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INFLUENCE OF GROUND MOTION SCALING ON SEISMIC RESPONSE OF CONCRETE SHEAR WALL BUILDINGS

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ABSTRACT: Four methods for scaling and selecting ground motions were investigated on 11 high-rise cantilever shear wall buildings from 10 to 50 stories: (i) scaling to uniform hazard spectrum (UHS) at the fundamental period and (ii) over a range of periods, (iii) spectrum matching to UHS, and (iv) matching to the Conditional Mean Spectrum (CMS) at different conditioning periods. Results indicate that top wall displacement, maximum inter-story drifts near top of wall, and maximum curvature at base of wall are all strongly influenced by first mode response. Spectrum matched ground motions can reasonably estimate these demands without a prior knowledge of how much the fundamental period will elongate. Top wall displacement is least sensitive to how ground motions are scaled, followed by maximum curvature at base. Inter-story drifts are significantly over predicted if ground motions are not scaled over a sufficient range of periods. Wall curvatures near mid-height and shear force demands over full height are influenced by multiple modes. The mean demand from ground motions scaled over the range and spectrum-matched records were found to be similar and generally larger than the mean envelope from CMS.

1. Introduction

Nonlinear time history analysis is the most rigorous method to estimate demands on structures due to earthquakes. It is used by researchers to investigate the seismic response of structures and it is increasingly used by design engineers undertaking performance-based earthquake engineering design. It is well known that selection and scaling of ground motions can greatly influence the results of nonlinear time history analysis. Of particular interest with high-rise cantilever wall buildings are: 1) maximum wall displacements at the top of buildings, which strongly correlate to many other demand parameters; 2) maximum inter-story drifts over the height, which strongly influence demands on the gravity-frame systems, e.g., punching shear failure of slabs around gravity-load columns; 3) maximum wall curvatures at the base and near mid-height, which directly influence maximum compression strains in concrete and maximum tension strains in vertical wall reinforcing steel, and; 4) wall shear forces.

In appropriate selection and scaling of ground motions for high-rise concrete cantilever walls can result, for example, in a large overestimation of the influence of higher modes on the base shear force and on the mid-height curvatures of the wall. In the current study, the influence of different methods for selecting and scaling ground motions were investigated for 11 different high-rise cantilever shear walls that are 10, 30 or 50 stories high, and are designed with force reduction factors (ratios of maximum elastic bending moment demands to bending moment capacities) varying from 1.3 to 3.7.

2. Background

Ground motions used for response history analysis are usually selected based on the magnitude of the expected earthquake and the distance from the site to the location of the earthquake. Selected records are usually scaled to match a target spectrum, such as the Uniform Hazard Spectrum (UHS), in one of three ways: 1) scale the records to the target spectral acceleration at the fundamental period of the structure T_1; 2) scale the records to match the UHS over a range of periods; 3) spectrum matching. Individual records are characterized by 5% damped elastic spectrum. Seismic code provisions such as ASCE standard 7-10 (ASCE 2010) recommends a period range of $0.2T_1$ to $1.5T_1$ for the second method. The limit $0.2T_1$ is to ensure that important higher modes are adequately excited, while the limit $1.5T_1$ is for considering the period lengthening due to nonlinearity. Katsanos et al. (2010) recommended using T_L instead of $0.2T_1$ as the lower bound, which is the period of the highest mode of vibration for which the activated mass is about 90% of total, and $2T_1$ as the upper bound for the structures that are located in the regions with high seismic intensities. The idea of scaling the records over the range of periods seems to be more rational than scaling at the fundamental period since it considers a wider range for spectral accelerations that can possibly influence different response parameters.

Spectrum matching is a process in which the frequency content of the input motions is altered to artificially match the response spectrum of individual records to the target spectrum. The advantage of using spectrum matched records is that the variability of the demand parameters is substantially reduced, i.e. fewer records can be used to estimate the mean response (Watson-Lamprey and Abrahamson 2006). Similar to the second method of scaling described above, spectrum matched records can be generated to match the target spectrum over a prescribed range of periods. Huang et al. (2011) concluded that compared to the real records, spectrum matched records underestimate the mean displacement of highly inelastic single-degree-of-freedom (SDOF) oscillators. Furthermore, they cannot be used to establish the distribution of structural response if the input motions are matched to the mean target spectrum. In order to estimate the distribution of demand parameters using spectrum matched records, Hancock et al. (2008) used 84^{th}-percentile spectrum as the target spectrum instead of the mean spectrum.

