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

Seismic pounding retrofits for closely spaced buildings

F.M. Lavelle & R. H. Sues
Applied Research Associates, Raleigh, N.C., USA

ABSTRACT: Structural retrofits that reduce damage caused by the pounding of closely spaced buildings during earthquakes are investigated. Because of the serious potential for structural pounding in many urban areas, there is a need for safe and efficient pounding retrofit systems. Two types of energy-dissipating pounding upgrades are studied: (1) hysteretic links and (2) viscous dampers in parallel with hysteretic links. The adjacent buildings are modeled as weak-beam/strong-column structures. Uncertainties in ground motions and structural properties are treated via Monte Carlo simulation. The retrofits are found to consistently provide substantial reductions in localized pounding damage without adversely affecting the overall seismic response of either adjacent building. Furthermore, the retrofit designs are robust with respect to loading and structural modeling uncertainties.

1 INTRODUCTION

Impact of adjacent buildings during earthquakes, known as seismic pounding, has been a contributor to structural damage and collapse in almost every major earthquake that has struck an urban area. For example, pounding contributed to damage in more than one hundred structures in the San Francisco Bay area during the 1989 Loma Prieta Earthquake (Kasai and Maison, 1991), and in the 1985 Mexico earthquake, pounding was identified as present in over 40% of the 330 collapsed or seriously damaged buildings in Mexico City (Rosenblueth and Meli, 1986). Because building separations in urban areas are often insufficient to preclude pounding, there is a need for safe and economical retrofitting methods to reduce structural pounding (Bertero, 1986).

The overall goal of this research program is to develop strategies for retrofitting closely spaced buildings to reduce the potential for damage due to seismic pounding, while minimizing the modifications to the existing structural system. The immediate objective of the research covered in this paper was to assess the feasibility of installing retrofits which we shall refer to as pounding reduction devices (PRDs). To meet this objective we focused our research on: (1) reviewing the extent of pounding damage potential in the U. S., (2) PRD hardware options, (3) PRD installation configurations, and (4) evaluation of PRD effectiveness via a nonlinear response analysis ethodology that includes treatment of uncertainty.

Previous numerical studies of structural pounding have focused on specific cases such as elastic multi-degree-of-freedom (MDOF) structures (Kasai, *et al.*, 1991; Maison and Kasai, 1990; Lavelle, 1990; Westermo, 1989) or inelastic single-degree-of-freedom (SDOF) buildings (Anagnostopoulis, 1988; Wada *et al.*, 1984). Other related works include: Bertero and Collins (1973); Mahin, *et al.* (1976); and Wolf and Skrikerud (1980).

The basic concept for the PRDs modeled in our pounding simulations is illustrated in Figure 1. As the schematic shows, the device is a link between the buildings that can be a hysteretic spring, a viscous damper, or both. The PRD serves three major purposes: maintaining building separation, limiting load transfer between buildings, and energy dissipation. The first purpose of the PRD is to produce forces that help maintain a constant building separation distance. That is, the PRD partially restrains the buildings from converging or separating. In this sense, the PRD is similar to previously proposed rigid or elastic links (Newmark and Rosenblueth, 1971; Westermo, 1989). However, the forces developed in rigid or elastic links can potentially lead to increased seismic damage even though pounding is avoided or reduced. Thus, the second purpose of the proposed inelastic link PRDs is to limit the link forces to levels that are within the existing lateral load capacities of the adjacent buildings. By limiting the peak link forces, the PRD can be designed for installation without upgrading the existing lateral load carrying systems of the buildings. The third purpose of the PRD is to dissipate energy. Inelastic links and/or viscous devices are used to damp the relative motions of the buildings at the PRD level. This concept has previously been applied to control the seismic response of widely separated office buildings (Kobori, *et al.*, 1988), but Lavelle (1990) and Sues,

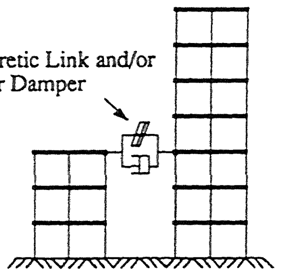


Figure 1. Schematic representation of pounding reduction device concept.

et al. (1991) are apparently the first studies of energy dissipating links as a means of controlling structural pounding.

