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Influence of simultaneous multi-axial ground excitation and a compliant base on the response of a non-structural component with multiple supports

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ABSTRACT

In an earthquake, non-structural components (NSCs) are subjected to vibrations coming from the ground through the main structure. Proper design of non-structural components should therefore include the interaction between main structure and the NSC as well as the influence of the surrounding soil, especially when the vertical component of the ground motion is considered. To simulate the system holistically, the multi-axial excitation has to be incorporated in the analysis. To date, only few research has explored the simultaneous influence of these factors. In this work, large-scale shake table experiments were performed to understand the response of a non-structural component attached at three locations on a main structure under the simultaneous influence of the interaction between main structure and non-structural component, multi-axial excitations and supporting soil. The excitation considered is a ground motion recorded in the 1995 Kobe Earthquake. The influence of each factor, separately and simultaneously, will be explicated.

1. Introduction

The importance of seismic analysis of non-structural components (NSCs) and secondary structures has been widely acknowledged by researchers and professional engineers in recent decades [1–3]. Post-earthquake observations have also provided multiple examples of severe implications of NSC failures [4–6]. 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 [7,8]. Secondary structures on the other hand, comprise load-bearing elements that are not carrying load in a particular direction [9]. Examples of NSC include roof-mounted air conditioners, generator sets, and shelving units inside buildings. Out-of-plane masonry wall, on the other hand, is considered secondary structure.

In this study, the experimental model includes a representative of an NSC with three supports. The term *primary-secondary structure interaction* (PSSI) is used for describing the interaction occurring at the interface between the NSC and the supporting main structure. While this interaction also occurs between secondary and primary structures, the PSSI described in this study is more appropriate for NSCs than secondary structures.

In some countries, NSCs are generally not designed to withstand external load, making them especially vulnerable [10]. As a consequence of inadequate design, seismic loads often lead to NSC detachment, damage, and injury or loss of life. Thus, property damage and life hazards due to failures of NSCs are major concerns [8,11–12].

The challenge in proper designs of NSCs lies mainly in the complex interaction between themselves and the supporting structures (PSSI) [2,13]. Past numerical and experimental investigations have established that PSSI affects the response of both the NSC and main structure during earthquakes [14–18]. PSSI depends on the dynamic properties of the main structure and NSC, as well as the characteristics of the loading [19,20]. In the case of multi-storey structures, different location of the NSC also influences PSSI, and consequently the structural response [21]. Quantifying PSSI has been difficult due to the wide array of objects and possibilities of NSCs in a building; each of them having different interaction with the main structure. To make matters worse, the interaction of one NSC could also potentially affect that of the other NSC [22,23].

During the past three decades, numerical analysis on NSCs considering PSSI focused mostly on elastic linear structures [16–19]. Closed form solutions to estimate the response of the secondary structure including the influence of PSSI had been developed. Most of the solutions, however, is not applicable for nonlinear cases. Meanwhile, in addition to PSSI, the main structure will also interact with the supporting soil. This interaction is known to affect the response of structures in earthquakes. Some studies and post-earthquake observations have emphasised that it benefits the main structure [24,25]. However,

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how the supporting soil affects the response of the NSCs attached to the main structure has not been reported as indicated in [2,26]. Although some studies such as [27,28] considered the inelastic behaviour of structures in developing floor response spectra approach for NSCs, none have considered the soil support. PSSI was also often ignored.

Most experimental studies on the response of both NSC and main structure consider only the response in the weak axis of the structure (or that of the NSC). This consideration was mainly taken due to limited resources and facilities that can perform multi-axial excitations on experimental models. The hypothesis is that the structure will likely experiences the largest response in its weak axis. This thought, however, has not been adequate. Nevertheless, recent advances in technology have made it possible to investigate the influence of simultaneous multi-directional excitations on the response of structures through physical experiments. This study particularly addressed the influence of multi-directional excitation, PSSI, and supporting soil on the response of both the NSC and the main structure, both individually and simultaneously. The results presented in this paper will showcase for the first time a simulation of main structure including the supporting soil and NSC as a whole system.

2. Methodology

2.1. Experimental model

A 1:4 scale four-storey building model with a simplified NSC supported at three locations was constructed and tested to reveal the simultaneous influence of PSSI and supporting soil on the structural response. Two support conditions of the main building were considered: (i) assumed fixed base, and (b) founded on sand. For a fixed-base assumption, the structure was bolted directly on a shake table. The shake table allows experimental study on the simultaneous effect of vertical and horizontal multi-axial excitation on the response of the non-structural component. The large 4 m × 4 m shake table with a payload of 30 tonnes is at the National Engineering Laboratory for High Speed Railway Construction, Central South University, Changsha in China.

