A state-of-knowledge review on the Endurance Time Method

H. E. Estekanchi¹, A. Vafai², G. Ahmadi³, M. Mashayekhi¹, M. Harati⁴ and S. A. Mirfarhadi¹

Abstract

Endurance time method is a time history dynamic analysis in which structures are subjected to predesigned intensifying excitations. This method provides a tool for response prediction that correlates structural responses to the intensity of earthquakes with a considerably less computational demand as compared to conventional time history analysis. The endurance time method is being used in different areas of earthquake engineering such as performance-based assessment and design, life-cycle cost-based design, value-based design, seismic safety, seismic assessment, and multicomponent seismic analysis. Successful implementation of the endurance time method heavily relies on the quality of endurance time excitations. In this paper, a review of the endurance time method from conceptual development to its practical applications is provided. Different types of endurance time excitations are explained. Features related to the existing endurance time excitations are also presented. Particular attention was given to different applications of the endurance time method in the field of earthquake engineering.

Keyword: endurance time method, time history analysis, seismic response assessment, performance-based design, value-based seismic design.

1. Introduction

For seismic analysis of new or existing structures, seismic codes such as ASCE-07 (2010), rehabilitation provisions (e.g. ASCE/SEI 41-17 (2017) and FEMA-356 (2000)) typically recommend several frameworks, including Linear Static Procedure (LSP), Linear Dynamic Procedure (LDP), Nonlinear Static Procedure (NSP), and Nonlinear Dynamic Procedure (NDP). Each of these procedures has its own merits and advantages. For example, the LSP and NSP are fast among the other frameworks and can be readily used by practicing design engineers. However, they are not capable of satisfactorily incorporating the dynamic characteristics of ground motions, and therefore, do not account for the corresponding seismic effects in the structural responses. To this end, the LDP can include the effects of earthquakes in terms of their dynamic characteristics, but it is incapable of considering nonlinearities in the structure (Chopra 1995; Bozorgnia and Bertero 2004).

On the other hand, the NDP is capable of considering nonlinearities that arise both from materials and structural elements. While NDP is not as fast as linear frameworks and is a rather time-consuming process, it incorporates the dynamic nature of the earthquakes and is thus the most reliable framework in the field of earthquake and structural engineering. A NDP can be used when structures with complex behavior are to be examined for initial design or for structural retrofitting. Examples of the cases that

¹ Department of Civil Engineering, Sharif University of Technology, Tehran, Iran
² Department of Civil Engineering and Engineering Mechanics, The University of Arizona, Tucson, AZ, USA
³ Department of Mechanical and Aeronautical Engineering, Clarkson University, Potsdam, NY, USA
⁴ Department of Civil Engineering, University of Science and Culture, Rasht, Iran
justify the application of the NDP procedure include base-isolated buildings and structures equipped with vibration control devices.

Other frameworks, such as Cloud Analysis (CLA) and Incremental Dynamic Analysis (IDA), have also been introduced for examining the structural behavior through several seismic levels up to the point recognized as the collapse point of the structural system. The IDA framework (Vamvatsikos and Cornell 2002), known as the most comprehensive and reliable dynamic analysis to date, is one of those incremental dynamic procedures through which structures are subjected to a multitude of NDPs. In order to reduce the uncertainties associated with the results of this procedure, several appropriate earthquake ground motion records are first to be carefully selected. Then, each ground motion record is scaled from a relatively lower intensity measure (IM) up to a level that may cause a complete collapse or dynamic instability for the considered structure. The IM is typically chosen to be the spectral acceleration of the records at a specific structural period of vibration. For one of those considered ground motions, and at each level of intensity measure (or at each scaled level of ground motion), the NDP should be used for the complete IDA analysis. Therefore, several NDPs should be performed for a selected earthquake since multiple seismic scaling levels are used in this framework. Therefore, the IDA procedure is too time-consuming for most practical engineering design routines.

Endurance time method is a rather fast incremental-based dynamic time history analysis in which structures are subjected to preselected intensifying base acceleration loading. This method offers structural response predictions in terms of the relationship between engineering demand parameters (EDPs) and intensity measures (IMs). Engineering demand parameter describes structural responses while intensity measures are related to the intensity of earthquakes at different seismic levels. In the ET method, a single time history analysis provides performance status of the structure for a continuous range of IMs while computational outputs of the conventional time history analysis are only valid for a particular IM level. In fact, structural responses at several levels of intensity measures, as it is provided by an IDA, are covered by the ET method using a minimal number of analyses (typically about three).

In the present study, a review of recent advances in the development of the endurance time method is presented. The basic concept of the ET method is described, and particular attention is given to the generation techniques of endurance time excitations. It is emphasized that the reliability of the ET method results depends on the quality and properties of the applied endurance time excitations. The important features of the available endurance time excitations are presented and discussed. Finally, applications of the ET method in different areas of earthquake engineering is explained.

2. Endurance Time Method Concept

The basic concept of the ET method is inspired by the so-call stress test in medical science. In this exercise test, patients run on a treadmill while the speed and slope of treadmill increase and their health indicators such as blood pressure and heart signals are monitored during the test. Doctors judge the patient’s well-being based on recorded indicators. The exercise test is relatively simple as compared to the complexity status of human bodies. Considering the fact that the most complicated structures do not have the complexity of human bodies, this motivated the concept of “Endurance Time” framework for evaluating the seismic performance of structures (Estekanchi et al. 2004). In this approach, the structures are exposed to increasing earthquake demands.

The concept of endurance time method is illustrated by a hypothetical shake table test. In this example, the objective is to determine the performance of three structures under earthquake excitation. These
structures are fixed on a shaking table as shown in Figure 1 and are subjected to an intensifying random excitation.

![Figure 1](image1.png)

**Figure 1.** The concept of the Endurance Time method for determining the seismic endurance

A sample of such intensifying ET excitations is displayed in Figure 2. The increasing trend of ET acceleration functions gives a new meaning to the time in the ET method; time in the ET method reflects intensity measures (IMs) of earthquake motions. At the beginning of endurance time excitations, the intensity of motions is low and hence endurance time excitations at initial time intervals are representative of low earthquake ground motions. At the middle time interval of endurance time excitations, the intensity of motions is moderate and therefore excitations are representative of moderate earthquakes. At the end of endurance time excitations, the intensity is high and ET excitations are representative of severe earthquakes. In other words, time is an intensity indicator in the endurance time method.

