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Engineering Structures 29 (2007) 2551–2562
ENGINEERING STRUCTURES
www.elsevier.com/locate/engstruct

Application of Endurance Time method in linear seismic analysis

H.E. Estekanchi*, V. Valamanesh, A. Vafai

Department of Civil Engineering, Sharif University of Technology, Iran

Received 15 June 2006; received in revised form 28 December 2006; accepted 6 January 2007
Available online 20 February 2007

Abstract

The Endurance Time (ET) method is a time-history based dynamic pushover procedure for seismic analysis and design of structures. In this procedure, structures are subjected to a specially designed intensifying accelerogram and their Endurance Time is measured based on the time interval during which they can resist the imposed dynamic actions. In this paper, application of the ET method in linear seismic analysis of structures has been investigated. The procedure for generating code compliant uniformly intensifying ET accelerograms has been explained. A set of three such accelerograms have been applied to various moment and braced steel frames and the results of analysis are compared to conventional equivalent static and response spectrum seismic analysis procedures. Code compliant ET analysis and base shear scaling in this method is discussed. Story drifts and internal forces are shown to be consistent with response spectrum analysis and static analysis results within acceptable tolerances. In the case of irregular structures, when static analysis results tend to diverge from response spectrum analysis results, the ET method's results are closer to the response spectrum's results. In general, it has been concluded that ET method can be considered as an alternative time-history based analysis in the linear range.

Keywords: Time-history analysis; Seismic design criteria; Dynamic pushover; Endurance Time

1. Introduction

The common philosophy of most well known seismic design codes is to achieve the dual goals of keeping the non-structural damage to a minimum in the case of service level earthquakes and to prevent structural failure in the case of collapse level earthquakes [1,2]. Three analysis methods that have been traditionally proposed by most well known seismic codes include equivalent static, response spectrum and time-history analysis. Each method has its own merits and some pitfalls. In the equivalent static procedure, lateral loading is applied using a predefined load pattern, which is similar to load distribution in the first mode free vibration of a shear building. This method is applicable in the case of relatively regular buildings with uniform mass and stiffness distribution. Dynamic properties of the structure are not directly included in the analysis phase and, therefore, in most practical situations, the applicability of this method is limited and raises some questions. Only a limited number of damage measures, such as stress and displacements, can be predicted by using this method and, therefore, the seismic performance of the structure under real earthquakes cannot be predicted with accuracy. However, the simplicity of and past experience with this procedure has kept it far from becoming obsolete and, in most practical applications, the equivalent static procedure is still being used as a bench mark by practicing engineers.

The response spectrum method can be considered as a major improvement over the static procedure. In this procedure, a linear decomposition is applied to the dynamic equations of motion of MDOF systems. This procedure can be applied to irregular structures as well. However, the applicability of this method in cases that involve complicated nonlinear characteristics is limited. Time-history has the advantage of potentially being capable of directly including almost all sources of nonlinear and time-dependant material and geometric effects. Its traditional pitfall has been in its being the most complex and time consuming procedure.

These limitations in traditional seismic analysis procedures, along with the advancement of knowledge and remarkable developments in the field of computation technology, have encouraged researchers and engineers to develop different

* Corresponding author. Tel.: +98 21 66022727; fax: +98 21 66014828.
E-mail address: stkanchi@sharif.edu (H.E. Estekanchi).

