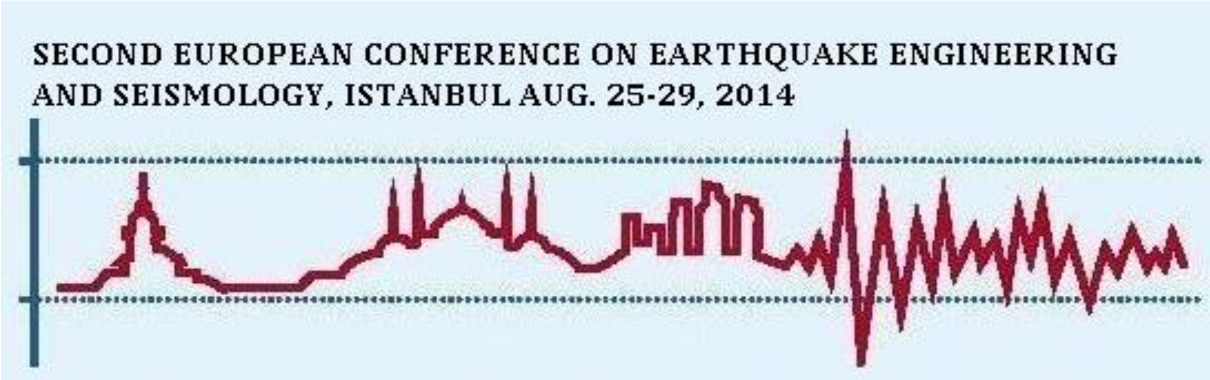

ADAPTATION OF ENERGY PRINCIPLES IN SEISMIC DESIGN OF TURKISH RC FRAME STRUCTURES. PART II: DISTRIBUTION OF HYSTERETIC ENERGY

Abdullah OKUR[1] and Murat Altug ERBERIK[2]

ABSTRACT

This is the second phase of the study regarding the efforts to adapt energy principles in seismic design of Turkish RC frame structures. In the first phase, design energy input spectra (DEIS) were constructed by using Turkish ground motion database. To achieve this, the variants of the elastic design acceleration spectrum in terms of seismic zone and site class, provided by the latest version of the Turkish Earthquake Code (TEC), were taken as reference.

In the second phase, assuming that the energy input to the structure is known, the main focus is the determination of how much of this energy is converted to hysteretic energy and also the spatial and modal distributions of the hysteretic energy within the structure. For this purpose, generic RC frame buildings with different number of stories and number of bays are designed according to TEC regulations. First, hysteretic to input energy ratios are obtained by conducting time history analyses on single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) models. It is observed that this ratio is rather a stable parameter and simple design rules can be established to estimate the hysteretic energy demand for code-conforming RC frame structures. The next step is to determine the spatial distribution of hysteretic energy demand. Based on the results of time history analyses by using the generic building models, the percent of hysteretic energy in each column and beam element of the structure can be established. In this way, it becomes possible to assess the critical members in a structure in terms of inelastic action. It is also important to know the modal distribution of hysteretic energy for design purposes. To achieve this task, a concept similar to modal pushover analysis is employed.

The results obtained from this study reveals that hysteretic energy proves to be a suitable design parameter in the sense that it is both enhanced and rather stable regarding spatial and modal distribution in code-conforming RC frame structures. Hence it seems to be practical and appropriate to employ an energy-based approach at least for the preliminary design of such structures.

INTRODUCTION

The earthquake-resistant design has been traditionally based on strength of structures where a certain amount of static lateral seismic force, combined with the gravity load, is applied to a structure as the strength demand. The members are selected based on the principle that the strength supply from the structure should not be less than the strength demand on it. Engineers have been seeking for more rational seismic design alternatives so that the earthquake resistant structure could be designed based on how it performs during an earthquake. One of these design alternatives is the energy-based design approach. The concept of energy seems to best explain the structural response to a strong ground

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motion. It is based on the premise that energy supply of a structural system should be greater than energy demand when the system is subjected to an earthquake or an ensemble of earthquakes, which can be represented by the following energy balance equation.

$$E_I = E_\xi + E_H + E_S + E_K \quad (1)$$

This equation is obtained by integrating the equation of motion with respect to the relative displacement of a single-degree-of-freedom (SDOF) system with an inelastic force-deformation relationship. In Equation 1, the left hand side represents the input energy (E_I), or in other words, the energy demand. There have been many attempts to predict the input energy of structural systems and to develop design energy input spectra (DEIS), which can be adapted to the current codes of practice in many countries like Japan (Akiyama 1985), Spain (Benavent-Climent *et al*. 2002), Iran (Amiri *et al*. 2008), Colombia (Benavent-Climent *et al*. 2010), Greece (Tselentis *et al*. 2010), including Turkey (Lopez Almansa *et al*. 2013, Dindar *et al*. 2013). The right hand side of the equation represents the elastic strain (E_S) and kinetic (E_K) energies, which vanish at the end of seismic action, together with energy supply terms that represents the energy dissipated through damping mechanisms (E_ξ) and energy dissipated through inelastic hysteretic action (E_H). It is not a straight forward procedure to predict the energy supply of structural components and systems because of the complex relationship between the energy demand and the supply itself. There are considerable efforts to achieve this task, but none of these previous studies give a complete and simple energy-based code approach, starting from the prediction of energy input to the design of the structural members in accordance with their energy dissipation capacities for reinforced concrete (RC) frame structures.

