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A study on determination of target displacement of RC frames using PSV spectrum and energy-balance concept

Taner Ucar*[1], Onur Merter[2a] and Mustafa Duzgun[2b]

[1]Faculty of Architecture, Dokuz Eylul University, Izmir, Turkey
[2]Faculty of Engineering (Civil), Dokuz Eylul University, Izmir, Turkey

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Abstract. The objective of this paper is to present an energy-based method for calculating target displacement of RC structures. The method, which uses the Newmark-Hall pseudo-velocity spectrum, is called the "Pseudo-velocity Spectrum (PSVS) Method". The method is based on the energy balance concept that uses the equality of energy demand and energy capacity of the structure. First, nonlinear static analyses are performed for five, eight and ten-story RC frame structures and pushover curves are obtained. Then the pushover curves are converted to energy capacity diagrams. Seven strong ground motions that were recorded at different soil sites in Turkey are used to obtain the pseudo-acceleration and the pseudo-velocity response spectra. Later, the response spectra are idealised with the Newmark-Hall approximation. Afterwards, energy demands for the RC structures are calculated using the idealised pseudo-velocity spectrum. The displacements, obtained from the energy capacity diagrams that fit to the energy demand values of the RC structures, are accepted as the energy-based performance point of the structures. Consequently, the target displacement values determined from the PSVS Method are checked using the displacement-based successive approach in the Turkish Seismic Design Code. The results show that the target displacements of RC frame structures obtained from the PSVS Method are very close to the values calculated by the approach given in the Turkish Seismic Design Code.

Keywords: Pseudo-velocity spectrum; energy demand; energy-based performance point; PSVS method; target displacement

1. Introduction

Seismic evaluation of structures is generally displacement-based and the estimation of maximum inelastic deformation demand, which is imposed by earthquake on the structure, is the key-aspect of displacement-based procedures. A number of studies about the displacement-based structural evaluation were proposed (Fajfar 2000, Goel and Chopra 2001, Panagiotakos and Fardis 2001, Lin *et al*. 2004, Sulliwan *et al*. 2006) and some studies appeared in technical reports such as ATC-40 (1996), FEMA 356 (2000) and FEMA 440 (2006). Nonlinear static analyses are widely used in

*Corresponding author, Research Assistant, Ph.D., E-mail: taner.ucar@deu.edu.tr
[a]Research Assistant, E-mail: onur.merter@deu.edu.tr
[b]Professor, E-mail: mustafa.duzgun@deu.edu.tr

these studies. Structures are subjected to a set of increasing lateral loads until the target displacement is reached. The target displacement is intended to represent the maximum displacement to be experienced during an earthquake. The Coefficient Method of FEMA 356 (2000) and FEMA 440 (2005) uses series of displacement modification factors to obtain the target displacement. The successive approach given in the Turkish Seismic Design Code uses pseudo-acceleration spectrum to calculate the target displacement. Additionaly Capacity Spectrum Method of ATC-40 (1996) and N2 Method (Fajfar 1996) are the other widely used methods in calculating target displacement.

The energy balance concept in earthquake-resistant structural design and evaluation has been widely studied over a half-century period. The input energy to a structure during an earthquake has a major importance for energy balance concept and it was investigated by some previous researchers (Housner 1956, Zahrah and Hall 1984, Fajfar and Vidic 1994, Sucuoglu and Nurtug 1995, Uang and Bertero 1998, Manfredi 2001, Park and Eom 2006). Housner (1956) showed that the pseudo-velocity spectra of typical earthquakes have a tendency to be constant over a wide period range. The earthquake input energy for a SDOF and MDOF systems can be estimated based on Housner's assumption (Housner 1956).

Leelataviwat *et al*. (2002) used the energy-balance concept to derive the seismic design forces for MDOF systems. In their method, Lee and Goel (2001) and Leelataviwat *et al*. (2002) predefined a plastic yield mechanism and target drift for the structures. Nonlinear time history analyses were performed to check the predefined interstory drift ratios and yield mechanism of the selected steel moment frames (Leelataviwat *et al*. 2002). Later, a seismic evaluation procedure based on energy balance concept was presented by Leelataviwat *et al*. in 2008 and 2009. The displacement demand was obtained from the intersection of energy demand and energy capacity curves in these studies. Energy demand curves were obtained from the nonlinear time history analyses and capacity curves were obtained from the conversion of pushover curves (Leelataviwat *et al*. 2008, 2009, Liao 2010).

The objective of this study is to determine the target displacement of RC frame structures using the idealised pseudo-velocity spectrum. The intersection of acceleration spectrum with capacity curve of a structure is the traditional way to obtain target displacement of structures and it is evident that none of the previous methods use pseudo-velocity spectrum. In this study, energy demand is obtained directly from the idealised pseudo-velocity spectrum without performing nonlinear time history analyses. First, pseudo-velocity spectrum is obtained from seven earthquakes, which are recorded in Turkey, and idealised according to the Newmark-Hall approximation within the scope of this study. Then nonlinear static analyses are performed for the chosen RC structures and the constructed pushover curves are converted to the energy capacity curves. Consequently, displacement demand values are determined from the energy capacity curves according to the corresponding calculated energy demands. In the study, target displacements of each RC frame structure is calculated using the proposed "PSVS Method" and these values are compared to the results obtained from the Turkish Seismic Design Code (2007).

