Engineering Structures 88 (2015) 138–153

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Generation of artificial accelerograms for efficient life-cycle cost analysis of structures

Chara Ch. Mitropoulou, Nikos D. Lagaros *, Manolis Papadrakakis

Institute of Structural Analysis & Antiseismic Research, Department of Structural Engineering, School of Civil Engineering, National Technical University of Athens, 9, Heroon Polytechniou Str., Zografou Campus, 157 80 Athens, Greece

ARTICLE INFO

Article history:
Received 27 June 2013
Revised 15 January 2015
Accepted 19 January 2015

Keywords:
Life-cycle cost analysis
Natural records
Artificial accelerograms
Uncertain hazard curves
Incremental dynamic analysis

ABSTRACT

The main objective of the study is to propose a methodology for generating the minimum number of required seismic accelerograms for performing with reliability and computational efficiency life-cycle cost analysis (LCCA) studies. The implementation of LCCA framework in earthquake engineering requires the calculation of different cost components that are related to structural performance assessed for multiple earthquake hazard levels. The selection of the ground motions plays an important role in the efficiency and reliability of the LCCA procedure. In this study, three different suites of accelerograms are considered and their effect on LCCA is examined in two 3D reinforced concrete buildings. The first suite is composed by natural records originated from the region of interest and are scaled to the hazard levels considered. The second suite comprises of artificial accelerograms generated based on the elastic response spectra of the considered hazard levels. Previous studies have shown that artificial accelerograms underestimate the maximum drift and maximum floor acceleration responses. On the other hand, the number of natural records required for reliable calculation of life-cycle cost is high, thus the computational effort also increases. Consequently, in order to combine robustness and computational efficiency, the third suite is formed by generating representative artificial accelerograms for the hazard levels considered, where the random characteristics of peak ground acceleration are taken into account.

1. Introduction

The principles of life-cycle cost analysis (LCCA) are based on economic theories and the probability theory and are related to the possible losses due to unsatisfactory system's performance under events with random occurrence and intensity during its life. LCCA has been implemented mainly to energy and water conservation projects as well as to transportation ones. Regarding structures, the application of LCCA is considered as a particularly important decision making tool for designing cost-effective structures especially in seismic prone regions, since LCCA takes into account future damages due to earthquakes. In a previous work [1], the authors presented the influence of certain parameters on the estimation of life-cycle cost of structural systems and it was found that the efficiency of LCCA is highly dependent on the set of records used for performing the structural evaluation.

Despite the increasing availability of databanks with natural records it is difficult to obtain code-compliant sets of natural records for design and assessment purposes. Moreover, the guidelines provided by code provisions for selecting ground motions are inadequate. The typical provisions refer to the compatibility with the design spectrum in specified range of periods [2]. This is why artificial accelerograms, compatible with design spectrum, are still popular both for practice and research purposes. The iterative procedure followed, when generating artificial accelerograms, aims to achieve spectral matching by adjusting its Fourier amplitude spectrum. This spectral matching technique is carried out in the frequency domain using an appropriate power spectral density function.

The main objective of the study is to propose a methodology for generating the minimum number of required seismic accelerograms for performing LCCA of buildings, with computational efficiency. For this purpose, in this study three different suites of seismic records are considered in the framework of LCCA and their influence is examined for two 3D reinforced concrete (RC) buildings, with symmetrical and irregular plan views, respectively. The increased computational effort required for reliable estimation of the life-cycle cost is due to the number of records needed. The first suite is composed by natural records originated from the region of interest which are scaled to the hazard levels considered.

* Corresponding author.
E-mail addresses: chmitrop@central.ntua.gr (C.Ch. Mitropoulou), nlagaros@central.ntua.gr (N.D. Lagaros), mpapadra@central.ntua.gr (M. Papadrakakis).

http://dx.doi.org/10.1016/j.engstruct.2015.01.029
0141-0296/

The second suite comprises of elastic response spectrum compatible artificial accelerograms; however, previous studies have shown that artificial accelerograms underestimate drift response [3] and maximum floor acceleration [1], while the number of records affects the standard error of the average response estimate [4].

Selecting, scaling and matching accelerograms are critically important for the design and assessment of structural systems, enabling structural response to be determined with greater confidence and through fewer analyses than if unscaled accelerograms are employed [5–9]. Extending the observations of the authors and others regarding the underestimation of the structural response when artificial accelerograms are used [1,3], in this study it was also found that the life-cycle cost calculations can be biased due to improper record selection. For this purpose, a third suite of seismic records is formed via an effective process for generating representative artificial accelerograms for the hazard levels considered. According to this procedure, in which the random characteristics of peak ground acceleration are taken into account, both reliability and computation efficiency are achieved, since a reduced number of randomly generated artificial accelerograms is derived. In particular, artificial accelerograms producing stationary signals that are subsequently enveloped in a trapezoidal shape to roughly simulate the non-stationary characteristics of ground motion [10] are generated. The design spectra compatible artificial accelerograms are generated based on the values of the PGA given in the mean hazard curve of the region; while the mean hazard curve is derived by considering important uncertainties related to the seismicity of the region, such as maximum magnitude, earthquake recurrence rate, distribution of seismicity between faults and attenuation relationships.

