Advances in Performance Based Design by Endurance Time Method

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SUMMARY

Endurance Time (ET) is a time-history based dynamic procedure for seismic analysis and design of structures. In this procedure, structures are subjected to an intensifying accelerogram and their performance is measured based on the time intervals during which they can satisfy particular response requirements. In this paper, correlation between time in the endurance time method and earthquake hazard return period is investigated. To achieve such a correlation, the response spectrum has been utilized as an intermediate criterion. ET performance curves are then modified by applying this substitution. Four steel and concrete moment frames have been modeled and their new ET performance curve has been depicted and compared to the former ET performance curve. The results show that substitution of the return period for ET time in the target and ET performance curves increases the usefulness of these curves and can simplify application of the ET method in performance-based design.

Keywords: Endurance time method, Performance-based design, Intensifying accelerograms.

1. INTRODUCTION

Performance-Based Design is a relatively new methodology that was developed initially for improving the design of structures in earthquake prone areas. The idea behind Performance-Based Design is to design a structure such that it meets certain predetermined performance criteria when exposed to the “design event” corresponding to various levels of earthquake hazard (SEAOC, 1995). In this methodology the structural design criteria are expressed in terms of achieving a set of different performance objectives (Ghobarah, 2001). Performance objective is a practical notion, which consists of the specification of a structural performance level (e.g. collapse prevention (CP), life safety (LS), or immediate occupancy (IO)) for a given level of seismic hazard (Krawinkler and Miranda, 2004). On the other hand, a recently introduced seismic analysis technique is the Endurance Time (ET) method. In this method the structure is subjected to a standard calibrated intensifying accelerogram and the time that it experiences a specified level of damage is considered as the seismic resistance criteria for that structure. Therefore, the seismic performance of the buildings can be compared directly with the time that they can endure the intensifying accelerogram. Higher endurance time is to be interpreted as a more suitable performance (Estekanchi et al., 2011).

To facilitate the evaluation of seismic performance of the structures using ET method, Mirzaee et al. (2010) introduced the concept of the “Target Curve”, which expresses the limit of the proper seismic performance of a structure along various seismic intensities as a continues function. By comparing the performance curve of a structure acquired by the ET method with the target curve, the seismic performance of the structure at different seismic intensities can be evaluated in a more versatile manner. Both mentioned curves (performance and target) represent changes in the seismic performance of the structures with time. It is not common and can, occasionally, be confusing to evaluate and express seismic performance with time. Therefore, in order to improve the readability of these curves, substituting a common parameter (such as PGA, return period or annual probability of exceeding) for time is suggested. The present study sought to address this issue by examining the correlation between time in ET analysis and the return period of ground motion. The ETA20jn series of ET accelerograms, that is created in such a way that the response spectrum at t=10 sec is equivalent to the ASCE-41 design spectrum for Tehran, IRAN (Mirzaee and Estekanchi, 2011), is used as the basic accelerogram in this study.

2. BASIC CONCEPTS OF ENDURANCE TIME ANALYSIS

The Endurance Time (ET) method is a time-history based analysis and design procedure. In this method the structure is subjected to a standard calibrated intensifying accelerogram and the time that it experiences a specified level of damage is considered as the seismic resistance criteria for that structure. Therefore, the seismic performance of the buildings can be compared directly with the time that they can endure the intensifying accelerogram. Higher endurance time is to be interpreted as a more reasonable performance (Estekanchi et al., 2011).

