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HYSTERETIC ENERGY TO ENERGY INPUT RATIO SPECTRUM IN NONLINEAR SYSTEMS

(DOĞRUSAL OLMAYAN SİSTEMLERDE HİSTERETİK ENERJİ /ENERJİ ORANI SPEKTRUMU)

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ABSTRACT

Even though some empirical formulas for hysteretic energy (E_H) to energy input (E_I) ratio have been proposed in the literature, they all assume that this ratio is the same for any period range and do not consider either the ground motion properties or the structural properties. This paper presents a study on E_H/E_I in inelastic single-degree-of-freedom (SDOF) systems and relates it to the inelastic multi-degree-of-freedom (MDOF) systems subject to severe earthquake ground motions. The response analyses are carried out through nonlinear dynamic time-history (NDTH) analyses on SDOF systems and steel moment resisting frames as MDOF systems for ninety EQGMs recorded on different soils. A spectrum for E_H/E_I ratio with different strength indices in SDOF systems is proposed based on the analyses results.

Keywords: Hysteretic energy, Energy spectrum, NDTH analysis, nonlinear systems, SDOF systems, MDOF systems

ÖZ

Literatürde histeretik enerji (E_H)/enerji oranı (E_I) için bazı ampirik bağıntılar olmasına rağmen, tüm bu bağıntılar anılan oranı her bir periyot aralığı için sabit kabul etmekte ve deprem yer hareketi özellikleri veya yapısal özellikleri gözönüne almamaktadır. Bu çalışma, doğrusal olmayan tek serbestlik dereceli sistemler için E_H/E_I oranlarının hesabı üzerinedir ve çeşitli deprem yer hareketine maruz doğrusal olmayan çok serbestlik dereceli sistemlere adaptasyonu ile ilgilidir. Bu bağlamda, tek serbestlik dereceli sistemler ile çok serbestlik dereceli sistemlerin (moment aktaran çerçeveler) dinamik analizleri farklı zeminlerde kaydedilmiş doksan adet deprem hareketi dikkate alınarak doğrusal olmayan zaman tanım alanında hesap yöntemi ile gerçekleştirilmiş, analiz sonuçları doğrultusunda tek serbestlik dereceli sistemlere ait E_H/E_I oranı için spektrum önerilmiştir.

***Anahtar Kelimeler:** Histeretik enerji, Enerji spektrumu, Doğrusal olmayan zaman tanım alanında hesap, Doğrusal olmayan sistemler, tek serbestlik dereceli sistemler, Çok serbestlik dereceli sistemler*

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1. INTRODUCTION

Response parameters of a structure subject to an EQGM may be the stress ratios, deformation and inter-story drift ratios, structural accelerations, ductility demand ratios, damage and nonlinearity indices. One way to define damage and nonlinearity is to use the energy concepts and damage indices. Energy concepts have gained great attention to be used as a seismic design parameter in the last decade. Since damage involves inelastic deformation (nonlinear behaviour), inelastic behaviour of the structure has to be taken into consideration to estimate damage. The most rational and reliable way to estimate damage of a structure is the amount of hysteretic energy (demand), E_H, imparted to the structure when subjected to an earthquake ground shaking. E_H is part of the total energy input, E_I, and dissipated through the hysteretic behaviour. Because the damage in structures is related to the hysteretic energy dissipated by the structure, it can be used a design parameter, especially, when the damage is expected not to exceed some specified limits [1].

Energy concept was first introduced into seismic response of SDOF systems by Housner [2]. Since then, the development on the energy concept has mainly continued on SDOF systems [3-7]. Total energy input is generally considered to rely on the characteristics of ground motions and be not affected from the structural properties (mass, strength of the structure, etc.), especially, for the medium and long period range [4,5,6]. In addition, when the energy is of concern, the EQGM characteristics used are generally peak ground velocity, predominant period of the ground motion and the strong motion duration, not including the mechanism of the fault strike, the geology, and soil conditions at the site of the structure. A recent study by Manfredi proposed a method for evaluating hysteretic and total energy based on equivalent number of cycles correlated to the earthquake ground motion characteristics [8]. Riddell and Garcia also developed a method for deriving the hysteretic energy spectrum of SDOF systems for elastoplastic, bilinear, and stiffness degrading systems [9]. Cruz and Lopez [10] investigated the hysteretic energy as a function of structural properties and ground motion characteristics.

Even though the studies provided important information on the relation between the energy input and characteristics of the ground motions, they have their limitations when applied to the seismic design. The energy parameters are nonlinear and the inelastic seismic behaviour of a MDOF and SDOF system differ dramatically. Equivalent SDOF systems may be used to estimate the energy input on low-rise moment-resisting frames, but they may underestimate the energy input on high-rise structures due to the contribution of higher modes, which may become important for earthquake ground motions having high frequency content [1]. It should also be noted that the damage to the structural component is due to the hysteretic energy, E_H, not total energy, E_I. The hysteretic energy, E_H, and its distribution throughout the structure depend on both the structural systems and the ground motion. Shen and Akbas investigated the energy response in regular steel moment resisting frames by nonlinear NDTH analysis [11]. Their study presented hysteretic energy demand and distribution in regular steel moment resisting frames, and demonstrated significant differences in the energy response between the nonlinear SDOF and MDOF systems.

Hysteretic energy demand to energy input (E_H /E_I) ratio can also be used as a design parameter to determine E_H once E_I is known. Even though numerous studies have been performed on energy concepts to predict the energy input with some simple empirical formulas in the literature, there are only a limited number of studies on E_H /E_I ratio. The reason for this is because this ratio can only be used to describe the nonlinearity of the structure but not the level of damage. This is due to the fact that if E_H is large for a structure, E_I is also large or vice versa, i.e. if E_H is small, E_I is also small. Thus, even though E_H and E_I are related quantities, their ratio to describe the level of damage may be meaningless. However, the hysteretic energy to energy input ratio E_H/E_I is a very useful parameter for determination of hysteretic energy, if the energy input is known. And knowing the hysteretic energy demand, the design of a structural member can be performed [11]. This ratio is generally affected from damping and, in general, in the range of 0.0-0.9 (<1.0) due to the inevitable viscous damping existing in every structure.

This paper presents a study on E_H/E_I ratio in nonlinear SDOF and MDOF systems. The objectives of this study are to:

a. determine the E_H and E_H/E_I ratio in SDOF systems with two basic design parameters (strength index and fundamental period) subject to severe EQGMs on different soil types through NDTH analyses,
b. establish an E_H/E_I spectrum in SDOF systems, to estimate the E_H/E_I in MDOF systems,
c. determine the E_H and E_H/E_I in MDOF systems subject to the same EQGMs through NDTH analyses,
d. propose modification factors for the E_H and E_H/E_I ratio between SDOF and MDOF systems.

