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Investigation of the Applicability of the FEMA P695 Approach for the Consideration of the Spectral Shape Effect in Canada

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ABSTRACT

A key component of the nonlinear time-history analysis of structures is the selection and scaling of ground motion records. The uniform hazard spectrum (UHS) is the most commonly used target response spectrum for record selection. However, due to the inherent conservatism of UHS, its appropriateness as a target spectrum has been raised in the research literature. A parameter epsilon (ε), which is an indicator of spectral shape, may be used to account for this conservatism of the UHS. In the US, FEMA P695 has introduced a spectral shape factor to account for the effect of epsilon in dynamic analysis of structures. In contrast, there is currently no such systematic and simplified method for consideration of the spectral shape effect in Canada. This study first provides a critical review of the theoretical basis and suitability of adopting a spectral shape factor for use in seismic design in Canada. The significance of considering spectral shape in nonlinear dynamic analysis of structures is investigated at two sites in Eastern and Western Canada with different seismic hazard characteristics. The conditional mean spectra (CMS) of the selected sites are constructed and used as the target spectrum for record selection. CMS takes into account the effect of spectral shape in a comprehensive manner using data obtained from the deaggregation analysis of the site. By comparing the results obtained from nonlinear dynamic analyses using the CMS-based selected records and a general record set without consideration of epsilon, the effect of the spectral shape factor for each site is determined and compared to that obtained from the FEMA P695 methodology. It is found that considering the spectral shape can substantially decrease the seismic demand on structures in Western Canada, while there is not a significant difference in Eastern Canada. It is shown that there can be a considerable difference between the results of CMS-based analysis and the simplified FEMA P695 consideration of spectral shape using a single factor. This difference is mainly attributed to simplifications made in FEMA P695 to facilitate its application. It is concluded that, if a specific set of challenges identified in this study are addressed, the suggested simplified approach of the FEMA P695 can be adapted for consideration of the spectral shape effect in Canada.

Keywords: seismic performance assessment, record selection, spectral shape, conditional mean spectrum, FEMA P695.

INTRODUCTION

With the advancement in computing technologies and development of reliable nonlinear material models, the nonlinear time history analysis (NLTHA) method has gained significant attention in recent years for seismic evaluation and performance-based design of structures under earthquake loads. A key component of the NLTHA is the selection and scaling of ground motion records so that the probable seismic hazard characteristics at the site of interest are considered. Generally, a target response spectrum that accounts for all possible earthquake scenarios at the site is constructed, and records with appropriate causal parameters such as magnitude (M), distance (R), and soil shear wave velocity ($V_{s,30}$) that properly represent the target spectrum over a period range of interest are selected. The uniform hazard spectrum (UHS) is recognized as the most commonly used target spectrum for NLTHA; however, several studies have shown that it may be overly conservative in estimating the structural response [1,2]. Since UHS is a single envelope of all spectral acceleration values at various periods resulted from all possible earthquake sources for a given ground motion hazard level, it is not possible for an individual record to have such high amplitudes at all periods [1,3]. According to Baker and Cornell [1], in addition to the general record selection criteria (e.g., *M*, *R*, etc.) another parameter called epsilon (ε) should also be considered. Epsilon represents the difference between the spectral acceleration of a recorded ground motion and the median value predicted by a ground motion prediction model (GMPM) and can be determined from the following equation at any given period:

$$\varepsilon(T) = \frac{ln\,Sa(T) - \mu_{ln\,Sa}(M,R,T,\theta)}{\sigma_{ln\,Sa}(M,T,\theta)} \tag{1}$$

where $\mu_{ln\,Sa}(M,R,T,\theta)$ and $\sigma_{ln\,Sa}(M,T,\theta)$ are the predicted mean and standard deviation of $ln\,Sa(T)$ at a given period calculated using an attenuation model, $ln\,Sa(T)$ is the log of the spectral acceleration of interest, and θ represents other input parameters of the GMPM, such as fault mechanism, dip angle, etc.

For a linear elastic single-degree-of-freedom (SDOF) system, the effect of a record on a structure can be adequately represented by using only the spectral acceleration at the fundamental period (T_1). For a nonlinear multi-DOF system, however, the dynamic structural response can also be affected by periods shorter and longer than T_1. The shorter periods correspond to excitations of higher modes of the structure, while the longer periods are important to account for the damage and nonlinearity effects. When a structure experiences damage and exhibits a nonlinear behavior, the effective period of its first mode increases to a period larger than T_1 due to reduction in the structural stiffness. Therefore, if a nonlinear multi-DOF system is analyzed under two records with the same $Sa(T_1)$ value, the record with higher spectral accelerations at periods other than T_1 will tend to result in higher structural demands (base shear, roof displacement, etc.). Baker and Cornell [1] investigated the relationship between $Sa(T_1)$ and spectral accelerations at periods other than T_1 by using two records with different epsilon values at T_1, one with a positive epsilon ("peak" record) and another one with a negative epsilon ("valley" record). By scaling the two records to have the same spectral acceleration at T_1, they demonstrated that the valley record tended to have higher spectral accelerations at other periods compared to the peak record (see Figure 1). Therefore, the authors concluded that records with a positive epsilon at T_1 will result in less structural damage than valley records. To consider this spectral shape effect (i.e., peak and valley effect) they suggested that epsilon should be considered in the selection of ground motion records in addition to the magnitude, distance, and soil conditions of the site.

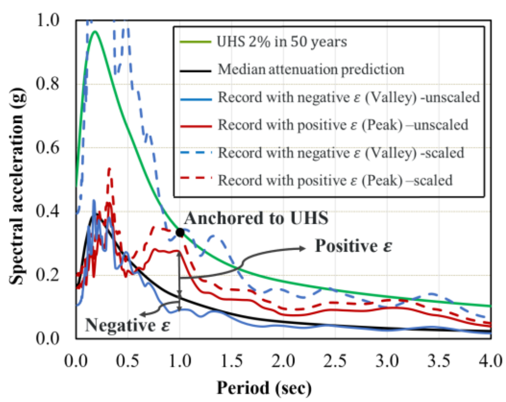

Figure 1. Effect of positive and negative epsilon values on response spectral shape.