![Figure 2](image2.png)

**Figure 2.** A sample of intensifying ET excitation, the ETA20f01(Estekanchi 2019)
As the amplitude of the ET excitation increases in time, the structures are expected to move gradually from an elastic response status to a nonlinear (plastic) behavior and they finally collapse. Damage indicators such as maximum inter-story drift ratio of these structures are monitored during the test and reported through an endurance time curve. A sample endurance time analysis curve relating maximum absolute response parameter and the time is depicted in Figure 3. In this figure, the vertical axis of these ET curves can be any measurable engineering demand parameter, e.g. here the \( V/V_{\text{Design}} \) denotes to the relative limit state of a damage indicator for collapse prevention (CP) status of the considered structures. The values related to the vertical axis of ET curves are computed as follow:

\[
\Omega(f(t)) = \max(|f(\tau)|) \quad 0 \leq \tau \leq t
\]  

(1)

In the above equation, \( \Omega \) is the maximum response in the time span \([0,t]\) and \(f\) is the response history as a function of time. For example, any damage indicators such as maximum drift, base shear and plastic rotation can be considered as response-related parameters. In view of Equation 1, if maximum inter-story drift is taken as a response parameter, \( \Omega \) is the maximum drift ratio that the structure experienced during a time interval from start up to time \( t \). So maximum seismic demand of structures can be found for different intensity levels, which is a function of intensity measure itself since time and intensity measures are correlated to each other in ET method. Hence, structural responses at different individual seismic intensity levels can be determined in a single time history analysis within the endurance time framework, reducing the computational demands encountered in such analyses.

![Figure 3. Increasing response plot (or ET curve) of three structures, A, B and C](image)

As can be seen from Figures 1 and 3, structure A failed first and hence has shown the minimum seismic resilience among the other structural models being considered in this hypothetical shake table experiment. On the other hand, structure B failed after structure A and C, therefore, structure B has shown the highest seismic endurance (resilience). In addition to ranking these structures, the damage capacity of the buildings can be also well quantified. In this case, Figure 3 demonstrates a damage indicator (the relative CP limit state for each structural system or the \( V/V_{\text{Design}} \)) versus analysis time for these above-mentioned models, which is obtained through the hypothesized shake table test in the endurance time framework. It displays that structure A, B and C collapse at 8sec, 18sec, and 13sec, respectively. In fact, the damage capacity of a specific structure can be defined by the maximum time that the structure can endure the
input ET excitation. So, if these three structures are designed for the same seismic design target, structure B shows that it has the best design in term of seismic lateral strength. Overall, the seismic performance of structures is quantified by the endurance time (or the time endured).

The interesting point is that the deductions made about aforementioned ET curves are merely according to a rather simple but direct observation we make on the dynamic behavior of each individual structure existed beside the other models selected to be comparatively evaluated. In this way, it is not essential to know much about the dynamic behavior of the considered structures beforehand because ET method can act as a blind predictor and demonstrate the seismic performance of selected structures on the basis of the time they endure. Besides, if input excitations are forced to be calibrated such that they fulfill the code design requirements, a minimum acceptable target endurance time, as explained in the next section, can be determined for a considered seismic level. Therefore, seismic performance of a specific structure in a desired seismic level can be simply evaluated by comparing the demand endurance time versus the target time that is computed at the intensity level of interest.

3. Generation of Endurance Time Excitations

Successful implementation of the ET method depends on the quality of the endurance time excitation functions (ETEFs). Simulating more accurate endurance time excitations is a fundamental step in improving the efficiency of the ET method. Endurance time excitations must be generated so that they predict real ground motion effects. Compatibility with real ground motions and intensification are two main features of endurance time excitations that must be considered in the simulation. The concept of response spectra can be used to simulate ET acceleration functions and provides a good starting point (Estekanchi et al 2004). In fact, response spectra of the original endurance time excitations are set to increase with time while they remain consistent with the design spectra or the response spectra of real ground motions. One simple approach is to consider a target spectrum and an intensifying function; therefore, response spectra of the endurance time excitation can be computed by multiplication of the target spectrum and the intensifying function. In this way, the shape of acceleration spectra of endurance time excitations will be the same at all times and only the amplitude of acceleration spectra changes. This is because in this approach, intensifying ET accelerations will be only a function of time, where the target spectrum may be the average acceleration spectra of a ground motion suite or a design code acceleration spectrum, e.g. the design spectrum of ASCE07 (2010). Acceleration and displacement spectra of endurance time excitations can be expressed as follows:

\[
S_{at}(T,t) = g(t) \times S_{at}(T) \tag{2}
\]

\[
S_{ut}(T,t) = g(t) \times S_{ut}(T) \tag{3}
\]

where \(S_{at}(T,t)\) and \(S_{ut}(T,t)\) are target acceleration and displacement response spectra of endurance time excitations at time \(t\), and structural period at first vibration mode, \(T\). \(S_{at}(T)\) and \(S_{ut}(T)\) are the corresponding target acceleration and displacement spectra. In this case, \(g(t)\) is the intensifying function which is an ascending function of time—for instance, an ascending linear or exponential function. Whereas there is no limitation for intensifying function except for ascending condition, in current endurance time excitations, linear and exponential intensifying functions have been adopted. In the generation of early endurance time excitations, linear profile was employed. The overarching advantage of this form was its simplicity. When using linear profile, it can be simply expected that acceleration
spectrum at 20sec is 2 times the corresponding acceleration spectrum at 10sec. Similarly, an acceleration spectrum at 5sec is half of the corresponding acceleration spectrum at 10sec. Other intensification profiles can also be applied. For example, by introducing exponential profile a cumulative absolute velocity (CAV) consistency for production of ET excitations can be achieved (Mashayekhi et al. 2018a). The linear and exponential intensification profile forms can be given as follows:

\[ g(t) = \frac{t}{t_{\text{target}}} \]  \hspace{1cm} (4)

\[ g(t) = b \tanh(\gamma t)e^{-\alpha t} \]  \hspace{1cm} (5)

where \( t_{\text{target}} \) is the time at which endurance time excitations are supposed to produce the target acceleration spectrum. For brevity, \( t_{\text{target}} \) is called \textit{target time}. Unlike the linear form of such functions—the \( g(t) \) in equations 4 and 5—that the target time is directly included in the formula, in the corresponding exponential form of such an intensifying function, the target is adjusted through assigning values to constant parameters \( b, \gamma \) and \( \alpha \). It should be mentioned that a target time equal to 10sec was usually used at the early stage of the ET method development, which was based on engineering judgment. In the production of 40sec CAV-consistent endurance time excitations, the target time is adjusted to be equal to 20sec.