2. Energy-balance concept

The input energy to a structure during an earthquake has a tremendous importance for energy balance concept in earthquake-resistant structural design and it was investigated by some previous researchers (Housner 1956, Uang and Bertero 1988, Kuwamura and Galambos 1989, Fajfar 1990).

Housner (1956) showed that the pseudo-velocity spectra of typical earthquakes have a tendency to be constant over a wide period range. The earthquake input energy (E_I) for a SDOF and MDOF systems can be estimated based on Housner's assumption

$$E_I = \frac{1}{2} \cdot M \cdot S_V^2 \tag{1}$$

where M is total system mass and S_V is pseudo-velocity. Housner's input energy equation is for linear elastic systems. Newmark and Hall (1982) proposed that the response of an elastic-plastic system is the same as its corresponding elastic system and so the input energy equation can be written in Eq. (2), as the sum of elastic energy (E_e) and plastic energy (E_p).

$$E_I = E_e + E_p \tag{2}$$

Newmark and Hall (1982) mentioned that the input energy in Eq. (1) is valid for the sensitive range of the pseudo-acceleration spectrum. However, Lee and Goel (2001) modified the energy input equation for all period ranges using the coefficient γ.

$$\gamma \cdot E_I = E_e + E_p \tag{3}$$

In Eq. (3), γ term is named as the energy factor and can be determined as the ratio of total dissipated energy by the inelastic system to the input energy of the elastic system (Leelataviwat *et al*. 2008, 2009) and it can be calculated with Eq. (4).

$$\gamma = \frac{E_e + E_p}{\frac{1}{2} \cdot M \cdot S_V^2} \tag{4}$$

Elastic and plastic energy may be put into the Eq. (4) using the inelastic force-displacement diagram in Fig. 1. In Fig. 1, V_y is yield force, V_e is maximum strength of the corresponding elastic system, δ_y is yield displacement, δ_e is maximum elastic displacement and δ_m is maximum displacement of the inelastic system. The energy factor γ can be obtained in terms of displacement ductility μ and strength reduction factor R_y as given in Eq. (5).

$$\gamma = \frac{2 \cdot \mu - 1}{R_y^2} \tag{5}$$

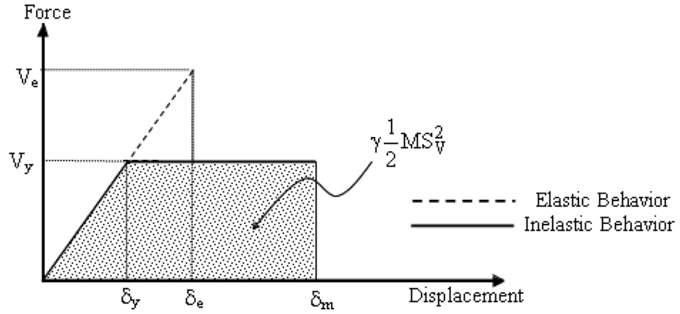

Fig. 1 Inelastic force-displacement diagram and energy-balance concept (Lee and Goel 2001)

2.1 Dynamic approach to the energy balance concept

The equation of motion of MDOF system subjected to earthquake excitation may be written as (Chopra 1995)

$$M \cdot \ddot{u} + C \cdot \dot{u} + K \cdot u = -M \cdot 1 \cdot \ddot{u}_g(t) \tag{6}$$

where u is a vector representing floor displacements, $\ddot{u}_g(t)$ is strong ground acceleration, M, C and K are mass, damping and stiffness matrices of the MDOF system, respectively and 1 is the unit vector. With some transformations (Chopra 1995), base shear of the MDOF system in its nth mode can be expressed as given in Eq. (7)

$$V_{bn} = M_n^* \cdot V_n = \frac{(\phi_n^T \cdot M \cdot 1)^2}{\phi_n^T \cdot M \cdot \phi_n} \cdot V_n \tag{7}$$

in which M_n^* is effective modal mass, ϕ_n is the nth mode shape vector, V_{bn} is base shear of the MDOF system in its nth mode and V_n is base shear of the corresponding SDOF system. Eq. (7) shows that the SDOF system carrying a mass M_n^* is equivalent to the nth mode of the MDOF system in terms of base shear (Chopra 1995).