Various methods have been proposed to account for the spectral shape effect in dynamic analysis of structures. One of the most well-known approaches, which was developed by Baker and Cornell [4], is to use the Conditional Mean Spectrum (CMS) as an alternative target response spectrum for record selection. The Conditional Spectrum (CS) by Jayaram et al. [5] and the Generalized Conditional Intensity Measure (GCIM) method by Bradley [6] are other variations of this approach. Another method proposed by the Federal Emergency Management Agency (FEMA) document *"Quantification of Building Seismic Performance Factors – FEMA P695"* [7] introduced a spectral shape factor (SSF) that accounted for the spectral shape effect in seismic collapse assessment of structures. In FEMA P695 [7], SSF was developed based on the work conducted by Haselton and Deierlein [8] on the relationship between the collapse capacity of structures and the epsilon corresponding to the site and the fundamental period of the structure. Currently, there is a lack of such a systematic methodology in Canada that considers the spectral shape effect on seismic behavior assessment of structures based on the Canadian design practice and the specific seismic hazard characteristics in Canada. Development of such a systematic procedure first requires assessment of the spectral shape effect in major Canadian cities using well-established methods from the literature and also evaluation of the applicability of the FEMA P695 [7] procedure to Canada. In this study, firstly a brief overview of the theoretical basis of the FEMA P695 [7] and CMS methods is presented, and then the necessity of considering the spectral shape effect in nonlinear dynamic analysis of structures for two sites in Eastern and Western Canada is evaluated. The evaluation process involved comparing the collapse capacity of a series of SDOF systems with various periods and nonlinear behaviour determined under a number of different ground motion record sets using both the CMS-based and FEMA P695 [7] methods. It is found that there can be a considerable difference between the results of CMS-based and FEMA P695 [7] methods that is mostly attributed to the simplifications made in the FEMA P695 [7] approach including accounting for the effect of epsilon only at a single period (fundamental period in this study) rather than the entire period range of the spectral response. The importance of accurate consideration of the complicated seismic hazard characteristics in Western Canada in the evaluation of the spectral shape effect is also demonstrated.

OVERVIEW OF CMS METHOD AND FEMA P695 SPECTRAL SHAPE METHOD

In order to account for the spectral shape effect, FEMA P695 [7] utilizes the SSF and adjusts the collapse margin ratio (CMR) of the structure which provides a quantitative measure of the life safety performance. The definition of the SSF is based on a closed-form equation originally developed by Haselton and Deierlein [8] and further improved by Haselton et al. [9]. As shown in Eq. (2), the SSF is computed by multiplying the β_1 factor that represents the sensitivity of the structure to the epsilon value by the difference between the target epsilon value obtained from the deaggregation analysis of the site ($\bar{\varepsilon}_0$) and the mean epsilon value of a predetermined set of earthquake records that are used to assess the building performance ($\bar{\varepsilon}_{records}$).

$$SSF = exp(\,\beta_1[\bar{\varepsilon}_0(T) - \bar{\varepsilon}(T)_{records}]) \tag{2}$$

Figure 2.a presents a schematic illustration of the application of Eq. (2) for collapse adjustment in FEMA P695. As shown in this figure, FEMA P695 approximates the relationship between the collapse capacity and epsilon with a simple linear relationship which may not be accurate for structural systems with different characteristics located at different sites. It also provides a simple equation for $\beta_1$which was originally developed by Haselton et al. (2011) based on collapse analysis of 111 reinforced concrete frame buildings. FEMA P695 extended these collapse analyses to light frame wood structures and derived an alternative relationship for β_1 (see Eq. (3)) in terms of the period-based ductility of the structure (μ_T). The period-based ductility is defined as the ratio of the ultimate displacement (δ_u) to the effective yield displacement ($\delta_{y,eff}$) of the structure determined based on a nonlinear pushover analysis. The value of β_1 in Eq. (3) tops out at a μ_T value of 8.0 which corresponds to a β_1 of 0.32. This is because the analysis data shows that β_1 does not change above this level of ductility. The applicability of Eq. (3) to other structural systems (steel moment frames, steel braced frames, etc.) has not been verified.

$$\beta_1 = (0.14)[\mu_T - 1]^{0.42} \tag{3}$$

In Eq. (2), $\bar{\varepsilon}_0(T)$ is the target epsilon value for the site and hazard level of interest that can be determined using data provided by the United States Geological Survey (USGS) for different regions in the US and for two different periods: 0.2 s and 1.0 s. In FEMA P695 [7], only the data for the 1.0 s period is used since according to the document "most building structures have periods closer to 1.0 second, or greater than 1.0 second. Buildings with periods near 0.2 seconds are relatively rare." [7]. For each Seismic Design Category (SDC), $\bar{\varepsilon}_0(T)$ needs to be related to the seismic hazard level at collapse, not necessarily the Maximum Considered Earthquake (MCE) level, since it will be used to modify the collapse margin ratio. FEMA P695 [7] uses the 0.5% in 50 years seismic demand for the calculation of $\bar{\varepsilon}_0$ since this is approximately 2.0 times the MCE level (2% in 50-year probability of exceedance) demand which is consistent with the target adjusted collapse margin ratio (ACMR) of 2.0 and also meets the 10% collapse probability acceptance criteria specified in [7]. As a further simplification, FEMA P695 [7] uses the average value of $\bar{\varepsilon}_0$ for each SDC which results in a value of 1.0 for SDC B and C, 1.5 for SDC D, and 1.2 for SDC E. Therefore, by assuming a vibration period of 1.0 s, using ACMR of 2.0, categorizing data based on SDC, and simplifying the 0.5% in 50-year values into two groups, only three $\bar{\varepsilon}_0(T)$ values are available in [7], $\bar{\varepsilon}_0$ = 1.0 for SDC B and C and $\bar{\varepsilon}_0$ =1.5 for SDC D, and 1.2 for SDC E. Thus, the calculation of the target epsilon $\bar{\varepsilon}_0$ in FEMA P695 [7] is not period-dependent (it assumes a building period of 1.0 s) which may not be accurate for structures with fundamental periods shorter than or higher than 1.0 s.

