Effect of simultaneous multi-axial loading and ground on the response of a non-structural component

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ABSTRACT

In earthquakes nonstructural components (NSCs) experience induced vibrations from the ground via the main structure. To design NSCs properly a holistic consideration of the whole system of NSCs, main structure and supporting ground including the multi-axial ground excitation is therefore necessary. To date, only few research has explored the simultaneous influence of the mentioned factors. In this work, large-scale shake table experiments were performed to understand the response of a nonstructural component attached at three locations of a main structure under the simultaneous influence of the interaction between main structure and nonstructural component, multi-axial excitations and supporting soil. The influence of each factor, separately and simultaneously, will be explicated.

Keywords: *Non-structural component, main structure-NSC interaction, multi-axial ground excitation, simultaneous effect*.

INTRODUCTION

Damage to nonstructural components (NSCs) or secondary structures has been observed in major earthquakes in the past, e.g. the 1995 Kobe earthquake [1]. Figure 1 shows the damage to the Avon House in the 2011 Canterbury earthquake. In some regions, NSCs are sometimes distinguished from secondary structures, i.e. NSCs being defined as all the non-load-bearing components in a building. Secondary structures on the other hand, are load-bearing elements, but they are not carrying load in a particular direction [2]. NSC can be a building facade, advertisement board, an air conditioner, generator set or shelving units in a building. A large number of investigations have been performed in the past, mainly numerically, e.g. [3-4]. The most frequent used approach is the floor response spectrum approach, even though it is well known that the assumption made does not reflect the reality [5].

Physical experiments were performed mainly using a small-scale models [6-7]. Large-scale experimental investigations using shake table are rare. Peterman et al. [8-9] e.g. performed a full-scale steel framed two-storey building using two 1994 Northridge ground motions. Soroushian et al. [7] investigated damage to suspended ceilings. The authors also performed a full-scale, five storey steel moment frame building with base isolators using the E-Defense shake table. In the investigations the vertical component of the ground motions was also considered. However, none of these investigations considered the influence of the supporting ground. The design specifications, e.g. ASCE seismic design requirements for nonstructural components [2, 11], also do not provide guidance for incorporating the influence of the supporting ground.

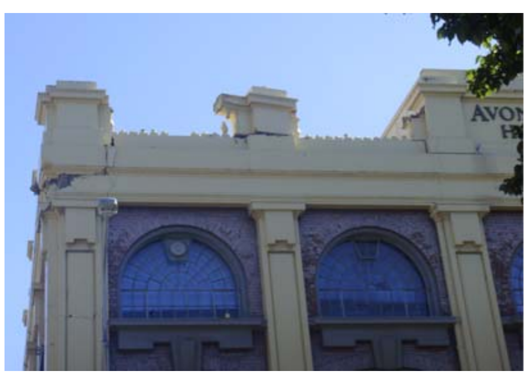

Figure 1. Damage to Avonmore House in the 2011 Canterbury Earthquake.

SHAKE TABLE EXPERIMENTS

Main structure and non-structural component on a sand box

To reveal the influence of supporting soil and multi-axial ground excitation a 1:4 scale four-storey frame structure with a simplified NSC supported at three top floor of the main structure was tested (see Figure 2). To reveal the influence of the supporting soil a fixed base assumption by bolting the main structure directly to the shake table was also considered. To simulate the effect of supporting soil a steel-reinforced wooden box of 3 m x 3 m with a height of 2 m was used. The sand was filled up to 1.1. m and compacted. The specific gravity of the sand was 2.75 and the relative density 58.9%. The water content in the sand was 27%. The compaction was necessary to ensure that the soil condition remains as consistent as possible for each experiment. A large shake table of 4 m x 4 m with a payload of 30 tonnes was used. To evaluate the effect of simultaneous vertical and horizontal ground excitation on the structural response one and two components of ground excitation were also considered separately. Figure 2 shows the actual experimental set-up on sand. Accelerometers and laser displacement transducers were installed on the main structure at the joint locations. The scaling approach for the model was adopted from the references [12-13]. The approach was selected because the authors intended to study the influence of structures with uplift capability on nonstructural components. This was achieved by placing the main structure on sand in a box. The approach allowed for a predefined mass to enable a simulation of structures with transient partial separation at the interface between their footing and the supporting sand.

