Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Seismic pounding effects – Survey and analysis

K. Kasai, V. Jeng, P.C. Patel & J.A. Munshi
Illinois Institute of Technology, Chicago, Ill., USA

B. F. Maison
SSD Inc., Berkeley, Calif., USA

ABSTRACT: The results from a pounding damage survey and analytical pounding studies are presented. These include, a pounding survey from the 1989 Loma Prieta earthquake, development of pounding dynamic analysis computer programs, parameter studies on building pounding response as well as appurtenance response, a spectrum method to obtain peak pounding responses, actual case studies, a spectrum method to determine required building separations to preclude pounding, and a possible pounding mitigation technique.

1. INTRODUCTION

Building collision, commonly called 'pounding' occurs during an earthquake when, due to their different dynamic characteristics, adjacent buildings vibrate out of phase and there is insufficient separation distance between them.

Many incidents of seismic pounding have been reported to date. Pounding of adjacent buildings has made damage worse, and/or caused total collapse of the buildings. The earthquake that struck Mexico City in 1985 has revealed the fact that pounding was present in over 40% of 330 collapsed or severely damaged buildings surveyed, and in 15% of all cases it led to collapse (Rosenblueth and Meli 1986). This earthquake illustrated the significant seismic hazard of pounding by having the largest number of buildings damaged by its effect during a single earthquake (Bertero 1986).

Continued research is urgently needed in order to provide the engineering design profession with practical means to evaluate and mitigate the extremely hazardous effects of pounding. The following describes the writers' current research efforts.

2. POUNDING SURVEY

The writers surveyed the damage due to pounding in the San Francisco Bay area during the 1989 Loma Prieta Earthquake (Kasai and Maison 1991). This survey is compiled from data provided by: engineers, government officials and engineers, building owners, and block-by-block inspections performed by the writers. The database contains the input of about 90 interested parties and records more than 200 pounding occurrences involving more than 500 structures. Significant pounding was observed at sites over 90 km from the epicenter thus indicating the possible catastrophic damage that may occur during future earthquake having closer epicenters.

Classification of Pounding Damage. - Pounding damage patterns are classified as follows: Type-1, major structural damage; Type-2, failure and falling of building appurtenances creating a life-safety hazard; Type-3, loss of building function due to failure of key mechanical, electrical or fire protection systems; and Type-4, architectural and/or minor structural damage.

Fig. 1 shows an example for Type-1 damage. The 10 story building is constructed of thick masonry walls (13 inch thickness) combined with 9 steel plane frames. It was built in 1904. This building experienced severe pounding with an adjacent massive 5 story building which occupies most of the city block. The 5 story building is originally a concrete frame building having a very stiff wall at the 2nd level, and was seismically upgraded by adding steel braces in 1980. Pounding was located at the 7th level in the 10 story building and at the roof level in the 5 story building (Fig. 1). Only 1 to 1.5 inches building separation is present. The 10 story building suffered structural damage above the pounding elevation as evidenced by the large diagonal shear cracks in the masonry piers (Fig. 1 right).

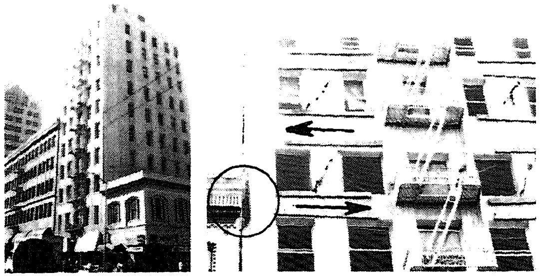

Fig. 1: Type-1 Pounding Damage Example.

Fig. 2 shows an example for Type-2 and possibly Type-1 damage. The building is 10 stories and constructed of reinforced concrete with a post-tensioned concrete floor system (Fig. 2 left, building at right). It was built in 1965. This building pounded with an older 7 story building whose lower 4 stories are composed of reinforced concrete, and its upper 3 stories are of steel construction (Fig. 2 left, building at left). The buildings have about 2 inch separation. The 10 story building suffered significant damage. Further study is needed to determine whether this damage is attributed to pounding. However, pounding caused the seismic hazard of falling building debris. The brick veneer at the boundary of the two buildings was damaged due to impact, and a large amount of falling debris fell on and through the canopy located at the 2nd floor level.

