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Effects of multi-directional excitations on the response of a secondary structure with two attachments

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ABSTRACT: Secondary structures with multiple attachments were known to exhibit spatial coupling behaviour, i.e. the response at one of the supports affecting that of the other. Examples of such structures include advertisement boards, façade and piping systems. Many past research performed were majorly numerical; experimental studies are exiguous. Additionally, the types of secondary structure attached across different floors of the primary structure are usually anticipated to be vulnerable to vertical excitation. Both numerical and experimental studies on the effect of vertical excitation on secondary structures are rare due to the intrinsic complexities involved. This paper experimentally investigates the response of the secondary structure with two attachments to multi-directional excitations. The experimental model consisted of an elastic four-storey primary structure with an assumed fixed base and an elastic secondary structure with two supports, attached to the beams of the top two floors of the primary structure. The structure was subjected to ground motions recorded in the 1995 Kobe earthquake. This earthquake was selected due to the high frequency component in the vertical direction. The responses at the top and bottom attachments of the secondary structure in all three directions due to one, two and three directional excitations were analysed. The effects of multi-directional excitations on the response of the secondary structure, especially when vertical excitation is involved, will be revealed along with the contributions to the spatial coupling behaviour. This paper will explicate the dynamic interaction between a primary structure and a secondary structure with two attachments.

1 INTRODUCTION

Secondary structures are non-structural components attached to a primary structure, e.g. parapet, ceilings, cladding, façade, equipment and heavy objects in a building. Secondary structures are not designed to carry loads thus make them vulnerable in earthquakes (e.g. Chen and Soong, 1988; Chouw, 1995; Villaverde, 1996; Naito and Chouw, 2003; Chen *et al.*, 2013; Lim and Chouw, 2015).

The response of secondary structure under seismic loads largely depends on its interaction with the primary structures. The dynamic interaction between the primary and secondary structure will give rise to the following effects: (1) Tuning effect: the resonance effect in the frequencies of the primary and secondary structures as well as the dominant frequencies of the excitation, (2) feedback effect: it is the effect of the interacting forces induced in the primary-secondary structure interface caused by the relative motions of the two subsystems under an excitation, (3) non-classical damping: the incongruity between the damping coefficients in the subsystems that obviates classical damping, and (4) spatial coupling due to multiple supports of secondary structures on the primary structure, i.e. the response at one support affecting that of the other.(e.g. Igusa and Kiureghian, 1985a, b; Asfura and Kiureghian, 1986; Lim and Chouw, 2015). To date, this interaction is not clearly quantified yet due to its intrinsic difficulty. For simplicity, the induced accelerations at the supports of secondary structures are commonly used as the design loading i.e. the floor response spectrum method. Since the response can only be as accurate as the assumption of the loading, no matter how good the calculation approach is, current design of secondary structures is not properly performed.

Different attachments of the secondary structures will introduce different interacting forces at the primary-secondary structure interface. Thus, seismic response of secondary structures depends strongly on how they are attached to the primary structure. If the secondary structure has multiple supports, the force occurs at one support might affect the response at the other support locations, i.e. spatial coupling (Asfura and Kiureghian, 1986; Igusa and Kiureghian, 1985a, b). In this paper secondary structure with two attachments is considered.

For multi-supported secondary structures, different directional excitation can have very different effects on the response. In this paper the experimental model is subjected to one, two and three directional excitations. Experimental studies performed reveals how the multi-directional excitations affect the response of the secondary structure with two attachments taking into account the primary-secondary structure interaction. Large-scale primary-secondary structure model was constructed in order to be able to capture the development of acceleration within the secondary structure itself that would otherwise be missing in small scale models.

2 EXPERIMENTAL SETUP

2.1 Model development

The experimental model comprises of an elastic four-storey primary structure with an assumed fixed base where a secondary structure was attached. The secondary structure had two supports attached across the top two floors of the primary structure. The primary structure model was constructed based on a four-storey prototype, scaled by 4 in dimension. The scale factor for the mass was 90. The sketch of the structural model is shown in Fig. 1.