Table 1. Scale factors and dimensions of parameters.

Parameters	Dimensions	Similitudes	Scale factors
Length	$[L]$	N_l	**4**
Mass	$[M]$	N_m	**90**
Time	$[T]$	N_t	**1**
Acceleration	$[LT^2]$	$N_a = N_l/N_t^2$	**4**
Stiffness	$[MT^2]$	$N_m\ N_a/N_l$	90
Frequency parameter	$[T^{-1}]$	$(N_a / N_l)^{0.5}$	1
Frequency	$[T^{-1}]$	$(N_a / N_l)^{0.5}$	1

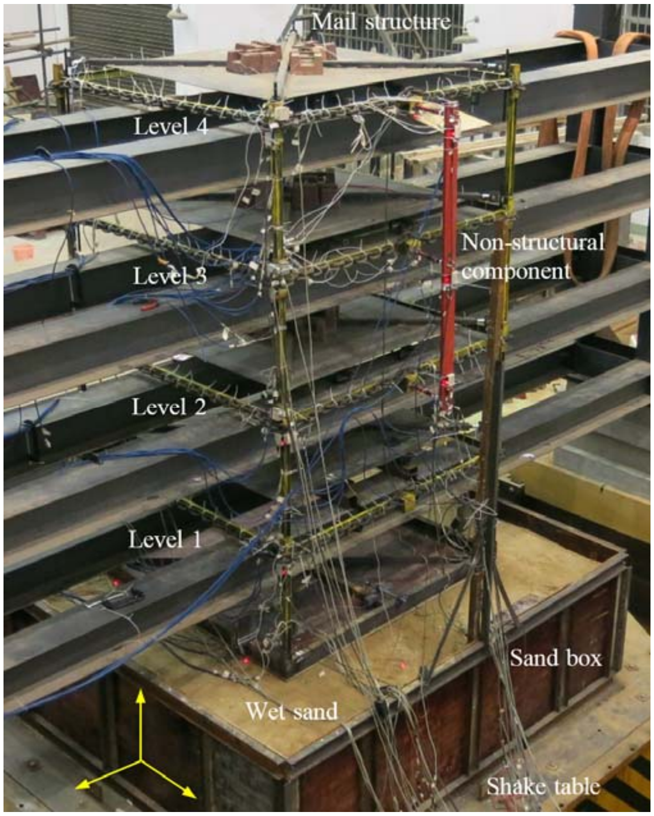

Figure 2. Main structure, non-structural component and sand box on shake table.

Table 1 lists the scale factors and dimensions of the parameters considered. Using the scaling approach, the length, mass and time scale factors (values in bold) are predefined. A frequency parameter is introduced in the selected dimensionless parameters according to Buckingham's π theorem. This parameter is required to fulfil the similitude requirement of a structure with uplift capability. The NSC was a rigid block of 24 kg. It was attached in the strong x-axis of the main structure. Both the main structure and the NSC have then the same weak y-axis. The fundamental frequency in the strong and weak axes of the structure with an assumed fixed base were respectively 6 Hz and 1.86 Hz. The frequency of the vertical vibration of the beam of the main structure was 26 Hz. The damping ratio of 4% was obtained from the average decay rate of free vibration from five tests.

Figure 3 shows the NSC. Each of the supports was bolted onto the beam of the main structure (see Figure 2). The natural frequency of the NSC in the weak axis and vertical direction was 8.6 Hz and 17 Hz, respectively. The damping ratio for both vibration directions was 2.5%. This value was obtained from five free vibration tests. Strain gauges at the supports, accelerometers and laser displacement transducers pointed at each level of the NSC were used respectively to obtain the bending moment, acceleration and displacement of the NSC. Details of the models are given in reference [14].