This research is an attempt to develop a preliminary energy-based design approach for RC frame structures, which can be further developed to become a final design tool for new structures or condition assessment tool for existing structures. The first phase of the study, which is briefly discussed in the next section, was focused on the prediction of seismic energy demand in terms of the DEIS (Okur and Erberik 2012). This paper includes the next phase, namely the efforts to predict the distribution of seismic energy within the building and stories of the building, also including the modal distribution of hysteretic energy.

THE FIRST PHASE: PREDICTION OF SEISMIC ENERGY DEMAND

In the first phase of the study, DEIS was developed as a substitute for the elastic acceleration spectrum, keeping the same seismic zonation and site classification of the current code, by scaling selected ground motions, which have been recorded mostly during earthquakes in Turkey (Okur and Erberik 2012). A bilinear shape was assumed for DEIS with two major parameters; corner period (T_C) and maximum input energy equivalent velocity (V_{EM}) as seen in Figure 1. Other parameters in the figure, namely V_{E0}, T_0 and T_F, are the initial energy equivalent velocity, initial period and final period, respectively. In this study, parameters T_0 and T_F were set to 0.1 and 4.0 seconds.

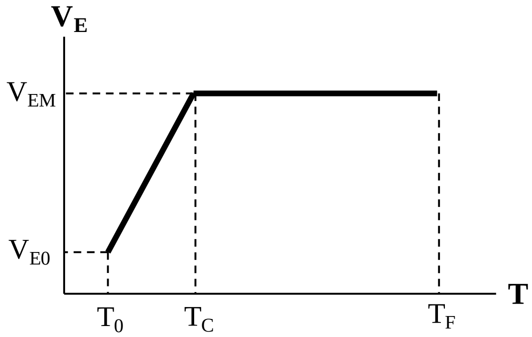

Figure 1. Representation of bilinear DEIS

In accordance with the current version of the Turkish Earthquake Code (TEC 2007), 16 variants of design acceleration spectrum were considered in terms of seismic zones (I-IV) and site classes (Z1-Z4) as defined in the code. In order to include earthquake magnitude within the proposed energy-based approach in an explicit manner, seismic zones proposed by TEC were defined in terms of some magnitude ranges by using the earthquake catalog and the zoning map of Turkey. Furthermore, the site classes proposed by TEC were defined in terms of mean shear-wave velocity of uppermost 30 m of soil/rock profile ($V_{s,30}$). More detailed information regarding the properties of the variants can be found elsewhere (Okur and Erberik 2012).

In order to cover all range of magnitudes and site classes in the energy-based approach, a different DEIS should be obtained for each variant. To achieve this task, the acceleration traces recorded in earthquakes that have occurred in Turkey for the last four decades were grouped and used to obtain the statistical variation of the DEIS. However, for some site classes (for Z1 and Z4 classes) and magnitude ranges (M>7 and 6<M<7), the number of ground motion records was not sufficient to gather the required data for the construction of the DEIS. To solve this issue, ground motions recorded during the earthquakes caused by the San Andreas Fault in California were included into the database since this fault emerges as a close analogue of the North Anatolian Fault (NAF), with the two continental transforms sharing similar slip rates, total length, and straightness relative to their poles of rotation according to Stein *et al*. (1997). Hence it was possible to gather sufficient number of records (i.e. at least 10 records) for each variant in the construction of the DEIS.

During the construction process, ground motion scaling in the time domain was used. The ground motion records in each group were scaled such that the mean scaled spectrum matched with the target design acceleration spectrum of the considered variant for a specific range of periods. Then the ground motion records scaled by the appropriate factors were used to construct the mean input energy equivalent velocity (V_E) spectra. These spectra were then used to determine the parameters V_{EM} and T_C, therefore the idealized (bilinear) DEIS for each variant that represents a pair of magnitude range and site class. Both DEIS parameters can be obtained by using the initial slope in the short period range and a constant line which envelopes the V_E values in the medium and long period ranges. The values of the DEIS parameters obtained in this study were also compared with some previous studies (Chai *et al*. 1998, Chai and Fajfar 2000). It was observed that although there exists some discrepancies, there is a reasonable match between the predicted DEIS parameters in this study and the ones proposed by other researchers.