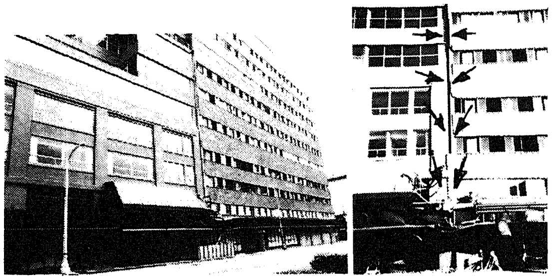

Fig. 2: Type-2 Pounding Damage Example.

Fig. 3 shows an example combining Type-2, 3, and 4 damage. The building is a large 6 story modern steel structure occupying an entire city block. It was built in 1981. The building in plan, consists of three segments separated by 4 inch expansion joints.

Due to the earthquake, these segments pounded at their floor slabs which are at common elevations, produces sharp irregular motions which results in large high frequency lateral accelerations (Kasai et al. 1990). The windows facing the atrium fell down, and the computer equipments shifted and/or turned over. Heavy building equipments in the penthouse shifted significantly (Fig. 3).

Fig. 3: Type-3 Pounding Damage Example.

Survey Findings and Comments. - The following are some of the general survey findings and comments:

(1) The majority of reported cases are in urban areas including San Francisco (e.g., Fig.4), Oakland (Fig. 5), Santa Cruz and Watsonville.

(2) Pounding typically involved multi-story buildings constructed prior to about 1930. They are typically of masonry construction with or without steel skeletal vertical load resisting systems. Very little consideration was given for separation between such buildings to preclude pounding. In many cases, they are in contact with each other.

(3) Fewer modern buildings suffered pounding. In such buildings, relatively larger separations exist. However, it is noted that many modern buildings having expansion joints suffered pounding due to small separations.

(4) There is evidence of correlation between occurrences of pounding and soft foundation soil conditions. This may be attributed to the more intense shaking typically reported for such soil conditions and/or from the possible settlement and rocking of the structures located on soft soils.

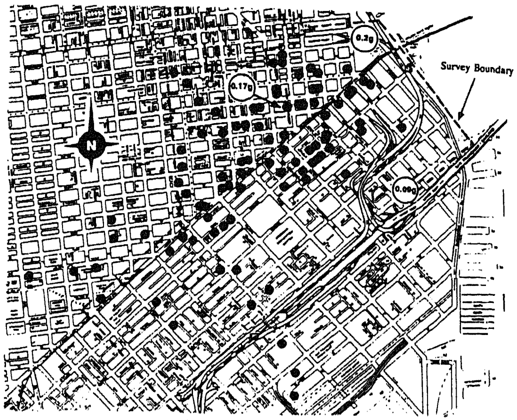

Fig. 4: Distribution of Pounding Damage in San Francisco Downtown.

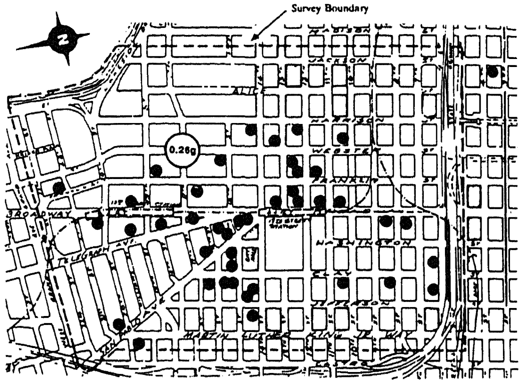

Fig. 5: Distribution of Pounding Damage in Oakland City Center.