Naeim and Lew (1995) questioned the validity of using UHS as the target spectrum for scaling ground motions since it is the envelope to spectral accelerations at different periods that will not necessarily occur within a single motion. As an alternative to UHS, Baker and Cornell (2006) proposed Conditional Mean Spectrum (CMS), which accounts for the correlation between spectral accelerations at other periods given a target spectral acceleration at the period of interest. The CMS will then be used as the target spectrum to select motions for use in time history analysis. Baker (2011) indicated that response parameters corresponding to the ground motions scaled and matched to the CMS are closer to the response parameters from unscaled records that have spectral accelerations equal to the target spectral acceleration at the conditioning period. Jayaram et al. (2011) extended the idea of Conditional Mean Spectrum to Conditional Spectrum (CS) in order to capture the variability in the input motions having a target mean spectrum. Selecting and matching the records to the CS results in a more accurate prediction of the variability in the demand parameters.

A number of previous studies have investigated the influence of ground motions on maximum inter-story drifts in medium-rise reinforced concrete moment-resisting frame buildings (Wood and Hutchinson, 2010; Heo et al, 2011; PEER GMSM, Haselton et al, 2009; ATC 82, 2011), but there have been limited studies on high-rise shear wall buildings. The GMSM program was the only study which investigated the sensitivity of the maximum inter-story drift ratio of a 12 story concrete shear wall corresponding to the records scaled to the UHS and the CMS computed at the fundamental period. The influence of ground motion scaling on the seismic response of high-rise shear walls and the sensitivity of other demand parameters to the scaling method still need to be examined. Particularly, the sensitivity of first-mode dominated and higher-mode dominated response parameters to various scaling schemes and conditioning periods is investigated in this work. The variability in the structural response using different sets of records is also studied.

3. Description of Shear Wall Buildings

Eleven different high-rise concrete shear wall buildings are included in the current study. The buildings are very typical of design practice in the seismically active west coast of Canada. The differences between the buildings are number of stories (heights) and strengths of shear walls. The buildings are 10, 30 and 50 stories with corresponding heights above grade of 30, 86 and 142 m. In all buildings, the first story height is 4.5 m, while all other stories are 2.8 m. The amount of vertical reinforcement was calculated to achieve a target force reduction factor R_g for each wall, specifically R_g = 1.7, 2.6, and 4.2 for 10 story walls; R_g = 1.4, 2.4, 3.1, and 4.3 for 30 story walls; and R_g = 1.4, 2.1, 2.4, and 4.1 for 50 story walls. Note that the R_g factor is the ratio of elastic bending moment demand calculated using the uncracked (gross-section) stiffness to the nominal flexural strength of each wall. The uncracked flexural stiffnesses resulted in fundamental periods of 1.0, 3.0, and 5.0 seconds for the 10, 30, and 50 story walls, respectively. The amount of vertical reinforcement in the walls was kept constant from the base to 1.5 times the wall length up from the base and then was decreased approximately linearly over the building height. The full description of the 11 shear wall buildings can be found in Dezhdar (2012).

4. Selection and Scaling of Ground Motions

4.1. Uniform Hazard Spectrum

The UHS used in the current study is the design spectrum for Site Class C (average shear wave velocity V_s between 360 and 760 m/s) in Vancouver BC, which is very similar to ASCE7-10 design spectrum for Site Class B in Seattle WA. De-aggregation of the UHS using computer program EZ-FRISK (Risk Engineering Inc, 2010) indicates the hazard representing the 2% probability of exceedance in 50 years has a mean magnitude M = 7.0 and mean source-to-site distance D = 50 km for periods greater than 1.0 s. In order to increase the number of available strong motion records, the bins were broadened to include ground motions with $6.5 \le M \le 8.0$ and $0.5 \le D \le 50$ km, recorded on site class B, C, and D ($180 < V_s < 1500$ m/s). Each ground motion was selected to have a minimum longest usable period of 8.0 s, which is slightly more than 1.5 times the fundamental period of the tallest (50-story) buildings. With the limitation that no more than seven ground motion records come from any one earthquake, a total of 80 ground motion records from 23 different earthquakes were selected: 51 ground motions recorded in the U.S. and Canada, 9 recorded in Taiwan, 8 in Turkey, 5 in Japan, 3 in each of Iran and Italy, and 1 in Jordan. Half the records had $0.5 \le D \le 20$ km, while the other half had $20 \le D \le 50$ km. Peak ground accelerations varied from 0.075g to 1.66g.

