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EVALUATION, PREVENTION AND MITIGATION OF POUNDING EFFECTS IN BUILDING STRUCTURES

R.E. VALLES-MATTOX and A.M. REINHORN

212 Ketter Hall, State University of New York at Buffalo
Amherst, NY 14260, USA

ABSTRACT

Critical issues for pounding problems are discussed: critical gap computation, analysis of pounding effects, and pounding mitigation techniques. Statistical linearization techniques are used to determine the correlation coefficient for bilinear structures, and an impact Kelvin element is presented to model impact.

KEYWORDS

Pounding; Energy; Pounding Mitigation; Impact; Statistical Linearization.

INTRODUCTION

During the 1985 Mexico City earthquake, about 40% of the damaged structures experienced some level of pounding, 15% of them leading to structural collapse (Rosenblueth and Meli, 1986). Pounding between two buildings occur when, due to the differences in dynamic characteristics, the structures oscillate out of phase, and the separation between them is insufficient to accommodate the relative displacements. Building codes in areas of active seismicity are concerned with the destructive effects that pounding can induce. The approach adopted by most of the building codes has been to provide a sufficient separation between the structures to avoid impact interactions (Valles, 1995). Nevertheless, at present there is an important number of buildings in major metropolitan areas that do not have adequate separations, and therefore, are prone to pounding damage.

A direct comparison of the building code requirements, of different countries, for critical gap estimation is not possible, because of the different design criteria, seismic risk, construction practice, design earthquake magnitudes, etc. Nevertheless, four different expressions have been used in building codes to calculate the critical gap: $factor(\text{sum of displacements})$, $factor(\text{height})$, fixed distance, or $SRSS(\text{displacements})$. Only the last expression takes into account the fact that the maximum displacements in the structures, in general, do not occur at the same time, and when the structures are approaching each other. However, the SRSS modal combination rule assumes that the response of the structures is uncorrelated, yielding conservative estimates when the responses are somewhat correlated. That is, when the structures have similar periods.

Based on the CQC combination rule, developed by Der Kiureghian (1979) as a simplification for a white noise input, the Double Difference Combination rule was introduced to estimate the critical gap between adjacent structures (Jeng *et al.*, 1992). Using formulas derived from numerical simulations, the method was extended to nonlinear structures. However, some earthquake excitations may differ considerably from a white noise input, such as the 1985 Mexico City SCT record, in which cases, the predominant period of the input motion may have an important influence on the critical gap computations.

The quantification of response amplifications, due to pounding interactions, is of interest to evaluate buildings separated by a gap less than critical. Maison and Kasai (1990) developed two post-processors for the SuperETABS to study the response of buildings subjected to pounding interactions. Anagnostopoulos and Spiliopoulos (1992) developed a program to study the response of multiple adjacent nonlinear structures when subjected to pounding. In parallel, some pounding mitigation techniques have been suggested to reduce undesirable amplifications induced by pounding interactions (Filiatrault and Folz, 1992; Kasai *et al.*, 1993).

In this paper, the energy approach to study pounding problems is briefly described (Valles and Reinhorn, 1996b). The Double Difference Combination rule is then reformulated in terms of energy, and using statistical linearization techniques, the procedure is extended to bilinear structures subjected to narrow band (i.e., Mexico City), or broad band (i.e., Taft), earthquakes. Later, mathematical models to study pounding effects are described, and a modified Kelvin model is introduced to model pounding. To conclude, available pounding mitigation techniques are discussed and compared.

ENERGY APPROACH TO POUNDING

When pounding occurs, an interaction force between the two structures is observed. The presence of this force alters the energy balance in the structures, leading to amplifications or reductions in the response. Therefore, energy is transferred from one structure to the other. An energy formulation to study pounding problems was introduced to calculate the critical gap to avoid pounding interactions, estimate the amplification effects if pounding occurs, and estimate the effectiveness of various mitigation techniques (Valles, 1995). The procedure is summarized in Valles and Reinhorn (1996b).

