Consequence of main-secondary structures interaction for seismic response of secondary structures

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ABSTRACT: Current seismic design practice for secondary structures is mainly based on loadings obtained from floor response spectra. However, observations in previous earthquake events, e.g. the 1994 Northridge and the 2011 Christchurch earthquakes, have revealed that a large number of secondary structures were severely damaged in the aftermath. This suggests that the floor response spectra approach might not be sufficient for proper design of secondary structures. In this study, an experimental work was performed to quantify the actual response of a secondary structure by considering the interaction between main and secondary structures. The main structure considered was an elastic single degree-of-freedom (SDOF) system. Fixed on the primary structure was an elastic SDOF secondary structure of a relatively higher frequency and considerably smaller mass. Numerical analyses on a similar shear frame setup were also conducted for comparison. For the case considered, the maximum accelerations of the secondary structure were significantly higher compared to the acceleration of the main structure. The secondary structure response also exceeded the maximum acceleration predicted by floor response spectra calculated from both experimental and numerical results. As anticipated, the effect of the main-secondary structure interaction was found to be more pronounced in the response of the secondary structure.

1 INTRODUCTION

Secondary structures are the elements of a building facility that are not part of the primary load-bearing structural members. Secondary structures include non-structural components on a building, such as façades, ceilings, piping systems; large objects in a building, such as furniture, museum collections, computer systems, communication equipment, and other crucial machinery. Depending on the connections to the main structure, transfer of loads from the ground motions through the main structure may have significant effects on secondary structures. Because secondary structures are usually not designed to bear extreme loads, they are particularly vulnerable during earthquakes (e.g. Villaverde 1996; Chen and Soong 1988, Naito and Chouw 2003, Chen et al. 2013). Detached heavy secondary structures may incur impact loads to the main structure, damage valuable properties, or even present threats to life safety. Damage to secondary structure itself may also cause buildings to lose their functionalities after strong earthquakes. This is an important consideration, particularly in the case of public utilities such as power stations, hospitals, and fire departments that need to be functional during and after earthquakes.

In the 1994 Northridge Earthquake, broken sprinkler pipes in a hospital had forced evacuation of patients in the hospital and prevented it from functioning as a first-aid facility in the aftermath (FEMA273 1997). Damaged parapets and canopies from buildings after the 2011 Christchurch earthquake had obstructed roads and walkways and damaged primary structures and nearby vehicles. In the 1995 Kobe earthquake, failure of secondary structures had even caused loss of life (Chouw 1995). For valuable secondary structures such as data acquisition systems and museum collections, damage to secondary structures could incur severe economic consequences or loss of valuable artefacts. Thus, the importance of preserving secondary structures as well as the main structure after earthquake necessitates proper seismic design of secondary structures.

Early seismic analysis method for secondary structures was the floor response spectrum approach. The floor response spectrum approach applies the floor response spectrum of the main structure as a design spectrum for the secondary structure in the same manner as the ground spectrum to the main structure. This approach was later considered inaccurate because it neglected the main-secondary structure interaction. Current seismic design codes still apply the floor response spectra approach, combined with the commonly used equivalent lateral force method. Usually, the main objective for the design of secondary structures is still limited to providing sufficient joints between the main and secondary structures in order to withstand the induced vibrations, without allowing the components to overturn. The integrity of the secondary structure is of no particular concern (Gillengerten 2001).

Many researchers, e.g. Igusa and Kiureghian (1985a-c) Asfura and Kiureghian (1986), have performed extensive numerical studies in order to accurately determine the seismic response of secondary structures. Their studies concluded that the actual response of secondary structures is influenced by a feedback effect, i.e. the effect of the interacting forces induced in the main-secondary structure interface from the relative movements between the two subsystems.

Although many numerical investigations have been conducted to account for the influence of these three factors, experimental work to validate the numerical models are still limited and fragmented.

This paper discusses the effect of secondary structure on the responses of the main and secondary structure through both experimental and numerical analyses. The experimental results are discussed first, followed by comparison to the corresponding numerical predictions. The results are focused on the acceleration of each subsystem as an indication of the main-secondary structure interaction. Floor response spectra are generated to evaluate the reliability of the response spectrum approach for the case considered.

