11 WCEE

Copyright © 1996 Elsevier Science Ltd
Paper No. 74. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

NONLINEAR SEISMIC POUNDING OF INELASTIC STRUCTURES

C. P. PANTELIDES
Department of Civil Engineering, University of Utah, 3220 Merrill Engineering Building,
Salt Lake City, UT 84112, U.S.A.

and

X. MA
Gamayo, Sanchez and Associates, Inc., Stockton, CA 95207, U.S.A.

ABSTRACT

The dynamic behavior of a damped single-degree-of-freedom (SDOF) structural system with one-sided pounding during an earthquake is examined. The response of a SDOF structural system with elastic or inelastic behavior is investigated. The pounding between neighboring structures is modeled as a Hertz impact force, which is believed to closely represent the behavior of two colliding concrete bodies during an impact which might occur in an earthquake. The effects of separation distance and inelastic structural behavior on the magnitude of the pounding force are examined. The present model and method of analysis can be used in investigations of pounding between buildings or pounding which occurs in bridges during earthquakes.

KEYWORDS

Building; elastic structure; impact; impact stiffness; inelastic structure; nonlinear pounding; pounding force; seismic gap; separation distance; structural pounding.

INTRODUCTION

Structural pounding during earthquakes is a well documented phenomenon. In the San Fernando earthquake of 1971, the second story of the Olive View hospital struck the outside stairtower ; in addition, the first floor of the hospital hit against a neighboring warehouse (Bertero and Collins, 1973). In the 1985 Mexico City earthquake, in at least 15 percent of the 330 collapsed or severely damaged buildings, collapse and damage were directly caused by pounding (Bertero, 1987). Structural pounding damage in buildings can arise in various situations: (1) between adjacent units of the same building which are separated through expansion or construction joints, (2) between units of the same building, or adjacent different buildings which are far apart but are connected by one or more bridges, and (3) between adjacent buildings having different structural characteristics which are separated by a distance small enough so that pounding can occur. The resulting damage from structural pounding can be divided into four categories: (1) major structural damage, (2) failure and falling of building appurtenances creating a life-safety hazard, (3) loss of building function due to failure of mechanical, electrical, or fire protection systems, and (4) architectural, nonstructural, and/or minor structural damage.

Most studies on structural pounding model the pounding phenomenon using a linear elastic spring which is placed at the contact point between the colliding structures (Maison and Kasai, 1992). A different model of the impact between two structures was proposed by Davis, who employed a nonlinear spring in an impact oscillator that was subjected to a harmonic excitation (Davis, 1992). In the present paper, the model proposed by Davis is utilized to examine the behavior of a damped SDOF structural system with one-sided impact during earthquakes. Elastic as well as inelastic behavior of the SDOF system are considered.

NONLINEAR POUNDING MODEL

A SDOF damped structural system subjected to a horizontal earthquake excitation and undergoing one-sided structural pounding is shown in Figure 1. In the present paper, attention is focused on the effects of pounding as they relate to the flexible structure in Figure 1. The rigid structure in Figure 1 is assumed to remain stationary ; $x(t)$ is the lateral displacement of the flexible structure relative to the ground, a is the separation distance between the flexible and rigid structure, and $\ddot{X}_g(t)$ is the earthquake ground acceleration. The inelastic behavior of the SDOF system is modeled using an elastoplastic force-displacement relationship for the structural stiffness. The equation of motion for the structure of Figure 1 is

$$m\ddot{x}(t) + c\dot{x}(t) + k(t)x(t) + F(t) = -m\ddot{X}_g(t) \qquad (1)$$

where an overdot denotes time derivative ; m, c, $k(t)$ denote the mass, damping, and inelastic stiffness of the structure; when the system is elastic, the elastic stiffness is a constant independent of time; $F(t)$ is the impact force between the SDOF system and the neighboring rigid structure modeled as a Hertz nonlinear spring (Davis, 1992)

$$F(t) = R[x(t) - a]^{3/2} \qquad x(t) > a \qquad (2a)$$

$$F(t) = 0 \qquad x(t) \leq a \qquad (2b)$$

where R is the impact stiffness parameter, which depends on the material of the two structures that come in contact, as well as the contact surface geometry (Van Mier et al., 1991).

