

A NEW INSIGHT TO THE EARTHQUAKE INPUT ENERGY AND ITS VARIATION WITH BUILDING'S DYNAMICAL CHARACTERISTICS

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ABSTRACT :

Damages created in several relatively new buildings in recent earthquakes have shown that some of seismic design codes, which are strength-based, do not necessarily result in reliable design. On the other hand, since mid 70s many researchers have claimed that input energy can be a good parameter to be considered in seismic design of building systems. However, up to now no straightforward method has been introduced for this purpose. Obviously, if the input energy can be reduced, it will help the building safety. This paper investigates the variation of input energy with variation of building's characteristics considering both elastic and inelastic behaviors, and seeks how this variation can be used for more reliable seismic design of buildings. To realize that how the building's characteristics, including natural period and damping as well as strength and ductility values can affect the input energy some sample 1-story frames with various parameters have been considered and the input energy have been calculated for them by using some accelerograms having various frequency content from low to high. In each case just one parameter of the building characteristic has been considered variable, to find out the effect of each characteristic independently. Numerical results show that in general the input energy in a building for each earthquake varies with the variation of building characteristics. Among the aforementioned characteristic the damping seems to be more tangible to work with, so that for each earthquake a specific damping value can be found to lead to a minimum input energy.

KEYWORDS: Input energy variation, Building characteristics, Energy-based design

1. INTRODUCTION

Recent earthquakes have imposed damages to several relatively new buildings, designed based on some of strength-based seismic design codes. These damages can be partially due to construction and design errors, and partially due to the shortcomings of the employed seismic design code. When the latter is the case it means that strength-based design does not result in reliable structural seismic design of building systems. Therefore looking for some other criteria for seismic design seems reasonable. Since mid 70s many researchers have claimed that input energy can be a good parameter to be considered in seismic design of building systems. 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 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 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.

2. INPUT ENERGY AND SEISMIC DESIGN

In this section a review is done on the researches with regard to input energy and seismic design, and then in



the next section the variation of input energy with building characteristics is investigated. Ohi and Tanaka (1984) have worked on frequency-domain analysis of energy input made by earthquakes. They have presented a simple method for estimating the statistical parameters of the work done by the seismic load acting on a structure, which have called it 'energy input', from the stochastic model parameters of the ground acceleration. Their method is based on a frequency-domain relationship between the energy input and the Fourier square amplitude spectrum of the ground acceleration, and method involves obtaining the mean and variance formulas for a linear single degree-of-freedom system under classical artificial earthquakes and demonstrating their application to an elastoplastic single degree-of-freedom system using a simple equivalent linearization technique.

Guo and Nishioka (1989) have worked on estimation of total input energy to structures under earthquakes by using stochastic models of earthquake motion. They have studied the relation between the total input energy and ground motion parameters such as maximum acceleration, duration time, integral of squared acceleration, and predominant period. They have derived an equation to express the mean of input energy and have developed normalized input energy spectrum with actual earthquake motions. They have used a bilinear model to develop a kind of design spectrum, however, have not shown how the presented spectrum can be used for practical design purposes.

Surahman and Merati (1992) have discussed the input energy based seismic design code for shear buildings up to four stories high, subjected to different earthquake loadings. 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.

Kuwamura and his colleagues (1994) have worked on the Prediction of earthquake energy input from smoothed Fourier amplitude spectrum. They have attempted to show analytically that the energy-based velocity spectrum is basically equal to the smoothed Fourier amplitude spectrum computed only from input acceleration and is free from structural properties. They have expressed that if the earthquake load can be defined as independent of complicated structural dynamic properties, the earthquake-resistant design procedure will be considerably facilitated, but have not shown that their results are true in general case.

Kinugasa and Nomura (1996) have studied on the development of seismic design based on energy concept. As the first part of their study they have worked on performance check of earthquake-proof by considering energy input velocity, and have proposed a performance check method of earthquake-proof based on the concept of energy balance between input energy and absorbed energy. The feature of their study is to be able to consider 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 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. They have calculated 'the amount of that energy' by considering the balance between energy input velocity of the earthquake and energy absorption velocity of the building. They have suggested the comparison of 'the amount of that energy' with the quantity of input energy caused by ground motion as a criterion for judgment on the seismic safety.

Kuwamura and his colleagues (1997) have worked on energy input rate of earthquake ground motion, and matching of displacement theory and energy theory. Mentioning that seismic design load for elastoplastic structures is reduced according to the permissible ductility, and in that method both displacement conservation theory and energy conservation theory are used, they have claimed that these theories are contradictory and give different reduction factors. They have tried to show that the two theories are not opposed when consider the fact that the cycle number of plastic excursions is inversely proportional to the yield strength. They have derived from their observation that the energy input rate is proportional to the yield strength, and thus the spectrum of energy input rate calculated for a particular yield strength can be easily adjusted to other systems



having different yield strengths. They have also found that spectrum values of energy input rate for near-field earthquakes are larger than those of oceanic type earthquakes because of the difference in hysteretic cycles.