The scaling and modelling approach adopted for the model was described in [29–31]. The particular approach is selected because the authors intend to study the effect of structures with uplift capability on non-structural components, i.e. by placing the main structure on sand in a box. The approach allowed for a predefined mass to enable a simulation of structures with uplift capability. The scale factors and dimensions of the parameters considered are listed in Table 1. Using this scaling approach, the length, mass and time scale factors are predefined (values in bold).

A frequency parameter is introduced in the selected dimensionless parameters based on Buckingham's π theorem. This parameter is needed to fulfil the similitude requirement of a structure with uplift capability.

Fig. 1 illustrates the experimental model placed on a sand box to simulate the influence of supporting soil. For convenience in describing the result, the convention for the two horizontal axes is defined in Fig. 1. The NSC was attached in the strong axis (x-axis) of the main

Table 1
Scale factors and dimensions of parameters considered.

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	$[T^{-1}]$	$\sqrt{N_a/N_l}$	1
Frequency	$[T^{-1}]$	$\sqrt{N_a/N_l}$	1

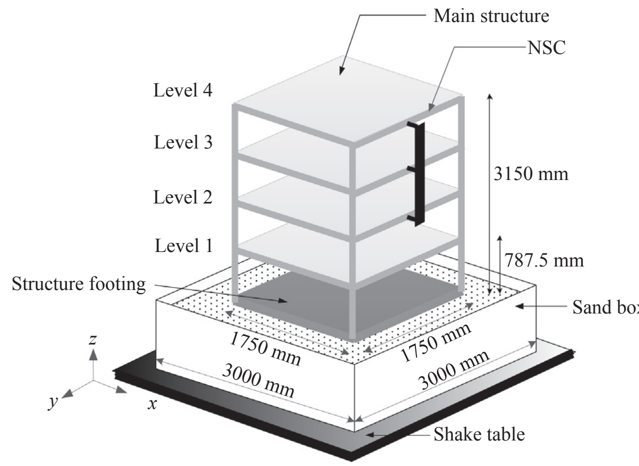

Fig. 1. Sketch of the experimental setup considering soil support.

structure. This was intended so that the weak axis of both the main structure and the NSC were both in the same direction (y).

The model of the main structure is an elastic four-storey three-dimensional steel building. The fundamental frequencies of the structure with an assumed fixed base are 6 Hz and 1.86 Hz in the strong (x) and weak (y) axes, respectively. The vertical frequency of the beam of the main structure is 26 Hz. The damping ratio was obtained from the average decay rate from five free vibrations. Other relevant dynamic properties of the main structure are given in Table 2.

The non-structural component was a slender frame with three supports as shown in Fig. 2. Each support was bolted onto the beam of the main structure, as illustrated in Fig. 1. The columns of the frame are made of PVC with a square 16 mm × 16 mm cross-section. The dimension of the columns is not specifically targeted as a scale-down of any particular NSC but rather to achieve specific dynamic properties, i.e. mass and frequency ratios that represent actual NSCs. The mass m_s is made of a rigid steel block of 24 kg. The natural frequencies f_s are 8.6 Hz and 17 Hz in the vertical and y-direction, respectively. The NSC is considered rigid in the x-direction due to the high axial stiffness of PVC columns compared to its bending stiffness. The damping ratio ξ_s of the NSC was 2.5% in both directions, obtained from five free vibrations of the NSC performed separately from the main structure. The dimensions of the NSC are shown in Fig. 2(a). In actual scale, this configuration represents possible NSCs with multiple supports, e.g. building façade and advertisement boards. Strain gauges and accelerometers were installed, and laser transducers were pointed at the NSC to obtain the bending moment, acceleration, and displacement of the NSC, respectively. The locations of the devices are illustrated in Fig. 2(a) and (b).

The mass and frequency ratios of the NSC to the main structure are shown in Table 3. Past numerical research [10,32] suggested that PSSI can be negligible for an NSC that weighs less than 10% of the floor

Table 2
Dynamic properties of the main structure.

Properties	Notation	
Inter-storey height	h_p	787.5 mm
Building height	h_{total}	3.15 m
Footing area	A_f	1750 mm × 1750 mm
Footing height	h_f	22 mm
Footing mass	m_f	295 kg
Floor mass (Level 1–3)	m_p	272 kg
Roof mass	m_{roof}	227 kg
Damping ratio in both directions	ξ_p	4%
Fundamental frequencies	$f_{p,weak}$	1.86 Hz
	$f_{p,strong}$	6 Hz
	$f_{p,vertical}$	26 Hz