2.2 Properties of the primary structure

The entire primary structure was made of steel with a Young's modulus of 200 GPa. The total height was 3150 mm with an interstorey height of 787.5 mm. The bay width was 1750 mm. The floor mass was 272 kg for the first three floors each and 227 kg for the roof floor. The fundamental frequency of the primary structure was 1.86 Hz and 6 Hz, in the weak and strong axis, respectively. The weak and strong axes are represented in the direction of x and y axis respectively in Fig. 1. The damping ratio from the decay rate of the free vibration tests performed on the structure in the weak axis was found to be 4.1%.

2.3 Properties of the secondary structure

The secondary structure was a frame structure with a distributed mass supported by two columns. The columns were made of PVC with a Young's modulus of elasticity of 2.5 GPa. The cross section of the column was 17.5 mm × 17.5 mm and the length was 229 mm. The secondary structure was made of steel of 8030 kg/m^3 density, with the dimension of 870 mm × 87 mm × 42 mm, resulting in a total mass of 24.24 kg. The length of the structure was specifically constructed so that the longitudinal direction spanned across two levels on the primary structure (see Fig. 1).

The natural frequency of the secondary structure were 8.6 Hz and 17 Hz, in the longitudinal and transversal direction of the structure, respectively. The damping ratio was 2.62%.The mass of the secondary structure was designed to be within 5-15% of the floor mass of the primary structure, while the natural frequency of the secondary structure was defined to be 5-10 times larger than that of the primary structure. This ratio was selected to simulate real cases of secondary structures, e.g. advertisement boards, facade of a building, and piping system outside buildings. Accelerometers were installed at each edge of the secondary structure. At each location, three accelerometers were installed to measure the acceleration in the x, y, and z directions to measure accelerations in the corresponding directions.

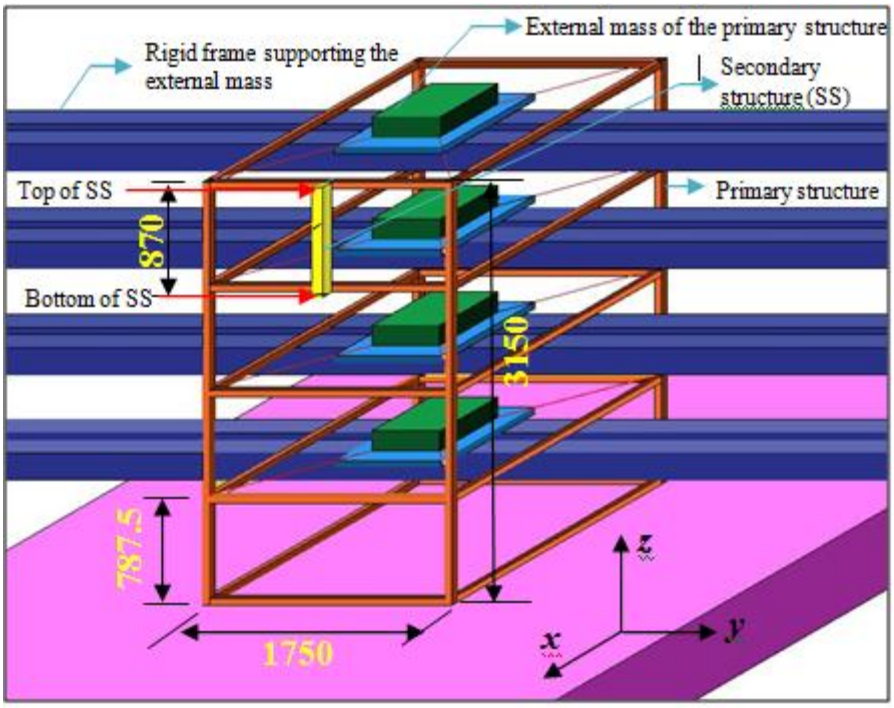

Fig. 1 Sketch of experimental setup

2.4 Shake table experiments

The entire structural model was bolted down onto a shake table capable of simulating excitations in all three directions. Scaled record from the 1995 Kobe earthquake measured at the Japan Meteorological Agency (JMA) station was used in the experiment. The ground motion record was scaled by 4 to match the scale of the model. The original data was recorded in north-south (NS), east-west (EW), and vertical directions. Between the two horizontal excitations, the one with the higher Peak ground acceleration (PGA), i.e. NS direction was selected as the excitation in the weak axis of the primary structure (*x* direction of the setup). The PGA for the scaled excitation in *x*, *y*, and *z* direction was 2.0500 m/s^2, 1.5500 m/s^2, and 0.8330 m/s^2, respectively. The time histories of the excitation in each direction are presented in Fig. 2.