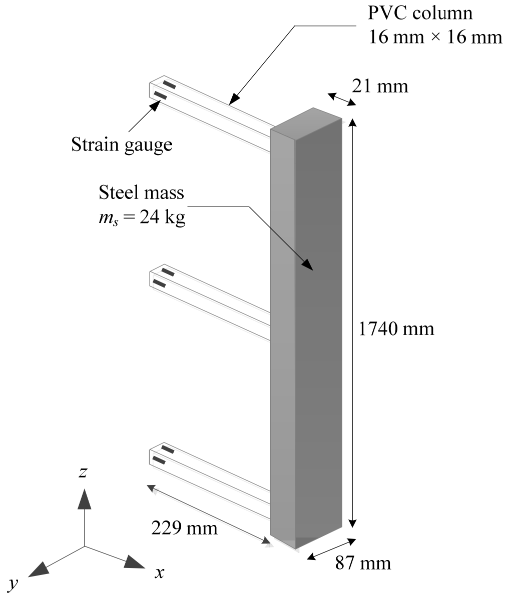

Figure 3. Sketch of the non-structural component.

Earthquake loading

The ground motions used in the experiments were the 1995 Kobe earthquake [1], measured at the station of Japan Meteorological Agency. Figures 4(a) and (b) show the horizontal and vertical components of the ground motion, respectively. The peak ground accelerations (PGAs) for the *x*-, *y*-, and *z*-directions were 2.04 m/s^2, 1.55 m/s^2, and 0.83 m/s^2, respectively. In the experiments it was intended to select ground motions with a vertical component with a PGA smaller than that of the horizontal components. This selection enabled the authors to investigate whether even a weak vertical component could have a significant contribution to the total NSC response.

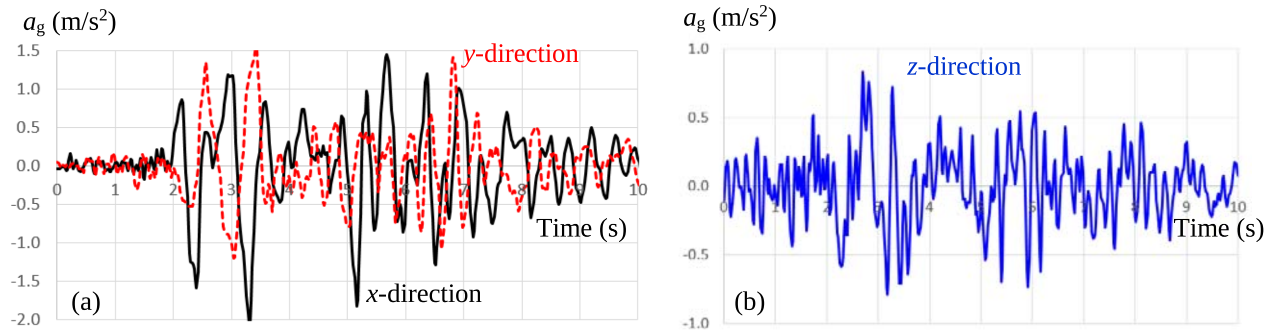

Figure 4. Ground excitation. (a) Horizontal components and (b) vertical component.

EXPERIMENTAL RESULTS

Influence of supporting soil

Figures 5(a) and (b) show the influence of the supporting soil on the top acceleration of the NSC in the x- and z-direction due to the horizontal component of the ground motion in the x-direction, respectively. The dashed lines show the response when the main structure is fixed to the shake table. The red solid lines are the horizontal response when the main structure is placed on sand. Most research in the past concluded that the supporting ground will be beneficial for the structure, because it will cause an elongation of the fundamental period of the soil-footing-structure system. A comparison of the solid line and the dashed line in Figure 5(a) shows indeed that the supporting ground elongate the period of the system. With the time the time delay in the response can be clearly seen. However, in reality the response to the ground excitation depends also on the characteristics of the ground motion. Consequently, an elongation of the system fundamental period might also cause an increase in the response when the system period coincides with the dominant periods of the loading.

Figure 5(a) indeed shows that the supporting ground causes a smaller response (solid line) in comparison to that (dashed line) of the main structure with an assumed fixed base. In the vertical direction, however, the same ground causes a larger response (solid line in Figure 5(b)). The results show clearly that the common belief of beneficial effect of the supporting ground should not be followed because this belief is based on one factor which is insufficient to reflect the interaction of all participating factors.