2. ENERGY RESPONSE OF A SDOF SYSTEM

Energy response terms of a SDOF system subject to an EQGM can be derived from the equation of motion [12] and stated as

$$E_k(t) + E_D(t) + E_e(t) + E_H(t) = E_I(t) \tag{1}$$

The four terms on the left-hand side of Equation 1 are considered as energy response of the structure (the capacity side of the basic design equation) and the term on the right-hand side as energy input (the demand side of the design equation). $E_k(t)$ is proportional to relative velocities of masses at time t, called kinetic energy which is only related to the instant response of the structure at time t. $E_D(t)$, called damping energy, is physically interpreted as the energy dissipated by the viscous damping of the system. The damping energy is a cumulative quantity, ever increasing with the time during the vibration. $E_e(t)$ is the elastic strain energy, an instant quantity depending on the current elastic deformation level at time t. $E_H(t)$, called hysteretic energy, is a cumulative quantity over the plastic deformation throughout the entire duration of the vibration, and it will be zero if the structure remains elastic. $E_I(t)$ is the seismic energy input of the deformed structure defined as the work done by the effective seismic force (the mass times ground acceleration) over the structural deformation. The instant kinetic energy and elastic strain energy consist of relatively small portion of the input energy at any time during the vibration and vanish at the end of the vibration. The cumulative damping energy and hysteretic energy, therefore, are major contributors to dissipating the input energy. The hysteretic energy, E_H, includes the inelastic deformation of structural members and is directly related to the cyclic deformation capacity of structural components. In an elastic response, E_H is equal to zero, whereas E_e is negligible compared to E_H in an inelastic response. Thus, E_k and E_e are negligible in an inelastic response and Eq. (1) can be practically written at the end of the EQGM as

$$E_D + E_H = E_I \tag{2}$$

For a given structure and EQGM, the quantities in Equation 2 at the end of the EQGM can be determined and the distribution of hysteretic energy throughout the structure can be evaluated.

3. STUDIES ON HYSTERETIC ENERGY / ENERGY INPUT (E_H/E_I) RATIO

Zahrah and Hall concluded that the E_H/E_I ratio is higher for impulsive type of EQGMs, than it is for symmetric type of EQGMs and increases as viscous damping decreases and the displacement ductility of the system increases [3]. Akiyama proposed the following empirical formula to describe E_H/E_I ratio [4].

$$\frac{E_H}{E_I} = 1 - \frac{1}{(1+3\zeta+1.2\sqrt{\zeta})^2} \tag{3}$$

where ζ is viscous damping ratio. However, Eq. (3) considers only the viscous damping ratio as the main effective factor on E_H/E_I ratio and neglects the strength of the system. Kuwamura and Galambos [6] studied E_H/E_I ratio and they observed that this ratio depends on the critical damping and cumulative ductility and proposed the following empirical formula.

$$\frac{E_H}{E_I} = 1 - \frac{\dfrac{\varphi}{\varphi+0.15}}{1+\dfrac{20(3\zeta+1.2\sqrt{\zeta}}{\varphi+10}} \tag{4}$$

where φ is defined as the ratio of cumulative plastic deformation to the yield deformation. Fajfar *et al.* also proposed an upper bound for E_H/E_I ratio based on the critical damping for stiffness proportional damping as follows [13].

$$E_H/E_I = 0.8 \ (\zeta=5\%) \tag{5a}$$

$$E_H/E_I = 0.9 \ (\zeta=2\%) \tag{5b}$$

Fajfar and Vidic observed that E_H/E_I ratio depends on the damping, the ductility factor and the hysteretic behaviour [14]. They proposed the following simple formula considering the hysteretic model, damping and stiffness proportional damping.

$$\frac{E_H}{E_I} = 1.05\frac{(\mu-1)^{0.95}}{\mu} \tag{6}$$

where μ is the ductility factor defined as the maximum displacement divided by the yield displacement). Akbas *et al.* proposed a simple relationship to determine the E_H/E_I ratio for medium and severe EQGMs as follows [15].

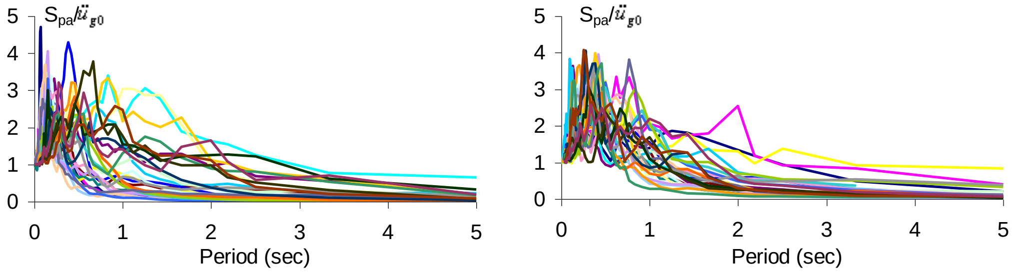
$$\frac{E_H}{E_I} = 1\text{-}0.09/(\ddot{u}_{g0}/\text{g}) \tag{7}$$

where $\ddot{u}_{g0}$ is the peak ground acceleration. None of the above relationships include soil effect which can be very important in MDOF systems.

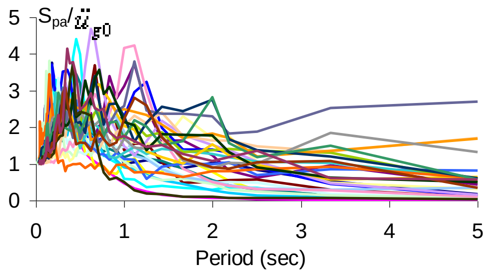
4. ENERGY INPUT (E_H) AND HYSTERETIC ENERGY/ENERGY INPUT RATIO (E_H/E_I) IN SDOF SYSTEMS

To determine the quantities of terms in Eq. (2) and E_H / E_I ratio, NDTH on SDOF systems are carried out using DRAIN-2DX, a general purpose nonlinear dynamic analysis program [16]. The bilinear inelastic behaviour is assumed with no strain hardening. A stable cyclic deformation is assumed and P-Δ effect is not included in the analysis. Damping ratio (ζ) is assumed to be 5% of critical damping. Stiffness proportional damping is used in the study. Two major parameters in seismic design, fundamental period and strength index (or lateral strength), are considered in the study. Strength index (η) is defined as the ratio of the base shear value at which the structure begins its inelastic deformation to the seismic weight of the structure.