2 CANDIDATE PRDs AND INSTALLATION METHODS

2.1 *PRD Concepts*

After an extensive literature review of structural energy dissipation devices, we were able to identify more than twenty potential PRD concepts. These concepts can be grouped into five categories: (1) metallic devices that dissipate energy through yielding; (2) viscoelastic material devices wherein the restoring force is proportional to the velocity at which the material is strained plus an elastic displacement proportional component, so that energy is dissipated via viscous damping; (3) frictional devices that dissipate energy by overcoming non-recoverable frictional forces; (4) fluidic damping devices wherein the restoring force is proportional to the strain rate and energy is dissipated through viscous damping; and (5) magnetic damping that dissipates energy by converting kinetic energy into electricity. Specific examples of energy dissipators in each category are discussed in Sues, *et al.* (1991).

Several criteria were developed for screening the most promising PRD concepts: (1) ability to sustain large force levels (*kips* to tens of *kips*) and dissipate large quantities of energy over short displacements; (2) ability to meet large stroke requirements; (3) ability to sustain many cycles of loading without degradation of mechanical properties; (4) predictable and stable mechanical properties over the range of possible loading amplitudes, displacements, and frequencies; (5) ability to tune the mechanical properties of the device; (6) resistance to weather; (7) low initial cost; and (8) low maintenance cost. The response of many of the leading PRD concepts (*i.e.*, metallic, frictional, and viscous devices) can be adequately modeled with either bilinear, nondegrading hysteretic elements or linear viscous dashpots. Thus, we selected the simple PRD models illustrated in Figure 1 for our pounding simulation studies.

2.2 *PRD Installation*

Several obstacles must be overcome to successfully install PRDs: limited space, unequal floor elevations in the adjacent buildings, disruption of building functionality during installation, PRD compatibility with existing structural systems, *etc.* Figure 2 is a schematic of one approach that we developed for very closely spaced buildings whose floors are not aligned. In this solution a frame is constructed on the roof of the shorter building and the PRD connects the frame to the floor of the taller building.

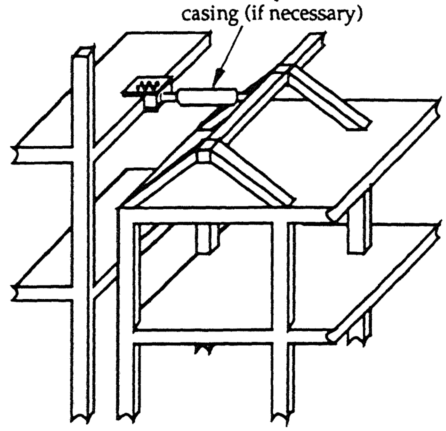


Figure 2. Roof-frame concept for PRD Installation.

3 STOCHASTIC ANALYSIS FOR SEISMIC POUNDING DAMAGE

In order to evaluate the effectiveness of PRDs, we have developed and implemented a special-purpose pounding analysis methodology. The methodology differs from pounding models used in previous studies in several different aspects: (1) inelastic, MDOF structural response models are used; (2) pounding collisions are permitted to occur at every floor level rather than at a single location; (3) in addition to considering stiff collisions between adjacent equal floor levels, soft inelastic collisions between the floor of one building and the wall of the adjacent building were also modeled; and (4) a probabilistic approach is taken since pounding response (with or without a PRD installed) can be sensitive to variability in the earthquake ground motion time history, which is a random process, and variability in the structure properties, which are random variables.

The pounding response analysis procedure is based on a lumped-mass, nonlinear-inelastic structure model that incorporates the essential features of the pounding problem while maintaining computational efficiency needed for performing parametric sensitivity studies and uncertainties analysis. The structural models are inelastic lumped-parameter models with one translational dynamic DOF per story. After initial studies on the pounding response of inelastic shear beam buildings, we selected the more realistic Weak-Beam/Strong-Column (WBSC) for our pounding simulations.

A summary of the eight finite elements used in our pounding simulation code is given in Table 1. The WBSC elements (Elements 7 and 8) both contain rotational degrees of freedom that are condensed out of the dynamic equations of motion since rotational inertia effects are not considered. This static condensation transformation is updated whenever there is a change in the tangent stiffness matrix.

