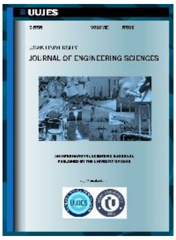

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Research article

AN INVESTIGATION OF DAMPING RATIO EFFECT ON EARTHQUAKE ENERGY INPUT

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Abstract

Recent earthquakes show that the strength and displacement-based methods in many seismic design codes are not as reliable as the energy-based methods in seismic design and evaluation of structures. The determination of earthquake energy input to structures is the main concern for the energy-based structural design methods. The seismic energy input to structures mainly depends on the strong ground acceleration and the velocity time history of the structures. Current studies about the seismic energy input show that the bases of researches are established almost entirely for the single-degree-of-freedom (SDOF) systems. This study investigates the variation of earthquake input energy of SDOF systems which have different period and damping ratio values. Five real earthquake records are selected to perform nonlinear time history analyses. SDOF systems are assumed to be located on the same type of soil profile according to the shear wave velocity values of the first thirty meters of the soil. Bilinear hysteretic model is used and constant ductility is considered. Three different damping ratios as three, five and ten percent are taken. Energy input-time histories of bilinear SDOF systems are obtained graphically for selected earthquakes and for different damping ratios. The main objective of the research is to see to what extent the energy input has changed for different damping ratio values.

Keywords: *Earthquake energy input; strong ground acceleration; single-degree-of-freedom system; damping ratio; energy input-time history.*

1. Introduction

Structures are generally designed to behave nonlinear under seismic effects and for this purpose many design methods are presented in different seismic codes of countries. The

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current seismic design codes which are generally based on strength principles do not directly take into account the hysteretic behavior and the influence of earthquake duration. The hysteretic behavior is considered indirectly in these codes by using a constant response modification factor. However, the energy-based seismic design take into account the hysteretic behavior of the structure and the duration effects of the earthquakes directly [1].

The energy concept in seismic design and evaluation of structures has been widely studied over a half-century period. The first proposal about the fundamental aspects of the energy-based seismic design was made by Housner [2]. The energy input to a structure with the earthquake plays principal role for the energy-based structural design and this subject is dwelled upon after Housner by numerous researchers. Zahrah and Hall [3] computed the input energy per unit mass for eight strong ground motions. Akiyama [4] proposed the input energy for an elastic SDOF system as a function of equivalent velocity. Kuwamura and Galambos [5] recommended the input energy based on the equivalent velocity and period. Fajfar et al. [6] used forty accelerograms to compute the earthquake input energy for constant velocity region. Uang and Bertero [7] investigated the input energy of SDOF system per unit mass and proposed two procedures for calculation. Manfredi [8] proposed the input energy formula by using 244 accelerograms for the constant-velocity region. Leelataviwat and Goel [9] presented a seismic design procedure which is based on yield mechanism and target displacement by using the seismic input energy as a function of pseudovelocity. Akbaş and Shen [10] studied the energy concepts in earthquake resistant design and obtained energy input-time histories of SDOF systems which have different ductility ratios. Seismic input energy is expressed creating the design input energy spectra based on Colombian earthquakes in the study by Benavent-Climent et al. [11]. It is suggested by López-Almansa et al. [12] that there is a relation between the input energy and the plastic energy and the seismic input energy is considered as the design energy spectra in terms of an equivalent velocity. Mezgebo [13] examined the earthquake input energy, hysteretic energy and its distribution in multi-degree-of-freedom systems in his dissertation. It is widely investigated by Dindar et al. [14] that the seismic demand on structures can be defined in the form of input and plastic energy demand spectra.

In this study, energy input-time histories for bilinear SDOF structures having the ductility ratio of $\mu = 2$ and post-yield stiffness ratio of $\alpha = 0.10$ is computed for different five real earthquake records. The selected SDOF systems have natural vibration periods as: T_n= 0.2 s, 0.6 s, 1.0 s and 1.4 s, respectively. Three various pre-yield damping ratios are selected as: ξ = 3%, 5% and 10%, respectively. Although there are many models such as Bouc-Wen, Takeda, Q-Hysteresis and etc. which define the nonlinear behavior more realistic, simple bilinear model is used in the study to characterize the nonlinear behavior of SDOF systems. This study only aims to obtain the variation in the seismic energy input for different pre-yield damping ratios. It is mainly obtained from this research that the input energy has a tendency to decrease with the increase in pre-yield damping ratios.

