Effect of Ground Motion Characteristics and Structural Properties on Energy Components of a Structure

Auta, S. M[1], Shiwua Aondowase John[2], Tsado T. Y[1]. and James Olayemi[1]
[1]Department of Civil Engineering, Federal University of Technology, Minna. Niger State Nigeria. E-mail; smahuta@yahoo.com [2]Dept. of Structural Mechanics,St. Petersburg State University of Architecture and Civil Engineering, Russia. Email: aondo.j@gmail.com

Abstract
Effect of ground motion characteristics and structural properties on energy components of a structure is presented. The energy-based criterion for design of seismic resistant structures envisages that a structure collapses or experiences significant damage when the amount of energy it can absorb and dissipate is less than energy demand of the structure. This follows that a structure would be seismic resistant if energy absorption capacity is greater than seismic input energy or seismic energy demand. The factors that influence the input energy and its components quantitatively are investigated. The result of the investigations shows that as the peak ground acceleration increases, the input energy also increases indicating that the input energy is related to the intensity of ground motion. It is shown that for a given peak ground acceleration, the effect of strong motion duration on the input energy is as significant as the influence of frequency content even for records with the same intensity and duration of strong motion. And all small damping ratios less than 5% have a minor influence on the input energy, but a major effect on the damage potentials of structures.

Keywords: Earthquake, Ground Motion characteristics, Influence, Seismic input energy.

Introduction

When earthquakes strike, it releases the strain energy stored inside the earth's crust resulting in vibratory waves propagating through the surface in all directions. The energy released disturbs functionality of infrastructures like buildings, bridges, dams, roads, canals and pipelines. The extent of disturbance, however, depends on the epicentre and severity of the earthquake induced ground motion at the site and the ability of the infrastructure to offer adequate resistance. Seismic resistance of an infrastructure depends on the design, materials, and construction practice prevailing in the region at the time when the infrastructure was built. Similarly, the ground motion severity depends, among others, on the soil conditions at the site and on the proximity of the location to tectonic plate boundaries and inter-plate faults. Seismic design aims to avoid/minimize the damage to infrastructures due to ground shaking resulting from all possible earthquake sources in the vicinity. The magnitude and damage caused to lives and property by earthquake today calls for concerted efforts in planning and constructing earthquake-resistant infrastructure.

The basic principle of seismic protection of structures consists of ensuring they have the capability to dissipate the input energy received from earthquake ground motion. Researchers have argued that present seismic design methods based on strength principles largely ignore the influence of duration of motion (strong motion) and hysteretic behavior effects on structural design and have advanced the used of earthquake input energy into a structure during earthquake ground motion as measure of potential damage

Housner (1956) first proposed the seismic design methodology based on energy and over the past decades it has been extensively researched and largely accepted (Zahrah and Hall (1984), Akiyama (1985), Uang and Bertero (1990), Fajfar et al (1992). Anderson and Bertero (2006) present a historical review of the past and present stages in the evolution of energy concept of seismic design. Energy based evaluations of the seismic performance of the constructions represent the best simulation of the real behaviour as it has the potential to address the effects of the duration, frequency content and hysteretic behaviour directly Khashaee *et al*. (2003).

Previously many of researches investigated the duration of ground motion, damping of structure and soil condition influences on input energy and obtained different conclusions.

Zahrah and Hall (1984) computed the input energy for eight earthquake records and they considered that ductility, damping and past to-pre yield stiffness ratios have small effects on the input and hysteretic energies for a structure with bilinear behavior. McKevitte *et al*. (1980), Akiyama (1985), and Nakashima *et al.* (1996) observed that damping does not have a significant influence on the earthquake input energy. Bruneau and Wang (1996), in their work indicated that damping ratios smaller than 5% have a minor influence on the input energy. Rahnama and Manuel (1996), computed the input energy for ductility ratios of 2 and 6 with 5% damping for six sets of 19 accelerations each, actual records and simulated records with the same duration 5, 10, 15 and 20 s and observed that input energy increases as duration increases. Khashaee *et al*. (2003) computed the relative input energy for 10 accelerations with short duration (shorter than 8 s) and 10 with long duration (longer than 18 s) of strong ground motions. They observed that as the duration of strong ground motions increases, the input energy also increases. They computed the relative input energy for structures with damping ratios 0, 2, 5, 10, 20 and 40% for 3 accelerations records with short duration and with long duration of strong ground motion respectively. They observed that for damping ratios smaller than 5%, damping has little influence on the input energy while for damping ratios greater than 5%, damping has a significant influence on the input energy spectra, particularly for very long natural periods as the damping increases, the input energy increases.

