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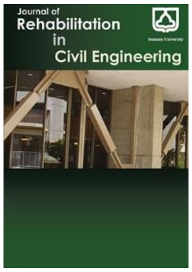

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Comparison of Seismic Input Energy Based on the Characteristics of Structural Hysteretic Behavior

S. Karimiyan[1*] and M. Hosseini[2]

1. Department of Civil Engineering, Islamshahr Branch, Islamic Azad University, Islamshahr, Iran
2. Structural Engineering Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran

Corresponding author: *s_Karimiyan@iiau.ac.ir*

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ABSTRACT

Alteration in earthquake input energy correspond with changes in characteristics of the various existing structures, particularly in hysteretic states, has not been examined to such extent that creates enough confidence to present diverse regulations or standards in field of earthquake energy in codes or guidelines. In this paper, at first, based on a somewhat new insight into the concept of earthquake input energy, two concepts of ‘Received Energy’ (ERec) and ‘Returned Energy’ (ERet) have been discussed. Consequently, by applying 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 inspected, by a series of Non-Linear Time History Analyses (NLTHA). Results reveal that when the structural hysteresis specifications, especially its resistance change the values of seismic input energy vary, remarkably. On this basis, structural hysteresis specifications are introduced as measures for limiting the values of damage in various structural systems.

1. Introduction

Since mid 70s, there are numerous researches in the field of seismic input energy (Kato and Akiyama 1975) [1], and since early 90s, part of this studies have been proposed and presented in the stage of energy based design in the structures [2]. In 1975, damage as a result to the earthquakes was examined pursuant Housner hypothesis. In this hypothesis, a relationship exists among the damage to the structural system and mass of the structures and its velocity as well. On that account the damage to the structure correlated to the absorbed energy caused by the plastic deformation and the elastic energy

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imported. They inspected all the components and parameters of Housner hypothesis and concluded that this hypothesis is applicable and valid without presenting any suggestion on the effect of energy in the seismic design of structures [1].

In 1992, the effect of the earthquake energy was investigated on the basis of seismic design codes in short-order shear structures. In this study, applying Newmark technique, the relationship between the absorbed energy as a result to the forces and the displacements which took place in structures in their nonlinear ranges was evaluated and examined and consequently, they claimed that as a basis for the seismic design of structures in the codes and guidelines, The energy approach is relatively better and more practical than the other approaches [2].

The velocity effect of the input energy on design of the structures was inspected in 1996. In this study, the relationship among the ruinous effect of earthquake on structures with energy and velocity of the earthquake applied to structures was examined. Regarding the design limitations in codes on deformations in the structures, they expressed that, the seismic capacity is directly related to the earthquake absorbed energy in the structures during the earthquakes [3].

A method for evaluating and estimating the energy spectrum of the earthquake exerted to the structures was presented to seismic design in 2000. Based on that, damage caused by the earthquake energy is related to its acceleration and the range of the amplification coefficient for the earthquake velocity spectrum can be computed and presented by contemplating the suitable shapes of the input energy spectra as well as the applying the Parseval theory. The range of the amplification coefficients was calculated between the 2 to 10 for that research [4].

For near field seismic areas, Jiang and Zhu (Sept.-Oct. 2006) presented the seismic design spectrum of earthquake energy for seismic design based on energy in structures. They expressed that in this type of structural design, a precise and complete definition of the earthquake energy spectrum and a proper consideration of the soil type and accurate distances from the fault are necessary. Pursuant to that, they have derived the energy spectra for the various seismic classifications of the soils [5].

A new earthquake energy-based approach was proposed by Hosseini et al. (2009) to increase safety in the structures and to optimize the structural design in the buildings as well. In that study, earthquake energy is divided into two positive and negative sections based on the work accomplished by the earthquake shear force at the base of the structure. Positive energy is energy which transmitted from the earth to the structure and negative energy is the energy coming back from the structure to the earth. Based on the results of this research, the safety of the structure can be enhanced and the structural design can be optimized by reducing the positive energy part or in other words by contemplated changes in the dynamic properties of the structure [6].

