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# INFLUENCE OF THE SUPPORT CONDITIONS ON THE SEISMIC PERFORMANCE OF SECONDARY STRUCTURES

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## *Abstract*

Multiply-supported secondary structures attached across different floors of a primary structure are ubiquitous in big cities. Examples include advertisement boards, fire escapes, and building façades. In a seismic event, this type of secondary structure experiences spatial coupling, i.e. the response at one of the attachments affects that of the other. The number of support of a secondary structure affects the spatial coupling behaviour, and hence its response. Current analysis methods for multiply-supported secondary structures are developed mostly from numerical studies with idealised assumptions. Experimental studies are still scarce. This paper investigates the influence of the number of attachments of a secondary structure on its seismic response through large-scale shake table experiments. The experimental model consisted of a 1:4 scale, four-storey three-dimensional primary structure with a secondary structure attached. Secondary structures with two and three supports were considered alternately. Both secondary structures have the same dynamic properties to ensure valid comparison. Large-scale testing was implemented to study the acceleration from the ground to the secondary structure, which would otherwise be too small to detect in a small-scale setup. For this purpose, the response were measured at the ground, each floor of the primary structure, beams of the primary structure where the secondary structure was attached, and each end of the secondary structure. The effect of the number of supports on the response of the secondary structure at each supports will be revealed. The interaction between the primary and secondary structures will also be explicated. The results will contribute as a first step to optimize the design of secondary structures with multiple supports.

*Keywords: multiply-supported secondary structures; primary-secondary structure interaction; large-scale shake table tests*

# 1. Introduction

Secondary structures are the non-load bearing components attached or placed on a structural system. They are usually not designed to resist external loads such as those from earthquakes or impact. A wide array of objects can be considered secondary structures, e.g. ceiling, cladding, parapet, building façade, fire escape, balcony, furniture, heavy building content, and even sensitive equipment such as data acquisition systems [1-3]. Even during minor earthquakes in which main structures are likely to survive, secondary structures are prone to damage [4]. Post-earthquake observations in the past have shown many examples of the serious implications of damaged secondary structures; Failures of parapets and canopies after the 2011 Christchurch earthquake had resulted in blocked roads and difficulties to rescue trapped building occupants [5]. Broken pipelines in a hospital had caused flood and required patients to evacuate during the 1994 Northridge earthquake [6, 7].

Seismic analysis of secondary structures was first introduced through a Floor Response Spectrum approach in the wake of the 1964 Alaska earthquake [8-10]. The approach was later shown to give inaccurate predictions because it neglected the primary-secondary structure interaction (PSSI) [11,12]. Subsequent numerical studies were performed [13-19] to improve the existing methods by incorporating PSSI to certain extents. In those studies, the secondary structure was usually distinguished as either that with a single support or multiple supports [2, 20]. Experimental reports on the subject had been exiguous, mainly due to the limited resources available to perform the required investigations.

This research aims to experimentally investigate the influence of the number of supports (which constitutes the boundary condition of the secondary structure) on the seismic response of the secondary structure itself and the supporting primary structure. The main benefit of experiments in this case is that the primary-secondary structure interaction will automatically be included in the physical model. Large-scale testing was implemented to represent the characteristics of the structural component more accurately. In this case, the local deformation of the structure caused by the secondary structure can be analysed.

# 2. Methodology

## 2.1 Model development and setup

The experimental model can be divided into two parts: (1) the primary structure, and (2) the secondary structure. The primary structure is an elastic, 1 : 4 four-storey model based on a four-storey prototype with an assumed fixed base. The inter-storey height was 787.5 mm, resulting in a total height of 3150 mm. The bay width was 1750 mm. The floor mass was 272 kg for each of the first three floors and 227 kg for the roof floor. The fundamental frequency of the primary structure was 1.86 Hz (T = 0.54 s) and 6 Hz in the weak ($x$) and strong ($y$) axes, respectively. The average damping ratio was 4.1%, found from the decay rate of the free vibration of the structure.

