*Paper No. 2105. (quote when citing this article)*
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

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# AN EXPERIMENTAL STUDY ON THE SEISMIC POUNDING OF BUILDINGS

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## ABSTRACT

Shake table tests of pounding between adjacent 3 and 8-storey single-bay steel framed model structures were carried out. The pounding response of the frames was measured for various earthquake intensities and initial separations. The experimental results were compared to the predictions resulting from two existing pounding analysis programs. The solution strategy of the first program, SLAM-2, is based on a modal superposition technique. The second program, PC-ANSR, is a nonlinear time-step analysis code in which an elastic gap element has been included. Modelling the pounding effect by elastic gap elements in the two programs produced accurate displacement and impact force results. Predictions of high amplitudes and short duration acceleration pulses are very sensitive to the mass distribution at the point of contact. Relative rotations between adjacent floors induced grinding contacts which cannot be captured by uni-axial gap elements.

## KEYWORDS

Impact; Pounding; Shake Table; Tests.

## INTRODUCTION

Valuable insights on the problem of pounding have been obtained recently from analytical studies. So far, the proposed analytical models have not been validated experimentally. This paper presents the results of shake table tests of pounding between adjacent 3 and 8-storey single-bay steel framed model structures. The experimental results are compared with the predictions resulting from two existing microcomputer pounding analysis programs.

## TEST FRAMES

Two adjacent 1/8 scale single-bay moment resisting steel framed models, one 3-storey the other 8-storey, were tested under uni-axial seismic exicitations on the 3 m x 3 m earthquake simulator of the Earthquake Engineering Research Laboratory at the University of British Columbia in Vancouver, Canada. The two structures were designed individually, at their reduced scale, according to the static method of the 1990 edition of the National Building Code of Canada (NBCC, 1990). An elevation view of the two test frames is presented in Fig. 1.

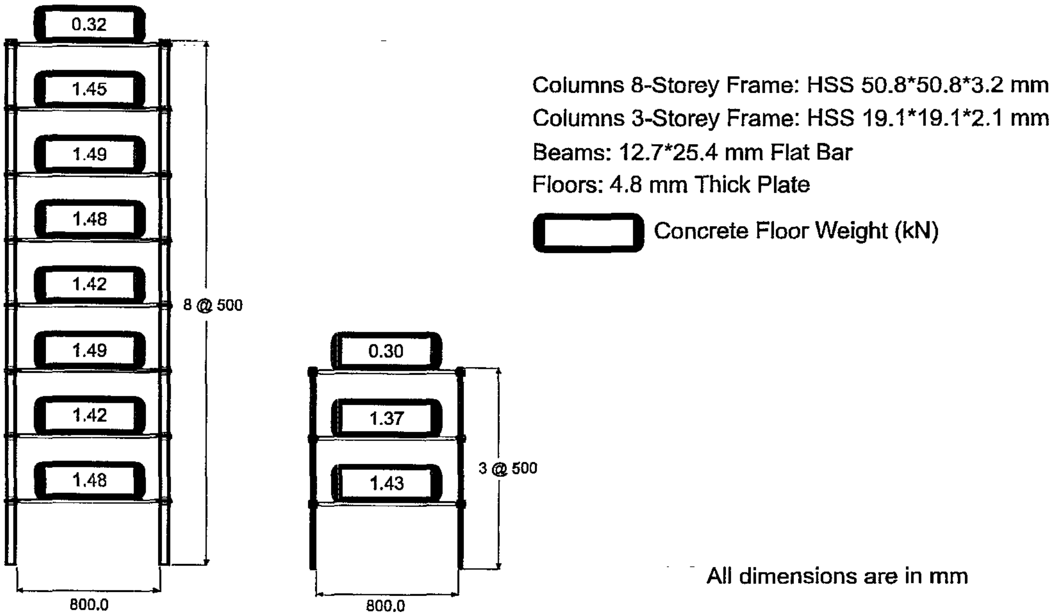


Fig. 1. Test Frames.

