The Effect of Foundation Uplift and Plastic Yielding on Induced Seismic Vibration of Secondary Structures

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ABSTRACT: Previous research has shown that footing uplift can reduce the strength demand of structural members in strong earthquakes. However, foundation uplift is normally excluded in conventional design. Within the engineering community there are concerns about the effect of foundation uplift on secondary structures, especially in ensuring the functionality of essential facilities. Currently only a few experimental studies have measured the induced seismic acceleration of structures with footing uplift. In this paper measured accelerations in three dimensions at different locations of a scaled six-story building are presented and discussed. The model is subjected to scaled earthquake motion, simulated from NZS 1170.5, using a shake table. Artificial plastic hinges were utilised to simulate the nonlinear action of structural elements. Micro-electro-mechanical system (MEMS) accelerometers were placed on the four corners of each floor. Measurements were made of the response of the structure with two support conditions, i.e. 1) fully fixed to the shake table and 2) uplift of the structure possible. The vibrations of the structure with both support conditions are described and recommendations are made for the design of secondary structures.

1 INTRODUCTION

The benefit of footing uplift on structural seismic performance was recognised in the early 1960's. Housner (1963) reported on the good performance of several elevated water tanks in the 1960 Chile earthquake. In this pioneering work he initiated the study of structural uplift using a rectangular rigid free standing block. In 21st century more experimental investigations of models with footing uplift have been conducted. Midorikawa et al. (2006) carried out shake table tests on an elastic three story steel frame with column uplift. A yielding base plate was installed that allowed uplift. The work established that the column base shear was significantly reduced when uplift was allowed. Hung et al. (2011) performed pseudo-dynamic and cyclic loading tests on bridge piers with and without a plastic hinge. The experimental results indicated that uplift can reduce the ductility demand of a structure. Ormeno et al. (2013) investigated liquid storage tanks with fluid-structure interaction including uplift and Loo et al. (2012) considered the beneficial effect of uplift on a wall.

Although the benefit of uplift is well recognized, usual seismic design practice does not support this action. One of the main concerns is the effect of uplift on the performance of secondary structures (Tingatinga & Arriesgado, 2012). A limited number of studies on induce vibration of secondary structures has been conducted. The Yao (1998) study investigated the rocking behaviour of secondary structures, e.g. book stacks in libraries and overturning of equipment in a power station, and suggested possible mitigation measures. Qin et al. (2013) performed a series of shake table tests on a single-degree-of-freedom model with uplift and a plastic hinge. They found concurrent uplift and plastic hinge development produced a mitigating effect on induced vibration. The research discussed in Yao (1998) and Qin et al (2013) focuses on the response in the direction of excitation only.

In order to reveal the effect of uplift on induced vibrations in three orthogonal directions, shake table tests on a three-dimensional six-storey model have been performed. The model was subjected to a uni-directional horizontal ground motion simulated to conform to a design spectrum from NZS

1170.5. Two support conditions were considered: 1) fixed at the base to the rigid shake table platform and 2) with uplift permitted. Artificial plastic hinges were used to simulate the damage to the structure during earthquake shaking. MESE based accelerometers were attached to the four corners of each floor to measure acceleration along the three principal axes of the structure. The peak accelerations and response spectra of each floor are discussed in this paper.

2 METHODOLOGY

2.1 *Experimental Model*

The 1/15 sized model used in this study is based on a prototype six-storey steel office building and the properties are shown in Table 1. The fundamental frequency of the prototype in the excitation direction is 1.24 Hz. The scaling is based on the Buckingham π theorem (Buckingham, 1914) and follows the modified Cauchy Number developed in the work of Chen et al. (2012), as described by Equation 1.

$$\pi_1 = \frac{a \times m}{l \times k} \text{ and } \pi_2 = \frac{\mathrm{E} \times l^2}{m \times a} \qquad (1)$$

where a is acceleration, m is mass, l is length, k is lateral stiffness in the direction of the applied motion and E is Young's modulus.