Hosseini and Pour Samad (2010) inspected the relationship between earthquake energy absorption with different dynamic and system hysteresis characteristics by comparing the structural behavior in various hysteresis models. Results of that study revealed that in several studied instances, when the structural characteristics change, especially the parameters related to the structural hardness, the earthquake imported energy varies remarkably as well. On this basis, the criterion of Changing Structure Specifications can be used to control the rate of structural damage that depends on the rate of import seismic energy [7].

At last, in the continuation of the previous study, in order to control and reduce the earthquake energy input to the structures that control and reduce the amount of damage in the structures, the most optimal way of distributing the hardness through the height of structures with different stories in 2010 was presented by Haddad and Hosseini and it was revealed that finding such a distribution was possible [8].

To assess the reliability of low rise one story structures as a result to the earthquake loads, a limit state measure was introduced by Kuwamura and V. Galambos (1989). In consonance to that study when the structure can survive that the structure pre collapse capacity of absorbed energy become larger than the seismic energy. Thus, critical load contemplated the greatest seismic energy that the structure is possible to confront in duration of its life. Dynamic specifications of the buildings, the level of seismic hazard and the earthquake records have been considered in that research to compute the mentioned critical load. The dynamic specification factor has been calculated through the spectrum of the earthquake energy in aforementioned structures and the seismic hazard factor has been contemplated from attenuation relationships and the seismic conditions. Also, the uncertainty involved in those factors has been evaluated to determine the probability of collapse [9].

Spectra of seismic input energy in 4 hysteresis models, 4 soil categories and 5 values of ductility were determined as a result to far field earthquakes 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, spectra of hysteresis energy were determined to inspect the demand feature of the structure in agreement to energy based design with ductility values between the amounts of 2 to 5 and 5% critical damping ratio. Consequently, by comparing the response spectra produced based on the results of nonlinear dynamic analyses and proposed hysteretic and input energy spectra were found to generate advisedly suitable findings in a moderately large period values [10].

Flag shaped hysteresis systems with seismic fuses have been applied lately to exploit in high performance seismic resistant buildings. In such a way that seismic fuses are used to protect flag shaped hysteretic systems by magnifying the absorption of input seismic energy in very severely ground motions. Nowadays, many studies have been concentrated on the flag shaped (SDOF) systems to investigate the dynamic behavior without mentioned fuses. Because, more comprehensive analytical studies on the dynamic behavior of the flag shaped systems with the mentioned fuses is essential. In order to do this, Joon Kim in 2012 performed comparative nonlinear time history analyses in flag shaped (SDOF) systems. The analyses results of the flag shaped (SDOF) systems showed that ductility demands reduce when post yielding hardness ratios, strength ratios and structural periods increase. Furthermore, factors which are relevant to energy dissipation have effect on the relations of the equivalent damping values. Results also revealed that with increasing the post yielding hardness ratios, re centering ranges and strength ratios, the medium greatest displacement demands of aforementioned fuses decrease [11].

Various studies have demonstrated that during intensive earthquake loads, a large number of structural systems inter in the nonlinear limitations. Hysteresis energies that is dissipated in their hysteresis loops, is extremely effective in computing the level of damage potential in the structural systems and is the most significant factor in the estimation of the energy in the structural calculations. Consequently, managing the values of Hysteresis energy leads to manage the structural dynamic performance. The values of hysteresis energy in the structural systems can be an indicator of the damage values or the vulnerability of that system. Abdollahzadeh and et.al in 2016 carried out the nonlinear dynamic analyses in the steel structures with a chevron brace [12]. Pursuant to the results, investigating the distributions of hysteresis energy and the extermum drifts along the height of those structures were under the effect of the near and far field earthquakes. Results also revealed that the drifts caused by the near field records is further than the far field records and the level of hysteresis energy as a result to the far field earthquakes are lower than the near field records. With increasing the height of structure, the level of the hysteresis energy in the upper stories enhances [13].