2. General energy balance equation

The general equation of motion of SDOF structure can be integrated over the displacement and the general energy balance equation of SDOF system is obtained [15]. The energy balance equation for SDOF system can be turned into a time integral and written as:

$$\int_0^t m \cdot \ddot{u} \cdot \dot{u}\, dt + \int_0^t c \cdot \dot{u}^2 dt + \int_0^t f_s \cdot \dot{u}\, dt = -\int_0^t m \cdot \ddot{u}_g(t) \cdot \dot{u}\, dt \qquad (1)$$

where m is the mass of SDOF system, c is the damping coefficient =$(2 \cdot m \cdot \xi \cdot \omega_n)$, f_s is the restoring force, u is the relative displacement of the mass with respect to ground, $\dot{u}$ is the velocity of the mass, $\ddot{u}$ is the acceleration of the mass, $\ddot{u}_g$ is the acceleration of the strong ground motion and t is the time (denotes the duration of earthquake). Eq. (1) can be rewritten with the same array using energy symbols as:

$$E_k + E_\xi + E_a = E_I \tag{2}$$

where E_k indicates the relative kinetic energy, E_ξ is the damping energy, E_a is the absorbed energy by the elastic and inelastic behavior of the system and E_I shows the earthquake energy input to the structure. E_k, E_ξ, E_a and E_I can be obtained from Eq. (1) in the same sequence. The most important energy component of the total energy input is the hysteretic energy (E_h) and it is included in the absorbed energy E_a in Eq. (2). Hysteretic energy is the dissipated energy by the hysteretic behavior of the structure and is generally referred as the energy type which directly contributes to the structural damage [16].

3. SDOF systems

Four SDOF systems having various natural periods of T_n= 0.2 s, 0.6 s, 1.0 s and 1.4 s are selected as shown in Fig. 1. Pre-yield damping ratios are taken as ξ = 3%, 5% and 10%, respectively. Bilinear model is used to characterize nonlinear behavior of the structures as in Fig. 2. Strength degradation and pinching effects are neglected. F_y is the yield load and K_i and K_p ("$\alpha \cdot K_i$") are the initial and post-yield stiffnesses, respectively. Constant ductility ratio (μ = 2) is taken and post-yield stiffness ratio is used as α = 0.10 within the study. The displacement ductility ratio (μ) can be defined as:

$$\mu = \frac{\delta_{max}}{\delta_y} \tag{3}$$

where δ_y is the yield displacement and δ_{max} is the maximum displacement. The initial stiffness K_i may be written as:

$$K_i = \frac{F_y}{\delta_y} \tag{4}$$

The post-yield stiffness of the system may be defined as:

$$K_p = \alpha \cdot K_i \tag{5}$$

where α is the post-yield stiffness ratio.

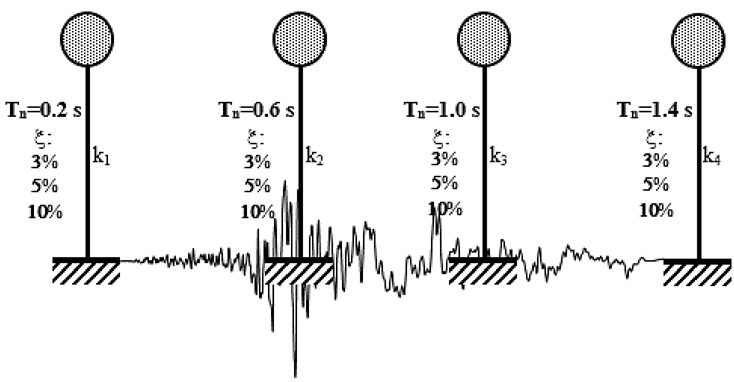

Fig. 1 SDOF systems having different natural periods.

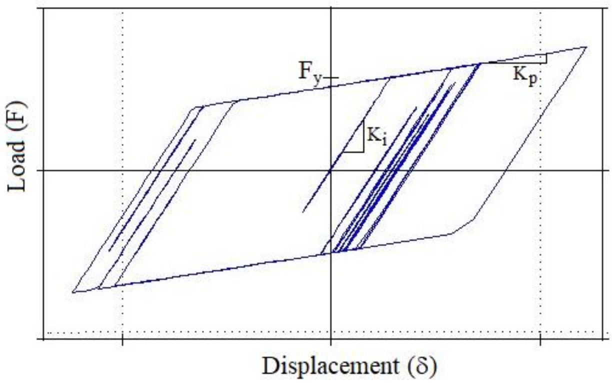

Fig. 2 A bilinear hysteretic model (α =0.10).