Two secondary structures are considered, i.e. a frame with either two (Case 2) or three supports (Case 3). The configuration and dynamic properties of the model were designed to simulate realistic cases, e.g. balcony, advertisement board, and building façade. Fig. 1 shows the experimental setup for Case 2. As shown in the figure, the secondary structure was attached in the direction of the weak axis ($x$) of the primary structure. The frequency of the primary structure in the vertical direction is 17 Hz. Since the primary structure is fixed to the ground, the frequency in the vertical direction is obtained from the average frequency of the beams. Three cases were considered in this research: Primary structure only (Case 1), primary structure with the secondary structure with two supports (Case 2) and that with three supports (Case 3). Three excitations were applied in each case resulting in a total of 9 tests.

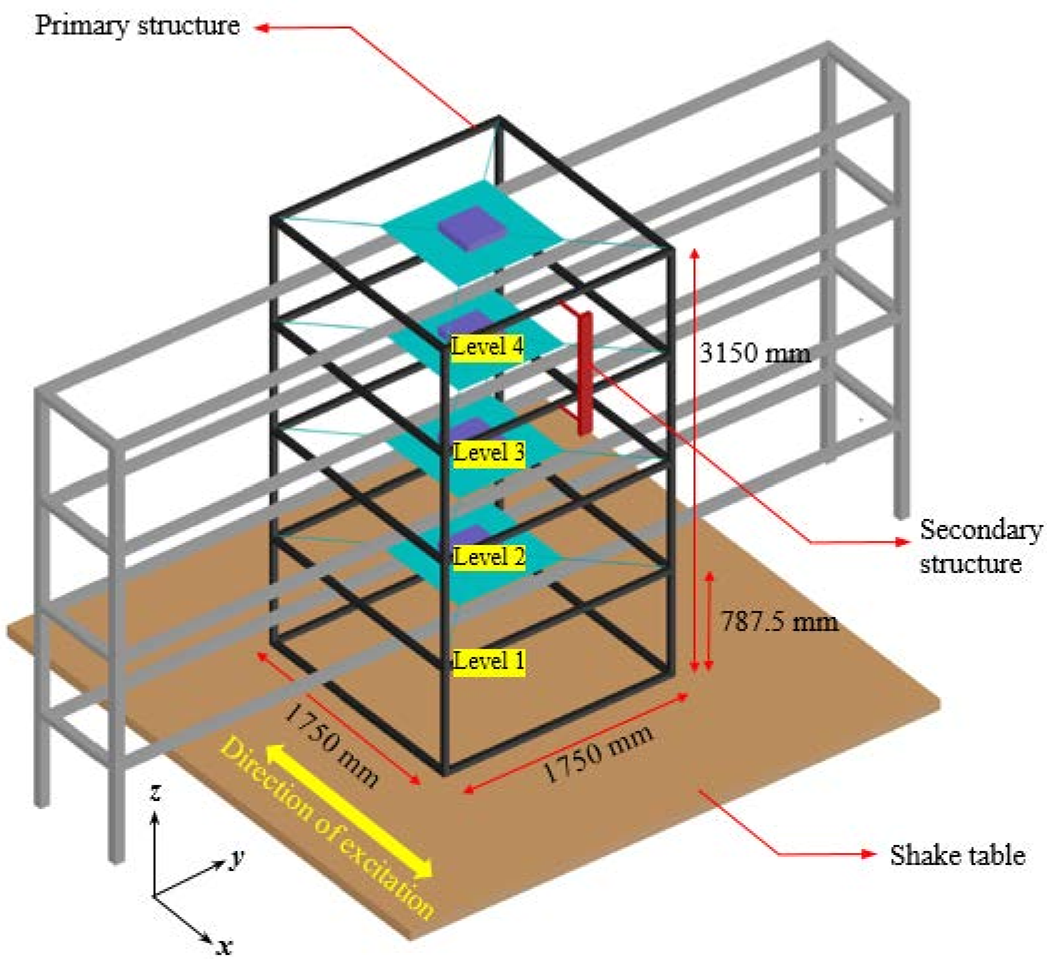


Fig. 1 – The experimental setup for the case of secondary structure with two supports (Case 2)

For Case 3, the third support of the secondary structure is located at Level 2. To ensure a valid comparison, the natural frequencies and mass of both secondary structures are designed to be the same. The mass was 24 kg, made of steel (density = 8030 kg/m$^3$). The natural frequency of the component was 8.6 Hz and 17 Hz, in the vertical ($z$) and horizontal ($y$) directions, respectively (see Fig. 1). The damping ratios of both secondary structures are not precisely the same, but were in a very similar range. Table 1 presents the comparison of the properties of the secondary structures.