EFFECT OF SEPARATION DISTANCE

The value of the separation distance (a in Figure 1) between two structures which is sufficiently large to prevent pounding in an earthquake is known as the seismic gap. Building Codes have recognized the existence of a safe seismic separation distance. The Uniform Building Code - UBC (International Conference of Building Officials, 1994) specifies that the separation distance between two buildings shall be at least ($0.375 \times R_W$) times the displacement due to seismic forces, where R_W is a factor which defines the lateral force resisting system.

A parametric study was undertaken to examine the above requirement for a structure modeled as a SDOF elastic structural system with period T=1 s, damping ratio $\xi = 2$ percent of critical, and impact stiffness

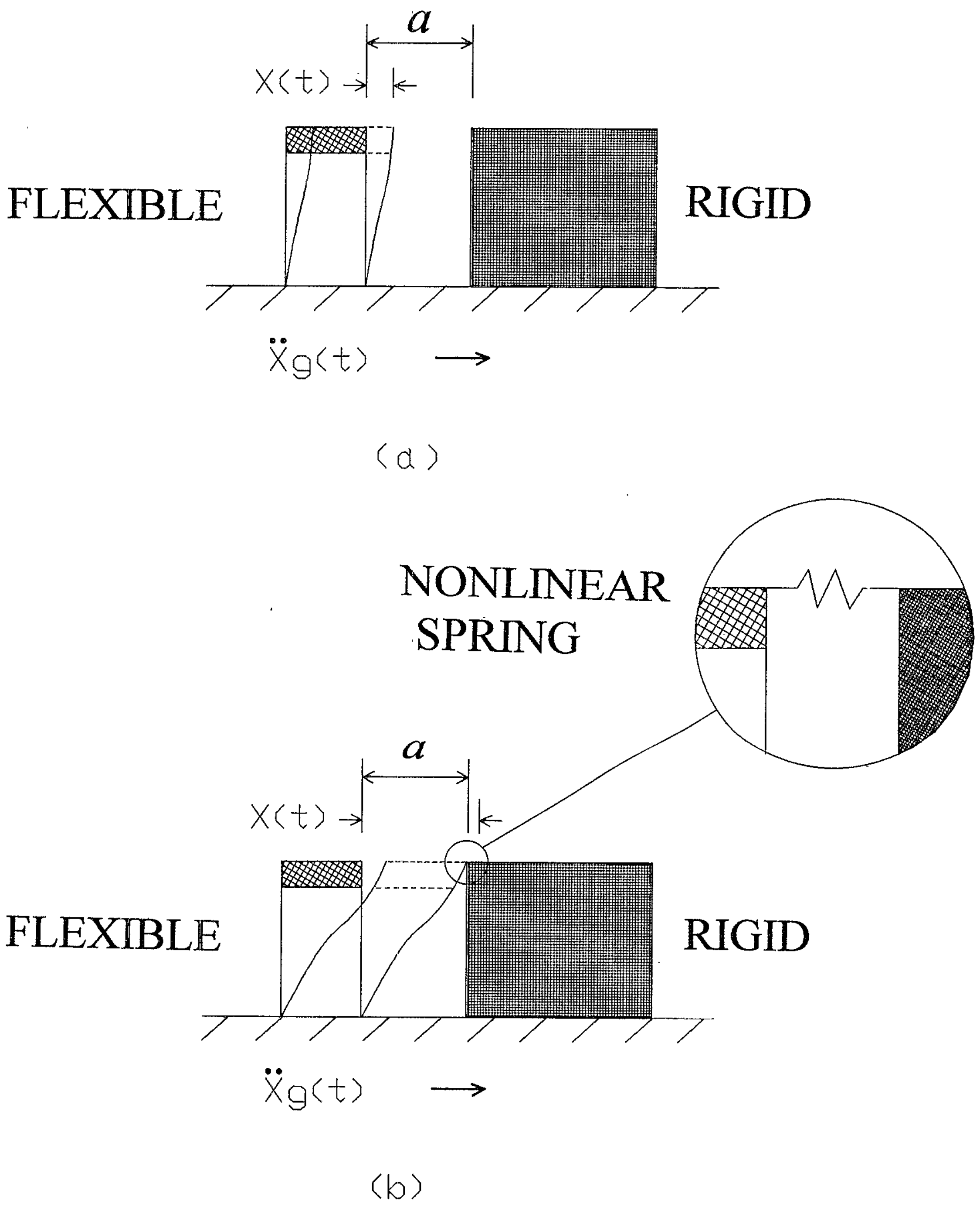

Figure 1. One-sided structural pounding: (a) before pounding $x(t) \le a$; (b) during pounding $x(t) > a$

parameter R = 80 $kN/mm^{3/2}$. A series of separation distances were studied from $a = 25$ mm to where a was sufficiently large to prevent pounding, at an interval of 12.5 mm. The results are shown in Figure 2 in which the vertical axis is the maximum pounding force during the earthquake, and the horizontal axis is the separation distance, a. Four earthquakes were examined: (1) the S00E component of the 1940 El-Centro, (2) the S16E component of the 1971 San Fernando, (3) the Channel 8 of the 1989 Loma Prieta, and (4) the 90^0 component of the Santa Monica record of the 1994 Northridge earthquake (NISEE, 1994). As shown in Figure 2, no pounding occurs when the separation distance is greater than 175 mm for the El-Centro earthquake, 237.5 mm for the Northridge and Loma Prieta earthquakes, and 337.5 mm for the San Fernando earthquake. Thus, assuming that the design earthquake was the 1940 El-Centro earthquake, and the basic structural system was a bearing wall system with a concrete shearwall lateral force resisting system ($R_w = 6$), the separation distance required by the UBC would be equal to 0.375(6)(175) = 394 mm; this separation distance would be sufficient to prevent pounding from occurring for any of the other three earthquakes. It should be noted that the above results are not very sensitive with respect to the value of the impact stiffness parameter, R.