(5) Special pounding cases were also observed. They include; severe pounding at unsupported part (e.g., midheight) of columns or walls; pounding promoted by torsional behavior of building; and pounding between the buildings sharing a common wall.

(6) Older buildings that suffered Type-1 damage typically also had Type-2 damage (i.e., falling bricks). Modern buildings that pounded usually had Type-4 damage, and several of them also suffered Type-3 damage. The survey has relative distributions for damage Types 1 and 4 of 21% and 79%, respectively. Many of the present Type-4 damage cases will become damage Types 1, 2, and/or 3 when a future more severe earthquake affects the region. The Type-4 damage cases may be thought of as precursors for the major pounding damage yet to occur.

3. POUNDING TIME HISTORY ANALYSIS

Idealization. - The writers have developed two microcomputer pounding analysis programs SLAM and SLAM-2, which are made publicly available (Maison and Kasai

1988, 1990). The programs idealize buildings as three-dimensional (3D) multi-degree-of-freedom (MDOF) systems. The SLAM program assumes that a building laterally collides with a rigid adjacent building and the SLAM-2 (Fig. 6) program considers that both buildings are flexible. Pounding is assumed to occur at a single floor level having a rigid diaphragm. The pounding problem is idealized as having two linear states: in "State 1", the buildings vibrate without contact, and in "State 2" the buildings are in contact. A nonlinear problem results as the response oscillates from one linear state to the other. These idealizations were made as a starting point in the pounding investigation in order to make the problem manageable, while retaining important 3D-pounding dynamic characteristics. The programs employ a theoretically exact solution scheme (Maison and Kasai 1990), and they are also computationally efficient.

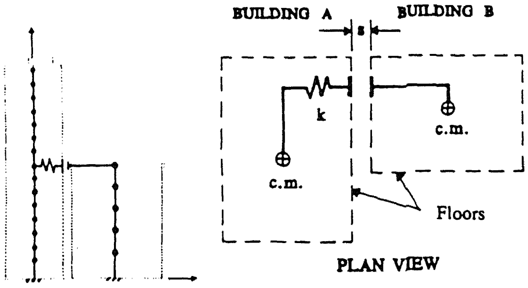

Fig. 6: The Pounding Problem and SLAM-2 Idealization.

Sample Analyses Results. - An existing 15-story steel moment resistant frame building (Building A, period = 1.13 sec) is assumed to collide with an adjacent flexible 8-story building (Building B, period = 0.8 sec.). The floor mass of Building B is considered three times that of Building A. SLAM-2 dynamic analyses were conducted using 0.4g artificial earthquakes (Kasai et al. 1990). Damping ratio is set to 5% and 1.5 inches separation is considered for pounding case. Local contact stiffness (Fig. 6) is set to 50000 k/in considering the past studies (Maison and Kasai 1990). Pounding is a severe load condition. Impacts at the pounding level results in large and quick acceleration pulses, and the peak floor accelerations can be more than 10 times those from the no-pounding case (compare Figs. 7(a) and (b)).

In both buildings, pounding produces peak drifts, shears, OTM's, torques, and accelerations at various story levels that are greater than those from the no pounding case (e.g., Fig. 8). Building midheight pounding (Building A) increases shears above pounding level as well as accelerations in the vicinity of the impact (Fig. 8). Building top level pounding (Building B) decreases the peak shears over the entire building height with the exception of the stories in the vicinity of the impacts. Further analyses were conducted by varying the floor mass. As the difference in the relative mass increases, the adverse effects of pounding increase in the building having the lessor mass. These locations of pounding amplified responses correspond to the observed damage locations in the recent earthquake (e.g., Fig. 1).

Fig. 8 also shows the response quantities when the buildings have 20% damping. It is clear from the figure that high damping reduces the responses significantly.

