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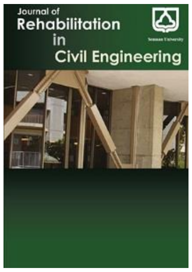

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Comparison of Seismic Input Energy Based on the Characteristics of Structural Hysteretic Behavior

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ABSTRACT

The variation of earthquake input energy with characteristics of various structural systems, particularly in hysteretic states, has not been studied to such extent that creates enough confidence for proposing energy-based design criteria. In this paper, at first, based on a somehow new insight into the concept of earthquake input energy, two concepts of ‘Received Energy’ (ERec) and ‘Returned Energy’ (ERet) have been discussed. Then, by using various hysteretic models for expressing the behavior of structures, including elasto-plastic, bilinear, Wen, Clough, and Takeda models, and two strength levels for the structure, variations of the ‘Total Input Energy’ (ETot) and also ERec and ERet with respect to the structural specifications have been investigated, by a series of Non-Linear Time History Analyses (NLTHA). Several earthquake accelerograms with various frequency contents from low to high, and peak ground acceleration values have been used for NLTHA. Results show that in some cases the amount of seismic input energy varies remarkably with the hysteretic specifications of the structure, particularly its strength. On this basis, it can be claimed that the hysteretic specifications can be used as measures for limiting the amount of earthquake input energy, and accordingly the level of overall damage to the structure.

1. Introduction

Since mid 70s many researchers have discussed about earthquake input energy (Kato and Akiyama 1975) [1], and since early 90s some of them have made efforts to use this concept in the seismic design of building systems (Surahman & Merati 1992) [2]. As one of the first works in this regard, Kato and Akiyama (1975) have studied the energy input and damage in structures subjected to severe earthquakes. Mentioning that Housner’s assumption that the energy input contributing to structural damage can be expressed as half the product of the mass of the structure and the velocity response spectrum, they have expressed that structural damage corresponds to the energy absorption due to plastic deformation, and the energy input causing damage may correspond to the sum of the energy absorption due to plastic deformation and the elastic vibrational energy. They have evaluated each component in the above law from some numerical analyses of inelastic vibrational systems, and have found that Housner's assumption is basically valid, however, they have not given any suggestion for the use of energy in seismic design.

Surahman and Merati (1992) have studied on the input energy based seismic design code for shear buildings up to four stories high, subjected to different earthquake loadings [2]. They have employed a Newmark linear acceleration direct integration method for computation of deformations, forces, and energy in the elasto-plastic ranges and have concluded that as a basis for a seismic design code, the energy approach is relatively more consistent than the base shear approach.

Kinugasa and Nomura (1996) have studied on development of seismic design based on energy concept [3]. The main feature of their study is the ability for considering the rapidity of energy input by introducing the idea of "Energy Input Velocity". In that study, the destructive power of an earthquake is expressed by the quantity of the input energy and its input velocity. They have expressed the seismic capacity of a building by the quantity of energy that can be absorbed within the continuation time of an earthquake on condition that the deformation is limited to the design maximum deformation.

Chai and Fajfar (Oct. 2000) have proposed a procedure for estimating input energy spectra for seismic design [4]. Mentioning that the damage potential of an earthquake ground motion is evaluated in terms of the total power of the acceleration of the ground motion, and by assuming an appropriate spectral shape for the input energy spectrum, and using the well-known Parseval theorem for evaluating the total power of a random signal, they have determined the peak amplification factor for the equivalent input energy velocity spectrum, which varies from about 2 to 10 for most of the recorded ground motions used in that study.

Jiang and Zhu (Sept.-Oct. 2006) have presented energy input design spectra for near-fault regions and application in energy-based seismic design [5]. Mentioning that the reliable definition of input energy spectra is an essential foundation for energy-based seismic design and evaluation method, and considering the influence of soil type and fault distance, they have derived the energy spectra for seismic design with the shape and amplitude adjustment according to different seismicity groupings.