Table 1. Properties of the prototype

Beams	410UB53.7	**Concrete slab**	170 mm thick
Columns (level 1 to 3)	310UC158	**Lateral stiffness (level 1 to 3)**	4.44E7 N/m
Columns (level 4 to 6)	310UC118	**Lateral stiffness (level 4 to 6)**	3.21E7 N/m
Footing dimension	6 m*8m	**Seismic mass (level 1 to 5)**	40.8 tonnes
Floor area	48 m^2	**Seismic mass (level 6)**	35.5 tonnes

The seismic mass and lateral stiffness are scaled down 4800 and 1200 times respectively. Only the stiffness in the excitation direction (x, as indicated in Figure 1) has been correctly scaled in the experimental model. PVC was used to constructed the columns (E_{PVC} = 2.5 GPa and E_{steel} = 200 GPa), and aluminium angle sections were selected to simulate the rigid beams. The dimensions of the model are shown in Figure 1.

Artificial plastic hinges were constructed and placed in the structure as highlighted in Figure 1. These hinges were located at the support and beam-column joints of the frames on the x-z plane. The moment capacity of each plastic hinge was controlled by applying a 5 Nm torque with a torque wrench. A torque of 20 Nm was applied to perform elastic analyses because this was sufficient to prevent any plastic hinge development. Rotational sliding will take place once the bending moment reaches the capacity of a hinge, thus simulating structural damage. Teflon washers were placed as shown in Figures 1b and c to aid in the repeatability of the artificial hinge performance.

To reveal the effect of structural uplift, the structure was placed free standing on the shake table platform. To minimise sliding in the free to uplift case, sand paper was attached to the top of the rigid platform and the bottom of the foundation to increase the friction between the contact surfaces.

2.2 *MEMS based accelerometers*

MEMS based accelerometers (Fig. 1a) have been widely used in different industries, e.g. aerospace, automotive and computer manufacturing. In Beskhyroun and Ma's (2012) work, these accelerometers were used to monitor building performance in Christchurch during the aftershocks of a major 2011 earthquake. These accelerometers record acceleration in 3 orthogonal directions and in this project a sample and store rate of 320 Hz was selected. MEMS based accelerometers have issues of drift in real time, delay in data acquisition and fluctuation of the sampling rate. In order to reduce these issues to an acceptable level a Matlab programme (Beskhyroun & Ma, 2012) was adopted to correct the records.