POUNDING OF ELASTIC VS. INELASTIC STRUCTURE

For an economical seismic design the inelastic behavior of the structure must be considered. In this paper the elastoplastic shear-displacement relationship (Blume et al., 1961) is used to model the inelastic behavior of a SDOF structural system with one-sided pounding in an earthquake. Equation (1) is used as the equation of motion and the inelastic behavior of the structure is modeled by $k(t)$ with a stiffness $k_e = 3.5$ kN/mm for the elastic portion and $k_p = 0$ for the plastic portion; in addition the following properties are assumed: ductility $\mu = 4$, mass = 87.55 Mg, damping $\xi = 2$ percent of critical; and the period of the structure for elastic vibrations T = 1 s. The value of the impact stiffness parameter $R = 80$ $kN/mm^{3/2}$.

The response of the inelastic structural system described above is compared to that of an elastic structure with the same mass, an elastic stiffness = 3.5 kN/mm and a damping level of $\xi = 2$ percent of critical. In both cases a separation distance of $a = 25.4$ mm is used. The time-histories of the responses of the elastic and inelastic structures for the four earthquakes used above are investigated. The acceleration response for the elastic and inelastic structure for the four earthquakes is shown in Figures 3-6. The inelastic structure produces considerably smaller accelerations as compared to the elastic structure. The ratio of the peak response of the inelastic structure to that of the elastic structure is determined for maximum displacement, acceleration, pounding force, and number of pounding occurrences as shown in Table 1. Even though the maximum displacement of the inelastic structure is larger than that of the elastic structure, the maximum acceleration is considerably less. Moreover, the maximum pounding force and number of pounding occurrences are considerably less in the inelastic case as compared to the elastic case. This may help explain why buildings which are not separated properly have shown satisfactory response in past earthquakes (Bertero, 1987).

