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Application of rigid-perfectly plastic spectra in improved seismic response assessment by Endurance Time method

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A B S T R A C T

The Endurance Time (ET) method is a dynamic analysis procedure in which structures are subjected to predesigned accelerograms that increase their intensity in time. The main advantage of the ET method over the standard time-history analysis, which uses ground motions as excitation, is its reduced computational effort. In this paper, the nonlinear rigid-perfectly plastic (RPP) spectra, instead of linear elastic spectra, are used to correlate the seismic hazard return period and the time in the ET analysis. Several elastic-perfectly plastic SDOF systems as well as two three-story steel frames—namely a moment-resisting frame and a frame equipped with friction dampers—are analyzed. The response curves obtained by this procedure are compared with the ones obtained by implementing nonlinear time-history analysis. Twenty-two recorded ground motions, which are scaled to multiple intensity levels, are employed to develop the response curves in the time-history method. The results suggest that applying the RPP spectra as the intensity measure is more appropriate for the intensity levels corresponding to large return periods, where the structure is expected to experience significant plastic deformations. However, for small return periods, where the structure experiences slight plastic deformations, elastic spectra provide an effective intensity measure.

1. Introduction

Among various methods of analysis that have been adopted by seismic codes for the analysis of structures subjected to earthquake loadings, the time-history analysis provides the most realistic prediction of structural behavior. However, the complexity and huge computational effort involved in this type of analysis has limited its widespread practical application. This drawback has motivated researchers during the past years to develop alternative analysis methods. These new methods are much less computationally intensive as compared to the time-history analysis; additionally, they can estimate the seismic demands with an acceptable degree of accuracy.

Within these methods, Endurance Time (ET) is one of the promising approaches, introduced by Estekanchi et al. in 2004 [1]. This method is a time-history-based analysis procedure, in which the structure is subjected to a set of predesigned accelerograms that increase their intensity in time—referred to as the *ET excitation functions*. The excitation functions are generated in such a way that their response spectra increase in time; hence, the response of the structure under this kind of accelerogram gradually increases with time. The performance of the structure is estimated based on the time interval during which it can sustain the imposed dynamic excitation. By using a properly designed excitation function, this endurance can be correlated to the intensity level of ground motions that the structure can carry on. More details about the concept of the ET method, as well as the characteristics of the ET excitation functions, can be found in the literature [2].

The main advantage of the ET method over the regular time-history method is that it requires a small number of analyses. In the ET method, the structural responses at different excitation levels are obtained in a single time-history analysis, thereby significantly reducing the computational demand. Therefore, by using the ET method and adopting the concepts of performance-based design [3,4], the performance of a structure at various seismic hazard levels can be predicted using a single time-history analysis. The application of the ET method in the seismic performance assessment of steel frames has been studied by Hariri-Ardebili et al. [2] as well as Mirzaee and Estekanchi [5].

The results of the ET analysis are usually presented by increasing ET response curves. The ordinate at each time t corresponds to the maximum absolute value of the required engineering demand parameter in the time interval $[0,t]$ as given in Eq. (1):

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$$\Omega(P(t)) \equiv max(|P(\tau)|) \quad \tau \in [0, t] \tag{1}$$

In this equation, Ω is the *Max_Abs* operator as was defined above, and $P(t)$ is the desired response history of an engineering demand parameter such as interstory drift ratio, base shear, or other parameters of interest. The abscissa of an ET response curve is time, which is an indicator of the intensity in the ET analysis. Fig. 1(a) shows a typical ET response curve in which the maximum interstory drift is used as the demand parameter. ET curves are usually serrated, due to the statistical characteristics and dispersion of the results of the ET analysis in the nonlinear range. Sometimes the response value does not pass the maximum value experienced before in a time interval and, therefore, the resulting ET curve has a constant value in that interval. In order to get more accurate and consistent ET curves, Estekanchi et al. [6] recommended using the average of the results from three ET excitation functions.