Consider a single-degree-of-freedom system, with frequency ω, subjected to an earthquake excitation. The response of the system can be visualized using the state space representation (displacement versus velocity over frequency), as shown in Fig. 1a. Using this graphical representation, the distance of any point along the response trace to the origin provides a measurement of the instantaneous structural energy (kinetic plus potential):

$$\frac{E_e}{m}=\frac{1}{2}\omega^2\left(\frac{\dot{u}^2}{\omega^2}+u^2\right)=\frac{\omega^2}{2}r^2\text{; or } r=\frac{1}{\omega}\sqrt{\frac{2E_e}{m}} \tag{1}$$

where u and $\dot{u}$ are the displacement and velocity of the system; and m is the corresponding mass. Therefore, the distance r can be interpreted as the radius of concentric circles defining constant energy levels in the structure. Therefore, changes in r correspond to changes in the energy level of the system.

The maximum experienced distance r (energy level), is referred to as the Pseudo Energy Radius (PER), and denoted as r_{PER}. Some differences between the PER and the commonly used input and viscous energies can be identified. First, the PER is expressed in units of displacement, and not energy. This will prove to be useful to study pounding problems, since r_{PER} can be directly related to the critical gap (g_{cr}), or the actual gap (g_p) between two adjacent structures. The second is that the PER is directly related to the maximum response quantities:

$$u_{\max}=r_{PER} \text{ and } \dot{u}_{\max}=\omega r_{PER} \tag{2}$$

while the other energy measurements are not, since other parameters, such as the duration of the event considerably change these quantities (see Fig. 1b).

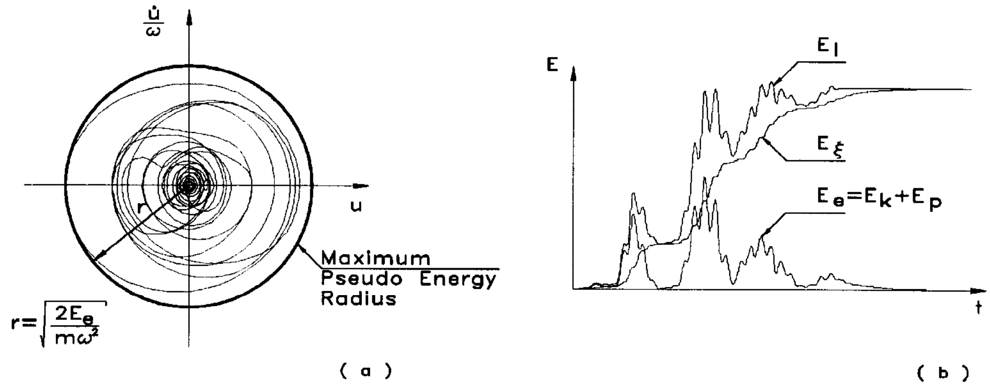

Fig. 1 Maximum Pseudo Energy Radius from a state space representation.

CRITICAL GAP COMPUTATION

The critical gap is defined as the minimum distance to avoid pounding effects. Therefore, the structures may come in contact, but with zero relative velocity. The critical gap (g_{cr}), is calculated using the Double Difference Combination rule (Jeng *et al.*, 1992), rewritten in terms of the PER:

$$g_{cr} = \sqrt{r_{PER1}^2 + r_{PER2}^2 - 2\rho r_{PER1} r_{PER2}} \tag{3}$$

where ρ is the correlation coefficient, and accounts for the phase difference in the response between the two structures. That is, the correlation coefficient controls the maximum overlapping of the energy levels (see Fig. 2).