The analyses are performed on an ensemble of SDOF systems with fundamental periods (T) ranging from 0.1 sec to 3.0 sec at 0.1 sec increments for three different η; 0.1, 0.3, and 0.5 to cover a large range of different structures. The SDOF systems with $0 < T < 0.3$ sec, $0.3 \leq T < 0.7$ sec, 0.7 sec $\leq T < 1.0$ sec, and $1.0 \leq T < 2.0$ sec, and $2.0 < T \leq 3.0$ sec will be referred to as very short, short, medium, long, and very long period systems. An ensemble of 90 EQGMs recorded on four different soil types (Type A, B, C and D) are used in the study [17]. For *Type A, B, C* and *D* soil types, shear velocities (V_s) are bigger than 750 m/sec, between 360-750 m/sec, 180-360 m/sec and less than 180 m/sec, respectively. *Type A&B, Type C* and *Type D* soil groups have 30 EQGMs each making a total of 90. Normalized response spectra of the each soil group are given in Figure 1. Detailed information about the EQGMs can be found at Sari [17]. The peak ground accelerations ($\ddot{u}_{g0}$) of the EQGMs are scaled to 0.6g to represent a severe EQGM.



a) *Type A&B* b) *Type C*



c) *Type D*

Figure 1. Normalized Response Spectra of the EQGMs

4.1. Hysteretic Energy Per Unit Mass (E_H/m)

E_H/m for *Type A&B*, *C* and *D* soil groups are given in Figures 2-4, respectively. Among the three soil groups, the smallest E_H/m is observed on *Type A&B*, while the highest is observed on *Type D*. For *Type A&B*, E_H/m is close to zero or very small for some EQGMs. E_H/m is maximum for medium- and long-period structures, but minimum for very short and very long period structures for *Type A&B* except for SIL000 EQGM (Figure 2). For *Type C*, E_H/m reaches its maximum in short-, medium-, and long-period range (Figure 3). For *Type D*, E_H/m, in general, tends to increase as T increases (Figure 4). For all soil groups, E_H/m is minimum for η=0.3 for very short and very long period range, while it is maximum in somewhere the short, medium, and long period range for η=0.5 in general.

E_H/m is affected by η in almost any period range. For very long period structures, E_H/m decreases as strength increases, while in medium and long-period range remains almost constant over the period. For η=0.1 (a low strength structure), E_H/m can be considered as bi-linear, linear in the very short and short period range and constant in the medium, long, and very long period range. However, for η=0.3 and 0.5 (high-strength structure), a tri-linear curve is more appropriate, linear in very short, short and very long period range and constant for medium and long period range.

The structures are very rigid in very short period range and as η increases they hardly reach their yield strength, i.e. almost zero hysteretic energy. However, E_H/m is the most sensitive to η in medium and long period ranges (0.3 sec<T<2.0 sec) due to the fact that the dominant periods of the EQGMs fall into this range causing the response of the structure to increase (Figures 2-4). For very long period structures, E_H/m tends to become zero as η increases, i.e. no yielding in very long period structures.

4.2. Hysteretic Energy / Energy Input (E_H / E_I) Ratio

For *Type A&B*, *C* and *D* soil groups, E_H / E_I ratios are given in Figures 5-7, respectively. For all soil groups, E_H / E_I ratio is at maximum at very short and short period range and decrease as T and η increases. The strength of the structure (η) plays an important role on E_H / E_I ratio. E_H / E_I ratio seems stable for η = 0.1 and reduces dramatically as η increases in the medium, long, and long very long period range. Dramatic reductions in E_H / E_I ratio occurs in medium- and long-period range. It is obvious that for *Type A&B* and *C*, as the strength of the structure increases, all the energy input is dissipated through viscous damping (Figures 5 and 6) in very long-period systems. However, for *Type D*, a large portion of input energy remains to be dissipated through hysteretic behaviour (Figure 7) in long-period range.

Figure 8 shows the mean E_H/E_I ratios for *Type A&B, C* and *D*. E_H/E_I ratio is minimum for *Type A&B* and except for very short period range, it decreases as the strength of the structure increases. For any η, the highest E_H/E_I ratio is for *Type D*. For long and very long period range, E_H/E_I ratio gradually decreases to less then 10% for *Type A&B* and *C*. However, it is around 20% for *Type D* for η=0.5. This implies that higher strength structures on long and very long period range have to dissipate more hysteretic energy if constructed on *Type D* than if constructed on *Type A&B* and *C*. For any η, the hysteretic energy to be dissipated on *Type D* is more than twice the hysteretic energy to be dissipated on *Type A&B* and *C*. For very short period range on Type A&B, very short and short period range on Type C and D, E_H/E_I ratio decrease as *T* decreases.

A polynomial of third order was fitted to E_H / E_I ratios with different strength indices to construct E_H / E_I ratio spectrum for each soil group as follows:

$$E_H / E_I (\eta) = aT^3 + bT^2 + cT + d \qquad (7)$$

The fitted curves for E_H/E_I ratio spectrum are plotted in Fig. 9 for *Type A&B, C* and *D*. Polynomial constants of the spectrum are given in Table 1. In Table 1, correlation coefficients (R^2) are also included. As can be seen from Table 1, the smallest R^2 value is 0.92. The E_H/E_I ratio spectrum in Figure 9 gives a very good approximation for E_H E_I ratio for any period range and strength of the structure as well as for any soil group.