Table 1 – Properties of the secondary structure

| **Properties** | **Non-structural component** | |
|---|---|---|
| | **Two supports** | **Three supports** |
| Cross-section of the column (mm$^2$) | 17.5 × 17.5 | 16 × 16 |
| Dimension of mass (mm$^3$) | 87 × 42 × 870 | 87 × 21 × 1740 |
| Average damping ratio (%) | 2.62 | 2.5 |

The mass ratio $\mu$, and frequency ratio $\eta$, of the primary-secondary system are shown in Table 2. Previous research on the significance of these ratios [1] stated that for PSSI to have a significant effect on structural response, the mass ratio should be larger than 10%. The mass ratio selected for the experiments are below 10% in order to exclude significant effect of heavy mass of the secondary structure and thus showcase the influence of the configuration of the secondary structures. Similarly, the frequencies of the secondary structure are very different from those of the primary structure in the corresponding direction. This is intended to remove the influence of resonance between the primary and secondary structures, while at the same time representing possible real cases.

Table 2 – Mass and frequency ratios between the primary and secondary structures

| $\mu = m_s/m_p$ | $\eta = f_s/f_p$ | | | |
|---|---|---|---|---|
| | ***Direction*** | $f_s$ **(Hz)** | $f_p$ **(Hz)** | $\eta$ |
| $\mu$=8.8% | *x* | 200 | 1.8 | $\eta_x$ = 111.10 |
| | *y* | 17 | 6 | $\eta_y$ = 2.83 |
| | *z* | 8.6 | 17 | $\eta_z$ = 0.51 |

## 2.2 Ground motions

Simulated earthquake based on the Japanese design spectrum (JDS) for hard soil condition was applied in the *x* direction of the main structure. Three excitations with similar peak ground acceleration (PGA) and dominant frequencies were used. The JDS was developed based on the 1995 Kobe earthquake. Simulated earthquake were chosen to ensure that the structure experiences excitations of similar characteristics. The target and response spectra of the excitations considered are shown in Fig. 2. The peak ground accelerations are 1.94, 1.91, and 1.93 m/s$^2$ for JDS 1, 2 and 3, respectively.

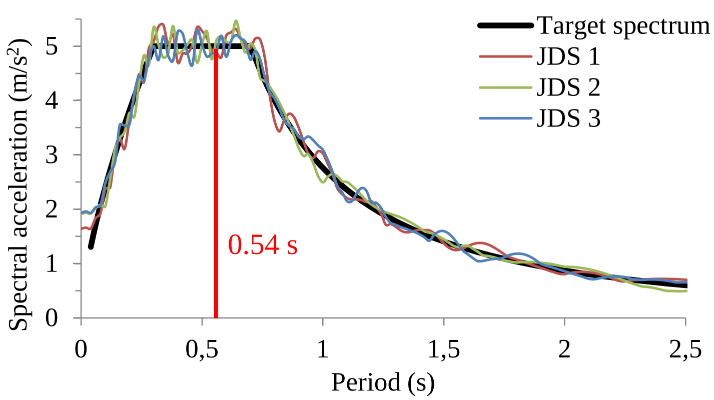


Fig. 2 – Target spectrum and response spectra of the simulated ground motions for hard soil condition

# 3. Results and discussion

## 3.1 Acceleration of the secondary structure

The locations of the accelerometers installed on the secondary structures are presented in Fig. 3. Each accelerometer measures the acceleration in all three directions.