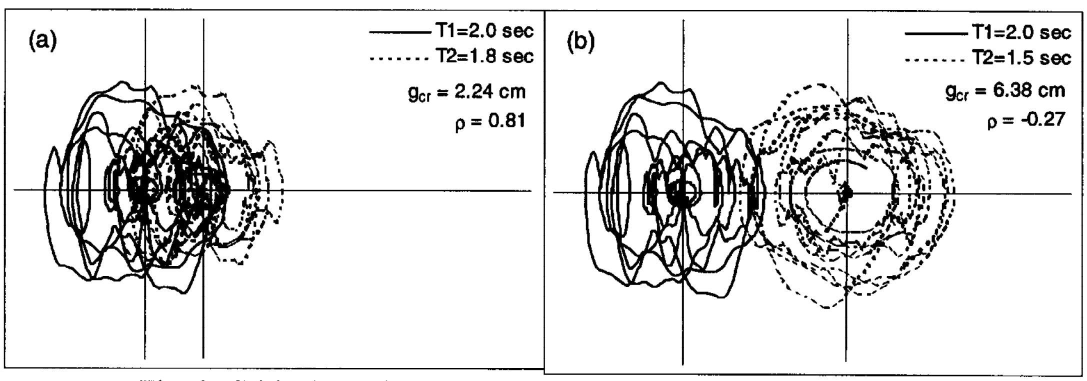

Fig. 2 Critical gap for various structural periods, Taft earthquake.

The correlation coefficient can be approximately calculated according to (Jeng *et al.*, 1992):

$$\rho = \frac{8\sqrt{\xi_1\xi_2}\left(\xi_2 + \xi_1 T_2/T_1\right)\left(T_2/T_1\right)^{3/2}}{\left[1-\left(T_2/T_1\right)^2\right]^2 + 4\xi_1\xi_2\left[1+\left(T_2/T_1\right)^2\right]\left(T_2/T_1\right) + 4\left(\xi_1^2+\xi_2^2\right)\left(T_2/T_1\right)^2} \tag{4}$$

that was derived as a simplification for linear oscillators subjected to white noise excitation. Figure 3a presents the variation of (4) as a function of the critical damping ratio, and the ratio of structural frequencies. Jeng *et al.* (1992) proposed simple formulas derived from numerical simulations, to calculate an effective period, and an equivalent critical damping ratio, for bilinear structures, that can be used with (4). Figure 3b presents the correlation coefficient modified according to Jeng *et al.* (1992) for bilinear structures. However, (4) was derived assuming a white noise input, and, therefore, may not be applicable for narrow band earthquakes, such as the earthquakes recorded in the lake zone of Mexico City.

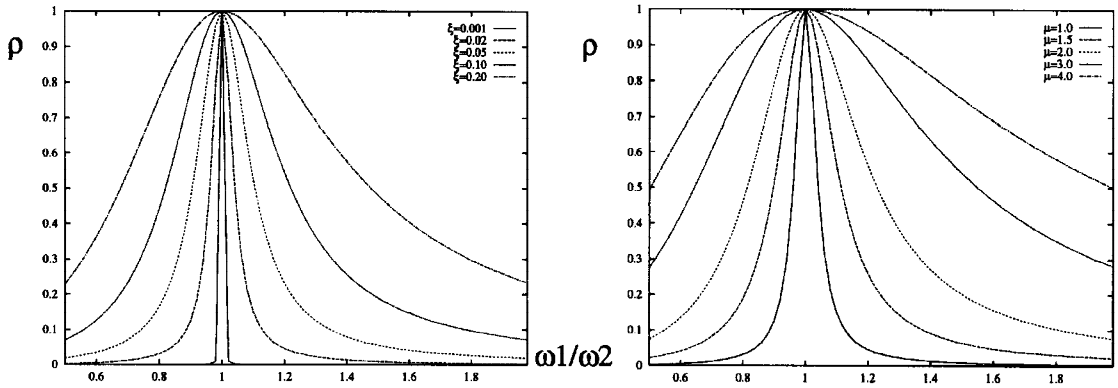

Fig. 3 Correlation coefficient for white noise input: a) linear structures, b) bilinear structures.

