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New insights in the analysis of the structural response to response-spectrum-compatible accelerograms

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ABSTRACT

This paper addresses the study of the seismic response of structures to response-spectrum-compatible accelerograms. The number of methodologies proposed in the last three decades to simulate artificial earthquake ground motion testifies the relevance of this subject in the scientific community. However, the implications of the selection of models and hypothesis adopted and their impact on the structural response have not been thoroughly highlighted yet. This contribution shows for the first time that different ground motion models, having identical response spectrum at 5% damping, peak ground acceleration, strong motion phase and total duration, can lead to significant discrepancies in the structural responses even for proportionally damped linear behaving structures, although all the models are satisfying the response-spectrum compatibility criteria. The results show clearly the weakness in the current response-spectrum-compatible criteria provided by seismic codes and the necessity of more robust conditions for the simulation of artificial earthquake ground motions.

1. Introduction

The design response-spectrum is up to now the basic representation of the seismic action and the most widespread analysis tool used by practitioners. Time-history representation of the seismic action is also allowed by seismic codes and it is employed for a broad number of engineering applications such as the analysis of non-linear behaving structures whereas the response-spectrum technique might not provide accurate results. Furthermore, time-history analysis provides additional information on damage mechanism and dissipation of energy due to cyclic loading that cannot be predicted through the response spectrum analysis. It is noted that the international seismic codes recommend only the response-spectrum-compatible criteria that have to be satisfied and do not give a method for generating the earthquake time-histories. As a consequence, several methods have been proposed in literature coping with the generation of response-spectrum-compatible accelerograms. Earlier contributions on this subject can be found in the review papers by Ahmadi [1] and by Cacciola [4]. Most common approaches rely on modelling the seismic action as a realization of a stationary or quasi-stationary stochastic Gaussian process (see e.g. [24,2]. Even if quasi-stationary Gaussian models reliably represent the inherent random nature of seismic action, they suffer the major drawback of neglecting the non-stationary characteristics of the real records. In this regard, in the framework of Gaussian stochastic models, very few procedures have been proposed in literature [23,17,12,3,5] to simulate fully non-stationary spectrum compatible stochastic processes (i.e. with amplitude and frequency variation). The above methodologies possess the common drawback that the simulated time-histories do not manifest the variability observed for real earthquakes. This is mainly due to the fact that recorded accelerograms, even if possessing the same magnitude and epicentral distance, have strongly different energy distributions leading to a large variability of ground motion parameters. On the other hand, the simulated accelerograms are generally determined from a single power spectral density function, as a consequence the ground motion time-histories possess very similar joint time–frequency distribution. Recently, Cacciola and Zentner [6] proposed a procedure to simulate response-spectrum-compatible accelerograms with ground motion parameters similar to those observed in nature. To this aim the evolutionary power spectral density function with random coefficients and compatible with given target response spectrum (i.e. spectrum-compatible) has been introduced. This procedure has been extended by D'Amico et al. [7] and Zentner et al. [25] to include enhanced variability models accounting of the correlation of spectral accelerations.

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The number of methodologies proposed up to now in the last three decades to simulate artificial response spectrum compatible accelerograms in addition to the alternative simulation techniques compatible with database of earthquakes (see e.g. [26] and/or site characteristics (see e.g. [19] testifies the interest of the scientific community in this topic. Nevertheless, to the best knowledge of the authors a thorough comparative study of the structural response to response-spectrum-compatible earthquakes aimed to provide a depth understanding of the hypothesis adopted and the implications of the selected ground motion model has not been carried out up to now.

Therefore, this paper aims to bridge this gap of knowledge by comparing for the first time through a Monte Carlo study the response of structures to the widely used Gaussian quasi-stationary and non-stationary models along with the most novel non-stationary model with imposed variability. All the simulated time-histories fulfill the Eurocode 8 provisions and all of them possess also the same peak ground acceleration (PGA), strong-motion-phase (SMP) and total duration. Three benchmark structures have been selected for the current study, namely the linear SMART 2008 nuclear building [14], IASC 1996 5-story building linear steel frame [10,20], and linear and non-linear SAC 1996 20-story building structure [15]. The structures have been selected to consider a spread scenario of high, medium and low fundamental frequencies.

2. Simulation of ground motion gaussian time-histories

In the framework of seismic engineering it is well known that only a probabilistic approach can afford a rigorous representation of earthquake ground motion. Accordingly, a ground motion acceleration $\ddot{u}_g(t)$ recorded at a given location can be seen as a sample of a stochastic process. A number of stochastic models have been proposed in literature, for an in depth discussion the readers could refer to the review paper by Shinozuka and Deodatis [22]. Mainly, these models can be categorized as Gaussian or non-Gaussian models. Due to their relative simplicity the Gaussian models are the most used to represent the seismic action. By assuming the ground motion as a realization of Gaussian stochastic process it is fully defined by the knowledge of its autocorrelation function $R_{\ddot{u}_g}(t_1,t_2)$ or by the generally known evolutionary power spectral density function $S_{\ddot{u}_g}(\omega,t)$ which representation can be alternatively given by the one-sided power spectral density by the following equation [18]

$$\begin{aligned} &G_{\ddot{u}_g}(\omega,t) = 2S_{\ddot{u}_g}(\omega,t) = |a(\omega,t)|^2 G(\omega),\ \ \omega \geqslant 0; \\ &G_{\ddot{u}_g}(\omega,t) = 0,\ \ \omega < 0. \end{aligned} \tag{1}$$

