



USING SHAKING TABLE TO STUDY DIFFERENT METHODS OF REDUCEING EFFECTS OF BUILDINGS POUNDING DURING EARTHQUAKE

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SUMMARY

Pounding of adjacent buildings has been one of major reasons of damages of building in earthquakes. Therefore there is a need to investigate this phenomenon, both experimentally and analytically. This paper begins with a general study on the effect of pounding. Then two series of shaking table experiments on small scale moment resisting frames subjected to harmonic excitation and seismic loading are described. For new buildings, there are provisions in the seismic design building codes regarding the distance between adjacent buildings to accommodate the potential of pounding. However, for existing building the solution is not as easy. Therefore, final part of the paper explains a series of experiments regarding some measures to reduce the damaging effects of pounding. The measures include increasing distance of the buildings, application of impact absorbing material, and connecting the two building together. The results of experiments indicate the effectiveness, also problems associated with each method.

INTRODUCTION

The 1985 Mexico City earthquake caused much attention to the damaging effects of pounding between adjacent buildings. Of course the effects of pounding as a cause of damage have been reported in numerous other earthquakes [1,2,3]. However, the wide spread damages resulted from pounding in the 1985 Mexico City earthquake illustrate it as a major mode of failure for building [2]. 40% of the buildings are reported to have pounding problem and 15% of the total collapses were related to pounding [1,2,4]. Although some other reports suggested that probably only 20 to 30% of structural damages were related to pounding [1], these numbers are big enough to show the problem. Reports on the Mexico City earthquake have suggested that connection between some buildings has been the probable reason for their suitable behavior. An investigation revealed that 42% of heavily damaged buildings were corner buildings that did not have the support of adjacent buildings. Thus research on the measures to reduce the effects of pounding was encouraged [2]. Nonlinear dynamic simulation of mass-spring-damper models, also procedures based on principle of energy and momentum conservation have been employed in some of the analytical research [1]. Computer modeling of pounding usually has been conducted using gap elements [5]. The impact of pounding between buildings usually results to producing high acceleration that causes

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damages to non structural, mechanical and electrical equipments. As an example, some non structural damages in Loma Prieta earthquake are related to pounding [5]. Analytical studies have shown that due to the impact effect, the produced peak acceleration is up to 10 times more than the cases without impact.

In almost all seismic design building codes, a distance between adjacent buildings are required to avoid pounding during earthquakes. Research has shown that usually the minimum distance between adjacent buildings, as required by building codes, is effective in reducing the pounding effects [6].

This paper presents shaking table experiments on two adjacent small scale (almost 1/10 scale) moment resisting frames, one 3 and the other 6-story subjected to harmonic excitation and seismic loading. To examine different techniques for reducing the effects of pounding, a series of experiments have been conducted. The measures include increasing distance of the buildings, application of impact absorbing material, and connecting the two building together. In the first approach, different distances between two frames are studied (such as 0.5 or 1.0 cm distances). In the second approach, polystyrene material is applied as an impact absorbing material. Three earthquake ground motion and sinusoidal harmonic excitation with different amplitudes and frequencies are applied to the specimens by the shaking table. Floor accelerations and displacements are measured as the response parameters. The results of experiments indicate the effectiveness, also problems associated with each method.

THE EXPERIMENTAL MODEL PROPERTIES AND SETUP

The specimens consist of two small scale (almost 1/10 scale) single bay moment resisting steel frames. The frames are designed based on static analysis approach of building code. The story height of the frames is 0.3 meter. The total height of the 6-story building is 1.8 meter, and the total height of the 3-story building is 0.9 meter.

Beam and column sections consist of 3mm*50mm and 4mm*50mm plates. The connections are built from 5mm*50mm*50mm angles with the length of 70cm. Fillet weld with 3mm dimension has been used to provide rigid connections. Column base is connected by angle to a 60mm*40mm*10mm plate. Shown in figures 1 and 2 are the two test frames and the column base connection.

