*7th Canadian Conference on Earthquake Engineering / Montreal / 1995*
*7ième Conférence canadienne sur le génie paraséismique / Montréal / 1995*

# Pounding Analysis of a Two Story Building during the 1989 California, Loma Prieta Earthquake

V. Latendresse[1] and C.E. Ventura[2]

## ABSTRACT

Pounding effects resulting from torsional response of an instrumented building during the 1989 Loma Prieta Earthquake are investigated in this paper. The building investigated is a two-story, moment resisting steel frame office building in Oakland, California. Although the building is symmetric in plan, reinforced masonry walls attached to the frame on two sides of the building force the center of rigidity towards one of the corners of the structure. The building was severely excited during the Loma Prieta earthquake, reaching peak accelerations of about 0.7g, and the records show strong evidence of torsional response. The recorded motions at one of the corners of the first floor show the effects of pounding with an adjacent one-story building. In addition to the strong motion records, data from forced and ambient vibration tests conducted in the late sixties provide excellent information to assess the dynamic characteristics of the building at different levels of excitation. A three dimensional computer model was developed and adjusted to fit the recorded strong motion data. The fit included matching accelerations, velocities and displacements at certain locations where instruments were located. The effects of pounding were investigated using specialized software packages. The results showed that due to the asymmetry of the lateral force resisting system, this building was heavily excited in torsion that caused it to pound on the adjacent structure and that this behaviour could be represented adequately reproduced by computer model.

## *INTRODUCTION*

Building pounding refers to the contact of two adjacent structures during an earthquake. Typically, pounding occurs in urban areas where, because of the high property values, the separation between two adjacent structures is relatively small when compared to their height. There are many factors that increase the risk of two buildings colliding with each other during a seismic event: small initial separation between buildings, acute differences in structural properties, asymmetric placement of lateral load carrying elements, etc. The effects of pounding on the structures vary greatly. It can cause from very light architectural and structural damage to total loss of building function because of the destruction of major structural components (SEAOC, 1991). The various building codes of North America have just recently started to address the problem of structural pounding and there are only a few tools available to help predict accurately the effects of pounding on structures.

---

[i] Research Assistant, Dept. of Civil Engineering, University of British Columbia, B.C., V6T 1Z4.
[ii] Assistant Professor, Dept. of Civil Engineering, University of British Columbia, B.C.

In this study, we developed a three dimensional computer model and adjusted it to match the recorded motions of a two-story building during the Loma Prieta earthquake. Two different models, one that considers pounding and one that does not, were used to assess the effects of the pounds on the recorded motion.

## BUILDING DESCRIPTION AND STRONG MOTION DATA

The building studied is a two story office building situated in Oakland, California. It is situated on the north-east corner of a street intersection and is adjacent to a three story building to the north and, more interestingly for us, a single story building to the east of it. The plan dimensions of the building are 49.7 *m* by 46.6 *m*, the first story height is 4.3 *m* and the second story height is 4.4m (see Fig. 1).

The building was constructed in 1965 using moment resisting steel frames and the its principal lateral load resisting components are two continuous 200 *mm* thick concrete brick walls on the east and north side of the building. Although this building was designed in 1964, the steel column to beam connections were carefully detailed and provide almost rigid connections. The asymmetric placement of the masonry walls produce a building with severe torsional eccentricity. The center of rotation of the structure is situated at the north-east corner of the building, which was confirmed by the results of experimental ambient and forced vibration tests conducted in 1965 (Bouwkamp, J.G., Blohm, J.K. 1966). These tests also identified the two first natural frequencies (2.35 *Hz* and 7.72 *Hz*) and corresponding mode shapes of the almost completed building. In addition, the California Strong Motion Instrumentation Program (CSMIP) instrumented this building in 1974 with ten accelerometers as shown in Fig. 1..

The 1989 Loma Prieta earthquake severely excited this building. The processed acceleration records in Fig. 1 illustrate that the structure was subjected to ground accelerations up to 0.26*g*. A peak structural response of 0.69*g* was recorded by channel number *3* situated at the south-east corner of the roof. The high frequency peaks in the acceleration time history of channels *3* and *5* indicate that the building pounded with the adjacent one story structure. The impacts are concentrated in the strong motion part of the record between 10 and 20 seconds. It is hard to judge precisely the number of impacts just by looking at the processed records, since a lot of the sharp peaks are smoothed by the filtering process of the recorded motions. The main blows are easily detectable but the smaller ones become masked. Although not shown here due to space limitations, the "raw" analog records show the occurrence on the pounds more convincingly. The evidence of pounding was observed by a post-earthquake visual survey of the building by one of the authors. This inspection determined that the pounding was concentrated at the south-east corner of the first floor where an accelerometer was located. Altogether, the building performed very well under the heavy seismic loading and further investigations found that there was practically no breakage to the structure except at the pounded corner (McClure, 1991).

