Soil Dynamics and Earthquake Engineering 103 (2017) 105–117

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Incremental dynamic based fragility assessment of reinforced concrete structures: Stationary vs. non-stationary artificial ground motions

Francesco Basone[a], Liborio Cavaleri[b], Fabio Di Trapani[c,*], Giuseppe Muscolino[d]

[a] *Università degli Studi di Enna "Kore", Facoltà di Ingegneria e Architettura, Cittadella Universitaria, 94100 Enna, Italy*
[b] *Università degli Studi di Palermo, Scuola Politecnica, Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali DICAM, Viale delle Scienze Ed. 8, 90128 Palermo, Italy*
[c] *Politecnico di Torino, Dipartimento di Ingegneria Strutturale, Edile e Geotecnica, Corso Duca degli Abruzzi, 24, 10128 Turin, Italy*
[d] *Università degli Studi di Messina, Dipartimento di Ingegneria Civile, Informatica, Edile, Ambientale e Matematica Applicata, 98122 Messina, Italy*

ARTICLE INFO

Keywords:
Artificial accelerograms
Non-stationary random processes
Nonlinear dynamic analysis
Incremental dynamic analysis
Fragility curves
Reinforced concrete structures

ABSTRACT

Artificial and natural records are commonly employed by researches and practitioners to perform refined seismic assessments of structures. The techniques for the generation of artificial records and their effectiveness in producing signals which are significantly representative of real earthquakes are still debated as well as results of the consequent seismic assessment to expect from their application. The paper presents an in-depth comparative study highlighting the effect of employing different typologies of artificial ground motion records on seismic assessment results, especially addressing seismic fragility curves. Three sets of 50 stationary, nonstationary evenly modulated and fully nonstationary accelerograms are generated based on design spectrum compatibility criteria. Standard nonlinear time history analyses of 4 reference structural models of reinforced concrete (RC) structures having different degree of complexity are firstly carried out monitoring results in terms significant engineering seismic demand parameters. So far, incremental dynamic analysis (IDA) is used to derive fragility curves. Peak ground acceleration and spectral acceleration are used as possible intensity measures in order to compare results of seismic fragility assessment. The combination of structural irregularity, severe damage and input typology is finally analyzed and discussed in order to assess the degree of dependence of fragility assessments on the typology of signal adopted.

1. Introduction

Nonlinear dynamic analysis is nowadays increasingly employed as the benchmark for seismic assessment of new and existing constructions, in particular when the quantification of the actual seismic demand becomes of crucial importance. In this context the selection of ground motions still constitutes a widely debated issue, mainly focusing on advantages and disadvantages associated with the choice of natural or artificial records. On the one hand, artificial records allow efficiently matching of criteria for spectrum compatibility and are easy to be generated. However, standard artificial generation methods provide signals which, differently from natural records, are stationary in amplitude and frequency. On the other hand, the use of natural ground motions records needs first a large data-set to make proper selections. Moreover scaling of signals is generally necessary to match spectrum compatibility conditions. To date, technical codes (e.g. Eurocode 8 [1], and Italian NTC 2008 [2]) do not provide specifications about the strategies to follow for the generation of artificial records, entrusting the reliability of the selection to the spectrum compatibility criteria. However, they imply the stationarity of artificial accelerograms at least for a given duration, leaving uncertain the possibility to use or not signals generated from nonstationary processes.

Several methods have been proposed in the literature in order to generate spectrum compatible artificial accelerograms [e.g. 3,4,5,6] also based on the use of a spectrum compatible power spectral density function (PSD). Response spectra and PSD have in fact a strong relationship as highlighted by Vanmarcke and Gasparini [7]. Based on this relationship, a number of procedures (e.g [8–12]) are available in the literature for determining, first, the spectrum compatible PSD and then spectrum compatible signals. The generation of spectrum compatible accelerograms filtered by samples of stationary random processes is widely faced in the literature (Shinozuka [13], Barenberg [14], Cacciola et al. [15]). Shinozuka's method provides that samples of spectrum compatible signals can be simulated through the superposition of harmonics with a random phase. In the approach followed by Barenberg [14] a single spectrum compatible accelerogram is

---

[*] Corresponding author.
E-mail address: fabio.ditrapani@polito.it (F. Di Trapani).

http://dx.doi.org/10.1016/j.soildyn.2017.09.019
Received 1 May 2017; Received in revised form 31 August 2017; Accepted 23 September 2017

generated using an artificial deterministic signal resulting by the superposition of a number of harmonics with amplitude scaled so as to match the target response spectrum. As regards to design-spectrum-compatibility of the stationary signals, the method proposed by Cacciola et al. [15], making use of samples of stationary random processes, has been proved to be effective. This method is based on the simple hypothesis of zero-mean stationary Gaussian random process, fully defined by a power spectral density function.

If on the one hand artificial signals having the characteristics of stationary Gaussian random processes are used for sake of simplicity, on the other hand, the assumption of stationarity is a strong idealization of the real ground accelerations during an earthquake, being not considered the amplitude and frequency modulation which is typical of real ground motion records.

The generation of spectrum-compatible non-stationary records is also discussed in the literature. For example in Refooei et al. [16] and Ghodrati et al. [17], the well-known Kanai–Tajimi model has been modified to include the nonstationary nature of both the amplitude and frequency content of earthquake records. Nonstationary stochastic ground-motion signals accounting for the time variation of both intensity and frequency were generated by Conte et al. [18] using the Thomson's spectrum estimation method. More recently an effective method for generating design-spectrum-compatible fully non-stationary seismic inputs was proposed by Cacciola [19]. This method assumes that the ground motion is modeled by the superposition of two contributions: the first one is a fully non-stationary counterpart modeled by a recorded earthquake; the second one is a corrective random process adjusting the recorded earthquake in order to match spectrum compatibility.