CORRELATION COEFFICIENTS FOR BILINEAR STRUCTURES

The response of two bilinear structures subjected to an input $f(t)$ satisfies the differential equations:

$$\ddot{\mu}_1 + 2\xi_1\omega_1\dot{\mu}_1 + \alpha_1\omega_1^2\mu_1 + \omega_1^2(1-\alpha_1)z_1 = f(t)/u_{y1} \tag{5}$$

$$\ddot{\mu}_2 + 2\xi_2\omega_2\dot{\mu}_2 + \alpha_2\omega_2^2\mu_2 + \omega_2^2(1-\alpha_2)z_2 = f(t)/u_{y2} \tag{6}$$

where μ_i is the ductility experienced by structure "i"; u_{y1} is the yield displacement; ξ_i is the critical damping ratio; α_i is the ratio of post-yielding stiffness to initial elastic stiffness. For bilinear oscillators, the functions z_1 and z_2 correspond to the elastoplastic model introduced by Suzuki and Minai (Roberts and Spanos, 1990), that satisfies the differential equation:

$$\dot{z}_i = G_i(\dot{\mu}_i, z_i) = \dot{\mu}_i\left[1 - \mathrm{U}(\dot{\mu}_i)\,\mathrm{U}(z_i - 1) - \mathrm{U}(-\dot{\mu}_i)\,\mathrm{U}(-z_i - 1)\right] \tag{7}$$

where $\mathrm{U}(x)$ denotes the unit step function of x. Note that other hysteretic models can be incorporated in the formulation. The bilinear model was selected because it involves only two additional parameters. Equation (7) can be linearized according to (Roberts and Spanos, 1990):

$$\dot{z}_i = -c_i^e\dot{\mu}_i - k_i^e z_i \tag{8}$$

where the linearized damping and stiffness, c_i^e and k_i^e, are calculated as a function of the response statistics. When $\dot{\mu}_i$ and z_i can be modeled as a jointly Gaussian process, the formulas for the equivalent linearized coefficients simplify (see Roberts and Spanos, 1990).

For a filtered white noise input, the ground motion satisfies the differential equations:

$$f(t) = \omega_g^2 x_g + 2\xi_g\omega_g\dot{x}_g \tag{11}$$

$$\ddot{x}_g + 2\xi_g\omega_g\dot{x}_g + \omega_g^2 x_g = n(t) \tag{12}$$

where $n(t)$ corresponds to a stationary white noise process; ω_g is the fundamental frequency of the ground filter; and ξ_g is the damping in the ground filter. Changing ξ_g different band widths for the input motion can be considered.

The correlation coefficient ρ, for the stationary solution, corresponding to a narrow band input ($\xi_g = 0.05$), is shown in Fig. 4 for three different values of ω_g. Note that some differences can be observed when comparing to the approximate solution (Fig. 3b). For narrow band inputs, the approximate solution yields, in some cases, higher correlation coefficients, underestimating the critical gap size. The approximate solution does not take into account the predominant period of the input motion, that is determinant on the response of structures subjected to narrow band inputs. For broad band input, the solution determined from statistical linearization, and the simplified formulas suggested by Jeng et al. (1992), yield similar estimates for the correlation coefficient.