The overall floor plan dimensions of both models are 0.8 m x 0.8 m. The 8-storey frame is 4 m high, while the height of the 3-storey frame is 1.5 m. The columns of both models are made of steel tubes, while the beams are represented by rectangular flat steel bars. At each floor, a 4.8 mm thick steel plate was bolted on top of the peripheral beams to provide a rigid diaphragm behaviour. To represent a rigid foundation, each column was fully welded to a 150 mm x 150 mm x 19 mm thick base plate. Each plate was attached to the shake table surface by six 19 mm bolts to insure complete base fixity of the models.

The mass of the models was simulated by three stacks of concrete blocks attached to the steel plate diaphragm at each floor. These blocks were connected to each floor plate by two threaded rods (6 mm in diameter) passing through each stack and floor plate. These rods were pre-stressed between the top of the stack and the under-side of the floor plate. The tolerances between the block and floor plate holes were reduced to a minimum to prevent sliding between the blocks. The general arrangement of the two test frames, in place on the shake table, is shown in Fig. 2.

## IMPACT ELEMENTS

Three special impact elements were designed to measure the impact force time-histories between the first 3 levels of the frames. The general arrangement of the impact elements is shown in Fig. 3.

Each impact element consists of two different components: a hammer and a receiver. The hammer is made of a steel tube bolted at its ends to the exterior beam-column connections of the 3-storey structure. A threaded top, at the centre of the tube, provides the impact force and allows adjustment of the initial separation between the two frames. The receiver is made of a similar tube whose ends are connected to a 125 mm long aluminum load cell. These load cells are in turn bolted to the exterior beam-column connections of the 8-storey frame. A system of light cables, linking the receivers to the fourth floor of the 8-storey structure, ensures that the load cells are free of bending. Compressive static tests were performed on each impact device to determine the element axial stiffness employed in the numerical studies (Filiatrault et al. 1995). On the basis of these tests, an element axial stiffness of 12.8 kN/mm was used in the 2-dimensional numerical studies.

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Fig. 2. Test frames on shake table.

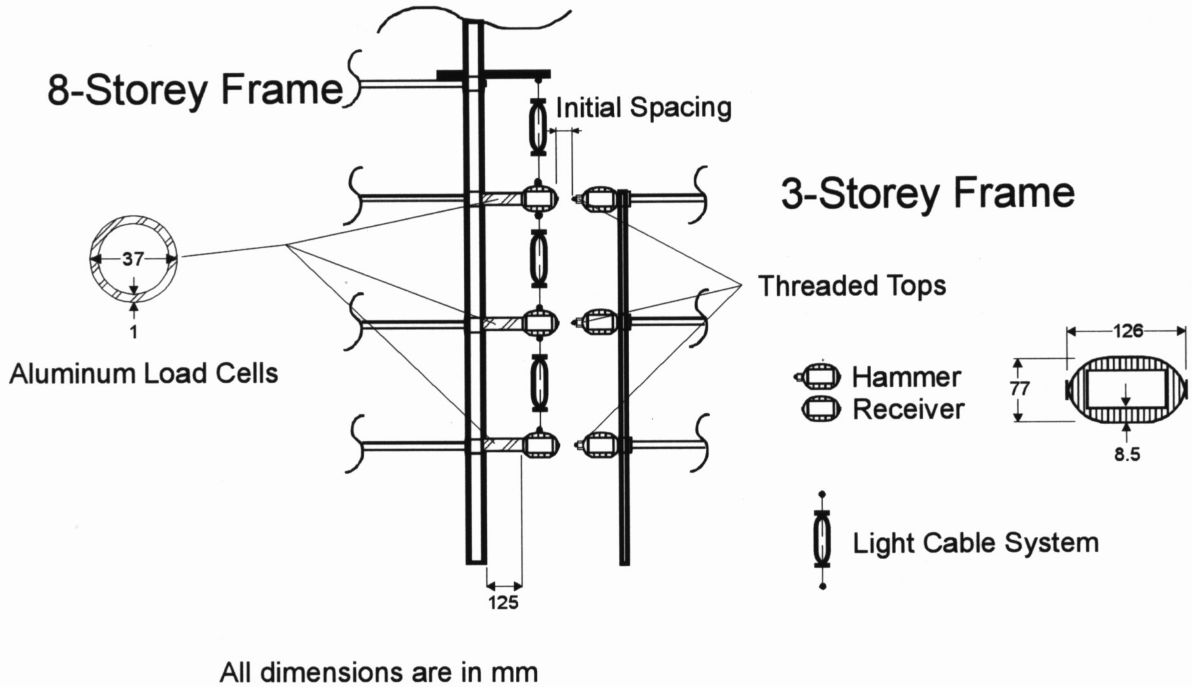



Fig. 3. Impact elements.