One of the parameters in the production of the ET accelerograms is the profile of the changes in the amplitude of the acceleration with time. All the ET accelerograms that have been produced so far have a linear intensification scheme. These accelerograms are created so that at a predefined time, t_{Target}, the response spectrum reaches a pre-specified template response spectrum. For example, three accelerograms, named “ETA20jn01-03”, are created in such a way that the response spectrum at t=10 sec is compatible with the ASCE-41 design spectrum for Tehran (Mirzaee and Estekanchi, 2011). In the accelerograms with linear intensification scheme, the response spectrum of an ET accelerogram is to intensify proportionally with time. Consequently, the target acceleration response of an ET accelerogram is defined as in Eqn. 2.1.

$$S_{aT}(T,t) \equiv S_{aC}(T) \times \frac{t}{t_{Target}} \tag{2.1}$$

where $S_{aT}(T,t)$ is the target acceleration response at time t, T is the period of free vibration and $S_{aC}(T)$ is the codified design acceleration spectrum (Estekanchi et al., 2007). It should be considered that these simplifications are just being made in order to synthesize a preliminary ET acceleration function (Estekanchi et al., 2011). The results of the endurance time method are usually interpreted by a curve called “ET Response Curve” or “ET Performance Curve”. Figure 1 shows the ET response curves for three sample steel moment frames.

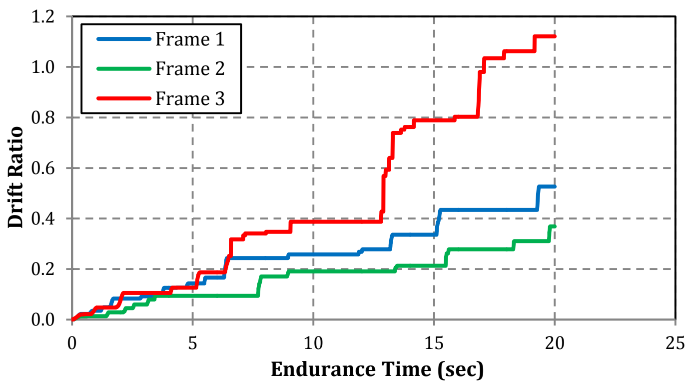


Figure 1. ET performance curves for three steel moment frames.

3. APPLICATION OF ET METHOD IN PERFORMANCE-BASED DESIGN

Application of the ET method in performance-based design was studied for the first time by Mirzaee et al. (2010). They proposed using a curve called the "Target Curve" to facilitate the evaluation of seismic performance of the structures using ET method. This curve expresses the limit of the proper seismic performance of a structure (acceptance criteria) along various times in ET analysis (note that times in ET analysis can be interpreted as seismic intensities). By comparing the ET performance curve with the target curve, the seismic performance of the structure at different seismic intensities can be evaluated. They also introduced an index called "Damage Level" or briefly "DL" to simplify the comparison between various parameters that are used for evaluating the seismic performance of the frames. The formulation proposed for the DL has been arranged is such a way as to assign an explicit number (preferably an integer) to each performance level and use the determining parameters (such as interstory drift and plastic rotation) to compute the DL in a clear and understandable way.

This formula is as follows:

$$DL = \sum_{i=1}^{n} \frac{\max[\theta_{i-1}, \min(\theta, \theta_i)] - \theta_{i-1}}{\theta_i - \theta_{i-1}} \tag{3.1}$$

where θ is the related parameter-like drift, which should be computed from analysis and θ_i is the ASCE-41(ASCE, 2007) boundary of that parameter for each performance level. In Fig. 2 the performance curves for drift and plastic rotation of beams in a steel frame are depicted and compared to the target curve using DL index.

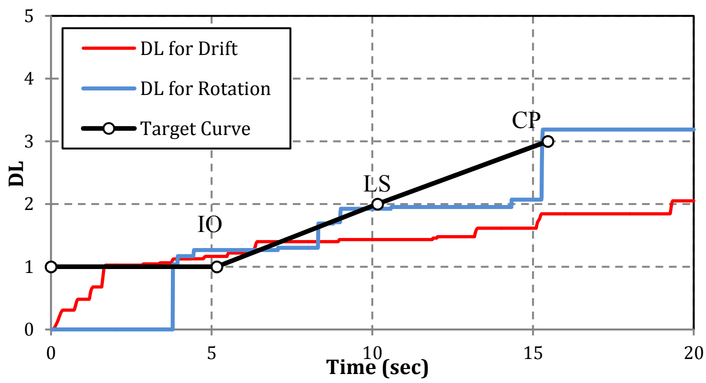


Figure 2. An example of target and performance curves (Mirzaee et al., 2010).