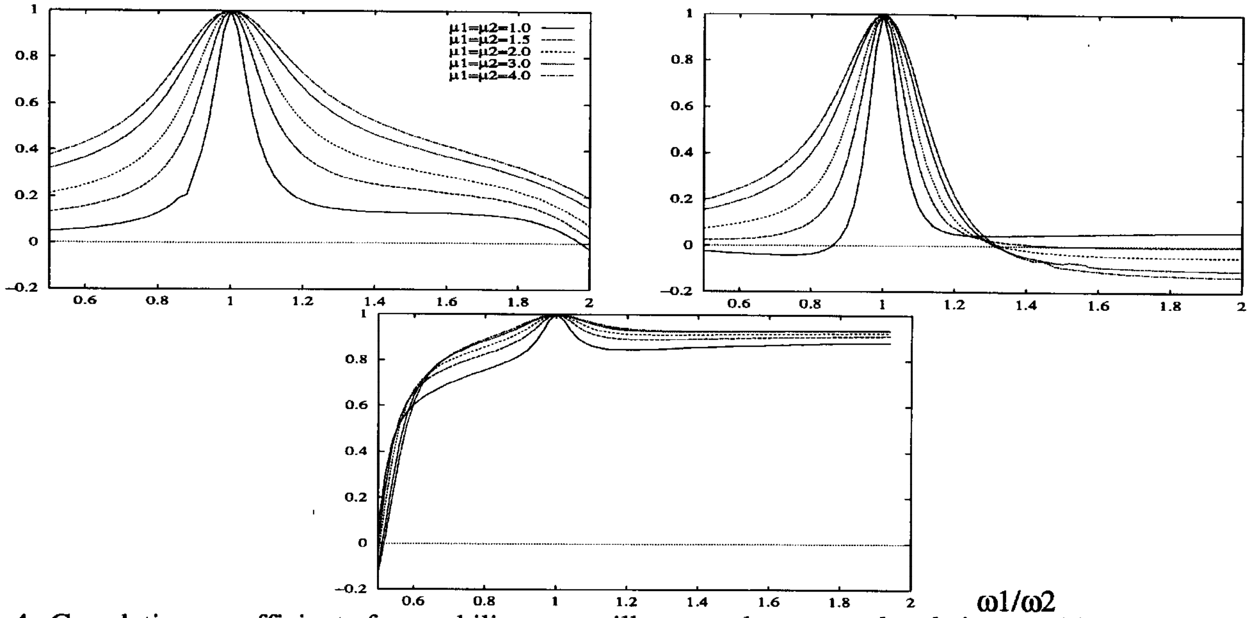

Fig. 4 Correlation coefficient for a bilinear oscillator and narrow band input: (a) $\omega_2 = 0.5\omega_g$, (b) $\omega_2 = \omega_g$, (c) $\omega_2 = 2.0\omega_g$.

Plots to calculate the correlation coefficient, based on the results from statistical linearization, are given by Valles and Reinhorn (1996a). Figure 5a presents a plot of the correlation coefficient for a reduction factor $R = 4$, and a narrow band input, as a function of the period of the structures, and the predominant period of the input motion. Figure 5b presents the amplification factor, D, to estimate the maximum inelastic displacement from the maximum elastic displacement.

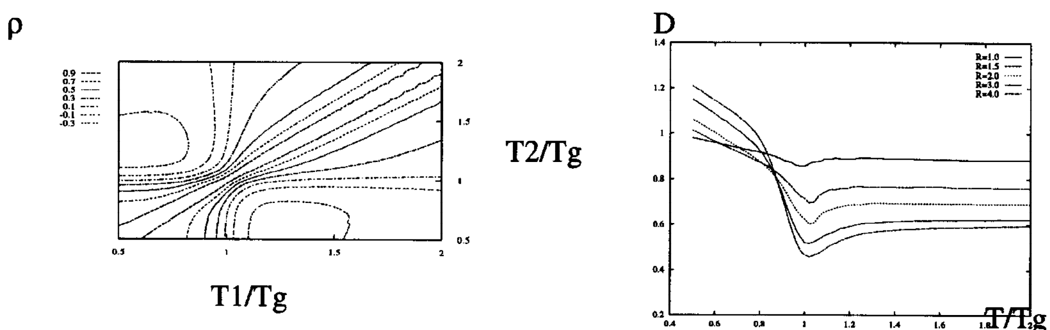

Fig. 5 Correlation coefficient and amplification factor for a narrow band input.