Based on the performance based seismic design approach and applying energy concept, Ghodrati Amiri and et.al in 2017 tried to investigate the influences of damping and duration on the elastic input energy due to strong earthquake records. Structures were analyzed to compute the equivalent velocity spectra in four categories of soils by using input energy pursuant 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 the earthquakes, the seismic input energy in structures enhances. Morovere, 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. Moreover, 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 portrayed a report to develop an energy based design procedure to evaluate the amounts of damage in the structures. They express that, the distribution of earthquake energy depends on the energy details: kinetic, damping, hysteretic, and elastic strain. They inspect 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 applied one and five story buildings as two case studies, using 20 earthquake records from short to long durations. Based on the results, the effect 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 energy and its propagation 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 applying 20 earthquake records. in consonance to the result of the nonlinear time-history analyses, duration of the earthquake records and the frequency content have no effect on the propagation of seismic energy through the height of the sample buildings. While semi-active control, supplemental damping and base isolation have significant effects on the propagation 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 an mention-worthy issue in earthquake and structural engineering to reduce the response of the structural systems to induced earthquakes. Bayat and Abdollahzade in 2011 inspected the effect of the supplemental ADAS instruments on the seismic behavior of the buildings by comparing the values of hysteresis energy and the input energy in various buildings located in far field regions. Their case studies contained 3, 5, 10 and 15 story buildings with 3 bays CBF system, with and without contemplating ADAS device. They performed nonlinear time history analyses applying 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 pursuant to the energy criterion [16].

It is observed that in spite of several studies on earthquake input energy, from the past till now, no clear and precise method has been presented for applying this issue in seismic design and none of the current guidelines and codes have such an approach. It is believed that the cause is distinction of the input energy with characteristics of various structural systems in elastic and particularly plastic conditions has not been explored adequate yet for proposing energy based design measures. Consiquently, now additional investigation in this field is necessary. In this study the distinctions of input energies for a Single Degree Of Freedom system (SDOF), including a cantilever column with a concentrated mass above it, with the steel material and with the box section, has been investigated in various hysteretic characteristics of the system. Two states of low and high ultimate strength have been examined for the aforementioned system by applying two different amounts of the box section dimensions and its wall thickness, in such a way that the cross sectional moment of inertia was kept constant. Consequently, in this paper, the stiffness of the system has been considered constant. Details of the case study are briefly explained in the next section.

2. The Used Hysteretic Models

For expressing the hysteretic behavior of structures, various nonlinear hysteresis models consisting of Clough, Wen, Elastoplastic, Bilinear and Takeda models were applied. The values of yield and ultimate stresses of the steel model were contemplated to be respectively 34.8 and

45.8 ksi and the values of yield and ultimate strains to be respectively 0.001 and 0.004. The nonlinear time history analyses were performed in the SDOF model. The height of a steel cantilever column was considered 118 in, with a concentrated mass above it and with box section, once 5.4 in x 0.2 in as the high resistance section and once 6.65 in x 0.1 in as the low resistance section. The moment of inertia of the column cross section is equal in both aforementioned models resulting in the equal and unchanged hardness and the period of the models.

Fig. 1 illustrated various types of utilized nonlinear hysteresis models in the single degree of freedom system.

3. Calculation of Earthquake Input Energies by NLTHA

Three earthquakes accelerograms from PEER strong motion database with different frequency contents, all normalized to the various Peak Ground Acceleration (PGA) levels of 0.20, 0.35, 0.50, 0.65 and 0.80g were applied 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 have been conducted by Opensees Software and energy values have been determined using relations presented by Poursamad and Hosseini [7].As mentioned above, in this reference, input earthquake energy is divided into two positive and negative sections based on the work accomplished by the earthquake shear force at the base of the structure. Positive energy that has been named 'received energy' (ERec) is energy which transmitted from the earth to the structure and negative energy that has been named 'returned energy' (ERet) is the energy coming back from the structure to the earth.