4. CORRELATIING TIME IN ET ANALYSIS WITH SEISMIC HAZARD RETURN PERIOD

Both the performance and target curves in ET analysis represent the changes in the seismic performance of the structures with intensity, which is increased with the time. One way to improve the usefulness of these curves is to substitute equivalent return period for time (Bazmuneh 2009). The present study sought to address this issue by examining the correlation between time in ET analysis and the return period of ground motion. The return period is defined as the average period of time, in years, between the expected occurrences of an earthquake of specified severity.

The ETA20jn series of ET accelerogram is used as the basic accelerogram in this investigation. It is noticeable that for present ET accelerograms, this correlation depends on the fundamental period of the structure. In other words, different structures with different fundamental periods will have different ET analysis times, relevant to a particular return period.

Since there is no direct relationship between time in ET method and return period, the response spectrum has been utilized as an intermittent criterion. The time at which the response spectrum is matched to the response spectrum corresponding to a particular hazard level (or return period) is traced. This procedure has been accomplished considering a range of periods (from 0.2 seconds to 1.5 seconds). In this research the ASCE Standard for Seismic Rehabilitation of Existing Buildings, known as ASCE-41 (ASCE, 2007) is considered and used to obtain the response spectrum for the desired site (Tehran, Iran) and different hazard levels.. It should be noted here that the site is classified as site class C with V_{s30}≈600 m/s and is generally similar to Los Angeles area.

To acquire the design response spectrum for different hazard levels, an appropriate approach is to identify the relation between the basic parameters of design response spectrum (S_s, short-period spectral response acceleration parameter and S_1, long-period spectral response acceleration parameter) and the return period (or identically annual probability of exceedance). In this regard, the seismic hazard curves for S_S and S_1 obtained by Mirzaee and Estekanchi (Mirzaee and Estekanchi, 2011) are used to develop a formulation for S_a (spectral acceleration) versus return period.

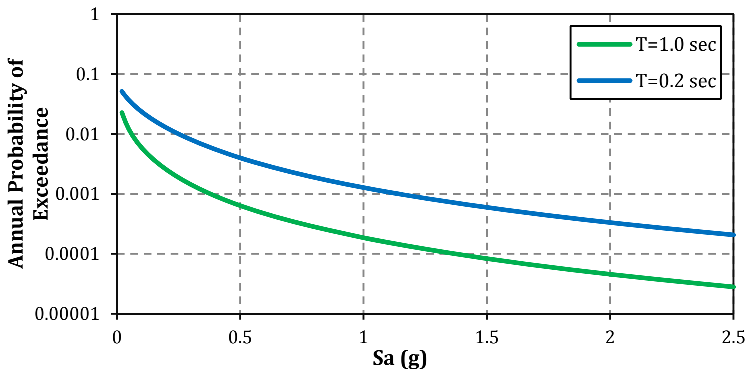


Figure 3. Seismic hazard curve for Sa (Mirzaee and Estekanchi, 2011).

In Figure 3, the seismic hazard curves for S_S and S_1, for Tehran, are shown. According to this figure, the relation between S_S and S_1 and the annual probability of exceedance (λ_m) can be derived as in Eqns. 4.1 and 4.2.

$$S_s = 0.072 \times \lambda_m^{-0.43} - 0.2674 \quad (4.1)$$

$$S_1 = 0.026 \times \lambda_m^{-0.44} - 0.16 \quad (4.2)$$

Considering that the annual probability of exceedance is equal to the inverse of the return period (Kramer, 1996), the ASCE-41 response spectrum can be introduced, according to the value of the return period, as indicated in Eqn. 4.3.

$$S_a = f(R,T) = \begin{cases} \dfrac{0.45T(R^{0.43} - 3.7)^2}{R^{0.44} - 6.17} + 0.029(R^{0.43} - 3.74) & T < T_0 \\ 0.072R^{0.43} - 0.27 & T_0 < T < T_S \\ \dfrac{0.034R^{0.44} - 0.21}{T} & T_S < T \end{cases} \tag{4.3}$$

Where S_a is the spectral acceleration, T is the period of free vibration, R is the return period and T_S and T_0 are equal to $\dfrac{R^{0.44} - 6.17}{2.12R^{0.43} - 7.90}$ and $0.2T_S$ respectively.