CONCLUDING REMARKS

A realistic pounding model was used for studying the response of an elastic or inelastic SDOF structural system under the condition of structural pounding. When pounding occurs, the number of pounding occurrences and the magnitude of the pounding forces are significant. Numerical simulations have shown that the pounding response is not sensitive to the exact value of the impact stiffness parameter. The seismic separation distance required to prevent pounding from the present formulation was compared to the requirements of the Uniform Building Code. It was found that the code values for moderate damping are conservative compared to the actual seismic separation distance found through analysis. Comparison of the pounding behavior of elastic with

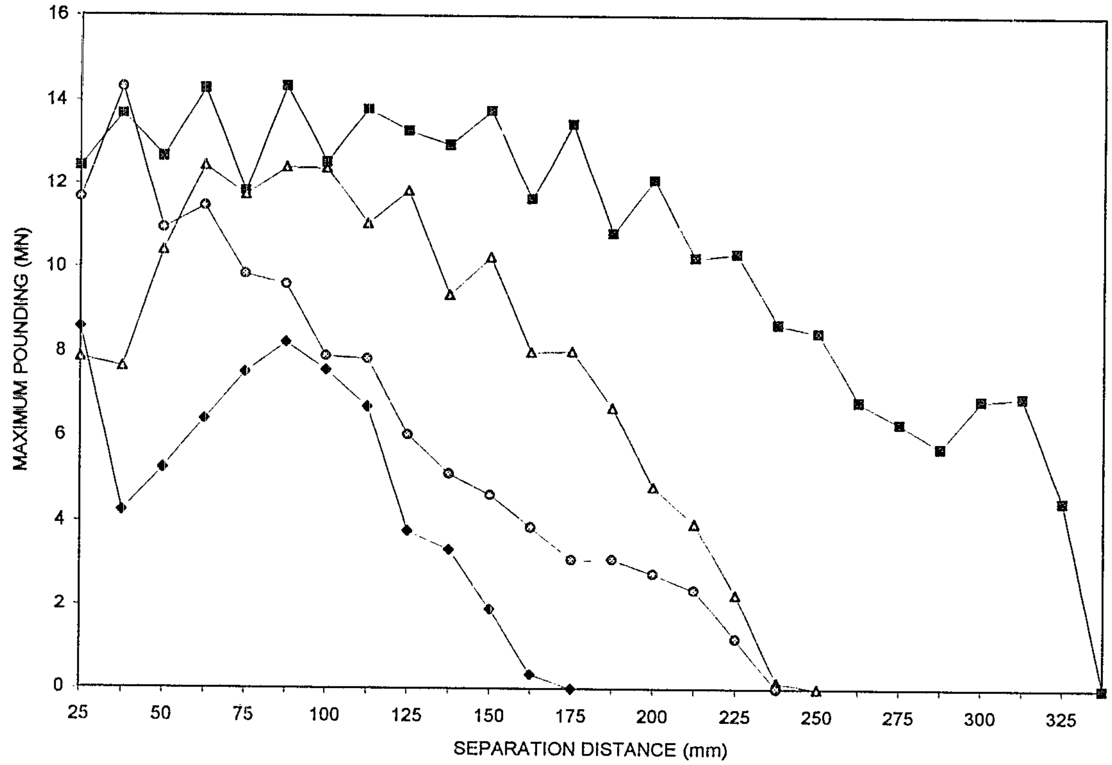

Figure 2. Maximum pounding force as a function of separation distance:
—◆— = El-Centro;—■— = San Fernando; -△- = Loma Prieta;-●-= Northridge