$\bar{\varepsilon}(T)_{records}$ in Eq. (2) is the mean of the $\bar{\varepsilon}(T)$ values for a predetermined far-field record set that is used for all analyses. To determine $\bar{\varepsilon}(T)_{records}$, the average of the epsilon values for all records at each period (*T*) between 0 s and 4.0 s was calculated, and based on a simplified trilinear trend, Eq. (4) was proposed as a function of the period. This equation is only applicable to the FEMA P695 [7] far-field record set. For other record sets, the value of $\bar{\varepsilon}(T)_{records}$ needs to be calculated by taking the average of the epsilon values for all records at each period.

$$0 \leq \bar{\varepsilon}(T)_{records} = (0.6)(1.5 - T) \leq 0.6 \tag{4}$$

A more accurate method to consider the spectral shape effect is to use an alternative target response spectrum called the Conditional Mean Spectrum (CMS) originally developed by Baker and Cornell [4] and later enhanced by Jayaram et al. [5]. Knowing the target epsilon value at the period of interest (*T**) (which is typically taken as the fundamental period of the structure, T_1), and using a correlation coefficient between $\varepsilon(T^*)$ and the epsilon value at periods other than *T**, the corresponding spectral acceleration values at all periods are determined. The resultant target response spectrum matches UHS only at the period of interest while providing lower spectral acceleration values at other periods making the response spectrum closer to the mean spectrum values obtained from the ground motion model. For constructing the CMS, first, using the deaggregation analysis results of the site for a specific hazard level, period of interest and a GMPM, the logarithmic mean and standard deviation of $Sa\ (T)$ at all periods, denoted as $\mu_{\ln Sa}(\mathrm{M, R, T}_i, \theta)$ and $\sigma_{\ln Sa}(\mathrm{M, T}_i, \theta)$, need to be computed. Then given $\varepsilon(T^*)$ value from deaggregation, the mean epsilon value at other periods is determined from Eq. (5):

$$\mu_{\varepsilon(T_i)|\varepsilon(T^*)} = \rho(T_i, T^*)\varepsilon(T^*) \tag{5}$$

where $\mu_{\varepsilon(T_i)|\varepsilon(T^*)}$ is the mean value of $\varepsilon(T_i)$ given $\varepsilon(T^*)$, and $\rho(T_i, T^*)$ is an empirical correlation coefficient between pairs of ε values at two periods. By combining $\mu_{\varepsilon(T_i)|\varepsilon(T^*)}$ with $\mu_{\ln Sa}(\mathrm{M, R, T}_i, \theta)$ and $\sigma_{\ln Sa}(\mathrm{M, T}_i, \theta)$ calculated from the deaggregation analysis, the conditional mean spectral acceleration values at any period (T_i) can be computed from Eq. (6). Figure 2.b shows a schematic representation of the CMS relative to the UHS and the median prediction spectrum. As it can be seen, the CMS matches the UHS at the conditioning period and is adjusted by $\mu_{\varepsilon(\mathrm{T_i})|\varepsilon(\mathrm{T^*})}\sigma_{ln\,Sa}(M, \varepsilon, T_i)$ term to consider the spectral shape effect at other periods.

$$\mu_{ln\,Sa(T_i)\,|\,ln\,Sa(T^*)} = \mu_{ln\,Sa}(M, R, T_i, \theta) + [\mu_{\varepsilon(T_i)|\varepsilon(T^*)}]\sigma_{ln\,Sa}(M, T_i, \theta) \tag{6}$$

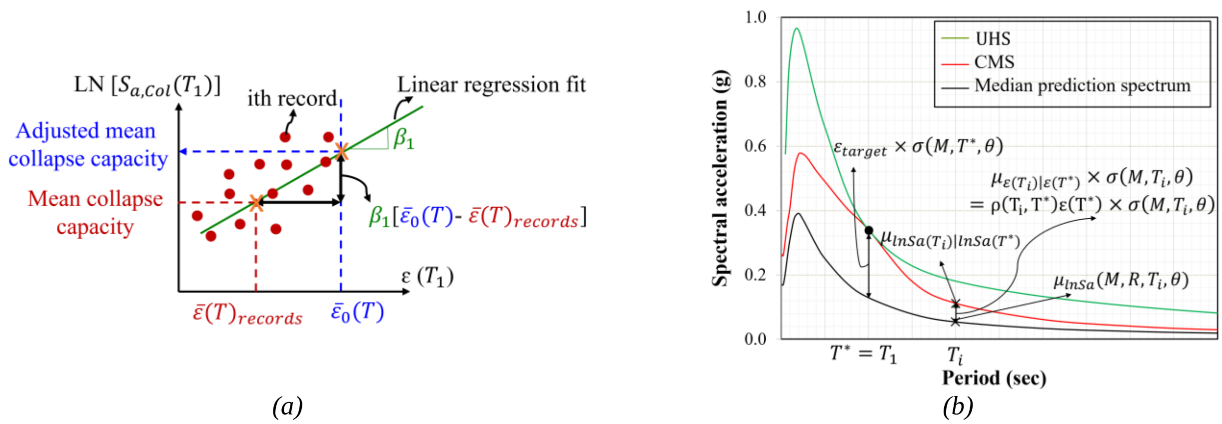

Figure 2. Consideration of the spectral shape effect: (a) FEMA P695 [7] approach, (b) CMS method.

Compared to the UHS which is the most commonly used target spectrum in practice, the CMS is more accurate and less conservative leading to a more efficient structural design in terms of cost and time. The CMS is also more comprehensive than UHS since it uses information obtained from deaggregation analysis (magnitude, distance, ε) to predict spectral acceleration values. In Canada, studies related to the spectral shape effect are mostly focused on the seismic behavior assessment of structures using CMS or other similar alternative target spectra [10-13]. To the best of the authors' knowledge, there has not been any study in the literature that has specifically investigated the effect of spectral shape and the applicability of the FEMA P695 [7] collapse adjustment method at different Canadian sites in a comparative manner. In the following section, the significance of considering the epsilon effect for two sites in Eastern and Western Canada is investigated by conducting a series of nonlinear dynamic analyses using different sets of records.