Analyses of the motion of the structure during the earthquake were done by frequency domain analysis using Frequency Response Functions (FRFs) between various combinations of recorded acceleration records. For instance, to enhance the recorded torsional motion characteristics of the structure, pairs of channels from opposite sides of the building were subtracted and the results were used

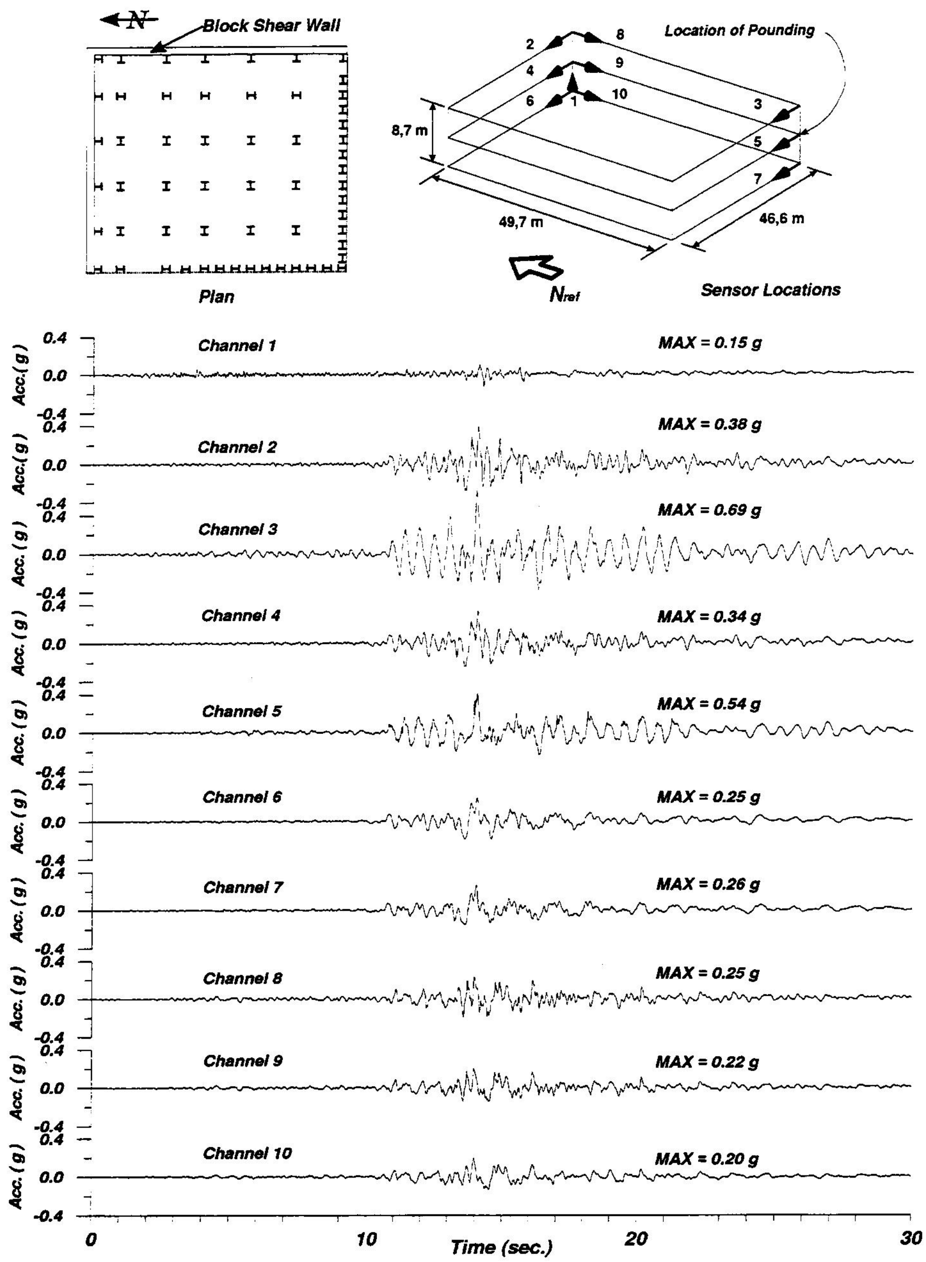



***Figure 1: Plan View, Sensor Locations and Recorded Accelerations***

for the analysis. The torsional response of the first floor was determined by subtracting the records from channels *6* and *7* at the ground level and subtracting the records from channels *4* and *5* at the first floor. The first set was then considered as input and the second set as output so that the FRF function of the torsional response could be calculated. The amplitudes of the resulting FRF of this analysis for the complete record are shown by the thick line in Fig. 2. It was discovered that three major peaks at 1.6, 1.75, and 1.87 *Hz* were present in the amplitude function at a lower frequency than the calculated first mode frequency (2.35 *Hz*) from the experimental results. This was surprising, and warranted further study to explain their presence.

The three close peaks in the analysis of the complete record seemingly illustrate a shift in the frequency of vibration of the structure during the strong motion shaking. It was decided to isolate, or window, certain parts of the record to try to pick up this shifting. The results for three different windows are shown in Fig. 2. During the early part of the strong motion shaking (11-20 seconds) the peak, at 1.6 *Hz*, is well represented and as time moves on, the frequency of the structure increases to the free vibration frequency of 1.87 *Hz* in the late part of the record. This frequency was interpreted to be the fundamental frequency of the building. The lower frequency of the structure during the 11-20 second period is caused by the pounding, which seemed to disturb the "normal" pattern of vibration of the building by either adding the one story building's mass to the system or by absorbing some energy from the motion. As the intensity of the pounds lessens, the frequency shifts up to its final value represented in the free vibration portion of the record. The overall lowering of the first natural frequency is probably due to the fact that as a structure grows older more and more occupational dead load is present thus increasing the dynamic mass.

If the peak at 1.87 Hz represented the fundamental frequency of the building, such a large drop in value compared to the forced vibration tests results is not easily accountable by the loss of stiffness of the non-structural elements of the building. Furthermore, had the building suffered significant structural damage, a significant drop of the value of the fundamental frequency could be easily explainable. However, as it was mentioned before, there was no reported structural damage to the building, and therefore a significant change of natural frequency is not justifiable.

## *COMPUTER MODEL AND CORRELATION*

A computer model was developed using the *SUPER-ETABS* (NISEE, 1985) structural analysis program. This program can be used with the *SLAM-1* (Maison B.F., Kasai K. 1988) post-processor to take into account pounding. A preliminary model was formulated using original blueprints of the building. The member sizes were directly taken from the plans and the mass calculated as the bare frame's plus a nominal occupation dead load. The first natural frequency obtained from this first attempt was quite close to that of the forced vibration test done in 1965.

Three input motions were used: translation in the North-South and East-West axis direction as well as rotation around the Vertical axis. The computer model's first natural period of vibration was adjusted by increasing the dead load so that the period matched as closely as possible the free vibration period obtained from the strong motion analysis. The damping of the first mode was taken as *5%* of