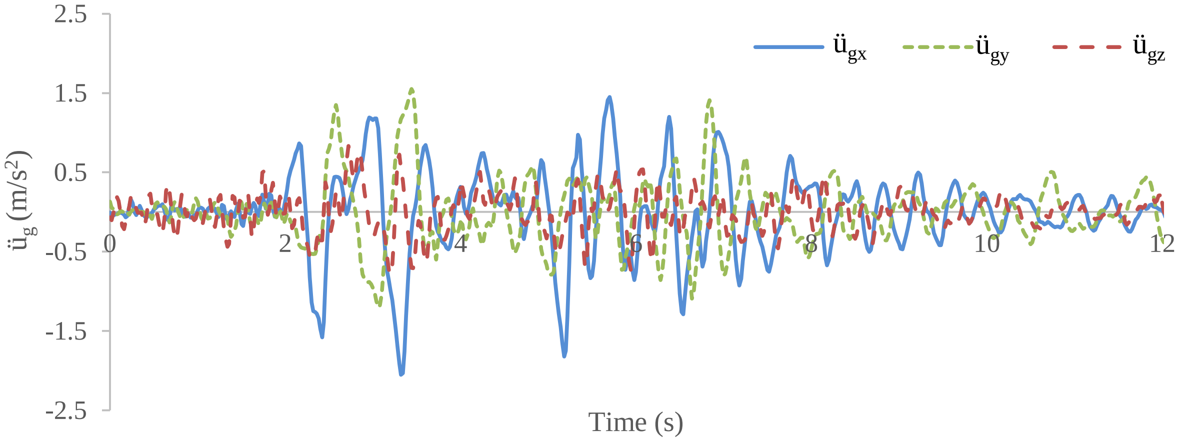

Fig. 2 Scaled acceleration recorded from the Kobe (1995) Earthquake at JMA station

The model was subjected to excitation in *x* direction only; *x* and *y* directions simultaneously; and all directions simultaneously, resulting in a total of three tests performed.

3 RESULTS AND DISCUSSION

For convenience purpose, the primary structure will herein be denoted as "PS" and the secondary structure "SS", "*xy*" directional excitation means the excitation consists of that in x and y components, while “*xyz*” directional excitation means the excitation is in all three directions. All graphs represented have been focused only in their peak values to get a lucid comparison between the results of different excitation, i.e. within 2 to 7 s time frame.

3.1 Response at the top of the secondary structure

Fig. 3 compares the horizontal acceleration at the top of SS in the *x* direction for one, two, and three directions. The maximum accelerations were 12.0366 m/s^2, 11.3929 m/s^2, and 11.5217 m/s^2 for excitations in *x*, *xy* and *xyz* directions, respectively. The maximum acceleration occurs when there was only *x* directional excitation.

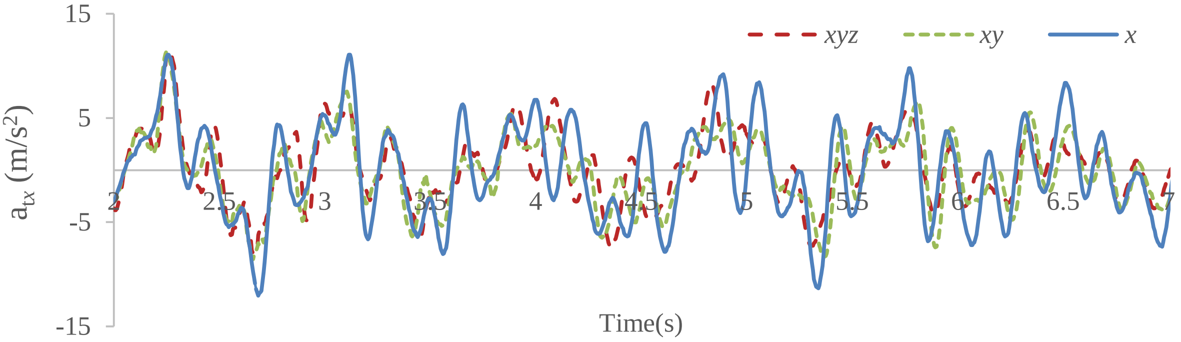

Fig. 3 Acceleration at the top of SS in /*x* direction due to excitation in *x*, *xy and xyz* directions