2. Life-cycle cost assessment based on incremental structural analysis

Total cost (C_{TOT}) of a structure, may refer either to the design-life period of a new structure or to the remaining life period of an existing or a retrofitted one. This cost can be expressed as a function of time and design vector $\boldsymbol{s}$, as follows [11]:

$$C_{TOT}(t, \boldsymbol{s}) = C_{IN}(\boldsymbol{s}) + C_{LC}(t, \boldsymbol{s}) \tag{1}$$

where C_{IN} is the initial cost of a new or retrofitted structure, C_{LC} is the present value of the life-cycle cost; $\boldsymbol{s}$ is the design vector corresponding to design loads, resistance and material properties that influence the design of the structural system, while t is the time period. Life-cycle cost calculated based on Eq. (1) has to be included in the main framework of contemporary performance based earthquake engineering (PBEE) that is based on the principle that performance can be predicted and evaluated within quantifiable confidence levels [12].

2.1. Incremental structural analysis procedures

In the framework of seismic assessment of structures a wide range of seismic records corresponding to different hazard levels should be considered in order to take into account the uncertainties inherent in seismic hazard analysis. In LCCA a multiple hazard level approach should be considered; the two most appropriate ones are the multi-stripe dynamic analysis and the incremental dynamic analysis [13], to be consistent with terminology in related literature the abbreviation IDA is used for both methods. The main objective of IDA [14] is to correlate the seismic intensity level and the corresponding maximum response of the structural system. The intensity level and the structural response are described through an intensity measure (IM) and an engineering demand parameter (EDP), respectively. More details on the implementation of IDA into the LCCA framework can be found in previous studies by the authors [15,16].

Selecting IM and EDP is one of the most critical steps of IDA. IM should be a monotonically scalable ground motion intensity measure [17]. In the current work the $S_A(T_1, 5\%)$ is selected, since it is the most commonly used intensity measure nowadays, for the analysis/design of buildings. On the other hand, the damage may be quantified by using any of the EDPs whose values can be related to particular structural damage states. In this study the maximum interstorey drift θ_{max} and maximum floor acceleration are chosen. The relation between inter-story drift values with limit states, employed in this study (Table 1), is based on the work by Ghobarah [18] for ductile RC moment resisting frames. On the other hand, the most appropriate intensity measure associated with the loss of contents, such as furniture and equipment, is the maximum floor acceleration. The relation of each limit state with the values of floor acceleration (Table 1) is based on the work of Elenas and Meskouris [19].

2.2. LCCA calculation procedure

Damage, in the context of LCCA, refers not only to structural damage but also to non-structural damage. The latter includes architectural damages, installation damages (mechanical, electrical and plumbing) as well as content damages (e.g., furniture, equipment); while demolition/clearing cost can also be considered. Life-cycle cost (C_{LC}), for the ith limit state, can thus be expressed as follows:

$$\begin{gathered} C_{LC}^{i,\theta} = C_{dam}^{i} + C_{con}^{i,\theta} + C_{ren}^{i} + C_{Inc.}^{i} + C_{inj}^{i} + C_{fat}^{i} \\ \text{and} \\ C_{LC}^{i,acc} = C_{con}^{i,acc} \end{gathered} \tag{2}$$

where C_{dam}^{i} is the damage repair cost, $C_{con}^{i,\theta}$ is the loss of contents cost due to structural damage that is quantified by the maximum interstorey drift, while $C_{con}^{i,acc}$ is the loss of contents cost due to floor acceleration [15], C_{ren}^{i} is the loss of rental cost, $C_{Inc.}^{i}$ is the income loss cost, C_{inj}^{i} is the cost of injuries, and C_{fat}^{i} is the cost of human fatality. The description of the different cost evaluation for each limit state cost can be found in Table 2 [20,21]. The "basic cost" provided in Table 2 refers to the first component of the calculation formulas, while they are given in monetary units (MU, corresponding to Dollars or Euros). The values of mean damage index, loss of function, down-time cost, expected minor injury rate, expected serious injury rate and expected death rate used in this study are based on [22]. Table 3 provides the ATC-13 [23] and FEMA-227 [24] limit state dependent damage and other severe consequences.

Based on a Poisson process model of earthquake occurrence and an assumption that damaged buildings are immediately retrofitted to their original intact conditions after major damage-induced seismic attack, Wen and Kang [11] proposed the following formula for the life-cycle cost calculation considering N limit states, while the addition of the maximum floor acceleration component in the calculation formula is based on the work by Mitropoulou et al. [15]:

Table 1
Drift ratio and floor acceleration limits for bare moment resisting frames.

Limit state	Interstorey drift (%) [18]	Floor acceleration (g) [19]
(I) – None	$\theta \leqslant 0.1$	$a_{floor} \leqslant 0.05$
(II) – Slight	$0.1 < \theta \leqslant 0.2$	$0.05 < a_{floor} \leqslant 0.10$
(III) – Light	$0.2 < \theta \leqslant 0.4$	$0.10 < a_{floor} \leqslant 0.20$
(IV) – Moderate	$0.4 < \theta \leqslant 1.0$	$0.20 < a_{floor} \leqslant 0.80$
(V) – Heavy	$1.0 < \theta \leqslant 1.8$	$0.80 < a_{floor} \leqslant 0.98$
(VI) – Major	$1.8 < \theta \leqslant 3.0$	$0.98 < a_{floor} \leqslant 1.25$
(VII) – Collapsed	$\theta > 3.0$	$a_{floor} > 1.25$