The return period can be expressed as a function of T and S_a developing the inverse of function *f(R, T)* given in Eqn. 4.3, with respect to variable R, (Eqn. 4.4).

$$R = h(S_a, T) = f^{-R}(S_a, T) \tag{4.4}$$

where R is the return period, $h(S_a, T)$ is a function that relates the return period to S_a and T, and f^{-R} represents the inverse of function f (given in Eqn. 4.3), with respect to variable R. On the other hand, the response spectrum for the ET accelerogram is defined, as indicated in Eqn. 4.5 (Estekanchi et al., 2004):

$$S_a(T,t) = \max(|a(\tau)|) \qquad \tau \in [0,t] \tag{4.5}$$

where T is the period of free vibration, t is time, and a is acceleration. Eqns. 4.4 and 4.5 illustrate that S_a is dependent on T and t. and the return period can be developed as a function of T and S_a. The consequence is that the return period can be expressed as a function of T and t, accordingly. Since expressing the return period via an explicit formulation is a complex process, this function is represented by a matrix called A_{RP}, as shown in Eqn. 4.6. To develop the matrix A_{RP}, the value of S_a is calculated for the intended T and t using Eqn. 4.5 (or Eqn. 2.1). Then, the desired return period can be calculated utilizing Eqn. 4.4 regarding the values of intended T and obtained S_a.

$$A_{RP} = \begin{array}{cc} & \text{T (sec)} \\ & \begin{array}{ccccccc} \cdots & 1 & \cdots & 3 & \cdots & 5 & \cdots \end{array} \\ \text{ET analysis time (sec)} \begin{array}{c} \vdots \\ 5 \\ \vdots \\ 10 \\ \vdots \\ 17 \\ \vdots \end{array} & \begin{bmatrix} & \vdots & & \vdots & & \vdots & \\ \cdots & 220 & \cdots & 187 & \cdots & 83 & \cdots \\ & \vdots & & \vdots & & \vdots & \\ \cdots & 490 & \cdots & 422 & \cdots & 408 & \cdots \\ & \vdots & & \vdots & & \vdots & \\ \cdots & 1108 & \cdots & 878 & \cdots & 868 & \cdots \\ & \vdots & & \vdots & & \vdots & \end{bmatrix} \end{array} \tag{4.6}$$

The variation of the return period with the structural period and time in ET analysis is shown in Fig. 4. As illustrated in this figure, for the structures with periods lesser than o.2 seconds and greater than 2 seconds, the effect of the fundamental period of the structure can be eliminated. In addition, for a particular return period, time in ET analysis increases as the period of the structure increases. It also can be observed from this figure that the maximum return periods are for lower structural periods and higher times.