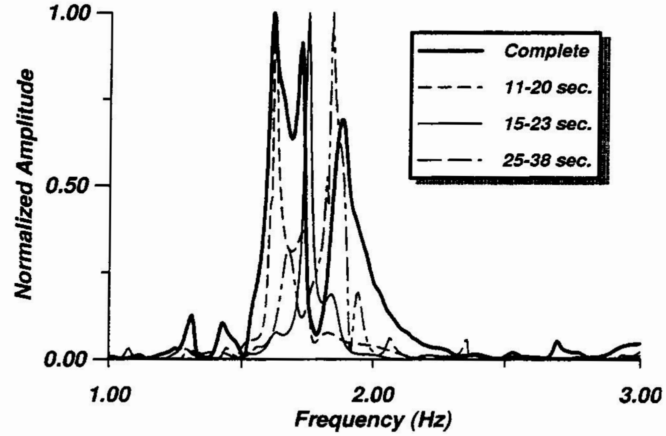
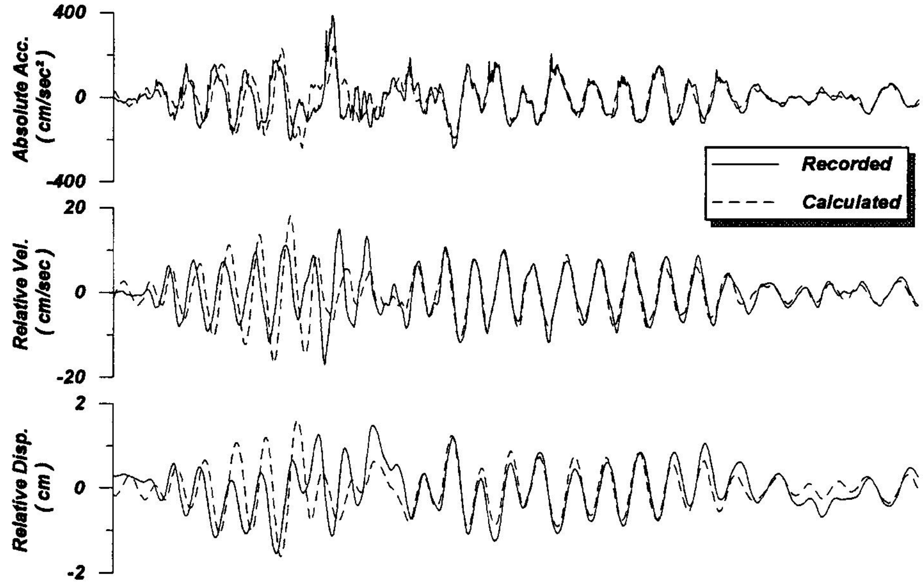


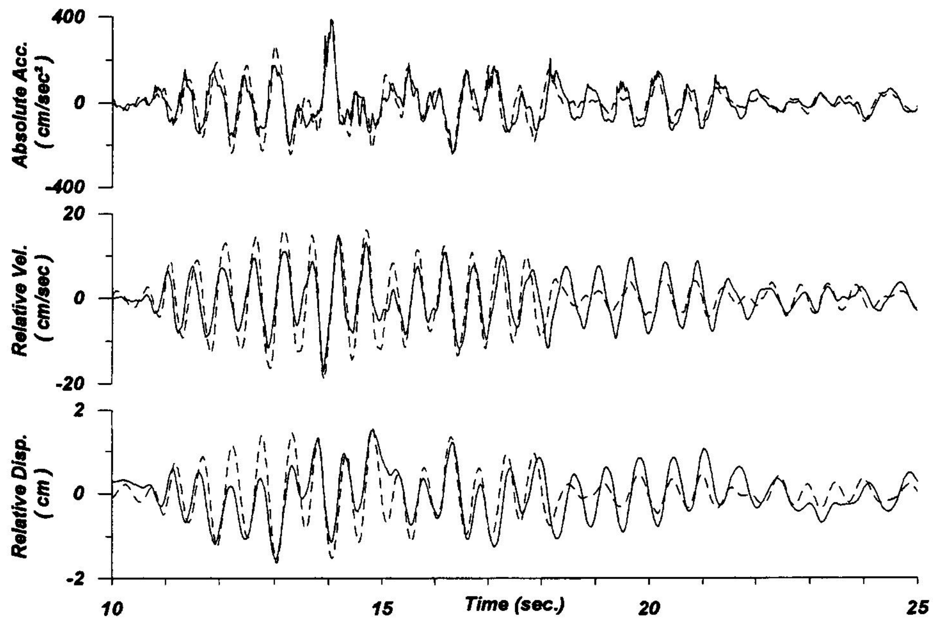

***Figure 2: Normalized FRF Amplitude vs. Frequency***

critical and for all other modes it was set at 8%. These values are a little higher than the one's quoted in the test results by Bouwkamp and Blohm, but equivalent viscous damping usually increases with the level of shaking. After a few iterations, the match between computed and recorded acceleration by channel *5* during the later part of the record was quite good. It was found that the East-West and North-South input motions contributed a great deal to the structural response at that location, and the structure primarily responded in its first mode of vibration. The rotational input motion was small in comparison to the others and was not critical to the gross matching of the records. The asymmetric placement of the structure's lateral force resistance components and the resulting shift of position of the center of rigidity made the translational and torsional components of the first mode highly coupled. The building was essentially rotating around it's north-east corner, both translational inputs produced significant twisting motion. This proved to be a major problem for the pounding analysis since the *SLAM-1* post-processor only accepts input motion in one direction because of its calculation assumptions. Hence, the total building response could not be well represented. The model was consequently modified so it could be executed with *ETABS ver.6.0* (Habibullah A., 1994) a structural analysis program that contains a non-linear gap element, a linear spring with an initial non-contact distance, and accepts simultaneous input motions in two directions. This permitted a much better representation of the problem.