Figure 3 shows the concentrated masses on beams. Two concentrated masses (700 to 750 grams each) are placed on roof level beams and four concentrated masses are placed on floor beams. The impacts between two frames are accomplished at the third level through a contact element (figure 4). The contact element consists of a 20mm*20mm*3.37mm box with the length of 24cm. The contact element is also used for changing the distance between the two frames.

SHAKING TABLE AND DATA ACQUISITION SYSTEM

The shaking table of International Institute of Earthquake Engineering and Seismology (IIEES) has been used to conduct the experiments reported in this study. It is a 130cm*120cm table, constructed by SEROTEST. The shaking table is able to apply acceleration, velocity or displacement time histories by actuator to the table platform. The actuator diameter is 150mm. The table is controlled by a DCS-2000 system which is able to control and process data simultaneously.

The ground motion records are applied to the table as ground displacement time history. The DMC PLUS data acquisition with 8 output channels, equipped with CATMAN software was used to store, process and filter the data. The accelerometers were AR-F from the Japanese company TML. An accelerometer was installed on the platform of the table and three other accelerometers were installed on the two structures at their beam-column connection. Figure 3 shows the acceleration sensor on beam-column connection.

Displacements are measured by four SPD 100C and CDP 50 displacement transducers (LVDT). A LVDT measured platform displacements, other transducers were used to measure the first and third floor displacements of 3-story structure, also the third floor displacements of 6-story structure. A SDP 100C LVDT is shown in figure 5.