At the final stage, the DEIS were obtained for 16 considered variants as presented in Figure 2. From the figure it is observed that V_{EM} increases by shifting from hard (Z1) to soft (Z4) sites and from small magnitude to large magnitude events. It can also be stated that parameter T_C is rather stable for cases with similar site classes but starts to increase (i.e. it elongates) shifting toward soft site conditions. These trends seem to be quite reasonable when compared to DEIS obtained in other studies (Decanini and Mollaioli 1998, Benavent-Climent *et al*. 2002, Amiri *et al*. 2008, Benavent-Climent *et al*. 2010). When the proposed DEIS is compared with the ones that were proposed by using Turkish ground motion records recently, the major difference seems to be the shape of the spectrum curve. In lieu of a bilinear shape used in this study, a three-part curve is preferred in the other studies, with an initial increasing linear branch, a constant valued plateau and a decreasing nonlinear branch with a power term. There are some reasons of selecting a bilinear spectral shape in this study. First of all, a design spectrum should have a simple shape and also should be conservative. Besides, constant spectral input energy in the medium and long period range is intended to include the energy contained in the higher modes of flexible structures, since the spectral input energy in multi degree of freedom (MDOF) systems is given by a direct summation of the input energy for all modes in the structure (Kuwamura and Galambos 1989 and Chai *et al*., 1998). In other words, the descending branch of a trilinear design energy spectrum shape may underestimate the actual energy amount due to the effect of higher modes.

Other than the major difference regarding the spectral shape, the classifications used in order to construct the DEIS are different. But overall, if the values of the parameters T_C and V_{EM} are compared, it is observed that the match is in justifiable limits since all studies had been using the Turkish ground motion database.

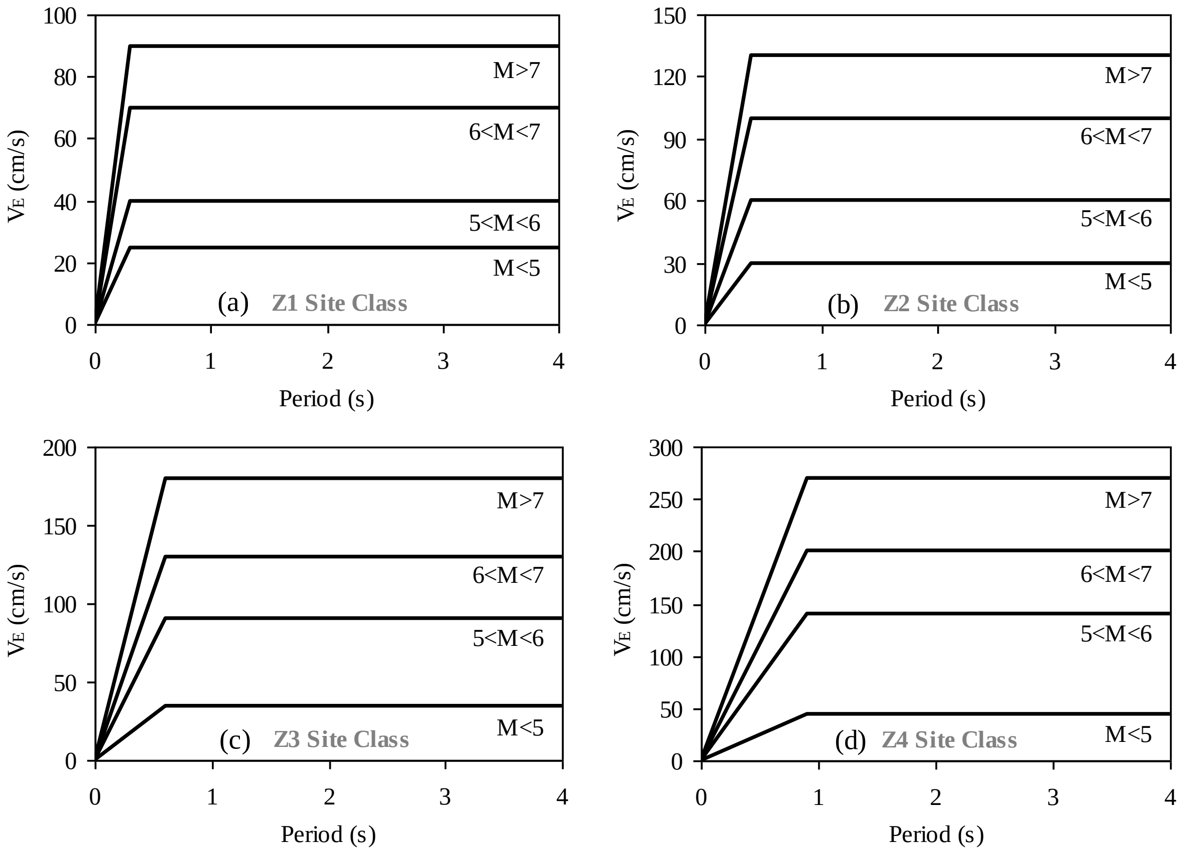

Figure 2. DEIS for all variants of seismic zone (magnitude range)-site class that are constructed as a substitute for elastic design spectra in TEC

THE PREDICTION OF HYSTERETIC ENERGY FROM INPUT ENERGY

After predicting seismic energy demand by using the DEIS, the next step is to assess what percentage of this input energy should be dissipated through inelastic hysteretic action. In the literature, this is realized by introducing hysteretic energy to input energy ratio (E_H/E_I). Many researchers tried to obtain consistent trends regarding this ratio. The findings in these studies are discussed in comparison with the outcome of this study in the following paragraphs.

