TORSIONAL POUNDINGS BETWEEN TWO ADJACENT ASYMMETRIC STRUCTURES

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ABSTRACT

Seismic pounding between adjacent buildings is one of the major causes for structural damages during the strike of earthquakes. This undesirable phenomenon has been observed in numerous earthquakes, including 1995 Kobe earthquake and 1989 Loma Prieta earthquake. Although a large number of investigations have been conducted, there has been no study on shaking-table-tests in investigating torsional seismic poundings between realistic building models, especially for modelling multi-storey asymmetric buildings with transfer system which are very common in Hong Kong. Developed upon our earlier theoretical study (Chau and Wei, 2001) and shaking table study (Chau et al., 2003), two multi-degree-of-freedom steel models are used to investigate the potential seismic poundings between two 21-storey adjacent buildings in Hong Kong. The two structures are of different natural frequencies and damping ratios. Both sinusoidal waves and 3 earthquake ground motions (i.e. 1941 El Centro, 1989 Loma Prieta and 1994 Northridge earthquake) have been used as input. Different impact phenomena were observed for various separation distances, frequencies and magnitudes of ground excitations. That is, the pounding phenomenon is highly nonlinear. The maximum responses as well as the maximum pounding forces have also been investigated. It was found that poundings between the two towers may be periodic or chaotic, depending on structural characteristics and the frequency content of the shaking table input. Torsional poundings between the two models were observed at both top and mid-levels because of the higher mode responses. Energy transferred from the more massive building to the lighter building through impacts causes abnormally large vibrational response of the lighter building, which when stands alone would not suffer any vibrational damages.

Keywords: Seismic pounding, multi-storey torsional buildings

INTRODUCTION

Pounding between adjacent structures, such as buildings or bridge decks, during major earthquakes has often been reported, and it has also been identified as one of the main causes for structural damages or for complete collapse of structures (Anagostopoulos, 1988, 1993, 1995, 1996; Bertero, 1985; Kasai and Maison, 1997; Penzien, 1997; Filiatrault et al., 1994). For example, poundings between structures have been observed in Alaska Earthquake of 1964, San Fernando Earthquake of 1971, Mexico City Earthquake of 1985, Loma Prieta Earthquake of 1989, Kobe Earthquake of 1995 and Taiwan Chi-Chi Earthquake of 1999. Both high-rise and low-rise inadequately separated adjacent structures are susceptible to damages induced by poundings. Therefore, pounding between adjacent

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buildings poses a serious seismic hazard, especially in highly populated areas prone to earthquake attacks.

A general introduction on seismic pounding was given by Chau and Wei (2001) and thus it will not be repeated here. Based upon the mode by Davis (1992), Chau and Wei (2001) also proposed a new analytical model for nonlinear pounding between two single-degree-of-freedom (sdof) oscillators. However, the shaking table experiments on two single storey steel structures by Chau et al. (2003) showed that seismic pounding between actual structures was more complicated. For example, the phenomenon of periodic responses in the form of a group of poundings was not predicted by the model. Clearly, the sdof model is not capable of modeling actual structural poundings, and it seems that higher mode effects are sometimes inevitable and important. To further extend this work, Chau et al. (2004) extended the experiments to two steel towers of off-set masses to simulate torsional pounding. Figure 1 shows a photograph of the two towers with a close-up view of how the masses at the top of the towers were off-set along a railing system. Similar to the shaking table experiments of Chau et al. (2003) for translational poundings, the pounding response can be periodic with a single pounding, periodic with a group of poundings, or chaotic. The main limitation on this work is that the two steel towers has only two degree of freedom (i.e. one translational and one torsional). The seismic pounding behavior of multi-storey buildings with asymmetry may not be modeled adequately by this simple towers. Therefore, more recently, additional works have been conducted, one on a new theoretical model for torsional pounding and one on shaking table tests between two scaled models of two asymmetric 21-storey buildings. This paper will summarize some of these results, but full details will be referred to our future journal publications.

