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Assessment of spectrum matching procedure for nonlinear analysis of symmetric- and asymmetric-plan buildings

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ABSTRACT

Current performance-based seismic design procedures rely on response history analysis (RHA) for estimating engineering demand parameters (EDPs) of base-isolated structures, high-rise buildings and irregular structural systems. Ground motion records for RHAs should be appositely selected in compliance with site-specific hazard conditions, and properly modified either by amplitude-scaling or spectrum matching (SM) to ensure that the modified records provide accurate and efficient estimates of "expected" median demands. While amplitude-scaling techniques change intensity of the ground motion record, SM methods also alter the record's waveform (in frequency or time domain) to match its response spectrum to a target (or design) spectrum. The research on adequacy of spectrum-matched records for nonlinear RHAs of buildings is not only limited to symmetric-plan buildings subjected to one component of ground motion but also lacks consensus. This study comprehensively examines the accuracy and efficiency of a SM method for nonlinear RHAs under bi-directional earthquake excitations by covering single- and multi-story buildings having symmetric- and asymmetric-plans. For this evaluation, three-dimensional computer models of 48 single-story and nine multi-story buildings were created. Their structural responses were obtained from subsets of seven records modified by SM and separately by amplitude-scaling according to the regulatory ASCE/SEI 7-10 scaling procedure. The accuracy and efficiency of both procedures are examined by comparing their median EDP estimates from subset of records against the median values of EDPs due to a larger set of unscaled records, and by comparing record-to-record variability of the response. It is shown that the time-domain SM procedure provides more accurate median EDP estimates as compared to the ASCE/SEI 7-10 amplitude scaling procedure; however, it critically vanishes the variability of EDPs associated with aleatoric uncertainty in ground motion records. Retaining a certain level of aleatoric variability in EDPs can be an important parameter to be considered for certain projects.

1. Introduction

According to the 2009 International Building Code [1] and 2010 California Building Code [2], earthquake resistant design of special buildings, such as base-isolated structures, high-rise buildings, and irregular structural systems requires the use of nonlinear response history analysis (RHA) according to the ASCE/SEI 7-10 [3] for estimating engineering demand parameters (EDPs: floor displacements, story drifts, internal forces, hinge rotations, etc.) for verification of performance level targeted. Nonlinear RHAs are usually conducted for seven ground motion records, which are selected and modified to obtain results close to the median demands from a large ensemble of ground motions. Selection and modification of ground motions are fraught with several unresolved issues [4].

The main objective of ground motion selection and modification process is to provide few modified records that lead to accurate estimates of median structural responses with reduced record-to-record variability. Most of the proposed procedures for modifying ground motion records fall into one of two categories: amplitude-scaling and spectrum matching (SM). Only the amplitude of the record is modified in the first approach. In contrast, SM methods not only modify the record's amplitude but also alter its frequency content to match its response spectrum to a target spectrum (or design spectrum).

Earlier approaches to generate spectrum-compatible ground motions did not modify an actual record; instead, artificial ground motions were generated from white noise. This approach is generally inaccurate and inefficient for structures responding in nonlinear range because artificially generated accelerograms may

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have unrealistic phase content, duration and number of cycles [5,6]. Spectrum compatible ground motions generated by modifying an actual ground motion in frequency domain (adjusting the Fourier amplitude spectra) were widely used in design of base-isolated structures [7,8]. Although this method has the advantage of using actual ground motions, it was shown that adjusting motions in frequency domain distorts their velocity and displacement time series, and led to ground motions having unrealistically high energy content [6]. An alternative approach modifies record's time series in time domain by adding wavelets to generate spectrum compatible ground motions; this method introduces less energy into the ground motion than frequency-domain methods, and also preserves the record's original non-stationary characteristics [5].

An early approach for time domain spectral matching was developed by Kaul [9], and it was extended to multiple damping levels by Lilhanand and Tseng [10,11]. Lilhanand and Tseng employed an adjustment wavelet, capable to ensure stability of the method, but their approach did not retain the non-stationary characteristics of the original acceleration time series, and distorted their velocity and displacement waveforms. Based on the work by Lilhanand and Tseng, a computer code "RspMatch" was developed by Abrahamson [12]. The first version of the code used a new adjustment wavelet that preserved the non-stationary characteristic of the original ground motion. Despite this improvement, the wavelet function used results in non-zero termination in the velocity and displacement time series. A modified version of this code "RspMatch2005" offers the following improvements [5]: (1) The wavelet adjustment does not cause drift in velocity or displacement time series; (2) the records may be modified to match relative pseudo-acceleration or absolute acceleration response spectrum at different levels of damping simultaneously. Grant [13] developed another version of RspMatch called RspMatchBi; in his version, two components of ground motion can simultaneously be matched to two different target spectra. A newer version of RspMatch has been recently proposed [14], which does not require baseline correction of the adjusted record after each iteration, and ensures stability and convergence of the solution by the use of an improved tapered cosine wavelet. In this study, RspMatch2005 (a non-commercial computer code), recommended as one of the appropriate spectral matching techniques in ATC-82 report [15], is utilized.