In this study, E_H/E_I ratio is obtained as a 84 percentile curve (mean plus one standard deviation) for each of the 16 variants by employing the same ground motion records that were used to construct DEIS. The curves are obtained for different values of strength reduction factor (R) in order to account for the effect of inelastic behaviour. It is considered that this parameter is a better indicator of the effect of inelastic behaviour rather than ductility (μ) since it is enforced by most of the current seismic codes, which makes it easier to compare the outcomes of the existing force-based and energy-based design approaches. The curves are obtained through dynamic analyses of SDOF systems for a constant damping ratio of 5% with modified Clough hysteresis model, since this stiffness degrading hysteresis model is a good candidate to simulate the dynamic response of well-designed RC frame structures. Example curves are presented in Figure 3 for the variants (M>7, Site Class Z3) and (5<M<6, Site Class Z2). By examining the results of this analytical study it is observed that E_H/E_I ratio is rather constant after a transition period (of approximately 0.2-0.3 seconds) regardless of the level of inelastic behaviour imposed by the parameter R (see Figure 3.a). Similar conclusions were obtained by Fajfar and Vidic (1994) while investigating the effect of different parameters on E_H/E_I ratio. As the site conditions gets softer and as the magnitude of the events decreases (low-to-moderate seismicity) the ratio slightly decreases with period. Overall, for the sake of simplicity and conservatism valid in seismic design philosophy, it can be assumed that a mean value of 0.7 can be assumed for all the variants by considering the whole range of periods and levels of inelasticity.

Other researchers used different parameters like damping ratio (Kuwamura and Galambos 1989), displacement ductility (Decanini and Mollaioli 2001), cumulative ductility (Benavent-Climent *et al*. 2010. Lopez Almansa *et al*. 2013) and ground motion intensity (Shen and Akbas 1999) to develop empirical formulations for E_H/E_I ratio. The results show some variations, but there is a consensus on the fact that this ratio is a stable quantity and it can be used to predict the energy content of a structure in a reliable manner.

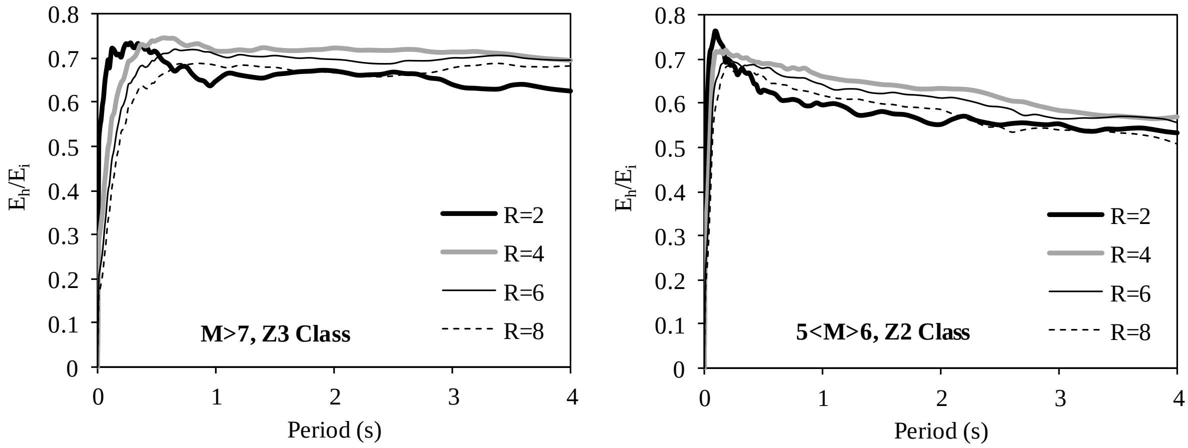

Figure 3. E_H/E_I ratio spectra for R=2, 4, 6 and 8 for the variants a) M>7, Site Class Z3, b) 5<M<6, Site Class Z2

MDOF MODELS USED FOR PREDICTION OF HYSTERETIC ENERGY

After predicting the hysteretic energy to be dissipated by the structure as a fraction of the energy input from SDOF response, the next step is to assess the spatial and modal distributions of this energy within the structure from MDOF response. The spatial distribution includes story-wise and component-wise distributions of energy. To propose an energy-based design approach, sufficient strength and energy dissipation capacity should be provided in structural members to control their seismic performances and to limit their potential damage.