MATHEMATICAL MODELS FOR POUNDING EVALUATION

The mathematical models for impact problems can be classified as: stereomechanical impact, and piece-wise linear impact. The stereomechanical theory of impact is the classical formulation to the problem of colliding bodies. The post-impact velocities ($\dot{u}_1^f$ and $\dot{u}_2^f$) can be determined from the approaching velocities ($\dot{u}_1^0$ and $\dot{u}_2^0$) prior to impact, according to:

$$\dot{u}_1^f = \dot{u}_1^0 - (1+e)\frac{m_2\left(\dot{u}_1^0 - \dot{u}_2^0\right)}{m_1 + m_2}; \text{ and } \dot{u}_2^f = \dot{u}_2^0 + (1+e)\frac{m_1\left(\dot{u}_1^0 - \dot{u}_2^0\right)}{m_1 + m_2} \tag{13}$$

where e is the coefficient of restitution, that takes into account nonlinearities and energy dissipation at the contact interface. The coefficient of restitution range from a value of 1 for elastic impacts, to a value of 0 for perfectly plastic impacts.

The second approach to model impact has been to consider a contact element that is activated when the gap between the structures close. Three types of contact elements have been used to study pounding: linear solid (Maison and Kasai, 1990), Kelvin solid (Anagnostopoulos and Spiliopoulos, 1992); and the Hertz contact law (Soong, 1983). The Kelvin model is commonly used for impact problems. It has the advantage that it can model energy dissipation at the pounding interface. The forces in the Kelvin element are given by:

$$f_c = \left[k_c\left(u_1 - u_2 - g_p\right) - c_c\left(\dot{u}_1 - \dot{u}_2\right)\right] \mathrm{U}\left[u_1 - u_2 - g_p\right] \tag{14}$$

where k_c and c_c are the spring and dashpot constants (see Fig. 6a). Considering two impacting masses, a relationship may be found between the dashpot constant and the coefficient of restitution (e) during stereomechanical impact:

$$c_c = 2\xi_i \sqrt{\frac{m_1 m_2}{m_1 + m_2}}\text{; and } \xi_i = \frac{-\ln e}{\sqrt{\pi^2 + (\ln e)^2}} \tag{15}$$

Note that the viscous component of the element remains active when the structures tend to separate, that is, it opposes the motion of the structures as they bounce back.

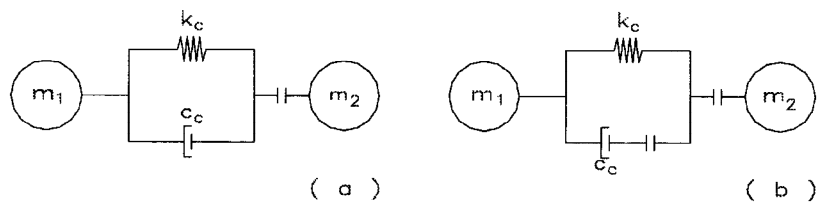

Fig. 6 Impact models: (a) Kelvin element, (b) Impact Kelvin element.

A variation of the Kelvin element, where the dashpot is only active for positive (approaching) velocities, is proposed (see Fig. 6b). Due to its potential application for pounding problems, the element is referred to as an Impact Kelvin element. Restoring forces in the element are calculated according to:

$$f_c = \left[k_c\left(u_1 - u_2 - g_p\right) - c_c\left(\dot{u}_1 - \dot{u}_2\right)\mathrm{U}\left[\dot{u}_1 - \dot{u}_2\right]\right] \mathrm{U}\left[u_1 - u_2 - g_p\right] \tag{16}$$

Figure 7 presents a comparison of the relative displacements and forces, during impact, for the Kelvin and the Impact Kelvin elements ($\xi_c = 0.5$). The response tend to diverge for higher critical damping ratios. Note that the Kelvin element opposes the separation of the masses when the collision process is near completion. Furthermore, as the damping in the contact element increases (nonlinear response), the time of contact in the Kelvin element increases, whereas the contact time decreases in the Impact Kelvin element. Since a reduction in the duration of contact reflects the expected physical response, the use of the Impact Kelvin element is recommended.