A sample endurance time excitation is shown in Figure (a). This excitation is selected from “ETA20in” series of endurance time excitations (Estekanchi 2019). Different series of endurance time excitations and their respective characteristics will be discussed later (in Section 4). From Figure (b) in which acceleration spectra of ETA20inx01 are depicted, it can be seen that the acceleration spectrum at the target time equal to \( t=20\text{sec} \) is twice the acceleration spectrum at \( t=10\text{sec} \). In addition, the acceleration spectrum at \( t=15\text{sec} \) is 1.5 times the acceleration spectrum at \( t=10\text{sec} \). Similarly, and as said before, the acceleration spectrum at \( t=5\text{sec} \) is half of the acceleration spectrum at \( t=10\text{sec} \). In this way and as can be seen from Figure 4, a single ET excitation record is simulated in a way that it produces different predefined target spectra at different relevant target times.
Because of the complexity of the requirements for ET excitations, optimization techniques are employed to simulate endurance time excitations. In the optimization context, appropriate objective functions should be defined. A simple and effective objective function for simulating endurance time excitations can be formed as follows:

\[
F(a_g) = \int_{T_{\text{min}}}^{T_{\text{max}}} \int_{t_{\text{max}}}^{t_{\text{max}}} \left( \left[ S_a(T,t) - S_{a_T}(T,t) \right]^2 + \alpha \left[ S_u(T,t) - S_{u_T}(T,t) \right]^2 \right) dt \, dT
\]

where \(a_g(t)\) is the input of this objective function, which is the acceleration time history of endurance time excitations, \(S_a(T,t)\) and \(S_{a_T}(T,t)\) are acceleration and displacement spectra of endurance time excitations at period \(T\) and time \(t\). \(T_{\text{min}}\) and \(T_{\text{max}}\) are the minimum and maximum considered periods. In addition, \(t_{\text{max}}\) is the duration of endurance time excitations for which ET records are to be simulated. \(S_u(T,t)\) and \(S_{u_T}(T,t)\) are, respectively, acceleration and displacement spectra of the endurance time excitation at period \(T\) and
time $t$. Acceleration and displacement spectra of the endurance time excitations are calculated through following equations:

$$S_a(T,t) = \max \left( |\ddot{x}(\tau) + g(\tau)| \right) \quad 0 \leq \tau \leq t$$

$$S_x(T,t) = \max \left( |\dot{x}(\tau)| \right) \quad 0 \leq \tau \leq t$$

where $x(\tau)$ and $\dot{x}(\tau)$ are displacement and acceleration time history of the single degree of freedom system with period $T$ at time $\tau$. In the objective function of Equation (6), acceleration and displacement spectra are typically considered. The constant $\alpha$ is a factor which normalizes and balances the relative weight of acceleration and displacement residuals in the objective function. In this objective function, residuals are computed in an absolute way while they could be quantified in a relative way too. Consequently, considering dynamic characteristics, the type of calculating residuals, values of $T_{\text{max}}$, $T_{\text{min}}$, and $t_{\text{max}}$, and intensifying functions diversify definitions of ET objective function for simulating endurance time excitations. Other objective functions rather than the one mentioned in equation (1) can be formed to simulate endurance time excitations. For different and more advanced generations of ET excitations, diverse dynamic characteristics were incorporated in the relevant objective functions. Although the recent generations of ET excitations are based on a set of quite complicated objective functions, more studies are still required to add other dynamic characteristics for simulation of more effective and reliable excitations.

Optimization algorithms are employed to solve equations which are represented by objective functions, where they aim to find values of optimization variables in a way that a minimum objective function value can be eventually reached. There are various ways to define optimization variables in the simulation problem of endurance time excitations. The common way of defining optimization variables in simulating endurance time excitations is using acceleration data points of endurance time excitations as unknown parameters. The main benefit of this selection of optimization variables, which also called time domain-space, is its simplicity and straightforwardness that comes from the fact that defining variables do not need signal decomposition. This is in contrast to other variable definitions that are based on signal decompositions. Another more effective way for defining variable definition is to use coefficients of discrete wavelet transform (DWT) (Newland 1993). Wavelet transform decompose a signal into its frequency- and time-domain. The main differences between Fourier transform and DWT is that frequency changes in time cannot be neatly captured by Fourier analysis. Mashayekhi et al. (2018b, 2019b) investigated a new optimization space, composed of discrete wavelet coefficients, for simulating endurance time excitation functions. They showed that filtered DWT coefficients create excitations with less objective function values and less standard deviations of simulated excitations as compared to the time-domain and DWT space. Simulating long-time endurance time excitations, e.g. 40second endurance time excitations, is more complicated than simulating normal-time endurance time excitations, e.g. 20 second endurance time excitations, due to the existence of a large number of optimization variables. In this case, Mashayekhi et al. (2018c) introduced another optimization space—which is called increasing sine function—for simulation of long-duration endurance time excitations. Further researches are still required in order to find more efficient optimization spaces for simulation of such ET excitations.