The 80 ground motions were scaled to the UHS at the fundamental period T_1 of each building, which is 1.0, 3.0, and 5.0 s for the 10, 30, and 50-story buildings, respectively. Figures 1(a) to 1(c) show the resulting mean spectrum of the ground motions (labelled ST1). When the 80 records were scaled to the UHS at 1.0 s (Figure 2a), the mean spectrum of the records matched the UHS over a wide range of periods. Thus one scaling procedure results in both the ST1 and SOR (scaled over range) records. When the records were scaled to the UHS at 3.0 and 5.0 s, the mean spectrum of the records deviated from the UHS by up to twice the value of the UHS at shorter periods (see Figs. 2b and 2c). Ground motions with very high spectral accelerations at short periods were eliminated resulting in 53 *SOR* ground motions for the 30-story (T_1 = 3.0 s) building and 35 SOR ground motions for the 50-story (T_1 = 5.0 s) building. The mean spectrum of the SOR ground motions shown in Figs. 2(b) and 2(c) match the UHS over a range wider than $0.2T_1$ to $1.5T_1$.

Forty ground motions were randomly selected from the 80 described above and were modified using computer program SYNTH so that the spectrum of each individual record matches the UHS. Figure 1(d) compares the response spectra of all 40 spectrum matched (SM) ground motions with the target UHS. There is very little deviation between the records.

4.2. Conditional Mean Spectrum

Ground motions were selected and scaled to match a number of different Conditional Mean Spectrum (CMS) at different conditioning periods for each building. The first step to compute CMS is to identify the conditioning period T^*. Although it is often assumed to be the fundamental period of the structure, it can be other periods depending on the structural characteristics and the response parameters to be investigated. For example, roof displacement and maximum inter-story drift are deemed to be influenced mainly by first mode response, whereas higher modes contribute significantly to the base shear force. Also, it is believed that the taller the wall is, the greater higher modes would influence particular response parameters such as mid-height curvature and base shear force demands. Consequently, multiple periods may need to be considered depending on the structural response to be studied. For this purpose, it was decided to include modal periods with a total modal mass equal to 90% of the total mass. Consequently, T_2 for the 10 story and T_2 and T_3 for the 30 and 50 story walls were included. Note that the second mode period for 10, 30, and 50 story walls is 0.15, 0.5, and 0.8 second, while the third mode period for 30 and 50 story walls is 0.15 and 0.28 second, respectively. In addition, two conditioning periods of $1.5T_1$ and $2T_1$ were considered for 10 story walls, which essentially represent the period elongation due to nonlinear behaviour. A period of 5.0 s was also considered for the 30 story walls for the same purpose. This conditioning period is approximately equal to 1.5 times the fundamental period of 30 story walls. Note that the maximum value for T^* is limited to 5.0 seconds since the simplified correlation model (Baker and Cornell 2006) was employed to computed the CMS. The Open source PSHA online package OpenSHA (OpenSHA ,2009) was used to compute the predicted mean and standard deviation values for the Boore and Atkinson attenuation model (Boore and Atkinson, 2008). Figure 1(a) to 1(c) compares the UHS with the computed CMS at different conditioning periods.