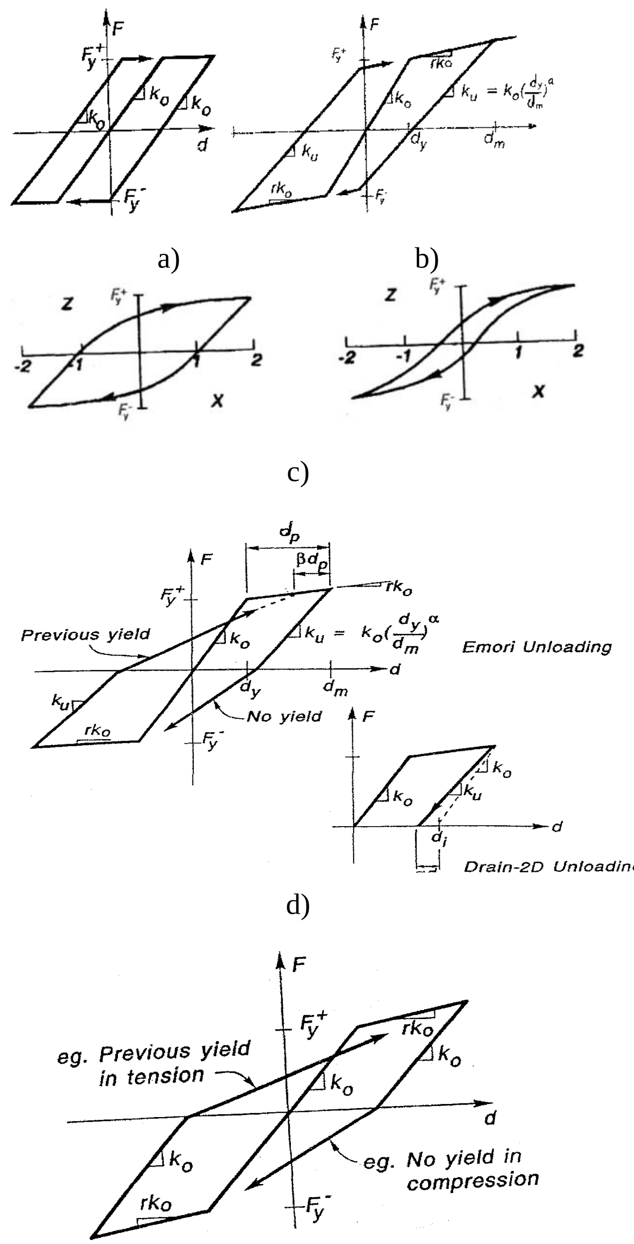

Fig.1. Various types of utilized nonlinear hysteresis models a) Elastoplastic model, b) Bilinear model, c) Wen model, d) Takeda model, e) Clough model [7]

Table 1 despites several case findings for PGA value of 0.8g, for two high- and low resistance samples of the structural models.

Table 1. Amounts of ERec, ERet, and ETot (in kips.in) for various hysteresis nonlinear models for PGA=0.8g in two high- and low resistance samples of the structural models

Hysteretic nonlinear 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

For a further comprehension of the alterations of the amounts of energy with alterations in the structural model features and PGA value, the amounts of (ETot) for both cases of high- and low strength are portrayed in Figures 2 and 3, and the amounts of (ERet/ERec) in Figures 4 and 5.

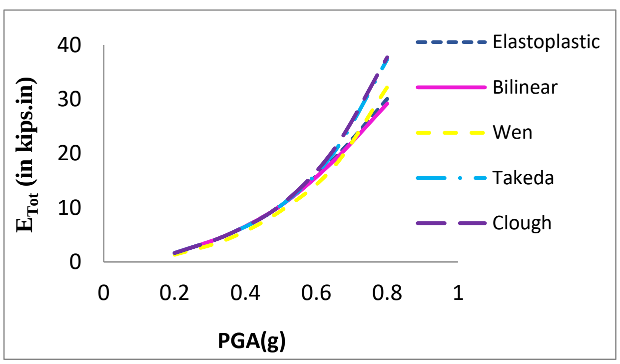

Fig. 2. Alterations between the values of total energy (ETot) and PGA values in different hysteresis models in case of high resistance of the system