EVALUATION OF THE EPSILON EFFECT IN EASTERN AND WESTERN CANADA

To investigate the applicability of the FEMA P695 [7] method in the Canadian seismic design context, two sites with different seismic hazard properties and with a site class of C ($V_{s30} = 450\ m/s$) were considered in this study; Montreal in Eastern Canada, and Vancouver in Western Canada. Due to the different characteristics of seismic wave propagation, separate sets of GMPMs were used for each site based on the Canada's fifth generation seismic hazard model [14]. For each site, a series of nonlinear SDOF systems with two periods of 0.5 s and 1.0 s and various ductility and post-yielding capacities were considered (see Table 1). Each SDOF system was subjected to three sets of twenty ground motion records; I) a site-specific record set selected based on the seismic hazard deaggregation results for the 2% in 50-year probability of exceedance and with no consideration to the epsilon values of the records; II) CMS-based record set at the same hazard level (conditioned at 0.5 s and 1.0 s), and III) the 22 far-field ground motion set from FEMA P695 [7]. Since the seismic hazard in southwestern of British Columbia is dominated by three earthquake types of crustal, subcrustal, and interface, ground motion records for Vancouver were selected to represent each of these earthquake types based on their relative contribution to the seismic hazard at the hazard level and period of interest. The seismic deaggregation results provided by Halchuk et al. [15] at the probability of exceedance of 2% in 50 years and periods of 0.5 s and 1.0 s were used in this study. For the site-specific record set, ground motion records were selected such that they satisfy the seismic hazard properties of the site in terms of magnitude, distance, and site conditions and also match the 2% in 50-year UHS for each site over the period range of (min [0.2 T_1,$T_{90\%}$], max [2.0 T_1,1.5 s]) as recommended by [16]. A linear scaling factor was applied to each individual record to match the UHS. According to [16], an additional scale factor was used to ensure that the mean of the selected records stays above 90% of UHS for the corresponding period range. The minimum and maximum scale factors were limited to 0.25 to 4.0, respectively. In cases that appropriate ground motions could not be selected, this limitation was extended to obtain the proper sets. Due to the different contributions of three earthquake types at 0.5 s and 1.0 s in Vancouver, two different site-specific sets were selected with different numbers of crustal, subcrustal, and subduction events; I) 5, 10, and 5, respectively for 0.5 s period, and II) 5, 5, and 10, respectively for 1.0 s period. The NGA-West2 database [17] was used to select shallow crustal events, the K-NET [18], KiK-net [19], and COSMOS [20] databases were used to select subduction events from Japanese and worldwide events, respectively. No more than three records were selected from a single event, except for the subduction records that were selected from $M_w = 9.0$ 2011 Tohoku-oki Japan, $M_w = 8.8$ 2010 Maule Chile, and $M_w = 8.3$ Tokachi-Oki Japan earthquakes. For Montreal, due to the limited number of sufficient recorded ground motions both the PEER NGA-East [21] and NGA-West2 [17] databases were used for record selection. To account for the differences between the seismic properties in Eastern and Western Canada, such as the relatively high spectral amplitudes at short periods and slower rates of ground motion attenuation at short periods in Eastern Canada, ground motion records were selected to meet the deaggregation results of the site and match the UHS over the period range of interest. Figure 3 shows the 2% in 50-year UHS for site class C in Vancouver and Montreal based on the NBC 2015 [16] and the response spectra of the site-specific record sets selected for each site.

To evaluate the results of the FEMA P695 [7] approach, the CMS method was used as an alternative approach for considering the spectral shape effect in selected sites. For this purpose, using the suggested ground motion models by Atkinson and Adams [22] for Eastern and Western Canada and the correlation model developed by Baker and Jayaram [23], conditional mean spectra were constructed for the considered SDOF systems (conditioned at 0.5 s and 1.0 s). Appropriateness of this correlation model for earthquake types other than the shallow crustal events that were used by [23], was studied by Daneshvar et al. [24] and Fairhurst [25] for Eastern and Western Canada, respectively. For Vancouver, three event-specific conditional mean spectra were developed and suites of twenty ground motions were selected to represent each of the three earthquake types using the same number of records used for each event type of the site-specific set discussed previously. The earthquake causal parameters (magnitude, distance, depth, and site conditions) were also considered for selection of the records based on the seismic deaggregation results at both sites. To compare the response spectral shape of the records with the target mean spectrum over the period range of interest [min (0.2 T_1,$T_{90\%}$), max (2.0 T_1,1.5 s)], the greedy optimization algorithm developed by Baker and Lee [26] was used for each individual component of ground motions. Figure 4 illustrates the 2% in 50-year CMS conditioned at 1.0 s and the mean response spectra of the selected records for Vancouver and Montreal. As it can be seen from Figure 4.a, the CMS-interface target spectrum has significantly higher spectral content at long periods compared to the subcrustal and crustal CMS target spectra. This fact as well as the remarkably longer duration of the interface events can lead to significant reduction in the collapse capacity of ductile structures with longer periods [12]. According to Figure 4.a, increasing the number of interface records can result in a record set with a mean response spectrum much closer to the UHS, and consequently, can reduce the effect of epsilon and spectral shape adjustment on collapse assessment results. Also, the mean response spectra of all the selected sets (including the FEMA P695 [7] far-field set) are scaled to match at 1.0 s to better illustrate the difference between the spectral shape of the selected records (see Figure 4.c and d).

Table 1. Summary of the response parameters of the considered SDOF models.

Model number	T_1 (sec)	μ	α_C
1	0.5	4.0	-0.1
2	0.5	4.0	-0.3
3	0.5	6.0	-0.1
4	0.5	6.0	-0.3
5	0.5	8.0	-0.1
6	0.5	8.0	-0.3
7	1.0	4.0	-0.1
8	1.0	4.0	-0.3
9	1.0	6.0	-0.1
10	1.0	6.0	-0.3
11	1.0	8.0	-0.1
12	1.0	8.0	-0.3