Despite the availability of efficient tools for the generation of non-stationary signals since four decades (e.g. [20]), and the problem of modelling stochastic input has been widely felt as crucial in structural analysis (e.g. [21–24]), the use of stationary accelerograms remains widely employed and also suggested by design codes.

On the other hand, fragility assessment of structures, based on design spectrum compatible ground motions is increasingly employed as a benchmark assessment procedure, especially when this is performed by means of incremental dynamic analysis (IDA). In fact the use of IDA allows simultaneously accounting the randomness of the input joint with the progressive achievement of limit states. In this framework the degree of dependence of results of fragility assessment on the strategy adopted to model seismic input remains uncertain. Based on this, the paper focuses on the influence of the input typology on the seismic assessment resulting from the use of one rather than the other typology of signal. In particular the probabilistic fragility assessment, resulting from the different inputs is addressed. In this context, the influence of structural regularity is also investigated. Preliminary analyses are carried out analyzing the nonlinear structural response of different classes of reinforced concrete framed structures subject to three sets of 50 stationary, nonstationary evenly modulated and fully nonstationary accelerograms artificially generated accelerograms equivalent in terms of response spectrum. Significant earthquake damage parameters such as interstorey drifts and floor torsion angles are monitored for each case comparing resulting outputs.

So far, the generated sets of accelerograms are used to perform incremental dynamic analyses for the derivation of fragility curves of the reference structural models at collapse limit state. To this aim, each accelerogram is scaled at each analysis up to the structural collapse. Fragility curves resulting from the different inputs are compared in order to evaluate the extent of their dependence with the typology of signal and give fundamental information for a fragility assessment based choice.

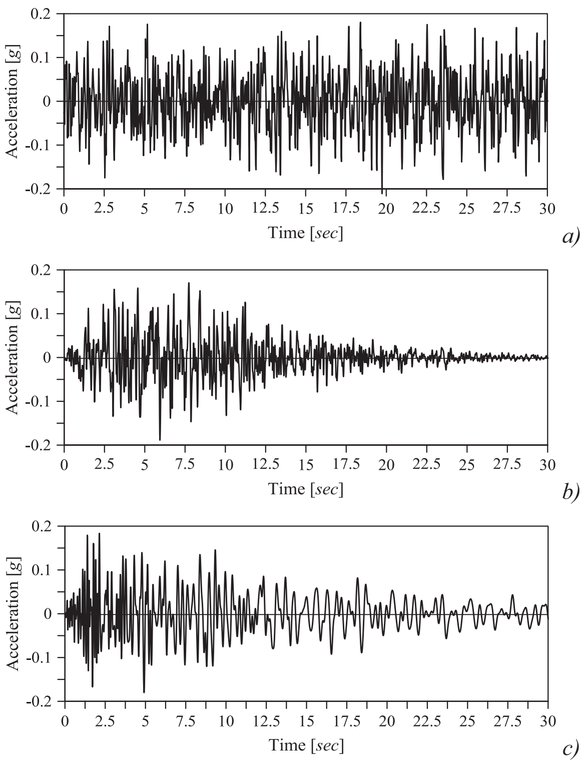

Fig. 1. Sample of a generated: a) stationary accelerogram; b) non-stationary evenly modulated accelerogram; c) fully non-stationary accelerogram.

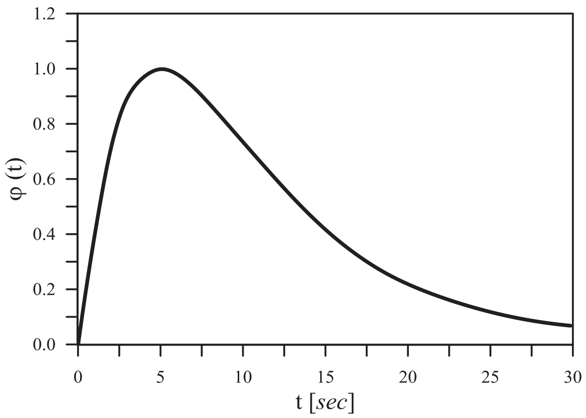

Fig. 2. Typical shape of the modulating function by Hsu and Bernard [21].

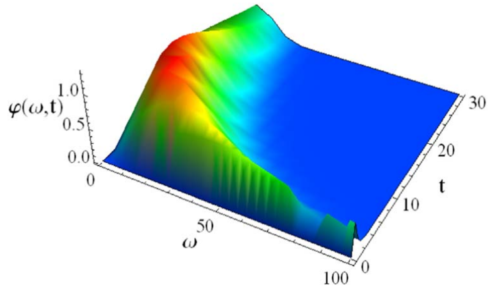

Fig. 3. Typical shape of the modulating function by Spanos and Solomos [22].

2. Generating of spectrum compatible accelerograms

2.1. Stationary accelerograms

Spectrum compatible stationary accelerograms are generated using the Shinozuka [13] expression, according to which the *i*th signal is obtained as:

$$\ddot{u}_{i,g}^{ST}(t) = \sum_{r=1}^{m_c} \sqrt{2\,G_{\ddot{U}_g}(r\Delta\omega)\Delta\omega}\,\sin(r\,\Delta\omega\,t + \theta_r^{(i)});\quad 0 \le t \le t_f \tag{1}$$