There are numerous optimization algorithms to solve the optimization problem described for simulation of ET excitations. However, most existing endurance time excitations are simulated by classical optimization algorithms—for example, the trust-region-reflective method (Nozari and Estekanchi 2011) is widely used. The main drawback of such classical optimization algorithms is that they may be trapped in
local minima. On the other hand, described objective functions of endurance time excitation problem seem to have many local optima due to its dynamic nature and the presence of many decision variables (typically in the order of 1000 decision variables or more). This obstacle can partly be overcome by using evolutionary algorithms, so further studies focusing to find appropriate evolutionary algorithms for the simulation of endurance time excitations may be an essential need. Many evolutionary algorithms have been developed to mimic natural process to solve optimization problems such as genetic algorithm (GA), particle swarm optimization (PSO), ant colony optimization (ACO), and imperialist competitive algorithm (ICA). Each of these evolutionary algorithms has several parameters that have to be calibrated prior to its implementation in a specific problem. Mashayekhi et al. (2019c) employed imperialist competitive algorithm (or ICA) in simulating endurance time excitations. They showed that better endurance time excitations are achieved by their proposed ICA-based evolutionary algorithm. However, the required computational time is increased by a factor of about 26 times in the proposed algorithm. This demanding computational time poses a major obstacle in using evolutionary algorithms to simulate endurance time excitations when nonlinear responses are also included in the objective function (Kaveh et al. 2013). Different evolutionary optimization algorithms and the hybridization of classical and evolutionary optimization algorithms have to be examined to find a better optimization framework for simulating endurance time excitations, which essentially needs further studies and comparisons between outputs obtained from such parametric studies.

Five generations of endurance time excitations have been developed so far for the ET method, where the general features of the excitations within each generation are almost identical. The distinguishing characteristics belonging to each of the five generations are as follows:

- **The first generation of ETEFs**: The theory of random vibration was employed to simulate the excitations of this generation and they were only produced to illustrate the concept of the ET method, not for its use in practical applications. Consequently, these type of excitations have not been used in any study except the original work by Estekanchi et al. (2004).

- **The second generation of ETEFs**: The second generation of ET records (Nozari and Estekanchi 2011; Valamanesh et al. 2010) provided usable ET excitation functions for practical applications due to the acceptable accuracy of the simulated excitations. It was the first time that optimization techniques were employed in simulating endurance time excitations. In addition, the linear response spectrum was included in the objective function. Classical optimization algorithms in time-domain are employed to simulate these excitations. It was later demonstrated that incorporating long periods in the objective function calculation improves the efficiency of these excitations in nonlinear response assessment despite the fact that nonlinear responses are not considered in the generation process. Series “a”, “b”, “c”, “d”, “e”, “f”, “g” and “h” are the ET records or subcategories of the second generation of ETEFs. But the long periods are only included to simulate some cases such as “d”, “e”, “f”, “g” and “h” series. Endurance time excitations of this series are available and reported in a website by Estekanchi (2019).

- **The third generation of ETEFs**: in this generation, nonlinear displacement responses are included in the generation process. The series “en”, “jn” and “in” belong to this generation. The letter “n” in the name of these series implies that nonlinear responses are considered in the simulation process. The series “in” and “jn” have three component time histories and can be employed in three component analysis (Valamanesh and Estekanchi 2014). Endurance time excitations of this series are available via Estekanchi (2019).
• **The fourth generation of ETEFs**: ground motion duration may have a significant impact on the structural responses (Hancock and Bommer 2007, Harati et al. 2019; Mashayekhi et al. (2019d, 2019e)), motion duration consistency is directly included and imposed for simulation of the fourth generation excitations. Prior to this generation, duration had not been incorporated in the generation process of ETEFs. In this regard, Mashayekhi et al. (2018a) included cumulative absolute velocity (CAV) in the generation process. They produced series “lc” in their study. This series is also available through the ET website provided by Estekanchi (2019).

• **The fifth generation of ETEFs**: in the fifth generation of endurance time excitations, damage consistency is included and implemented in the generation process. Mashayekhi et al. (2018d) included hysteretic energy compatibility in the simulation process. Because damages induced on a structure are a function of both maximum displacement and absorbed hysteretic energy, incorporating hysteretic energy in the simulation process implies that damage consistency is satisfied for ET excitations of this generation. They produced series “kd” and made the respective excitations available through Estekanchi (2019).

### 4. Seismic Response Assessment by Endurance Time Method

The main purpose of ET method implementation is a reliable prediction of the engineering demand parameters (EDPs). In this regard, a great amount of efforts within the past decade has been made to assess the applicability of the ET method in structural seismic response prediction. This section reviews the research efforts in the seismic response assessment by the ET method. In this regard, previous studies concerning the structural type are categorized into two groups: building structures and non-building structures. The related studies are provided in following sub-sections.

#### 4.1. Assessment of Building Structures

Initial studies employed a simplified structural mathematical model to assess the response of structures. As the first study, Estekanchi et al. (2007) employed the ET method in response assessment of moment and braced steel frames with linear material behavior. They compared the EDPs of ET method with results of traditional equivalent static and response spectrum seismic analysis procedures. Moreover, Riahi et al. (2009) used the ET method in response assessment of the nonlinear single degree of freedom systems with different ductility factors, strength and damping ratios.

Next studies employed more realistic building structural models for the assessment of the ET method. Riahi and Estekanchi (2010) assessed the applicability of the ET method in the response estimation of steel moment frames in which the nonlinear characteristics of considered prototypes were incorporated by distributed plasticity models. In the study, the local and global demand parameters estimated by the ET method are compared with those obtained by two well-known procedures; static pushover analysis and nonlinear time history analysis. Moreover, in another study by Estekanchi et al. (2011), the validity of ET results has been confirmed for a set of material models, the model of elastic-perfectly plastic and models with stiffness deterioration and strength degradation. Also, Hariri-Ardbili et al. (2014) presented a state-of-the-art of ET method procedure for structural response estimation. Recently, Mashayekhi et al. (2018d, 2019a) assessed the last generation of ET excitation functions in response estimation of building structures. In this case, considerable improvement in response prediction of the ET method has been reported. They also show that the results obtained by ET method are quite comparable with the ones computed by IDA procedure (Vamvatsikos and Cornell 2002).
Additional studies have been employed the ET method in demand prediction of special structural systems. Estekanchi et al. (2011), Vaezi et al. (2014) as well as Foyouzat and Estekanchi (2016a, 2016b) utilized the ET method in response assessment of passively controlled structures by viscous dampers, metallic dampers and friction dampers, respectively. Estekanchi et al. (2018) employed the ET method in an assessment to discover the interaction of moment-resisting frames and shear walls in RC dual systems. Moreover, Bai et al. (2018) assessed the performance of steel plate shear wall (SPSW) system by the ET method.