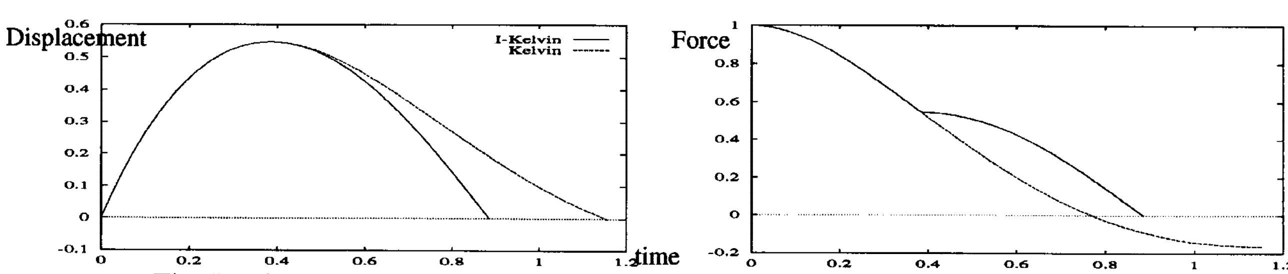

Fig. 7 History of deformations and forces for Kelvin and Impact Kelvin elements.

Both approaches to model impact, the stereomechanical and piece-wise linear, are related. Figure 8 presents the equivalent coefficient of restitution (e) for different critical damping ratios of the Kelvin and Impact Kelvin elements. In general, the impact models have been incorporated in deterministic analysis programs to study the response of multi-story buildings. Besides the deterministic approach to pounding, a probabilistic model and a hybrid model have been suggested for pounding studies (Valles, 1995). The probabilistic formulation considers an evolutionary power spectrum to characterize the input, and determines the confidence of no pounding, and the instantaneous probability of pounding. The hybrid model considers a deterministic analysis, in which the occurrence of pounding is determined in a probabilistic sense.

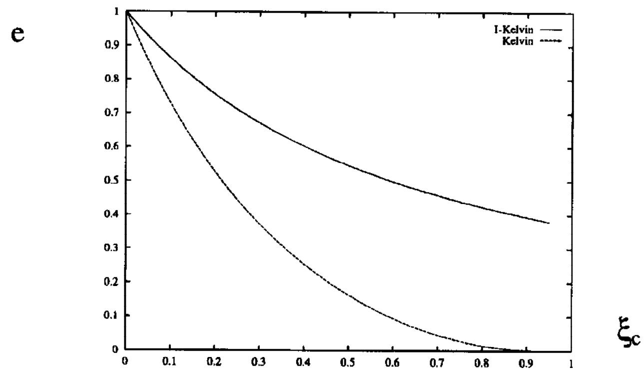

Fig. 8 Coefficient of restitution versus critical damping ratios of Kelvin and Impact Kelvin models.

POUNDING MITIGATION TECHNIQUES

Pounding interactions may impose severe response demands to the impacting structures. In some cases, the level of forces exerted may be larger than the available capacity in the structures. The use of some pounding mitigation techniques is of interest for these cases. A number of pounding mitigation techniques, using damper elements, have been proposed, and can be broadly classified according to their installation as: link elements, bumper damper elements, and supplemental energy dissipation elements. Link elements connect two buildings, therefore, combining the two structural systems in one. However, forces at the links, for extreme cases, can be in the same order of magnitude as the base shears. Furthermore, the links may induce force distributions that differ considerably from the original design forces, and significant retrofitting may be necessary to withstand them. Retrofit solutions using link elements can be analyzed using linear or nonlinear structural analysis programs, depending on the link behavior, as well as the structural response.