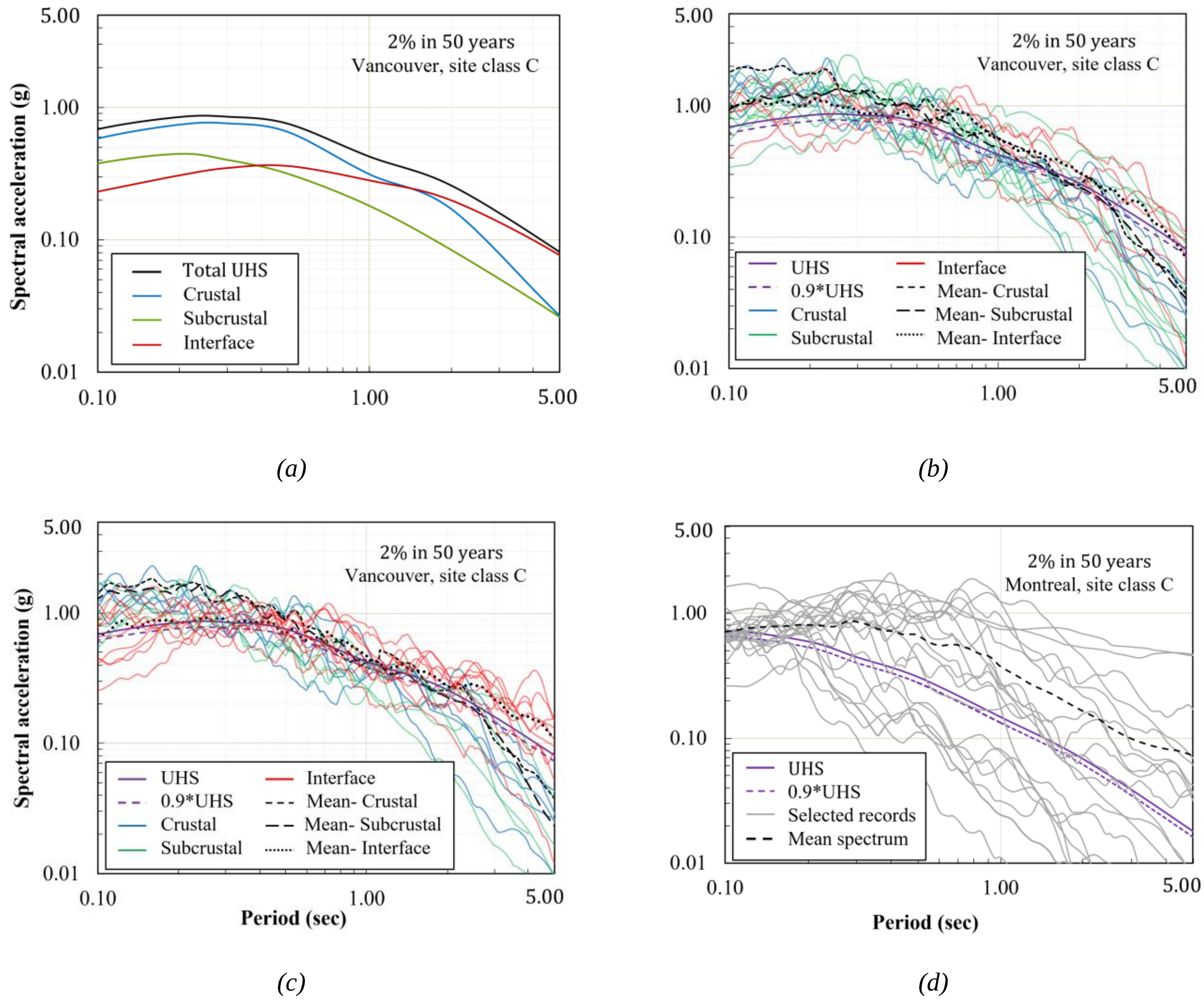

Figure 3. (a) Event-specific 2% in 50-year UHS for Vancouver. Comparison of the response spectra of the site-specific set in: (b) Vancouver for $T_1 = 0.5\ s$, (c) Vancouver for $T_1 = 1.0\ s$, (d) Montreal.

For conducting incremental dynamic analysis (IDA) [27], the SDOF systems were modeled in the OpenSees software [28] using the trilinear force-displacement model developed by Ibarra et al. [29]. According to Table 1, different pre-capping and post-capping regions were considered to capture various nonlinear responses under selected record sets (see Figure 5). For collapse simulation of the system subjected to a given ground motion, the collapse point was defined as the first-mode spectral acceleration that results in dynamic instability or the ductility value ($\mu = \Delta_{cap}/\Delta_y$) of 5.0 [2]. To assess the effect of spectral shape on collapse capacity of the models, the site-specific record set (selected with no consideration to epsilon), the CMS-based set, and the FEMA P695 [7] far-field set were utilized for performing the IDA. Using the cumulative distribution function of the IDA results, collapse fragility curves for each site were generated. Using the collapse fragility curves, the median collapse capacity values of the SDOF models based on the three types of record sets are determined and presented in Table 2. The ratio of the median collapse capacity given the CMS-based set ($\hat{S}_{CT,CMS}$) to that obtained from the site-specific set ($\hat{S}_{CT,SS}$) and far-field set ($\hat{S}_{CT,FF}$) are also presented in Table 2 for each model. Except for the CMS-based set, none of the record sets included the effect of spectral shape. Median collapse capacity ratios larger than 1.0 indicate the significance of spectral shape effect and the necessity of adjusting the collapse capacities for a more appropriate estimation of collapse points. Among the SDOF models at both sites, the maximum and minimum median collapse capacities were observed for the models with $\mu = 8.0$ and $\alpha_c = -0.1$ (the most ductile system) and $\mu = 4.0$ and $\alpha_c = -0.3$ (the least ductile system), respectively.

According to the results, in Montreal, the estimated collapse capacities of the 0.5 s and 1.0 s models given the CMS-based set were on average 12% and 8% larger than those obtained by the far-field set, respectively. Also, the CMS-based set estimated the median collapse values of the 0.5 s and 1.0 s models to be 14% and 5% larger than those obtained by the site-specific set, respectively. The difference between the CMS-based set and the other two sets (in which the epsilon effect was not considered) is more significant for the short-period systems, which is consistent with the larger difference between the mean response spectra of the record sets at periods longer than 0.5 *s* as shown in Figure 4.

In Vancouver, the far-field set of FEMA P 695 [7] over-estimated the median collapse values of all the SDOF models, indicating the deficiency of the shallow crustal far-field set in representing the complicated seismic hazard in Vancouver. This overestimation was more apparent for the 1.0 s models which is mainly due to the larger number of interface events in the CMS-based record set and the richer spectral content of these events at periods longer than 1.0 s. However, for the site-specific set that was selected to represent different event types and match the 2% in 50-year UHS of Vancouver, all the estimated median collapse capacities were lower than those obtained by the CMS-based set (which also included different earthquake event types). By comparing the scaled mean response spectra of the site-specific set and the CMS-based selected records shown in Figure 4, it can be seen that the spectral accelerations of the CMS response spectrum are considerably lower which explains the larger collapse capacities of CMS compared to the site-specific method. The median collapse capacities obtained from the CMS-based set were on average 1.33, and 1.22 times that of the site-specific set for the 0.5 s and 1.0 s models, respectively. Given the above discussion, it can be seen that the ground motion spectral shape (epsilon), is less important for Montreal, while in Vancouver, epsilon can make a noticeable effect on collapse capacity of the models. It is noteworthy that these observations are based on the SDOF models and record selections used in this study. More research is required to draw generalized conclusions on this subject.