The capability to model random processes and variables has been integrated with the deterministic pounding analysis in the simulation program PROPOUND (PRObabilistic assessment of seismic POUNDing response). Response statistics are generated via Monte Carlo simulation. For each set of pounding simulations, at least 64 time histories were evaluated to obtain reliable estimates of the means and variances of the damage indicators.

Several damage models were investigated for possible use in assessing both the economic and life/safety benefits of installing PRDs. Local and global measures of structural pounding damage were studied. Global damage measures selected for evaluation in the feasibility analyses included: (1) story drift; (2) root mean square (rms) floor accelerations; (3) story shear; (4) story ductility (beams); (5) story hysteretic energy dissipation (beams). Local damage measures included: (1) maximum impact velocity; (2) sum of squared impact velocities (a measure of total impact energy); (3) number of impacts; and (4) floor response spectra.

4 POUNDING SIMULATIONS

The adjacent structures selected for the pounding simulations are three and seven story WBSC buildings (referred to as Buildings A and B, respectively). Analyses were performed for both staggered and equal floor elevation configurations. A schematic diagram of the staggered floor buildings is shown in Figure 3. The buildings were designed according to 1960's era UBC-type requirements (to be representative of typical older buildings) for the zone of highest seismicity. The mean structural parameters were chosen such that Building A remains elastic up to a total static lateral load equal to 7.0% of its weight while Building B begins to yield at a lateral load coefficient of 5.3%. Beam and column stiffnesses and beam moment capacities were modeled as lognormally distributed random variables with 20% coefficients of variation. Impacts between the adjacent buildings were modeled with gap spring elements. For buildings with equal floor heights, the impact stiffness is taken as 30,000 *k/in*. For unequal floor elevations, the impact stiffness was reduced to 300 *k/in* and a limit of 100 *k* was placed on the impact force. Complete details of the structural design and modeling are given in Sues, *et al.*, (1991).

Simulation studies were performed to investigate the effect of different types of idealized PRDs for several different situations. Table 2 summarizes the pounding simulation studies performed on the example buildings. Except for Case g, the buildings were assumed to have essentially no initial separation distance (*i.e.*, 0.1 *in*). In Case g, the initial separation distance was set at the mean separation needed to completely avoid pounding (with no PRD installed) for the 0.2 *g* earthquake ensemble (*i.e.*, 1.1 *in* initial separation). As discussed earlier, two generic types of PRDs were used in each case: a yielding bilinear hysteretic energy dissipator, called PRD 1, and a yielding device in parallel with a relatively small

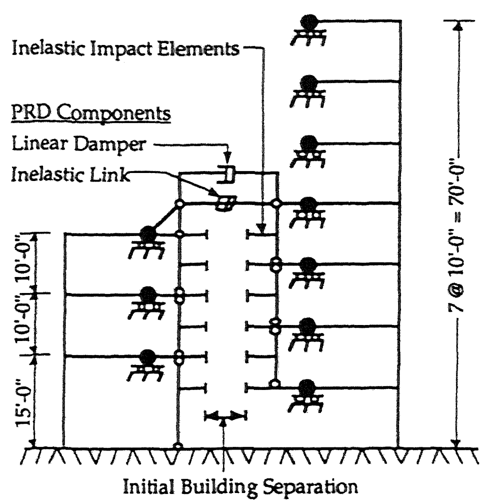


Figure 3. Example WBSC adjacent buildings with unequal floor heights and PRD retrofits.

Table 1. Finite Element Library.

Element	DOF	Description/Use
1. Bilinear spring	2	PRD for equal floor buildings or columns in SBWC buildings
2. Bilinear link	3	PRD for buildings with unequal floor levels
3. Bilinear impact	2	Collision element for equal floor levels
4. Bilinear impact link	3	Collision element for unequal floor levels
5. Linear dashpot	2	Concentrated damping element
6. Linear dashpot link	3	Concentrated damping link
7. Linear beam	4	Column elements in WBSC buildings
8. Bilinear torsional spring	1	Beam elements in WBSC buildings

dashpot, called PRD 2. In most cases, the yielding device was assigned an initial stiffness of 1000 *k/in* with a yield force of 75 *k*, and the dashpot was assigned a damping rate of 5 *k-s/in*. For each case, the simulations were also executed without PRDs to generate the "No PRD" pounding response and the "No Pounding" or uncoupled building responses (*i.e.*, assuming wide building separation). Artificial ground motion ensembles having mean peak ground accelerations of 0.2 *g* and 0.4 *g* were generated to excite the adjacent buildings. The earthquake motions were generated using the Clough and Penzien (1975) power spectrum modulated by an Amin and Ang (1968) intensity function. Firm soil conditions and a strong motion duration of 8 *sec* were assumed. A few key results are described below.