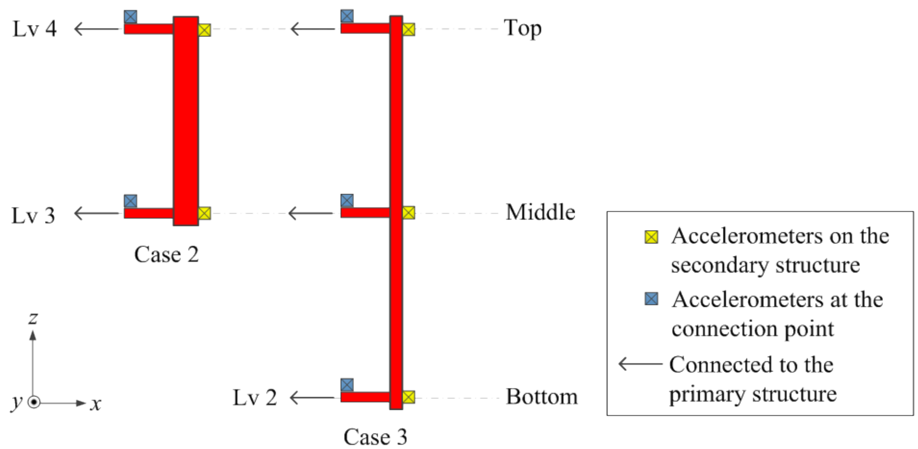


Fig. 3 – Locations of accelerometers attached on the secondary structure

The accelerations at the top and bottom of the secondary structure in the *x* direction were larger when there were only two supports compared to three as shown in Fig. 4. This is anticipated because the force exerted by the same mass to two supports will likely be larger than that to three supports. Due to the larger response of the primary structure at the top floor compared to the floors below, the acceleration induced at the top support is also higher than that induced at lower floors. This is apparent when comparing the range of acceleration (indicated by the horizontal dashed lines) in both graphs in Fig. 4.

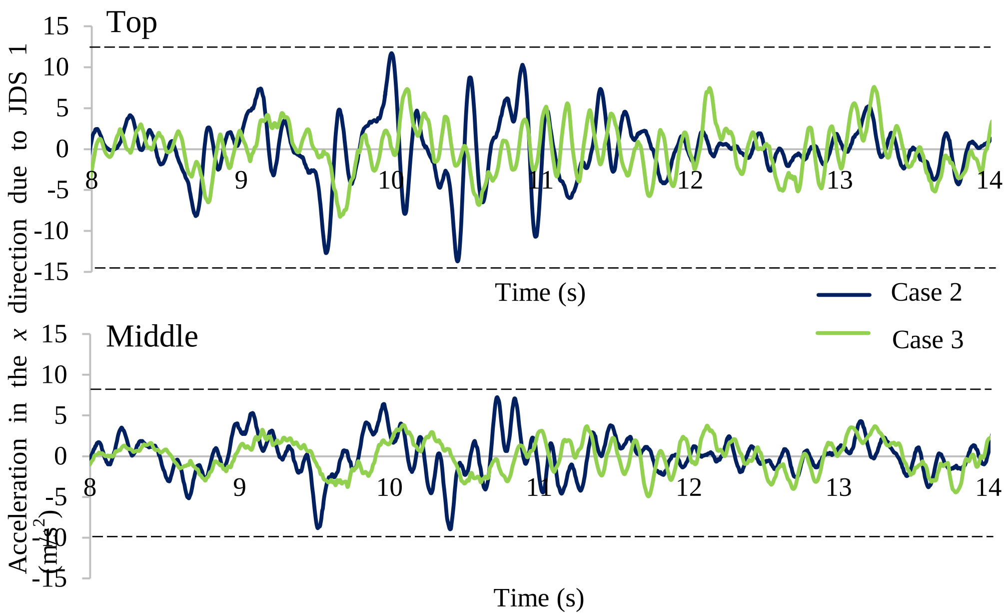


Fig. 4 – Larger acceleration was recorded in Case 2 compared to that in Case 3

Figs. 5 (a) and (b) compare the acceleration at the top of the secondary structure in *y* and *z* directions, respectively. Similar to that in the *x* direction, the acceleration in *y* direction was larger in Case 2 compared to that in Case 3. On the contrary, the vertical acceleration was larger in Case 3 compared to that in Case 2.