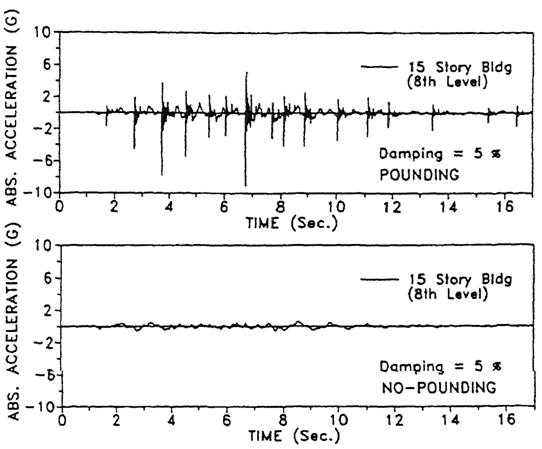

Fig. 7: Absolute Floor Accelerations, Pounding Case (15-story against 8-story Building) vs. No-Pounding Case.

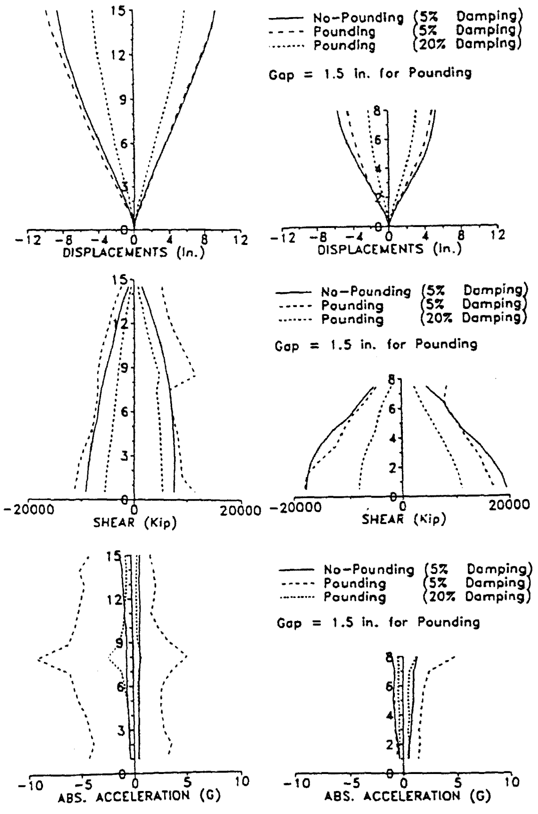

Fig. 8: Response Envelops: Pounding Case (Damping = 5% or 20%) vs. No-Pounding Case (Damping = 5%).

This issue is further discussed in Sec. 8.

The flexible adjacent building cases studied have many trends that are similar to those from a rigid adjacent building case. The rigid adjacent building case, therefore, was the first subject of the writers' study, results of which are discussed below.

4. SPECTRAL RULE FOR POUNDING RESPONSE

Through numerous SLAM analytical studies, the writers found that the non-linear pounding peak response of SDOF as well as MDOF systems is not sensitive to the details of the particular earthquake history as long as the earthquakes have a common spectrum characteristics (Kasai et al. 1990). Based on this, the following method to predict the peak pounding responses were developed.

No Pounding and Fixed Spring Systems. - The technique is based on response spectrum analyses of two basic linear systems (Fig. 9): (1) no pounding system (the building vibrating without contact), and (2) fixed spring system (the building vibrating in continuous contact with the adjacent structure). The peak response of the pounding system is predicted by considering the distribution of earthquake energy in both systems in the form of kinetic energy and strain energy in each linear state. The peak pounding responses of MDOF system are calculated as follows (Kasai et al. 1990):

$$\{u^-\} = \alpha\{u_{np}\} \quad \text{, and} \quad \{u^+\} = \beta\{u_{np}\} + \gamma\{u_{fs}\} \qquad (1)$$

in which $\{u^-\}$ and $\{u^+\}$ = the peak negative and positive displacement vectors, respectively; $\{u_{np}\}$ and $\{u_{fs}\}$ = the peak displacement vectors obtained from commonly used multimode response spectrum analysis of the no pounding system and the fixed spring system, respectively. The separation ratio β is defined as the ratio of the at-rest separation distance divided by the peak displacement of the no-pounding system at the corresponding story level. The α and γ are obtained from simple equations consisting of the kinetic energies as approximately computed using the first modal participation factor and earthquake pseudo-velocity spectra (Kasai et al. 1990). Estimations of the other peak pounding responses such as drifts, shears, and OTM's can be made in a similar manner.