2 EXPERIMENTAL SETUP AND DATA ACQUISITION

The experimental model consisted of an elastic fixed base single degree-of-freedom (SDOF) main structure and an SDOF secondary structure that was rigidly fixed to the top of the main structure (Figure 1). The main structural frame has the fundamental mode of a four-storey building prototype with 1:15 scale. The dynamic properties of the main structure and the secondary structure are shown in Table 1.

Table 1. Structural properties of the two subsystems

	Main structure			Secondary structure		
Effective height	h_m	575	mm	h_s	45	mm
Mass	m_m	57	kg	m_s	0.967	kg
Fundamental frequency	fn_m	1.51	Hz	fn_s	12.5	Hz
Fundamental period	Tn_m	0.662	s	Tn_s	0.08	s
Stiffness	k_m	5130.84	N/m	k_s	5964.94	N/m
Damping ratio	ξ_m	4.8	%	ξ_s	6.52	%
Damping coefficient	c_m	52.74	Ns/m	c_s	9.9	Ns/m

Significantly higher frequency and smaller mass (compared to those of the main structure) were assumed for the secondary structure to represent a realistic case. Damping ratios of each subsystem were calculated separately from the decay rate of the corresponding free vibrations of the two subsystems.

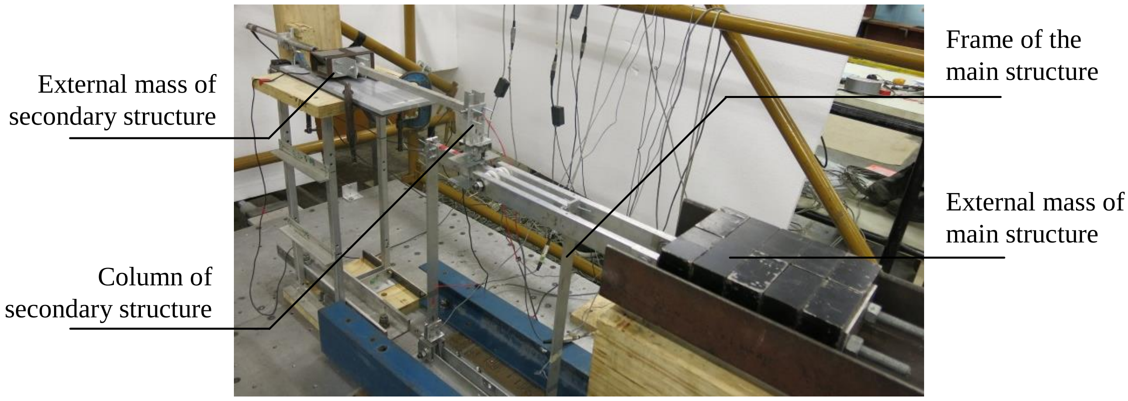

Figure 1. Experimental setup

The stiffness of the main structure was defined by the two columns of the frame, and the stiffness of the secondary structure was defined by the secondary column on top of the frame. The mass of each frame was relatively small compared to the mass of each subsystem. For simplicity, the columns are considered to be massless. The inertial force in the system was assumed to be from the masses only. Damping ratios ξ_p and ξ_s for each subsystem were controlled to be within realistic damping ratio range for actual structures.

Accelerations in the main structure and the secondary structure were recorded by using accelerometers located at the frame of the main structure and at the mass of the secondary structure. Strain gauges were attached at the lower ends of the main and secondary structure columns to measure the bending moments occurred in each subsystem. A draw wire and a linear variable differential transformer (LVDT) were used to measure the lateral displacement at the top of the main and secondary structure, respectively.

An earthquake motion shown in Figure 2 is simulated based on the Japanese design spectrum (JDS) for hard soil condition (JSCE 2000).