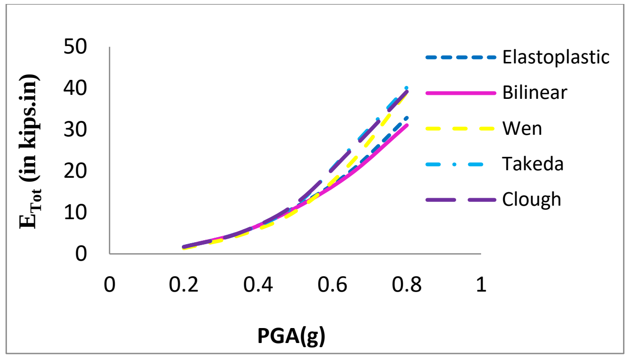

Fig. 3. Alterations between the values of total energy (ETot) and PGA values in different hysteresis models in case of low resistance of the system

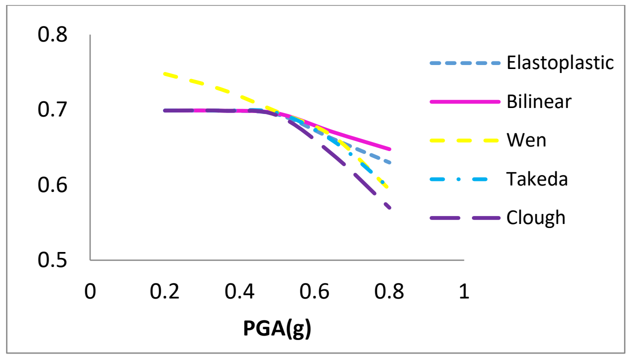

Fig. 4. Alterations between (E_{Ret}/E_{Rec}) and PGA values in different hysteresis models in case of high resistance of the system

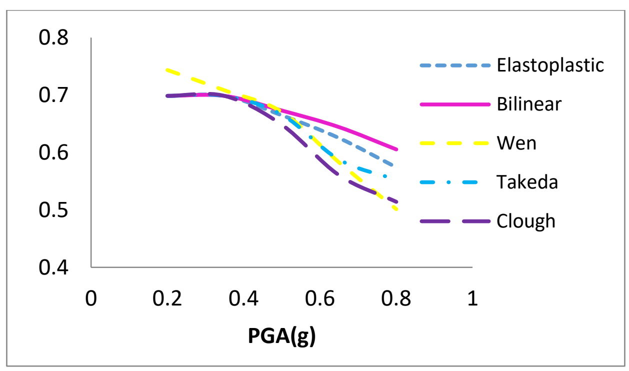

Fig. 5. Alterations between (E_{Ret}/E_{Rec}) and PGA values in different hysteresis models in case of low resistance of the system

It can be observed in Figures 2 and 3 which, as expected, generally when the amounts of PGA enhance, the values of total input energy (ETot) enhance and its trend are various in different hysteresis nonlinear models and also this difference increases when the amounts of PGA enhances. Furthermore, the amount of total input energy (ETot) for the sample of low resistance structural model is approximately higher than the value in the sample of high resistance structural model.

Figures 4 and 5 reveal that when the amounts of PGA enhance, the amounts of (ERet/ERec) reduces. Beside, amount of mentioned reduction and its trend are various in different hysteresis nonlinear models. Furthermore, this distinction enhances when the amounts of PGA enhances. 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 even though the diagrams of ERet/ERec with alteration of PGA in both samples of low- and high resistance structural models are similar, their tendencies are various in different hysteresis mathematical models.

4. Conclusions

- Alterations of seismic received- (ERec), returned- (ERet), and total input energy (ETot) of the structure with increase in PGA level of the exerted earthquake records are analogous, however they are dissimilar in various hysteresis mathematical models. For an instance, Clough models leads to larger amounts of energies almost in all cases.
- The amounts of abovementioned energies rely not only on the natural period of the system, but also on the hysteresis characteristics of the structural models and their resistances, in such a way that the structural models with similar period and different resistance have different input earthquake energies.
- On this basis, it sounds feasible to have several control criteria on the amount of earthquake input energy and therefore the amount of damage, by creating appropriate hysteretic features and level of strength for the system. Despite to that, more research is necessary in this regard.

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