Figure 1: View of two structures on shaking table



Figure 2: Connection of structure to shaking table



Figure 3: Masses and the AR-F accelerometer sensor

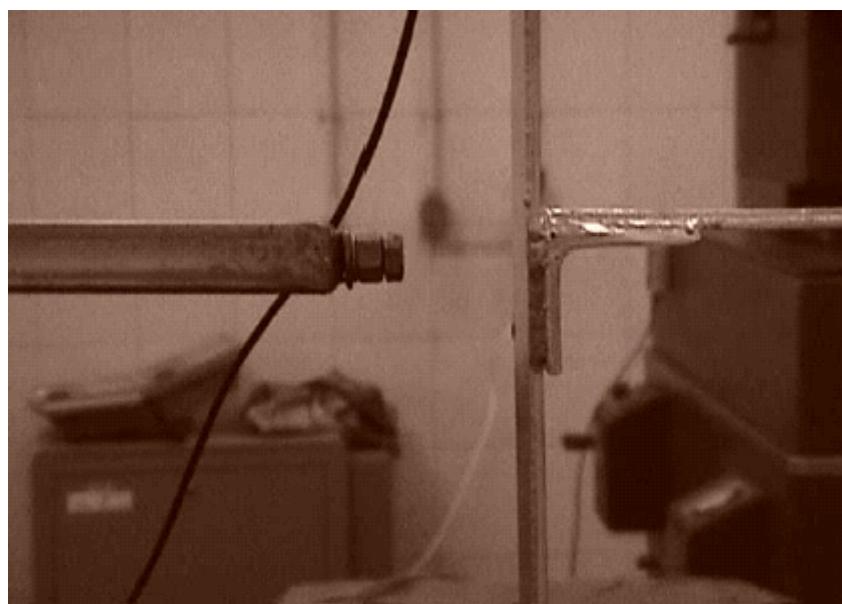


Figure 4: Contact element and gap adjustment system



Figure 5: Displacement measurement with SDP 100C LVDT

THE CONDUCTED TESTS

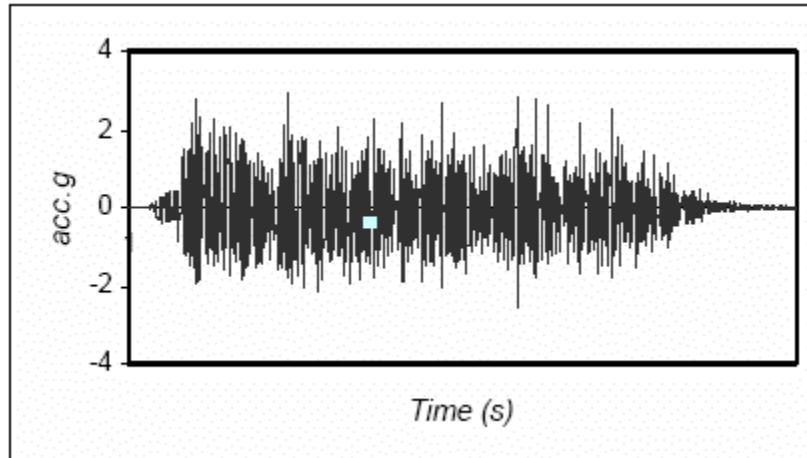
The main tests conducted in the experimental study were:

1. Vibration of structures without pounding;
2. Vibration of structures with pounding in two cases with 0.5cm and 1.0cm distance between structures;
3. Vibration of structures with pounding, when polystyrene material is installed at the third floor of the 6-story structure;
4. Vibration of the buildings, when they are connected at their third floors;
5. Vibration of the buildings, when they are connected at their first and third floors.

Some preliminary tests are conducted to select the frequencies for sinusoidal harmonic excitations and the distances required between the structures to have or to avoid pounding. To examine the accuracy of input motion, accelerometer and LVDT are installed on the table. Comparison between the input and applied motions indicate quite satisfactory agreement. The duration of sinusoidal harmonic excitations was 25 seconds in most cases. However, to include free vibration of structures in the study, the duration of responses measurement was 35 seconds.

In the case of sinusoidal harmonic excitation with vibration amplitude of 1mm and distance of 1cm between structures, pounding did not occur. Also with vibration amplitude of 2mm and frequencies of 1 and 1.5 hertz, pounding did not occur. With 0.5cm distance between structures, the vibration amplitude of 2mm was not applied as it produces accelerations that are out of range for the sensors. In all other cases, pounding occurred and its effects were within acceptable range for sensors (figure 6).

In the next stage of work, the application of polystyrene as an impact absorbing material was examined. It was installed at the expected location of pounding that was at the third floor of 6-story building. In the literature [7], the effect of connecting the structures has been analytically studied. As this method is a suitable retrofitting technique in some cases, it also was tested in this study.



**Figure 6: Acceleration at the third floor of 3-story structure
vibration amplitude = 2mm, f = 6.5 Hz, gap = 1cm, with pounding**

In the case of earthquake excitation, three different earthquake ground motion records were used. Two Iranian ground motion: Tabas with PGA equal to 925.3 (cm/square of seconds) and Naghan with PGA equal to 849.2 (cm/square of seconds) and El Centro with PGA equal to 308 (cm/square of seconds) were used. In the case of earthquake excitation, the following experiments are conducted:

1. Vibration of structures with pounding in case with 1.0cm distance between structures;
2. Vibration of structures with pounding in case with 0.5cm distance between structures;
3. Vibration of the buildings, when they are connected at their third floors;
4. Vibration of the buildings, when they are connected at their first and third floors.

In total 68 earthquake and sinusoidal harmonic excitations tests were performed.

THE TEST RESULTS

In the sinusoidal harmonic excitation without pounding, the maximum acceleration and displacement responses were at the third floor of 6-story structure. A pulse type vibration was observed in acceleration response of the third floor of 6-story structure at frequency of 6.5 hertz (figure 7). Applying Fast Fourier Transform (FFT) technique, showed that the excited frequency of structure is equal 6.2 hertz which probably was one of the natural frequencies of the structure. In the case with pounding, the maximum responses occurred at frequency of 4.5 hertz.

It was observed that when the distance of the two structures reduced to 0.5cm, the acceleration is decreasing with decrease in vibration amplitude. It is concluded that with increase in distance between the two buildings, if pounding occurs, due to increase in velocity, acceleration response also increases. With installing the polystyrene, the acceleration response decreases considerably (figure 8). The decrease in

acceleration response is more pronounced at the level of pounding in the two structures. Besides decreasing in acceleration response, installation of polystyrene has decreased the displacement response (figure 9). Of course vibration amplitude is a very important factor in magnitude of responses.