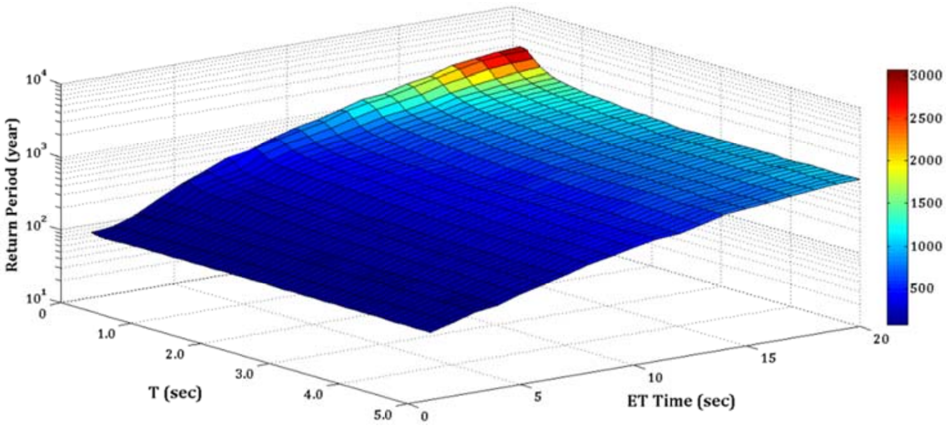


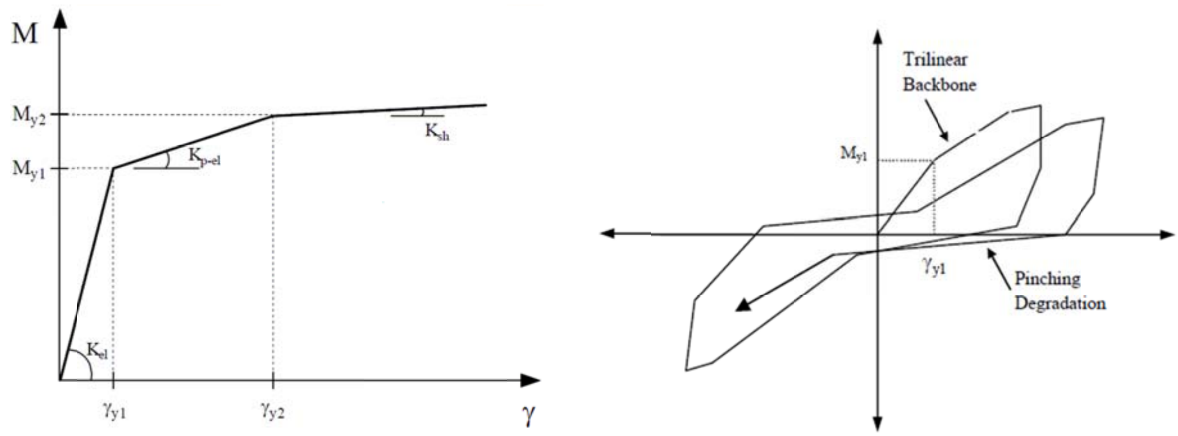
Figure 4. Return period vs. structural period and ET analysis time (Average method).

It should be pointed out here that the type of ET accelerogram strongly affects the role of the fundamental period of the structure on the relation between ET analysis time and earthquake return period. For example, generating an ET accelerogram in such a way that its response spectra at any time are completely coincident with a specific seismic hazard response spectrum can completely eliminate the effect of the fundamental period of the structure; then the return period can be interpreted as a single-variable function of ET time.

5. EXPLANATORY CASE STUDY

The methodology introduced in this paper will be explained by considering two groups of steel and RC moment frame models that have been subjected to ETA20jn series of ET accelerograms. Each group includes two frames, where the only difference between these two frame models is that in the first one the panel zone is not included in the model and the connections are modeled as rigid, since the panel zone has been considered and modeled in the second frame. Here, the scissors model has been applied for modeling the panel zone in the frames. In this model the beams and column are modeled with a rigid link through the panel zone region and a hinge in the beam is placed at the intersection of the beam and column centerlines. A rotational spring is then used to tie the beam and column together.

For steel frames, the Krawinkler proposed moment distortion response of the panel zone has been used (Krawinkler *et al.*, 1975), while a pinching model with a tri-linear backbone curve (Anderson, 2003) has been considered for the panel zone in RC frame (See Fig. 5). These frames have been designed according to ASCE/SEI 7-05 (ASCE 2005) considering a design spectrum with S_s, S_l, F_a and F_V equal to 0.768, 0.229, 1.093 and 1.57 respectively. The frames will be studied by subjecting them to "ETA20jn" series of ET accelerograms. The properties of these frames are given in Table 1. The modeling and nonlinear analysis were performed using PEER's OpenSees platform (OpenSees, 2004).



(a) (b)

Figure 5. Moment distortion response for panel zone (a) Krawinkler model for steel frame (Krawinkler et al., 1975) (b) backbone curve for RC frame (Lehman et al., 2004).