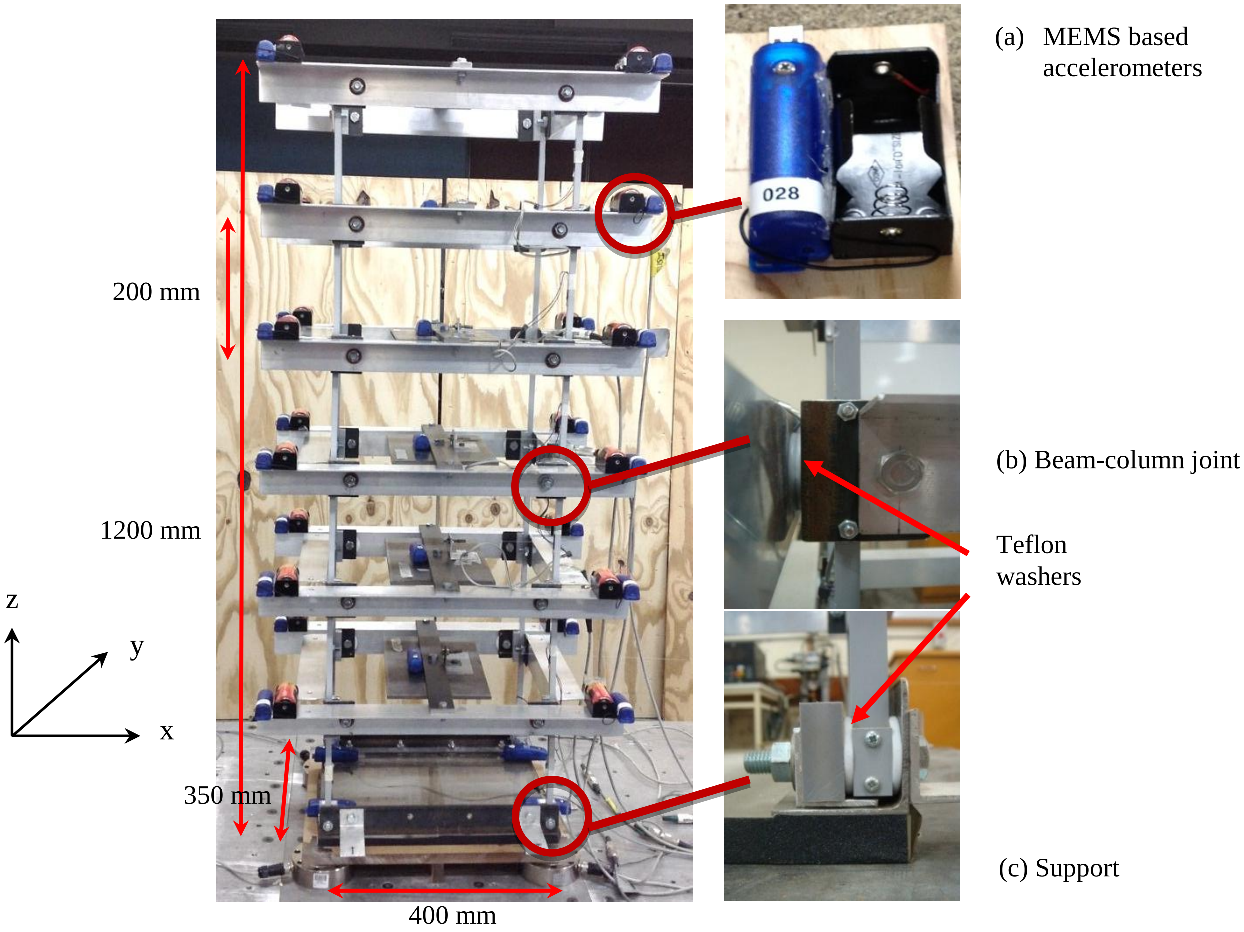

Figure 1. Experimental model with MEMS based accelerometers attached

2.3 *Ground motion*

Since gravity cannot be scaled, the effect of structural weight on the model will be l (15) times larger than that on the prototype. The effect of a correct gravity scaling of the small-scale experimental model was not considered, although an over weighted structure will significantly restrict uplift. Instead of preserving the correct relationship between horizontal and vertical acceleration, a time scale factor of two was selected to arrive at a scaling factor for horizontal acceleration using Equation 2 (Chen et al., 2012). The use of Equation 2 results in the applied horizontal ground acceleration being scaled by a factor of 3.75. The fundamental frequency of experimental model is 2.48 Hz.

$$\pi_3 = t\sqrt{\frac{a}{l}} \qquad (2)$$

where t is time, a is horizontal acceleration and l is length.

The unscaled ground motion was developed using the procedure of Li et al. (2012) and was designed to match a subsoil class D site from NZS 1170.5 with maximum Z of 0.6 and return period 1000 years. The scaled time history and response spectrum of this motion, with a 5% damping ratio, is shown in Figure 2. The predominant period of this ground motion is approximately 10 Hz.