When the two structures are connected, the maximum responses were occurred at the frequency equal to 2.5 hertz. It can be due to increase in the stiffness of the combined structure. Figure 10 shows the displacement responses. In general, connecting the structure has reduced their responses. A comparison of responses in the combined structures compare with the case with polystyrene and pounding with 0.5cm distance between structures is shown in figure 11.

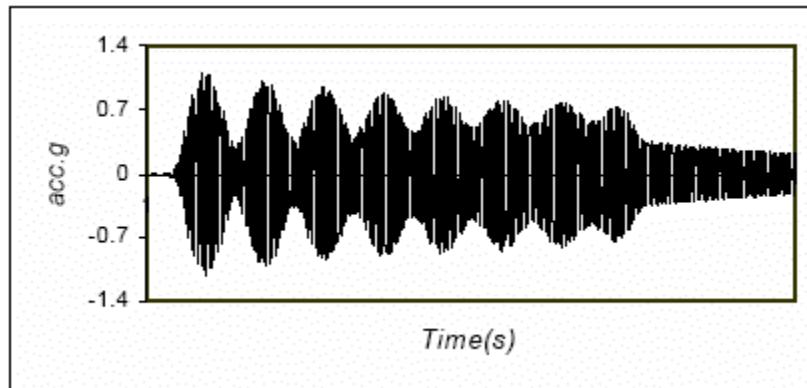


Figure 7: Impulse at the third floor of 6-story structure, $f = 6.5 \text{ Hz}$

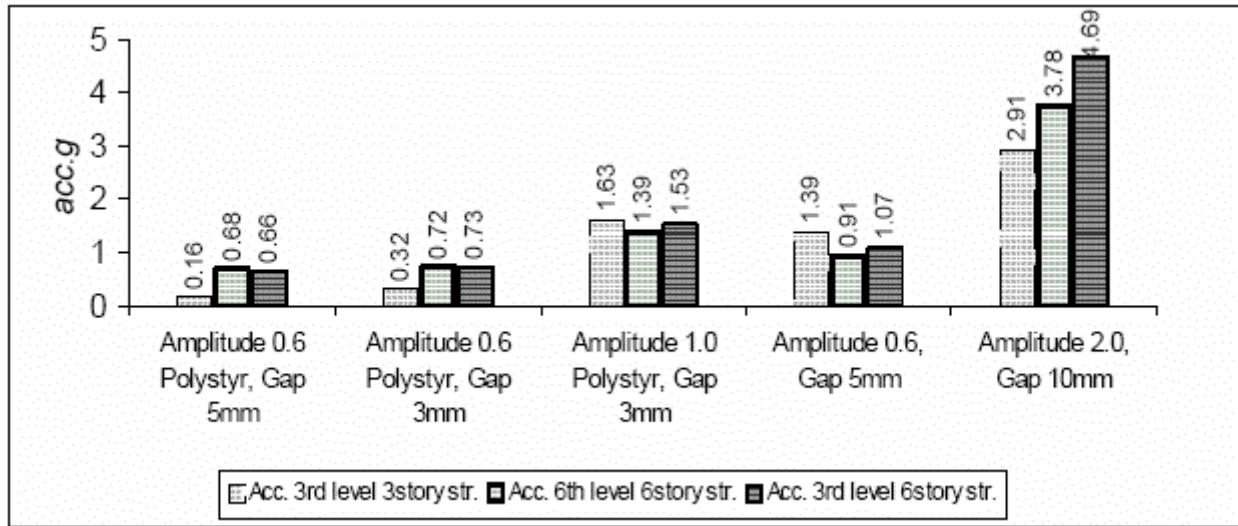
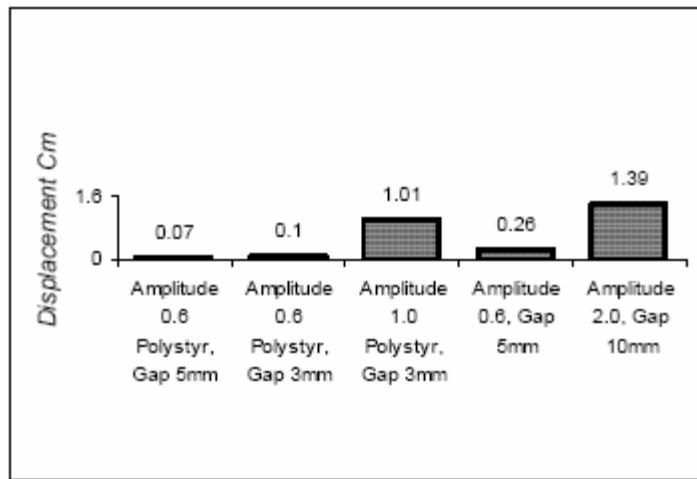