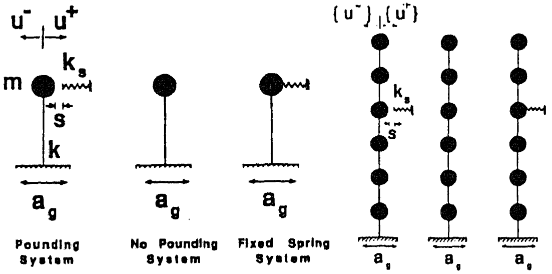

Fig. 9: Proposed Theory on Pounding.

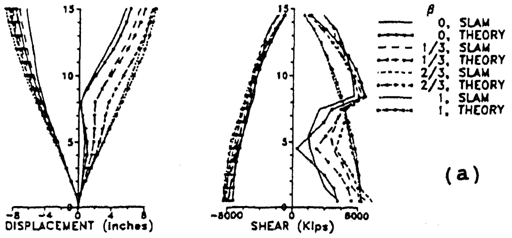

Fig. 10: Theory vs. Average of SLAM-Analysis Results (Six Artificial Earthquakes, 0.4g).

Accuracy. - The theory was verified by more than 700 cases (Kasai and Patel 1990) comparing the theoretical results to those from SLAM analyses for SDOF systems as well as MDOF systems. Fig. 10 illustrates the good accuracy of the theory for predicting MDOF pounding system peak response for various separations in a mid-height pounding case and a top pounding case, respectively. Note that vertical location of pounding significantly influences the distribution of story peak responses through the height of the building, and that the shears remain almost the same with the separation ratios from 0 to 2/3.

5. BUILDING APPURTENANCES RESPONSE

The writers observed damage to building appurtenances such as electrical and mechanical equipments, building parapets, and curtain walls which was caused by pounding of buildings during Loma Prieta earthquake (Type-3 damage, Sec. 2). As discussed earlier (Fig. 7(a)), the peak floor accelerations can be more than 10 times those from the no-pounding case. It was also found that a rigid adjacent building case gives the results similar to those from a relatively heavy flexible adjacent building case. The following studies consider the rigid adjacent building case (Kasai et al. 1990).

Floor Acceleration Response Spectra. - The floor acceleration response spectra (FARS) at the top pounding level of the 15-story building are shown in Fig. 11. They indicate that pounding is especially harmful for equipment or secondary systems having short periods ($\leq$1.0 sec). This effect is not covered by existing industrial design spectra. For example, see the Network Equipment-Building System (NEBS) design spectrum given by Bell Communication Research (BELLCORE 1988), which is very close to the FARS of no-pounding case. The FARS in the pounding case can be as much as 30 times higher than those in no-pounding case. Based on these, the commonly considered method of designing the secondary systems to have shorter periods to reduce the system response may be effective only when no pounding occurs, but would be significantly unconservative in a pounding condition.

Neglecting the effect of damping, the acceleration $\ddot{u}_i$ of i-th pounding level during pounding (State 2) is approximately expressed from equilibrium as:

$$\ddot{u}_i = [\, V_{i+1} - V_i - k_s(u_i - s) \,] \,/\, m_i \qquad (u_i > s) \qquad (2)$$

where V_i, u_i, and m_i = story shear, displacement, and mass of the i-th floor level, respectively, k_s = local contact stiffness (Fig. 6), and s = at-rest separation distance. The writers have found that the peak $\ddot{u}_i$ at State 2 is approximately obtained by substituting into Eq. 2 the peak V_i, peak V_{i+1}, and peak u_i that are estimated using the simplified method explained earlier (Eq. 1).