Table 2. Summary of WBSC Pounding Simulations.

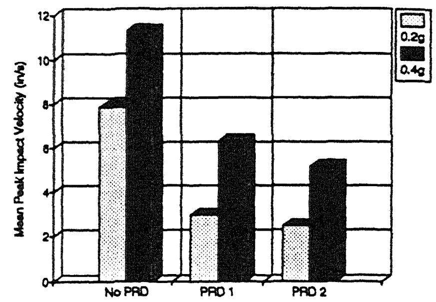
Case	Description
a	Basic Pounding Example
b	Deterministic Structural Properties
c	Unequal Floor Levels
d	Elastic Buildings
e	Elastic PRDs
f	Disproportionate Buildings
g	Intermediate Separation Distance

4.1 *Basic pounding case results -- local damage*

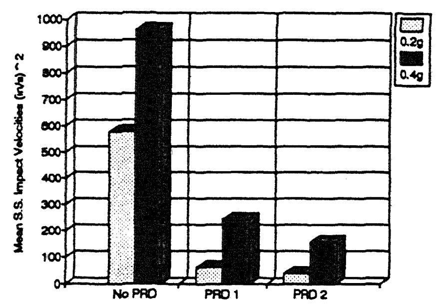
Figure 4 shows that the PRDs significantly reduce both of the primary localized damage indicators: mean peak impact velocity and mean total impact energy (approximated by the sum of the squared impact velocities). For the 0.4 *g* earthquakes in the basic pounding simulations (Case a), installing the PRDs reduces the damage measures by 44 to 84%. The PRDs are even more effective at reducing localized damage caused by the 0.2 *g* earthquakes because the link is better able to maintain building separation in less intense earthquakes.

4.2 *Basic pounding case results -- global damage*

The effect of pounding and PRDs on global structural response was less dramatic than their effect on local response. This result is desirable since we seek to reduce pounding-related damage without adversely affecting the global structural response behavior of either building. Two factors contribute to this behavior: the forces transferred by the yielding PRDs are limited, and the nonlinear ductile response behavior of the buildings tends to attenuate the propagation of the pounding shocks. Installing the PRDs slightly reduces the mean peak story shear forces in every story of both buildings. The reductions range from 2 to 10%.



(a) Mean peak impact velocity.



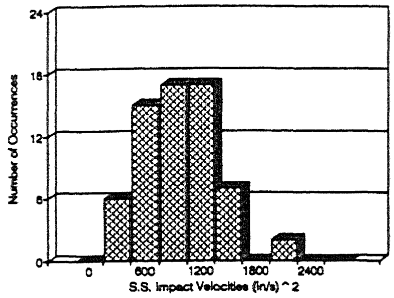
(b) Measure of mean total impact energy.

Figure 4. Mean localized damage indicators for the basic pounding example.

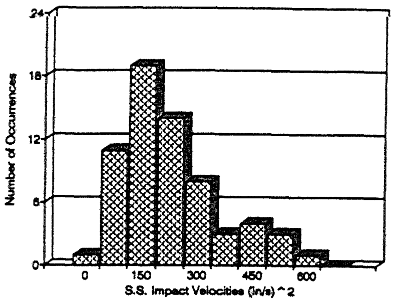
The mean story drifts of Building A (the three-story building) are also reduced by the installation of the PRDs. However, a slight increase (roughly 10%) in drift for Stories 5 through 7 (Building B) is noted for both PRDs 1 and 2. The increase is due to the continuous presence of the link force, which deforms Building B into more of a second mode type of response. The mean ductility demands and energy dissipations in the inelastic beams follow trends similar to those described for the mean story drifts.