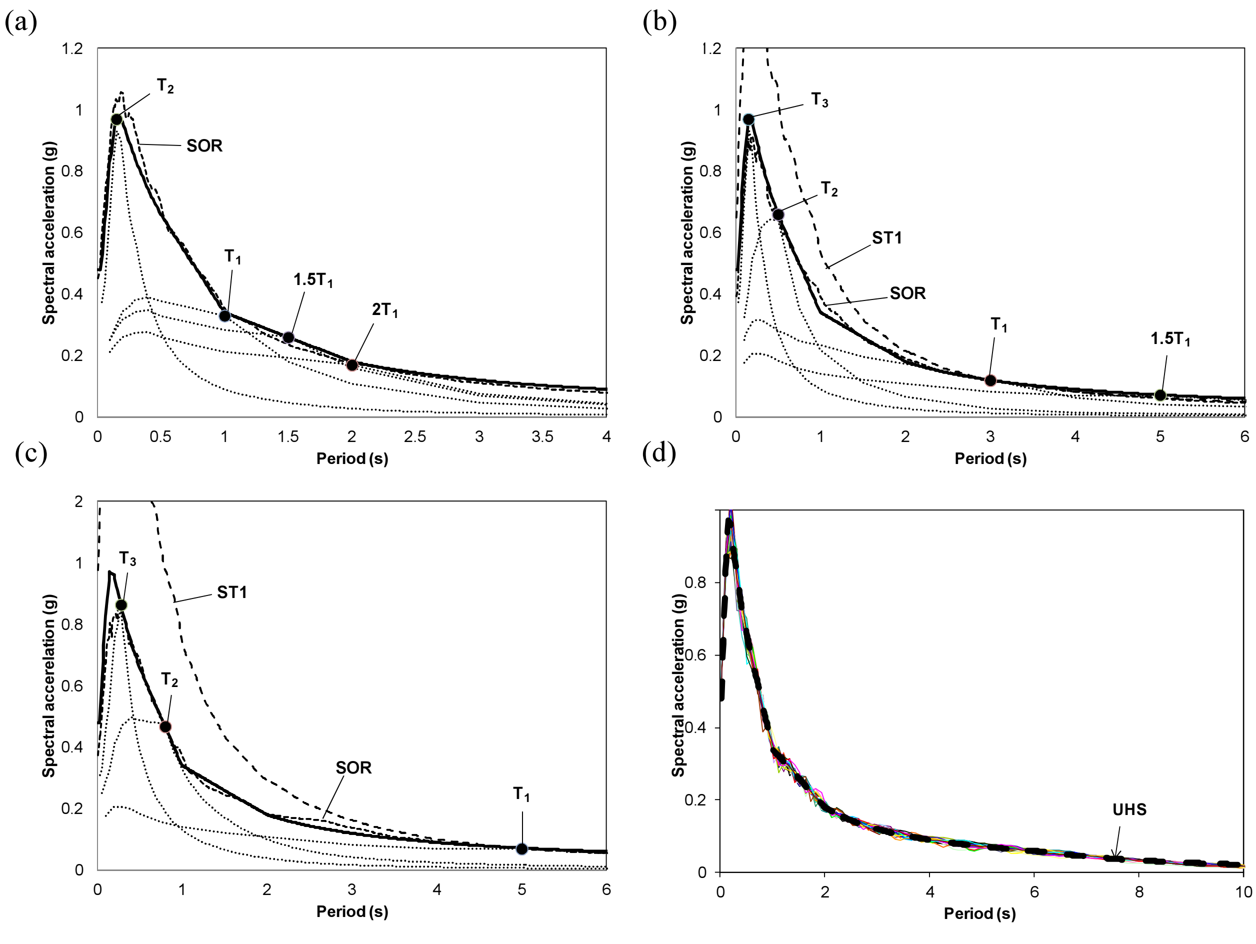

Fig.1 – Comparison of UHS (solid line) with mean of records scaled to UHS over range (*SOR*), mean of records scaled to UHS at fundamental period T_1 (*ST1*), and CMS computed at different periods for: (a) T_1 = 1.0 s, (b) T_1 = 3.0 s, (c) T_1 = 5.0 s; and (d) comparison of UHS with 40 spectrum-matched ground motions.

5. Nonlinear Modelling of Shear Walls

Nonlinear time history analysis of the 11 shear walls was conducted in OpenSees (OpenSees, 2008) using a specially developed trilinear hysteretic bending moment - curvature relationship (Dezhdar, 2012). The trilinear bending moment - curvature relationship was originally developed for pushover analysis (Adebar and Ibrahim, 2002). The parameters that define the hysteretic model were calculated at each floor level considering the level of axial compression force and amount of vertical reinforcement at that level. A force element was defined at each floor level to model the vertical spread of plasticity in the walls. The base was assumed to be fixed and shear deformations were not considered in the analytical model. Rayleigh damping was assumed with mass proportional and initial stiffness matrixes. A damping ratio of 3% was assigned for the first and third modes. This is consistent with the recommendations of ATC 72 (2010) for modelling viscous damping in high-rise buildings. The time step was set equal to 0.0025, and the Newton-Raphson iteration method was used to satisfy equilibrium at each time step. Lastly, the Newmark integration method with coefficients $\beta = 0.5$ and $\gamma = 0.25$ was used in time history analysis.

6. Discussion of Results

6.1. Sensitivity of Response Parameters to Conditioning Period T^*

Figure 2 compares the mean envelope of various demand parameters associated with the ground motions the ground motions selected and scaled to the CMS at different conditioning periods for a selected number of walls. Note that the term "CMSTi" refers to the CMS corresponding to the conditioning period of T_i. The results for other walls can be found in Dezhdar (2012).

The following observations can be made:

1. The CMS1.5T1 set gives highest roof displacement demand for 10 story walls with force reduction factors of 2.6 and 4.2. Selecting $1.5T_1$ as the conditioning period increases roof displacement demand 22% compared to the roof displacement demand from CMST1 or CMS2T1 sets for the 10 story wall with R_g = 4.2. For the 30 story walls, on the other hand, using CMST1 set gives higher roof displacement demand than the CMS1.5T1 set.

2. In terms of mean inter-story drift demand at top of walls, the CMS1.5T1 set gives highest values for 10 story walls with R_g factors of 2.6 and 4.3, while the mean inter-story drift ratio corresponding to the CMST1 set is slightly higher than that for the CMS1.5T1 records for R_g = 1.7. Similar to roof displacement demand, using T_1 as the conditioning period results in higher inter-story drifts than using $1.5T_1$ for 30 story walls.