The writers have also found that the ratio between pounding FARS and no-pounding FARS, hereby defined as a spectrum amplification, remains very stable regardless of different separation ratios (0 to about 2/3) and earthquakes types (Fig. 12) (Kasai et al. 1990). Because of this effect and considering Eq. 2, a simplified method of obtaining pounding FARS seems possible.

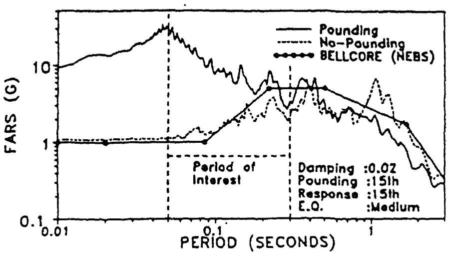

Fig. 11: FARS, Floor Acceleration Response Spectra (15-Story Building).

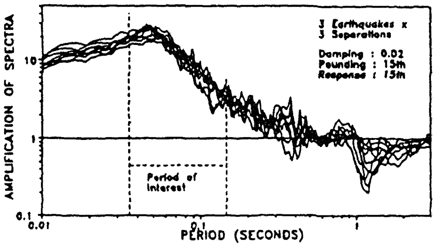

Fig. 12: FARS (due to pounding) Normalized to FARS (due to no-pounding), 15-Story Building.

6. ANALYSIS OF DAMAGED BUILDINGS

The writers are conducting correlative pounding analyses of actual buildings damaged during Loma Prieta earthquake. The following describes one of the sample analytical studies:

Pounding between the 10 story building and 5 story building explained in Sec. 2 was analyzed (see Fig. 1). The building pounded near the corner of the buildings (Fig. 13). A 3D-dynamic analyses were performed using SLAM-2. Fig. 14 shows an analysis result using a 2-directional earthquake motion (0.16g) recorded near the study buildings during the Loma Prieta event. Note the large shear above pounding level and large torsion developed due to pounding. Very small drift at the 2nd level of the 5 story building is due to large stiffness provided by the shear wall (see Sec. 2). The pounding analysis results appear to explain the observed damage.

Other existing buildings are also being studied (e.g., see Kasai et al. 1991).

7. SEISMIC GAP REQUIRED TO AVOID POUNDING

Spectral Difference Method. - Based on random vibration theory and considering a first mode approximation for displacements of elastic multi-story buildings, the writers have found a simplified method to obtain an accurate estimate of the required building separation, s, to preclude pounding. In contrast to the commonly known spectrum modal combination method, it is called a "spectral difference method". The method considers the difference of vibration phase between the adjacent buildings. i.e.,

$$s = \sqrt{u_A^2 + u_B^2 - 2\,\rho_{AB}|u_A|\,|u_B|} \qquad (3)$$

In which u_A and u_B are the peak lateral displacements at the possible pounding location under the no pounding condition in Building A and B, respectively, the magnitude of which are simply obtained by the commonly used spectrum approach. The ρ_{AB} is a cross-correlation coefficient that determines significance of in-phase motion between different vibration modes (see Sec. 8, also), and is obtained by substituting the fundamental periods and damping ratios for Buildings A and B into the expressions such as given by Der Kiureghian (1980). The Eq. 3 is analogous to the double sum combination (DSC) rule commonly used in response spectrum analysis, except that a "minus" ρ_{AB} instead of a "plus" ρ_{AB} is used. It is found that the proposed spectral difference rule is much more accurate than other combination rules such as square-root-of-sum-of-squares (SRSS) rule (i.e., $s = \sqrt{u_A^2 + u_B^2}$) or the absolute sum (ABS) rule (i.e., $s = |u_A| + |u_B|$). The use of ABS rule is specified by SEAOC/UBC (1990). The writers also extended the rule for inelastic structures. See more details in the writers' other papers (Jeng et al. 1992, Kasai et al. 1992).