Recently, Hosseini and his colleagues (2009) have discussed a new insight to the ‘input energy’ concept and its usage for more reliable seismic design of buildings [6]. In that study the input energy, calculated as the work done by the shear force at the building foundation during an earthquake, is divided into two positive and negative parts. The positive part can be considered as the energy which is transferred from ground to the building, while the negative part can be considered as the energy which is returned back from the building to the ground. They have analyzed some sample buildings with various distributions of parameters along their heights and have calculated the values of 'received energy' and 'returned energy' for them by using some accelerograms with various frequency content from low to high. Also Poursamad and Hosseini (2010) have performed a study on the dependency of seismic input energy on the characteristics of structural hysteretic behavior by using an explicit hysteretic mathematical model [7]. Results of that study show that in some cases the amount of input energy varies remarkably with the characteristics of the system, particularly the parameter which control the rate of change of stiffness. On this basis it can be claimed that this parameter can be used as a controlling tool for limiting the amount of earthquake input energy and accordingly the level of overall damage to the structure. Finally, Haddad Shargh and Hosseini (2010) have studied the existence of an optimal distribution of stiffness over the height of mid- to high-rise buildings to minimize the seismic input energy, and have shown that finding such a distribution is possible [8].

Kuwamura and V. Galambos (1989) presented an ultimate limit state criterion to investigate the seismic reliability of single story structures. According to that study when the structure can survive that the structural pre collapse energy absorption capacity is larger than the seismic energy input. Therefore, the critical load is the maximum seismic energy input which the structure is possible to confront during its lifetime. The dynamic characteristics of the buildings, the seismic hazard potential and the earthquake records have been considered in that research to determine the mentioned critical load. The dynamic characteristic factor has been determined from the energy input spectrum of inelastic single degree of freedom structural systems and the seismic hazard factor has been determined from attenuation models and seismic source. Also, the uncertainty involved in those factors has been evaluated in order to calculate the collapse probability [9].

Seismic input energy spectra for four hysteresis models, four soil site categories and five ductility values were developed for far field ground motion effect by Mezgebo and M. Lui in 2016. A quantity called velocity index which was allowed for creating the dimensionless spectra were considered to normalize those energy spectra. In that study, Hysteretic energy spectra were developed to investigate the demand feature of energy based seismic design of the structures with ductility values with ranges from 2 to 5 and 5% critical damping ratio. Then, by comparing the response spectra produced using nonlinear time history analyses and proposed hysteretic and input energy spectra were found to generate advisedly suitable results over a relatively large period range [10].

Flag shaped hysteretic systems with seismic fuses have been developed lately to exploit in high performance seismic resistant structural systems. In such a way that seismic fuses are used to protect flag shaped hysteretic systems by magnifying the dissipation of input seismic energy in very severely ground motions. Nowadays, many studies have been concentrated on the seismic response of flag shaped single degree of freedom systems without mentioned fuses. Because, more comprehensive analytical studies on the seismic response of the flag shaped systems with seismic fuses is needed. To do this, Joon Kim in 2012 carried out comparative nonlinear time history analyses of flag shaped and elasto plastic single degree of freedom systems. The analyses results of the flag shaped single degree of freedom systems showed that ductility demands decrease when post-yielding stiffness ratios, strength ratios and structural periods increase. Also, parameters relating to energy dissipation have effect on the equations of the equivalent damping ratios. Results also showed that with increasing the post yielding stiffness ratios, re centering limits and strength ratios, the medium maximum displacement demands of aforementioned fuses decrease [11].

Different studies have demonstrated that during intensive earthquakes, a large number of structural systems enter non reactionary range. Hysteretic energy, which is dissipated within its hysteresis rings, is very influential on the level of damage potential of the structural systems and is the most important factor in the equation of the energy in the structural calculations. Consequently, controlling the values of Hysteretic energy leads to controlling the structural behavior. The values of hysteretic energy in the structural systems can be an index of its damage values or its vulnerability. Abdollahzadeh and et.al in 2016 carried out nonlinear dynamic analyses on the steel buildings with a V-shaped brace [12]. According to the results, investigations of the hysteretic energy distributions and the maximum inter story drift in the height of those buildings were under the influence of the near and far fault earthquake records. Results also showed that the inter story drift caused by near fault records is more than the far fault ones and the level of hysteretic energy caused by far fault earthquake records are lower than the near fault ones. What is more, with increasing the building height, the level of the hysteretic energy in the higher stories increases [13].

Based on the performance based seismic design approach and using energy concept, Ghodrati Amiri and et.al in 2017 tried to study the effects of damping and duration on the elastic input energy due to strong earthquake records. Structures were analyzed to calculate the equivalent velocity spectra in four categories of soils by using input energy according to reliable Iranian ground motions. In such a way that mentioned spectra which were normalized in various PGA levels were presented in various damping ratios, soil types and durations. Then the influences of the aforementioned parameters were studied on the spectra. Results demonstrated that, in various soil types, with increasing the duration of ground motions, the seismic input energy to structures increases. Furthermore, the input energy to structures in stiff soils is lower than the soft ones and with increasing the stiffness of the soil type, the seismic input energy decreases. Also, the influence of damping on input energy is not very large and in damping ratio about 5%, input energy to structure has the least value [14].