Energy-based seismic design methodology actively being research today and various proposals put forward to facilitate seismic design of structures, Choi, J. and Kim, J. (2009), Benavent-Climent and Zahran (2010), Benavent-Climent (2011), Ali et al (2013), Rutman and Shiwua (2015). The key to successful seismic resistant design based on the energy concept is dependent on accurate estimation of the input energy into the structures. It is therefore, important to consider all factors that might possibly, affect the value of the input energy. The present study seeks to evaluate the effects of ground motion intensity, duration of motion, frequency content, and structural properties (damping) on input energy.

Theoretical background

The fundamental equation regulating the energy balance of the seismic response can be formulated according to Uang and Bertero (1988) from the following expression (1):

$$m\ddot{u}_t + c\dot{u} + f(u) = 0 \qquad (1)$$

where m is the mass of the structure, $u_t = u + u_g$ is absolute (or total) displacement of the mass, c is the damping coefficient, $f(u)$ is the restoring force, u is relative displacement of the mass with respect to ground,

$$m\ddot{u} + c\dot{u} + f(u) = -m\ddot{u}_g \qquad (2)$$

where $\ddot{u}$ is the second derivative of u with respect to time or acceleration of mass with respect to ground and is ground acceleration.

Therefore, the structural system in a moving base system can be treated conveniently as an equivalent system with a fixed base subjected to an effective horizontal dynamic force of magnitude Depending on whether the energy equation is derived from Equation (1) or (2) different definitions of input energy can result into absolute energy and relative energy equations.

Derivation of absolute energy equation

If both sides of Equation (1) are multiplied by and then integrated over the entire duration (t) of an earthquake, reduces to the following energy balance equation:

$$\frac{m\dot{u}_t^2}{2} + \int_0^t c\dot{u}^2 dt + \int_0^t f(u)\dot{u}dt = m\int_0^t \ddot{u}_t \dot{u}_g dt \qquad (3)$$

$$E'_K + E_\xi + E_A = E_K^* \qquad (4)$$

;

$$E'_K + E_\xi + E_S + E_H = E_I^* \qquad (5)$$

where $E_K^* = \frac{m\dot{u}_t^2}{2}$ $E_\xi = \int_0^t c\dot{u}^2 dt$ $E_A = E_S + E_H = \int_0^u f(u)du = \int_0^t f(u)\dot{u}dt$ $E_I^* = -m\int_0^t \ddot{u}_t \dot{u}_g dt$

Here E_K^* E_ξ and E_A are absolute kinetic energy, the damping energy and the absorbed energy, respectively, and E is defined as the absolute input energy. The absorbed energy consists of the recoverable elastic strain energy E_S and the irrecoverable hysteretic energy E_H where $E_S = \frac{ku^2}{2}$; where k is the pre-yield stiffness of the structure. Thus, E_I^* represents the work done by the total base shear at the foundation through the foundation displacement.

Derivation of relative energy equation

If both sides of Equation (2) are multiplied by $du = (\dot{u}dt)$ and integrated over the entire duration (t) of an earthquake, it reduces to the following energy equation:

$$\int_0^t m\ddot{u}\dot{u}dt + \int_0^t c\dot{u}^2 dt + \int_0^t f(u,\dot{u})\dot{u}dt = -\int_0^t m\ddot{u}_g \dot{u}dt \qquad (6)$$

$$E_K + E_\xi + E_A = E_I \qquad (7)$$

$$E_K + E_\xi + E_S + E_H = E_I \qquad (8)$$

Where $E_k = \int_0^u \ddot{u}(t)du = \int_0^t \dot{u}(t)d\dot{u} = \frac{m\dot{u}^2}{2}$

$E_A = E_S + E_H = \int_0^u f(u)du = \int_0^t f(u)\dot{u}dt$

While E_k is relative kinetic energy, E_A is the relative input energy which is the work done by the static equivalent lateral force ($-m\ddot{u}_g$) on the equivalent fixed-base system.