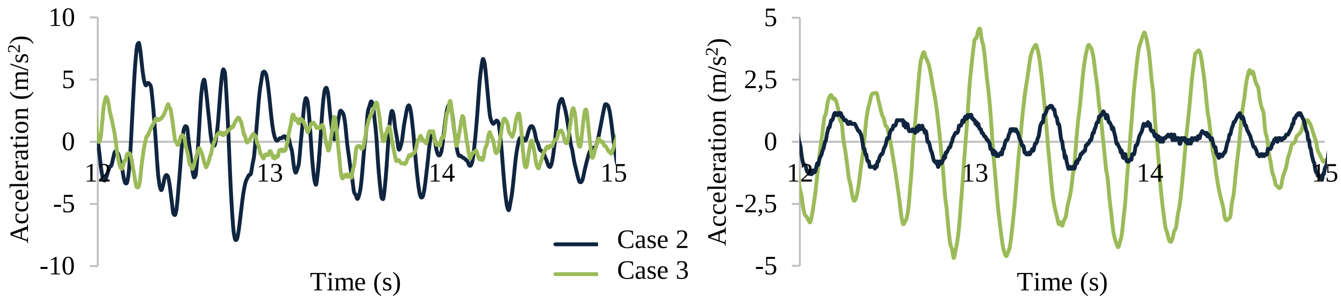


Fig. 5 – Acceleration at the top of secondary structure in Case 2 vs Case 3 in (a) *y* direction, and (b) *z* direction

The summary of the peak accelerations recorded at each location (top, middle, bottom) of the secondary structure due to each excitation in all three directions is recorded in Table 3. The results from JDS 2 and JDS 3 concurred with the hypothesis deduced from Figs. 4 and 5 for JDS 1. The acceleration at the top of the secondary structure is always larger than that at the middle for all cases. In the horizontal directions, the acceleration measured in Case 2 is always larger than that in Case 3. The vertical acceleration however, is always larger when there is three supports compared to two supports.

Table 3 – Summary of peak accelerations at each location of secondary structure

| **Location** | | **Peak acceleration (m/s²)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **due to JDS 1** | | **due to JDS 2** | | **due to JDS 3** | |
| | | **Case 2** | **Case 3** | **Case 2** | **Case 3** | **Case 2** | **Case 3** |
| Top | *x* | 13.71 | 8.24 | 9.53 | 7.47 | 14.61 | 11.07 |
| | *y* | 9.72 | 7.95 | 8.63 | 8.14 | 10.81 | 10.62 |
| | *z* | 4.54 | 9.74 | 4.33 | 6.63 | 4.33 | 7.71 |
| Middle | *x* | 8.97 | 4.93 | 7.25 | 4.14 | 8.97 | 5.44 |
| | *y* | 7.74 | 7.16 | 8.23 | 5.36 | 7.91 | 4.49 |
| | *z* | 4.39 | 11.77 | 4.39 | 10.27 | 4.47 | 7.85 |
| Bottom | *x* | -- | 9.66 | -- | 7.59 | -- | 11.84 |
| | *y* | -- | 6.92 | -- | 6.79 | -- | 6.00 |
| | *z* | -- | 7.45 | -- | 7.65 | -- | 7.64 |

For a multi-storey structure where the response of the structure is dominated by the first mode, it is anticipated that the acceleration is to be larger on the higher level of the structure. Since this is the case, the acceleration of the component attached directly to the floors is expected to be largest at the top and smallest at the bottom. Interestingly, this was not the case. As shown in the measured peak acceleration in Table 3 and the time histories in Fig. 6, while the largest acceleration did occur at the top, acceleration at the midpoint of the secondary structure was always smaller than that at the bottom. Similar development can be observed in the y-horizontal direction. In contrast, the vertical acceleration appeared to be highest at the midpoint.