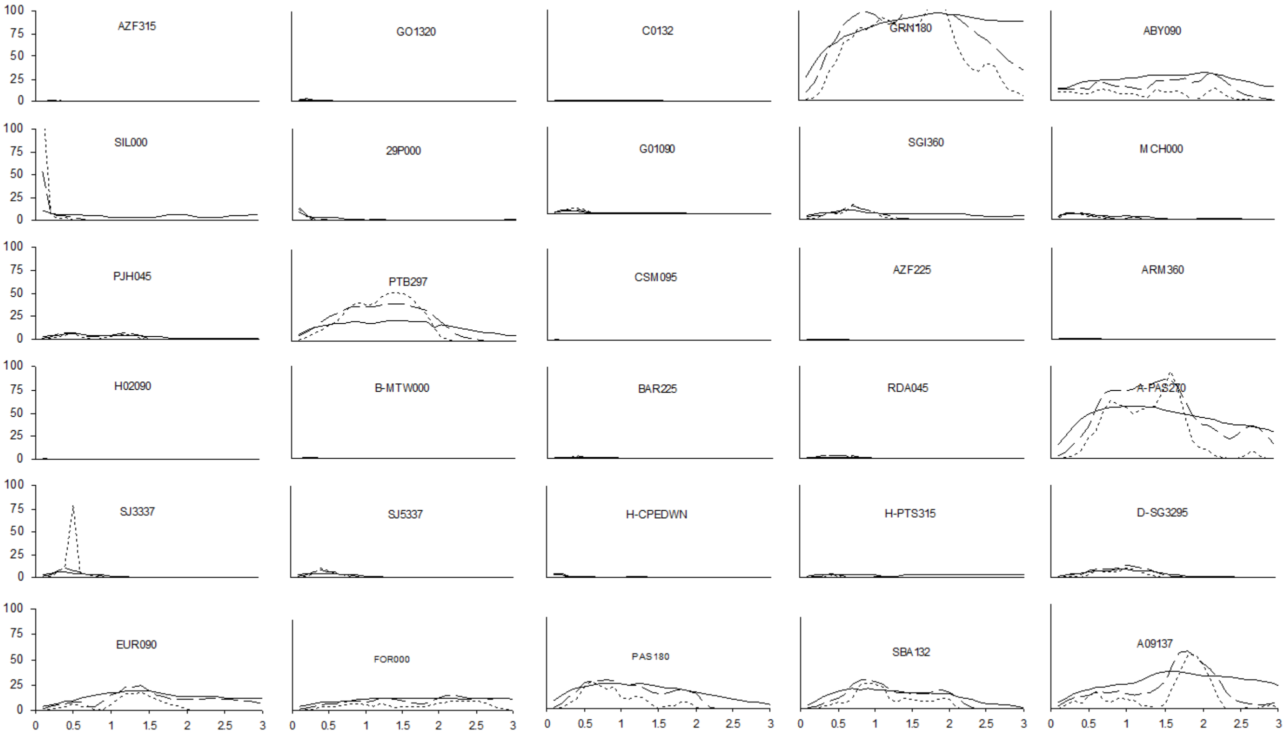


Figure 2. E_H/m for *Type A&B* (——η=0.1, - - - -η=0.3, ⋯⋯η=0.5), (x1000 (cm/sec)^2)

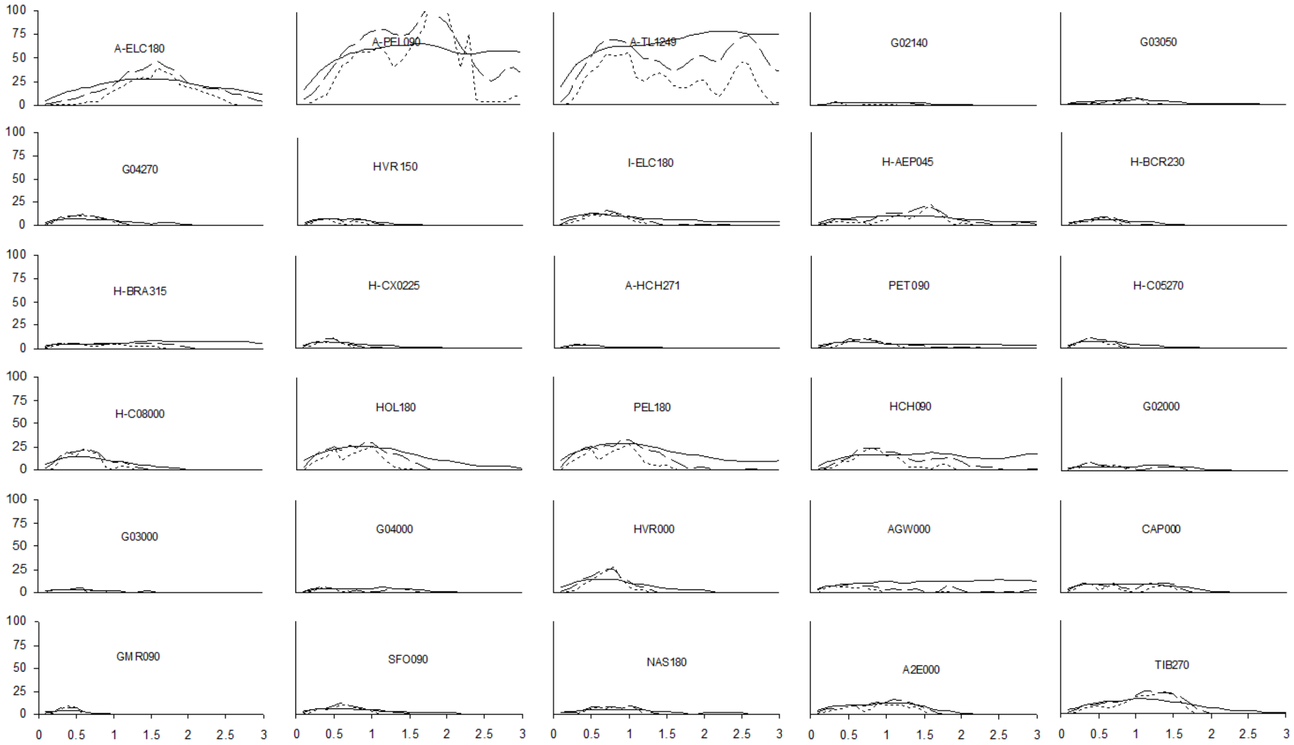


Figure 3. E_H/m for *Type C* (—— η=0.1, ------ η=0.3, ·········η=0.5), (x1000 (cm/sec)^2)