The difference between the two energy formulations therefore can be written as follows:

$$E_I^* - E_I = E_K^* - E_K = \frac{1}{2} m(\dot{u}_g{}^2 + 2\dot{u}_g{}^2\dot{u}) \quad (9)$$

The difference between the two procedures is less important in damage assessment since the hysteretic energy, which is associated with the damage potential of structures, is independent of the approach used. It is argued that the input energy in terms of the relative motion is more meaningful than the input energy in terms of the absolute motion since internal forces within a structure are computed using relative displacements and velocities according to Chopra (1995), Bruneau and Wang (1996) and Akiyama (1999).

Figure 2 shows energy time-histories and energy ratios for an elastoplastic SDOF structure (Fig. 1) with pre-yield period T=0.5s, pre-yield damping ratio ξ =5%, and zero post to pre-yield stiffness subjected to the 90° component of Imperial Valley – El Centro of May 18, 1940. The maximum kinetic and elastic strain energies occur in the initial stages of the excitation, whereas the maximum damping, hysteretic, and input energies occur at the end of the excitation. Therefore, the duration of strong motion significantly affects the maximum damping energy, the maximum hysteretic energy, and the maximum input energies, but not the maximum kinetic energy and the maximum elastic strain energy. The time-histories in figure 1 (b) shows that $(E_K + E_S)/E_I$ have large oscillations during the linear portion of the response with the peak ratio decaying rapidly as the structure experiences nonlinear deformation because a significant portion of the input energy is distributed among hysteretic and damping energies rather than kinetic and elastic strain energies.

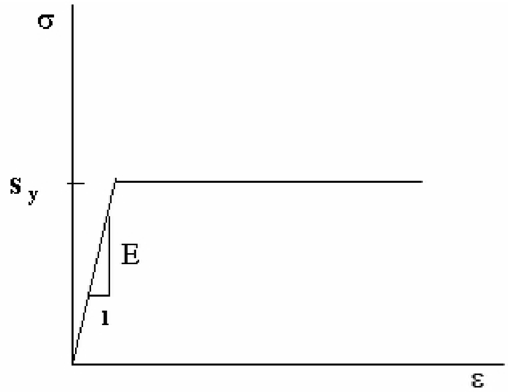


Figure 1 Elastic-perfectly plastic (elastoplastic) model

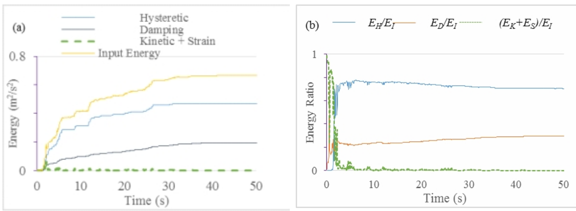


Figure (a) Energy time-histories (b) energy ratios for a elastoplastic SDOF structure with a pre-yield period T = 0.5 s, a pre-yield damping ratio ξ = 5%, and zero post- to pre-yield stiffness ratio subjected to the 90° component of Imperial Valley - El Centro, May 18, 1940

Methods

An elastoplastic system with single degree of freedom (SDOF) with zero (0) post yield stiffness ratio is subjected to three sets of earthquake records selected from records available in the software package NONLIN

(2003) on Table 1. The records all have a PGA of 3.4m/s^2. The duration of strong motion (t_{sd}) is computed in SEISMOSIGNAL using the definition proposed by Trifunac and Brady (1975), and in shown graphically in Figure 3 (a-c) The Arias intensity plot on how energy accumulates is shown for two records (Northridge and Imperial Valley) with the same PGA but different t_{sd} to single out the effect of duration of strong motion on the input energy. The elastic input energy spectra of two records (Kobe and Northridge) with the same PGA and t_{sd} is plotted by running the records in SEISMOSIGNAL to show case how the frequency content of earthquake records influence the input energy.

To determine the effect of earthquake intensity on the input energy into a system, an elastoplastic systems with single degree of freedom (SDOF) with zero (0) post yield stiffness ratio is subjected to two earthquake records (Northridge and Imperial Valley), scaled to PGA of 0.4g, 0.5g and 0.6g respectively. The input energy into various systems with periods (T) ranging from 0.02s to 5s for a given scaled value of the PGA were evaluated. By varying the damping ratio of each system through ξ = 0%, 2%, 5%, 10%, 20%, 30% and 40%, the effect of damping on the input energy into a system and energy ratios was investigated and the result presented. The input energy is obtained through nonlinear dynamic time-history analysis using NONLIN.