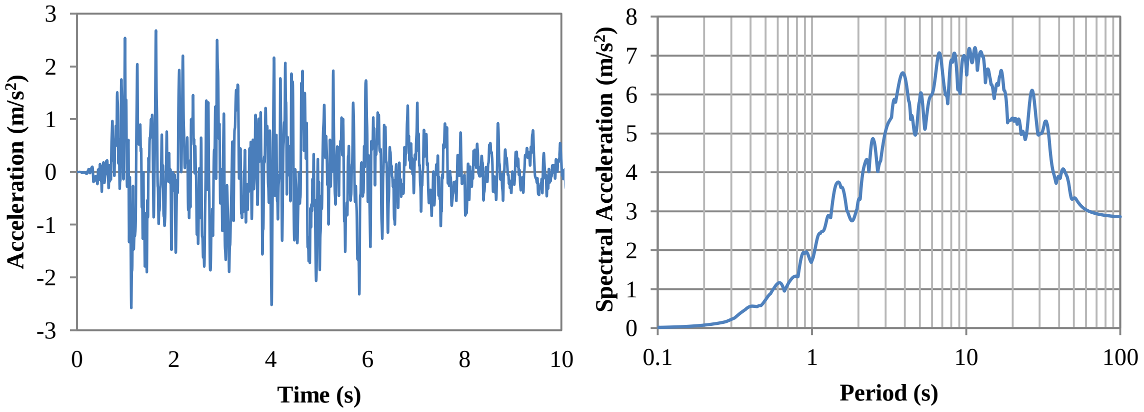

Figure 2. Scaled ground motion, (a) acceleration time history and (b) its response spectra

3 RESULTS AND DISCUSSION

3.1 *Peak accelerations*

The accelerations recorded on the back corners of the left hand side of the structure shown in Figure 1 are presented in this section. The maximum recorded accelerations were normalised by the maximum *x* component of the shake table acceleration recorded during the test and are shown in Figure 3. The results show that the accelerations in the excitation direction, *x*, are approximately four times larger than in the other two directions.

The peak accelerations in the *x* direction increases with height as shown in Figure 3a. It may be seen that the fundamental mode has the dominant contribution. Comparing the four cases, the strongest response can be observed when there is footing uplift of an elastic structure. These strong accelerations are the result of large foundation rotations increasing the horizontal displacement of each floor at the instance of uplift. Since the increment of displacement associated with uplift is approximately proportional to the floor height, the difference of the normalised maximum acceleration between the uplift elastic case and the other cases increases with height. However, when both plastic hinge development and footing uplift occur, the footing rotation is significantly reduced. Thus, small induced accelerations are recorded .

A comparison of accelerations in the *y* direction (Fig. 3b) shows the effect of in-plane plastic hinge development and footing uplift on out-of-plane vibration. Both uplift and plastic hinge development reduce the response in the out-of-plane direction. The reduction is more significant when plastic hinge rotation occurs. However, only an acceleration in *x* direction was applied and thus any contribution to uplift from an applied acceleration in the *y* direction was not involved. The beneficial effect of uplift on induced acceleration in the *y* direction may not be observed if uplift in this direction occurs. Further investigation should be carried out.

The largest accelerations in the *z* direction were measured with an elastic structure with uplift (Fig. 3c). The maximum vertical acceleration at the top is nearly the same as the maximum applied horizontal acceleration. These strong accelerations are induced by large footing rotation. A comparison of the response of structures fixed at the base shows that plastic hinge development will also slightly increase the vertical accelerations. This small increment is due to the very small rotation of beam-column joints.

Considering the responses in three directions shown in Figure 3, the beneficial effect of combining plastic hinge development and footing uplift on induced vibration can be observed.

