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Development of hysteretic energy compatible endurance time excitations and its application

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ABSTRACT

The aim of this study is to develop a new simulation procedure of endurance time excitations in which hysteretic energy compatibility is included. Existing methods for simulating excitations consider only amplitude and frequency content of motions and disregard parameters related to cumulative damage of structures. Hysteretic energy consistency, as a cumulative damage-related parameter, is included in the process. The proposed method is applied to generate new excitations. Efficiency of the proposed method is examined in two ways: (1) comparing damage spectra of simulated excitations with recorded ground motions; (2) applying simulated excitations in seismic assessment of three concrete special moment frame structures. Results show considerable compatibility of damage spectra with time history analysis as compared to previous excitations and, therefore, imply an improvement in the simulation process. In the second examination, engineering demand parameters in terms of maximum values and distribution of responses over structural height are predicted by the endurance time analysis and, then, are compared with incremental dynamic analysis results. These comparisons show that the endurance time method can successfully predict seismic demands of structures using the new generated excitations in comparison with existing ones. Finally, it is deduced from results that the proposed method can be employed as an alternative simulation approach for new applications.

1. Introduction

An issue at stake in *Performance-Based Earthquake Engineering* is accurate estimation of seismic demands [1,2]. To address this issue, a body of methods has been developed [3,4]. One reliable method for such an estimation is Incremental Dynamic Analysis (IDA), which offers thorough demand prediction by using a series of nonlinear dynamic analyses under multiple-scaled ground motions records (GMs) [3]. IDA has been utilized as a useful tool in performance-based earthquake engineering and, also, as a bridge between *intensity measure* (IM) and *engineering demand parameter* (EDP). Professional practice favors simpler methodology and sets out to avoid the complexities associated with record selection [5,6]. In addition, it prefers a large number of nonlinear dynamic analyses and massive computational time demands for IDA [7]. Several studies have intended to take a load of computational efforts off IDA [8]. For example, Azarbakht and Dolsek [9] proposed that their method could reduce the number of ground motion records required for a reliable prediction of seismic response by means of IDA.

With respect to the aforementioned challenges, Endurance Time (ET) method is proposed as an efficient tool for prediction of seismic demands. The ET method is a simple, yet accurate, dynamic analysis method which structures are subjected to pre-designed intensifying acceleration functions, otherwise known as Endurance Time Excitation Functions (ETEFs).

ET method was introduced by Estekanchi et al. [10] and has recently been used in several studies as a seismic assessment tool. For instance, Estekanchi et al. [11] investigated the application of ET method in linear seismic assessment; Basim and Estekanchi [12] applied ET method in performance-based optimum design; Hariri-Ardebili et al. [13] adopted ET method for performance-based seismic assessment of steel frames; Foyuzat and Estekanchi [14] used the ET method to analyze frames equipped with friction dampers. Results of these aforementioned studies demonstrate that the ET method has acceptably estimated dynamic responses obtained by conventional time history analysis.

ETEFs play a notable role in the ET method. ETEFs are acceleration time histories with increasing intensities, in which Intensity Measures (IMs) of multiple-scaled GMs are covered. In the ET method, the entire

