 mm, with a total mass of 36.6 kg.

The fundamental frequency of the secondary structure in the X- and Y-directions was 4.31 Hz and 12.77 Hz, respectively. The damping ratio was 2%, like that of the primary structure. The natural frequencies and damping ratio of the NSC were obtained through impact tests conducted to the NSC mounted on fixed supports, without connection to ground.i In the vertical direction, the secondary structure was considered rigid. The mass of the secondary structure was only 2.75% of the primary structure, while the fundamental frequency of the secondary structure was far away from that of the primary structure. The dimension of the secondary structure is not specifically targeted as a scale-down of any non-structural component, but rather to achieve specific mass and frequency ratios to represent a realistic structure, such as piping and cable tray systems. Three-directional accelerometers and vertical displacement sensors were installed at each connection between primary and secondary structures to measure the response in all three directions. The measurement point on the primary is herein denoted as ‘P’, and the secondary structure ‘S’ (see Fig. 2).

## 2.4 Test program

The dynamic characteristics of the primary structure in X-, Y- and Z-directions are significantly different. The response due to excitation in each direction was investigated to understand the influence of the interrelationship between the ground motion and structural characteristics on the structural response. The Taft ground motions, recorded in the 1952 California Earthquake, were used. They were scaled by $\sqrt{6}$ to match the scale of the model (see Table 1). The larger one between 2 horizontal excitations was chosen as the excitation in the X-direction, with the peak ground acceleration (PGA) adjusted to 1.96 m/s$^2$, according to the Chinese design specification (Standards China, 2010). Fig. 3 shows the time history of the excitation in each direction. Before each experiment, the model undergoes a tri-directional white noise sweep with an amplitude of 0.4 m/s$^2$ to obtain dynamic characteristics of the structures.

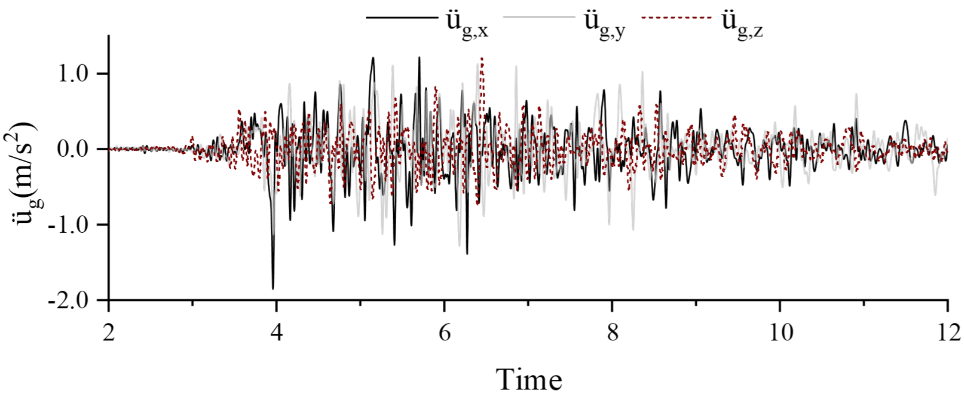


*Fig. 3 Scaled acceleration time histories of the Taft earthquake motions.*

## 3 RESULTS AND DISCUSSION

To show how the existence of the secondary structure alters the dynamic characteristics of the entire structure, the Fourier spectra of the acceleration in three directions at P2 with and without NSC under the white noise excitation is shown in Fig. 4. For comparison, the spectrum at S2 is also shown. The difference in spectrum with and without secondary structure is insignificant in the X- and Y-directions. Only a slight variation in the high-frequency range can be observed. The frequencies of the secondary structure in these two directions are well separated from that of the primary structure, as indicated by the first and second peaks in Figs. 4(a) and (b). However, in the Z-direction, the system's frequency without a secondary structure is significantly shifted from 2.81 Hz to 3.17 Hz of the system with the secondary structure. Because of the rigidity of the secondary structure in the vertical direction, the frequency of the vibration of the main and secondary structures is the same.