Fig. 4 compares the horizontal acceleration at the top of SS in the *y* direction for one, two, and three directions. The maximum accelerations were 9.9769 m/s^2, 20.1468 m/s^2, and 21.3698 m/s^2 for excitations in *x*, *xy* and *xyz* directions, respectively. As anticipated, a significant increase of the response was observed when two-directional excitation was considered (102%). An additional increase of 6% was found when the structure was subjected to *xyz* directional excitation. This means the maximum response in the top *y* direction occurred when the structure was subjected to *xyz* directional excitation rather than *xy* directional excitation. This result is contradictive to that observed in Fig. 3 where multi-directional excitation reduced the maximum response in *x* direction.

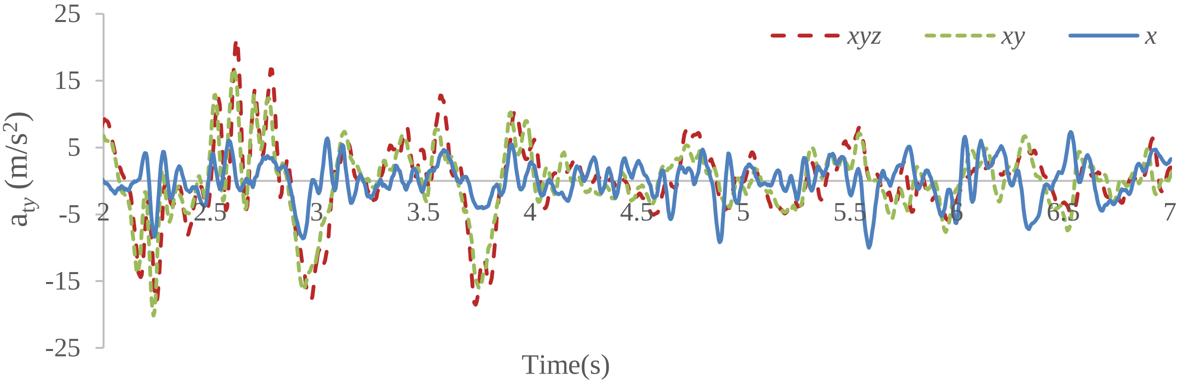

Fig. 4 Acceleration at the top of SS in *y* direction due to excitation in *x*, *xy and xyz* directions

Fig. 5 shows the vertical acceleration at the top of SS for one, two, and three directions, respectively. The maximum accelerations were 5.2626 m/s^2, 5.4789 m/s^2, and 6.7765 m/s^2 for excitations in *x*, *xy* and *xyz* directions. Compared to the response in the other two directions, the response in the *z* direction was significantly smaller. Nevertheless, two-directional horizontal excitation increased the vertical acceleration (a_{tz}). The vertical component in three directional excitation appeared to further increase the overall acceleration at the top of SS in the *z* direction.

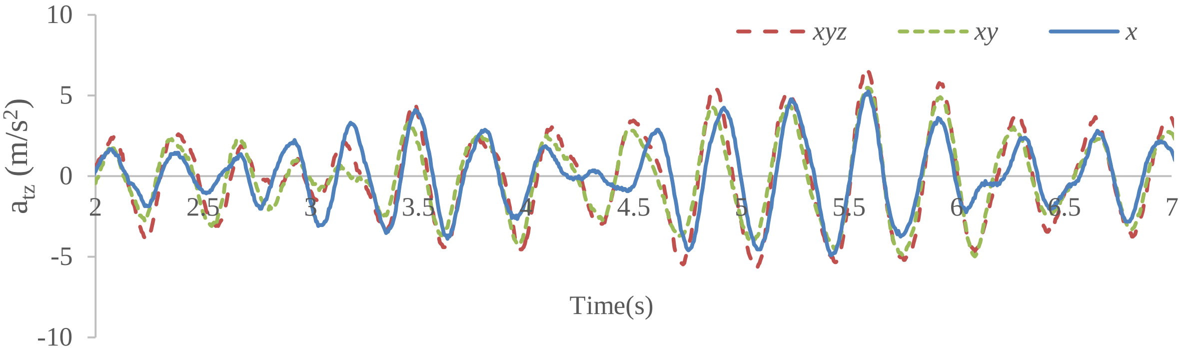

Fig. 5 Acceleration at the top of SS in z direction due to excitation in x, xy *and* xyz directions