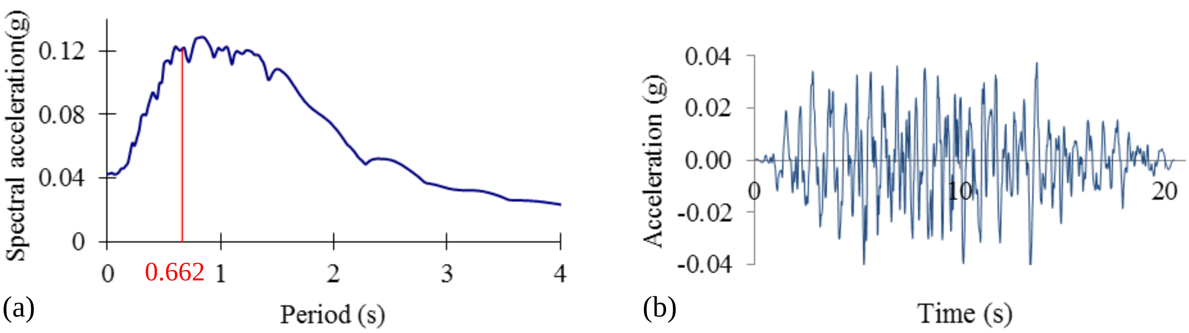

Figure 2. Ground motion characteristics, (a) response spectrum (b) ground acceleration time history

Shake table tests were performed for two configurations: (1) main structure only, and (2) main structure with secondary structure.

Floor response spectra were calculated from the measurements of acceleration at the top of the main structure, with and without secondary structure. The results were then compared to the numerical predictions for the same configuration.

3 NUMERICAL ANALYSIS

Numerical analyses to estimate the response of both the main and secondary structures were performed using Newmark's integration method for linear system as described in literature, e.g. in Chopra (2011). The algorithm is a time-stepping methods used for integration of differential equations developed by Newmark in 1959. The basic principle of the method follows these equations:

$$\dot{u}_{i+1} = \dot{u}_i + [(1-\gamma)\Delta t]\ddot{u}_i + (\gamma \Delta t)\ddot{u}_{i+1} \quad (1)$$

$$u_{i+1} = u_i + \Delta t \dot{u}_i [(0.5-\beta)\Delta t^2]\ddot{u}_i + (\beta \Delta t^2)\ddot{u}_{i+1} \quad (2)$$

Numerical analyses were performed for two cases: (1) without secondary structure, i.e. SDOF main structure only, and (2) with secondary structure. For the case with secondary structure, the system was simulated as a two degree-of-freedom shear structure. The dynamic properties used for this simulation were based on the combination of the two subsystems (Equation 3):

$$M = \begin{bmatrix} m_m & 0 \\ 0 & m_s \end{bmatrix} kg \qquad K = \begin{bmatrix} k_m + k_s & -k_s \\ -k_s & k_s \end{bmatrix} N/m \qquad C = \begin{bmatrix} c_m + c_s & -c_s \\ -c_s & c_s \end{bmatrix} Ns/m \quad (3)$$

Subscripts *m* and *s* denote the dynamic properties of the main and secondary structure, respectively. All the values used correspond to the values in the experimental model as shown in Table 1.

4 RESULTS AND DISCUSSION

4.1 Response of the secondary structure

The response of the secondary structure was quantified in terms of acceleration. Figure 3 compares the horizontal acceleration at the top of the secondary structure from experimental measurement and numerical prediction.

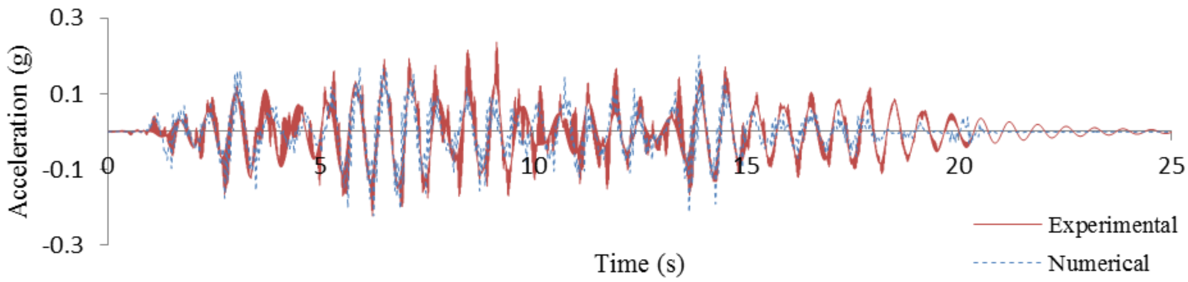

Figure 3. Acceleration at the top of the secondary structure

4.2 Response of the main structure

Acceleration at the top of the main structure with and without secondary structure acquired from experiments and numerical analyses are presented in Figures 4 and 5, respectively.