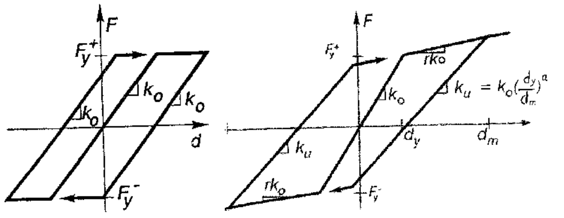
Khashaee and et.al in 2003 presented a report to develop an energy-based design procedure and evaluate the damage potential of structures. They express that, the distribution of earthquake input energy depend on the energy components: kinetic, damping, hysteretic, and elastic strain. They investigate the influences of the earthquake specifications such as frequency content, duration and intensity and the structural features such as hysteretic behavior on the distribution of seismic input energy, ductility and damping. They used one and five story buildings as two case studies, using 20 earthquake records from short to long durations. According to the results, the influence of ductility on seismic input energy and its distribution in members of the structures is substantial for specific damping ratios. The influence of low damping ratio, less than 5%, on seismic input energy is minor, but on energy distribution in the structures is major for a certain ductility ratio. While large Damping ratios, more than 5%, has a considerable effect on the seismic input energy and its distribution in the structures. The effects of structural features and earthquake specifications on propagation of seismic energy parameters for the case study buildings with base-isolation, fixed-base, semi-active control and supplemental damping were evaluated using 20 earthquake records. According to the result of nonlinear time history analyses, the duration of earthquake records and the frequency content have no effect on the distribution of seismic input energy through the height of the case study buildings. While semi-active control, supplemental damping and base isolation have significant effects on the distribution of input energy through the height of the mentioned buildings. These parameters decrease the damage potential of the buildings by decreasing the hysteretic and input energy demands [15].

The efficiency and influence of supplementary energy dissipation instruments is one of the most important issues in earthquake and structural engineering to reduce the response of the structural systems to induced earthquakes. Bayat and Abdollahzade in 2011 studied the effect of the supplemental ADAS instruments on the seismic behavior of the buildings by comparing the ratio of the hysteretic energy to input energy in various structural systems located in far field regions. Their case studies were three five, ten and fifteen story buildings with three bay Concentric Braced Frames, with and without ADAS device. They carried out nonlinear time history analyses using PERFORM 3D.V4 software under three Tabas, Imperial Valley and Northridge accelograms. They investigated the influences of the ADAS dampers, the PGA values and height of the frames on increasing the energy damping values to decrease the destructive effects of the earthquakes according to the energy criterion [16].

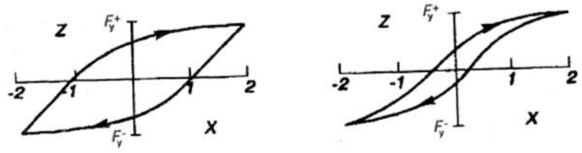
It is seen that in spite of several studies on earthquake input energy, up to now no straightforward method has been introduced for using this concept in seismic design, and none of the existing codes have such an approach. It is believed that the reason behind this fact is that the variation of input energy with characteristics of various structural systems in both linear and particularly nonlinear states has not been studied enough yet for proposing energy-based design criteria. Therefore, still more investigation in this regard is necessary. In this study the variations of input energies for a Single-Degree-Of-Freedom (SDOF) system, consisting of a cantilever steel column with box section, with a lumped mass at its top, has been investigated with the system hysteretic features. Two states of low and high ultimate strength have been considered for the SDOF system by using two different values of the box section dimension and its wall thickness, while the cross-sectional moment of inertia have been kept constant so that the system stiffness does not change. Details of the study are briefly explained hereinafter.