4.3 *Effect of added dashpot and uncertainties*

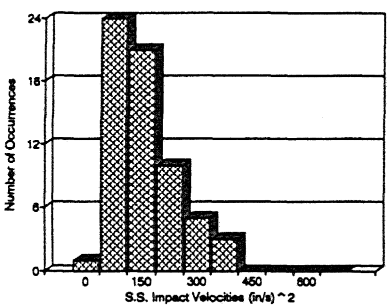
The mean localized damage results (Figure 4) seem to indicate that adding the small dashpot in parallel to the yielding device produces only a marginal benefit for PRD 2 as compared to PRD 1; however, this conclusion should not be drawn. The histograms shown in Figure 5 illustrate both the importance of the dashpot and the importance of considering earthquake ground motion randomness. The histograms show the variability of impact energy over the 64 pounding simulation time histories for Case b (same as Case a, but with deterministic structural properties).



(a) No PRD (Scale = 0 - 2400 in^2/s^2).



(b) PRD 1 (Scale = 0 - 600 in^2/s^2).



(c) PRD 2 (Scale = 0 - 600 in^2/s^2).

Figure 5. Distributions of the sum of the squared impact velocities (a measure of total impact energy) for Simulation Case b.

The narrow spread of the PRD 2 histogram clearly demonstrates how effective PRD 2 is over the range of possible earthquake motions. For PRD 2, damage never exceeds 400 in^2/s^2 (note that the damage axis in the No PRD figure is a factor of 4 greater than in the other figures). Thus, PRD 2 is a more reliable design.

In general, pounding damage is highly variable (*e.g.*, coefficients of variation on the order of 50%), which is indicative of the sensitivity of pounding to the earthquake ground motion time history. *Structural* uncertainties contribute little to the localized damage, story drift, and story shear variabilities; however, structural uncertainties may contribute as much as half of the total ductility demand uncertainty.

4.4 *Floor response spectra as a damage measure*

Another means of measuring damage, in particular to structure contents, is the floor response spectrum. Figure 6 shows a typical set of floor acceleration spectra for Story 3 of Building A (Case a). Although the precise location and amplitude of the high frequency portion of the spectra can be sensitive to the impact element stiffness, the figure demonstrates the effectiveness of the PRDs in reducing the high-frequency accelerations caused by pounding.

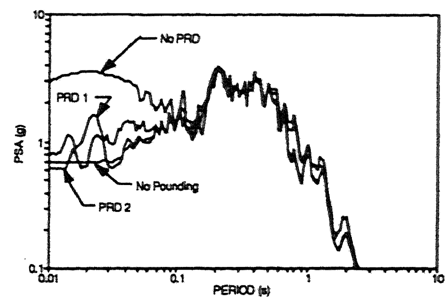


Figure 6. Typical floor acceleration response spectra (Building A, Level 3).

4.5 *Elastic buildings*

In Simulation Case d, the girders in the WBSC building were not permitted to yield. The localized pounding damage for No PRD, PRD 1, and PRD 2 is much more severe in this case. The increase in number and severity of the collisions is due to the higher effective frequencies and response velocities of the linear buildings. These results demonstrate that linear models will overstate the severity of pounding damage for ductile buildings under strong ground motion. The results also demonstrate, however, that closely spaced buildings that are over-designed, or are designed to respond elastically under strong ground motions, would be at increased risk for pounding damage.

4.6 *Elastic vs inelastic link PRDs*

Simulation Case e was performed to compare an elastic link PRD to the inelastic PRD. The stiffness of the elastic link was set equal to the initial stiffness of the inelastic link. Since elastic links can produce much larger building separation forces, one might expect less *localized damage with a non-yielding PRD. Although* the mean peak impact velocities were up to 20% lower with elastic PRDs in the 0.4g earthquakes, total impact energy *increased* by up to 50% and the number of building collisions more than doubled. Furthermore, the mean story drifts, acceleration, and ductility demands are all slightly to moderately larger in the elastically linked buildings than in the inelastically linked buildings. The increases are most significant in the stories of Building B that are above the PRD level.

5. CONCLUSIONS

1. Pounding damage potential throughout the world is large. The severe pounding damage in past earthquakes and the large numbers of closely spaced buildings (*i.e.*, separation distances of less than a few inches) in urban areas are evidence of the pounding damage potential. Practical and reliable pounding damage retrofit strategies are needed to reduce the potential for economic loss and the life safety hazard.

2. PRDs can reduce localized pounding damage in closely spaced buildings without adversely affecting the global structural response behavior of either building. In general, inelastic PRDs are more effective than elastic links because they control the peak forces imposed on the adjacent buildings, in addition to reducing total impact energy.