Figure 1. Shaking table tests for torsional poundings between two single storey steel towers. Note that railing on the top plate allows for eccentric mass center comparing to the stiffness center.
TORSIONAL POUNDING EXPERIMENTS OF TWO 21-STOREY STEEL TOWERS

Two adjacent 21-storey buildings in Wanchai on the Hong Kong Island were selected for the present experimental studies, as shown in Fig. 2. Both buildings are 21 storey, and the channel-shaped building is a hotel (called Empire Hotel which is referred as EH hereafter), which is highly unsymmetric, and the smaller one is a residential and commercial building (called Gold Star which is referred as GS hereafter), which is more regular in shape. These two buildings were built nearly touching each other, probably with a nominal separation of 25 mm (i.e. the thickness of a typical wooden formwork used in Hong Kong). It is expected that even under unidirectional ground shaking, torsional response of the hotel is likely to be excited; and due to different shapes and masses per floor for the two buildings, their dynamic characteristics (including natural frequency of vibration) are quite different. Therefore, seismic pounding between these two buildings are likely due to out of phase seismic responses. This type of asymmetry building is known being highly susceptible to seismic damages as well. In addition, both buildings are having a transfer plate system connecting the upper building blocks and the lower parking or shopping mall structures. Both shear and bending stiffness of the building blocks above the thick transfer plate differs drastically from those of the lower structures. This kind of sudden change of stiffness along the height is against prone to structural damages during earthquake.

Two scaled models of 1:45 were built using steel, although the original buildings (or so-called prototypes) are built of reinforced concrete. The main reason of using steel to build the model is to allow repeated pounding of the two models, without suffering substantial damages. Thus, parametric studies can be conducted. The full mechanical properties and building design will not be reported due to space limitation. We just want to mention that ratio of the natural period of the prototype building to that of the model is set to the square root of the length scale (i.e. $\sqrt{45} \approx 6.7$).

![Figure 2. Two adjacent buildings selected for the present experimental study. The plans for the upper floors of these two buildings are also given.](image)

Two different laboratory models were tested on our MTS shaking table for investigating the complex phenomenon of seismic pounding between multi-storey asymmetric buildings with transfer plate system.
The first model is shown in Fig. 3, two 21-storey steel towers with transfer plate system. The building blocks below and above the transfer plate level have been painted with different color. To enable nonlinear as well as torsional poundings between the two buildings being simulated, two contactors were built at the top level as well as at the mid level, as shown in Fig. 3. If any higher mode response of either or both buildings is excited (note that higher mode is more important for taller buildings like these two), pounding at the mid-level contactors are expected to occur. To measure the impact force between the buildings, strain gauges were pre-installed at the impactors. Note that the smaller building is much more flexible than the hotel building. Note also the floor level between the two buildings were slightly off-set, thus damages may occur when floor slab smashes on the wall of the adjacent building. However, this situation cannot be duplicated in the present model.

Figure 3. Two steel models were used to investigate the phenomenon of seismic pounding. Contact elements were installed at the top as well as at the mid-level. The structures below and above transfer floors have been painted with different color.

Figure 4. Two steel models were used to investigate the phenomenon of seismic pounding. Contact elements were installed at the top as well as at the mid-level.
The second model for the pounding is an approximate situation that the more massive building was modeled by a more massive and rigid wall, as shown in Fig. 4. However, for this model only top level contactors have been installed. The full details of the dimensions and properties of the model will not be reported here due to space limitation.

The experiments were conducted at the Hong Kong Polytechnic University using the unidirectional shaking table by MTS, which is capable of inputting 1-g horizontal acceleration even with the maximum payload of 10 tons on the table.

**EXPERIMENTAL RESULTS OF THE SHAKING TABLE TESTS**

Hundreds of experiments have been conducted by changing the input frequency, input magnitude, separation distance between the two buildings and between GS and the nearly rigid wall. The input frequency is typically from 2 Hz to about 10 Hz, the peak ground acceleration ranges from 0.05g to about 0.3g, and the separation distance is from 0 to about 15mm. Independent experiments have also been conducted to gauge the separation distance between the two models such that they do not pound (or called stand off distance between two buildings).