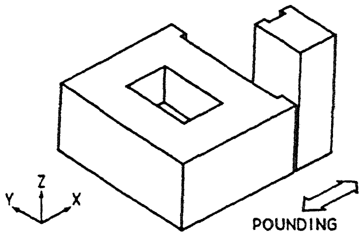

Fig. 13: Existing Buildings Damaged.

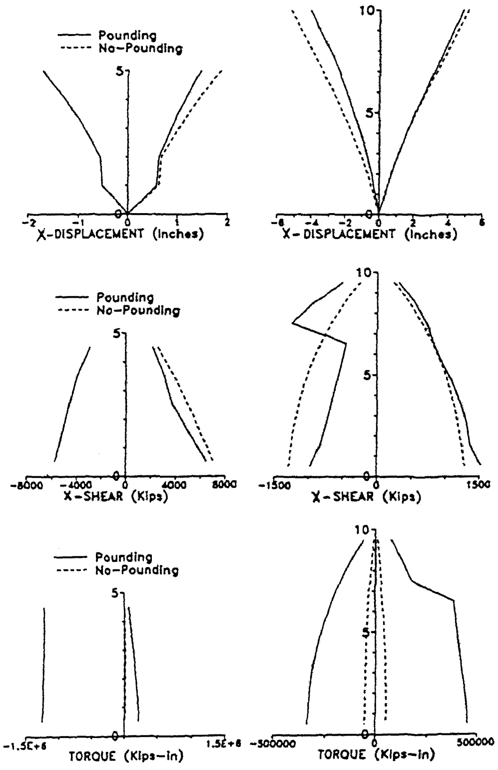

Fig. 14: Peak Pounding Responses of Existing Buildings Due to 2-Directional Loma Prieta Earthquake Motion.

8. DAMPERS FOR POUNDING MITIGATION

The writers are currently studying various pounding mitigation techniques. One promising technique is to insert viscoelastic or viscous dampers in the closely spaced adjacent buildings thereby increasing their damping properties substantially.

Fig. 15 compares the displacements of the 8th levels of the 15-story building and 8-story building discussed in Sec. 3, assuming that no pounding occurs between them. Note that with 5% damping ratio (Fig. 15(a)) maximum displacements of the buildings at the 8th levels are 5.3 and 5.6 inches, whereas with 20% damping ratio (Fig. 15(b)) they are 3.3 and 3.1 inches, respectively. Accordingly, the maximum displacements of 20% damping case are about 60% of those in 5% damping case. Note also that 20% damping case shows prominent in-phase motion of the two buildings in spite of different periods of the buildings (1.13 sec. and 0.8 sec., respectively). The resulting maximum relative displacement in 20% damping case is 2.6 inches, merely 38% of that in 5% damping case (i.e., 6.8 inches). This occurs, since out-of-phase motion of the buildings caused mainly by free vibration is damped out due to high damping, and in-phase motion closely following the earthquake excitation history dominates (i.e., forced vibration dominates the response). Note that these interesting effects are accurately estimated using the spectral difference method discussed in Sec. 7.

Sample pounding analyses were conducted assuming 1.5 inches gap between the buildings. Responses under 5% damping and 20% damping are compared. Earlier Fig. 8 shows a significant benefit of increased damping for pounding mitigation, in which all the pounding response quantities in 20% damping case are much smaller than those in 5% damping case, and they are even significantly smaller than no-pounding response in 5% damping case.

In summary, the dampers placed inside the adjacent buildings have the potential to significantly reduce the effect of pounding due to the following reasons: (1) they reduce the maximum displacement of the buildings, (2) they promote in-phase motion of both buildings, and (3) should the pounding occur, the impact is absorbed by the dampers in the vicinity of pounding level, thereby preventing propagation of its effect to other story levels.