In order to assess the spatial and modal distribution of hysteretic energy within the structure, several RC frames with different numbers of stories and bays, which are designed according to TEC, are developed. Since the study is focused on developing a standard preliminary design procedure for ordinary RC moment resisting frames, planar analytical models are generated with number of stories ranging between 1-9 and number of bays between 1-4. Story height and bay width are assumed as 3 m and 5m for all generic frames. Design strengths of concrete and reinforcing steel are taken as 25 MPa and 420 MPa, respectively. The frame members are detailed in accordance with TEC (2007) and TS500 (Turkish Standards Institute 2000).

Analytical models of the frames are developed by using OpenSees (which stands for *Open System for Earthquake Engineering Simulation*) analysis platform (McKenna *et al*. 2006). This platform has advanced capabilities for modeling and analyzing the nonlinear response of systems using a wide range of material models, elements, and solution algorithms.

The modeling procedure in OpenSees is basically summarized in Figure 4. First, material models are defined, and then a section model is constructed by using material models. Finally, element model is defined by the combination of section models. In this study, the material models that have been selected for concrete and reinforcing steel are “Concrete01” (concrete with zero tension) and “ReinforcingSteel”, for which the stress-strain curves are demonstrated in Figure 5. In the next step, the fiber section model is selected. There are reasons for this selection. First, among the existing alternatives, it is the best model to simulate the behaviour of a reinforced concrete section. It gives the most realistic results since failure of each fiber is checked during an analysis. Besides, it is the only model that takes moment and axial load interaction into consideration at the same time.

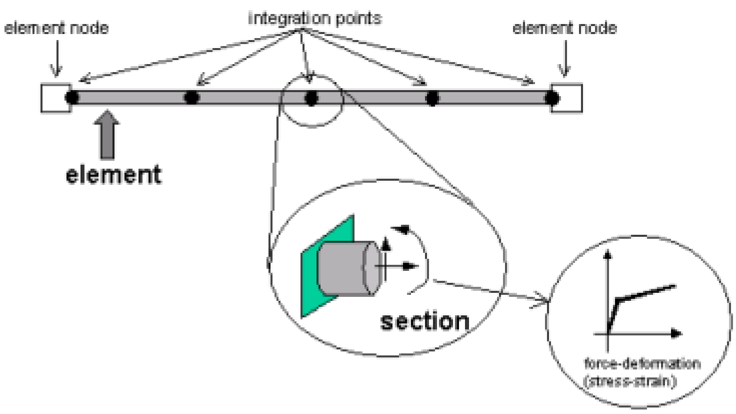

Figure 4. Details of OpenSees Element Modeling

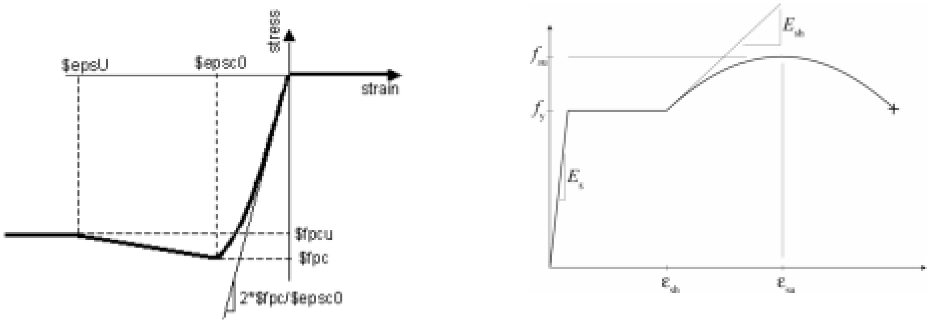

Figure 5. Material models used: “Concrete01” and “ReinforcingSteel”

Beam and column elements are modelled by “beamWithHinges”, which is a force-based element in OpenSees with concentrated plasticity at the ends and elastic interior region (see Figure 6) since all the hysteretic action and energy dissipation is expected at member ends. The plastic hinge length is assumed as half of the cross-section depth.

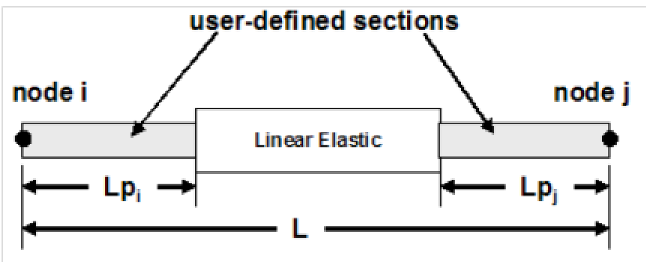

Figure 6. Representation of BeamWithHinges element

Story mass is distributed along the beam-column joints as lumped masses. Masses of inner joints are considered as twice of the mass of outer joints due to tributary area concept. The contribution of infill walls to mass and stiffness are ignored in this study.

