ASSESSMENT OF GROUND MOTION SELECTION AND SCALING METHODS FOR RESPONSE HISTORY ANALYSES OF MID-RISE SYMMETRIC-PLAN BUILDINGS

J. C. Reyes¹, N. S. Kwong² and J. E. Acosta³

ABSTRACT

To determine a set of ground motions that is employed for response history analysis (RHA), it is necessary to modify and select the seismic records that represent the hazard of the site. In current practice, either the uniform hazard spectrum (UHS) or the conditional mean spectrum (CMS) are target spectra used to select ground motion records. For structures whose response is influenced significantly by multiple vibration modes, multiple CMSs (mCMS) are implemented to determine the maximum of mean demands; however, this method increases the number of GMs that must be implemented in RHA. Two target spectra were proposed to reduce the computational effort of mCMS, these spectra are the simplified generalized conditional mean spectrum (sGCMS) and the CMS-UHS composite spectrum. The results of the implementation of these target spectra performing nonlinear RHAs of three symmetric-plan buildings with 5, 10, 15 stories and ten idealized structures, suggest that the sGCMS and the composite spectrum lead to conservative estimates of seismic demands in comparison to the mCMS method. However, in most cases, their estimates are smaller than the UHS procedure.

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To determine a set of ground motions that is employed for response history analysis (RHA), it is necessary to modify and select the seismic records that represent the hazard of the site. In current practice, either the uniform hazard spectrum (UHS) or the conditional mean spectrum (CMS) are target spectra used to select ground motion records. For structures whose response is influenced significantly by multiple vibration modes, multiple CMSs (mCMS) are implemented to determine the maximum of mean demands; however, this method increases the number of GMs that must be implemented in RHA. Two target spectra were proposed to reduce the computational effort of mCMS, these spectra are the simplified generalized conditional mean spectrum (sGCMS) and the CMS-UHS composite spectrum. The results of the implementation of these target spectra performing nonlinear RHAs of three symmetric-plan buildings with 5, 10, 15 stories and ten idealized structures, suggest that the sGCMS and the composite spectrum lead to conservative estimates of seismic demands in comparison to the mCMS method. However, in most cases, their estimates are smaller than the UHS procedure.

Introduction

Nonlinear response history analysis (RHA) of buildings aims to predict the level of damage of structural elements during a seismic event. Nonlinear RHA of a 3D computer model requires a set of ground motion (GM) acceleration records that represent the hazard level of the site under study. In this study, only one horizontal component of ground motion is used. To conduct the analyses, records are selected and modified to match predefined target spectra. One of the alternatives for defining the target spectrum is the uniform hazard spectrum (UHS), which is obtained from a probabilistic seismic hazard analysis (PSHA) [1]. However, the UHS is a conservative target spectrum given that the spectral values share a common hazard level; hence, it is unlikely for all values to occur in a single earthquake scenario. The conditional mean spectrum (CMS) was developed to overcome these limitations [2]. The CMS is based on the spectral acceleration value

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A at only one period $T^*$ obtained from the UHS. For periods other than $T^*$, the CMS is less intense than the UHS. In current practice, ground motions are selected and modified to match the CMS [3]. Multiple vibration modes may have significant participation in the response of irregular and tall buildings. For these structures, a single CMS may underestimate the engineering demand parameters (EDPs). Consequently, researchers have proposed to implement multiple CMSs (mCMS) to determine the demand of the building. Generally, at least two CMSs are used to evaluate the participation of multiple vibration modes; examples of conditioning periods include: $T_1$ (the fundamental period of the building), $T_3$ (a lower-bound period that captures 90% mass participation in the direction of analysis), and $2T_1$ (an upper-bound period to account for period elongation due to nonlinearity). Using several CMSs significantly increases the number of nonlinear RHAs necessary for estimating the seismic demands of the structure [2]. Fig. 1 shows schematically a comparison between the target spectra obtained by using the arbitrary orientation definition for the horizontal component of ground motion.

Recently, two target spectra were proposed to reduce the computational effort of multiple CMSs considering the participation of multiple vibration modes. These methods are the simplified generalized conditional mean spectrum (sGCMS) and the composite spectrum [4, 5]. The sGCMS is an extension of the CMS in which two acceleration values share a common hazard level. The composite spectrum is constructed by combining the characteristics of the CMS and the UHS. Firstly, in periods less than $T_3$ the composite spectrum has the acceleration values of the CMS ($T_3$); secondly in periods between $T_3$ and $2T_1$ the composite spectrum is equal to the UHS, and finally, in periods greater than $2T_1$ the composite spectrum matches the CMS ($2T_1$) [5]. This research evaluates the ground motion selection and modification (GMSM) methods to determine which of the methods provide a balance between accuracy, precision, and computational effort. The estimated EDPs from the procedures are compared against the maximum of median demands obtained from multiple CMSs ([2], [6]).