3. The CMS1.5T1 set gives highest base curvature demand in 10 story walls with force reduction factors of 2.6 and 4.2. For the 10 story wall with R_g = 4.2, using the CMS1.5T1 set results in mean base curvature demands that are 40% and 31% higher than those corresponding to the CMST1 and CMS2T1 sets, respectively. Similar to roof displacement and inter-story drift demands, the CMST1 set gives highest base curvature demand for 30 story walls. Also, it was observed that although the CMST2 and CMST3 sets result in low base curvature demands, they give higher mid-height curvature demands compared to the CMST1 or CMS1.5T1 records.

4. The lowest base shear force demands belong to the conditioning periods of $2T_1$, $1.5T_1$, and T_1 for 10, 30, and 50 story walls, respectively. The CMST2 set gives highest base shear forces for 10 and 30 story walls, while using the CMST3 set results in highest demands for 50 story walls. Using higher mode periods as the conditioning period rather than the fundamental period T_1 increases the base shear force demand up to 23%, 26%, and 73% for 10, 30, and 50 story walls, respectively.

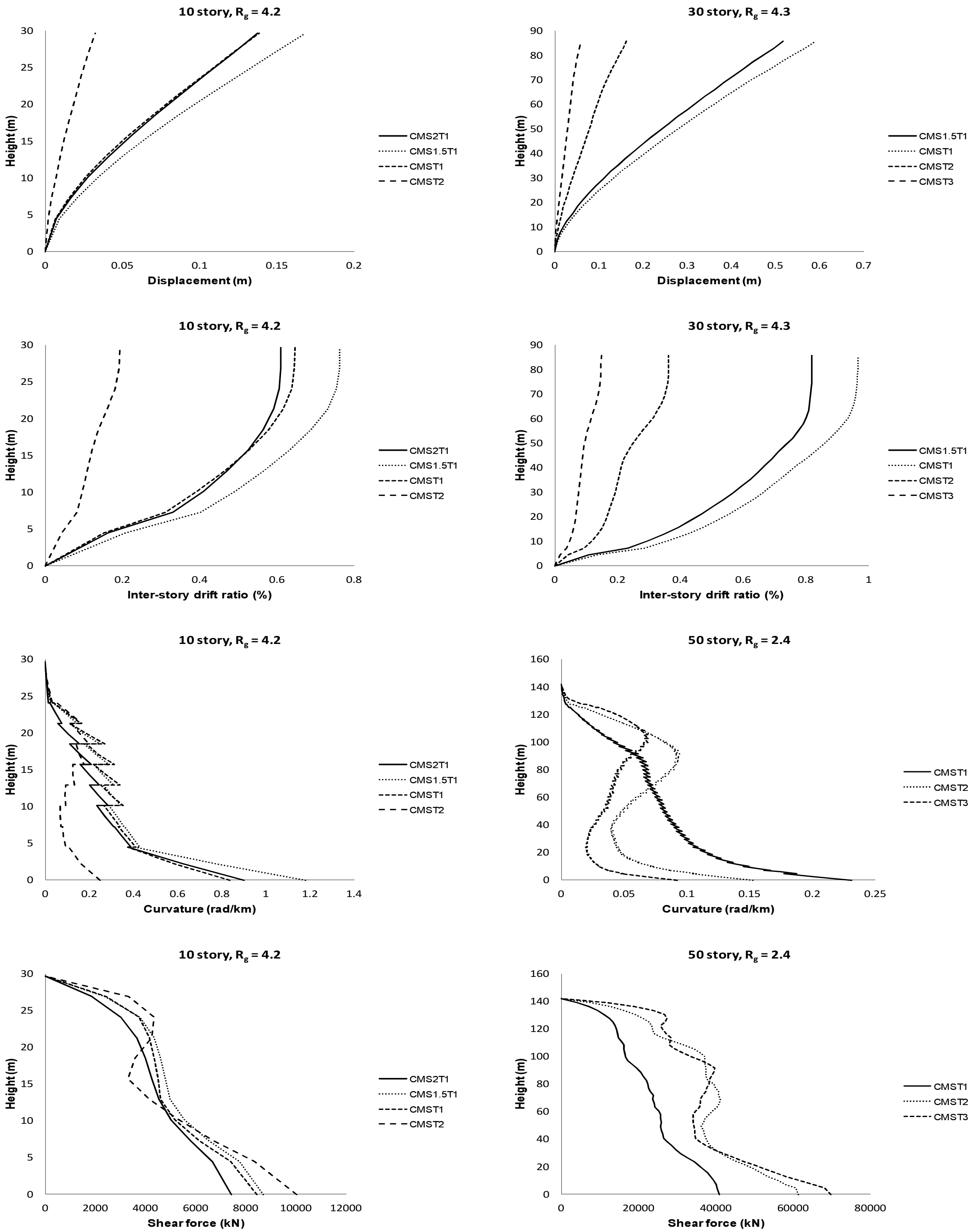

Fig.2 – Sensitivity of demand parameters to conditioning period for various walls.