Figure 8: Acceleration responses, $f = 6.5 \text{ Hz}$

In the earthquake excitation cases, the results were similar to the sinusoidal harmonic excitation cases. As an example, figure 12 shows that with decrease in the distance between the two structures, acceleration response either decreases or is constant. However, the displacement responses decrease with increase in distance between the two structures (figure 13). By connecting the two structures at their third floor the

acceleration responses decrease. Connecting the two structures at two levels instead of only at one floor did not cause much further improvement in the responses.

Some sources of errors in the experiments reported here are: the probability of inelastic actions in the buildings due to impact of pounding, error in measuring the responses, the operational limits of sensors, difference between actual applied motions and the intended ones and connection and impact element characteristics.



**Figure 9: Displacement responses of the third floor of 3-story structure
f = 6.5 Hz, with pounding**

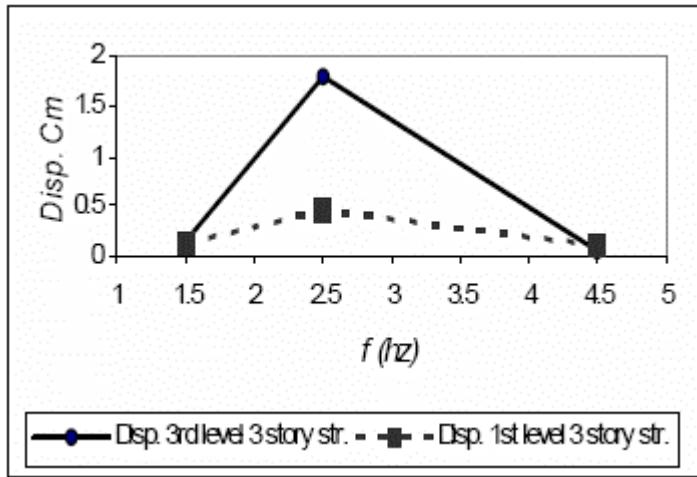


Figure 10: Displacement responses of connected structures, vibration amplitude = 1mm

The general conclusions of this study are:

1. By using impact absorbing material, the acceleration response of structures has reduced which can be very important, especially for non-structural elements.

2. Connecting the structures at a floor level reduced the responses. Connecting the two buildings at more than a level did not improve very much the responses of the structures.
3. If by increasing the distance of the two buildings still pounding occurs, this increase of distance increases the responses.

Of course the results are valid only for the structures used in this study and much more study is needed before the findings can be extended to other structures.