Bumper damper elements consist of link elements that are activated when the gap is closed. Such elements should be dissipative to reduce the energy transfer during pounding, and the high frequency acceleration pulses. This type of mitigation technique can be analyzed incorporating the rheological damper model into a nonlinear analysis program, or using an equivalent coefficient of restitution. Preliminary estimates on the damper effectiveness can be obtained using the PER (Valles and Reinhorn, 1996b). The bumper damper element yields a smaller value for the coefficient of restitution, leading to smaller response amplifications.

Supplemental energy dissipation devices have been proposed to reduce the response of one or both structures. Depending on the amount of supplemental damping provided, this solution can be used for pounding prevention or pounding reduction. The PER formulation allows for a simple estimate of the minimum supplemental damping required to avoid contact, or reduce amplification effects to an allowable level (Valles and Reinhorn, 1996). This pounding mitigation technique can be combined with the use of bumper damper elements to reduce the energy transfer. This mitigation technique is preferred, since not only pounding effects are reduced, but also the structural performance of the buildings is enhanced.

CONCLUSIONS

Critical issues in pounding problems have been discussed: critical gap computation, analysis of pounding effects, and pounding mitigation techniques. The use of the Pseudo Energy Radius (PER) allows for a simple formulation of pounding problems in terms of energy. Providing a sufficient separation between structures is the commonly adopted criteria to deal with pounding. The Double Difference Combination rule takes into account the correlation between the response of the structures. For linear structures, subjected to a broad band input, (4) can be used. However, for bilinear structures, specially when subjected to a Mexico City type of earthquake (narrow band), the use of results obtained from statistical linearization is encouraged.

Evaluation of pounding effects is of interest in structures separated by a gap less than critical. The impact models for pounding were described: stereomechanical and piece-wise linear impact. An impact Kelvin element was presented for pounding problems. The dashpot in this element is only active for approaching velocities, yielding more realistic response characteristics. Finally, three different techniques for pounding mitigation were discussed.

REFERENCES

Anagnostopoulos, S.A. and K.V. Spiliopoulos (1992). An investigation of earthquake induced pounding between adjacent buildings. *Earthquake Engineering and Structural Dynamics*, *21*, 289-302.

Der Kiureghian, A. (1979). On the response of structures to stationary excitation. *Earthquake Engineering Research Center*, *Report No. UCB/EERC-79/32*, University of California, Berkeley.

Filiatrault, A. and B. Folz (1992). Nonlinear earthquake response of structurally interconnected buildings. *Canadian Journal of Civil Engineering*, *19*, 560-572.

Jeng, V., K. Kasai, and B.F. Maison (1992). A spectral difference method to estimate building separations to avoid pounding. *Earthquake Spectra*, *8*, No. 2, 201-223.

Kasai, K., J.A. Munshi, and B.F. Maison (1993). Viscoelastic dampers for seismic pounding mitigation. *Proc. ASCE Structural Congress*, Irvine, CA, April, 730-735.

Maison, B.F., and K. Kasai (1990). Analysis for type of structural pounding. *Journal of Structural Engineering*, ASCE, *116*, No. 4, 957-977.

Roberts, J.B. and P.D. Spanos (1990). *Random vibration and statistical linearization*. John Wiley and Sons.

Rosenblueth, E. and R. Meli (1986). The 1985 earthquake: causes and effects in Mexico City. *Concrete International*, *8*, No. 5, 23-34.

Soong, T.T. (1983). Dynamics of a simple system subjected to random impact. *The Shock and Vibration Bulletin, 53*, Part 2, 125-129.

Valles, R.E. (1995). Evaluation, prevention and mitigation of pounding effects in building structures. *Ph.D. Dissertation*, Department of Civil Engineering, State University of New York at Buffalo.

Valles, R.E. and A.M. Reinhorn (1996a). Evaluation, prevention and mitigation of pounding effects in building structures. *NCEER Report 96-xxxx* (in print), State University of New York at Buffalo.

Valles, R.E. and A.M. Reinhorn (1996b). An energy approach to pounding of structures. *11th World Conference on Earthquake Engineering*, *STS-Pounding of Buildings*, Acapulco, Mexico.