6.2. Comparison of Demand Parameters from Different Scaling Methods

Figure 3 compares the mean envelope from different scaling methods - namely SM (spectrum matched), SOR (scaled over range) - with the CMS envelope associated with the largest response (denoted as CMS-E). A summary of the results for displacement and shear force demands are presented in Table 1 and Table 2, respectively.

The following observations can be made:

1. The shapes of displacement envelopes are similar to a first mode dominated displacement profile. The mean roof displacements associated with the CMS-E were found to be between 90 and 100% of the mean roof displacement determined using the SM ground motions. For the 10 and 30-story walls, the mean roof displacements from ST1 and SOR are within 90 to 105% of the mean roof wall displacements from the SM records. For the 50-story walls, the mean roof displacements from the SOR and ST1 ground motions are from 100 to 110% and 110 to 120% of the mean roof displacements from SM ground motions, respectively.

2. The inter-story drift envelopes are generally dominated by the first mode displacement profile except for those corresponding to the ST1 records. The mean inter-story drift at the top of walls from CMS-E is 88%, 95%, and 86% of the value from the SM ground motions for the 10, 30, and 50 story walls with the highest force reduction factors, respectively. For 30 and 50 story walls, the mean inter-story drifts at the top from the ST1 records is 15% and 50% higher than those using the SM ground motions, respectively.

3. The base curvature demand from the SOR ground motions are generally between 90 and 100% of the mean base curvature from the SM records. The mean base curvature demands from the CMS-E are generally lower than those from the SM ground motions (minimum of 80%) except for three 30-story walls. For 50 story walls, the ST1 set gives higher base curvature demands that are at least double the results from the SM ground motions.

4. Mean base shear force demands from the SOR records are between 93 and 102% of the mean base shear force demands using the SM ground motions. The CMS-E typically gives mean base shear force demands that are 80 to 95% of the mean base shear force demands from SM and SOR sets. The SOR ground motions gives higher shear forces near mid-height than the SM records for 50 story walls with force reduction factors of 1.4, 2.1, and 2.4. Mean base shear force demands from ST1 set are about 35% and 200% higher than those from the SM ground motions for the 30 and 50 story walls, respectively.

Table 1 – Mean roof displacement demand using different sets of ground motions.

Mean Roof displacement (m)										
	R_g	ST1	SM	SOR	CMS-E	CMS				
Wall						$2T_1$	$1.5T_1$	T_1	T_2	T_3
10 story	1.7	-	0.119	0.11	0.114	0.08	0.111	**0.114**	0.040	-
	2.6	-	0.134	0.13	0.126	0.09	**0.126**	0.124	0.036	-
	4.2	-	0.190	0.18	0.169	0.13	**0.169**	0.138	0.032	-
30 story	1.4	0.45	0.437	0.43	0.431	-	0.331	**0.431**	0.141	0.055
	2.4	0.56	0.561	0.52	0.520	-	0.457	**0.520**	0.148	0.054
	3.1	0.61	0.651	0.56	0.586	-	0.531	**0.586**	0.158	0.055
	4.3	0.66	0.641	0.59	0.592	-	0.518	**0.592**	0.163	0.058
50 story	1.4	0.80	0.710	0.74	0.656	-	-	**0.656**	0.237	0.095
	2.1	0.89	0.810	0.81	0.771	-	-	**0.771**	0.262	0.103
	2.4	0.89	0.801	0.82	0.731	-	-	**0.731**	0.289	0.105
	4.1	0.83	0.690	0.75	0.635	-	-	**0.635**	0.267	0.095