4. Selected earthquakes

A total of five recorded accelerograms are assembled according to the magnitude, distance, fault type, and soil profile type information. The accelerograms with a moment magnitude range of 6.5≤M_w≤7.5 and source-to-site distances (R_{JB}: Joyner-Boore distance) less than 100 km are compiled from the PEER-NGA strong-motion database which is used as the main source in the study [17]. The soil conditions of the accelerograms depict features of $Z3$ site class for the Turkish Seismic Design Code [18]. Soil profile type definitions of $Z3$ is considered according to the V_{S30} velocity (the average shear wave velocity in the first 30 m of the soil) which is classified as 180≤V_{S30} ≤360 m/s. The selected ground motions to compute the seismic energy input have all strike-slip fault mechanisms and effects of near faults are not considered. The list of selected ground motion records and the overall characteristics of accelerograms are presented in Table 1, where PGA is the peak ground acceleration, PGV is the peak ground velocity and PGD is the peak ground displacement.

Table 1 Properties of the selected accelerograms.

# Earthquake, Year	**Station**	M_w	R_{JB} (km)	V_{S30} (m/s)	**PGA (g)**	**PGV (cm/s)**	**PGD (cm)**
1. Big Bear-01, 1992	San Bernandino-E&H.	6.46	34.98	296.97	0.101	11.85	3.36
2. Borrego Mtn, 1968	El Centro Array #9	6.63	45.12	213.44	0.133	26.71	14.56
3. Erzincan, 1992	Erzincan	6.69	0.0	352.05	0.496	78.16	28.04
4. Kocaeli, 1999	Duzce	7.51	13.60	281.86	0.312	58.85	44.05
5. Landers, 1992	Yermo Fire Station	7.28	23.62	353.63	0.152	29.60	24.83

The constant-ductility inelastic acceleration spectra of selected earthquakes (for μ =2 and ξ =5%) are shown in Fig. 3. Erzincan earthquake has the maximum nonlinear spectral acceleration (S_a) values between the other records. The energy input-time histories of SDOF systems are analyzed by using these earthquakes within the study.

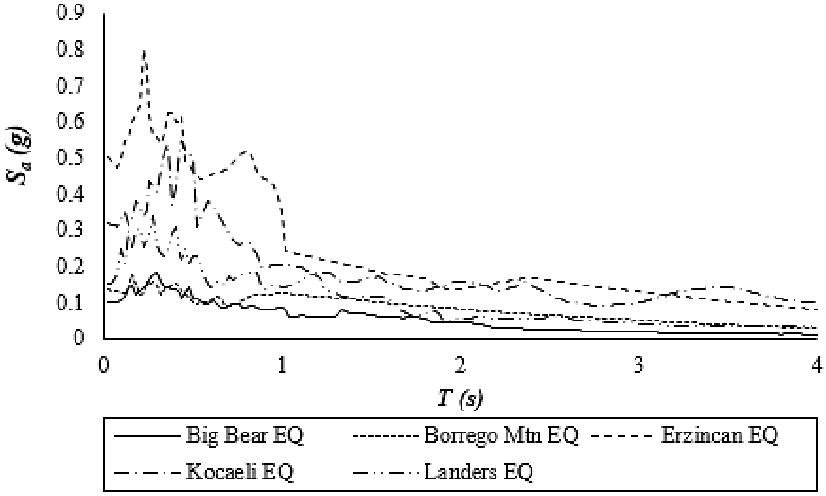

Fig. 3 The inelastic acceleration spectra of earthquakes for μ =2, α =0.10 and ξ =5%.

5. Energy input-Time histories for bilinear SDOF structures

Nonlinear time histories of constant-ductility SDOF structures are performed by using PRISM software [19]. Velocity time histories ($\dot{u} - t$ graphs) are used to create the energy input-time histories of structures. Fig. 4 shows the velocity time histories of bilinear SDOF systems having different natural periods as T_n= 0.2 s, 0.6 s, 1.0 s and 1.4 s and different damping ratios as ξ = 3%, 5% and 10% under the effect of Kocaeli Earthquake.