STORY-WISE DISTRIBUTION OF HYSTERETIC ENERGY

Estimating the story-wise distribution of hysteretic energy is one of the milestones in energy-based design and assessment procedures. It is important to see the regions with high hysteretic energy demand so that the capacities of the structural members are adjusted accordingly. There exist numerous studies that focused on the story-wise distribution of hysteretic energy (Shen and Akbas 1999, Chou and Uang 2003, Khashaee *et al.* 2003, Surahman 2007), but most of these studies have been conducted for steel moment resisting frames. In this study, the story-wise distributions of hysteretic energy are obtained for the generated RC frame models subjected to a single ground motion record for demonstration purposes. The selected ground motion record is the NS component of the recording at Bolu station of 12 November 1999 Duzce, Turkey earthquake (M_w=7.1).

The story-wise distributions of hysteretic energy from 3-story to 8-story buildings with varying number of bays are presented in Figure 7. In the figures, horizontal axes represent dissipated energy (E_h) of that story as a percentage of total energy of the building under consideration. The legends represent the number of stories and bays of the considered analytical models. For instance, "*4S3B"* means the analytical model with 4 stories and 3 bays. From the figures it is observed that hysteretic energy demand increases at lower stories. This trend is more dominant for low-rise buildings. As the number of stories increases, the variation of energy with respect to number of bays vanishes. These observations are in accordance with the previous studies (Shen and Akbas 1999, Chou and Uang 2003, Khashaee *et al*. 2003, Surahman 2007). Since higher mode effects are not significant for low-rise and mid-rise analytical models developed in this study, there exists no significant increase of hysteretic energy demand at the upper stories as expected.

Although not presented in this paper, the story-wise distribution of E_H/E_I ratio has also been obtained for the generic frames. The distributions seem to be more uniform when compared to the distribution of hysteretic energy individually, but yielding similar trends when compared to hysteretic energy distribution (i.e. higher ratios in the lower stories).

It should be mentioned that the member sizes and detailing is considered as the same for the case study buildings during the design phase. However, in the case of upward linearly decreasing stiffness, the energy distribution can be shifted upwards, making the lower parts of the building suffer less damage as also suggested by Surahman (2007).

From the energy point of view, the ideal energy dissipation pattern is such that hysteretic energy demand is distributed to as many members as possible. This can be achieved satisfactorily by imposing some specific requirements within the energy-based approach. For instance, the design strength of the structural members for a *n*-story building can be adjusted to ensure that yielding is more likely to occur at all the storey levels simultaneously by the following formulation (Durucan and Dicleli 2010)

$$\frac{R_1}{V_1} = \frac{R_2}{V_2} = \cdots\cdots = \frac{R_i}{V_i} = \cdots\cdots = \frac{R_n}{V_n} \tag{2}$$

where R_i is the strength of the building at story level i and V_i stands for elastic shear at story level i. Therefore it is possible to control the energy dissipation within the structure and to carry out the design of the structural members accordingly in energy-based approach.