In a study accomplished by Mirzaee et al. [7], the correlation between time—as an indicator of the intensity in ET analysis—and seismic hazard return period was investigated. Substituting the time with the return period increases the readability and efficiency of response curves and can considerably improve the presentation of the results of the ET analysis. They used the elastic response spectrum defined in ASCE41-06 as an intermediate criterion [8]. The response spectrum (S_a) for any hazard level can be expressed as a function of the return period (R) and the period of free vibration (T). Acquiring the inverse of this function with respect to variable R, the return period can be expressed as a function of T and S_a (Eq. (2)):

$$R = f(S_a, T) \tag{2}$$

where R is the return period, and f is a function that relates the return period to S_a and T. Apart from this, the response spectrum for the ET excitation function is defined as:

$$S_a(T, t) = \max(|a(\tau)|) \quad \tau \in [0, t] \tag{3}$$

where T is the period of free vibration, t is time, and a is acceleration. In view of Eqs. (2) and (3), it turns out that the seismic hazard return period can be expressed as a function of T and t (Eq. (4)):

$$R = f(S_a(T, t), T) = h(T, t) \tag{4}$$

where h is a function that relates the return period to T and t. Since the establishment of an explicit formulation for this function is not straightforward, they developed a matrix form for the return period where for each period of vibration (T) and each ET time (t), a particular return period was specified.

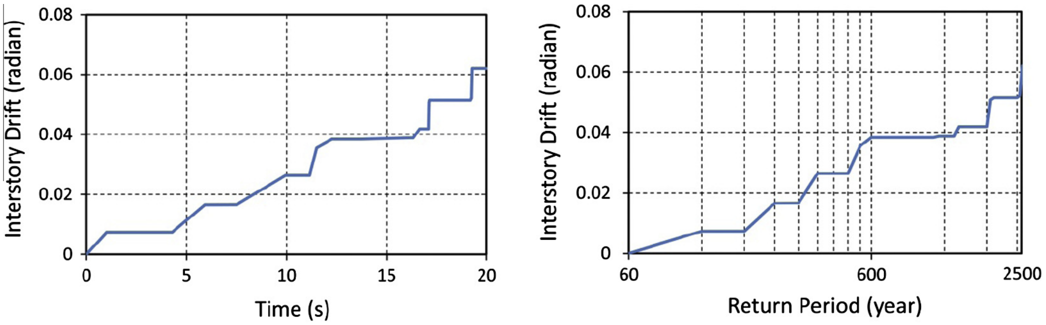
Applying Eq. (4), the abscissa of response curves, originally expressed by time (see Fig. 1(a)), can be replaced with the return period (R). A sample response curve obtained in such a manner is illustrated in Fig. 1(b), where the return period axis is displayed in a logarithmic scale. The ET time at which Eq. (4) holds is referred to as the *equivalent time* corresponding to return period R and period of free vibration T.

Estekanchi et al. [9] studied the results of the ET analysis in the estimation of the maximum interstory drift of the frames with elastic-perfectly plastic (EPP) material model and compared them with the results of time-history analysis, using ground motions. It was shown that in the frames which experience a linear behavior, the results of ground motions match the results of the ET analysis more closely. However, in the frames which experience large nonlinear deformations, the difference between the results increases, and the ET method gives unreliable estimations. It is believed that this inconsistency can be alleviated by using a more appropriate intensity measure [10,11] in correlating the ET time and the return period.

The basic philosophy of the modern earthquake resistant design procedures is to achieve a reliable structural performance while maintaining an economical design. This goal is achieved by ensuring energy dissipation capabilities under strong ground motions [12,13]. Such energy dissipation is usually attained through high levels of plastic deformation in certain specially designed elements, namely displacement-controlled elements, while elastic behavior is ensured in other structural members, namely force-controlled members. Regarding this design philosophy, the improvement of the ET method in the prediction of the maximum response of structures that experience large nonlinear deformations is necessary, which is the main purpose of this paper.

The key idea is that, if elastic deformations become relatively insignificant (e.g. at large deformation levels), rigid-perfectly plastic (RPP) models rather than EPP models can be adopted to assess the structural response. Paglietti and Porcu [14] concluded that RPP single-degree-of-freedom (SDOF) systems can be used to evaluate the maximum plastic displacement of any EPP-SDOF system under strong earthquakes. Their study also introduced the idea of the so-called *RPP spectrum* defined as the relationship between a structural response parameter (such as peak structural displacement) and the plastic capacity of the RPP model. Such a spectrum is much easier to be developed than the EPP one and depends only on one parameter, namely the yield strength of the system over its own weight. Fan and Ji [15] remarked the same conclusions by applying a finite element program. Makris and Black [16] used a rigid-plastic model to study the response of ductile structures as well.

Domingues Costa et al. [17] presented a simplified seismic design method, based on the assumption that the dynamic response of the structures with large ductility capacity may be derived by neglecting the contribution of their elastic properties. Málaga-Chuquitaype et al. [18] demonstrated the applicability of response history analysis based on RPP models for the seismic assessment and design of steel buildings. They also indicated that such RPP models are able to predict global seismic demands with



(a) (b)

Fig. 1. Sample ET response curve with horizontal axis in (a) time, and (b) return period.