Table Characteristics of selected records

No	Earthquake, Year	Station	Component	*PGA* (m/s^2)	t_{sd} (s)
1	Imperial Valley, 1940	El Centro	270°	3.4	24.5
2	Northridge, 1994	Arleta Nordhoff	90°	3.4	13
3	Kobe, 1952	Kakogawa	90°	3.4	13

Source: NONLIN (2003) – a computer program for nonlinear dynamic time-history analysis of single and multi-degree of freedom systems.

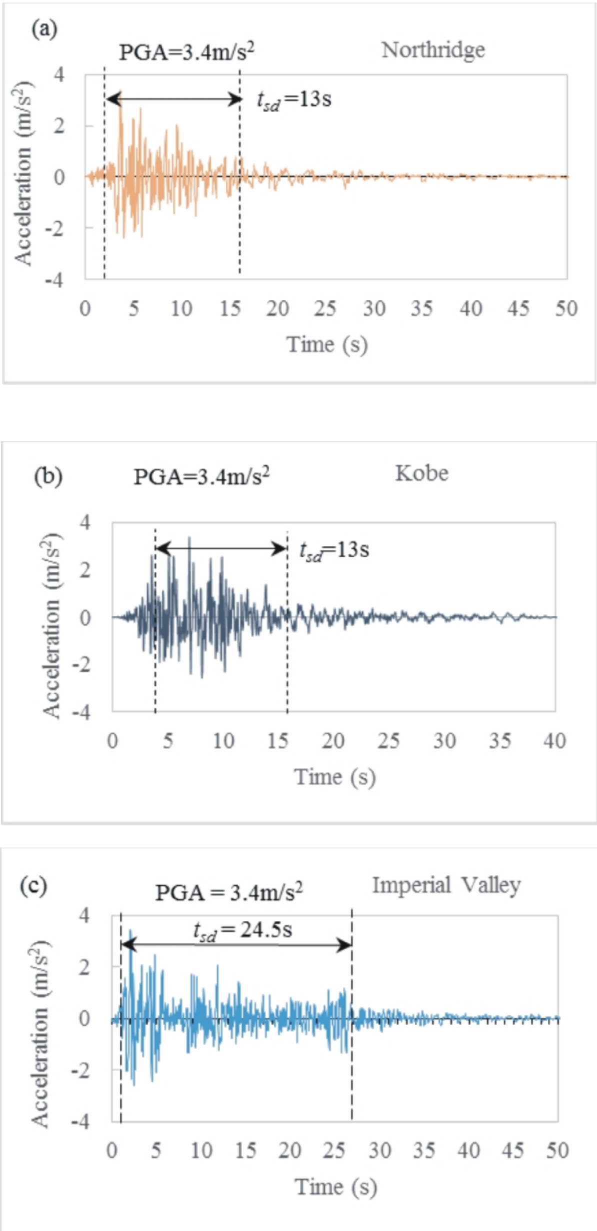
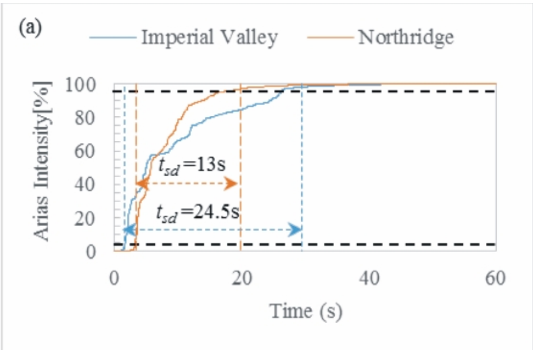


Figure 3 Accelerograms (a) Northridge earthquake, (b) Kobe earthquake and (c) Imperial Valley earthquake

Results and Discussion

The Arias intensity plot of two ground motion records having the same peak ground accelerations (PGA), but different durations shown in Figure 4(a) indicates that the energy accumulates over more time for the longer duration ground motion as compared to the shorter duration ground motion. Figure 4 (b) shows the elastic energy spectra of Northridge and Kobe earthquakes at 5% damping. The result shows that even for records with the same intensity and duration of strong motion the input energy spectra are different. This variation is a result of the difference in the frequency content of the two records.