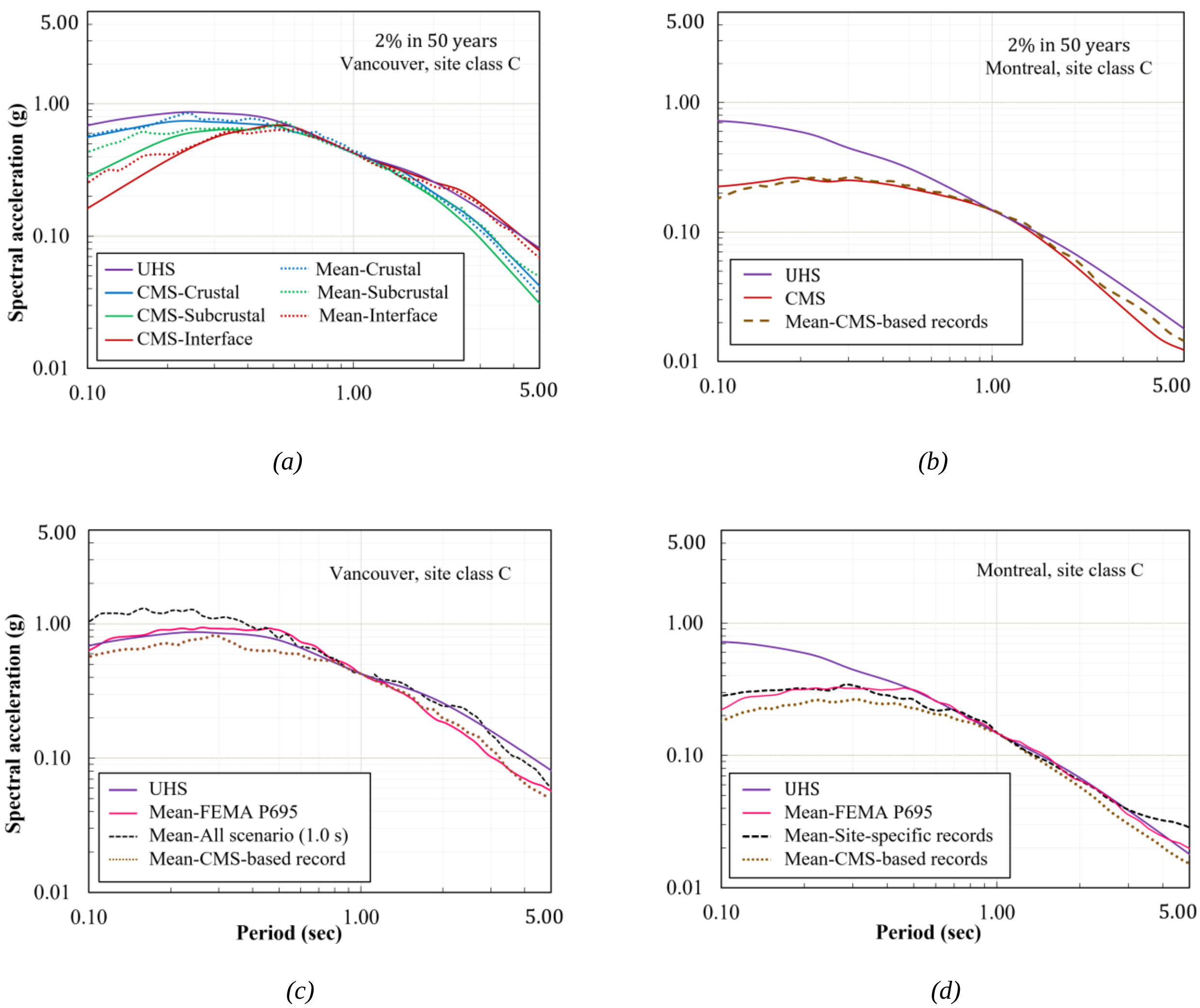

Figure 4. Conditional mean spectra and the mean response spectra of the CMS-based selected records for: (a) Vancouver, (b) Montreal (site class C, return period of 2500 years). Comparison of the mean response spectra of all the selected record sets and the FEMA P695[7] far-field set scaled to match the UHS at 1.0 s for: (c) Vancouver, (d) Montreal.

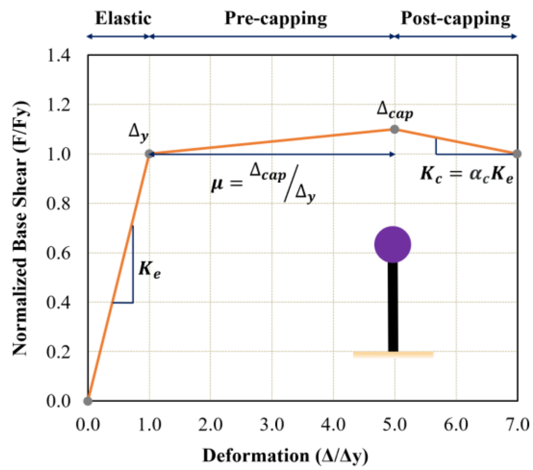

Figure 5. Backbone curve of the studied SDOF models.

Table 2. Summary of the collapse assessment results based on the unadjusted FEMA P695 [7] method and CMS.

Model number	Median collapse capacity (g): FEMA P695 method (Without SSF adjustment): Far-field set ($\hat{S}_{CT,FF}$)		FEMA P695 method (Without SSF adjustment): Site-specific set ($\hat{S}_{CT,SS}$)		CMS method: Site-specific set ($\hat{S}_{CT,CMS}$)		Median collapse capacity ratio: $\hat{S}_{CT,CMS}/\hat{S}_{CT,FF}$		$\hat{S}_{CT,CMS}/\hat{S}_{CT,SS}$	
	MTL	VAN	MTL	VAN	MTL	VAN	MTL	VAN	MTL	VAN
1	1.02	1.17	1.01	0.88	1.14	1.16	1.12	0.99	1.13	1.32
2	0.94	1.03	0.93	0.79	1.04	1.03	1.11	0.99	1.12	1.30
3	1.15	1.31	1.13	0.92	1.29	1.27	1.12	0.97	1.14	1.38
4	0.98	1.14	0.97	0.81	1.10	1.08	1.12	0.95	1.13	1.33
5	1.24	1.44	1.24	1.00	1.43	1.31	1.15	0.91	1.15	1.31
6	1.10	1.28	1.08	0.89	1.23	1.19	1.12	0.93	1.14	1.34
7	0.39	0.41	0.39	0.27	0.42	0.33	1.08	0.81	1.08	1.22
8	0.29	0.35	0.30	0.25	0.31	0.30	1.07	0.86	1.03	1.20
9	0.41	0.43	0.42	0.29	0.45	0.36	1.10	0.84	1.07	1.24
10	0.33	0.38	0.34	0.27	0.35	0.32	1.06	0.84	1.03	1.19
11	0.44	0.47	0.46	0.33	0.49	0.40	1.11	0.85	1.07	1.21
12	0.36	0.43	0.38	0.30	0.39	0.37	1.08	0.86	1.03	1.23

In order to investigate the suitability of the FEMA P695 [7] approach, the median collapse capacities of the SDOF models presented in Table 2 are adjusted by SSF values computed by Eq. (2) based on the mean deaggregation results provided by Halchuk et al. [15], $\bar{\varepsilon}(T)_{records}$ of each record set, and β_1 factors determined from ductility values of each SDOF model. The obtained SSF values for Montreal ranged from 1.027 to 1.039 for the 0.5 s models and from 1.016 to 1.022 for the 1.0 s models. In Vancouver, the computed SSF values ranged from 1.28 to 1.42 for the 0.5 s models and from 1.26 to 1.40 for the 1.0 s models. According to the results, the SDOF system in sites with larger difference between the target epsilon value and the mean epsilon values of the records must be adjusted with a larger SSF. In fact, a large target epsilon value at a site does not necessarily result in a high SSF value. The adjusted median collapse capacities of models given the site-specific and far-field sets are presented in Table 3 and compared with the CMS-based results.