Two types of analysis were done; one taking into account the pounding, one that did not. The calculated and recorded motions are both included in the graphs shown in Fig. 3. The absolute acceleration time history of the no-pounding case in Fig. 3a, shows a good match in the later part of the plot and that the model is deficient only when the pounding is strong. In contrast, when the pounding is included in the analysis, the first part of the acceleration plot matches very well, but when the hard pounds die down, the fit degrades. This may indicate that there was a shift in the system properties. The




*a) No Pounding Case*




*b) Pounding Case*

***Figure 3: Comparison of Time Histories***

linear spring used to represent the pounding is probably not sophisticated enough to represent the situation at such a refined level. Also, it is believed the additional rotational input that could not be included, would provide an improved simulation. Nevertheless, all the major trends of the accelerogram are well represented and the model replicates the recorded motion quite well.

The comparison between recorded and calculated motions is not as satisfactory for the relative velocity and relative displacement time histories. When the pounding is included, the variation in the recorded and calculated values seem to be more in phase. Overall, the match is not nearly as good as for the accelerations. The computer model might be deficient in some way and it is not reproducing one of the trends of the system. Another source of difference may be the effects of the algorithms used to process the recorded accelerations and to compute the associated velocities and displacements. The records were processed by CSMIP using an Orsmby filter with a high-pass ramp at 0.09 to 0.18 *Hz* and a low-pass ramp between 23 to 25 *Hz*. A change in these parameters may result in somewhat different velocities and displacements. It is for this reason that the correlation effort concentrated on the acceleration records.

The local changes in properties detected by the fitting procedure are very hard to asses. Conventional signal processing procedures are of little help since they tend to represent general trends in the records and not particular ones like pounding. Further study is being conducted using the wavelet transform, since this method can analyze the temporal variation of the frequency content of the signal. This will permit an accurate tracking of individual pounds and might lead to a better understanding of the pounding effects.

## CONCLUSIONS

- The structure response was modified by pounding with the adjacent 1-storey building. This results in a shift of the first natural frequency of vibration. To represent this feature of the response, the time domain signals were windowed before the Frequency Response Functions were calculated. Individual peaks in the FRF of the complete records could then be isolated. Pounding seemed to temporarily lengthen the apparent period of the building.

- For this case study, the ability of the computer program to simulate pounding effects of an asymmetric building subjected to two simultaneous, orthogonal input motions permitted to achieve a good match between the computed and measured motions.

- The correlation of relative velocities and relative displacements time histories were not as satisfactory as the acceleration. Either the computer model is not reproducing a trend of the system or the numerical processes used to integrate recorded accelerations have a significant influence when pounding occurs.

- Some local changes in the properties were detected by the time domain matching of the recorded and calculated signals of channel *5*. These changes are hard to quantify using conventional methods. Further analysis will require the use of more sophisticated methods.

## *ACKNOWLEDGEMENTS*

Partial funding for this study was provided by a research grant from the Natural Sciences and Engineering Research Council of Canada (NSERC). Valuable discussions with Dr. Andreas J. Felber and Mahmoud Rezai during the course of this study are acknowledged with thanks.

## *REFERENCES*

Bouwkamp, J.G., Blohm, J.K. 1966. *Dynamic Response of a Two Story Steel Frame Structure.* Bulletin of the Seismological Society of America. Vol. 56, No. 6, pp. 1289-1303.

Habibullah, A., 1994. *ETABS User Manual.* Computer and Structures, Inc., Berkeley, CA.

Maison, B.F., Kasai K. 1988. *SLAM User Manual.* National Information Service for Earthquake Engineering, University of California, Berkeley, Ca.

McClure, F.E. 1991. *Analysis of a Two Story Oakland Office Building During the Loma Prieta Earthquake.* Proceedings of SMIP91, Sec. 13.

NISEE/Computer Applications. 1985. *SUPER-ETABS User Manual.* EERC, University of California, Berkeley, CA.

SEAOC. 1991, *Reflections on the Loma Prieta Earthquake October 17, 1989.* Ad Hoc Earthquake Reconnaissance Committee, Structural Engineers Association of California, Sacramento, CA. pp. 91-112.