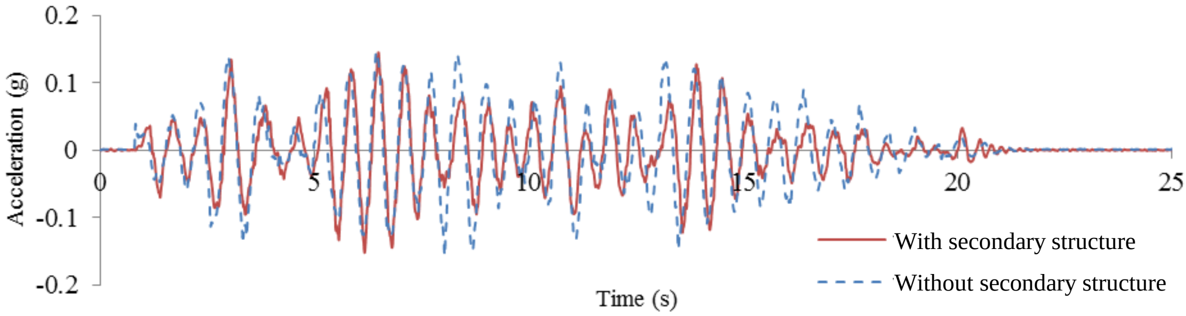

Figure 4. Acceleration at the top of the main structure measured in experiments

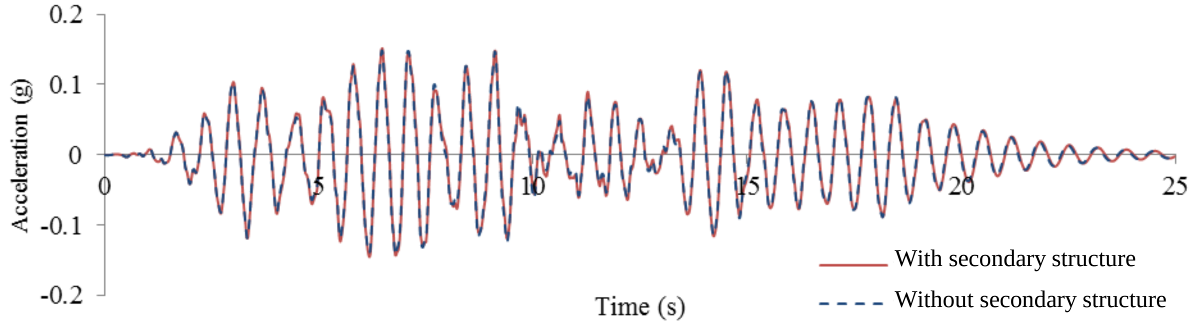

Figure 5. Acceleration at the top of the main structure obtained from numerical analysis

Table 2. Maximum acceleration at each subsystem

Location	Experimental measurement	Numerical calculation
Top of the main structure (without secondary structure)	0.1570 g	0.1481 g
Top of the main structure (with secondary structure)	0.1524 g	0.1532 g
Secondary structure (from Figure 3)	0.2389 g	0.2224 g

For the case considered, the maximum acceleration at the top of the secondary structure was significantly higher compared to the maximum acceleration of the main structure, for both with and without secondary structure cases. This suggests that the main-secondary structure interaction affects the secondary structure more prominently than it affects the main structure. The accelerations at the top of the main structure, with and without secondary structure, were almost identical for the numerical predictions. However, considerable differences were observed from the experimental results (Figure 4). These differences could be attributed to the actual damping in the system that cannot be adequately described by the viscous damping used in the numerical calculations. With this effect, the system with secondary structure appeared to have a lower overall acceleration compared to the case without secondary structure, as shown in Figure 4.