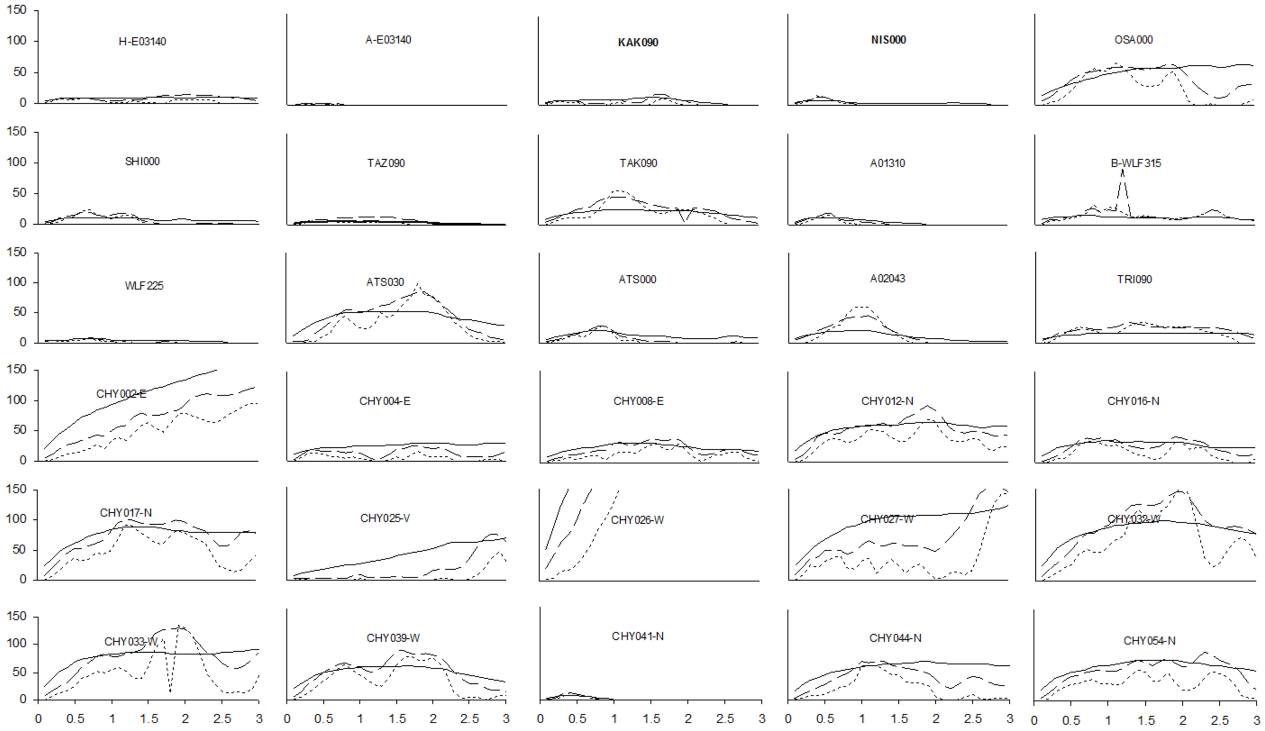


Figure 4. E_H/m for *Type D* (—— η=0.1, ------ η=0.3, ·········η=0.5), (x1000 (cm/sec)^2)

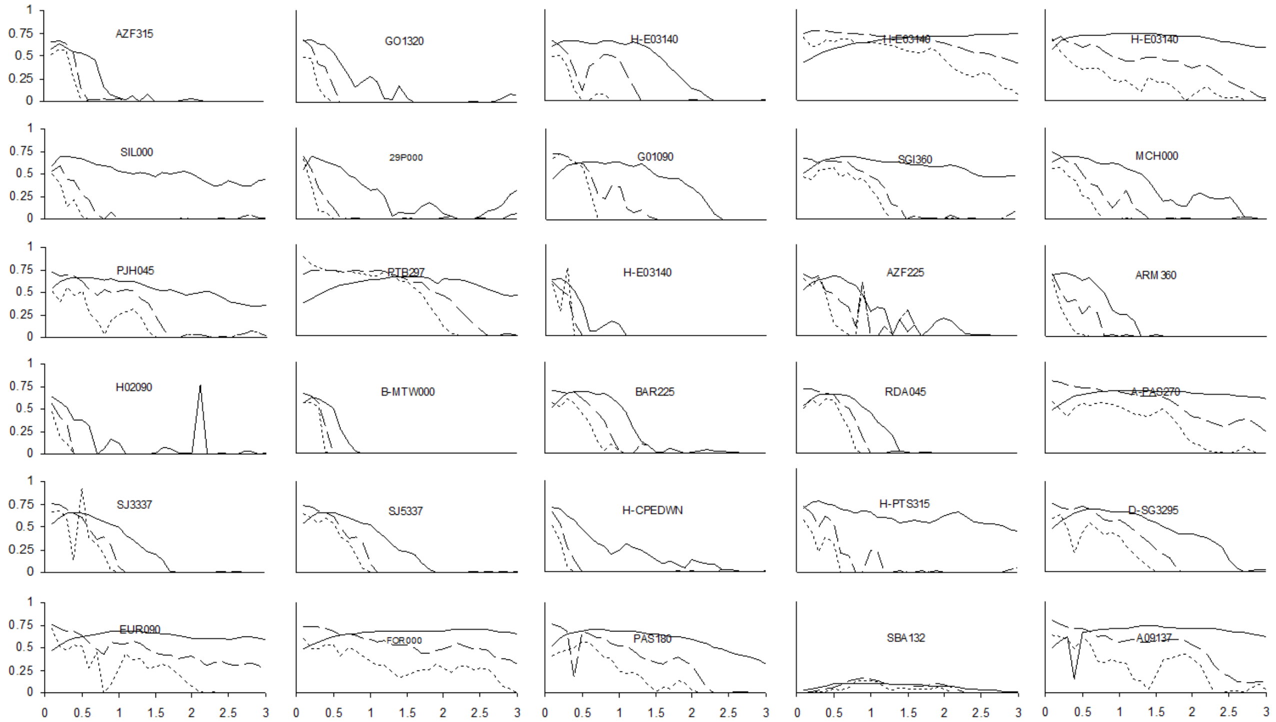


Figure 5. E_H/E_I for *Type A&B* (—— η=0.1, ------η=0.3, ...η=0.5)