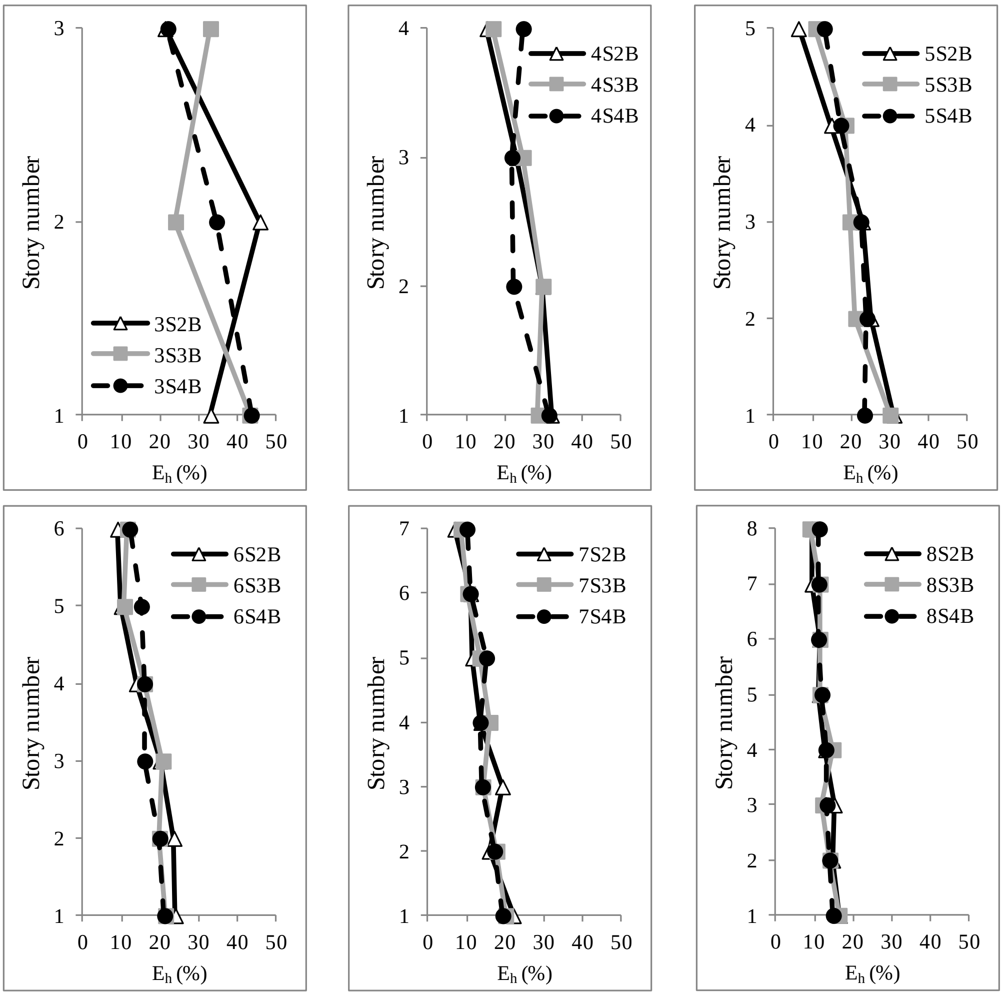

Figure 7. Story-wise distribution of hysteretic energy

MODAL DISTRIBUTION OF HYSTERETIC ENERGY

Prediction of the modal distribution of hysteretic energy is not as straight-forward as estimating its spatial distribution. In the nonlinear condition, modes of the structure do not vibrate independently, and therefore, the amount of hysteretic energy is definitely affected by the vibration of the other modes. However, assuming the modes to be independent in the nonlinear condition, which is an acceptable and reasonable assumption as stated by Zarfam and Mofid (2009), it can be stated that the amount of hysteretic energy at the n^{th} mode is only affected by the equation of motion of the same mode.

Hence, in order to obtain the modal energy responses of an MDOF structure, it should be separated into equivalent SDOF systems for each mode. Chopra and Goel (2000) proposed a method called as "*Modal Pushover Analysis*", in which an MDOF structure is subjected to vertical loads at each story level and the load pattern is the modal shape of the corresponding mode. In mathematical terms it can be expressed as

$$s_n = M\,\phi_n \tag{3}$$

where s_n is the load pattern of n^{th} mode pushover analysis, M is the mass matrix of the MDOF system and ϕ_n is the mode shape. Accordingly, the structure is pushed with this load pattern until the ultimate state. At the end of the analysis, base shear (V_{bn}) versus roof displacement (u_{rn}) curve is obtained for the n^{th} mode, which is then converted to resisting force (F_{sn}/L_n) versus modal coordinate (D_n) curve (see Figure 8). Hence it becomes possible to conduct inelastic SDOF analyses by using the obtained F_{sn}/L_n-D_n relationship as the bilinear hysteresis rule through the modified version of the equation of motion obtained for the n^{th} mode.

$$\ddot{D}_n + 2\xi_n\omega_n\dot{D}_n + \frac{F_{sn}}{L_n} = -\ddot{u}_g(t) \qquad (4)$$

The period of the n^{th} mode inelastic SDOF system can be obtained from

$$T_n = 2\pi\left(\frac{L_n\, D_{ny}}{F_{sny}}\right)^{1/2} \qquad (5)$$

where F_{sny}/L_n and D_{ny} are the yield values of F_{sn}/L_n and D_n, respectively.

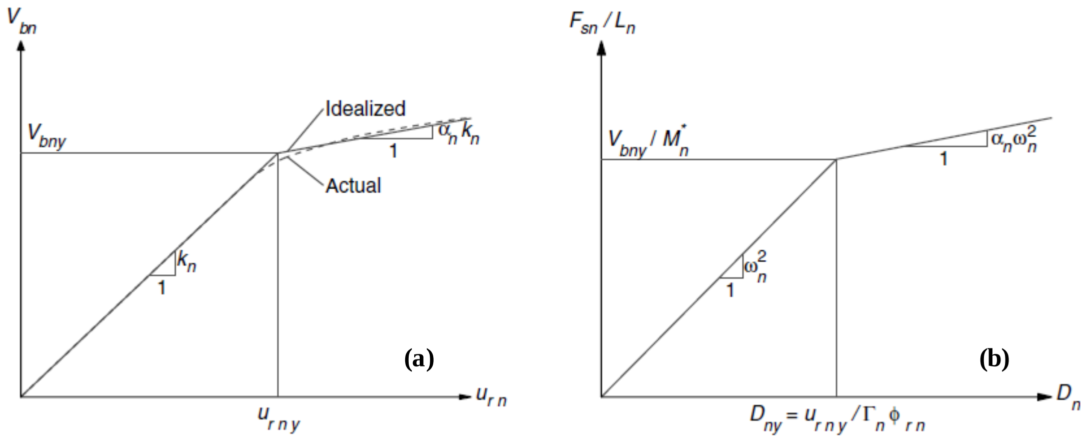

Figure 8 Properties of the n^{th} mode inelastic SDOF system: a) idealized pushover curve, b) F_{sn}/L_n-D_n relationship (Chopra and Goel 2002).