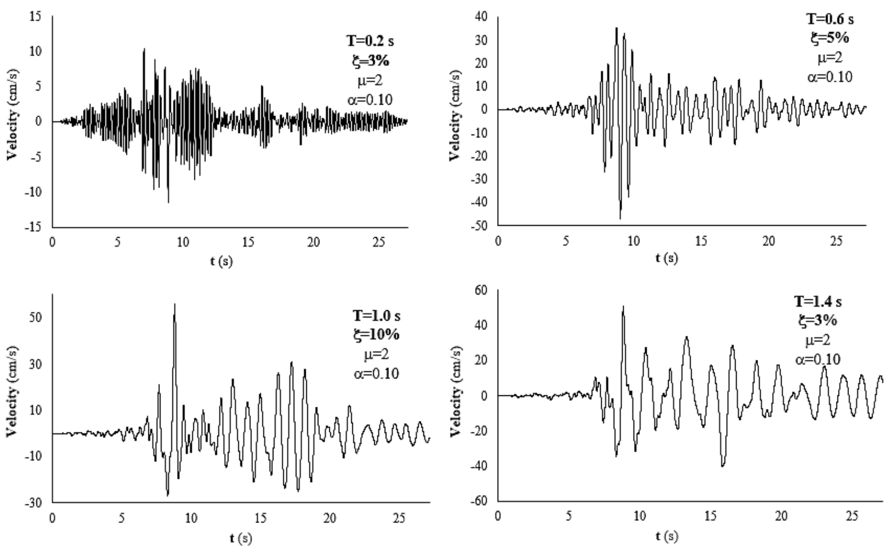

Fig. 4 Velocity time histories from Kocaeli Earthquake of SDOF systems having different periods and damping ratios.

The energy input to structures can be computed by using the right term of Eq. (1). This is the total input energy of SDOF systems under the effect of earthquake. The energy "E_I" can be rewritten independent of the mass (per unit mass) as:

$$\frac{E_I}{m} = -\int_0^t \ddot{u}_g(t) \cdot \dot{u}\, dt \tag{6}$$

Fig. 5 shows the energy input-time history of bilinear (μ = 2, α = 0.10) SDOF structures having different natural periods (T_n = 0.2 s, 0.6 s, 1.0 s and 1.4 s) and different pre-yield damping ratios (ξ = 3%, 5% and 10%) under the effect of the first selected earthquake (Big Bear-01, 1992 Earthquake). Figs. 6-9 show the energy input-time history of bilinear (μ =2, α =0.10) SDOF structures having different natural periods (T_n= 0.2 s, 0.6 s, 1.0 s and 1.4 s) and different pre-yield damping ratios (ξ = 3%, 5% and 10%) under the effect of earthquakes Borrrego Mtn. 1968, Erzincan 1992, Kocaeli 1999 and Landers 1992, respectively.

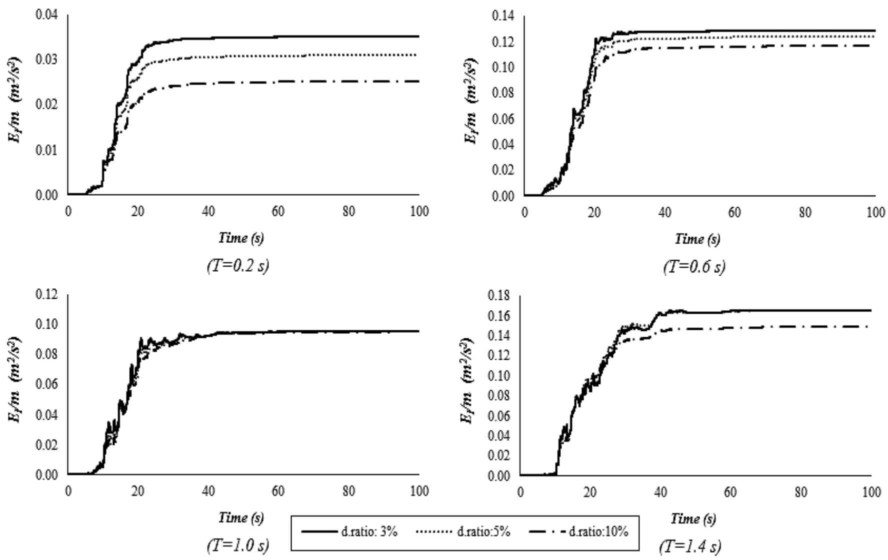

Fig. 5 Energy input-time history for bilinear (μ=2, α=0.10) SDOF structures with T_n=0.2 s, 0.6 s, 1.0 s and 1.4 s and ξ (d.ratio)=3%, 5% and 10%, subjected to Big Bear-01, 1992 Earthquake (San Bernandino-E&H.).