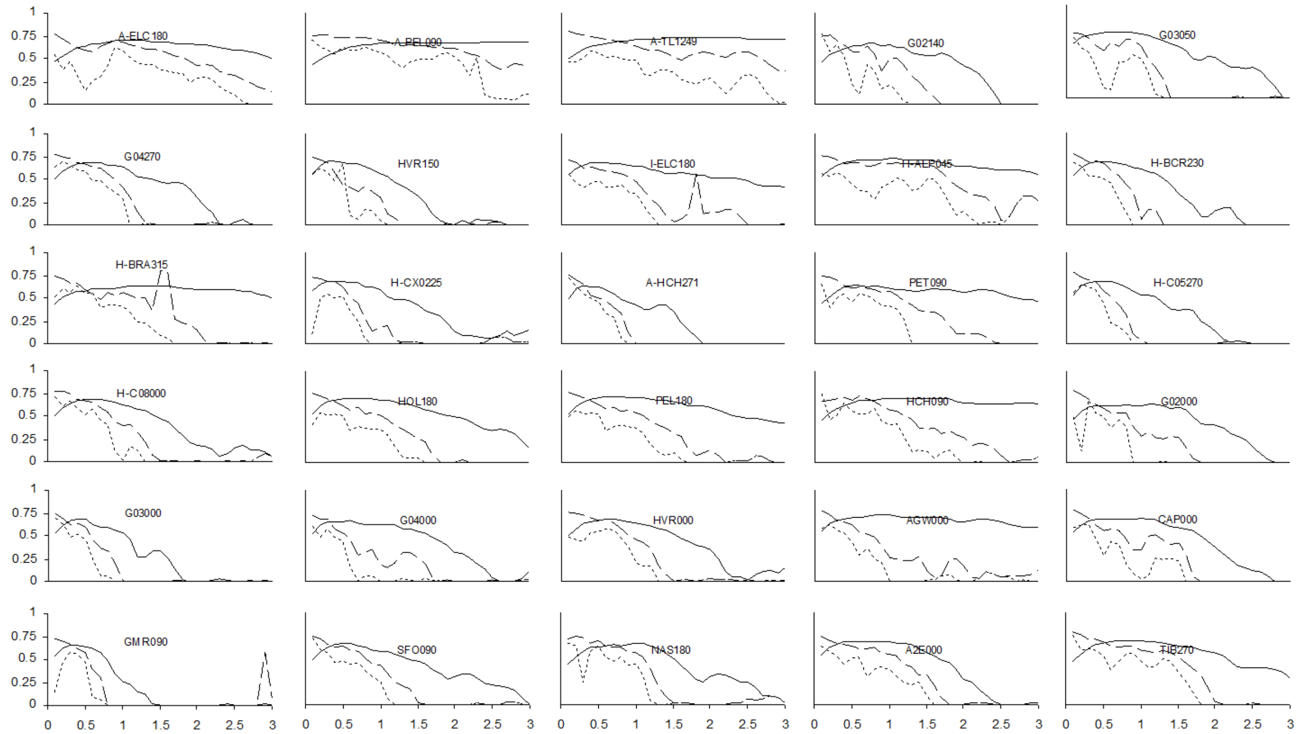


Figure 6. E_H/E_I for *Type C* (—— η=0.1, ------ η=0.3, ...η=0.5)

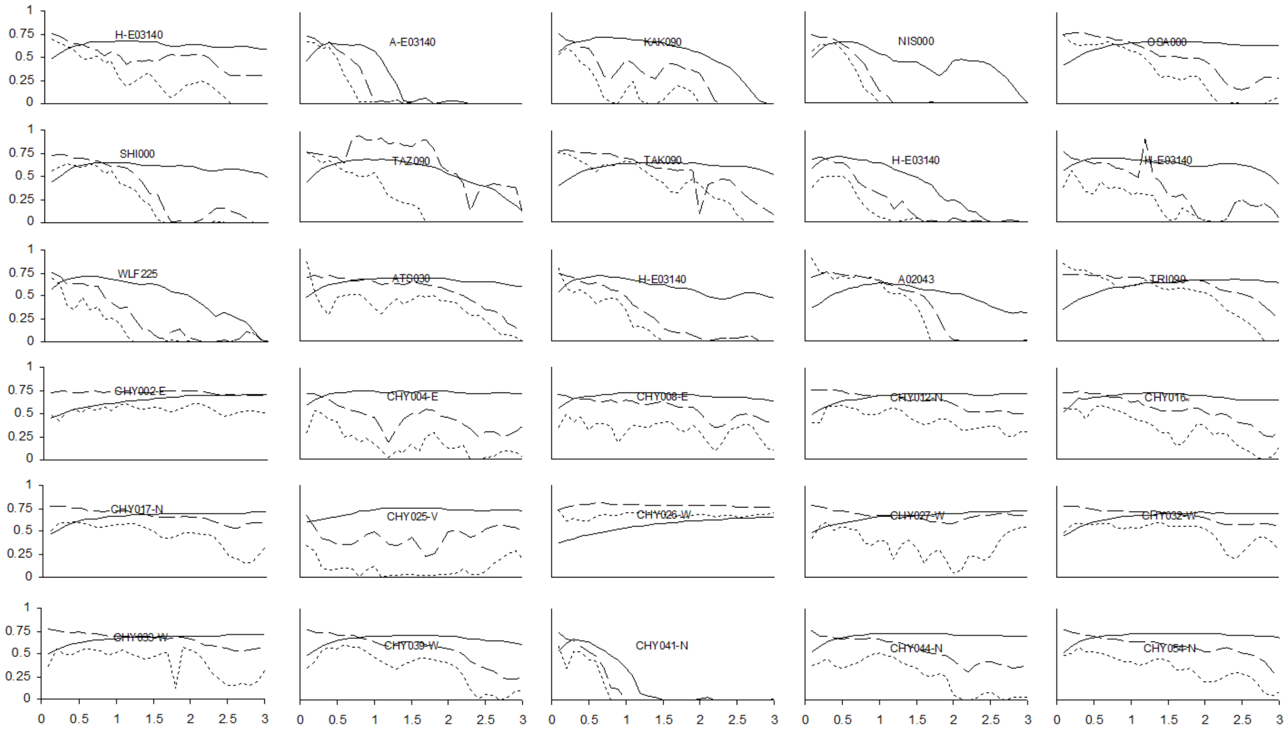


Figure 7. E_H/E_I for *Type D* (—— η=0.1, ------ η=0.3, ········ η=0.5)

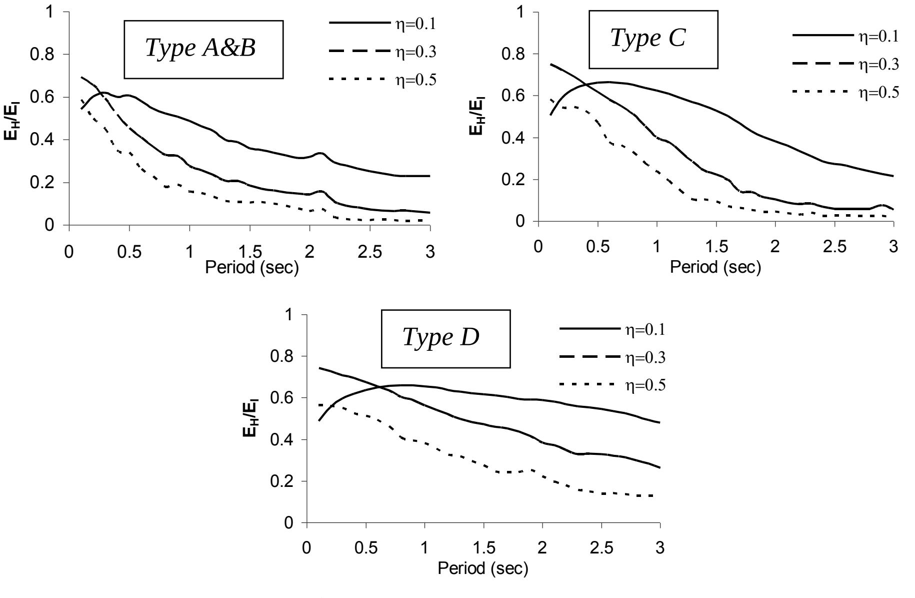


Figure 8. Mean E_H/E_I ratios

Table 1. Polynomial constants of the fitted curves for E_H/E_I ratio spectrum

Soil Type	*Strength index*	*Polynomial Coeeficients*				
	(η)	*a*	*b*	*c*	*d*	R^2
A&B	0.1	0.0293	-0.1155	-0.041	0.6129	0.97
	0.3	-0.0458	0.3064	-0.7517	0.7729	0.99
	0.5	-0.0586	0.3632	-0.7777	0.6348	0.98