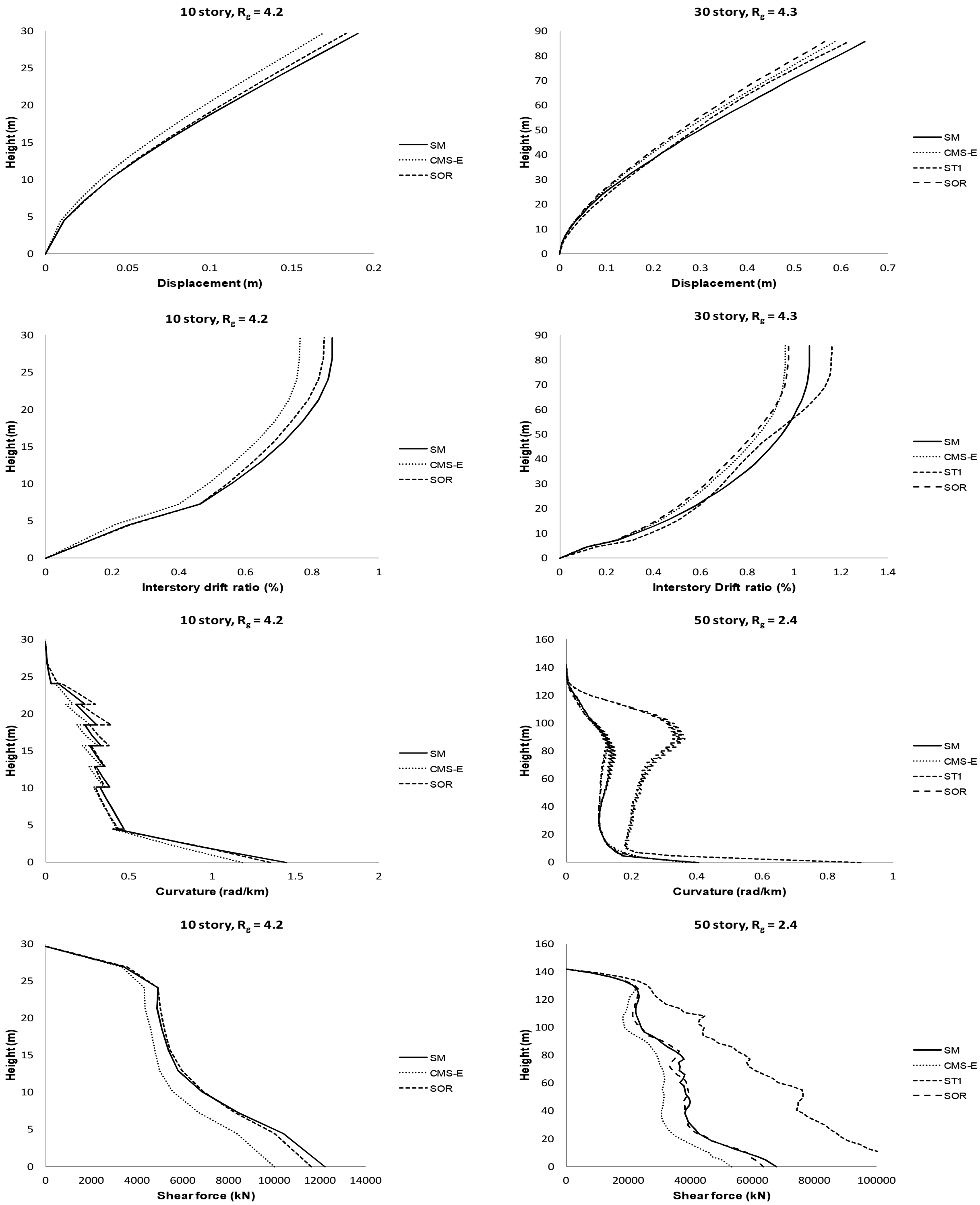

Fig. 3 – Comparison of mean demand parameters using spectrum matched (SM), scaled over range (SOR), and the envelope of results using CMS ground motions (CMS-E).

Table 2 – Mean base shear demand using different sets of ground motions.

Mean base shear force (kN)										
	R_g	ST1	SM	SOR	CMS-E	CMS				
Wall						$2T_1$	$1.5T_1$	T_1	T_2	T_3
10 story	1.7	-	22747	22001	20531	13763	16129	16601	**20531**	-
	2.6	-	18924	17593	14504	10067	11714	12176	**14504**	-
	4.2	-	12207	11628	10014	7438	8708	8435	**10014**	-
30 story	1.4	46177	35985	34574	31706	-	21680	26077	**31706**	26344
	2.4	39855	29351	28582	23972	-	16055	21516	**23972**	22182
	3.1	38695	30478	29658	23969	-	16012	21069	**23969**	21791
	4.3	36307	24415	23899	21462	-	13895	17055	**21462**	18733
50 story	1.4	136331	76289	75949	71763	-	-	42584	62923	**71763**
	2.1	158176	75532	74984	71072	-	-	41092	61982	**71072**
	2.4	173146	75179	76618	69876	-	-	41020	61277	**69876**
	4.1	141076	67737	63476	53332	-	-	33130	53292	**53332**

7. Summary and Conclusions

Multiple conditioning periods need to be considered to estimate the largest response depending on the structural characteristics and the structural response under investigation. Choosing fundamental period as the conditioning period is appropriate for estimating roof displacement, top wall inter-story drift, and base curvature demands in taller walls or walls with low force reduction factors, while for shorter walls with high R_g factors, the results from CMS at $1.5T_1$ are larger. Higher mode periods must be considered for estimating mid-height curvature and base shear force demands since choosing T_1 as the conditioning period significantly underestimates these parameters in taller buildings.