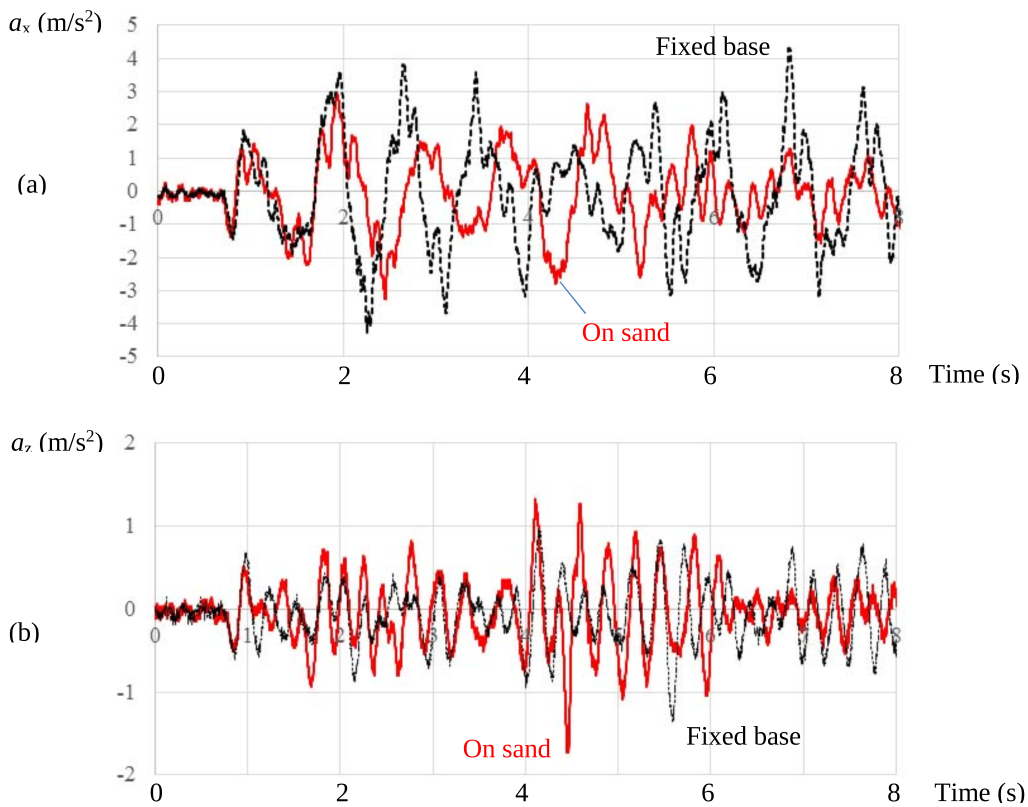

Figure 5. Influence of supporting soil on the top acceleration of the NSC (a) in the x-direction and (b) the vertical direction due to the horizontal ground excitation in the x-direction.

Influence of multi-axial ground excitation

Figure 6(a) shows the influence of a simultaneous horizontal and vertical ground excitation $a_{gx,y,z}$ on the acceleration at the top of the NSC in the x-direction (solid line). The sand support of the main structure is considered. A comparison with the response due to one axial x-component of the ground motion clearly shows a different result. A consideration of all components of the ground motion cause not only high-frequency components, but also a larger peak response. The results clearly show that a consideration of a single horizontal component of the ground excitation is insufficient to provide a realistic response. To have proper design of NSCs an all component consideration is necessary.