Ogawa and his colleagues (2000) have performed a study on earthquake input energy causing damages in structures. Their work is concerned with the definition and prediction of damage-causing earthquake input energy used in energy-based seismic design. They have claimed that it is necessary for the input energy to be closely related to structural damage such as maximum plastic deformation and cumulative plastic deformation. In that study, input energy has been defined as the maximum response of the sum of elastic strain energy and the energy dissipated by plastic deformation, and kinematic energy is not included in this definition. They have mentioned that both Housner and Akiyama predicted input energy by using a pseudo-velocity response spectrum corresponding to the initial natural period calculated from the elastic stiffness, and that the apparent natural period of frames (the time required for one cycle of vibration) accompanied with plastic deformations under earthquakes is longer than the initial natural period, and the input energy depends primarily on the apparent natural period. Then they have proposed to use the apparent natural period calculated from the mean of the plastic deformation per half-cycle in the whole vibration in predicting the input energy.

Chai and Fajfar (Oct. 2000) have proposed a procedure for estimating input energy spectra for seismic design. 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. They have shown that the peak amplification factor for the input energy spectrum depends on the peak ground acceleration to peak ground velocity ratio and duration of the strong motion phase of the ground motion. Values for the equivalent input energy velocity amplification factor vary from about 2 to 10 for most of the recorded ground motions used in that study. They have claimed that a considerable scatter of data is observed, however, the peak amplification factor predicted by the Fourier amplitude spectrum of the ground acceleration provides a fairly good estimate of the mean value of the peak input energy compared to that determined from inelastic dynamic time history analyses, particularly for systems with high damping and low lateral strength. They have expressed that the peak amplification factor derived in their study provides a more consistent approach for estimation of seismic demand when compared to an earlier empirical expression used for the formulation of duration-dependent inelastic seismic design spectra, even though only a slight difference in the required lateral strength results from the use of the new formula.

Hung and Chai (2006) have worked on estimation of seismic input energy in yielding structural systems. They have expressed that: 1) in seismic design of structures, the damage potential of an earthquake ground motion may be evaluated in terms of the energy input to the structure; 2) the energy (per unit mass of the structure) may be obtained in the time domain by integrating the product of ground acceleration and response relative velocity with respect to time up to the end of the ground motion; 3) for elastic systems, the input energy may also be determined in the frequency domain using the transfer function between the relative velocity and ground acceleration; 4) input energy spectra established via frequency domain is more efficient than in the time domain because the entire response history of the structure needs not to be calculated in the process, however, a direct evaluation of the input energy in the frequency domain using the transfer function is not appropriate for many structures since yielding may occur in these structures at the design level earthquake. Then they have attempted to estimate the energy imparted to two simple yielding systems using an effective transfer function having a shifted period and increased damping to account for the effects of yielding. They have evaluated the accuracy of their procedure by using 15 ground motions for different levels of structural yielding. Results have indicated that empirical equations for effective period and damping ratio available for estimation the maximum inelastic displacement of structures are capable of predicting the energy input to elasto-plastic structures within 20% for structures in the intermediate and long period regions.

Jiang and Zhu (Sept.-Oct. 2006) have presented energy input design spectra for near-fault regions and application in energy-based seismic design. 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 selected a world-wide ensemble of 224 records within 15km of fault projective distance as a data base, and have derived the energy spectra for seismic design with the shape and amplitude adjustment according to different seismicity groupings. They have compared their proposed energy input design spectra (EIDS) with that from the Japanese Building Code (1985 and 2001) and the actual energy demand of earthquakes that occurred near faults. They have claimed that the proposed spectra can meet the practical earthquake energy demand, and have advised a procedure for energy-based seismic evaluation and design and have tried to confirm it by 3 RC bridge piers.

Liu and his colleagues (2006) have done a study on input energy and momentary input energy spectra of earthquake strong motion. They have expressed that most of current methods in seismic design of structures require the provision of sufficient strength against anticipated seismic effects, and have claimed that the corresponding design response spectra can't reflect the effect of duration. Then, mentioning that energy-based seismic design is known as an alternative design methodology, they have carried out a parameter study on input energy and momentary input energy spectra of linear single degree of freedom (SDOF) system under 42 earthquake ground motions in this paper. They have found that: 1) the input energy and momentary input energy spectra of 5% can be estimated from the pseudo-velocity spectra with damping factor of 5% can be estimated from the pseudo-velocity spectra with damping factors of 0.5% and 10%; 2) the maximum of momentary input energy spectra is insensitive to the ratio of peak ground velocity to acceleration (V/A) and effective duration (At); 3) the maximum of input energy spectra is linearly increased with At when the V/A ratio of ground motions is more than 1.5; 4) the characteristic period of input energy and momentary input energy spectra of linear SDOF system, which can be employed in an energy-based seismic design procedure for determining the required energy dissipation capacity of a structural system.