The ET method has also been extended in the other application areas of time history analysis, which are all within the framework of the Performance-Based Earthquake Engineering (PBEE). For example, Valamanesh and Estekanchi (2013, 2014) extended the ET method in bi- and tri-directional seismic response analysis. Also, Mashayekhi et al. (2019a) worked on the ET method to estimate record-to-record variability in seismic response assessment. In such assessments, Bai et al. (2018) used the ET method for modelling a complex system like the one equipped with the soil-structure interaction. To show the capability of ET method in more complex building models, Estekanchi et al. (2008), as well as Maleki-Amin and Estekanchi (2018), developed the ET method further to estimate the Park-Ang damage index for a number of building structures. Moreover, Rahimi and Estekanchi (2015) and Tajmir Riahi et al. (2015) established a creative and novel collapse analysis procedure by the ET method.

4.2. Assessment of Non-Building Structures

The ET method was also employed in the performance assessment of non-building structures. Estekanchi and Alembagheri (2012) and Tavazo et al. (2012) hired the ET method in shell structures such as liquid storage tanks. In this case, they modeled the liquid-structure interaction in the finite-element model. Moreover, Valamanesh et al. (2011), Hariri-Ardebili and Mirzabozorg (2014) as well as Hariri-Ardebili and Saouma (2015) employed the ET method in response analysis of concrete gravity and arch dam structures. Also, Guo et al. (2017) used the ET method in multi-span highway bridge, where they modeled the pounding effect of bridge basement. Since the finite element modelling of aforementioned structures results in a considerably large number of solving equations, the ET method will be very efficient compared to the traditional time-history analysis. For this reason, Hasani et al. (2017) and Dastan Diznab et al. (2019) utilized the ET method to reduce a demanding computational time required for the analysis of offshore structures.

As a significant contribution, Zeinoddini et al. (2012) extended the concept of the ET method to marine engineering. They introduced the Endurance Wave Analysis (EWA) as a novel approach for nonlinear dynamic assessment of offshore structures subjected to sea waves. The wave analysis is similar to earthquake response analysis since the wave loads have dynamic and probabilistic nature and extreme value of demands is the interest of designers. In the EWA method, the offshore structure is subjected to an intensifying wave function. The wave height and its spectral density increase over time and the damage indices is monitored over time. In this regard, additional studies investigated and developed the concept of EWA analysis (Diznab et al. 2014; Jahanmard et al. (2017); Zeinoddini et al. (2018)).

5. Seismic Design by ET Method

The ET method is a robust platform for seismic response analysis of infrastructures. Ideally, this tool can be used not only for the seismic response assessment but also for cases relating to the structural design. In this regard, in parallel to developing the ET procedure for response assessment, various efforts have been made to develop ET-based frameworks for structural design. Previous studies concerning the design
approach using the ET method are categorized into three groups for reviewing in this study: performance-based, life cycle-based and value-based design. The relevant review of the related studies is provided in the following parts.

5.1. Performance-Based Design
Performance-based design (PBD) procedure (ASCE/SEI 41-17 (2017)) has been developed as an enhanced alternative to the conventional code-based procedures offered by ASCE-07 (2010). In the performance-based procedure, the actual performance of structures is evaluated by employing a more realistic mathematical model and a more precise response assessment tool. Moreover, using the PBD framework the seismic performance of the structures can be controlled under multi-level of earthquake hazards. In this case, pushover procedure and time history dynamic analysis are two traditional methods for checking the design requirements. However, low accuracy of pushover procedure and high computational demand of time history analysis motivate researchers to develop alternatives for the available response analysis tools (Hariri-Ardebili et al. 2014).

In this regard, the ET method is an efficient alternative considering its acceptable accuracy and low required computational demand. Mirzaee et al. (2010) developed a practical procedure for the application of the ET method in the performance-based design of structures. They proposed a method to find an equivalent ET target time for each arbitrary seismic hazard level. For instance, Figure displays the target and existing performance curves of a hypothetical building. In this case, this building meets the Immediate Occupancy (IO) and Life Safety (LS) limit states, but it fails to satisfy the Collapse Prevention (CP) criterion. In another study, the same authors proposed a continuous mapping between ET excitation time and seismic hazard return period (Mirzaee et al. 2012). This mapping paved the way for the presentation of the ET response curve to be consistent with the median response curve computed by IDA (Vamvatsikos and Cornell 2002). Moreover, based on the proposed framework, Mirzaee and Estekanchi (2015) developed a PBD-based retrofitting procedure by the ET method.

It is of the essence to note that finding an economical structural design which meets the desired performance objectives needs a high number of try and error, and consequently, considerable computational time would be demanded in case conventional time history procedures are employed. However, this issue can be overcome if the ET method is utilized as an analytical framework. In this regard, Estekanchi and Basim (2011) presented a performance-based optimum design of passively controlled structures by the ET method. They optimized the location function of damper placement and design properties of existing viscous dampers.
5.2. Life-Cycle Cost Based Design

Some deficiencies in the current performance-based seismic design procedure encouraged researchers to develop a more improved performance-based design framework (FEMA 445 (2006)). In the current or conventional PBD procedure, the seismic performance is expressed in a discrete and qualitative manner. The performance of non-structural components is not assessed and the level of reliability is not clear for the designer (Hamburger et al. 2012). In this regard, the next-generation performance-based design has been planned to develop in ATC-58 project. In the new design framework, the performance of an individual building is expressed with continuous and quantitative measures. These metrics are comprised of new definitions that include repair cost, time of occupancy interruption, injuries and casualties. Moreover, the procedure explicitly incorporates the performance of non-structural components and potential uncertainties. As a result, the next-generation performance-based design has been directed to Life-Cycle Cost (LCC) based design (Frangopol and Soliman 2016). In the LCC-based design, the LCC includes the quantitative consequences as well as the construction considerations. So, the structure designer should find a balance between the acceptable risk of seismic consequences and the construction costs (Matta 2017).