The nth mode displacement of MDOF system, u_n^*, may be expressed as the equivalent SDOF system displacement, δ_n, with transformations of structural dynamics as shown in Eq. (8) (Chopra 1995).

$$u_n^* = \delta_n \tag{8}$$

Leelataviwat *et al.* (2009) applied the structural dynamics conclusion in Eq. (8) to the energy balance concept, and the energy balance equation of the inelastic system was obtained for the nth mode of the MDOF systems. The energy-balance equation of the SDOF system can be seen in Eq. (9). Energy balance equation of the nth mode of the MDOF system, which is taken into account as a SDOF system carrying a mass M_n^*, is presented in Eq. (10).

$$\gamma \cdot E_I = \frac{1}{2} \cdot V_y \cdot \delta_y + V_y \cdot (\delta_m - \delta_y) \tag{9}$$

$$\gamma \cdot \frac{1}{2} \cdot M_n^* \cdot S_V^2 = \frac{1}{2} \cdot V_y \cdot u_{ny}^* + V_y \cdot (u_{nm}^* - u_{ny}^*) \tag{10}$$

3. Determination of target displacement using pseudo-velocity spectrum and energy-balance concept (PSVS method)

Earthquakes push structures up until a theoretic displacement value, which is called “Target Displacement”, is reached. There are some methods in literature to calculate the target displacement values without performing a nonlinear time history analysis. These methods are mostly displacement and force based. As an example; the Coefficient Method of FEMA 356 (2000) and FEMA 440 (2005) reports, gives a target displacement formula that is based on nonlinear static procedures. In the Turkish Seismic Design Code (2007), a successive approach calculates the target displacement using capacity curve of the structure and elastic design pseudo-acceleration spectrum.

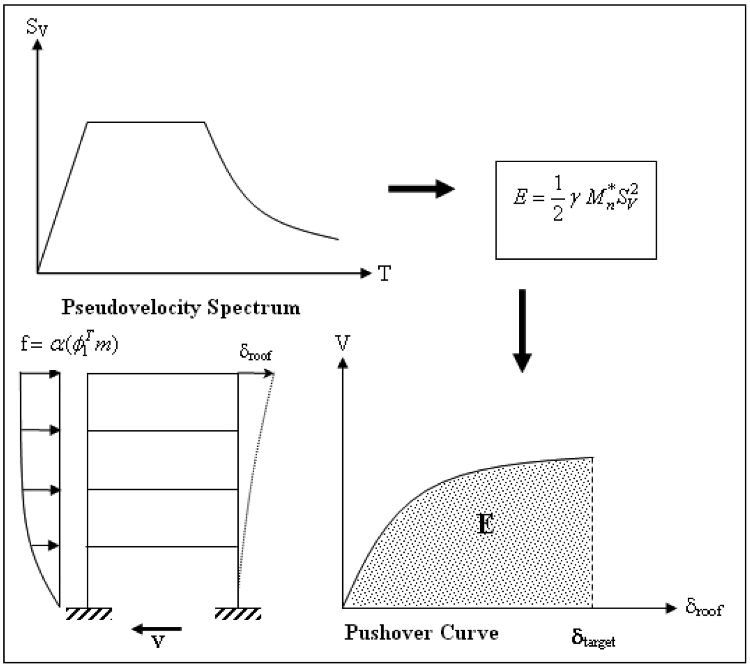

Fig. 2 Schematic representation of the PSVS method

In this study, the target displacement of a structure is calculated using energy-balance concept. The approach used to calculate the dissipated energy by the structure is based on the bilinear representation of pushover curves by using the procedure given in FEMA 356 (2000). Pushover curve of a structure is represented by two lines and the dissipated energy is determined from the work done due to lateral forces by summing the areas under these lines. Linear functions of the lines are obtained and by using these functions, the dissipated energy values are calculated for small variations in roof displacement.

On the other hand, for the demand side, earthquake records are chosen to obtain the elastic pseudo-velocity spectra. Using the peak values of the recorded earthquakes, elastic pseudo-velocity earthquake spectra are constructed by the procedures of Newmark and Hall. As a conclusion, the energy demand of the structure is obtained using the left hand side of Eq. (10) from idealised mean pseudo-velocity design spectrum. The displacement, which yielded the energy-demand value at the same point, is accepted as performance point of the structure. It is called the "Energy-Based Performance Point" or "Energy-Based Target Displacement" of the structure. The method that is used in this study to calculate the energy-based performance point is proposed as the "Pseudo-velocity Spectrum (PSVS) Method" and schematic representation of the PSVS Method is shown in Fig. 2.

4. Application of PSVS method to RC frame structures

The proposed "Pseudo-velocity Spectrum (PSVS) Method" is based on the energy balance concept that uses the equality of energy demand and energy capacity of the structure. In this study, the method is applied to RC frame structures with different stories. First, pushover curves of the frames are obtained from nonlinear static analysis and then these curves are converted to energy capacity diagrams. Subsequently, energy demands for the RC structures are calculated using the Newmark-Hall idealised pseudo-velocity spectrum. Finally, the target displacements obtained from the proposed method are compared with the values which are determined according to the procedure described in the Turkish Seismic Design Code (2007).