Table 1. Frames properties

Frame	No. of Stories	No. of Bays	Beam Sections (cm)	Column Sections (cm)	Panel Zone	Period of Free Vibration (sec)
SF1	3	1	HE160A	HE140B	No	2.0677
SF2	3	1	HE160A	HE140B	Yes	2.1645
RCF1	3	1	25x30T16	30x30T16 35x35T16	No	0.8902
RCF2	3	1	25x30T16	30x30T16 35x35T16	Yes	0.9854

Evaluating seismic performance of the frames has been done based on the ASCE-41 regulations. Interstory drift and plastic rotation in beams, columns and panel zones are the engineering demand parameters (EDP's) that are utilized for the seismic evaluation of each frame. In this research the concept of "Damage Level" has been used to compare the condition of various EDP's and to identify the critical parameter at different seismic hazard levels. Fig. 6 shows the former performance and target curves of various EDP's for SF1 frame. The final performance curve has also been drawn as the maximum of the EDP's performance curves at each time. This figure illustrates that for this frame the interstory drift is the critical parameter at all seismic intensities. Thus to upgrade the performance of the frame, controlling this parameter should be taken into account.

Considering the fundamental period of the frame, and utilizing the transformation obtained in section 4 for return periods versus ET analysis times, the return period has been substituted for time in Fig. 6, and the new target and performance curves are depicted in Fig. 7. Comparison of the new target and performance curves with former ones reveals that while they basically show the same information, the seismic performance of the structures has been more clearly conveyed in Fig. 7, since it has replaced a redundant time axis with a more relevant return period axis.

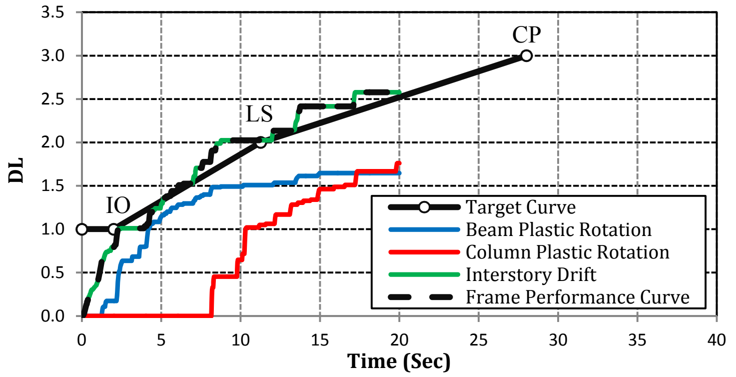


Figure 6. EDP's and final performance curves vs. target curve for SF1.

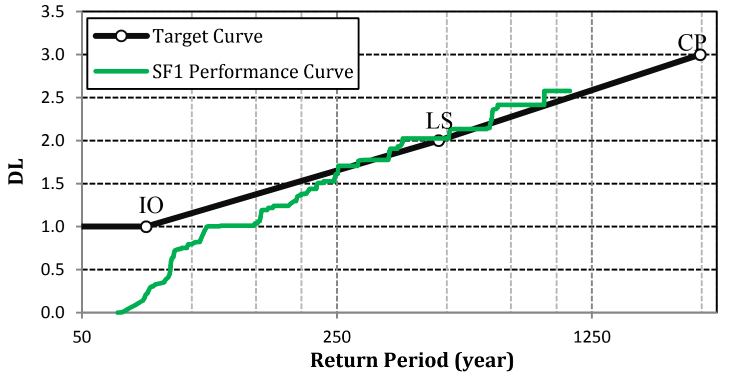


Figure 7. Target and performance curves for SF1 by return period.

The seismic performance of other frames has also been evaluated using similar performance and target curves. Fig. 8 shows the performance curves of SF1 and SF2 frames (steel frames without and with panel zone). As can be seen in this figure, the seismic performance of the SF2 frame is worse than the SF1 frame almost at all return periods.