## TEST SERIES

The first 10 seconds of the acceleration time-history corresponding to the well known 1940 El-Centro record (S00E component) was selected as the input for the shake table tests. The earthquake intensity, expressed by the Peak Horizontal Acceleration (PHA), was adjusted to provide different levels of shaking of the models. The overall experimental program consisted of 34 different tests incorporating various structural configurations, initial building separations, and earthquake intensities (Filiatrault et al., 1995).

PRELIMINARY TESTS

Several preliminary tests were carried out on the model frames to determine their basic dynamic properties at the no-pounding and pounding states. For the no-pounding condition, the two structures were tested separately. To simulate the pounding state, the hammer and receiver of the third floor impact element were bolted together to simulate the dynamic characteristics at the times the roof of the 3-storey frame is in contact with the third floor of the 8-storey structure. The fundamental natural periods and damping ratios obtained from these preliminary tests are summarized in Table 1. As expected, the fundamental period of the linked system lies between the periods of the uncoupled structures.

Table 1. Experimental fundamental natural periods and damping ratios.

| Structural Configuration | Period (s) | Damping (%) |
|---|---|---|
| 3-Storey (No-Pounding) | 0.341 | 1.0 |
| 8-Storey (No-Pounding) | 0.605 | 1.5 |
| 3-Storey/8-Storey (Pounding) | 0.567 | 1.6 |

EXPERIMENTAL RESULTS

The envelopes of maximum absolute horizontal accelerations measured for two different structural configurations, floor-to-floor and floor-to-column impacts, and excited by the El-Centro earthquake scaled to a PHA value of 0.50 g are shown in Fig. 4. For the no pounding situation, the peak acceleration recorded on the 8-storey structure was just above 2.5 g, which represents a PHA amplification of 5.0. For the pounding cases, the results are drastically different. When the adjacent structures have similar floor elevations, short acceleration pulses of up to 12.0 g were produced in the 8-storey structure at an elevation equal to the roof level of the adjacent 3-storey frame for both initial separations (0 and 15 mm). Very large acceleration peaks of 15.0 and 23.0 g were also recorded at the roof level of the 3-storey structure, for spacing of 0 and 15 mm, respectively. The situation is even worse when the roof of the 3-storey frame collides with the fourth floor columns of the 8-storey structure.