4.1 Description of RC frame structures

The structural systems considered in this paper are three frames with five, eight and ten stories which are designed in accordance with the Turkish Standards-TS500 (2000) and the Turkish Seismic Design Code (2007) considering both gravity and seismic loads. Frames are assumed to be on Seismic Zone 1. Local Site Class is taken as *Z2*, for which the design acceleration spectrum characteristic periods are 0.15 sec and 0.40 sec. All frames are designed as systems of high ductility level. Typical story height is 2.7 m for all frames. Material properties are assumed to be 25 MPa for the concrete compressive strength and 420 MPa for the yield strength of both longitudinal and transverse reinforcements.

Uniform dead and live loads on the beams are assumed to be 16.75 kN/m and 5 kN/m, respectively. Live load participation factor, *n*, is taken as 0.30 and floor weights and related masses, which are considered in seismic calculations, are determined as the combination of dead loads and 30% of live loads. All beams have rectangular sections with dimensions of 250 mm × 500 mm. Stirrups with 8 mm diameter are used as transverse reinforcement in all beams and stirrup spacing is taken as 10 cm at beam ends, which are potential plastic hinge regions. Column dimensions, longitudinal and transverse reinforcement details of columns and also analytical model of the analysed frames are given in Fig. 3. Frames with five, eight and ten stories are regarded as RC_5, RC_8 and RC_10, respectively.

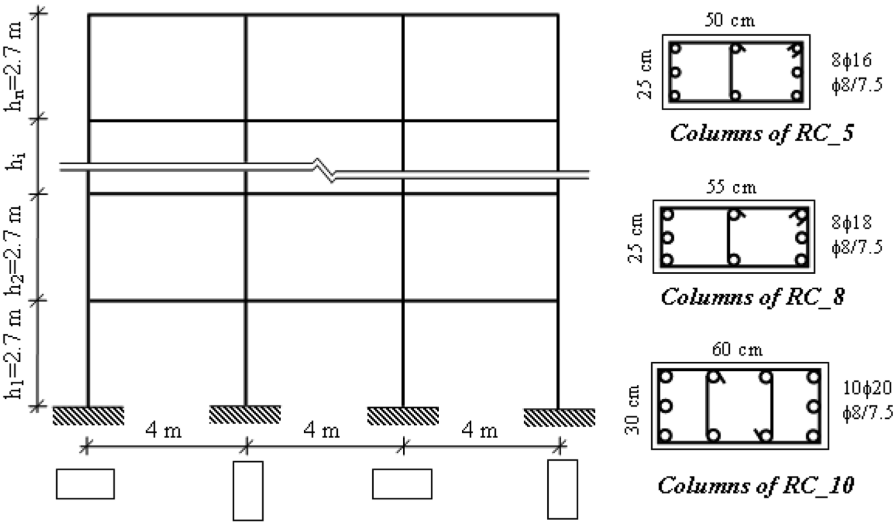

Fig. 3 Analytical model of analysed frames and reinforcement detail of columns

4.2 Nonlinear modelling details and pushover analysis of the frames

In this study, a two-dimensional nonlinear mathematical model of each frame is created in the SAP2000 Nonlinear, Version 14.2 (2010) in order to evaluate seismic performance of the frame buildings by using nonlinear static analysis, so-called pushover analysis. While defining the component sizes of the frames, confinement zones are considered as infinitely rigid end zones. The initial effective stiffness values of structural elements are reduced according to the Turkish Seismic Design Code (2007) in order to account for cracking in sections during the inelastic response of building. Masses of floors are calculated from gravity loads (the dead loads plus 30% of the live loads) and are assumed to be lumped at each story level. Modal properties of the first mode, which are determined by using cracked section properties of frame components, are given in Table 1.

In order to define plastic hinge properties, nonlinear behavior of structural elements is considered by adopting a lumped plasticity model. Moment-curvature analysis of sections is performed by using the cross section analysis program XTRACT (2006). Axial force of the columns is determined from gravity loads while it is assumed to be zero on the beams. The stress-strain relationships, proposed by Mander *et al*. (1988), are implemented for unconfined and confined concrete. Reinforcement steel is modeled by parabolic strain hardening steel model, which is given in the Turkish Seismic Design Code (2007). Plastic rotations are calculated by multiplying plastic curvatures by the plastic hinge length, which is considered as half of the section depth. Thus, plastic rotation-moment relationships of plastic hinges, which are the required inputs for SAP2000, are obtained. Column capacities are calculated from axial force-bending moment diagrams, which are also obtained by the computer code XTRACT (2006). Plastic hinges are assigned at both ends of

Table 1 Dynamic characteristics of the frames

Frame ID	Period T_1 (sec)	Mass Participation Factor U_1	Effective Modal Mass M_1^* (kNsec^2/m)	Modal Participation Factor Γ_1
RC_5	0.685	0.851	126.108	1.266
RC_8	1.028	0.821	196.819	1.284
RC_10	1.165	0.810	252.227	1.290