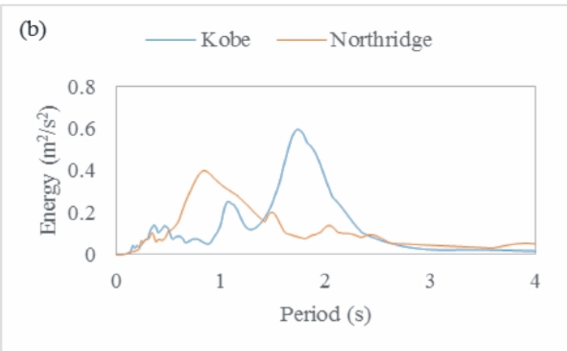
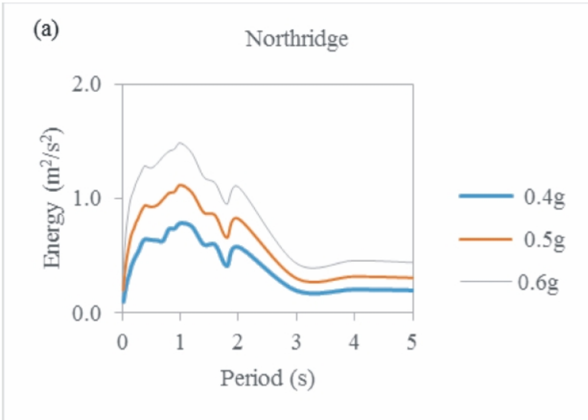


Figure. 4 (a) Arias intensity plot for Imperial Valley earthquake and Northridge earthquakes, (b) Input energy spectra for Northridge and f Kobe earthquake, both having the same peak ground acceleration (PGA) and duration strong motion

The relative input energy into an elastoplastic SDOF structure with 5% damping and zero post- to pre-yield stiffness ratio subjected ground motion records with the PGA of the records scaled to 0.4g, 0.5g, and 0.5g, respectively shows that as the PGA increases, the input energy increases as reflected in Figure 5 (a-b). This demonstrates clearly, that the input energy is related to the intensity of ground motion.



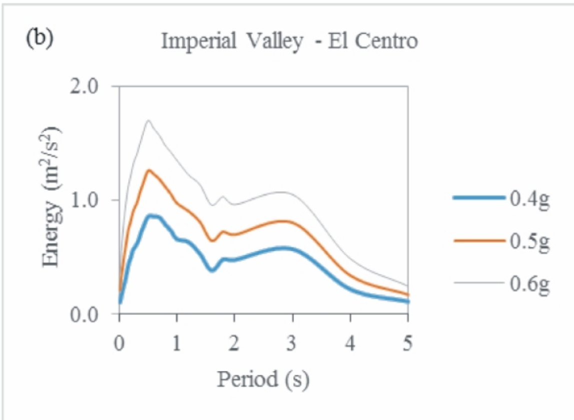
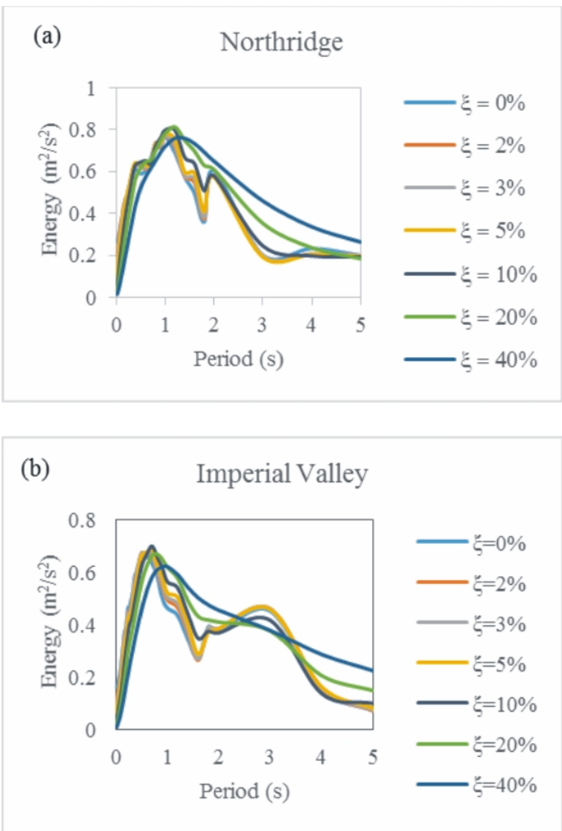


Figure 5 Earthquake input energy E_I of records scaled to 0.4g, 0.5g and 0.6g respectively for a damping ratio $\xi = 5\%$.