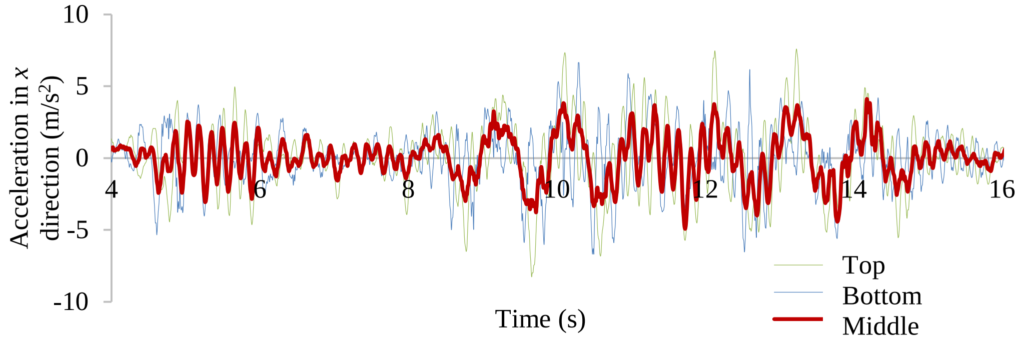

Fig. 6 – Smallest acceleration observed at midpoint compared to those at the top and bottom of the secondary structure

## 3.2 Acceleration of the primary structure

Many studies on secondary structures had concluded that considering certain secondary structures in design could cause reduction in the response of the supporting primary structure [4, 21]. The response analysis of the primary structure with and without the secondary structure in this study supports this conclusion. In addition, it can be deduced that higher number of supports of the secondary structure results in smaller response of the primary structure. The acceleration shown in Fig. 7 was measured at the top of the Level 4 column in the *x* direction. The conclusion however, is valid for the measurement in all directions.

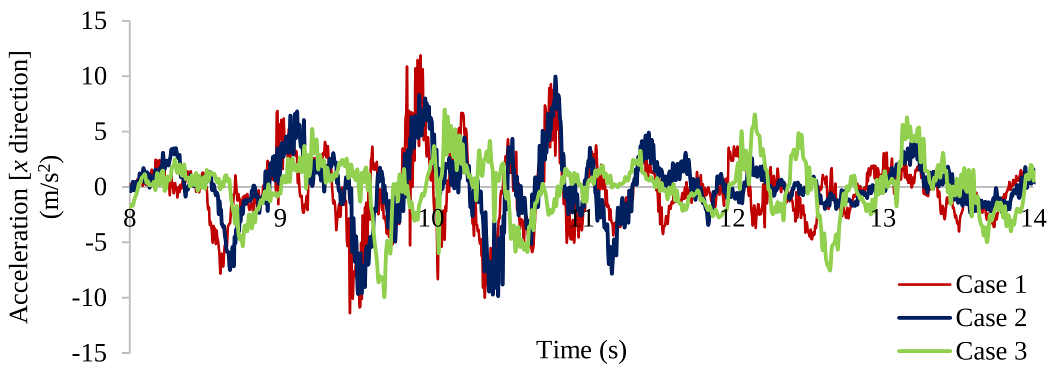

Fig. 7 – Smaller response of the primary structure due to the presence of a secondary structure

In the cases considered, the secondary structure not only affects the amplitude of the response of the primary structure, but also affects its frequency content. As shown in Fig. 8, the dominant frequency of the response (peak value) increases as the number of supports increases. This is likely due to the configuration of the secondary structure, which poses as an additional "bracing" to the primary structure that causes smaller acceleration and deformation in the *x* direction. Secondary structure with three supports across the primary structure will naturally provide more restriction on the movement of the primary structure rather than that with only two supports.