where $a(\omega,t)$ is the frequency dependent modulating function while $G(\omega)$ is the one-sided power spectral density function of the stationary counterpart of $\ddot{u}_g(t)$. The processes defined by the evolutionary power spectral density function in Eq. (1) are able to represent the common feature of the ground motion acceleration to possess both amplitude and frequency varying with respect to time (temporal and spectral non-stationarities), generally known as fully non-stationary (or non-separable). In the case in which only the amplitude of the process varies with respect to time, (i.e. $a(\omega,t) = a(t)$, temporal non-stationarity), the process is generally known as quasi-stationary (or separable or also uniformly modulated). Accordingly, Eq. (1) for quasi-stationary processes modifies as follows

$$\begin{aligned} &G_{\ddot{u}_g}(\omega,t) = 2S_{\ddot{u}_g}(\omega,t) = |a(t)|^2 G(\omega),\ \ \omega \geqslant 0; \\ &G_{\ddot{u}_g}(\omega,t) = 0,\ \ \omega < 0. \end{aligned} \tag{2}$$

Finally in the particular case in which the modulating function $a(t) = 1$ the process is called stationary. Once the power spectral density $G_{\ddot{u}_g}(\omega,t)$ is evaluated, it is possible to simulate the r-th sample of ground acceleration process via the superposition of N_a harmonics with random phases. That is [21]

$$\ddot{u}_g^{(r)}(t) = \sum_{i=1}^{N_a} \sqrt{2G_{\ddot{u}_g}(i\Delta\omega,t)\Delta\omega}\cos(i\Delta\omega t + \varphi_i^{(r)}) \tag{3}$$

where $\varphi_i^{(r)}$ are independent random phases uniformly distributed in the interval $[0,2\pi)$.

For simulating artificial accelerograms according to the spectral representation method, the definition of the power spectral density function is the crucial point necessary to assess structural systems through a proper Monte Carlo simulation approach.

3. Quasi-stationary models

When artificial ground motions time-histories are used in the engineering practice, the mean response-spectrum determined from the simulated time histories has to match the target response-spectrum provided by the code over a fixed frequency range and within a specified tolerance (i.e. the artificial ground motion time-histories have to be response-spectrum-compatible). Vanmarcke and Gasparini [24] pointed-out the fundamental relationship between the response-spectrum and the ground motion power spectral density of the input via the so-called "first passage problem", specifically by assuming the ground-acceleration process as zero-mean Gaussian stationary process. The pseudo-acceleration response-spectrum, $RSA(\omega_0,\zeta_0)$, for a given damping ratio ζ_0 and natural circular frequency ω_0, can be related to the median value of largest peak of the response of a single degree of freedom system by means of the following expression [24,8] as follows

$$RSA(\omega_0,\zeta_0) = \omega_0^2 \eta_U(T_s; p = 0.5; \lambda_{0,U}, \lambda_{1,U}, \lambda_{2,U})\sqrt{\lambda_{0,U}} \tag{4}$$

where η_U is the peak factor, T_s is the time observing window, p is the not-exceeding probability and $\lambda_{i,U} i = 0,1,2$ are the response spectral moments defined as

$$\lambda_{i,U} = \int_0^\infty \omega^i |H(\omega)|^2 G(\omega) d\omega, \tag{5}$$

in which $|H(\omega)|^2 = \left((\omega_0^2 - \omega^2)^2 + 4\zeta_0^2\omega_0^2\omega^2\right)^{-1}$ is the energy transfer function of the single degree of freedom system. Based on this relationship various procedures have been proposed in literature for determining the response-spectrum-compatible power spectral density function. A handy recursive expression determining the power spectral density compatible with a given response-spectrum has been proposed by Cacciola et al. [2]. Specifically,

$$\begin{aligned} &G(\omega_i) = 0, \quad \forall 0 \le \omega \le \omega_\alpha \\ &G(\omega_i) = \frac{4\zeta_0}{\omega_i\pi - 4\zeta_0\omega_{i-1}}\left(\frac{RSA(\omega_i,\zeta_0)^2}{\bar{\eta}_U^2(\omega_i,\zeta_0)} - \Delta\omega\sum_{k=1}^{i-1} G(\omega_k)\right), \quad \forall \omega > \omega_\alpha \end{aligned} \tag{6}$$

where $\bar{\eta}_U$ is the peak factor approximately determined according to the hypothesis of a barrier out-crossing in clumps and spectral moments determined assuming that the input PSD possesses a smooth shape and $\zeta_0 \ll 1$:

$$\bar{\eta}_U(\omega_i,\zeta_0) = \sqrt{2\ln\left\{2N_U\left[1 - \exp\left[-\delta_U^{1.2}\sqrt{\pi ln(2N_U)}\right]\right]\right\}} \tag{7}$$

With

$$\begin{aligned} &N_U = \frac{T_s}{2\pi}\omega_i(-\ln p)^{-1}, \\ &\delta_U = \left[1 - \frac{1}{1-\zeta_0^2}\left(1 - \frac{2}{\pi}arctan\frac{\zeta_0}{\sqrt{1-\zeta_0^2}}\right)^2\right]^{1/2} \end{aligned} \tag{8}$$

Moreover, in Eq. (6), $\omega_\alpha \cong 1 rad$ sec, is the lowest bound of the existence domain of $\bar{\eta}_U$. The accuracy of Eq. (6) is generally satisfactory, however the match can be improved applying iteratively the following scheme