The design framework by the ET method has also been upgraded to incorporate the LCC as a design objective. Basim and Estekanchi (2015) developed an optimum LCC-based structural design procedure. In their proposed procedure, for each design alternative, the ET method estimates the engineering demand parameters at multi-level of seismic hazards. Then, the LCC including the construction cost and seismic consequences is evaluated based on the structural properties and results of the ET method, respectively. The try and error procedure will be continued until the solution is converged to the best design. It is worthwhile to mention that since the LCC-based seismic design requires the EDPs at much more hazard levels than the PBD procedure, the efficiency of the ET method implementation would be more pronounced in this case because the ET method predicts the structural responses as a continuous function of seismic intensity by default.

Figure 5. Target performance and existing performance curves (Mirzaee et al. 2010)
5.3. Value Based Design

As the most recent developed design framework by the ET method, Basim and Estekanchi (2014) as well as Basim et al. (2016) introduced a Value-based Seismic Design (VBSD) concept. In their approach, the “value” parameter is considered as a more general description of design target. The value parameter can incorporate the financial economic value of seismic losses such as structural damages, damage to building contents, losses due to occupancy interruption and casualties. They employed this developed value-based framework for the design of a five-story steel moment frame by the ET method.

Mirfarhadi and Estekanchi (2019) have recently improved the framework of existing value-based design. The value parameter is extended to incorporate a more comprehensive set of decision indicators available in the literature as listed in Figure 6. In the new framework, first, the significant decision indicators are selected and then all of the selected indicators are evaluated and weighted using a decision-making tool. The structure is designed in a way that the maximum total value is gained, where an optimization algorithm is employed to find the optimum solution. Considering the fact that optimization procedure demands a high number of performance evaluations, employment of conventional time history analysis such as IDA surely leads to an unpractical design process. Nevertheless, the ET method paves the way for a straightforward and efficient structural design.

It is interesting to note that the value-based design framework, based on Figure 6, will be equivalent to traditional performance-based structural design (e.g. Estekanchi and Basim 2011) if the performance-based criteria are only selected as a decision indicator. Likewise, if the risk of seismic consequences and construction consideration are only taken as decision indicators, the design process will be similar to LCC-based seismic design (e.g., Basim and Estekanchi 2015). In a similar way, Estekanchi et al. (2016) hired only the structural resilience as the desired decision indicator and proposed a framework of resilience-based seismic design by the ET method.

Figure 6. Extended framework of Value-based Design approach (Mirfarhadi and Estekanchi 2019)
6. Conclusion

Endurance time method is a time history dynamic analysis in which structures are exposed to predesigned intensifying acceleration time histories. This method can be employed as an alternative to conventional time history dynamic procedures such as incremental dynamic analysis. In this paper, the basic concept of the ET method was presented. The main core of the ET method is its endurance time excitations, where the reliability of the ET method results heavily relies on the quality and efficiency of these excitations. The generation process of these excitations was briefly explained, and features of existing endurance time excitations were presented. Besides, challenges in the production of endurance time excitations were also discussed. Afterwards, practical applications of the ET method in different areas of earthquake engineering were described briefly. In conclusion, this paper summarizes recent advances in the development of the endurance time method. Considering various aspects and potentials of the Endurance Time procedure, its application can be expected to become more popular among researchers and practitioners in near future.

7. References

ASCE/SEI 41-17. (2017). Seismic evaluation and retrofit of existing buildings (41-17). American Society of Civil Engineers: Reston, VA.

ASCE/SEI 7-10. (2010). Minimum design loads for building and other structures. American Society of Civil Engineers: Reston, VA.

Bai, J., Jin, S., & Ou, J. (2018). Seismic analysis and evaluation of SPSW structural systems by the ET method. Journal of Constructional Steel Research, 147, 444–456. https://doi.org/10.1016/j.jcsr.2018.05.007

Basim, M. C., & Estekanchi, H. E. (2014). Application of Endurance Time Method in Value Based Seismic Design of Structures. In Second European Conference on Earthquake Engineering and Seismology, August 25-29, 2014. Istanbul, Turkie.

Basim, M. C., & Estekanchi, H. E. (2015). Application of endurance time method in performance-based optimum design of structures. Structural Safety, 56, 52–67. https://doi.org/10.1016/j.strusafe.2015.05.005

Basim, M. C., Estekanchi, H. E., & Vafai, A. (2016). A Methodology for value based seismic design of structures. Scientia Iranica, 23(6), 2514–2527.

Bozorgnia, Y., & Bertero, V. v. (2004). Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering. CRC Press.

Chopra, A. K. (1995). Dynamics of structures: Theory and applications to earthquake engineering (4 edition). Pearson.

Dastan Diznab, M. A., Mehdigholi, H., & Seif, M. S. (2019). Seismic performance assessment of fixed offshore structures by endurance time method. Ships and Offshore Structures, 1–14.

Diznab, M. A. D., Mohajernassab, S., Seif, M. S., Tabeshpour, M. R., & Mehdigholi, H. (2014). Assessment of offshore structures under extreme wave conditions by Modified Endurance Wave Analysis. Marine Structures, 39, 50–69.

Estekanchi, H., & Basim, M. C. (2011). Optimal damper placement in steel frames by the Endurance
Time method. *The Structural Design of Tall and Special Buildings*, 20(5), 612–630.

Estekanchi, H. E., Valamanesh, V., & Vafai, A. (2007). Application of Endurance Time Method in Linear Seismic Analysis. *Engineering Structures*, 29(10), 2551–2562. https://doi.org/10.1016/j.engstruct.2007.01.009

Estekanchi, H.E. (2019). Endurance Time Method Website.

Estekanchi, H.E., Riahi, H. T., & Vafai, A. (2011). Application of endurance time method in seismic assessment of steel frames. *Engineering Structures*, 33(9), 2535–2546.