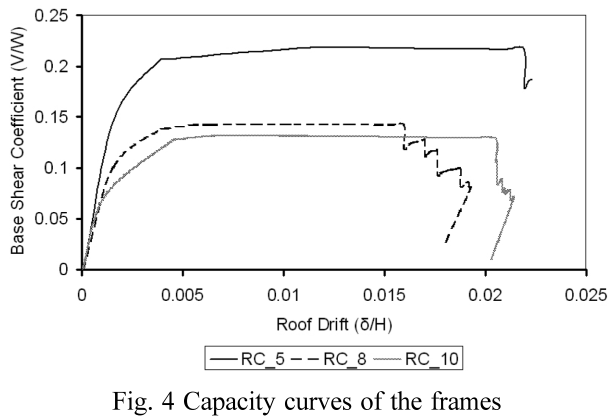

Fig. 4 Capacity curves of the frames

the beams and columns.

A lateral load distribution proportional to the respective first mode shapes is applied to all frames. The capacity curves are obtained by conducting a displacement controlled pushover analysis on the two-dimensional nonlinear models. Geometric nonlinearity (P-Δ effect) is taken into consideration. The results of the pushover analysis are presented in Fig. 4.

4.3 Creation of a Smooth Spectrum

The response spectrum provides a convenient means to summarize the peak response of all possible linear SDOF systems to a particular component of ground motion (Chopra 1995). The response spectrum for any quantity can be constructed by plotting the peak value of a response quantity as a function of the natural vibration period T_n of the system, or a related parameter such as; circular frequency w_n or cyclic frequency f_n (Chopra 1995).

Response spectra are for individual earthquakes recorded at particular sites with particular soil characteristics and they cannot be used for design purposes. Design spectra need to be smoothened to use for design purposes. Otherwise, the design would only be valid for that particular earthquake and small variations in natural period of the structure would provide very different design demands.

In order to create a smooth spectrum for design based on response spectra, a set of seven strong ground motions, that were recorded at different soil sites in Turkey and have a magnitude range of

Table 2 Strong ground motion details

EQ. No.	Earthquake	Date	Magnitude (M_w)	Recording Station	Epicentral Distance (km)	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)
1	Kocaeli-1	17.08.1999	7.6	Kocaeli Meteorological Station	15.9	230.80	38.59	21.89
2	Kocaeli-2	17.08.1999	7.6	Duzce Meteorological Station	15.9	365.60	58.33	25.16
3	Kocaeli-3	17.08.1999	7.6	Sakarya Directorate of Public Works and Settlement	15.9	408.70	70.99	90.70
4	Duzce	12.11.1999	7.1	Duzce Meteorological Station	11.0	406.20	68.57	48.27
5	Bingol	01.05.2003	6.3	Bingol Directorate of Public Works and Settlement	6.0	296.04	21.87	5.05
6	Erzincan	13.03.1992	6.6	Erzincan Meteorological Station	23.0	478.77	78.22	29.5
7	Denizli	19.08.1976	6.1	Denizli Meteorological Station	20.0	266.84	16.78	1.30

6.1 to 7.6 are used. As specified in the Turkish Seismic Design Code (2007), duration of all ground motions is more than five times of the first natural vibration period of the structures and 15 seconds. Details of the ground motion records are given in Table 2.

The accelerograms for all earthquakes are constructed by using the data provided from the official web site of the Strong Ground Motion Database of Turkey (http://www.deprem.gov.tr). The acceleration time histories of the earthquakes are shown in Fig. 5.