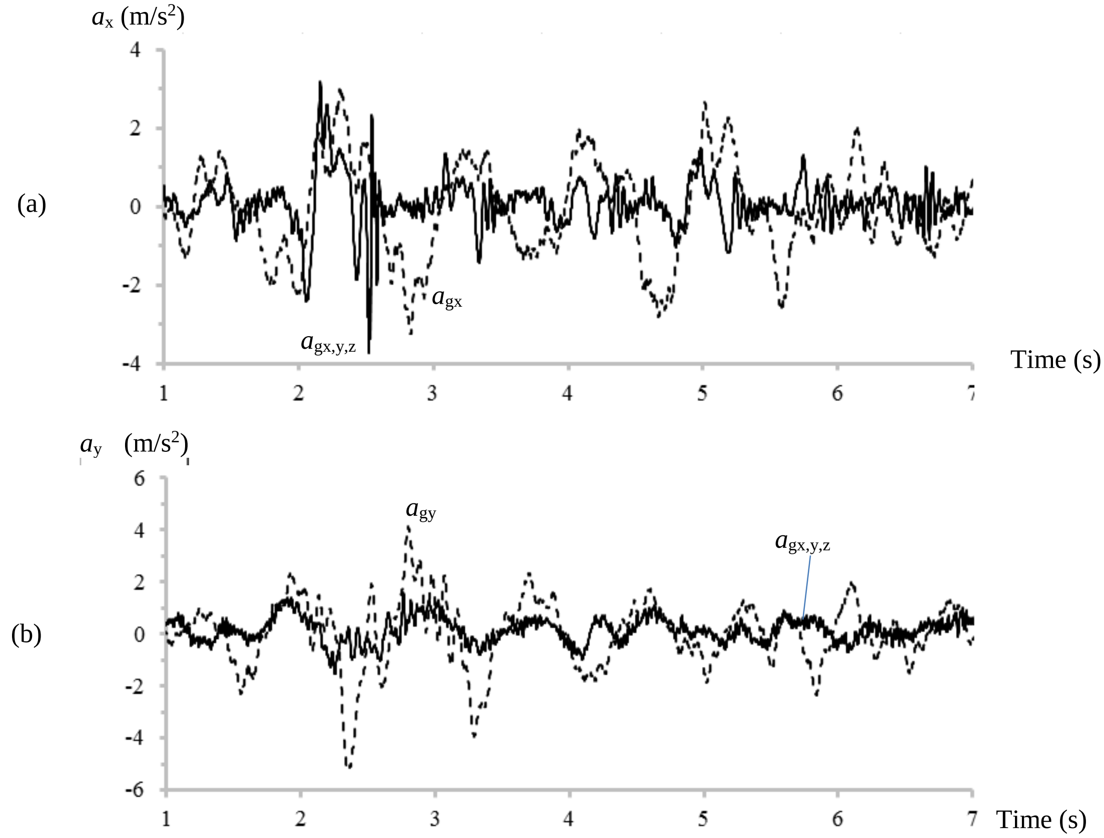

Figure 6. Influence of simultaneous three-directional ground excitation on the top acceleration of NSC in (a) the x- and (b) y-direction.

Figure 6(b) shows the corresponding response at the top of the NSC in the y-direction. In contrast, a consideration of all excitation components results in a smaller response (solid line), even though the high-frequency component is also clearly visible. The results show the influence of the multi-axial ground excitation is complex due to multiple influence factors, e.g. as a result of differently and simultaneously excited modes. The results also show that an adequate design can only be achieved when all components of the ground motion are incorporated in the analysis.

Simultaneous influence of soil and NSC-main structure interaction

Figure 7(a) shows the vertical displacement of the beam support of the NSC due to the x-component of the ground motion. The solid and dashed-dotted lines are the response with and without the NSC attached. The main structure is assumed to be fixed at the base. The results show that an attachment of the NSC cause a significant amplification of the response at the support location of the top beam of the main structure. The commonly used floor-spectrum approach, i.e. without considering the interaction between NSC and member of the main structure, will clearly underestimate the response.

Figure 7(b) displays the vertical displacement at the same location due to the same excitation. However, the main structure is placed on sand. The solid and dotted lines are also the response with and without an attachment of the NSC. The results also show that an attachment of the NSC increases the response. The response also has a different characteristic. As anticipated an attachment causes a lower-frequency response.