0141-0296/$ - see front matter
doi:10.1016/j.engstruct.2007.01.009

Nomenclature

$a_g(t)$	Ground acceleration
B	Building response factor
BF	Braced frame
DR	Design ratio
EQX	Earthquake load in X direction
ET	Endurance Time method
$F(a_g)$	Optimization target function
F_x	Lateral force at story level x
F_t	Part of base shear applied at top story
h_x	Height of story x
I	Importance factor (=1.0 here)
M	End moment
MMP	Modal mass participation ratio (%)
MRF	Moment resisting frame
P	Axial force
R	Response modification coefficient
S_a	Acceleration response
$S_a(T,t)$	Acceleration response for period T at time t
$S_{aC}(T)$	Code acceleration response for period T
$S_{aT}(T,t)$	Target acceleration response for period T at time t
$S_u(T,t)$	Displacement response value for period T at time t
$S_{uT}(T,t)$	Target displacement response value for period T at time t
t	Time
$t_{\max}$	Time corresponding to the end of accelerogram
T	Free vibration period (s)
$T_{\max}$	Maximum free vibration period (s) to be considered in the optimization
t_{Target}	Target time
V_{Static}	Static base shear per code
V_{Spectrum}	Response spectrum base shear per code
w_i	Seismic weight of story i
α	Weighing factor in optimization target function
γ	Base shear scale factor

methods for earthquake engineering applications [3–6]. Nonlinear pushover and incremental dynamic analysis (IDA) procedures are some of the most significant types of these new methods. In recent years, Performance Based Seismic Engineering (PBSE) has gained increased interest among practitioners in the earthquake engineering field [2,7,8]. Development of these new methods and criteria should be mainly contributed to the amazing improvements in computational tools that have made possible the solution of sophisticated nonlinear models [9]. The use of static pushover analysis is becoming standard practice in structural engineering design offices and the application of nonlinear time-history analysis is also gaining popularity. It can be predicted that time-history based analysis procedures will become more and more popular in the near future among both researchers and practicing engineers. This is due to the fact that on the one side, advances in the knowledge of earthquake engineering has resulted in the development of theories that describe material and structural behavior in a more complex way that do not lend themselves to simplified analysis methods, and on the other side, the available level of knowledge and computational power justifies resorting to more involved analysis procedures.

The Endurance Time (ET) method is a time-history based analysis and design procedure that has recently been introduced as a potential alternative to the numerous available procedures [10]. The concept of ET method has some common grounds with the IDA procedure as will be explained in the next section. In this paper, the application of ET in linear seismic analysis of structures has been explained. The basics of the ET procedure are briefly reviewed and its potential applications are discussed. The results of analysis of several 2D steel frames (rigid and braced) have been presented and compared to equivalent static and response spectrum analysis. It has been shown that even though the ET method is a time-history based analysis, its concept and application are quite intuitive and straightforward. While mainly being intended for nonlinear applications, it is shown that ET analysis may also be considered as an alternative method in linear elastic analyses, which is much less complicated as compared to traditional time-history analysis.

2. Basic concepts of ET analysis

Physical interpretation of the concept of ET analysis can best be described by a hypothetical shaking table experiment. Three different structures with unknown structural properties are to be ranked according to their seismic resistance performance. All three structures are fixed on a shaking table and the test begins by subjecting the structures to a very low amplitude random vibration, as shown in Fig. 1(a). The experiment commences by gradually increasing the amplitude of the shaking table vibrations. As the vibration amplitude increases, a point will be reached when one of the structures fails as shown in Fig. 1(b). As the amplitude of vibration is constantly increased, a point will be reached when the second and third structures will also fail. This has been shown in Fig. 1(c) and (d) where structure ‘C’ has failed at $t = 15$ s and structure ‘B’ has failed at $t = 20$ s. Based on these results, and considering that the lateral loads induced by the shaking table somehow correspond with earthquake loads, structure ‘A’, which failed earliest, is ranked as the worst and structure ‘B’, which endured longest, is ranked as the best performer.

This hypothetical experiment describes the essence of the Endurance Time method. In the ET method, structures are subjected to a pre-designed intensifying accelerogram and their performance is judged based on the time interval during which they can meet predefined performance criteria, e.g. resisting failure in the above test. The ET concept is somewhat analogous to the exercise test used by cardiologists in assessing the cardiovascular system condition of athletes or heart patients. In exercise tests, the subject is put on a treadmill and the speed and slope of the treadmill is gradually increased at each stage until the subject quits or signs of distress or abnormal biological measures are observed. The status of the subject’s