As shown in Table 3, there is a good consistency between the site-specific set estimations adjusted by SSF and the CMS-based collapse capacities for the Eastern site. The CMS-based selected records for Montreal resulted in slightly larger median collapse capacity than that obtained from the adjusted site-specific set for the 1.0 s models. The ratio of collapse capacities increases to 1.10 on average for the 0.5 s models. For the far-field set, the same pattern of the ratios was observed. Based on the results, it can be concluded that in Montreal the collapse capacities of the FEMA P695 [7] and CMS methods were reasonably close with the P695 method always providing a conservative collapse adjustment compared to the CMS method. However, in Vancouver, a different trend was observed. Applying the FEMA P695 [7] approach generally resulted in larger median collapse capacity values compared to that obtained from the CMS method. Except for the SDOF models 1 to 3, all the median collapse capacity ratios were less than 1.0 with the largest difference occurring for model 11 which has a period of 1.0 s and highest level of ductility. Therefore, the SSF factors obtained from the FEMA P695 [7] method overestimate the collapse capacity in Western Canada where the target epsilon is relatively large and there is a contribution from three different earthquake types. This may be due to the fact that the FEMA P695 [7] method accounts for the spectral shape effect by considering the difference between the target epsilon and the mean epsilon of the record set only at a single period (fundamental period in this study). Thus, unlike the CMS method, the actual shape of the spectral response of the selected records at periods larger than T_1 (that plays a significant role in nonlinear response of structures under earthquake excitation) cannot be properly considered. This limitation would be even more severe for structures with higher mode effects like high-rise buildings, since a broader range of vibration periods affects the seismic behavior of the structure. These results highlight that using an SSF for adjusting the collapse capacity of a structure given a general record set selected without consideration to the epsilon values over the effective period range of the structure can lead to bias and underestimation of the probability of reaching the considered damage limit states. Since the far-field record set of FEMA P695 only contains the shallow crustal earthquakes that generally have lower spectral acceleration values compared to the response spectrum of the CMS-based set, lower earthquake loading was imposed on the structure by the far-field set. Adjustment of this estimated collapse capacity by a relatively large SSF value (1.26-1.42), led to a considerable overestimation of the collapse capacity. In fact, despite of the large target epsilon values in southwestern BC, the contribution of interface events at long periods raises the response spectrum beyond the conditioning period and increases the applied seismic force on the structure.

According to these results, it can be concluded that the FEMA P695 [7] approach for adjusting the collapse capacity can be reasonably applied to Montreal. However, in Vancouver, besides the necessity of using a site-specific ground motion set including the crustal, subcrustal and interface events (with respect to their relative contribution to seismic hazard of the site), greater caution should be exercised regarding the SSF application. In fact, due to the higher spectral content of the interface events compared to the crustal and subcrustal events at long periods, adjusting the collapse capacity estimation by an SSF value that only accounts for the effect of epsilon at a single period can lead to overestimation of the results, particularly for long-period structures with high nonlinearity. Therefore, it seems to be necessary to use a more comprehensive method such as CMS or apply a more refined spectral shape factor specifically developed for Canadian sites that can consider the effect of epsilon over the effective vibration period range of the structure. The FEMA P695 method did not overestimate the results for the short-period models with lower ductility, which can be associated with the higher contribution of crustal and subcrustal events at short periods and the lower spectral content of these records compared to the interface events. Figure 6, compares the adequacy of the adjusted median collapse capacities of all the studied models given the site-specific and far-field sets with respect to the CMS-based results for Vancouver and Montreal.

Table 3. Summary of the collapse assessment results based on the adjusted FEMA P695 [7] method and CMS.

Model number	**Median collapse capacity (g)**						**Median collapse capacity ratio**			
	FEMA P695 method (Adjusted by SSF)				**CMS method**					
	Far-field set ($\hat{S}_{CT,FF}$)		**Site-specific set ($\hat{S}_{CT,SS}$)**		**Site-specific set ($\hat{S}_{CT,CMS}$)**		**$\hat{S}_{CT,CMS}/\hat{S}_{CT,FF}$**		**$\hat{S}_{CT,CMS}/\hat{S}_{CT,SS}$**	
	MTL	**VAN**	**MTL**	**VAN**	**MTL**	**VAN**	**MTL**	**VAN**	**MTL**	**VAN**
1	1.04	1.46	1.04	1.12	1.14	1.16	1.10	0.79	1.10	1.04
2	0.95	1.29	0.96	1.01	1.04	1.03	1.09	0.80	1.09	1.02
3	1.17	1.72	1.17	1.24	1.29	1.27	1.10	0.74	1.10	1.02
4	1.00	1.50	1.00	1.10	1.10	1.08	1.10	0.72	1.09	0.98
5	1.27	1.98	1.29	1.42	1.43	1.31	1.13	0.66	1.11	0.92
6	1.12	1.76	1.12	1.26	1.23	1.19	1.10	0.68	1.10	0.94
7	0.40	0.52	0.40	0.34	0.42	0.33	1.05	0.63	1.05	0.97
8	0.29	0.45	0.30	0.32	0.31	0.30	1.07	0.67	1.03	0.94
9	0.42	0.58	0.43	0.39	0.45	0.36	1.07	0.62	1.05	0.92
10	0.34	0.51	0.35	0.36	0.35	0.32	1.03	0.63	1.01	0.89
11	0.45	0.67	0.47	0.46	0.49	0.40	1.09	0.60	1.04	0.87
12	0.37	0.61	0.39	0.42	0.39	0.37	1.05	0.61	1.00	0.88