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Nomenclature

a_g	acceleration time history of endurance time excitations
C	earthquake coefficient
dE_H	incremental hysteretic energy demand
D_{PA}	modified Park-Ang damage index
EDP	engineering demand parameter
$E_H^{target}(T,\mu)$	target hysteretic energy of GMs
$E_H(t,T,\mu)$	hysteretic energy of ETEFs at time t, period T, and ductility μ
$E_{HC}(t,T,\mu)$	target hysteretic energy of simulating ETEFs at time t, period T, and ductility μ
Err_1	error function 1
Err_2	error function 2
ET	endurance time
ETEF	endurance time excitation function
FEMA	federal emergency management agency
$F_{ETEF}(a_g)$	objective function of simulating ETEFs
f_s	restoring force
$F_y(T,\mu)$	minimum lateral strength capacity that a SDOF system with a period of T requires to avoid the average ductility ratio demands larger than μ
GM	ground motion
$h_{EH}(t,T,\mu)$	time-dependent variation function of target hysteretic energy demand
$h_u(t,T,\mu)$	variation function of target nonlinear response in time
IDA	incremental dynamic analysis
IM	intensity measure
IM_{ET} (edp)	ordinate of endurance time method curve
IM_{IDA} (edp)	ordinate of incremental dynamic analysis curve
k	linear stiffness
m	number of period points used for discretization of objective function
M_y	yield moment capacity
n	number of time points used for discretization of objective function
$NRes_{s_a}$	normalized residual associated with acceleration spectra
$NRes_{E_H}$	normalized residual associated with hysteretic energy
$NRes_{u_m}$	normalized residual associated with nonlinear displacement
r	number of ductility points used for discretization of objective function
RP	return period
$S_a^{target}(T)$	target acceleration spectra
$S_a(t,T)$	acceleration spectra of ETEFs at time t and period T
$S_{aC}(t,T)$	target acceleration spectra of simulating ETEFs at time t and period T
SDOF	single degree of freedom
T	period
t	time
t_{target}	target time
T_{max}	maximum considered period in simulating endurance time excitations
t_{max}	duration of endurance time excitations
$u_m(t,T,\mu)$	nonlinear displacement of ETEFs at time t, period T, and ductility μ
$u_{mC}(t,T,\mu)$	target nonlinear displacement of ETEFs at time t, period T, and ductility μ
$u(\tau)$	displacement response of nonlinear SDOF subjected to ETEF
$\dot{u}(\tau)$	velocity response of nonlinear SDOF subjected to ETEF
$\ddot{u}(\tau)$	relative acceleration response of SDOF subjected to ETEF
α_{E_H}	weight factor of hysteretic energy in objective function
α_{u_m}	weight factor of nonlinear displacement in objective function
β	model parameter of modified Park-Ang damage index
θ_m	member-end rotation
θ_r	recoverable rotation
θ_u	ultimate rotation
λ	scale factor
μ	ductility ratio
μ_{max}	maximum considered ductility ration in simulating ETEFs
ζ	damping ratio
τ	time

IMs are continuously covered by any single time history of ETEF; consequently, the need to scale GMs for a multitude of times is obviated. This substantially reduces the time required for dynamic analysis. Generating efficient ETEFs is of paramount importance in developing the ET method. ETEFs are generated so that dynamic characteristics of ETEFs can be compatible with multiple-scaled GMs.

Current approaches of generating ETEFs consider the parameters that are directly related to amplitude and frequency content of motions. Even though the ET method well predicts the responses of time history analysis by using existing ETEFs, several studies have recommended considering extra dynamic characteristics in the simulation process to improve the accuracy of results. For example, Maleki-Amin and Estekanchi [15] estimated damage indices of several steel moment frames using the ET method, and found that current ETEFs produce imprecise results for some frames (error about 20–40%). They proposed a method to overcome these errors and reduce errors to an acceptable range, and recommended that related cumulative damage parameters be included in the production of excitations by future researchers.

This study is designed to generate new ETEFs with a consideration of cumulative energy damages in the generating process. Nonlinear displacement spectra, absorbed hysteretic energy, and acceleration spectra are all included in the process of generating these new ETEFs. Formulation of ETEF equations is generalized to include nonlinear spectra as well as absorbed hysteretic energy. Dynamic characteristics of the newly generated ETEFs are investigated and compared with targets, while their efficiency is examined through a case study. Finally, results are compared with those of IDA and ETEFs generated without cumulative energy damage consistency.

2. Methodology

Seismic demand of structures subjected to ETEFs should be a reliable predictor of the seismic demand associated with a multiple-scaled set of ground motions. To meet such a requirement, dynamic characteristics of ETEFs should be compatible with multiple-scaled ground motions. In this regard, intensity measures (IM) are used to simulate ETEFs. IMs reflect different aspects of earthquake ground motions that affect inelastic responses of structures. IMs of ETEFs are supposed to be consistent with IMs associated with multiple-scaled earthquake ground motions. Multiple scales of ground motions produce IMs that correspond to different seismic hazard levels. Indeed, for any given set of ground motions and any set of considered IMs, IMs of ETEFs are consistent with those associated with ground motions, and they increase in time with a certain increasing function. With intensification of IMs in time, diverse seismic hazard levels are covered from frequent earthquake events at an early time to rare ones at a later time. Later, it will be discussed that the increasing function of different IMs is not necessarily the same, and their corresponding increasing function must be specified in advance.

In this study, acceleration spectra, nonlinear displacement spectra, and absorbed hysteretic energy are included in the generating process. It should be mentioned that absorbed hysteretic energy demand is used