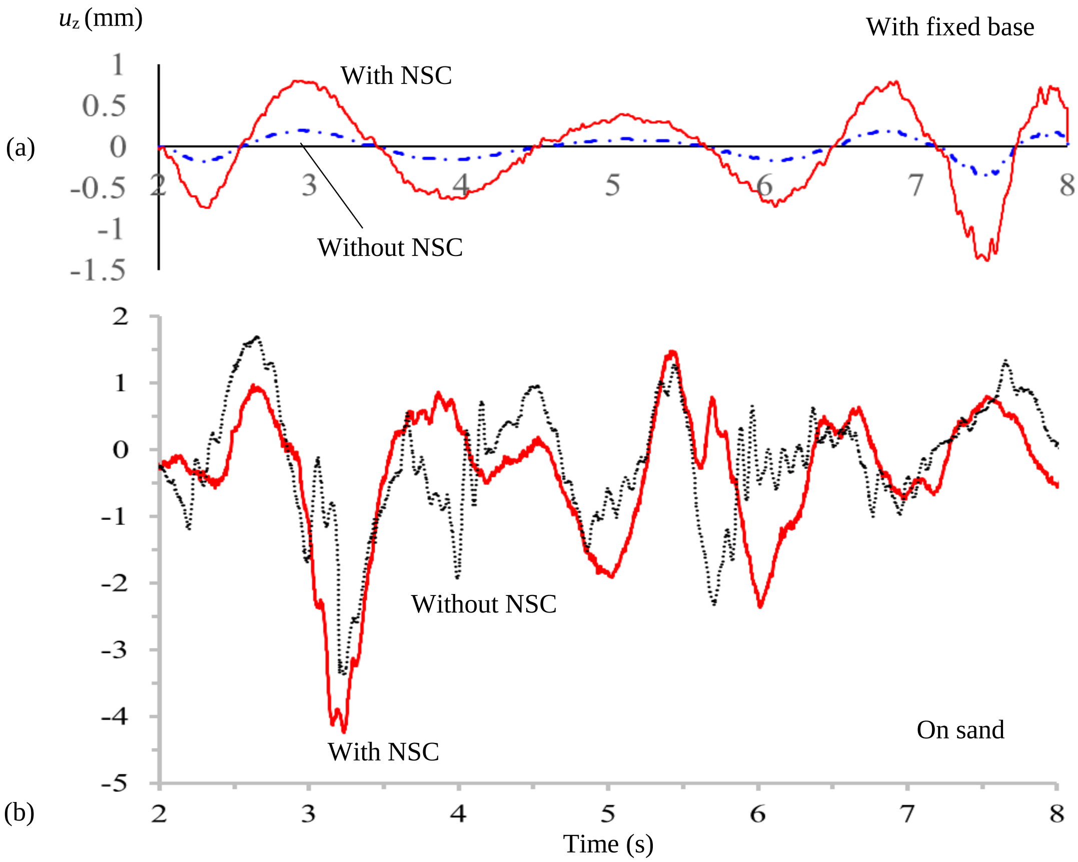

Figure 7. Influence of NSC and supporting soil on the vertical displacement at the NSC-main structure connection due to the horizontal ground excitation in the x-direction. Main structure with (a) an assumed fixed base and (b) on sand.

A comparison between Figures 7(a) and (b) clearly shows that without a simultaneous consideration of the interaction between the structural member of the main structure and the nonstructural component and the supporting ground a realistic design of the nonstructural component is not possible.

CONCLUSIONS

To reveal the consequence of multi-axial ground excitation, interaction between structural members of the main structure and nonstructural component and supporting ground for the response of nonstructural component a 1:4 scale four-storey building with a multiply supported component was tested using a large shake table. The ground motion considered was the ground motion recorded at the station of Japan Metrological Agency in the 1995 Kobe earthquake. To incorporate the influence of the supporting ground a box filled with wet sand was used. The main structure was placed on the sand. Transient and partial separation at the interface between the footing of the structure and the supporting soil was permitted.

In the cases considered, the results reveal:

1. A considering the supporting soil must not necessarily be beneficial. Depending on the direction and the component of the ground excitation considered the supporting soil can cause a larger response.
2. A consideration of only one component of the ground motion will not be sufficient to provide a realistic NSC response.
3. The interaction between the nonstructural component and the supporting member of the main structure can significantly increase the NSC response.
4. A simultaneous consideration of the NSC-main structure interaction and the supporting soil can further increase the NSC response.
5. The currently commonly used floor spectrum approach is inadequate for designing nonstructural components.

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