Takewaki (2006) has proposed a probabilistic critical excitation method for earthquake energy input rate. He has expressed that since earthquake ground motions and their input effects on structures are very uncertain even with the present state of knowledge, it is desirable to develop a "robust" structural design method taking into account these uncertainties. He has also claimed that approaches based on critical excitation methods have been proven to be promising for such robust structural design. On these bases, he has developed a critical excitation method in which the mean earthquake energy input rate is chosen as a measure of criticality. The earthquake energy input rate is closely correlated with the story deformation and this supports the suitability of the energy input rate as a criticality measure in the case where the deformation is crucial in the design. He has described the ground motion as a uniformly modulated nonstationary random process. Assuming that the power [area of power spectral density (PSD) function] and the intensity (magnitude of PSD function) are fixed he has found the critical excitation under these restrictions. The key for finding his random critical excitation is the interchange of the order of the double maximization procedures with respect to time and to the PSD function. He has presented examples for a specific envelope function of the ground motion are for demonstrating the validity of the proposed method.

It is seen that in spit of several studies on earthquake input energy, up to now no straightforward method has been introduced for this purpose, and none of the existing codes have such 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 nonlinear states has not been studied to such extent that make confidence for proposing energy-based design criteria. Therefore, still more investigation in this regard is necessary. To realize that how the building's characteristics, including mass, stiffness, and damping values, as well as their distribution in the building height can affect the input energy, in the next section of the paper some sample buildings with various parameters have been considered and the input energy have been calculated for them by using some accelerograms with various frequency content from low to high. In each case just one parameter of the building characteristic has been considered variable along the building height, and others have been considered as constant, to find out the effect of each characteristic independently.



3. VARIATION OF INPUT ENERGY WITH BUILDING'S CHARACTERISTICS

To realize that how the building's characteristics, including mass, stiffness (and resulting natural period, T_n), damping values (D), ultimate strength, r_u , and ductility factor, μ , can affect the input energy some sample frames with various values of these parameters have been considered and the total input energy, E_i , have been calculated for them by using recorded accelerograms of four earthquakes, each representing one soil type of I to IV of the seismic design code. These are respectively Tabas (1978), Zanjiran (1994), Bam (2003) and Manjil-Rudbar (1990) earthquakes. Of these earthquakes the time histories and various spectra of Bam earthquake are shown in Figures 1 to 5 as samples of the inputs.



Figure 1. Acceleration time history of Bam earthquake



Figure 2. Velocity time history of Bam earthquake



Figure 3.Displacement time history of Bam earthquake





Figure 4. Acceleration and displacement spectra of Bam earthquake



Figure 3. Pseudo-velocity spectra and Fourier spectra of Bam earthquake

For each earthquake the dynamic response of the considered frame in both elastic and inelastic cases have been obtained. For the inelastic cases the nonlinear behaviors of frame elements have been introduced to the computer program based on using FEMA 356 guidelines. In each case of the time histories just one parameter of the frame characteristic has been considered as variable, and others have been constant, to find out the effect of each characteristic independently. As samples of numerical results those of Tabas earthquake are shown in Figures 4 to 6. More results can not be presented here because of lack of space, and may be found in the main report of the study (Vaseghinia 2007). In Figure 4 the variation of input energy, Ei, with building damping ratio in both linear and nonlinear states are shown. It can be seen that the two curves are different just in low damping values, and that Ei decreases with increase in damping ratio, and for damping values larger than 10% the Ei value is almost constant. Figure 5 shows Variation of input energy with building period in both linear and nonlinear states due to has been 0.02). It is seen that in linear state by increase of period value from 0 at first there is an increase in Ei and then it decreases with increase in period value, but for nonlinear state the trend is always descending with increase in period value. Figure 6 shows the variation of input energy with building ductility and strength in nonlinear state. It is seen that input energy is much sensitive to variation of building ductility, but it decrease wit decrease in building strength.





Figure 4. Variation of input energy with building damping ratio in linear and nonlinear states



Figure 5. Variation of input energy with building period in both liner and nonlinear states



Figure 6. Variation of input energy with building ductility and strength in nonlinear state

CONCLUSIONS

Based on the numerical results it can be said that in general the input energy changes not only with the earthquake itself, it also varies from building to building depending on the buildings' characteristics. Among



the aforementioned characteristic the damping seems to be more tangible to work with, so that for each earthquake some specific value of damping ratio can be found to lead to a minimum input energy. It is believed that by including the hysteretic energy dissipation characteristic of the system, finding a very low minimum input energy will be possible. It should be noted that this study was limited to just one story frames, and to get more general conclusions much more investigations are necessary on various building systems with different distribution of mass, stiffness, damping, strength, and ductility in their height as well as different hysteretic behaviors.

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