The measured maximum bending moments at the lower end of the main structure were 90.95 Nm and 88.63 Nm, without and with secondary structure, respectively.

For the combined system, the fundamental period of vibration T_n and the corresponding fundamental frequency of vibration f_n were predicted numerically as follows:

$$T_n = \begin{bmatrix} 0.6679 \\ 0.0793 \end{bmatrix} s \qquad f_n = \begin{bmatrix} 1.4972 \\ 12.6071 \end{bmatrix} Hz$$

4.3 Evaluation of floor response spectrum approach

Figure 6(a) shows the floor response spectra calculated by using the measured acceleration at the top of the main structure, with and without secondary structure. Figure 6(b) shows another set of floor response spectra generated by using numerically predicted accelerations at the top of the main structure, for the SDOF main structure (without secondary structure) and the 2-DOF system (with secondary structure). The damping ratio and fundamental period used were the values of the secondary structure, $\xi_s = 6.52\ \%$ and $T_n = 0.08\ s$, in Table 1.

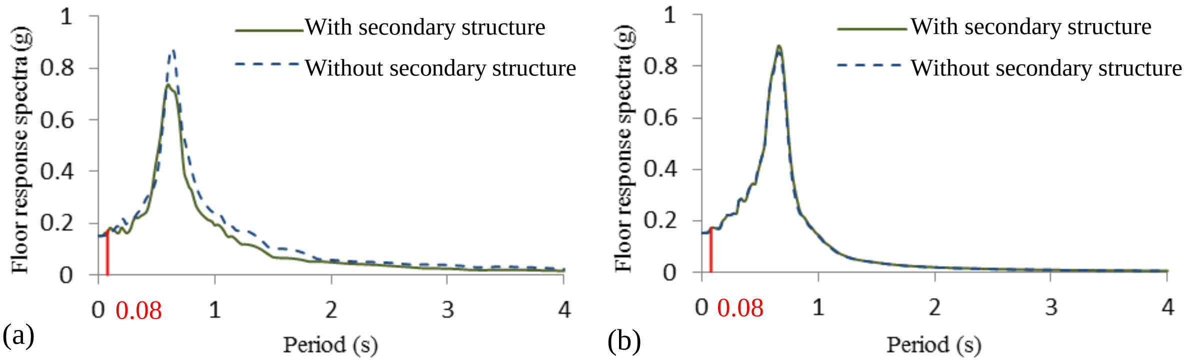

Figure 6. Floor response spectra from (a) experimental data and (b) numerical prediction

The maximum accelerations of the secondary structure predicted using floor response spectra were listed in Table 3.

Table 3. The maximum acceleration of the secondary structure obtained from experimental and numerical results

Subsystem	Using experimental data	Numerical prediction
without secondary structure	0.1564 g	0.1629 g
with secondary structure	0.1631 g	0.1714 g

As shown in Table 2, the measured maximum accelerations at the top of the secondary structure were 0.2389 g (measured) and 0.2224 g (calculated using the 2-DOF system) Both these values exceeded the maximum acceleration predicted by using floor response spectra. Thus, analysis using floor response spectra significantly underestimates the measured maximum acceleration at the top of the secondary structure.

5 CONCLUSIONS

Experiments were carried out to investigate the behaviour of main and secondary structures under seismic loading, and how they interact with each other. Numerical analyses were also performed for comparison. Effects of the main-secondary structure interaction were characterized in terms of acceleration of each subsystem. For the case considered, this study has revealed that,

1. Accelerations at the top of the secondary structure were considerably higher compared to the acceleration at the top of the main structure.
2. Differences in the measured accelerations of the main structure with and without secondary structure may be attributed to the damping behaviour in the experimental system that cannot be adequately described by a viscous damping used in the numerical calculations.
3. Floor response spectra were not capable of accurately predicting the maximum accelerations in the secondary structure.

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