The draft of chapter 16 of the ASCE/SEI 7-16, which will supersede ASCE/SEI 7-10, allows spectrum-matched ground motions to be used in RHAs. According to this draft, each component of the spectrum-matched record is scaled such that the average of their response spectra is not less than the target spectrum over a period range from $0.2T_1$ to $2.0T_1$, where T_1 is the first-"mode" period of the building in the direction considered. This is deliberately a stricter requirement, as compared to the requirement for amplitude scaled ground motions. The use of this procedure is also restricted to far-field ground motions only because of concern that the pulse characteristics of the motions may not be appropriately retained after the spectral matching processes has been completed [Curt Haselton, personal communication, 2013]. Furthermore, the spectrum-matched ground motions are scaled to meet the maximum direction spectral demands individually for both of the horizontal directions. Those criteria are conservative for any particular direction, and are especially conservative when applied to both directions [16]. This requirement imposes another penalty on the use of spectrum-matched ground motions, which is mainly due to lack of consensus in published studies; for example, Carballo [17], Bazzurro and Luco [18], and Huang et al. [19] found that the use of spectrum-matched records could lead to underestimations of nonlinear seismic response, although this conclusion is not supported in Watson-Lamprey and Abrahamson [20], Hancock et al. [21], Grant and Diaferia [22] and Heo et al. [23].

Considering the contradictory conclusions in previous studies, this research examines the SM method proposed by Hancock et al. [5] in order to answer whether this SM technique is accurate (providing unbiased estimates), and to what extend it is efficient (reducing dispersion) for nonlinear RHAs of single- and multi-story buildings having symmetric- and asymmetric-plans subjected to two components of ground motions.

2. Spectrum matching procedure for three-dimensional analysis

The SM procedure developed by Hancock et al. [5] for single component of ground motion is extended here to two horizontal components. The step-by-step procedure applicable to three-dimensional (3D) analysis of buildings is as follows [24–26]:

1. For a given site, select ground motions compatible with site-specific seismic hazard conditions governing the seismic design.
2. Compute the response spectrum $A(T)$ for each ground motion for various damping values (e.g., 2%, 5% and 10%) at evenly spaced periods T_i in a logarithmic scale over the period range from $0.2T_1$ to $1.5T_1$ (in this study, $i = 1, 2, 3, \ldots, 100$).
3. Determine the target pseudo-acceleration response spectrum $\widehat{A}(T)$ as the median spectrum determined in step 2 for various damping ratios. Define $\widehat{A}$ as a vector of spectral ordinates $\widehat{A}_i$ at 5% damping level at the same periods T_i.
4. Estimate the scaling factor SF to minimize the difference between the response spectrum (step 2) and the target spectrum (step 3) for 5% damping by solving the following minimization problem for each ground motion:
$$\min \left\| \ln\left(\widehat{A}\right) - \ln(SF \times A) \right\| \to SF \quad \|.\| = \text{Euclidean norm}$$
Required for this purpose is a numerical method to minimize scalar functions of one variable. Such methods are available in textbooks on numerical optimization [27]. This minimization ensures that the scaled response spectrum is as close as possible to the target spectrum. At the end of steps 1–4, implemented separately for the two horizontal components of each ground motion record, scaling factors SF_x and SF_y are determined for the x and y components of the ground motion, respectively.
5. Compute the difference between the scaled spectrum $SF \times A(T)$ and the target spectrum for 5% damping (step 2) for each ground motion. Define the error E_{SM}, and rank the scaled records based on their E_{SM} value; the record with the lowest E_{SM} is ranked the highest.
$$E_{SM} = \left\| \ln\left(\widehat{A}_x\right) - \ln\left(SF_x \times A\right) \right\| + \left\| \ln\left(\widehat{A}_y\right) - \ln\left(SF_y \times A\right) \right\|$$
6. From the ranked list, select the first k records with their scale factors determined in step 4. In this study, we used $k = 7$ because previous research shows that minimum of seven records are sufficient for unbiased estimates of EDPs from nonlinear RHAs [28,29].
7. Modify each scaled ground motion, independently, by adding wavelets in time domain to match the target spectrum for various damping values: 2%, 5% and 10%. In the present research, this step is implemented using the non-commercial computer program RspMatch2005. This modified ground motions are used to conduct nonlinear RHA of the structure. Note that this step should be implemented for each horizontal component of ground motion, separately.