![Figure 1 Comparison of target spectrums in logarithmic scale.](image-url)
Alternative procedures for obtaining target spectra

Simplified generalized conditional mean spectrum (s-GCMS)

An alternative target spectrum for selecting and scaling ground motions is the sGCMS. This spectrum is conditioned by two vibration periods ($T_1^*$ and $T_2^*$), that coincide with the UHS (Figure 1). Construction of the sGCMS involves several steps: (1) specify the return period and the two-conditioning periods to determine the target spectral accelerations ($A(T_1^*)$, $A(T_2^*)$) as the UHS ordinates. In this research, $T_1^*$ is the third modal period and $T_2^*$ is twice the fundamental period of the structure ($2T_1$). (2) Perform vector-valued disaggregation as described in Reference [4] to determine the controlling scenario. (3) For this scenario and for all vibration periods $T_j$, determine the median spectrum $A_{GCMS}(T_j)$ and marginal standard deviation $\sigma_j$ using a ground motion prediction model (GMPM). (4) The number of standard deviations between the intensity of the target spectral acceleration ($A(T_1^*)$, $A(T_2^*)$) and the median from the controlling rupture scenario is known as “epsilon” at the conditioning periods ($\epsilon_1$, $\epsilon_2$) [8] and determined from Eq. 3 of reference [4]. (5) For each period $T_j$, determine the “generalized epsilon” $\epsilon_j^*$ using Eq. 5a of reference [4] and an appropriate correlation model; e.g., Eq. 8 in reference [7]. In summary, the target spectral acceleration $A_{SGCMS}(T_j)$ may be computed as [4]:

$$A_{SGCMS}(T_j) = A_{GMPM}(T_j) \times \exp(\sigma_j \epsilon_j^*)$$

(1)

Composite Spectrum

The composite spectrum is the combination between two CMSs and the UHS. The composite spectrum is defined as:

$$A_{CS}(T) = \begin{cases} CMS(T_3) & T \leq T_3 \\ UHS & T_3 < T < 2T_1 \\ CMS(2T_1) & T \geq 2T_1 \end{cases}$$

(2)

In Eq. 2, the composite spectrum is obtained as follows; firstly, in periods less than $T_1^*$ the composite spectrum has the acceleration values of the CMS ($T_3^*$); secondly in periods between $T_1^*$ and $T_2^*$ the composite spectrum coincides with the UHS, and finally, in periods greater than $T_2^*$ the composite spectrum matches the CMS ($T_2^*$) [5].

Ground motions selected

The case studies of this research are located in Santa Clara, CA with latitude and longitude coordinates of 37.35°N and 121.96°W, respectively, and a shear wave velocity $V_{S30}$ of 300 m/s. OpenSHA [9] was used to implement probabilistic seismic hazard analysis (PSHA); the “USGS/CGS 2002 Adj. Cal. ERF” model was chosen for the earthquake rupture forecast using 5 km for the rupture offset; background seismicity was excluded, and the specified return period was 2475 yrs. The ground motion prediction model (GMPM) due to Campbell and Bozorgnia [10] was employed for all PSHA related calculations. In total, 3294 records were collected from the NGAwest2 database [11] to select the final sets of records for testing the ground motion selection.
and scaling methods of this investigation. Modification of ground motions is usually necessary to obtain an adequate number of ground motions that match the target spectrum corresponding to a long return period in highly seismic regions. In this paper, we modify one component ground motions by scaling their amplitudes. To select the \( N_{gm} \) ground motions of this investigation the following procedure was applied. First, the agreement or misfit between the response spectrum of a prospective ground motion \( A_P(T) \) and the target \( A_T(T) \) is quantified by the sum-of-squared differences (SSD) metric:

\[
SSD = \sum_{j=1}^{N_p} \left[ \ln[A_P(T_j)] - \ln[A_T(T)] \right]^2
\]  

(3)

where \( N_p \) refers to the total number of vibration periods chosen to quantify the misfit between the two spectra. Various period ranges have been considered for this metric [2], [12], [13], [14], but we used the period range of 0.05 to 10 sec. Second, the ground motion is scaled by \( SF_{optimal} \) so that the SSD between the scaled spectrum and the target spectrum is minimized [12]. The scale factor is given by

\[
SF_{optimal} = \left[ \prod_{j=1}^{N_p} \frac{A_T(T_j)}{A_0(T_j)} \right]^{\frac{1}{N_p}}
\]  

(4)

After scale factors have been determined for all ground motions in the database via Eq. 4, the selection of the eleven records for each structure studied is made based on the minimum values SSD (Eq. 3).