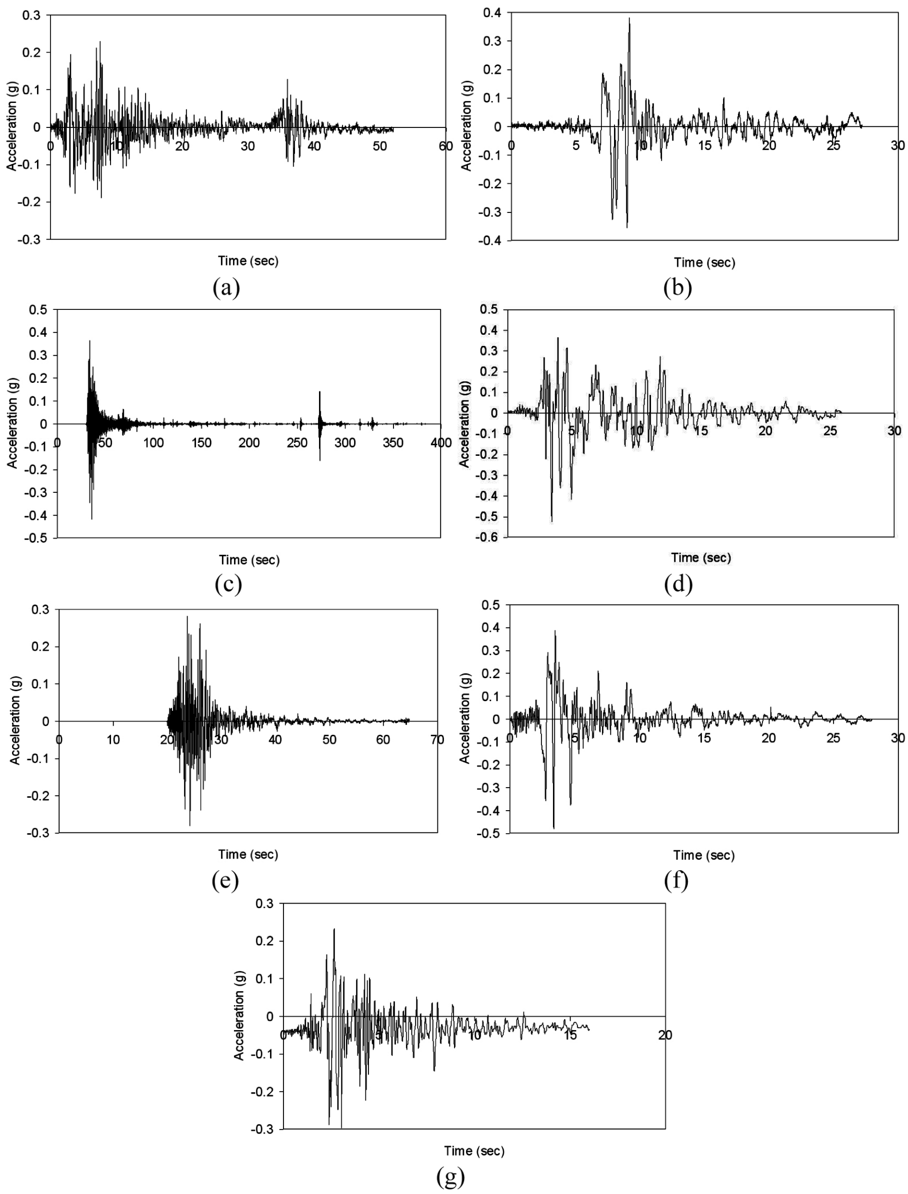

Fig. 5 Acceleration time histories of the earthquakes. (a) Kocaeli-1 earthquake, (b) Kocaeli-2 earthquake, (c) Kocaeli-3 earthquake, (d) Duzce earthquake, (e) Bingol earthquake, (f) Erzincan earthquake, (g) Denizli earthquake

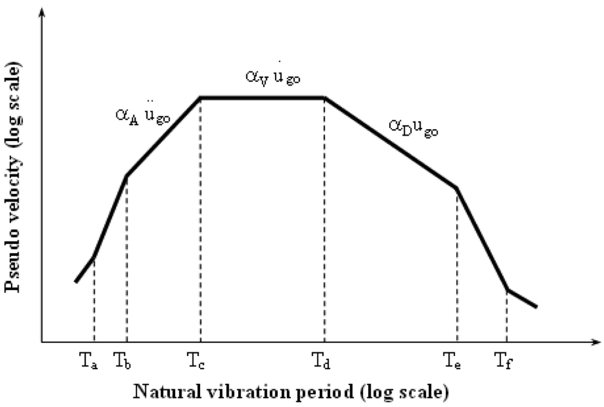

Fig. 6 Creation of the Newmark-Hall smooth spectrum

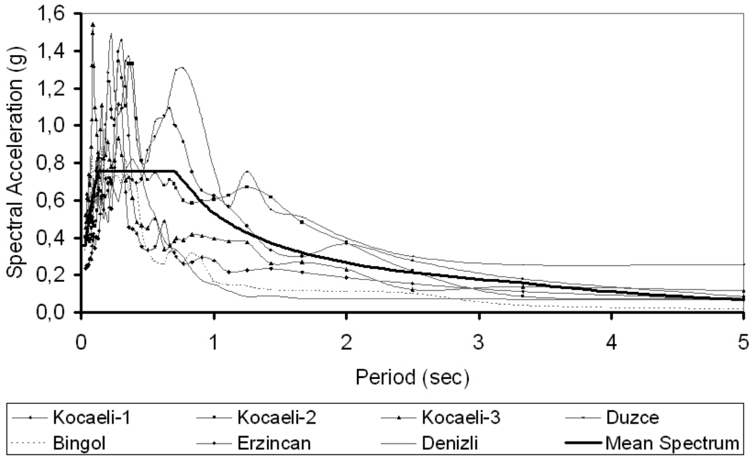

Fig. 7 Mean spectrum and spectra of the ground motion records

The procedure used in this study to construct smooth design spectra from ground motion parameters was originally developed by Newmark and Hall (1982). This procedure is schematically illustrated in Fig. 6. Newmark-Hall design spectrum consists of series of straight lines and three amplification zones. The period values T_a, T_b, T_e and T_f are fixed for all design spectra and are taken as recommended values from Newmark and Hall (T_a = 1/33 sec, T_b = 1/8 sec, T_e = 10 sec and T_f = 33 sec). T_c and T_d periods are located at intersections of the constant acceleration, constant velocity and constant displacement branches of the spectrum.