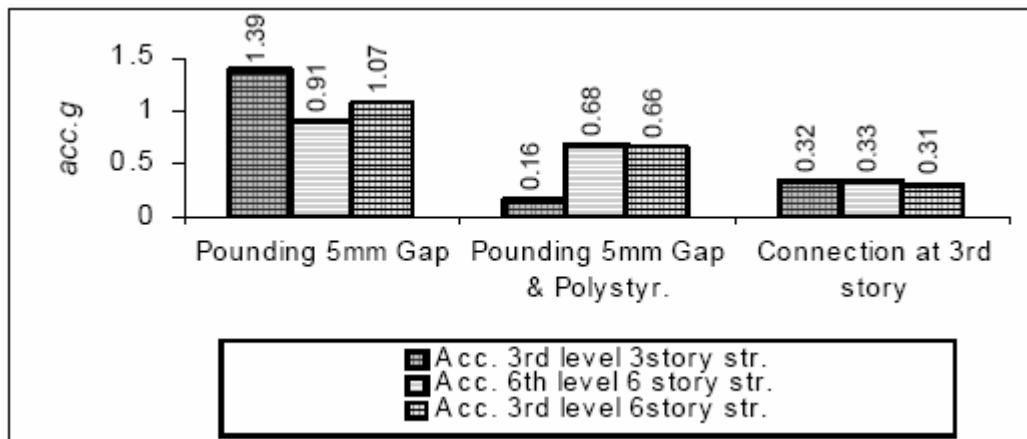


Figure 11: Acceleration responses, $f = 6.5$ Hz, vibration amplitude = 0.6mm

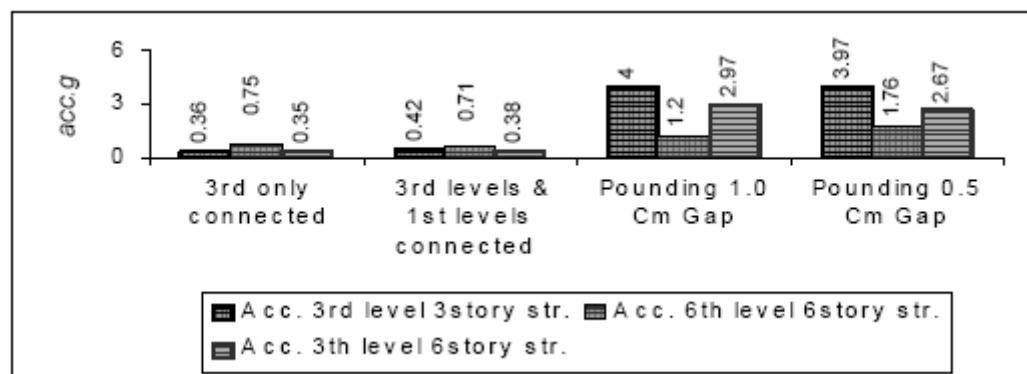


Figure 12: Acceleration responses, Tabas earthquake

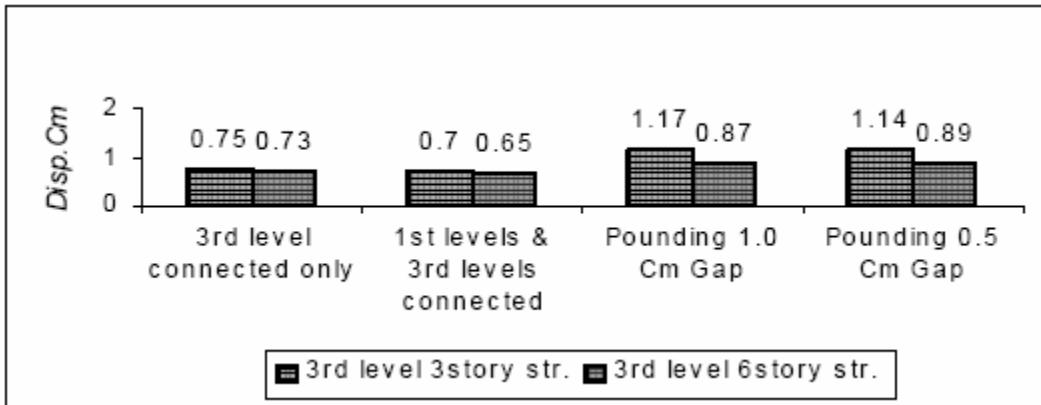


Figure 13: Displacement responses, El Centro earthquake

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