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Ground Motion Selection Using Code-Compliant Conditional Mean Spectra: Effects of Conditioning Period and Amplitude Constraints

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ABSTRACT

The spectral target used for ground motion selection greatly influences the results obtained from nonlinear response history analysis. In particular, the conditional mean spectrum (CMS) has been recognized as an appealing alternative to the uniform hazard spectrum (UHS) as a spectral target due to the former's more realistic shape and reduced conservatism. This work uses a tall building in a high-seismicity region as a case study to evaluate the building demands generated by simplified, code-compliant procedures which use CMS-based target spectra and compares the results with those of UHS-based and theoretically rigorous CMS-based selection. Implementation of the CMS-based procedure codified in ASCE 7-22 with apt choice of two conditioning periods is found to satisfactorily capture theoretical results while also reducing the conservatism of UHS-based results. Additionally, raising the amplitude constraint on target spectra from the codified 75% of the UHS to 90% is shown to introduce a modest level of conservatism above theoretical CMS demands. Findings further illustrate the contrast in how various building demands, such as interstory drift and base shear, depend on the choice of conditioning period and the modal properties of the structure.

Introduction

Ground motion record selection is a key step in performing nonlinear response history analysis of structures for seismic design applications. The most commonly used target spectrum for record selection, the uniform hazard spectrum (UHS), constitutes an envelope across all periods of spectral acceleration (*Sa*) values having a specified exceedance probability (e.g., 2% in 50 years). The UHS is inherently conservative because it is unlikely for a single ground motion to achieve spectral amplitudes of equally rare exceedance probability at all periods simultaneously. Alternatively, use of the conditional mean spectrum (CMS) [1-2] for target spectra has been shown to better approximate the shape and realism of individual ground motion response

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spectra. Examples of lowered structural demands obtained using CMS-based target spectra exist [e.g., 3-4] and performance-based tall building design guidelines currently recommend use of CMS over UHS [e.g., 5-6]. However, the effects of simplifying provisions in codified CMS-based selection procedures on the resulting building demands have not been thoroughly investigated.

Using a tall building located in a high-seismicity region as a case study, this work compares the building demands produced by the simplified CMS-based procedures of ASCE 7-22 [7] and Carlton and Abrahamson ("C&A-14") [8] against the results of UHS-based and theoretically rigorous CMS-based ground motion selection procedures. In particular, we evaluate the effects of different lower-bound constraints on spectral amplitudes (i.e., 75% of the UHS from ASCE 7-22 and 90% of the UHS from C&A-14) and of different choices of conditioning period (T^*) for CMS-based target spectra. Further discussion of the work presented herein can be found in [9].

Building of Study

The structure under consideration in this study is a 42-story reinforced concrete core wall building located in Los Angeles, California. It was originally developed as building 1C in the Task 12 report of the PEER Tall Buildings Initiative (TBI) [10] and designed to meet "performance-based plus" design criteria (relative to [6, 11]) at 2475- and 43-year return period shaking levels. Fig. 1 illustrates the two-dimensional OpenSees [12] analysis model of the building. The total seismic weight of the building as-modeled is 200 MN, and its first three natural periods are 4.2s, 1.0s, and 0.5s. Further modeling details are provided in [13].

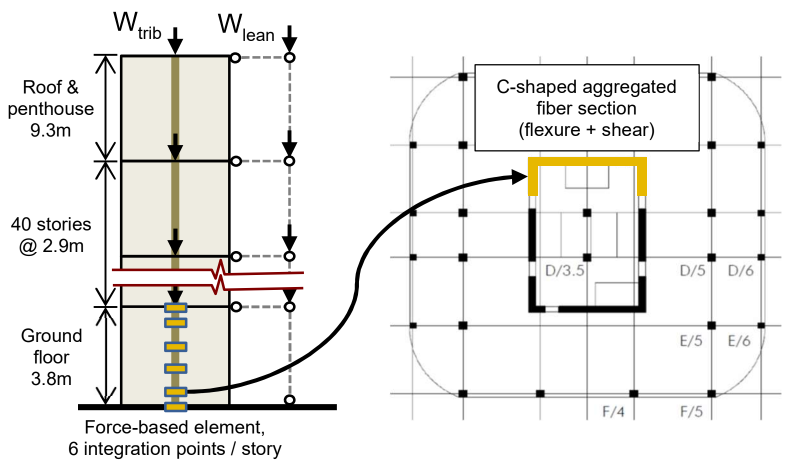

Figure 1. Diagram of the two-dimensional analysis model of the 42-story concrete core wall building of study, in elevation (left) and section (right). Figure adapted from [10, 13].