2. The Used Hysteretic Models

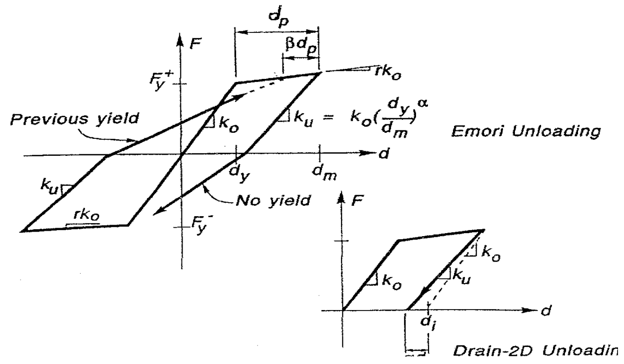
For expressing the hysteretic behavior of structures various mathematical nonlinear hysteretic models including elasto-plastic, bilinear, Wen, Takeda and Clough models were used. Yielding and ultimate stresses of the steel material have been assumed to be respectively 34.8 and 45.8 ksi, and its yielding and ultimate strains to be respectively 0.001 and 0.004. The considered SDOF system for Nonlinear Time History Analyses (NLTHA), consists of a cantilever steel column, 118 in high, with a lumped mass at its top, and with box cross-section, once 5.4 in x 0.2 in as the high strength section and once 6.65 in x 0.1 in as the low strength section. The moment of inertia of the column cross-section is the same in these two cases, leading to the same stiffness and natural period. Figure 1 shows different types of used nonlinear hysteretic models of the SDOF system.



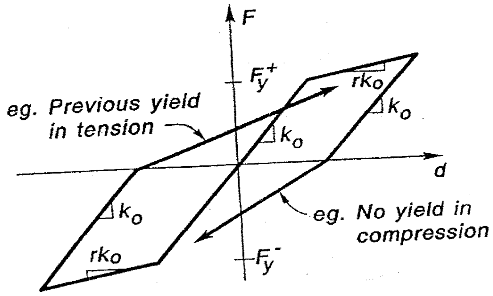
Elasto-plastic model Bilinear model



Wen model



Takeda model



Clough model

Fig. 1. Various nonlinear hysteretic models used in the study [7]

3. Calculation of Earthquake Input Energies by NLTHA

Three earthquakes accelerograms from PEER strong motion database with different frequency contents, from low to high, all scaled to various Peak Ground Acceleration (PGA) levels of 0.20, 0.35, 0.50, 0.65 and 0.80g were used for time history analyses. Mentioned accelerograms have been recorded in Northridge 1994, Colinga 1983 and Chalfant Valley 1986. Durations of the used accelerograms were between 21.71 to 25.00 seconds. NLTHA were conducted by Opensees Software, and energy values were calculated by formulas given by Poursamad Bonab and Hosseini [7]. In that study the input energy, calculated as the work done by the shear force at the building foundation during an earthquake, is divided into two positive and negative parts. The positive part which is named 'received energy' can be considered as the energy which is transferred from ground to the building (ERec), while the negative part which is named 'returned energy' can be considered as the energy which is returned back from the building to the ground (ERet). Table 1 shows some sample results for PGA level of 0.8g, for both high- and low strength cases of the system.

Table 1. Amounts of ERec, ERet, and ETot (in kips.in) for various hysteretic models in case of PGA=0.8g for both high- and low strength cases of the system

Hysteretic model	*Received energy* (E_{Rec})		*Returned energy* (E_{Ret})		*Total energy* (E_{Rec}- E_{Ret})	
	High strength	*Low strength*	*High strength*	*Low strength*	*High strength*	*Low strength*
Elsto-plastic	7.5	77.17	51.20	44.32	30.08	32.85
Bilinear	82.85	78.83	53.65	47.67	29.19	31.06
Wen	79.47	78.32	47.22	39.27	32.25	39.04
Takeda	93.46	89.85	55.71	49.65	37.74	40.19
Clough	86.85	80.65	49.49	41.47	37.35	39.18

To have a better understanding of the variations of energy values with changes in the system's features and PGA level the values of ETot for both cases of high- and low strength are shown in Figures 2 and 3, and the values of ERet/ERec in Figures 4 and 5.