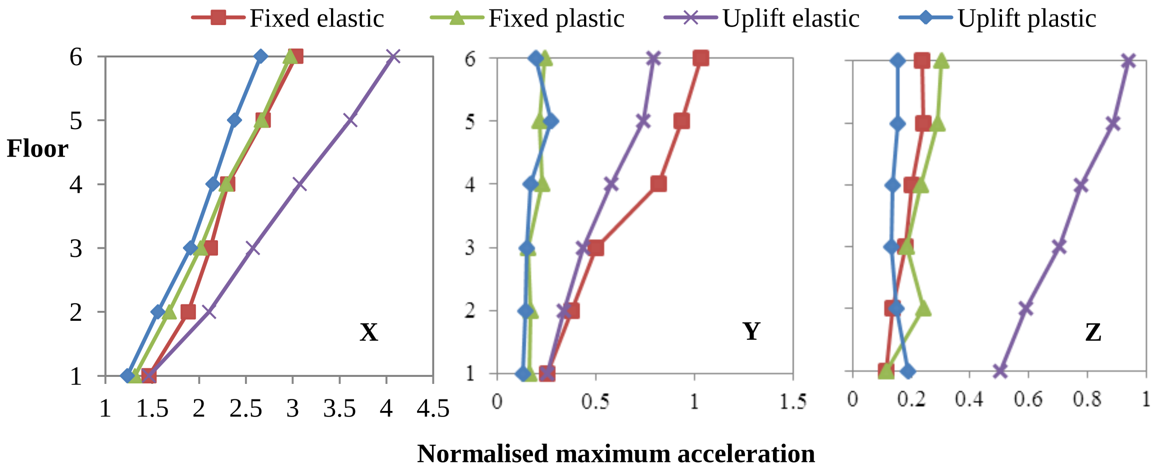

Figure 3. Normalised maximum acceleration of each floor

3.2 *Response spectra*

Response spectra were computed in order to reveal the effect of uplift and plastic hinge development on the frequency content of induced vibration. The response spectra, with 5% damping, based on the acceleration recorded on levels 1, 3 and 6 are shown in Figures 4 and 5. Figures 4 and 5 are the spectra of the *x* and *y* components, respectively. Generally speaking, the high frequency vibration is more pronounced on the lower floor of the structure, especially in the fixed base elastic case. The predominant frequency of induced acceleration on level 1 is 17.8 Hz, while that of the acceleration on level 6 is 2.5 Hz.

As illustrated by the response in the excitation direction in Figure 4a and b, plastic hinge development reduces the spectral values of all frequency components. It also shifts the predominant frequencies of levels 3 and 6 responses from 2.5 Hz to 2.9 Hz, while that of the level 1 response remains the same. Seismic energy has been dissipated to overcome the friction of hinge. Only very small rotation of plastic hinge has been induced by this ground motion. Thus, the predominant frequencies slightly increase. Footing uplift has a similar effect on the predominant frequencies, as seen in Figures 4a and c, except that a shift of the first dominant frequency of level 1 also occurs. Table 2 shows the spectral acceleration at the first two dominant frequencies. Foundation uplift increases the spectral value at the fundamental frequency, but decreases those at the higher frequencies. Comparing the response of level 6, the spectral acceleration at the first dominant frequency shows an increase of 31.4% due to uplift. However, the spectral value at the second dominant frequency (8.0 Hz) is reduced by uplift from 11.4 m/s^2 to 9.6 m/s^2. Similar effects of uplift can also be seen on the response of levels 1 and 3. The smallest spectral values are observed when both uplift and plastic hinge development occurred, as shown in Figure 4d. The combined effect of uplift and hinge rotation on the frequency content of the response at all levels is close to the case where only plastic hinge development takes place.

Since the severity of induced vibration at the predominant frequency is significant for the higher floors of a structure with uplift, it is recommended that utilisation of a secondary structure with a natural frequency similar to the fundamental frequency of the primary structure should be avoided. If such a secondary structure has to be placed in the building, it should be located on the lower level if possible.

The *y* component accelerations, represented by response spectra, are shown in Figure 5. It is clear that the induce vibrations are reduced by uplift and plastic hinge development, especially those of levels 3 and 6. Table 3 summarises the predominant frequencies of induced vibration at different locations. Figures 5a and b, show that the plastic hinge development greatly increases the predominant frequencies of the level 3 and 6 vibrations (Table 3). Although uplift does not shift the predominant, it concentrates the energy over a more limited range of frequencies. The predominant frequency of level 6 is reduced from a range of 2.6 to 4.3 Hz to a value of 3.6 Hz (Fig. 5a and c, Table 3). A similar effect is also found with level 3.

Overall, the contribution of the higher frequency components increases when either uplift or plastic hinge development takes place. It is recommended that the primary axis of structural strength of the secondary structure should be aligned with the weaker structural axis of the primary structure when plastic hinge development and footing uplift are possible.