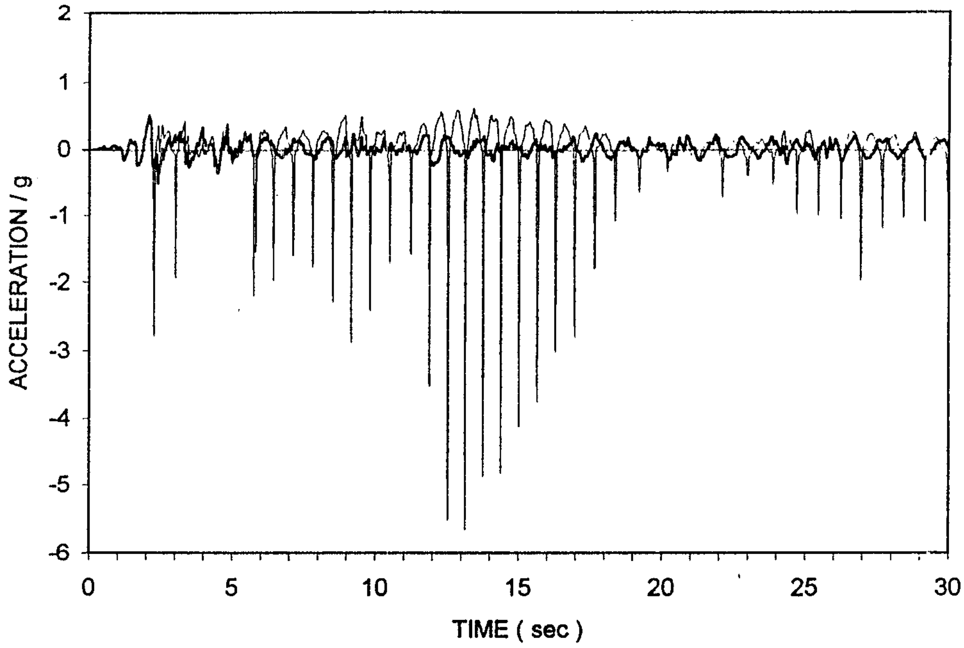

Figure 3. Comparison of SDOF elastic with inelastic acceleration response - 1940 El-Centro earthquake: ____ = elastic; ____ = inelastic

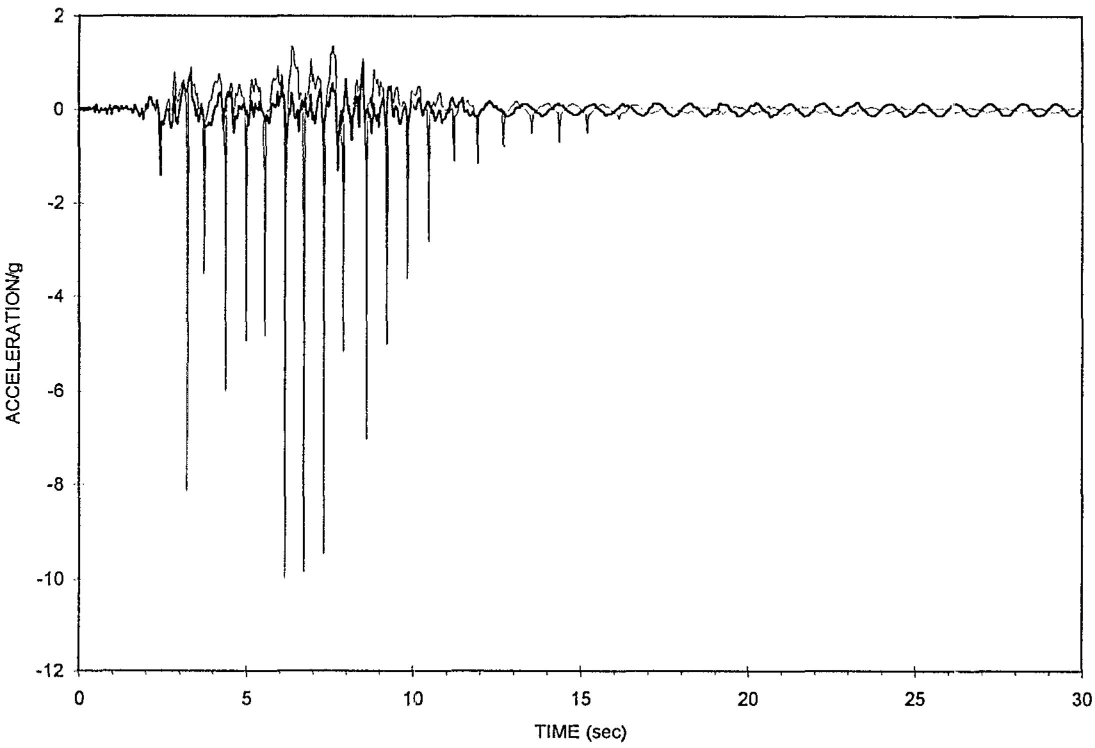

Figure 4. Comparison of SDOF elastic with inelastic acceleration response - 1971 San Fernando earthquake: —— = elastic; ━━ = inelastic