It can be seen from the figures (Fig. 5, Fig. 6, Fig. 7, Fig. 8 and Fig. 9) that the energy input has generally tendency to decrease with the increase in pre-yield damping ratios. The decrease may differ from one earthquake to another and from the period value to another. This situation depends on characteristics of accelerograms and velocity time histories of earthquakes. The energy input to the structures generally increases as the natural period of structures (T_n) increases. At the initial times of earthquake durations the input energy is nearly zero, it increases with time and tends to be constant for a large time.

Table 2 and Table 3 show the maximum values of earthquake energy inputs ($(E_I/m)_{\max}$) to the bilinear SDOF structures. Energy input-time histories from the earthquakes show that the maximum energy input value decreases with the increase in pre-yield damping ratio (from ξ = 3% to 10%).

There is relatively small variation in the energy inputs for different damping ratios at initial times but the variations become greater with time. In this study, the maximum variation in energy input for damping ratios is obtained from Erzincan Earthquake for the system with the period of T_n=1.0 s (Table 3).

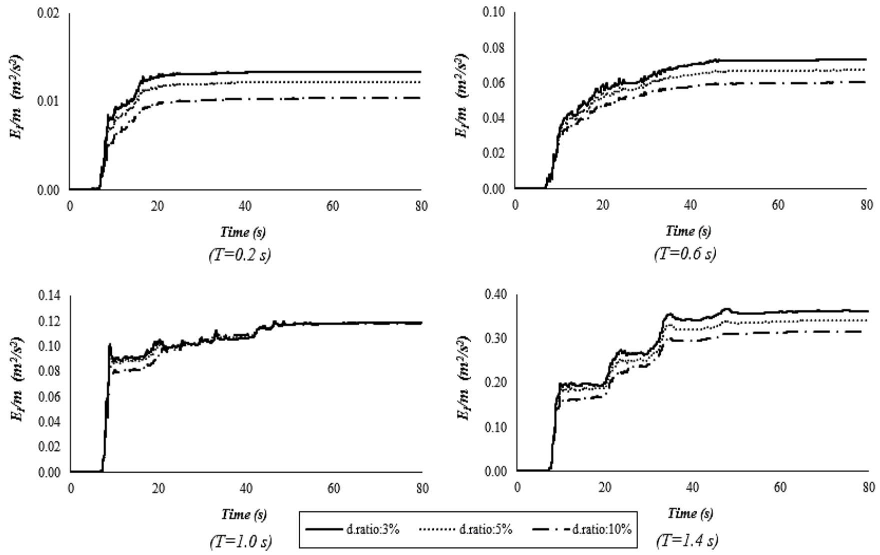

Fig. 6 Energy input-time history for bilinear (μ=2, α=0.10) SDOF structures with T_n=0.2 s, 0.6 s, 1.0 s and 1.4 s and ξ (d.ratio)=3%, 5% and 10%, subjected to Borrego Mtn, 1968 Earthquake (El Centro Array #9).