(a) Northridge earthquake and

(b) Imperial Valley earthquake

The relative input energy and energy ratios for SDOF with zero post- to pre-yield stiffness ratio and damping ratios ξ = 0, 2, 5, 10, 20, 30 and 40% are shown in (a-b) shows that for damping ratios smaller than 5%, damping has little effect on the input energy. For damping ratios greater than 5%, on the other hand, damping has a significant influence on the input energy spectra. According to Khashaee et al. (2003), a damping ratio ξ = 40% may reduce the input energy by approximately 50% for periods close to the predominant period in the energy spectra. Figure 6 (c-f) shows that the ratios E_{Hmax}/E_{Imax} and $(E_H/E_I)_{max}$ decreases as the damping increases. Since damage potential is a measure of mostly, the hysteretic energy component, smaller damping ratios will increase the damage potential of the structure



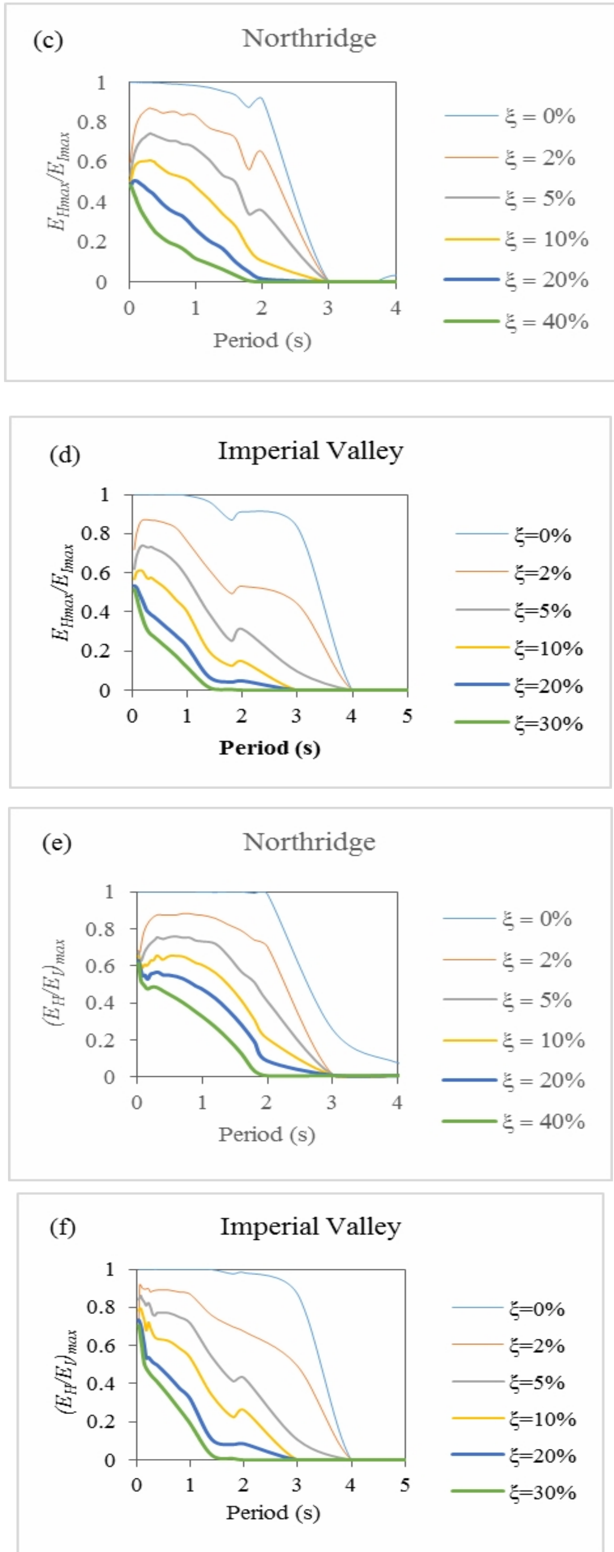


Figure Variation of input energy (a-b) and energy rations (c-f) with damping for Northridge and Imperial Valley earthquakes