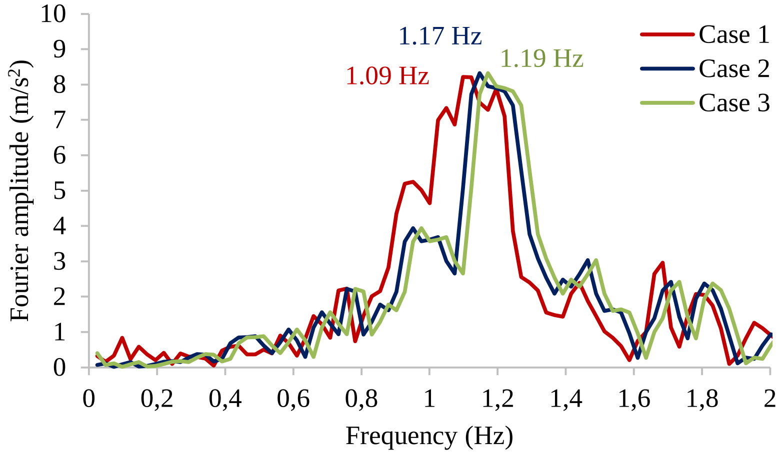


Fig. 8 – Increased dominant frequency with the presence of a secondary structure

### 3.3 Response at the interface between primary and secondary structures

As shown in Fig. 9(a), the response at the connection point was almost exactly the same as the response at the column at the same level when there is no secondary structure. However, an amplification of the response at the connection was found when secondary structure was considered (see Fig. 9(b)). The amplification can be attributed to the local deformation of the beam member itself that was induced by the response of the secondary structure.

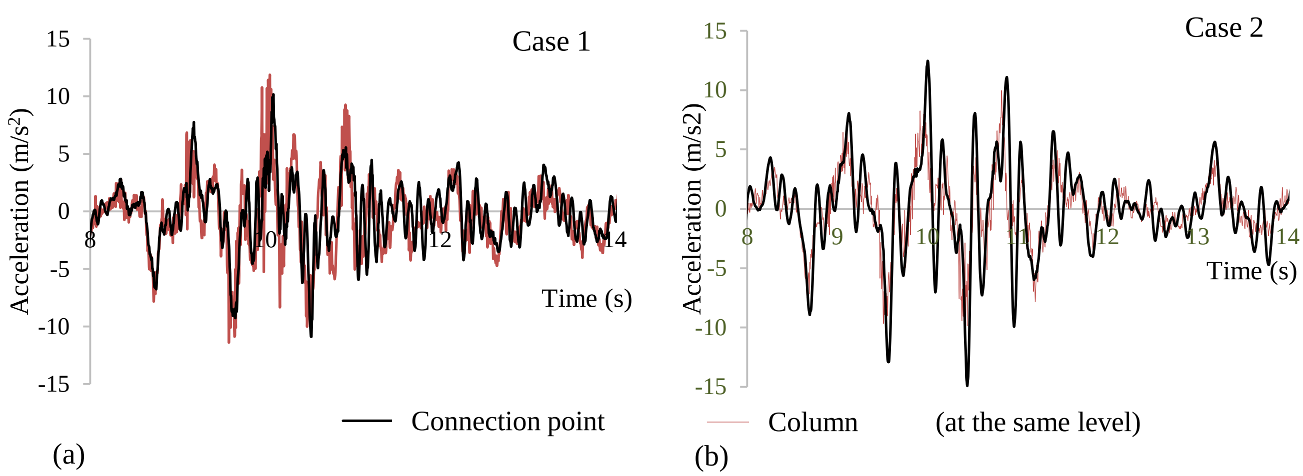


Fig. 9 – Effect of the secondary structure on the local response at the connection point

## 4. Conclusions

This study experimentally investigates the influence of the number of supports of a secondary structure on the seismic performance of the primary structure and itself. The primary structure is a four storey model. Secondary structures of the same dynamic properties with two and three supports were considered. The ground motions used were simulated earthquake based on the Japanese design spectrum (JDS) for hard soil condition. The top attachment of the secondary structure was connected to the beam of the primary structure at its top level, while the middle and bottom attachment was connected to those at the levels below.

In the considered cases,

1. The horizontal acceleration of the secondary structure with two attachments is always larger than that with three attachments. The opposite is the case for the vertical direction.
2. Within the secondary structure, the largest response always occur at the top connection. Acceleration at the midpoint of the secondary structure is always smaller than that of the bottom connection.
3. The overall response of the primary structure is reduced when there is a secondary structure attached to it. More attachments of secondary structure caused slightly larger reduction.
4. The secondary structure also caused higher dominant frequency of the response of the primary structure. This is likely due to the secondary structure posing as a "bracing" on the primary structure, thus slightly restricting its movement.
5. The response at the connection point was larger when there was a secondary structure attached. This can be attributed to the local deformation of the beam member induced by the response of the secondary structure.