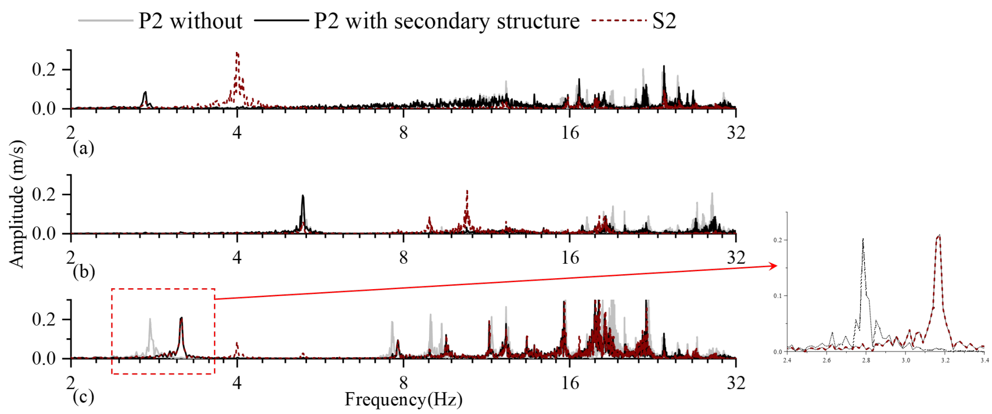


*Fig. 4 Fourier spectrum of accelerations at P2 with or without NSC and response at S2 in the (a) X, (b) Y and (c) Z directions.*

Fig. 5 compares the horizontal acceleration at P2 in the Y-direction with and without the secondary structure due to the Y-excitation. There are only minor differences between both time histories. The horizontal responses due to the excitation in the other directions are similar (not presented here). This suggests that the existence of the secondary structure has no significant consequence for the response in the horizontal direction.

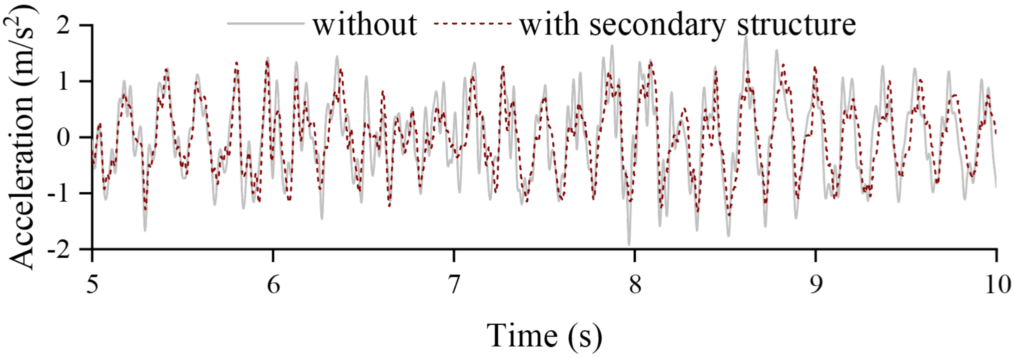


*Fig. 5 Acceleration at P3 of the primary structure with and without secondary structure in the Y-direction due to the Y-excitation.*

Unlike multi-storey buildings, reticular structures have a significant vertical response even due to horizontal excitations. Fig. 6 shows the vertical acceleration at P2 due to the Y-excitation. Compared to the response without the secondary structure, the maximum acceleration at P2 was significantly reduced from 3.70 m/s$^2$ to 2.42 m/s$^2$.

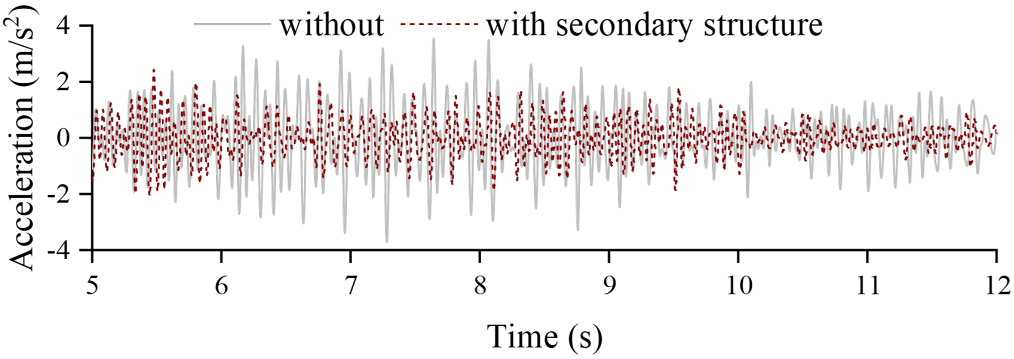


*Fig. 6 Vertical acceleration of primary structure at P2 with and without the secondary structure due to the Y-excitation.*

Fig. 7 shows the vertical response at P2 due to the Z-excitation. In contrast, the maximum acceleration increases from 3.73 m/s$^2$ to 4.65 m/s$^2$ after installing the secondary structure.