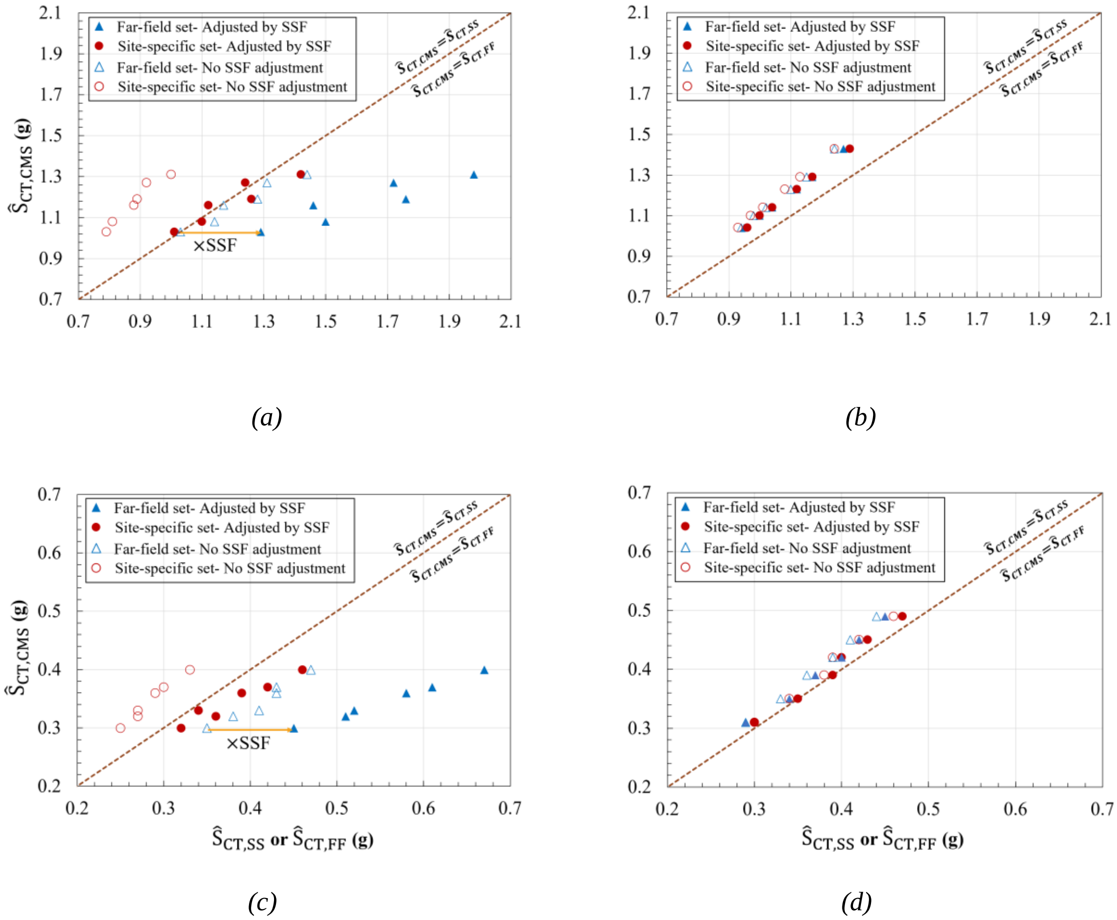

Figure 6. Comparison of the adequacy of the adjusted median collapse capacities of the site-specific and far-field sets with respect to the CMS-based results for: (a) 0.5 s models in Vancouver, (b) 0.5 s models in Montreal, (c) 1.0 s models in Vancouver, (d) 1.0 s models in Montreal.

SUMMARY AND CONCLUSIONS

In this study, to evaluate the effectiveness of the FEMA P695 method in consideration of the spectral shape effect on collapse capacity of structures in Canada, two sites in Eastern and Western Canada were considered and a series of SDOF systems with various nonlinear responses were subjected to different ground motion record sets. Ground motion sets for each site were selected based on the seismic hazard deaggregation results and a proper match with the UHS over the significant period range of the models. As an alternative approach, the conditional mean spectrum (CMS) of each site was developed, and CMS-based record sets were selected. Using the IDA results given the selected records, the median collapse fragility curve of each site was constructed. The estimated median collapse capacity of each SDOF model under the site-specific and CMS-based sets were compared to assess the significance of considering the spectral shape effect in Montreal and Vancouver. It was found that the spectral shape effect (epsilon) is less important in Montreal than Vancouver. For both sites, models with the fundamental period of 0.5 s were more affected by the difference between the response spectra of the CMS-based and site-specific record sets. Also, increasing the nonlinearity of the models by using higher ductility and lower post-capping ratios, resulted in larger differences between the estimated capacities of the two record sets. On average, the CMS-based sets estimated the median collapse capacity by 9.3% and 27.1% larger than the site-specific sets (with no consideration to epsilon) in Montreal and Vancouver, respectively, demonstrating that there is a noticeable spectral shape effect in Vancouver that needs to be considered in the seismic performance assessment.

Following the FEMA P695 method, the spectral shape factors (SSFs) for all the models were computed and applied to the median collapse capacity values to account for the effect of epsilon. Comparing the results of the CMS-based set and the adjusted site-specific set showed a reasonable consistency between the two methods in the estimation of the collapse capacity in Montreal with the SSF factors always providing a conservative adjusted collapse capacity. However, in Vancouver, the collapse capacities obtained from the adjusted site-specific set were higher than the CMS-based set, specifically for the models with longer period and higher ductility capacity, indicating that the application of SSF factors in Western Canada may not be safe. The overestimation of collapse capacity by FEMA P695 can be attributed to the fact that this method only considers the effect of epsilon at a single period (the fundamental period) and therefore cannot thoroughly capture the actual shape of the spectral response at other periods which can significantly affect the seismic collapse capacity of structures with a high ductility or higher mode effects. This limitation of P695 was more pronounced in the Western Canada because of the high contribution of the interface events with longer excitation durations and rich spectral content at long periods which resulted in a higher seismic demand on the models.

Unlike the P695 method, the CMS method accounts for the correlation between the epsilon values over the effective period range of the structure and therefore provides a more accurate estimation of the seismic response. In addition to the CMS-based and site-specific sets, the SDOF models were also analyzed under the FEMA P695 far-field set to investigate the appropriateness of this record set for seismic collapse assessment in Canada. It was observed that in Montreal, the estimated collapse capacities given the far-field set were in a good consistency with the site-specific set, and the corresponding ratios to CMS-based results were approximately equal, however, in Vancouver, the far-field set significantly overestimated the collapse capacity of all the models. This overestimation, which was more pronounced in models with a longer period and a higher nonlinearity, was due to the fact that the far-field record set only contains the shallow crustal earthquakes that generally have lower spectral amplitudes at longer periods compared to the other earthquake events that are active in Western Canada.

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