3.2 Response at the bottom of the secondary structure

Fig. 6 compares the horizontal acceleration at the bottom of SS in the x direction for one, two, and three directions, respectively. The maximum accelerations were 8.3252 m/s^2, 8.6841 m/s^2, and 8.4687 m/s^2 for excitations in x, xy and xyz directions. In contrast to the acceleration at the top of SS, multi-directional excitation has minimal effect on the maximum acceleration at the bottom of SS in x direction.

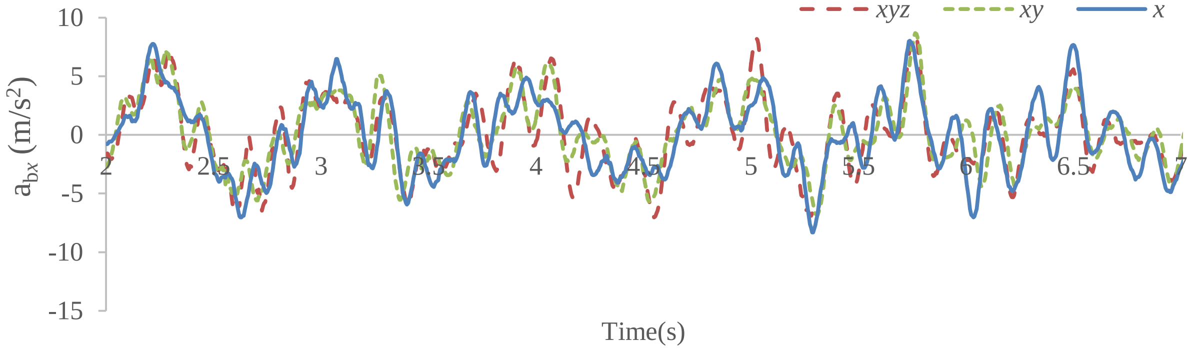

Fig. 6 Acceleration at the bottom of SS in x direction due to excitation in x, xy *and* xyz directions

Fig. 7 presents the horizontal acceleration at the bottom of SS in the y direction for one, two, and three directions. The maximum accelerations were 8.0142 m/s^2, 17.4460 m/s^2, and 16.5737 m/s^2 for excitations in x, xy and xyz directions, respectively. Similar to that of the top of SS, a significant increase of the response was observed when two and three directional excitations were considered.

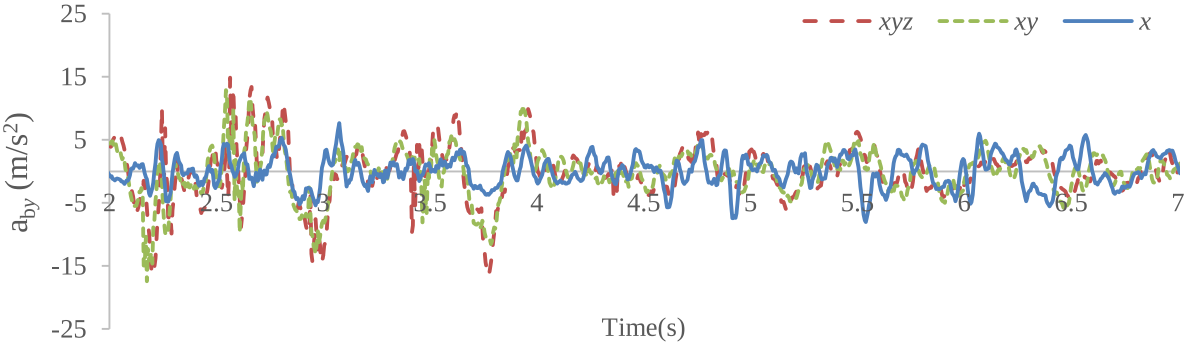

Fig. 7 Acceleration at the bottom of SS in y direction due to excitation in x, xy *and* xyz directions