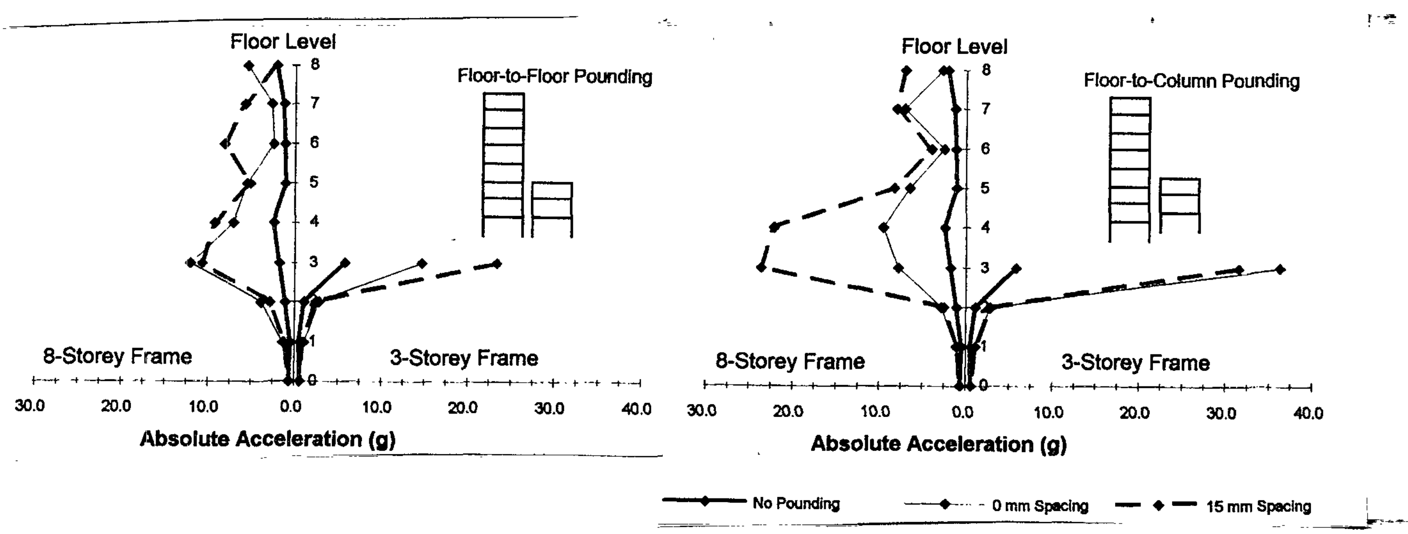



Fig. 4. Envelopes of absolute accelerations for PHA = 0.50 g.

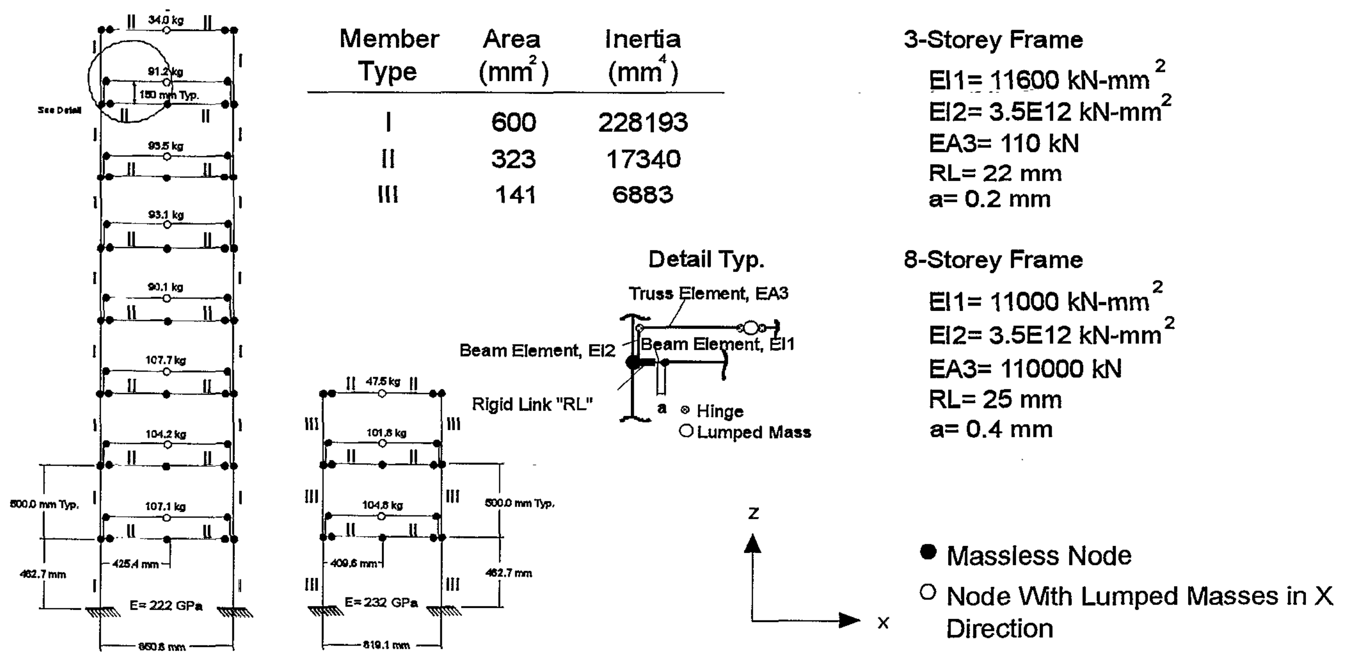
## NUMERICAL STUDY

The predictive capabilities of two existing microcomputer structural pounding analysis programs were evaluated in this study. Both programs consider the pounding effect by an elastic gap element, which introduces a linear elastic compressive spring between predetermined nodes when contact is detected.