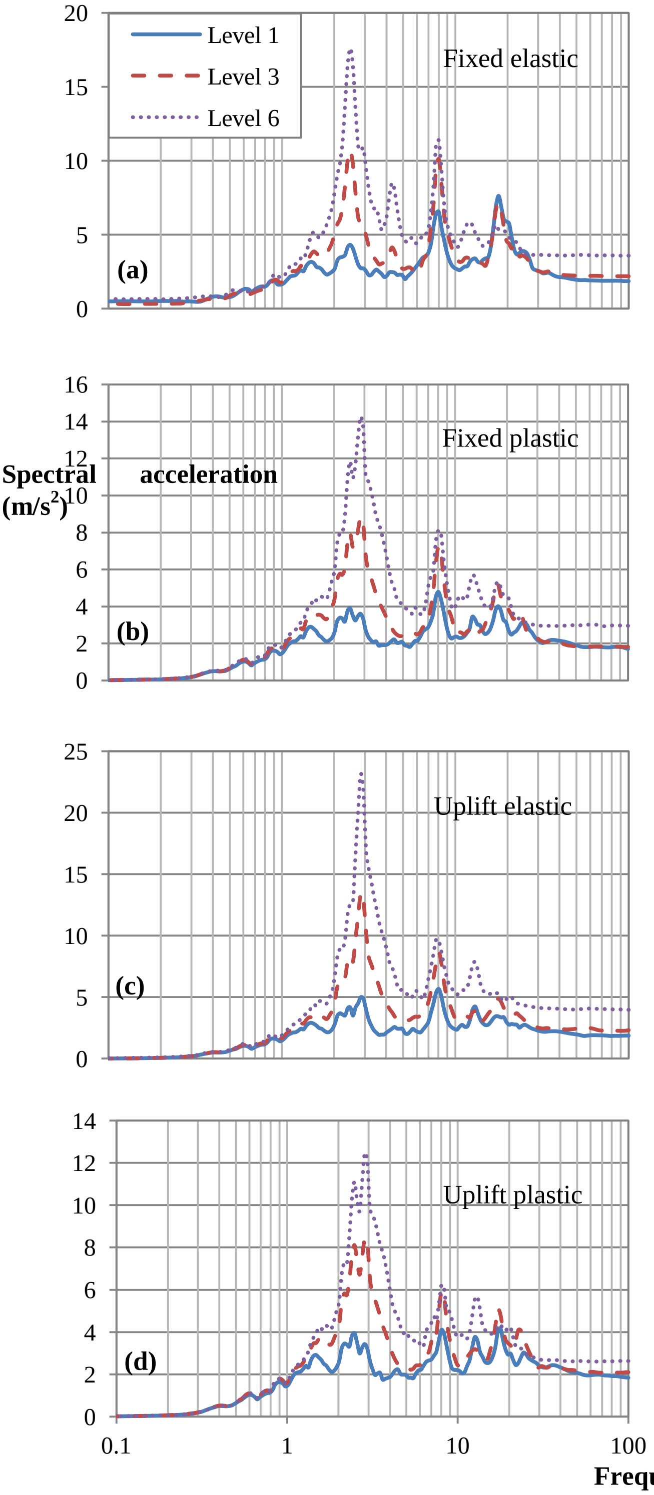

Figure 4. Response spectra of accelerations in x direction on different floors.