Using the peak values of the recorded earthquakes, the mean elastic design spectrum is constructed by the procedures of Newmark and Hall with amplifications factor of $\alpha_A = 2.12$, $\alpha_V = 1.65$ and $\alpha_D = 1.39$ for system with a 5% damping ratio and for a 50% probability of exceedance. Five-percent damped elastic acceleration response spectra of the earthquakes and the Newmark-Hall idealized mean response spectrum, which is fitted by the Method of Least Squares, are shown in Fig. 7. The elastic acceleration response spectra are constructed by using structural analysis program SAP2000 Nonlinear, Version 14.2 (2010).

4.4 Determination of target displacement by the PSVS method and according to the Turkish seismic design code

In order to determine the target displacement of the frames by using the proposed PSVS Method, the pushover curve of each frame is represented by two lines according to the procedure given in FEMA 356 (2000). The idealization of the pushover curve of RC_5 is shown in Fig. 8.

Subsequently, the dissipated energy is determined from the work done due to lateral forces by summing the areas under these lines. Linear functions of the lines are obtained and by using these functions, the dissipated energy values are calculated for small variations in roof displacement. The energy capacities of the frames obtained in this way are shown in Fig. 9.

Afterwards, for the demand side, using the peak values of the selected earthquakes, elastic pseudo-velocity earthquake spectra are constructed by the procedures of Newmark and Hall (1982) and the mean pseudo-velocity spectrum of these earthquakes is shown in Fig. 10.

Finally, the energy demand of the structure is obtained using the left hand side of Eq. (10) from idealised pseudo-velocity design spectrum graph. The displacement, which yielded the energy-demand value at the same point, is accepted as the energy-based target displacement of the structure. The energy-based target displacements, which are calculated by the PSVS Method, and the energy demands, which are also equal to the dissipated energy values calculated for these displacements, are given in Table 3.

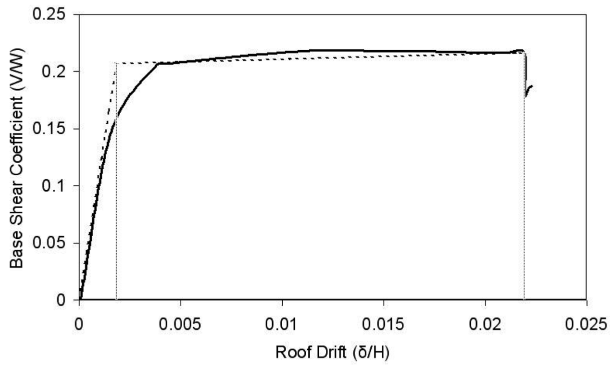

Fig. 8 Idealization of pushover curve with two lines

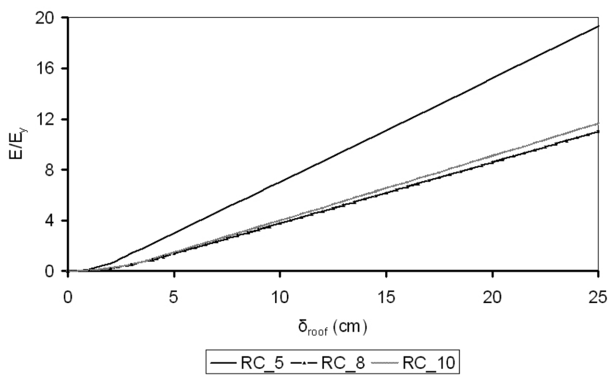

Fig. 9 Energy capacity diagrams of the frames

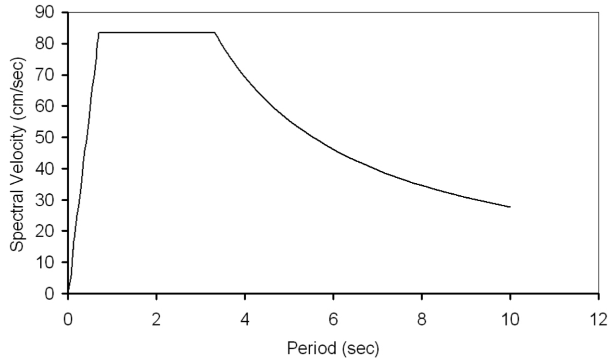

Fig. 10 Newmark-Hall pseudo-velocity spectrum

Table 3 Energy-based target displacement of the frames

Frame ID	Effective Modal Mass M_1^*(kNsec^2/m)	Energy Demand (kNm)	Energy-Based Target Displacement (cm)
RC_5	126.108	21.841	8.752
RC_8	196.819	40.788	14.759
RC_10	252.227	52.514	16.200