The first program, SLAM-2, considers two colliding linear-elastic buildings (Kasai et al., 1991; Maison and Kasai, 1990). The collisions are assumed to take place only at a single location specified by the user (usually the roof of the shorter building). The solution strategy of this program is based on a modal superposition technique and involves two different uncoupled linear elastic states. In the first state, the buildings vibrate by themselves. In the second state, the buildings are in contact through a single elastic compressive spring. During the analysis process, the program first determines whether there is contact or not and then calculates the response by solving the corresponding linear problem. This program uses the dynamic characteristics of each building, generated by the computer program SUPER-ETABS (Maison and Neuss, 1983), to perform the pounding analysis.

The other program considered, PC-ANSR (Maison, 1992), is a microcomputer version of the well known nonlinear time-step analysis ANSR-1 code (Mondkar and Powell, 1975). An elastic gap element has been implemented for pounding analysis. The program can consider collisions between several adjacent nodes.

A 2-dimensional computer model was developed for each test structure as shown in Fig. 5. These models were calibrated, based on preliminary test results, to match the experimental responses for the no pounding case (Filiatrault et al., 1995). The purpose of this calibration was to isolate the pounding effect for the evaluation of the capabilities of the two different pounding analysis programs.




| Member Type | Area ($mm^2$) | Inertia ($mm^4$) |
|---|---|---|
| I | 600 | 228193 |
| II | 323 | 17340 |
| III | 141 | 6883 |

Fig. 5. Numerical Models.

## COMPARISON BETWEEN ANALYTICAL AND EXPERIMENTAL RESULTS

Figure 6 compares analytical and experimental relative displacement time-histories at the top of the 3-storey frame for a PHA = 0.15 g and an initial separation of 0 mm. The amplitude and phase are very well predicted by both computer programs. The PC-ANSR predictions are in better agreement with the experimental results than the SLAM-2 predictions. For this situation, it was observed during the tests that pounding occurred between the three floor levels. The SLAM-2 idealization assumes impacts take place only between the third floor levels, while PC-ANSR considers collisions between the three levels.

The experimental and analytical time-histories are not symmetrical with respect to the zero displacement axis. This result shows that the adjacent 8-storey structure prevents large deformations of the 3-storey frame.