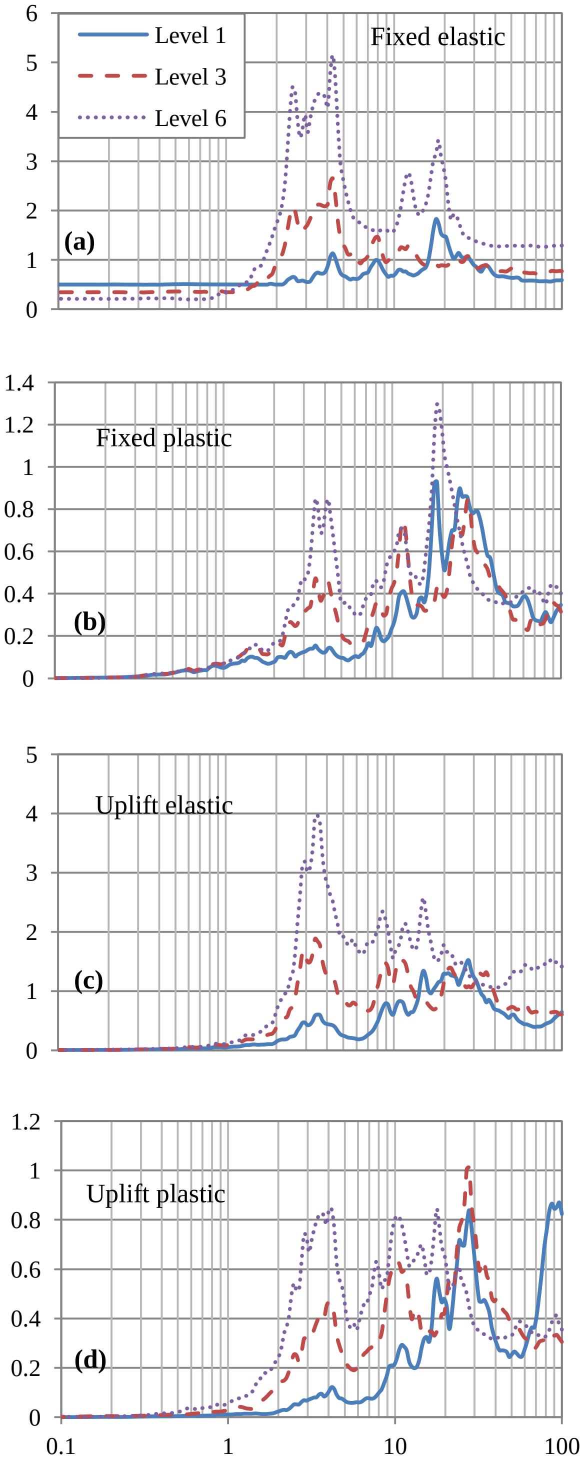

Figure 5. Response spectra of accelerations in y direction on different floors.

Table 2. The spectral accelerations in the *x* direction at the first two dominant frequencies

		Fixed Elastic		Fixed Plastic		Uplift Elastic		Uplift Plastic	
Order		1st	2nd	1st	2nd	1st	2nd	1st	2nd
Frequency (Hz)		2.48	8.04	2.85	8.04	2.85	8.04	2.85	8.04
Spectral Acceleration (m/s^2)	**Level 6**	17.62	11.39	14.28	8.13	23.15	9.55	12.48	6.24
	Level 3	10.68	10.12	8.81	7.24	13.43	8.61	8.42	5.93
	Level 1	4.33	6.56	3.91*	4.79	4.99	5.65	3.44*	4.11

*Occurs at a first dominant frequency of 2.48 Hz

Table 3. Predominant frequencies (Hz) of *y* component accelerations

	Fixed Elastic	Fixed Plastic	Uplift Elastic	Uplift Plastic
Level 6	2.57 - 4.32	19.01	3.63	3.51 – 4.47
Level 3	2.16 – 4.96	28.84	3.63	27.86
Level 1	18.41	17.18	27.86	24.27

4 CONCLUSIONS

Shake table tests on a small scale six storey building were performed to investigate the effect of plastic hinge development and foundation uplift on induced vibration at various points in a model structure. Artificial plastic hinges were constructed to allow simulation of damage to the structure under strong earthquake shaking. Simulated ground motion based on NZS 1170.5 was applied. Two support conditions were considered: 1) the structure fixed at the base and 2) uplift of the footings permitted. MEMS accelerometers were placed on the four corners of each floor to measure the tri-directional acceleration. The study reveals that for one directional horizontal ground motion:

- Large footing uplift will induced strong accelerations of an elastic structure in the main horizontal and vertical directions. This effect increases with floor height.
- Both footing uplift and plastic hinge development in the in-plan direction (co-linear with the applied acceleration) will reduce the out-of-plane vibration of a structure.
- Plastic hinge development in a structure concurrent with footing uplift will generally reduce vibration in all principal axes of the structure.
- In the direction of applied ground excitation, the frequencies of induced vibration close to the fundamental frequency of the primary structure are more pronounced on the higher floors, especially when uplift occurs with an elastic structure. A secondary structure with a natural frequency similar to the fundamental frequency of primary structure should be placed on a lower floor if possible.
- In the out-of-plane direction both uplift and plastic hinge development may reduce the effect of low frequencies but increase that of the high frequencies of the secondary structure. Therefore, the primary structural axis of the secondary structure should be aligned with the weaker structural axis of the primary structure.

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