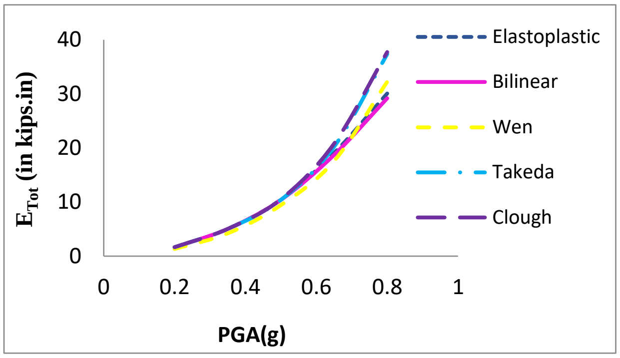


Fig. 2. Variations of ETot with PGA level for various hysteretic models in case of high strength of the system

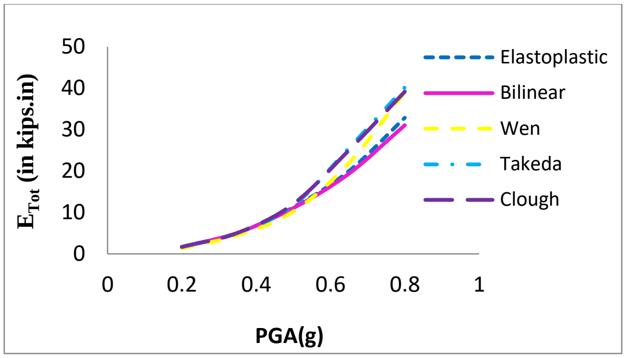


Fig. 3. Variations of ETot with PGA level for various hysteretic models in case of low strength of the system

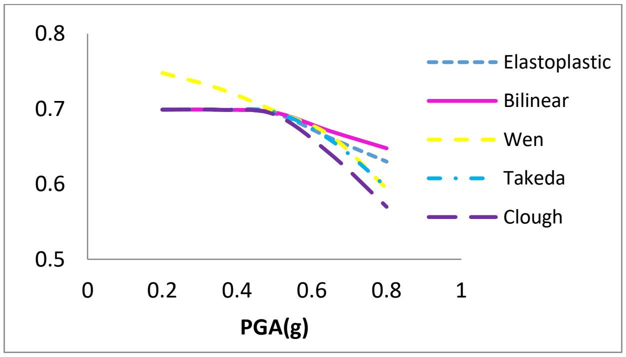


Fig. 4. Variations of E_{Ret}/E_{Rec} with PGA level for various hysteretic models in case of high strength of the system

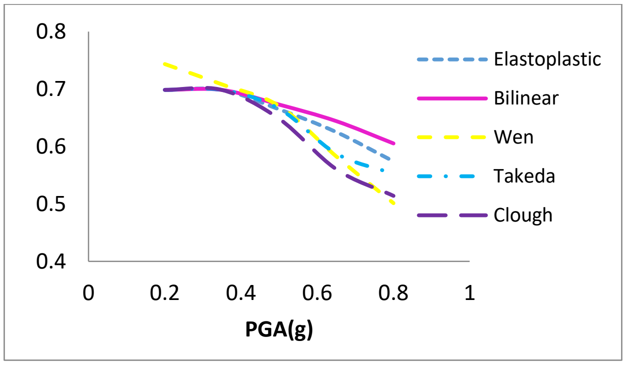


Fig. 5. Variations of E_{Ret}/E_{Rec} with PGA level for various hysteretic models in case of low strength of the system

It can be seen in Figures 2 and 3 that, as expected, generally the amount of total input energy increases as the PGA value of the applied earthquake increases, however, the amount of this increase and its trend are different for different hysteretic models, and this difference increases as the PGA value increases. Furthermore, it can be observed that the amount of ETot for the case of low strength system is relatively higher than that value for the case of high strength system. Figures 4 and 5 show that with increase in the PGA value the ratio of ERet/ERec, decreases. Again the amount of this decrease and its trend are different for different hysteretic models, and this difference increases as the PGA value increases. For example, in case of lower PGA values Wen model has higher ratios, comparing to other models, while in case of higher PGA value the bilinear model has the higher value of ERet/ERec. Finally, from Figures 4 and 5 it can be observed that although the curves of ERet/ERec versus PGA for the two cases of low- and high strength systems are similar their trends are different for different hysteretic models.

4. Conclusions

- Variations of earthquake received-, returned-, and total input energy of the structure with increase in PGA value of the applied earthquake are similar, but are not the same for different hysteretic models. For example, Clough models leads to higher values of energies almost in all cases.
- The amounts of aforementioned energies depend not only on the natural period of the system, but also on the system’s hysteretic features and its strength, so that systems with the same natural period, but different strengths have different input energies.
- On this basis, it seems possible to make some control on the amount of the seismic input energy, and therefore the amount of damage, by creating appropriate hysteretic features and level of strength for the system. However, more research is necessary in this regard.

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