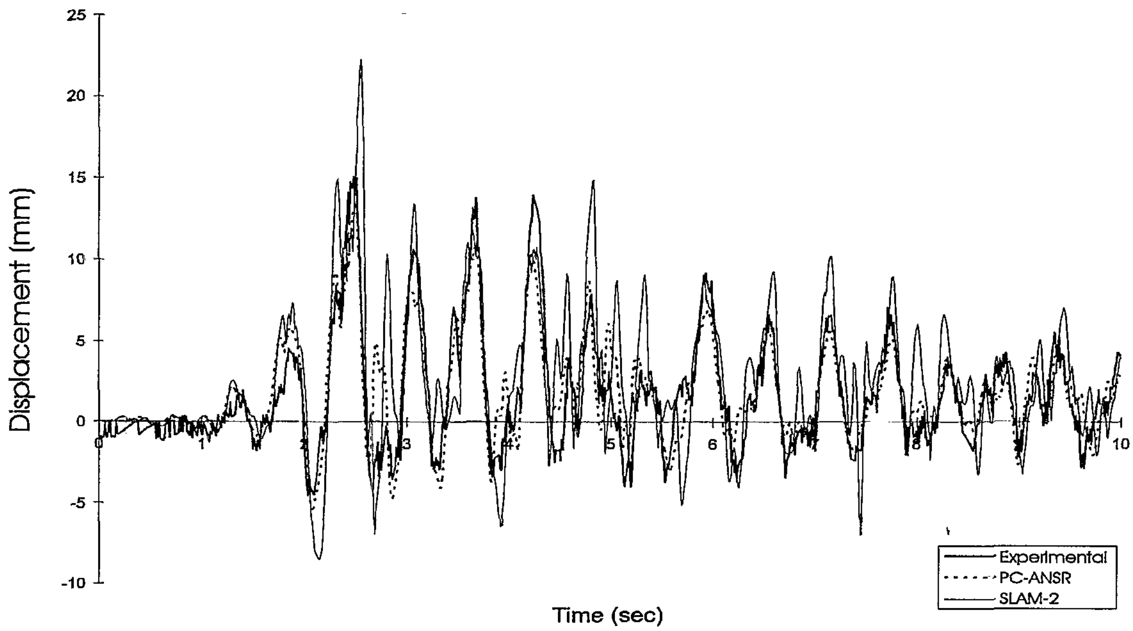



Fig. 6. Relative displacement time-histories at top of 3-storey frame, PHA = 0.15 g.

Figure 7 compares two absolute acceleration time-histories obtained numerically with PC-ANSR at the top of the 3-storey structure for a PHA = 0.15 g and an initial separation of 15 mm. The first history is for all the masses lumped at the centroid of the concrete stack at each floor, as shown in Fig. 5, with the contact nodes being massless. This history is contaminated by very high frequency vibrations as soon as the first impact occurs. The second history is obtained when only 1% of the storey mass is lumped at the contact nodes. The presence of this small mass stabilize the response after contact occurs. This result illustrates that the mass distribution has a major influence in a numerical pounding model.

The third floor impact force time-histories for an initial separation of 15 mm are presented in Fig. 8 for the calibrated models with similar floor elevations. Only four impacts occurred within the first 5 seconds of the response. No impact was recorded between the first and second floors. The times and amplitudes of the contact forces are well predicted by both programs. The experimental curves exhibit a double contact for each impact. After reviewing video and sound tapes of the tests, it was established that this phenomenon was related to the rotations of the beam-column joints, which caused a relative angle between the hammer and the receiver at the moment of impact. This misalignment prevented a clean longitudinal contact. Rather, a grinding impact was observed, which lengthened the contact time. This behaviour cannot be captured by the numerical simulations using a purely axial spring element. Also, some tensile forces were recorded in the load cells. This tension results from the axial vibration of the receiver unit of the impact element which acts as a spring-mass system. Introducing an axial spring in series with the lumped mass of the tubular section in the numerical model yields tension in the spring elements as obtained experimentally (Carr, 1995).

The third floor impact force time-histories for no initial separation between the two adjacent buildings with similar floor elevations are presented in Fig. 9. The SLAM-2 idealization allows only one impact element to be incorporated in the analysis. This element was specified at the roof of the shorter building. Therefore, the impact forces between the first and second floors cannot be predicted by the SLAM-2 model. Despite this limitation, the impact force time-history predicted by the calibrated SLAM-2 model between the third floors still correlates well with the experimental data. The correlation of the PC-ANSR predictions with the measured contact forces is also reasonable.