Conclusions

The effects of ground motion duration of earthquake, earthquake intensity, frequency content and damping ratios on the input energy in *SDOF* systems and compare results with existing works are presented. This study shows that as the peak ground acceleration increases, the input energy also increases indicating that the input energy is related to the intensity of ground motion. It is shown that for a given peak ground acceleration, the effect of strong motion duration on the input energy is as significant as the effect of frequency content even for records with the same intensity and duration of strong motion. Results from the above analysis indicate that damping significantly influences the input energy and its distribution among the energy components. All small damping ratios less than 5% have a minor influence on the input energy, but a major effect on the damage potential of structures.

References

Advanced structural concepts (2003). NONLIN - A computer program for nonlinear dynamic time-history analysis of single and multi-degree of freedom systems.

Akiyama, H. (1985). Earthquake-resistant limit-state design for buildings. University of Tokyo Press, Japan.

Anderson, J.C., Bertero, V.V. (2006). Use of Energy Concepts in Earthquake Engineering: a Historical Review. *Proceedings of the 8th National Conference on Earthquake Engineering, Paper* 908. San Francisco, CA.

Arias, A. A. (1970). Measure of earthquake intensity. *Seismic Design for Nuclear Power Plants*, Cambridge: MIT Press, pp.438-483.

Benavent-Climent, A. (2011). An energy-based method for seismic retrofit of existing frames using hysteretic dampers. *Soil Dynamics and Earthquake Engineering*, 31, 1385–1396.

Benavent-Climent, A. and Zahran, R. (2010). An energy-based procedure for the assessment of seismic capacity of existing frames: Application to RC wide beam systems in Spain. *Soil Dynamics and Earthquake Engineering,* 30, 354–367.

Bruneau M. and Wang N. (1996). Some aspects of energy methods for the inelastic seismic response of ductile SDOF structures. *Eng. Struc*., 18(1), pp. 1-12.

Choi, J. and Kim, J. (2009). Evaluation of seismic energy demand and its application on design of buckling-restrained braced frames. *Structural Engineering and Mechanics,* Vol. 31, No. 1, 93-112.

Habibi, A., Chan, R.W. K., Albermani, F. (2013). Energy-based design method for seismic retrofitting with passive energy dissipation systems. *Engineering Structures,* 46, 77–86.

Housner, G.W. (1956). Limit design of structures to resist earthquakes. *Proceedings of the First World Conference on Earthquake Engineering*, Berkeley, California.

Khashaee, P., Mohraz, B., Sadek, F., Lew, H. H., Gross, J. L. (2003). Distribution of Earthquake Input Energy in Structures. *Report No. NISTIR 6903, Building and Fire Research Laboratory National Institute of Standards and Technology Gaithersburg*, MD 20899.

McKevitt W. E., Anderson D.L., and Cherry S. (1980). Hysteretic energy spectra in seismic design. *Proc. of the 2nd World Conference on Earthquake Engineering*, Vol. 7, pp. 487-494.

Nakashima M., Saburi K., and Tsuji B. (1996). Energy input and dissipation behaviour of structures with hysteretic dampers", *Earthquake Eng. & Struct. Dyn*., 19(1), pp. 77-90.

Rahnama M. and Manuel L. (1996). The effect of strong motion duration on seismic demands. *Proc. of the 11th World Conference on Earthquake Engineering*, Mexico, paper No. 924.

Rutman, Yu. L., Shiwua, A. J. (2015). Evaluation of seismic energy absorbed elastoplastic system with single degree of freedom. *Bulletin of Civil Engineers*, 2 (49). 64-74.

Seismosoft (2013). SeismoSignal - A computer program for signal processing of time-histories. URL: www.seismosoft.com

Trifunac, M. D., Brady, A. G. A. (1975). Study on the duration of strong earthquake ground motion. *Bulletin of the Seismological Society of America*, 65, 581–626.

Uang, C. M., Bertero, V. V. (1990). Evaluation of seismic energy in structures. *Earthquake Engineering and Structural Dynamics*, 19(1), 77–90.

Zahrah, T. F., Hall, W. J. (1984). Earthquake energy absorption in SDOF structures. *Journal of Structural Engineering, ASCE*, 110(8), 1757–1772.