Fig. 8 compares the vertical acceleration at the bottom of SS in the z direction for one, two, and three directions. The maximum accelerations were 5.3744 m/s^2, 10.6671 m/s^2, and 8.4813 m/s^2 for excitations in x, xy and xyz directions, respectively. When the response was measured in the z direction at the bottom of the SS, the maximum response was due to the xy directional excitation as opposed to those due to xyz directional excitation observed at the top. A phenomenal difference was observed between the maximum vertical acceleration at the top and bottom of SS when xy directional excitation was considered, i.e. 94.7%. Unlike the response in x and y directions, the maximum accelerations at the bottom of SS in *z* direction were always higher than those at the top.

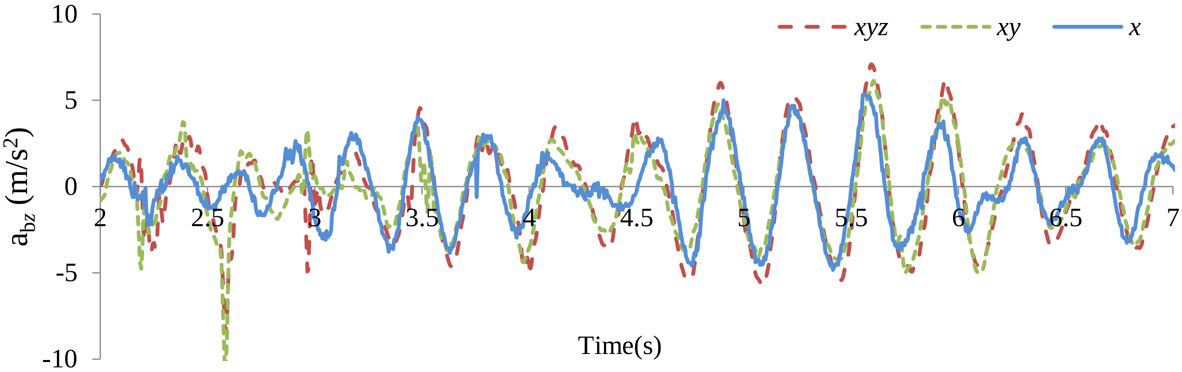

Fig. 8 Acceleration at the bottom SS in *z* direction due to excitation in *x*, *xy and xyz* directions

The peak accelerations at the top and bottom of the secondary structure in all directions were listed in Table 1.The bold values are the largest peak acceleration in the direction considered. The maximum accelerations at the bottom of the secondary structure in both horizontal directions were always lower than their counterpart at the top. On the contrary, the response in the vertical direction (*z*) was always higher in the bottom compared to the top.

Table 1. Peak accelerations of the secondary structure

Direction of excitation	Acceleration (m/s^2) Top of SS *x*	*y*	*z*	Bottom of SS *x*	*y*	*z*
x	**12.0366**	9.9769	5.2626	**8.3252**	8.0142	5.3744
xy	11.3929	20.1468	5.4789	8.6841	**17.4460**	**10.6671**
xyz	11.5217	**21.3698**	**6.7765**	8.4687	16.5737	8.4813

The maximum acceleration at the top of the secondary structure in the *y* and z directions was the highest when *xyz* directional excitation was considered whereas, those at the bottom was when the *xy* directional excitation was considered. This indicated that spatial coupling, i.e. the difference in the response of the secondary structure at its connection points, was always present within the secondary structure.

To further prove the presence of spatial coupling, the time histories of the top and bottom of SS were plotted together in the cases of the *x* and *y* directions (Figs. 9 and 10). Planar (*xy*) excitation appeared to increase the spatial coupling between the two supports in *x* direction compared to one directional excitation. This is indicated by the differences in the top and bottom accelerations in opposite directions resulting in a double-helical pattern (refer the circled region in Fig. 9(b)). However, vertical excitation (*z*) appeared to reduce the coupling (Fig. 9(c)).