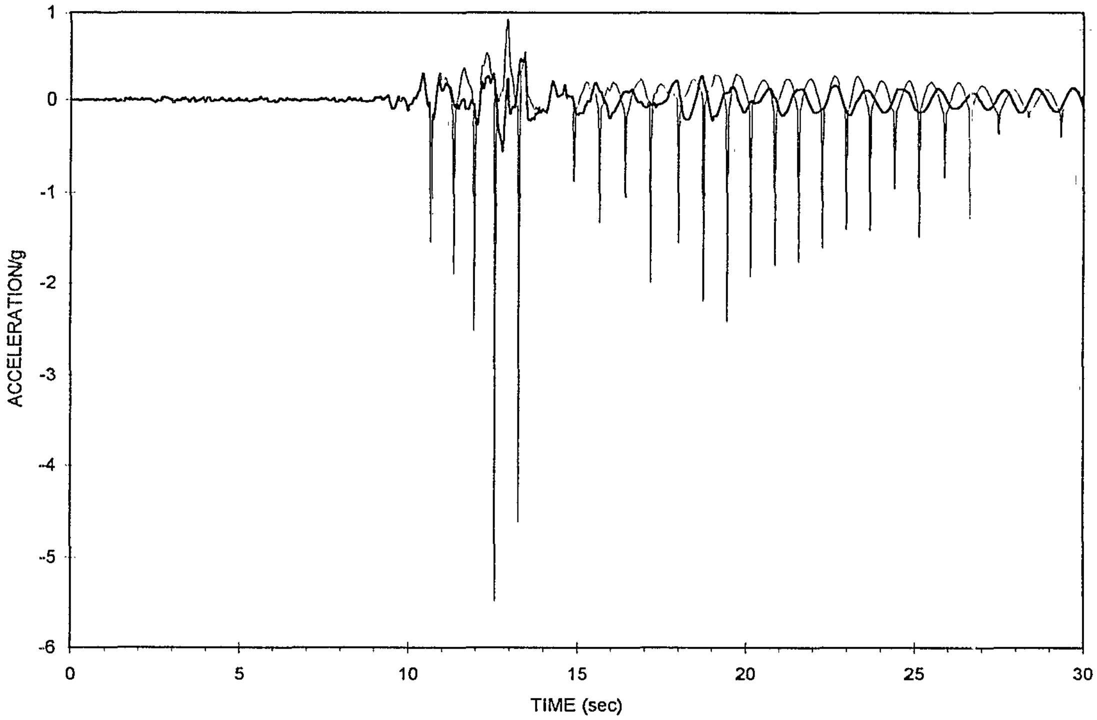

Figure 5. Comparison of SDOF elastic with inelastic acceleration response - 1989 Loma Prieta earthquake: —— = elastic; ━━ = inelastic