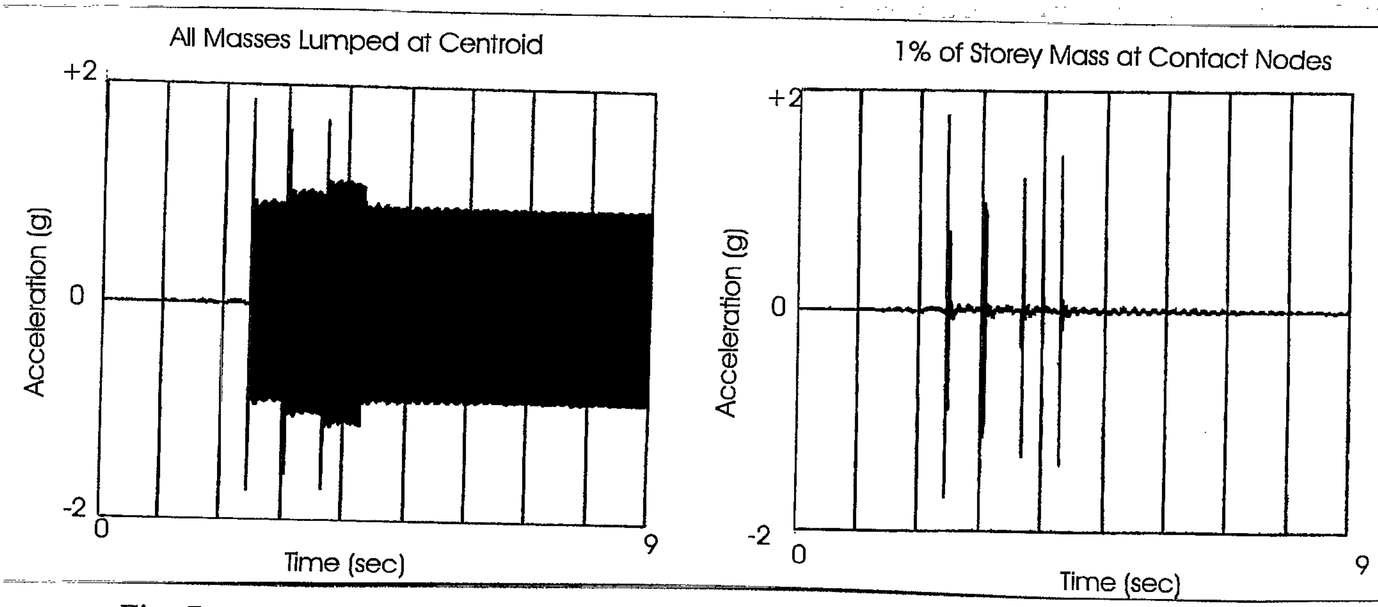



Fig. 7. Numerical absolute acceleration time-histories at the top of the 3-Storey frame, PHA = 0.15g, 15 mm spacing.

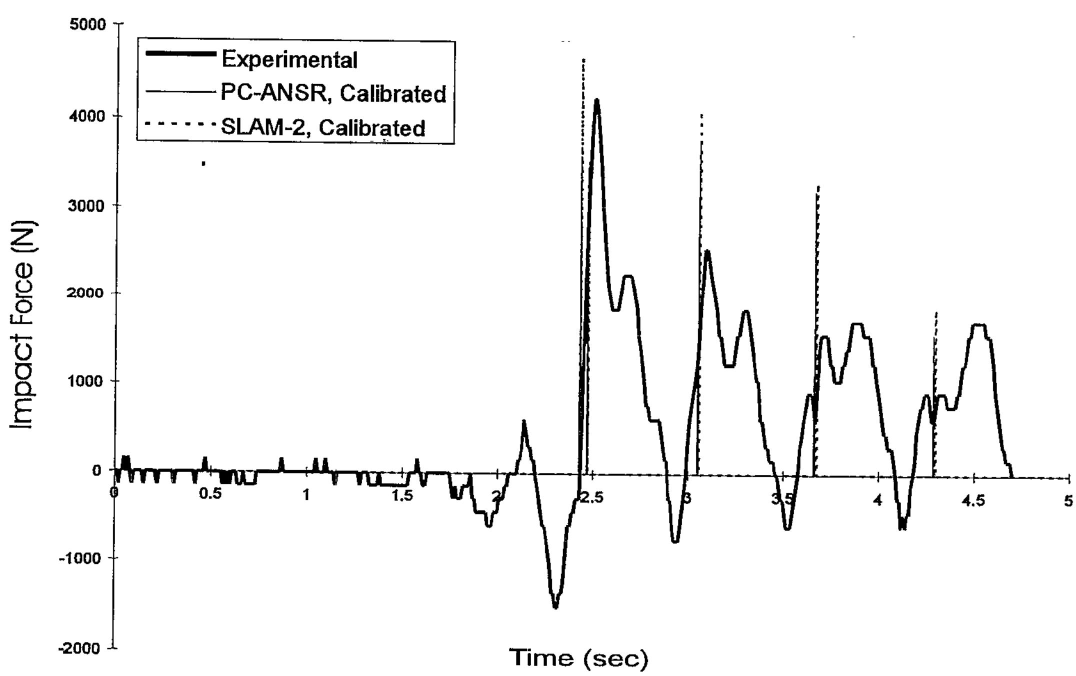



Fig. 8. Third floor impact forces time-histories, PHA = 0.15g, 15 mm spacing.