First of all, some results for the model shown in Fig. 4 are discussed here. In particular, for non-pounding cases Fig. 5 shows three typical phase diagrams of the response of the flexible GS model. The case of NPI shows a highly periodic situation, NPII shows a more complex response with smaller oscillations within a bigger cycle of oscillations, and NPIII shows a rather chaotic response. These results are for sinusoidal wave input.

![Figure 5. Three typical phase diagrams of the responses of the structures for the non-pounding cases.](image)

When the separation distance between the two models decreases or when the input magnitude of shaking acceleration increases, pounding starts to occur. Figure 6 shows eight typical phase diagrams of the response of the more flexible GS structure. Note that only the responses of 10 input cycle of the shaking were plotted in Fig. 6, excluding the initial non-periodic response when the shaking table has just started. The phase diagrams for the pounding cases are much more complex. Note that any vertical line in the displacement-velocity phase diagram indicates an impact between the nearly rigid wall and the flexible model, because during impact the displacement is fixed while the direction of velocity change suddenly (moving from left to right or from right to left). Although it is not apparent
in Fig. 6, there are also cases of double impact within a big cycle of periodicity. For example, in the phase diagrams of velocity versus displacement for PVI and PVIII (see Fig. 6), there are two oscillations of the structure before it impacts on the nearly rigid wall again. However, the periodicity is highly repeatable in this case. In general, the torsional response is more chaotic than the translational response.

We have also checked the natural frequency of oscillation of the nearly rigid wall by hammer test, and confirmed that the natural frequency of the first mode of the wall is much higher than that of the GS model. Thus, the assumption of rigid wall is justified. In fact, a new analytical model has been derived for this case of flexible structures impacting on rigid wall, but the discussion of this model is out of the scope of the present study.

![Figure 6. Eight typical phase diagrams of the responses of the structures for the pounding cases.](image)

The pounding forces between two adjacent structures are of utmost importance in determining the degree of damages that the building may suffer. Therefore, for the case of two flexible models shown in Fig. 3 the maximum pounding force are plotted versus the input frequency. Similar to the conclusion by Chau and Wei (2001) and Chau et al. (2003), the pounding force is a function of the input frequency. As shown in Fig. 7, when the separation distance is 4 mm, pounding occurs only at the top level whilst for the case of zero separation, poundings were observed both at the top and at the mid-level of the model. It is important to note that the maximum pounding force did not observe at the natural frequency of either the EH or the GS model, but rather it was observed at a natural frequency of about 6.5 Hz, which is between the frequencies of first translation mode of the EH and...
GS models. Therefore, clearly the two-model system (including both EH and GS model) somehow behaves as one unit and their response are linked by periodic impacts, and is with a natural frequency different from either one of the model EH and GS. Therefore, there is clear evidence of energy transfer between the two models through impacts, and the process is highly nonlinear. More analyses of our results are referred to our later publications, and will not be given here.

**CONCLUSIONS**

This paper summarizes our recent shaking table experiments on the seismic pounding between 21 storey models made of steel. Some experiments were also conducted on the pounding between a nearly rigid wall and the more flexible GS model. For the case nearly rigid wall and flexible model (see Fig. 4), the periodic response of the structure is very complicated. When there is no pounding occurring, three different types of responses were identified; when there are poundings, eight different type of structural response were identified through the use of phase diagrams. There can be two oscillation cycle between each impact. For the case of two flexible structures (see Fig. 3), it was observed that when the separation distance is zero, pounding at the top and at the mid-level are both possible, whilst for nonzero separation distance the pounding is predominantly at the top. The maximum pounding force between the wall and the GS model is observed when the input frequency is between the natural frequencies of the two models. Therefore, transfer of energy from one structure to the other occurs during the experiments, and we expect the same will happen between real buildings in earthquakes. This also implies that when two stand-alone structures behave satisfactorily under certain ground excitations may behave quite differently when pounding occurs due to the proximity of the two structures. Therefore, special consideration must be made when a new building is proposed to construct right next to a pre-existing building, like many cases in Hong Kong.

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REFERENCES