Estekanchi, H E, & Alembagheri, M. (2012). Seismic analysis of steel liquid storage tanks by Endurance Time method. *Thin-Walled Structures*, 50(1), 14–23.

Estekanchi, H E, Arjomandi, K., & Vafai, A. (2008). Estimating structural damage of steel moment frames by endurance time method. *Journal of Constructional Steel Research*, 64(2), 145–155.

Estekanchi, H E, Vafai, A., & Basim, M. C. (2016). Design and assessment of seismic resilient structures by the endurance time method. *Scientia Iranica. Transaction A, Civil Engineering*, 23(4).

Estekanchi, H E, Vafai, A., & Sadeghazar, M. (2004). Endurance Time Method for seismic analysis and design of structures. *Scientia Iranica*, 11(4), 361–370.

Estekanchi, Homayoon E., & Basim, M. C. (2011). Optimal damper placement in steel frames by the Endurance Time method. *The Structural Design of Tall and Special Buildings*, 20(5), 612–630.

Estekanchi, Homayoon E, Harati, M., & Mashayekhi, M. R. (2018). An investigation on the interaction of moment-resisting frames and shear walls in RC dual systems using endurance time method. *The Structural Design of Tall and Special Buildings*, 27(12), e1489.

FEMA-356. (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Washington D.C: Federal Emergency and Management Agency, Washington (DC).

FEMA 445. (2006). *Next-Generation Performance-Based Seismic Design Guidelines Program Plan for New and Existing Buildings*. Federal Emergency Management Agency: Washington, DC.

Foyouzat, M. A., & Estekanchi, H. E. (2016a). Application of rigid-perfectly plastic spectra in improved seismic response assessment by Endurance Time method. *Engineering Structures*, 111, 24–35. https://doi.org/10.1016/j.engstruct.2015.11.025

Foyouzat, M. A., & Estekanchi, H. E. (2016b). Evaluation of the EDR performance in seismic control of steel structures using endurance time method. *Scientia Iranica. Transaction A, Civil Engineering*, 23(3), 827.

Frangopol, D. M., & Soliman, M. (2016). Life-cycle of structural systems: recent achievements and future directions. *Structure and Infrastructure Engineering*, 12(1), 1–20. https://doi.org/10.1080/15732479.2014.999794

Guo, A., Shen, Y., Bai, J., & Li, H. (2017). Application of the endurance time method to the seismic analysis and evaluation of highway bridges considering pounding effects. *Engineering Structures*, 131, 220–230. https://doi.org/10.1016/j.engstruct.2016.11.009

Hamburger, R., Rojahn, C., Heintz, J., & Mahoney, M. (2012). FEMA P58: Next-generation building seismic performance assessment methodology. In *Proceedings of the 15th World Conference on Earthquake Engineering*. International Association for Earthquake Engineering, Lisbon, Portugal.

Hancock, J., & Bommer, J. J. (2007). Using spectral matched records to explore the influence of strong-
motion duration on inelastic structural response. *Soil Dynamics and Earthquake Engineering*, 27(4), 291–299. https://doi.org/10.1016/j.soildyn.2006.09.004

Harati, M., Mashayekhi, M., Ashoori Barmchi, M., & Estekanchi, H. E. (2019). Influence of ground motion duration on the structural response at multiple seismic levels. *Submitted for Publication*.

Hariri-Ardebili, M. A., & Mirzabozorg, H. (2014). Estimation of probable damages in arch dams subjected to strong ground motions using endurance time acceleration functions. *KSCE Journal of Civil Engineering*, 18(2), 574–586.

Hariri-Ardebili, M. A., & Saouma, V. (2015). Quantitative failure metric for gravity dams. *Earthquake Engineering & Structural Dynamics*, 44(3), 461–480.

Hariri-Ardebili, M. A., Sattar, S., & Estekanchi, H. E. (2014). Performance-Based seismic assessment of steel frames using Endurance Time analysis. *Engineering Structures*, 69, 216–234. https://doi.org/10.1016/j.engstruct.2014.03.019

Hasani, H., Golafshani, A. A., & Estekanchi, H. E. (2017). Seismic performance evaluation of jacket-type offshore platforms using endurance time method considering soil-pile-superstructure interaction. *Scientia Iranica*, 24(4), 1843–1854. https://doi.org/10.24200/sci.2017.4275

Jahanmard, V., Diznab, M. A. D., Mehdigholi, H., Tabeshpour, M. R., & Seif, M. S. (2017). Performance-based assessment of steel jacket platforms by wave endurance time method. *Ships and Offshore Structures*, 12(1), 32–42.

Kaveh, A., Kalateh-Ahani, M., & Estekanchi, H. E. (2013). Production of endurance time excitation functions: The CMA evolution strategy approach. 37(C), 383–394.

Maleki-Amin, M. J., & Estekanchi, H. E. (2018). Damage Estimation of Steel Moment-Resisting Frames by Endurance Time Method Using Damage-Based Target Time. *Journal of Earthquake Engineering*, 22(10), 1806–1835.

Mashayekhi, M., Estekanchi, H. E., Vafai, A., & Mirfarhadi, S. A. (2018). Simulation of Cumulative Absolute Velocity Consistent Endurance Time Excitations. *Journal of Earthquake Engineering*. https://doi.org/https://doi.org/10.1080/13632469.2018.1540371

Mashayekhi, M., Estekanchi, H. E., & Vafai, H. (2018). Simulation of Endurance Time excitations via wavelet transform. *Iranian Journal of Science and Technology - Transactions of Civil Engineering*.

Mashayekhi, M., Harati, M., Ashoori Barmchi, M., & Estekanchi, H. E. (2019). Introducing a response-based duration metric and its correlation with structural damages. *Submitted*.

Mashayekhi, M, Estekanchi, H. E., & Vafai, H. (2018). Simulation of Endurance Time Excitations Using Increasing Sine Functions. *International Journal of Optimization in Civil Engineering*, 9(1), 65–77.