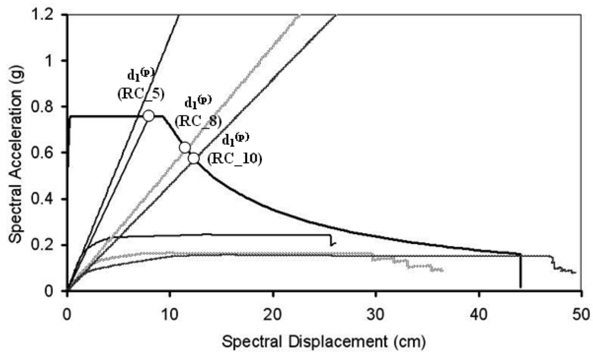

Fig. 11 Determination of spectral displacement demands of the frames

To check the accuracy of the proposed method, the target displacement of the same frames are also determined according to the procedure described in the Turkish Seismic Design Code (2007). This is a successive approach, where the capacity curve of a structure is used together with the elastic design acceleration spectrum. So, as a first step the pushover curve of the frames is transformed to capacity spectrum by using the equations of structural dynamics. The capacity spectrum and the mean acceleration spectrum given in Fig. 7 are used together to determine the spectral target displacement of the considered frames as shown in Fig. 11.

As a final step, these spectral quantities are transformed to target displacements and all values are given in Table 4, where Φ_{N1} is the first mode shape amplitude of the top point, Γ_1 is the modal participation factor belonging to first mode, $d_1^{(p)}$ is the target spectral displacement and $u_{N1}^{(p)}$ is the target displacement of the considered structures.

Table 4 Target displacement of the frames

Frame ID	Φ_{N1}	Γ_1	$d_1^{(p)}$ (cm)	$u_{N1}^{(p)}$ (cm)
RC_5	1.000	1.266	7.048	8.923
RC_8	1.000	1.284	11.634	14.938
RC_10	1.000	1.290	12.426	16.030

5. Conclusions

In this paper, the target displacement of RC frame structures under earthquake effects is calculated using the energy-balance concept. The main findings of this study may be summarized as follows:

1. The most important contribution of this paper is the proposal of a new procedure to calculate target displacement of RC structures, namely the "Pseudo-velocity Spectrum (PSVS) Method", which is developed by using the balance of the seismic energy demand and energy capacity of the structures. The difference between the PSVS Method and other energy-based methods is that, in the PSVS Method the energy demand is obtained directly from the elastic pseudo-velocity spectrum instead of performing any considerably time consuming nonlinear time history analyses. In this procedure, first the pseudo-velocity spectrum is obtained using Newmark-Hall approximation for the chosen earthquake records. Later, nonlinear static analyses are performed for the structures and pushover curves and energy capacities of the structures are constructed. Finally, the displacement demand is calculated by using the energy-balance between the energy demand and energy capacity. It is called the "energy-based target displacement" or the "energy-based performance point" of a structure.
2. Another important point worthy of notice is that the calculated energy-based target displacements and the values obtained from the successive approach given in the Turkish Seismic Design Code (2007) correspond; the results are very close to each other. The displacement demand from the developed energy-based method is approximately the same with the displacement-based code method. The small differences (1-2%) between two methods result from the representation of pushover curves with two lines in the PSVS Method. In the Turkish Seismic Design Code pushover curve is used directly without any idealisation.
3. The proposed process includes the calculation and drawing of the elastic pseudo-velocity spectrum for a certain period range using Newmark-Hall approximation. The energy demand is calculated by using the idealised pseudo-velocity spectrum graph. The elastic pseudo-velocity response spectrum is derived from the chosen major earthquake records in Turkey region and having a moment magnitude range of 6.1 to 7.6. Eventually, the calculated target displacements within the study are both energy-based and pseudo-velocity spectrum-based.
4. In the study, the seismic demand and capacity of the structures are presented in terms of energy. The energy demand is obtained depending on the displacement ductility of the MDOF system together with the pseudo-velocity response spectrum. The displacement ductility of the system plays an important role in calculating the energy factor, the seismic energy demand and finally the energy-based target displacement.

In this paper, the energy-balance concept is applied to the regular RC frame structures for which the mass participation factor of the first mode is in the range of 80-90%. The PSVS Method can be extended for the multiple mode analyses and further research is needed to apply the procedure for multi-modal effective structures. In this case; multi-mode pushover analyses will be needed to apply the procedure.

Another feasible study to obtain the seismic energy demand and check the energy-based target displacement results may be nonlinear time history analyses. However, in this study, the nonlinear time history analyses are not performed, the seismic energy demand is obtained practically from the Newmark-Hall pseudo-velocity response spectrum, since the calculations are more practical and brief when the nonlinear time history analyses are not performed and it is easier to set up the seismic energy demand expression.

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