Target Spectra and Analysis Procedure

The model was subjected to suites of MCE-level ground motions selected in accordance with the CMS-based procedures of ASCE 7-22 and C&A-14. Both procedures allow for a minimum of two target spectra with distinct conditioning periods (T^*). In addition, ASCE 7-22 requires that the amplitude constraint only be enforced within a specified range of periods. This period range for the case study building is shown in Fig. 2(a) along with one example pair of ASCE 7-22-compliant CMS-based target spectra. From the numerous possible choices of T^*, we select three representative pairs to use with each procedure to illustrate the effects on the resulting building demands: {1s, 5s} (preferred choice, based on modal properties and theoretical CMS results of [9]), {0.15s, 9s} (very poor choice), and {3s, 8s} (intermediate choice). Fig. 2(b) and (c) show these three pairs as implemented in accordance with ASCE 7-22 (b) and C&A-14 (c). Suites of 40 ground motions in the one-dimensional horizontal component were selected for each target spectrum according to the algorithm of [14] using a subset of the NGA-West2 database [15].

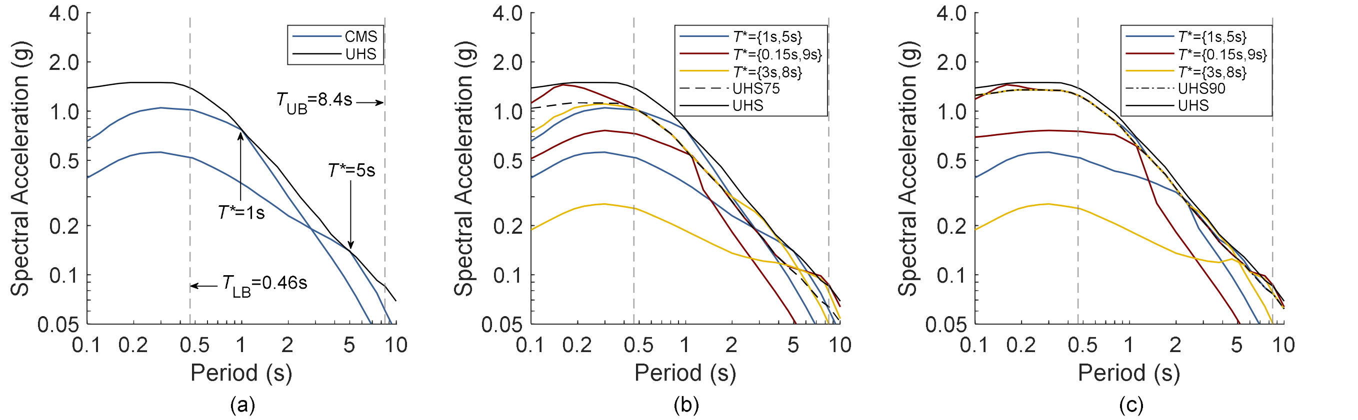

Figure 2. Sets of CMS-based target spectra used for ground motion selection: (a) single pair of target spectra compliant with ASCE 7-22 requirements [7]; (b) all pairs compliant with ASCE 7-22; (c) all pairs compliant with C&A-14 [8]. For reference, dashed vertical lines indicate lower and upper bounds T_{LB} and T_{UB} of ASCE 7-22 period range of amplitude constraint.

Results and Discussion

For each of the 40 ground motions selected per target spectrum, demand envelopes over the building height were constructed by recording peak values of three engineering demand parameters (EDPs) at each story: interstory drift ratio (*IDR*), story shear (*V*), and floor acceleration (*FA*). These EDPs were selected to collectively capture the effects of both short- and long-period modal properties of the structure on various types of building demands. The 40 envelopes over the building height were averaged at each story for each EDP, and the maximum average value across all stories was recorded. These maximum values are plotted in Fig. 3 for the three EDPs, with abscissas corresponding to the T^* of the respective target spectra and square and diamond markers denoting ASCE 7-22 and C&A-14 results, respectively. Horizontal lines demarcate the demands produced using UHS- and theoretical CMS-based procedures from [9] for reference. We treat the theoretical CMS results as the "true" results of CMS-based ground motion selection in ensuing discussion. As in Fig. 2, vertical lines demarcate the extents of the ASCE 7-22 period range for amplitude constraint.