Mashayekhi, M, Estekanchi, H. E., Vafai, H., & Mirfarhadi, S. A. (2018). Development of hysteretic energy compatible endurance time excitations and its application. *Engineering Structures*, 177(April), 753–769. https://doi.org/10.1016/j.engstruct.2018.09.089

Mashayekhi, M, Harati, M., & Estekanchi, H. E. (2019). Estimating the duration effects in structural responses by a new energy-cycle based parameter. *Submitted for Publication*.

Mashayekhi, Mohammadreza, Estekanchi, H. E., Vafai, A., & Mirfarhadi, S. A. (2018). Simulation of Cumulative Absolute Velocity Consistent Endurance Time Excitations. *Journal of Earthquake Engineering, in press*. https://doi.org/10.1080/13632469.2018.1540371

Mashayekhi, Mohammadreza, Estekanchi, H. E., Vafai, H., & Ahmadi, G. (2019). An evolutionary
optimization-based approach for simulation of endurance time load functions. *Engineering Optimization*, 1–20. https://doi.org/10.1080/0305215X.2019.1567724

Mashayekhi, Mohammadreza, Harati, M., & Estekanchi, H. E. (2019). On the optimal parameters of a PSO-based algorithm for simulation of Endurance Time Excitation Functions. *Submitted for Publication*.

Mashayekhi, Mohammadreza, Mirfarhadi, S. A., Estekanchi, H. E., & Vafai, H. (2019). Predicting probabilistic distribution functions of response parameters using the endurance time method. *The Structural Design of Tall and Special Buildings*, 28(1), e1553. https://doi.org/10.1002/tal.1553

Matta, E. (2017). Lifecycle cost optimization of tuned mass dampers for the seismic improvement of inelastic structures. *Earthquake Engineering & Structural Dynamics*, 47(3), 714–737. https://doi.org/10.1002/eqe.2987

Mirfarhadi, A., & Estekanchi, H. E. (2019). Value Based Seismic Design of Structures using Performance Assessment by the Endurance Time Method. *Submitted for Publication*.

Mirzaee, A., Estekanchi, H. E., & Vafai, A. (2012). Improved methodology for endurance time analysis: From time to seismic hazard return period. *Scientia Iranica*, 19(5), 1180–1187. https://doi.org/10.1016/j.j.scient.2012.06.023

Mirzaee, A, Estekanchi, H. E., & Vafai, A. (2010). Application of endurance time method in performance-based design of steel moment frames. *Scientia Iranica. Transaction A, Civil Engineering*, 17(6), 482.

Mirzaee, Amin, & Estekanchi, H. E. (2015). Performance-based seismic retrofitting of steel frames by the Endurance Time Method. *Earthquake Spectra*, 31(1), 383–402. https://doi.org/10.1193/081312EQS262M

Newland, D. . (1993). *Random Vibrations, Spectral and Wavelet Analysis* (3rd Editio). New York: Longman Scientific & Technical.

Nozari, A., & Estekanchi, H. E. (2011). Optimization of Endurance Time acceleration functions for seismic assessment of structures. *International Journal of Optimization in Civil Engineering*, 2, 257–277. Retrieved from http://ijoce.iust.ac.ir/files/site1/user_files_5jkw45/admin-A-10-1-15-72bfa80.pdf

Rahimi, E., & Estekanchi, H. E. (2015). Collapse assessment of steel moment frames using endurance time method. *Earthquake Engineering and Engineering Vibration*, 14(2), 347–360. https://doi.org/10.1007/s11803-015-0027-0

Riahi, H. T.; Estekanchi, H. E. and Vafai, A. (2009). Application of Endurance Time Method in Nonlinear Seismic Analysis of SDOF Systems. *Journal of Applied Sciences*, 9(10), 1817–1832.

Riahi, H. T., & Estekanchi, H. E. (2010). Seismic assessment of steel frames with the endurance time method. *Journal of Constructional Steel Research*, 66(6), 780–792. https://doi.org/10.1016/j.jcsr.2009.12.001

Tajmir Riahi, H., Amouzegar, H., & Falsafioun, M. (2015). Seismic Collapse Assessment of Reinforced Concrete Moment Frames Using Endurance Time Analysis. *The Structural Design of Tall and Special Buildings*, 24(4), 300–315.

Tavazo, H., Estekanchi, H. E., & Kaldi, P. (2012). Endurance time method in the linear seismic analysis of shell structures. *International Journal of Civil Engineering*, 10(3), 169–178.
Vaezi, D., Estekanchi, H. E., & Vafai, A. (2014). A parametric study of seismic response in anchored steel tanks with endurance time method. *Scientia Iranica*, 21(5), 1608–1619.

Valamanesh, V., & Estekanchi, H. E. (2013). Compatibility of the endurance time method with codified seismic analysis approaches on three-dimensional analysis of steel frames. *The Structural Design of Tall and Special Buildings*, 22(2), 144–164.

Valamanesh, V., & Estekanchi, H. E. (2014). Nonlinear seismic assessment of steel moment frames under bidirectional loading via Endurance Time method. *The Structural Design of Tall and Special Buildings*, 23(6), 442–462.

Valamanesh, V., Estekanchi, H. E., & Vafai, A. (2010). Characteristics of second generation endurance time acceleration functions. *Scientia Iranica*, 17(1), 53–61.

Valamanesh, V., Estekanchi, H. E., Vafai, A., & Ghaemian, M. (2011). Application of the endurance time method in seismic analysis of concrete gravity dams. *Scientia Iranica*, 18(3), 326–337.

Vamvatsikos, D., & Cornell, C. A. (2002). Incremental Dynamic Analysis. *Earthquake Engineering and Structural Dynamics*, 31(3), 491–514. https://doi.org/10.1002/eqe.141

Zeinoddini, M., Namin, Y. Y., Nikoo, H. M., Estekanchi, H., & Kimiaei, M. (2018). An EWA framework for the probabilistic-based structural integrity assessment of offshore platforms. *Marine Structures*, 59, 60–79.

Zeinoddini, M., Nikoo, H. M., & Estekanchi, H. (2012). Endurance Wave Analysis (EWA) and its application for assessment of offshore structures under extreme waves. *Applied Ocean Research*, 37, 98–110.