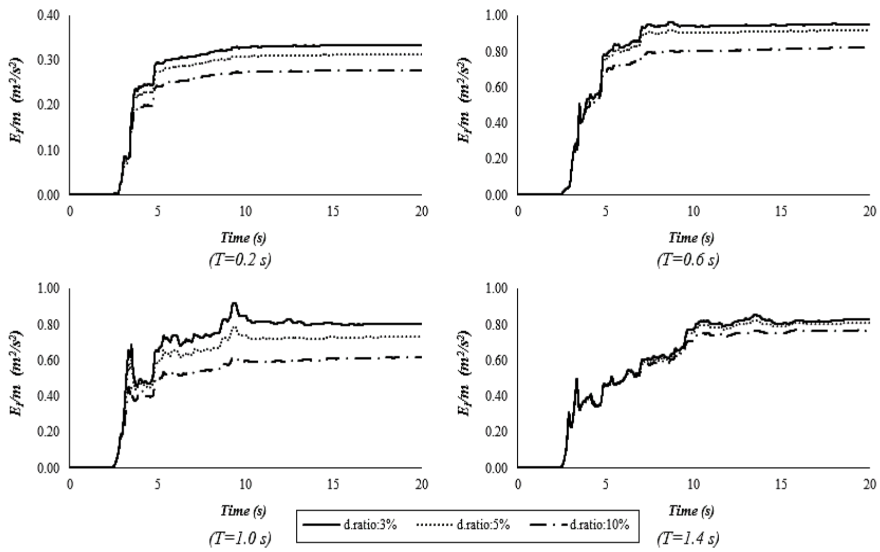

Fig. 7 Energy input-time history for bilinear (μ=2, α=0.10) SDOF structures with T_n=0.2 s, 0.6 s, 1.0 s and 1.4 s and ξ (d.ratio)=3%, 5% and 10%, subjected to Erzincan, 1992 Earthquake (Erzincan).

It can be seen from the results of the study that Erzincan earthquake among the other selected earthquakes has given the maximum energy input for all period values of SDOF systems (Table 2 and Table 3). The results of the study are restricted for only bilinear SDOF systems having μ = 2 and α = 0.10. Taking more advanced hysteretic models and selecting different ductility ratios, more valid results can be obtained from time history analyses.

Energy input-time history analyses can be improved for multi-degree-of-freedom (MDOF) systems in further studies.

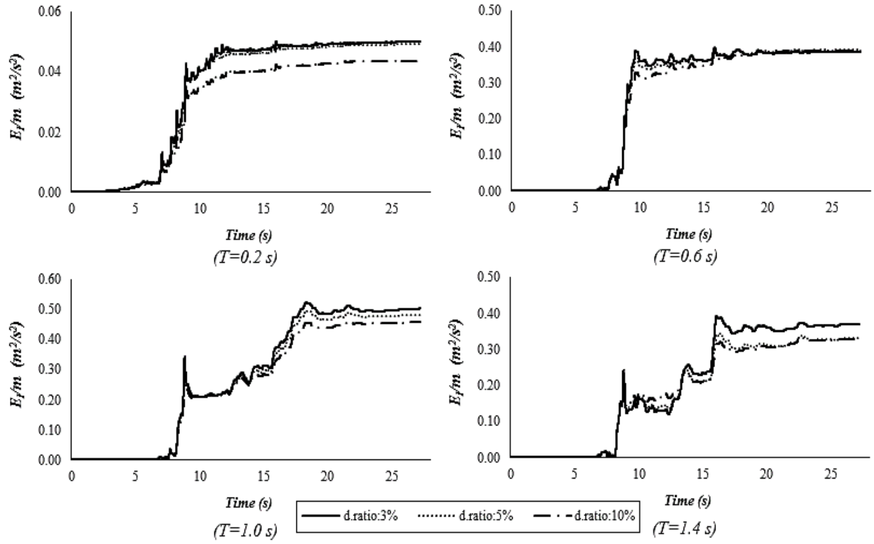

Fig. 8 Energy input-time history for bilinear (μ=2, α=0.10) SDOF structures with T_n=0.2 s, 0.6 s, 1.0 s and 1.4 s and ξ (d.ratio)=3%, 5% and 10%, subjected to Kocaeli, 1999 Earthquake (Duzce).

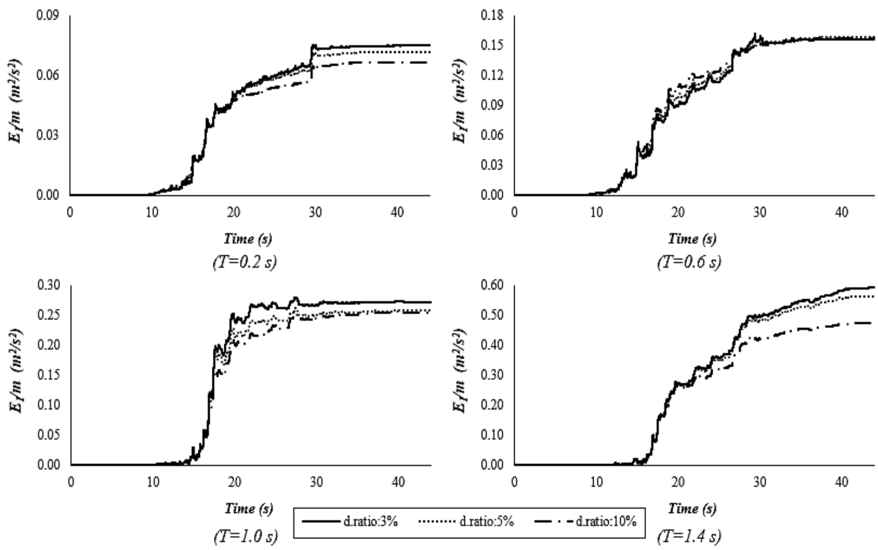

Fig. 9 Energy input-time history for bilinear (μ=2, α=0.10) SDOF structures with T_n=0.2 s, 0.6 s, 1.0 s and 1.4 s and ξ (d.ratio)=3%, 5% and 10%, subjected to Landers, 1992 Earthquake (Yermo Fire).