C	0.1	0.0789	-0.4248	0.4735	0.5045	0.99
	0.3	0.0306	-0.0417	-0.3923	0.8102	0.99
	0.5	-0.0076	0.1495	-0.5956	0.6880	0.99
D	0.1	0.0362	-0.2216	0.341	0.4979	0.92
	0.3	0.0062	-0.0057	-0.204	0.7702	0.99
	0.5	0.0087	-0.0011	-0.2367	0.6109	0.99

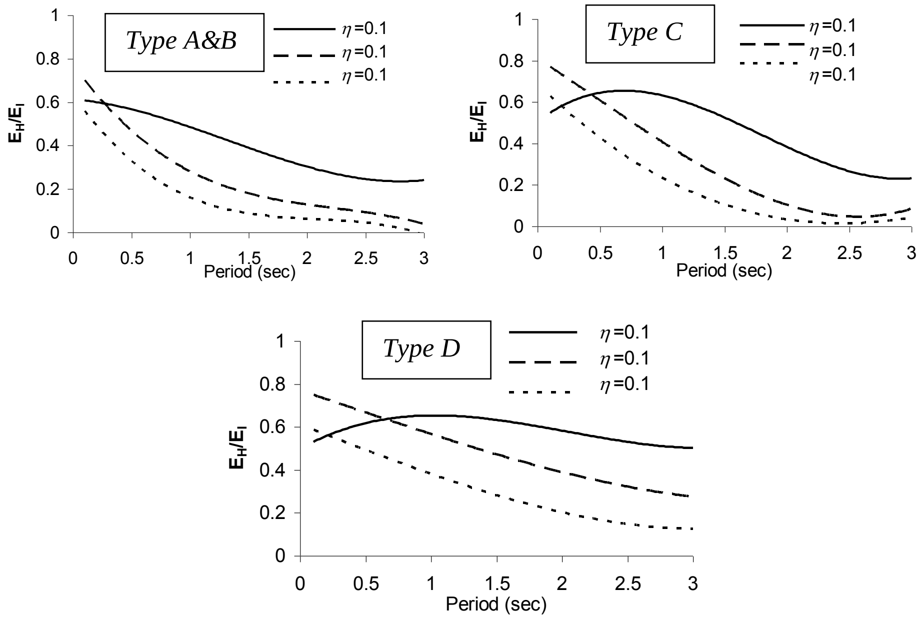


Fig. 9. E_H/E_I ratio spectrum

5. ENERGY INPUT (E_H) AND HYSTERETIC ENERGY / ENERGY INPUT RATIO (E_H/E_I) IN MDOF SYSTEMS

The results obtained from SDOF systems have always been considered inadequate and underestimated the energy parameters in MDOF systems [11]. A modification is required to be able to estimate both E_H/m and E_H/E_I in MDOF systems. This modification can be defined as

$$(E_H/m)_{MDOF} = C_{E_H} \text{ x } (E_H/m)_{SDOF} \qquad (8)$$

and

$$(E_H/E_I)_{MDOF} = C_{E_H/E_I} \text{ x } (E_H/E_I)_{SDOF} \qquad (9)$$

where C_{E_H} is the modification factor for E_H/m obtained from a SDOF system ($(E_H/m)_{SDOF}$) and C_{E_H/E_I} is the modification factor for E_H/E_I obtained from SDOF system ($(E_H/E_I)_{SDOF}$). $(E_H/m)_{MDOF}$ and $(E_H/E_I)_{MDOF}$ are the hysteretic energy per unit mass (E_H/m) and hysteretic energy to energy input ratio (E_H/E_I) in MDOF systems.

To determine C_{E_H} and C_{E_H/E_I}, energy response analyses through NDTH analyses are carried out on three steel buildings with 3-, 9-, and 20-stories. These buildings are designed for gravity, wind, and seismic loads as part of the SAC Steel Project and represent typical low-, medium-, and high-rise steel buildings [18]. The structural system for all buildings consists of steel moment resisting frames and interior simply connected frames for gravity, i.e. lateral loads are carried by perimeter frames. The seismic masses of the buildings are 2950 t, 9000 t, and 11100 t for 3-, 9-, and 20-story buildings, respectively. The first natural periods of the 3-, 9-, and 20-story frames are 1.0109 sec, 2.2862 sec, and 3.7863 sec, respectively. The frames are subjected to the same EQGMs, a total of 90 (thirty for each soil group) scaled to 0.6g [19]. The frames are modelled by DRAIN-2DX [16]. The two-dimensional models of the frames are built for nonlinear dynamic time history analyses. Beam-column elements are used in the analyses and inelastic effects are assigned to plastic hinges at member ends. The bilinear inelastic behaviour is assumed with a strain hardening of 5% of the initial stiffness in all elements. A stable cyclic deformation is assumed. Mass is assumed to be lumped at the joints. Damping ratio is assumed to be 5% and Rayleigh damping with the first, second and fourth, and third and sixth natural frequencies for the 3-, 9-, and 20-story frames, respectively, is used in the analyses. *P-M* (axial load-moment) interaction relation, suggested by AISC-LRFD [20], is used as yielding surface of column elements. Beams are modelled as flexural elements. The panel zone effect is neglected in the analyses, but large deformation (P-Δ) effect is considered on the analyses of 9- and 20-story frames. Pushover analyses are also carried out on the frames to obtain the strength indices (η) which are found to be 0.22, 0.11, and 0.058 for the 3-, 9-, and 20-story frames, respectively. These three-frames cover the fundamental period from 1.0109 to 3.7863 sec, and the strength index from 0.058 to 0.22. Strong column-weak beam requirement is observed to be strictly imposed to avoid early inelastic deformation in columns.

The energy input per unit mass (E_H/m) and energy input/hysteretic energy (E_H/E_I) in the frames are calculated and compared with those in SDOF systems corresponding to the same strength index and fundamental period. Table 2 summarizes the comparison of E_H/m in the 3-, 9-, and 20-story frames shown as MDOF systems vs. corresponding SDOF systems. C_{E_H} is also given in Table 2. Linear interpolation is applied to obtain the values of η=0.22, 0.11, and 0.058 for the 3-, 9-, and 20-story frames, respectively. C_{E_H} increases as the number of stories increases for Soil Type A&B. For *Type C,* it is maximum for 20-story frame, but minimum for 9-story frame. C_{E_H} is the lowest for *Type D* for all frames. The minimum C_{E_H} is obtained for 9-story frame for *Type D*. The highest C_{E_H} is for *Type D* on the 20-story frame. C_{E_H} is higher than unity and can take a value of 18, i.e. the hysteretic energy is 18 times highrer than the corresponding SDOF system (Table 2). Table 2 also shows that SDOF systems highly underestimates the E_H/m in MDOF systems.