For demonstrative purposes, the modal distribution of hysteretic energy for 7-story 4-bay RC frame model subjected to the aforementioned ground motion record is presented in Figure 9, by considering the first three modes. The equivalent SDOF parameters used in the analyses are summarized in Table 1. From the figure it is observed that only first mode contributes to inelastic response, i.e. to hysteretic energy dissipation, whereas the other two modes remain in the elastic range with no contribution. Similar results had been obtained by Prasanth *et al.* (2008) for symmetric and regular plan buildings. This result further simplifies the energy based design approach since it encourages the use of simple inelastic SDOF systems in order to assess the modal distribution of energy within a MDOF structure.

Table 1 List of SDOF parameters used in the analysis for the first three modes

Mode	Period (s)	α_n	F_{sny}/L_n (m/s^2)	D_{ny} (m)
1	1.15	0.03	2.10	0.070
2	0.37	0.02	18.50	0.066
3	0.21	0.06	46.10	0.055

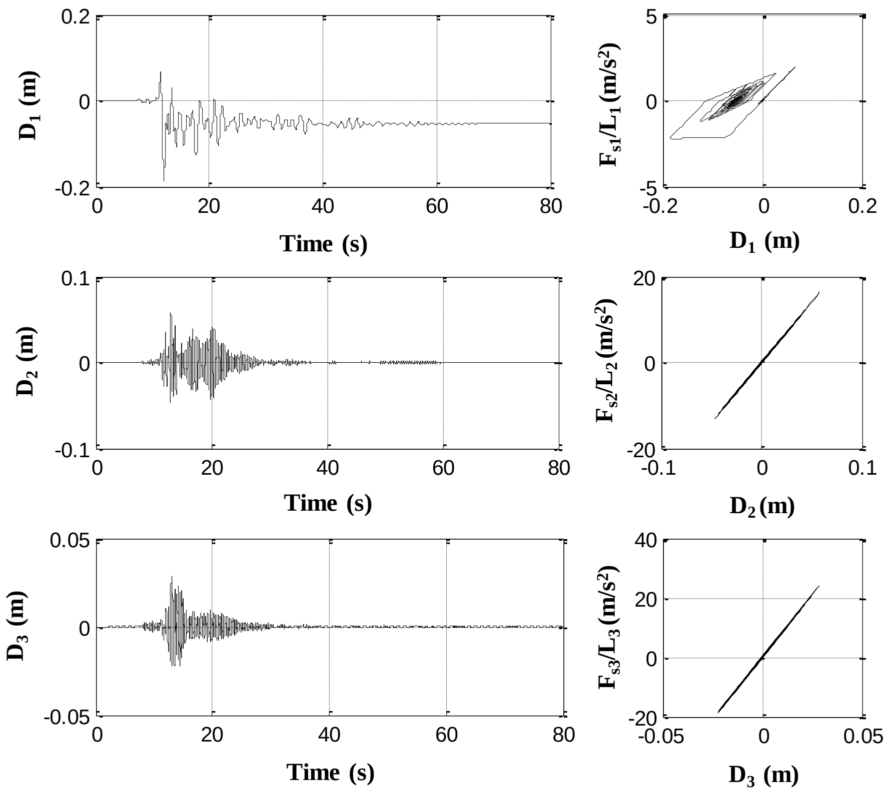

Figure 9 Time history analysis results of the inelastic SDOF systems defined for the first three modes

CONCLUSIONS

This is the second phase of the study regarding the efforts to adapt energy principles in seismic design of Turkish RC frame structures. In the first phase, design energy input spectra (DEIS) were constructed by using Turkish ground motion database. In the second phase, assuming that the energy input to the structure is known, the main focus is the determination of how much of this energy is converted to hysteretic energy and also the spatial and modal distributions of the hysteretic energy within the structure.

The results show that for well-designed, symmetrical and regular plan buildings, simple yet reliable guidelines can be proposed for energy based procedures, also noting the fact that energy is rather a stable quantity when compared to its counterparts, i.e. force and displacement. Assuming that the energy input to the structure is known, basic design rules can be accomplished regarding the distribution of energy within the structure. Then the last phase is to estimate the energy dissipation capacities of structural members by using simple parameters, which is the most challenging task for energy-based approaches.

When the third phase is accomplished, the completed procedure can be used at least for the preliminary design of RC frame structures since it is very difficult to abandon the existing force-based design approach that is being used for decades in an abrupt manner. The energy-based procedures require some time and effort before they are approved as the main approach in next generation codes. In addition, such procedures should be flexible in the sense that they can easily be converted into an assessment procedure for existing building by making some slight modifications.

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