The seismic performance of two RC frames (RCF1 and RCF2, reinforced concrete frames without and with panel zone) can be studied by viewing Fig. 9. Similar to Fig. 8 this figure shows that considering the panel zone in the modeling of the frame aggravates the seismic performance of the frame.

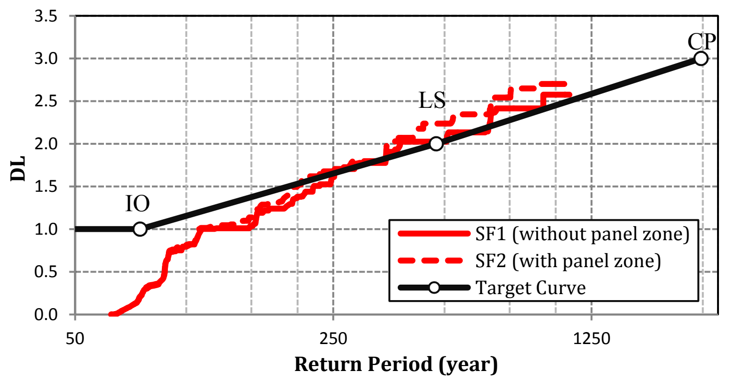


Figure 8. Target and performance curves for SF1 and SF2.

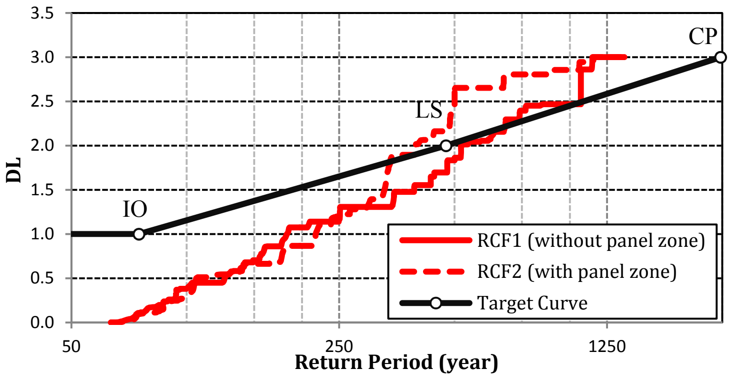


Figure 9. Target and performance curves for RCF1 and RCF2.

The authors believe that this new presentation of ET analysis results is more suitable for practical applications by the structural designer. The target curve represents which EDP levels are to be considered as acceptable by performance criteria. While resultant EDP need to be compared to allowable ones only at specific points marked as IO, LS and CP considering code requirements; a continues target performance curve conveys a better image of a desirable performance objective in general. Also note that the comparison of relative performance of two different designs becomes much more intuitive using such diagrams.

6. SUMMARY AND CONCLUSION

The correlation between time as an indicator of intensity in ET analysis, and the return period as a function of fundamental structural periods, is investigated. The proposed procedure is based on the coincidence of response spectra obtained from ET accelerograms at different times and response spectra defined by ASCE-41 at different hazard levels.

Results of the study suggest the following conclusions:

1. Substitution of the return period for time in the target and ET performance curves increases the readability of these curves and can considerably improve the presentation of ET analysis results in performance-based design.
2. The effect of the fundamental period of the structure on the relation between time in ET analysis and the return period is strongly dependent on the compatibility of ET accelerogram template spectrum with design spectra at various intensity levels. Ideally, if an ET accelerogram is generated in such a way that its response spectra coincide with design seismic hazard response spectra, then the equivalent return period will only become a function of time, instead of a function of time and fundamental period.
3. Generating an ET accelerogram in such a way that its response spectrum for a number of ET analysis times becomes compatible with the design response spectra of several significant hazard levels would improve the versatility of such accelerograms in seismic assessment of structures.
4. For structural periods greater than 0.5 sec, the maximum return period that could be covered was less than 1500 years. Hence, ET accelerograms with longer durations or higher intensities should be generated to cover entire return periods of interest. The accelerograms with duration of 40 seconds seem to be appropriate for this purpose.

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