3. There are many challenges to incorporating PRDs between closely spaced buildings; however, there are a number of approaches that have the potential to meet these challenges, including retrofits for adjacent buildings with unequal floor elevations.

4. Pounding response of adjacent buildings can be very sensitive to uncertainties in ground motion time history. Hence, use of a single earthquake ground motion time history can give misleading results for pounding damage assessment.

5. PRD designs are robust with respect to loading and structural response uncertainties. That is, a single PRD design was found to be effective over the range of earthquake ground motions. In addition, PRDs reduce both the mean and variance of the pounding damage indicators.

6. Buildings with unequal floor levels are particularly vulnerable to pounding damage.

7. Closely spaced buildings that are either over-designed or designed to remain linear and elastic under strong ground motions are particularly susceptible to severe pounding damage. Similarly, the use of linear elastic response models for ductile buildings under strong ground motion is overly conservative for pounding damage assessment.

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance of Dr. K. Kasai in providing pounding damage data and Dr. D. Bergman for sharing his knowledge and database on energy dissipation devices. This research was supported by the National Science Foundation through the Small Business Innovation Research program, Grant No. ISI-9060500, under the direction of Dr. H. Lagorio. This support is gratefully acknowledged.

7. REFERENCES

1. Amin, M. & A.H.-S. Ang, 1968. Nonstationary Stoch Model for EQ Motions, *Eng Mech,* 94: 559-583.
2. Anagnostopoulos, S., 1988. Pounding of Bldgs in Series During EQs, *EQ Eng Struc Dyn,* 16:443-456.
3. Bertero, V.V., 1986. Obs on Struc Pounding, *The Mexico EQs -- 1985, Factors Involved and Lessons Learned,* ed. by Casaro, M. A., Romero, E. M., ASCE.
4. Bertero, V.V. & R. Collins, 1973. Investigation of the Failures of the Olive View Stairtowers During the San Fernando EQ & Their Impl on Seis Des, *EQ Eng Res Ctr,* EERC 73-26, Berkeley, CA.
5. Clough, R.W. & J. Penzien, 1975. *Dynamics of Structures,* McGraw-Hill, New York.
6. Kasai, K. & B.F. Maison, 1991. Obs of Struc Pounding Damage from 1989 Loma Prieta EQ, *6th Canadian Conf on EQ Eng,* Toronto, June 12-14.
7. Kasai, K., *et al.,* 1991. A Study on EQ Pounding Between Adj Struc, *6th Canadian Conf on EQ Eng,* Toronto, June 12-14.
8. Kobori, *et al.,* 1988. Effect of Dynamic Tuned Connector on Reduction of Seis Resp -- Appl to Adj Office Bldgs, *9th WCEE,* 5:773-778.
9. Lavelle, F.M., 1990. *A Lanczos Component Mode Synthesis Algorithm for Locally Nonlinear Systems with Appl to Seis Struc Pounding,* Ph.D. Thesis, Rice Univ., Houston, TX.
10. Mahin, S., *et al.,* 1976. Resp of the Olive View Hosp Main Bldg During the San Fernando EQ, *EQ Eng Res Ctr,* EERC 76-22, Berkeley, CA.
11. Maison, B. & K. Kasai, 1990. Analysis for a Type of Struc Pounding, *J our Struc Eng,* 116:957-977.
12. Newmark, N.M. & E. Rosenblueth, 1971. *Fundamentals of EQ Eng,* Ch. 15, Prentice-Hall.
13. Rosenblueth, E. & R. Meli, 1986. The 1985 EQ: Causes & Effects in Mexico City, *Conc Int'l,* 8:223-24.
14. Sues, R.H., F.M. Lavelle, & B.D. Westermo, 1991. *Res & Dev of an Opt. Device to Reduce Seis. Struc Pounding,* ARA 5655, NSF ISI-9060500.
15. Wada, A., *et al.,* 1984. Collapse of Bldgs with Expansion Joints through Collision Caused by EQ Motion, *8th WCEE,* San Francisco, CA, 4:855-862.
16. Westermo, B., 1989. The Dynamics of Interstructural Connections to Prevent Pounding, *EQ Eng & Struc Dyn,* 18:687-699.
17. Wolf, J.P. & P.E. Skrikerud, 1980. Mutual Pounding of Adj Struc During EQs, *Nuc Eng & Des,* 57:253-275.