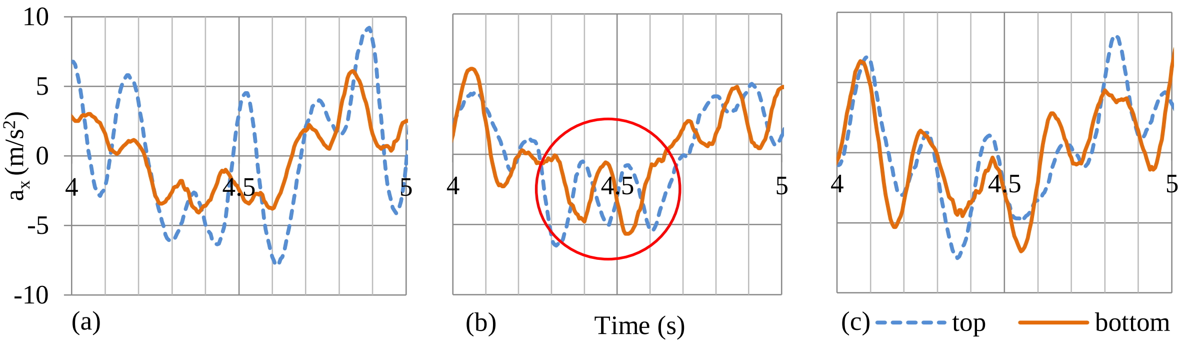

Fig. 9 Top and bottom of SS in *x* direction due to the (a) *x*, (b) *xy*, and (c) *xyz* directional excitation

On the other hand, the most significant spatial coupling in *y* direction was observed when only *x* directional excitation was considered (refer the circled region in Fig. 10(a)). Although not as strong the coupling effect was still present when the excitation consisted of more than one directional component, as shown in Fig. 10(b) and 10(c).

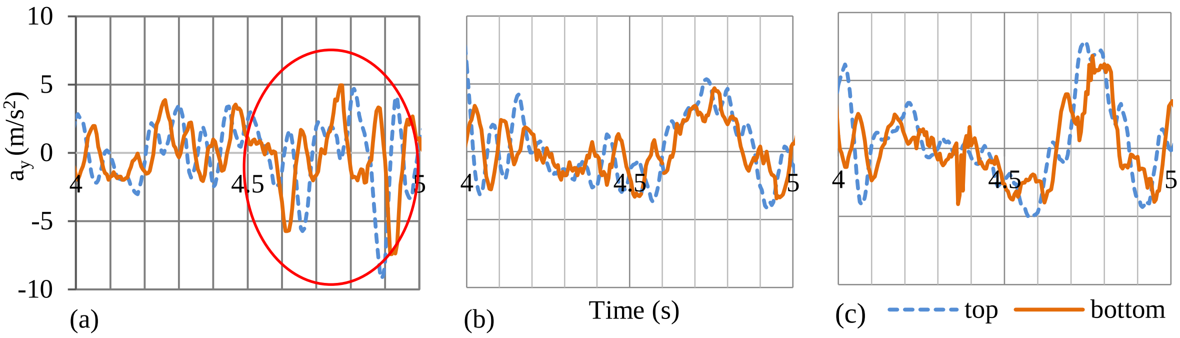

Fig. 10 Top and bottom of SS in *y* direction due to (a) *x*, (b) *xy*, and (c) *xyz* directional excitation

4 CONCLUSIONS

This study experimentally investigates the effects of multi-directional excitation on the response of the secondary structure with two attachments, especially focusing on the effect of vertical excitation. The considered primary structure is a four storey model. The top attachment of the secondary structure was connected to the beam of the primary structure at its top level, while the bottom attachment was connected to that at the level below. It was revealed that,

1. The maximum acceleration at the top of the secondary structure in the *x* direction was slightly reduced when multi-directional excitation was considered, while that at the bottom was almost unaffected.
2. The maximum accelerations at the bottom of the secondary structure in *x* and *y* directions were always lower than their counterpart at the top. This however, was contradictive to the response in the vertical (*z*) direction.
3. The maximum accelerations at the top of the secondary structure in the *y* and *z* directions were the highest when *xyz* directional excitation was considered whereas; those at the bottom were when *xy* directional excitation was considered.
4. The difference in the behaviour of the response at the top and bottom of the secondary structure proved the presence of spatial coupling behaviour within the secondary structure.

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