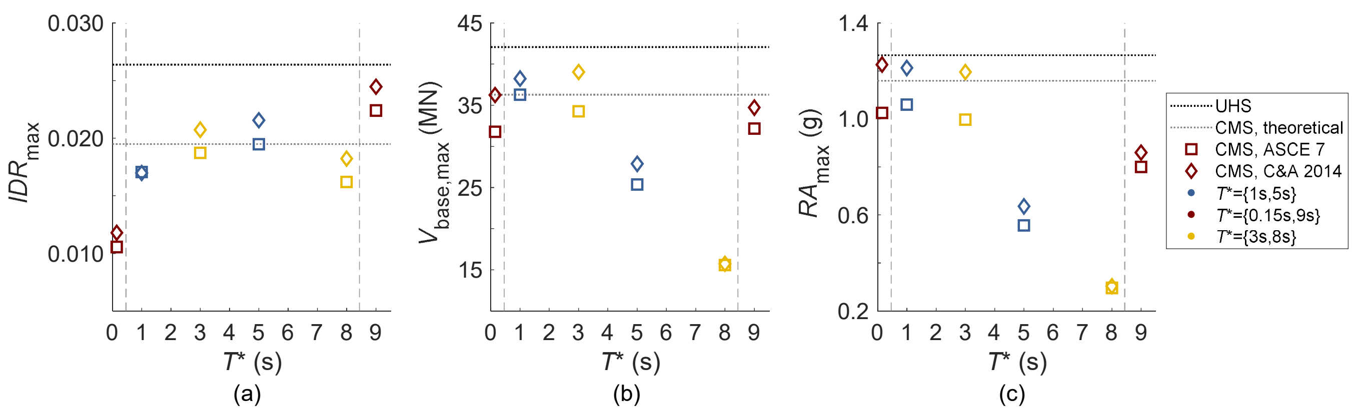

Figure 3. Maximum building demands produced using ground motion selection procedures based on UHS, theoretical CMS, ASCE 7-22 CMS, and Carlton and Abrahamson 2014 CMS: (a) interstory drift ratio (IDR_{max}); (b) base shear (B_{aseman}); (c) roof acceleration (RA_{max}).

Fig. 3 shows that all demands produced by ASCE 7-22 target spectra sets in this study are lesser in magnitude than the UHS-based demands of 2.64% drift, 42.1 MN base shear (21% of seismic weight), and 1.27g roof acceleration. In particular, the UHS results exceed the demands generated using the preferred and intermediate choices of *T** with ASCE 7-22 by 16-35% and 23-41%, respectively. Among ASCE 7-22 target spectra, the preferred set with *T**={1s, 5s} produced the largest base shear and roof acceleration demands, and the second-highest drift demand. These results satisfactorily corroborate those of the theoretical CMS procedure, particularly for interstory drift and base shear, with a small amount of underestimation (9%) for roof acceleration. The other two cases of {0.15s, 9s} and {3s, 8s} similarly tend to underestimate the theoretical CMS procedure's results by a modest amount (4-14%).

The one exception to this trend is the drift demand produced by the {0.15s, 9s} set, which exceeds the theoretical CMS demand by 15%. While this discrepancy is conservative in nature, it illustrates one unfavorable aspect of poor choice of *T**. When only two target spectra are being used and there is a large difference between their respective *T**, artificially raising the two target spectra to meet the 75% UHS constraint may need to be substantial and may, for targets with long-period *T**, lead to high spectral amplitudes over a wide range of longer periods that serve to magnify interstory drift-related demands. Apart from this exception, the results across the three pairs of target spectra reflect the dependency of building demands on the modal properties of the structure. It is thus uncoincidental that the target with *T**=5s, which is equivalent to the fundamental period of the case study building elongated by 20%, produces the greatest drift demand among the ASCE 7-22 target spectra used in this study, and the target with *T**=1s produces the greatest base shear and roof acceleration demands. In terms of which *T** are observed to maximize various EDPs, these results generally agree with those of [16] as well as with known relationships between modal properties and building demands explained by structural dynamics. Interstory drift is a largely first-mode-dominated phenomenon whereas story shear and floor acceleration are more sensitive to higher mode effects.

Turning to the results of the alternative amplitude constraint specified by Carlton and Abrahamson, Fig. 3 indicates that the demands for all three types of EDPs are consistently greater than those produced using ASCE 7-22 while not exceeding those of UHS-based selection. The demands produced using Carlton and Abrahamson with all three target sets are 3-11% greater than those produced using the theoretical CMS procedure, with two exceptions. The base shear demand of the poor target set is insignificantly lower (by 0.10%) than its theoretical CMS counterpart, and the drift demand of the poor target set is 26% greater than its theoretical CMS counterpart for similar reasons as the analogous ASCE 7-22 poor target set previously discussed.

Conclusions

This work has demonstrated that the simplified conditional mean spectrum (CMS)-based ground motion selection procedure in the current building code considerably reduces the conservatism inherent to uniform hazard spectrum (UHS)-based selection while also yielding comparable results to theoretically rigorous CMS-based selection. We have shown this for a two-dimensional analysis of a tall building by using just two CMS-based target spectra, with ideal or slightly perturbed conditioning periods (*T**), for story drift-, story shear-, and floor acceleration-related demands. Modest conservatism over the “true” results of theoretical CMS-based selection is obtained by enforcing a sufficiently high amplitude constraint such as 90% of the UHS, rather than the current building code’s 75% UHS provision. Choices of *T** should consider the modes which most greatly influence the types of structural response of interest, and should avoid large gaps between *T** which may inflate building demands as a result of substantial augmentation of target spectra to meet amplitude constraints.

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