Damping ratio is one of the parameter which effects the energy input to structures with earthquakes. It is investigated in this study how the increase in the damping ratio will affect the energy input values of bilinear SDOF structures. Accelerogram number used in dynamic analyses had better be increased to obtain more accurate variation in the energy input of SDOF structures. In this study, only five real accelerograms are used and the obtained results are valid only for these earthquakes.

Table 2 Maximum values of earthquake energy inputs (SDOF systems with T_n=0.2 s and T_n=0.6 s).

# Earthquake	$(E_I/m)_{max}$ [m²/s²]					
	T_n=0.2 s			T_n=0.6 s		
	ξ=3%	ξ=5%	ξ=10%	ξ=3%	ξ=5%	ξ=10%
1. Big Bear-01	0.0352	0.0311	0.0252	0.1291	0.1242	0.1168
2. Borrego Mtn.	0.0134	0.0123	0.0104	0.0733	0.0674	0.0603
3. Erzincan	0.3342	0.3134	0.2779	0.9665	0.9215	0.8216
4. Kocaeli	0.0503	0.0494	0.0439	0.3981	0.3971	0.3906
5. Landers	0.0753	0.0718	0.0667	0.1616	0.1603	0.1579

Table 3 Maximum values of earthquake energy inputs (SDOF systems with T_n=1.0 s and T_n=1.4 s).

# Earthquake	$(E_I/m)_{max}$ [m²/s²]					
	T_n=1.0 s			T_n=1.4 s		
	ξ=3%	ξ=5%	ξ=10%	ξ=3%	ξ=5%	ξ=10%
1. Big Bear-01	0.0961	0.0958	0.0953	0.1660	0.1656	0.1493
2. Borrego Mtn.	0.1201	0.1195	0.1183	0.3680	0.3427	0.3172
3. Erzincan	0.9181	0.7886	0.6201	0.8532	0.8232	0.7707
4. Kocaeli	0.5240	0.4970	0.4583	0.3924	0.3429	0.3343
5. Landers	0.2802	0.2621	0.2559	0.5920	0.5642	0.4748

6. Conclusions

The distribution of earthquake input energy is researched using five accelerograms for bilinear SDOF systems having ductility ratio of μ = 2 and post-yield stiffness ratio α = 0.10. Natural periods of vibrations are taken as T_n = 0.2 s, 0.6 s, 1.0 s and 1.4 s and three different damping ratios as ξ = 3%, 5% and 10% are used, respectively.

As earlier studies indicated that structural properties such as ductility, damping ratio and the shape of hysteresis loop do have a significant influence on earthquake energy input; it is obtained once more in this study that the damping ratio variation has a direct influence on energy input-time history of bilinear SDOF structures. But, ground motion characteristics play the most important role in obtaining the energy input. The analytical results show that the earthquake input energy is inversely proportional to the damping ratio and it decreases a bit as the damping ratio increases. However, this degradation is not substantial and the maximum values of energy inputs are obtained very approximate for ξ = 3%, 5% and 10%. Each earthquake reflects its properties to the results of nonlinear dynamic analyses and therefore for all earthquakes, the variations in energy input values (for different damping ratios) are not obtained the same. The maximum variation in energy input for damping ratios is obtained from Erzincan Earthquake for bilinear SDOF system with the period of T_n = 1.0 s. The decrease in the energy input of Erzincan Earthquake is about 14.11% for the variation in ξ = 3% to ξ = 5%. It is obtained that the decrease in the energy input for the same earthquake is about 21.37% if the damping ratio differs from ξ = 5% to ξ = 10%. The results indicate that small damping ratios have a minor influence on the energy input of SDOF systems and the variation in the energy input value becomes greater as the damping ratio increases.

Accelerograms used and structure samples should be increased to obtain more detailed and effective results for energy input-time histories of SDOF systems and to determine the effects of structural properties on the energy input more precisely.

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