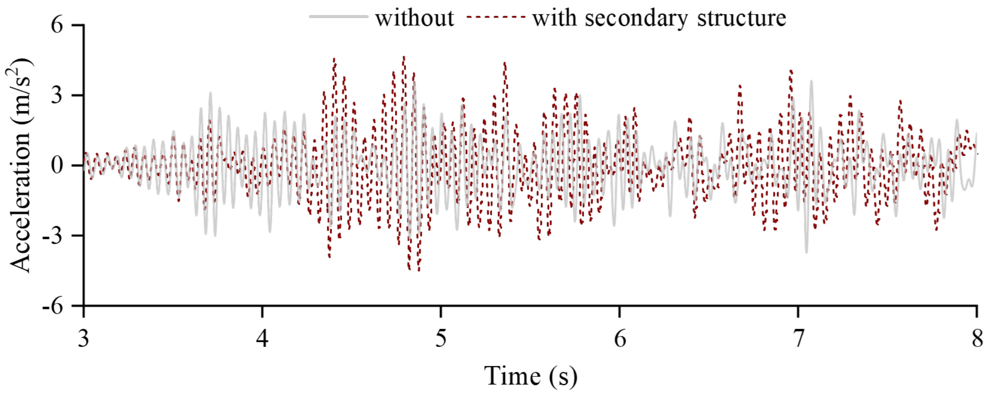


*Fig. 7 Vertical acceleration at P2 of the primary structure with and without the secondary structure due to the Z-excitation.*

To explain this observation, the Fourier spectra of these two cases are shown in Fig. 8. In the case of the Y-excitation, the secondary structure suppresses the high-frequency components in the range between 10 – 20 Hz, which results in a reduced structural response (Fig. 8(a)). Whereas, when the system is subjected to vertical excitation (Fig. 8(b)), the first peak of the response, which corresponds to the 1st vertical mode of the structure, shifts from 2.81 Hz to 3.17 Hz with an increased amplitude. This indicates that the presence of the secondary structure changes the vibration shape of the reticular structure, thus affecting the response of the entire main and secondary structures. This result shows that the response of both structures can no longer be obtained separately. A similar insight can also be observed in the second peak of the Fournier spectra, which shifts from 7.66 Hz to 7.79 Hz with a significantly decreased amplitude.