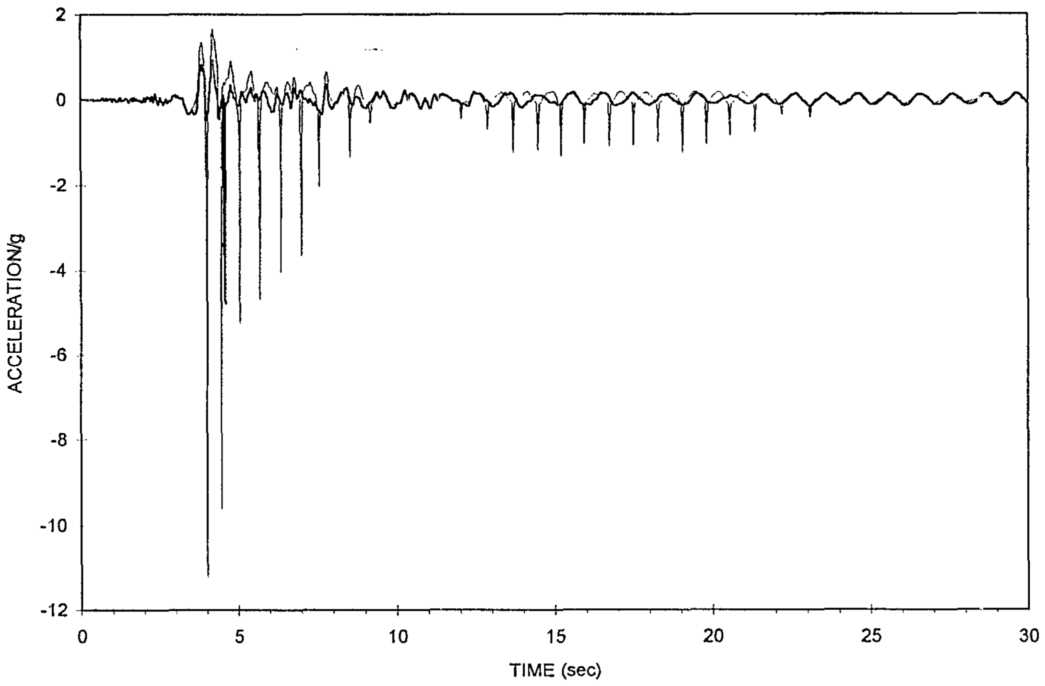

Figure 6. Comparison of SDOF elastic with inelastic acceleration response - 1994 Northridge earthquake: —— = elastic; ▬▬ = inelastic

Table 1. Ratio of inelastic to elastic response of SDOF system with pounding

Earthquake	Maximum Displacement	Maximum Acceleration	Maximum Pounding Force	Number of Poundings
El-Centro	1.00	0.31	0.24	2/35
San Fernando	2.41	0.14	0.13	1/21
Loma Prieta	1.03	0.27	0.27	1/25
Northridge	2.21	0.44	0.44	1/24

inelastic structures showed that for moderate damping levels the values for peak acceleration and pounding force of the inelastic structure are significantly less than those of the elastic structure; in addition, the number of pounding occurrences for the structure with inelastic behavior is much less than those for the elastic structure. This observation may help explain why buildings that are not separated in accordance with the minimum seismic separation distance respond in a satisfactory manner during earthquakes.

REFERENCES

Bertero, V. V., and R. G. Collins R. G. (1973). Investigation of the failures of the Olive View stairtowers during the San Fernando earthquake and their implications on seismic design. *Technical Report No. EERC 73-26*, Earthquake Engineering Research Center, University of California, Berkeley, California.

Bertero, V. V. (1987). Observations on structural pounding. *Proc. Int. Conf. Mexico Earthquakes*, ASCE, 264-278.

Blume, J. A., Newmark, N. M., and Corning, L. H. (1961). Design of Multistory Reinforced Concrete Buildings for Earthquake Motions. *Portland Cement Association*, Skokie, Illinois.

Davis, R. O. (1992). Pounding of buildings modeled by an impact oscillator. *Earthq. Engrg. Struct. Dyn.*, **21**, 253-274.

International Conference of Building Officials. (1994). Uniform Building Code. Vol. 2, Section 1631.2.11, Whittier, California.

Maison, B. F., and Kasai, K. (1992). Dynamics of pounding when two buildings collide. *Earthq. Engrg. Struct. Dyn.*, **21**, 771-786.

NISEE (1994). Corrected Motion Records, *Earthquake Engineering Research Center*, Berkeley, CA.

Van Mier, J. G. M., Pruijssers, A. F., Rienhardt, H. W., and Monnier, T. (1991). Load-time response of colliding concrete bodies. *J. Struct. Engrg., ASCE,* **117**, 354-374.