## 5. Acknowledgements

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## 6. References

[1] Chen Y, Soong TT (1988): State-of-the-art-review: Seismic response of secondary systems. *Engineering Structures*, **10**, 218-228.

[2] Villaverde R (1997): Seismic design of secondary structures: State of the art. *Journal of Structural Engineering*, **123** (8), 1011-1019.

[3] Naito K, Chouw N (2003): Measures for preventing secondary structures from uplift during near-source earthquakes. *Proceedings of the 40 year of European Earthquake Engineering*, 26-29 August, Ohrid, Macedonia.

[4] Lim E, Chouw N (2014): Consequence of main-secondary structures interaction for seismic response of secondary structures. *Annual New Zealand Society of Earthquake Engineering Conference*, paper no. 20, 21-23 March, Auckland, New Zealand.

[5] Ferner H, Wemyss M, Baird A, Beer A, Hunter D (2014): Seismic performance of non-structural elements within buildings. *Annual New Zealand Society of Earthquake Engineering Conference*, paper no. 69, 21-23 March, Auckland, New Zealand.

[6] FEMA (1997): NEHRP guidelines for seismic rehabilitations of buildings. *Report no. FEMA* 273, Federal Emergency Management Agency, Washington, DC, USA.

[7] FEMA (1997): NEHRP commentary on the guidelines for seismic rehabilitations of buildings. *Report no. FEMA* 274, Federal Emergency Management Agency, Washington, DC, USA.

[8] Penzien J, Chopra AK (1965): Earthquake response of an appendage in multi-storey building. *Proceedings of the Third World Conference on Earthquake Engineering*, paper no. 2, New Zealand.

[9] Kapur KK, Shao LC (1973): Generation of seismic floor response spectra for equipment design. *Proceedings of ASCE Specialty Conference on Structural Design of Nuclear Power Plant Facilities*, 29-71, Chicago, Illinois.

[10] Sackman JL, Kelly JM (1978): Rational design methods for light equipment in structures subjected to ground motion. Report UCB/EERC-78/19, Earthquake Engineering Research Center, University of California, Berkeley, USA.

[11] Sackman JL, Kelly JM (1979): Seismic analysis of internal equipment and components in structures. Engineering Structures, **1** (4), 179-190.

[12] Igusa T, Kiureghian AD (1992): Interaction in Primary-secondary systems. Journal of Pressure Vessel Technology, **114**, 53-59.

[13] Igusa T, Kiureghian AD (1985): Dynamic characterization of two-degree-of-freedom equipment-structure systems. Journal of Engineering Mechanics, ASCE, **111** (1), 1-19.

[14] Igusa T, Kiureghian AD (1985): Dynamic response of multiply supported secondary systems. Journal of Engineering Mechanics, ASCE, **111** (1), 20-41.

[15] Igusa T, Kiureghian AD (1985): Generation of floor response spectra including oscillator-structure interaction. Earthquake Engineering and Structural Dynamics, **13**, 661-676.

[16] Asfura A, Kiureghian AD (1986): Floor response spectrum method for seismic analysis of multiply supported secondary systems. Earthquake Engineering and Structural Dynamics, **14**, 245-265.

[17] Burdisso RA, Singh MP (1987): Multiply supported secondary systems part I: response spectrum analysis. Earthquake Engineering and Structural Dynamics, **15**, 53-72.

[18] Burdisso RA, Singh MP (1987): Seismic analysis of multiply supported secondary systems with dynamic interaction effects. Earthquake Engineering and Structural Dynamics, **15**, 1005-1022.

[19] Bernal D (1999): A dynamic stiffness formulation for the analysis of secondary systems. Earthquake Engineering and Structural Dynamics, **28** (11), 1295-1308.

[20] Lim E, Chouw N (2015): Review of approaches for analysing secondary structures in earthquakes and evaluation of floor response spectrum approach. *International Journal of Protective Structures*, **6** (2), 237-257.

[21] Lim E, Chouw N, Pot G (2015): Identification of the interacting force at the interface between primary-secondary structures. Proceedings of the Tenth Pacific Conference on Earthquake Engineering, paper no. 114, 6-8 November, Sydney, Australia.