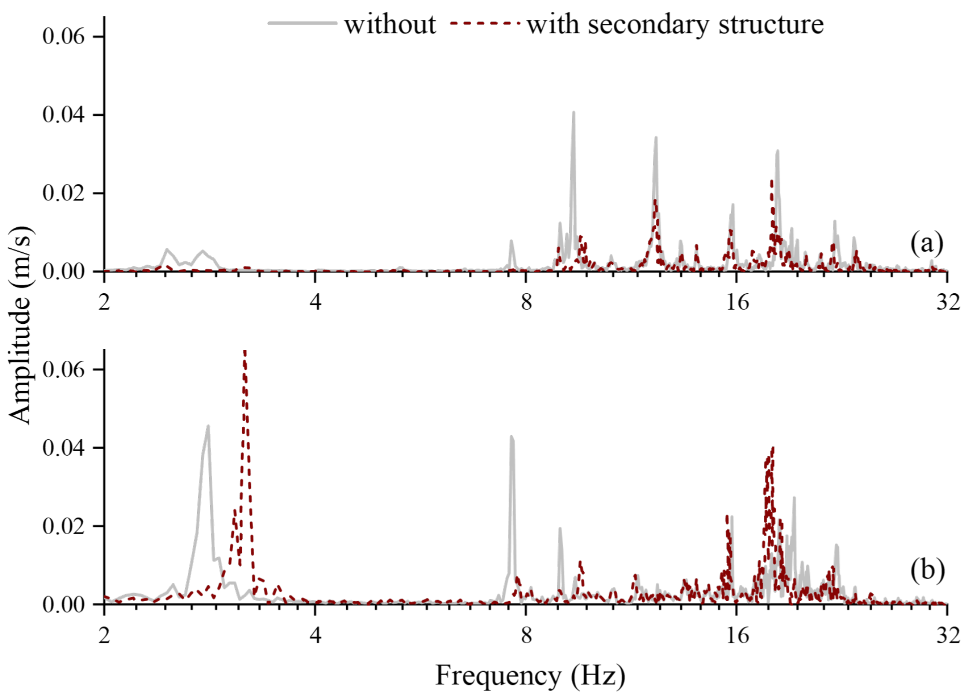


*Fig. 8 Fourier spectrum of the vertical acceleration at P3 of primary structure due to (a) Y- and (b) Z-excitation.*

The consequence of the spatial coupling between the main and secondary structures is presented in the form of a response spectrum of the vertical acceleration at P2 of the primary structure (Fig. 9). The difference in the development of the spectral value of the dashed line relative to that of the solid line reflects the change in the characteristic of the structural vibrations, which cannot be observed otherwise. When the ground motion excites both structures in the Y-direction, the presence of the secondary structure reduces the spectrum value by about 17%, while the overall shape of the spectrum remains almost unchanged. In contrast, when the structures are excited in the Z-direction (see Fig. 8(b)), the peak spectral acceleration increases by 73% compared to the case without the secondary structure, while the original peak near the period of 0.15 s disappears. The peak at the period of 0.36 s shifts to near 0.3 s. The results show that although the influence of spatial coupling on the primary structure is negligible in multi-story buildings, it is an important factor that should not be ignored in large-span spatial structures. Understandably, the response does not simply increase or decrease as it depends on the combined influence of many factors.

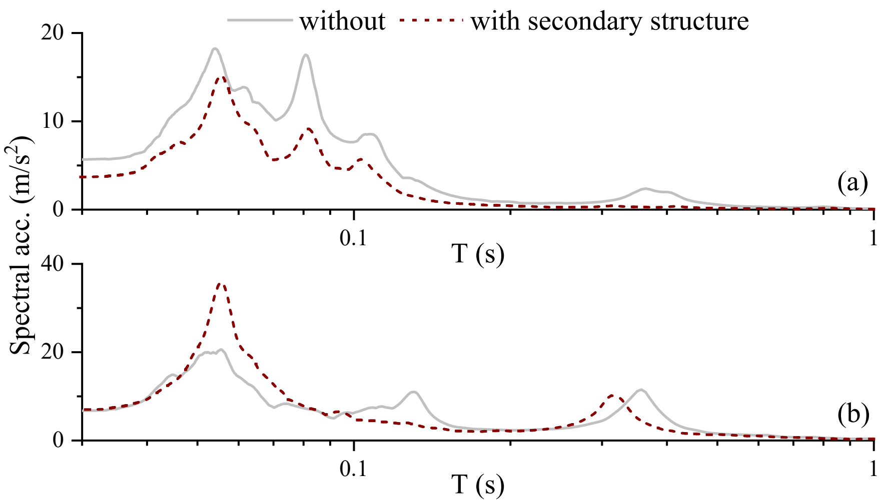


*Fig. 9 Response spectra of the vertical acceleration at P3 of the primary structure with or without the secondary structure due to the (a) Y- and (b) Z-excitations.*

## 4 CONCLUSIONS

This study experimentally investigated the interaction between primary and secondary structures and their influences on seismic responses. The considered primary structure was a reticular structure. The secondary structure was a frame with three supports attached in the primary structure's middle range.

In the cases considered, the study reveals:

1. The interaction between primary and secondary structures predominantly influences the response of reticular structures in the vertical direction. It has a negligible effect on the response in the horizontal direction.
2. Under horizontal excitation, the presence of a secondary structure reduces the high-frequency components and, thus, the vertical response of the structure. In contrast, the spatial coupling shifts the structure's vertical response frequency under vertical excitation and amplifies the structural response.
3. The interaction significantly changes the response spectrum of the reticular structure. In particular, the presence of the secondary structure increases the peak spectral acceleration by 73% due to vertical

excitation, while making the spectral shape change. Neglecting the spatial coupling effect will lead to unrealistic estimates and, thus, an inadequate design of secondary structures.

## 5 ACKNOWLEDGMENTS

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