The amplitudes of the impact forces are significant. A maximum impact force of about 7 kN was recorded between the third floor levels when the structures were initially in contact. This value corresponds to 225% of the weight of the 3-storey frame. The corresponding figure for the 8-storey structure is 66%. The maximum forces are not strongly affected by the initial separation. The initial separation has a major effect, however, on the number of impacts between adjacent floors. When the initial separation was zero, more than 15 series of impacts were recorded by the load cells. When the frames were separated by a 15 mm gap, the number of impacts reduced to only 4.

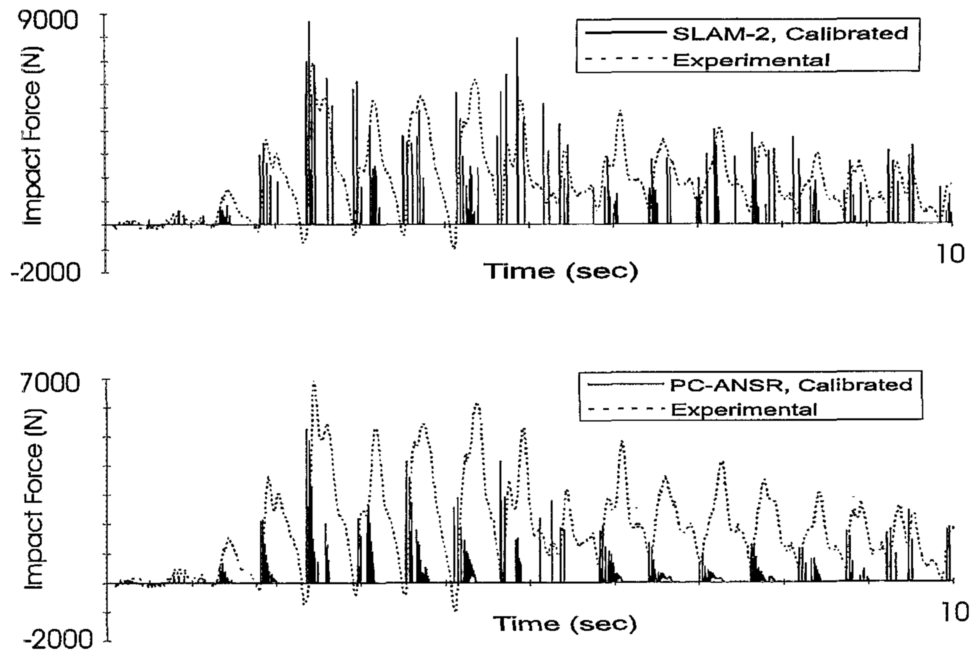



Fig. 9. Third floor impact forces, PHA = 0.15 g, 0 mm spacing.

## CONCLUSION

The results of shake table tests between building models have provided an opportunity to evaluate the predictive capabilities of 2 microcomputer pounding analysis programs: SLAM-2 and PC-ANSR. Modelling the pounding effect by elastic gap elements produces accurate displacement and impact force results with respect to both amplitude and phase. Amplitude and phase of short acceleration pulses at locations experiencing pounding are very sensitive to the mass distribution at the contact nodes. The multiple grinding contacts observed experimentally during impact were caused by relative rotations between adjacent beam-column joints. This behaviour cannot be properly modelled by uni-axial gap elements.


## ACKNOWLEDGEMENTS

The authors acknowledge the assistance of the Natural Science and Engineering Research Council of Canada (NSERC) which provided research grants and a post-graduate scholarship in support of this project.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