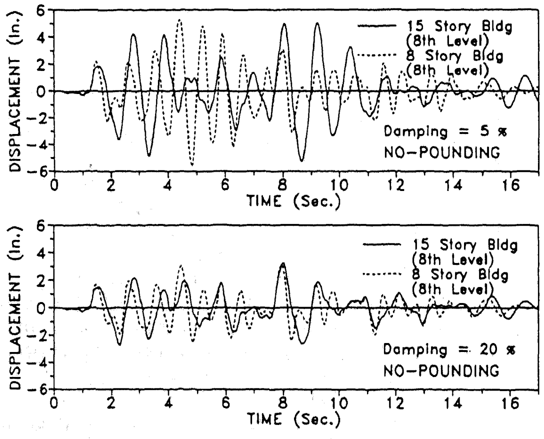

Fig. 15: Displacement Histories of Adjacent Buildings in (a) 5% Damping Case, and (b) 20% Damping Case.

9. CONCLUSION

Pounding is a more severe load condition than the case where it is ignored. Continued research is urgently needed in order to provide the engineering design profession with practical means to evaluate and mitigate the effects of pounding. Pursuant to this need, the writers are conducting further research on pounding.

ACKNOWLEDGEMENT

The study presented here is supported by the United States National Science Foundation (NSF) and 3M Company. The cognizant NSF program officials are Dr. Shih-Chi Liu and Dr. Henry J. Lagorio, and 3M official is Dr. Edmond J. Nielsen. The supports are gratefully acknowledged.

REFERENCES

Bell Communication Research 1988. "Network Equipment-Building System (NEBS) Generic Equipment Requirements", Issue 3, Piscataway, NJ 08854-4196.

Bertero, V.V. 1986. "Observation of Structural Pounding," Proc. Internat. Conf.: The Mexico Earthquake - 1985, ASCE.

Jeng, V., Kasai, K., and Jagiasi, A., "The Separation to Avoid Seismic Pounding", Proc. 10WCEE, 1992.

Der Kiureghian, A. 1980. "A Response Spectrum Method for Random Vibrations", EERC Report, 80/15, Earthq. Eng. Res. Center, U. of Calif. Berkeley.

Kasai, K., Maison, B.F., and Patel, D.J. 1990. "An Earthquake Analysis For Buildings Subjected to a Type of Pounding," Proc. 4th U.S. Nat. Conf. Earthq. Eng.

Kasai, K., Jeng, V., and Maison, B.F. 1990. "Significant Effects of Pounding Induced Accelerations on Building Appurtenances," Proc. Seism. Design and Perform. of Equipmt. and Nonstruct. Compts. in Bldgs. and Indust. Structs., Appl. Tech. Council Seminar ATC-29.

Kasai, K., and Patel, D. 1990. "A Proposed Method of Evaluating Response For a Type of Collision Between Buildings", IIT-CE-91-02, Illin. Inst. of Tech.

Kasai, K., and Maison, B.F. 1991. "Structural Pounding Damage," Reflections on the Loma Prieta Earthquake of October 17, 1989, Chapter 6, Struct. Engnrs. Assoc. of Calif.

Kasai, K. and Maison, B.F. 1991. "Observation of Structural Pounding Damage from 1989 Loma Prieta Earthquake", Proc. 6th Canad. Conf. on Earthq. Eng.

Maison, B.F., and Kasai, K. 1990. "Analysis for Type of Structural Pounding," J. of Struct. Eng., ASCE, 116(4).

Maison, B.F., and Kasai, K. 1988. "SLAM: A Computer Program for the Analysis of Structural Pounding". Nat. Inf. Serv. for Earthq. Eng., U. of Calif.

Maison, B.F., and Kasai, K. 1990. "SLAM-2: A Computer Program for the Analysis of Structural Pounding". Nat. Inf. Serv. for Earthq. Eng., U. of Calif.

Rosenblueth, E., and Meli, R. 1986. "The 1985 Earthquake: Causes and Effects in Mexico City," Concrete International. 8(5).

Struc. Engrs. Assoc. of Calif. (SEAOC), Reccommended Lateral Force Requirements and Commentary, Sacramento, Calif., 1990.