**Structural systems**

**Idealized Buildings**

Ten idealized building models with 3, 6, 9, 12, 15, 18, 21, 24, 27, and 30 stories having similar plan and floor weights were created using a Matlab script [16]. The structures have story heights of 3.2 m (9.84 ft) and uniformly distributed floor loads of 10 kN/m² (208.85 psf). The modal damping ratio was calculated based on the recommendations of reference [17]. The idealized structure with three main degree of freedoms in three-dimensions (3D) was described as a shear model containing two vertical elements in each horizontal direction Fig. 2a. Based on pushover curves of several structures, a trilinear constitutive model was used to define the nonlinear characteristics of these elements (Fig. 2b). The structural system has a constant initial stiffness \( k_1 \) over its height. \( k_1 \) was adjusted to achieve a prescribed fundamental period \( T_1 \) obtained from Eq. 12.8-7 in Chapter 12 of ASCE/SEI 7 including the amplification coefficient \( C_u \) from Table 12.8-1 [9]. The earthquake design forces \( V_s \) were determined by bi-directional linear response spectrum analysis of the buildings. The maximum shear force in the elastic range was estimated by dividing the earthquake design forces \( V_s \) by a response modification coefficient \( R=8 \).
Realistic Buildings

To confirm the results obtained from the idealized structures, three symmetric plan realistic buildings with 5, 10 and 15 stories were also considered [18]. These buildings were designed according to the 2009 International Building Code [19]. The lateral force resisting system of the buildings consists of moment resisting frames; their plan shapes are shown in Fig. 3. The buildings have similar plan areas and floor weights, with span lengths of 30 ft and story heights of 10 ft. The earthquake design forces were determined by bi-directional linear response spectrum analysis of the building with the design spectrum reduced by a response modification factor \( R = 8 \), but member sizes were governed by drift limits instead of strength requirements [12]. The selected damping ratio was determined based on the recommendations of reference [17] for steel buildings.
Analyzed by the PERFORM-3D computer program [20], the buildings were modeled as follows: (1) beams and columns were represented by a linear element with tri-linear plastic hinges at the ends of the elements that can include in-cycle strength deterioration, but not cyclic stiffness degradation; the axial load-moment interaction for the columns was based on plasticity theory; (2) panel zones were modeled as four rigid links hinged at the corners with a rotational spring that represents the strength and stiffness of the connection; (3) ductility capacities of girders, columns, and panel zones were specified according to the ASCE/SEI 41 standard [21]; (4) columns of moment resisting frames and the gravity columns were assumed to be clamped at the base; and (5) effects of nonlinear geometry were approximated by a standard P-Δ formulation.

Evaluation of the GMSM procedures

Idealized buildings

Fig. 4 presents the maximum story drift ratio (MSDR) of some selected idealized structures obtained by four GMSM methods: mCMS, sGCMS, composite (Comp.), and UHS. For each structure, the plot shows the individual responses as black circles; the horizontal solid red line shows the median response and the black dashed lines the 25 and 75 percentiles of the data. For the mCMS method, only the most critical results of one of the three CMS analyses are shown. In general, the lowest median estimates and interquartile range of story drifts is obtained by the mCMS method. The UHS method lead to the largest values of MSDR and interquartile range for the structures considered. For structures with fundamental periods larger than 3 seconds, the difference between the UHS and the mCMS methods may be as large as 90% (structures R21, R24, R27 and R30). These results are consistent with the observations from other researchers [22]. In most cases, the results from the sGCMS and composite methods are similar. For structures with fundamental periods less than 3 seconds, the sGCMS and composite methods provide conservative results that are within 20% difference in comparison with the mCMS method. For larger fundamental periods, the median estimates and dispersion of story drifts obtained by the UHS, sGCMS and composite methods are much larger than those of the mCMS. For this case, the three methods give similar results because there is not a remarkable difference between their target spectra.

Realistic buildings

Fig. 5 shows maximum story drift ratios (MSDR) and peak floor accelerations (PFA) for the three realistic buildings considered in this research. The results for building R05 are consistent with the results of the idealized building R06 presented in Fig. 4. In general, it is confirmed that the UHS method give larger results and dispersion than the other three methods. It is evident that the sGCMS story drifts estimates are much closer to the mCMS method than the results obtained from the composite and UHS methods. The interquartile range of the mCMS results is, in general, smaller than the other three methods because the conditional mean spectra represent in a better way the spectral shape of recorded records, and therefore the ground motions of the mCMS may be less intense.
Figure 4. Comparison of MSDRs estimated from GMSM Methods for idealized structures.
Figure 5. Comparison of MSDRs and PFAs estimated from GMSM Methods for R05, R10 and R15 buildings.
Conclusions

In this study, alternative target spectra for estimating seismic demands and reducing computational effort of mCMS were evaluated. Based on nonlinear RHAs of three multistory buildings and ten idealized buildings, we obtain the following conclusions:

1. The mCMS method leads to the smallest median and interquartile range of story drift estimates.
2. The UHS method provides over-conservative estimates and interquartile range of maximum story drifts in comparison to the mCMS.
3. The sGCMS and the composite methods lead to conservative estimates of story drifts in comparison with the mCMS method, but they are smaller than those from the UHS method.
4. Because the sGCMS and the composite procedures provide conservative, but generally not overly conservative, estimates of seismic demands, it should be useful for practical application in estimating seismic demands for evaluating existing buildings or proposed designs of new buildings.

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