Table 2. Comparison of E_H/m in MDOF vs. SDOF Systems

MDOF Systems						SDOF Systems	C_{E_H}
No. Of Story	Soil Type	Period (sec)	η	E_H (x10^6)	E_H/m (m/sec)^2	E_H/m (m/sec)^2	
3	A&B	1.0109	0.22	1..61	1092	116	9.41
	C			1.65	1119	125	8.95
	D			2.06	1397	431	3.24
9	A&B	2.2862	0.11	2.16	1467	96	15.28
	C			0.56	379	76	5.00
	D			1.06	721	465	1.55
20	A&B	3.7863	0.058	2.26	1534	85	18.05
	C			1.74	1178	78	15.5
	D			2.50	1692	446	3.79

Table 3 shows the comparison of E_H/E_I in MDOF vs. SDOF systems. Linear interpolation is applied to obtain the values of η=0.22, 0.11, and 0.058 for the 3-, 9-, and 20-story frames, respectively. C_{E_H/E_I} is maximum for the 9-story frame for *Type A&B* and at minimum for 20-story frame for *Type D*. The highest C_{E_H/E_I} is obtained for the 9-story frame for all soil groups. C_{E_H/E_I} is changed in the range of 1.19 and 3.42. E_H/E_I in the frames is between 0.75 and 0.89. However, it is between 0.26 and 0.70 in the corresponding SDOF systems. Table 3 shows that SDOF systems highly underestimates the E_H/E_I in MDOF systems.

Table 3. Comparison of E_H/E_I in MDOF vs. SDOF Systems

MDOF Systems					SDOF Systems	C_{E_H/E_I}
No. Of Story	Soil Type	Period (sec)	η	E_H/E_I	E_H/E_I	
3	A&B	1.0109	0.22	0.88	0.35	2.51
	C			0.86	0.49	1.74
	D			0.89	0.60	1.43
9	A&B	2.2862	0.11	0.89	0.26	3.42
	C			0.78	0.30	2.60
	D			0.86	0.54	1.59
20	A&B	3.7863	0.058	0.83	0.47	1.77
	C			0.75	0.59	1.27
	D			0.83	0.70	1.19

Table 4. Comparison of E_H/E_I ratios in MDOF systems with the propesed formulas in literature

MDOF Systems			Akiyama (Eq.3)	Kuwamura and Galambos for φ =20 (Eq. 4)	Fajfar (Eq. 5)	Fajfar and Vidic forμ=12 (Eq. 6)	Akbas et al. (Eq. 7)
No. Of Story	Soil Type	E_H/E_I	E_H/E_I				
3	A&B	0.88	0.50 (43)	0.22 (75)	0.80 (9)	0.85 (3)	0.85 (3)
	C	0.86	“ (42)	“ (74)	“ (7)	“ (1)	“ (1)
	D	0.89	“ (44)	“ (75)	“ (10)	“ (4)	“ (4)
9	A&B	0.89	“ (44)	“ (75)	“ (10)	“ (4)	“ (4)
	C	0.78	“ (36)	“ (72)	“ (3)	“ (9)	“ (9)
	D	0.86	“ (42)	“ (74)	“ (7)	“ (1)	“ (1)
20	A&B	0.83	“ (40)	“ (73)	“ (4)	“ (2)	“ (2)
	C	0.75	“ (33)	“ (71)	“ (7)	“ (13)	“ (13)
	D	0.83	“ (40)	“ (73)	“ (4)	“ (2)	“ (2)

(Numbers in parentheses indicate the error rate in %)

Table 4 gives a comparison of the E_H/E_I ratio for the 3-, 9-, and 20-story frames with the proposed formulas in literature. None of the proposed formulas in literature contains either soil effect or strength of the structure, i.e. all the formulas give the same E_H/E_I ratio for any soil type and strength index. The highest error rate is for Kuwamura and Galambas [6](Eq. 4), while the lowest error rate is for Fajfar and Vidic [14](Eq. 6) and Akbas et al. [15](Eq. 7). Fajfar and Vidic [14](Eq. 6) consider the ductility factor as the main parameter effecting E_H/E_I ratio while Akbas et al. [15](Eq. 7) considers the intensity of EQGM.

6. CONCLUSIONS AND RECOMMENDATIONS

This study has attempted to evaluate and propose modification factors for E_H/m and E_H/E_I ratio in inelastic SDOF and MDOF systems subject to severe EQGMs considering the effects of design variables such as strength index, fundamental period, and soil type. Estimating the strength index (or lateral strength) and fundamental period of a MDOF system by pushover and mode analyses, E_H/m and E_H/E_I ratio can be estimated from a corresponding SDOF system with the same fundamental period and strength index subject to a severe EQGM using the modification factors. A spectrum for E_H/E_I ratio based on strength index, fundamental period, and soil type is also given. A higher value of E_H/E_I ratio indicates more nonlinearity, while a small value of E_H/E_I ratio indicates less nonlinearity.

The main conclusions obtained from this study and some recommendations for further studies are summarized below.

(1) E_H/m is not a constant value and depends significantly on the properties of the system such as fundamental period and strength ratio (η) and on the EQGM properties.

(2) Strength index and fundamental period are major design parameters in energy response.

(3) For very short- and very long-period range, hysteretic energy decrease, while for short-, medium-, and long-period range, it increases as the strength increases.

(4) SDOF systems highly underestimate the hysteretic energy and hysteretic energy to energy input ratio in MDOF systems. A modification is required to apply the energy response parameters obtained from SDOF systems to corresponding MDOF systems.

(5) Structures in very short period range ($T < 0.3$ sec) behave like a rigid body when subject to a severe EQGM and energy input and hysteretic energy decrease as η increases.

(6) As η increases, structures in very long period range ($T > 2.0$ sec) respond in elastic range causing no hysteretic energy.

(7) C_{E_H} and C_{E_H/E_I} relate the E_H/m and E_H/E_I ratio of a SDOF system with its two design parameters, strength index and fundamental period, to a MDOF system with the same properties.

(8) The proposed E_H/E_I ratio spectrum can also be applied to establish the performance level thresholds of structures for low performance levels such as life safe and collapse. For a given period and E_H/E_I ratio, one can easily find the required strength that the structure must supply or the required E_H/E_I ratio for a given strength index and period.

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