It was also found that the mean roof displacement and mean inter-story drift at the top of walls using ground motions matched to the CMS at different conditioning periods is between 90 and 100% of the mean values from the spectrum matched (SM) records. For base curvature and base shear force demands, on the other hand, the mean results from the CMS ground motions are generally higher than 80% of the base curvature and base shear force demands from the SM records.

Findings of this study indicate that using SM ground motions results in demand parameters that are close to the results associated with the SOR records, yet fewer number of input records can be used because using spectrum matched ground motions reduces the variability in the structural responses considerably. The demand parameters corresponding to the records matched to the CMS are generally lower than those from the spectrum matched records; however, it should be noted that the conditioning periods used in this work were limited to the first three modal periods as well as two periods representing the fundamental period elongation due to nonlinearity. Any other period may be considered as the conditioning period with corresponding demand parameters more critical than those associated with conditioning periods considered in this study. Including more conditioning periods will increase the computational cost of the time history analysis.

8. References

ADEBAR, Perry, IBRAHIM, Ahmed, "Simple nonlinear flexural model for concrete shear walls", Earthquake Spectra, Vol. 18, No. 3, August 2002, pp. 407-426.

ASCE 7, "Minimum Design Loads for Buildings and Other Structures" ,American Society of Civil Engineers, Reston, VA, 2010.

ATC 72, "Modeling and acceptance criteria for seismic design and analysis of tall buildings", Applied Technology Council, Redwood City, California, 2010.

ATC 82, "Selection and scaling earthquake ground motions for performing response-history analyses", NEHRP Consultants Joint Venture, 2011.

BAKER, Jack, "The conditional mean spectrum: A tool for ground motion selection", Journal of Structural Engineering, Vol. 137, March 2011, No. 3, pp. 322-331.

BAKER, Jack, CORNELL, Allen, "Spectral shape, epsilon, and record selection", Earthquake Engineering & Structural Dynamics, Vol. 35, No. 9, July 2006, pp. 1077-1095.

BOORE, David, ATKINSON, Gail, "Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s", Earthquake Spectra, Vol. 24, No. 1, February 2008, pp. 99-138.

DEZHDAR, Ehsan, "Seismic Response of Cantilever Shear Wall Buildings", Ph.D. Thesis, The University of British Columbia, December 2012.

HANCOCK, Jonathan, BOMMER, Julian, and STAFFORD, Peter, "Numbers of scaled and matched accelerograms required for inelastic dynamic analyses", Earthquake Engineering & Structural Dynamics, Vol. 37, No. 14, November 2008, pp. 1585-1607.

HEO, Yeongae, KUNNATH, Sashi, and ABRAHAMSON, Norman, "Amplitude-scaled versus spectrum-matched ground motions for seismic performance assessment", Journal of Structural Engineering, Vol. 137, No. 3, March 2011, pp. 278-288.

HUANG, Yin-Nan, Whittaker, Andrew., Luco, Nicolas, and Hamburger, Ronald, "Scaling earthquake ground motions for performance-based assessment of buildings", Journal of Structural Engineering, Vol. 137, No. 3, March 2011, pp. 311-321.

JAYARAM, Nirmal., LIN, Ting, and BAKER, Jack, "A computationally efficient ground motion selection algorithm for matching a target response spectrum mean and variance", Earthquake Spectra, Vol. 27, No. 3, August 2011, pp. 797-815.

KATSANOS, Evangelos, SEXTOS, Anastasios, and MANOLIS, George, "Selection of earthquake ground motion records: A state-of-the-art review from a structural engineering prospective", Soil Dynamics & Earthquake Engineering, Vol. 30, No. 4, April 2010, pp. 157-169.

NAEIM, Farzad, and LEW, Marshall, "On the use of design spectrum compatible time histories", Earthquake Spectra, Vol. 11, No. 1, February 1995, pp. 111-127.

NAUMOSKI, Nove. Program SYNTH Generation of Artificial Accelerograms Compatible with a Target Spectrum, Computer Program and Supporting Documentation, Carleton University, Ottawa, 2001.

OPENSEES, Open System for Earthquake Engineering Simulation (OpenSees), Computer Program and Supporting Documentation, Pacific Engineering Research Centre, University of California, Berkeley, May 2008.

OPENSHA. Open Seismic Hazard Analysis, http://www.opensha.org, 2009.

PEER GMSM, HASELTON, Curt, editor, "Evaluation of ground motion selection and modification methods: predicting median interstory drift response of buildings", Pacific Engineering Research Centre, University of California, Berkeley, 2009.

Risk Engineering Inc, EZ-Frisk™ (version 7.01), 2010.

WATSON-LAMPREY, Jennie, and ABRAHAMSON, Norman, "Selection of ground motion time series and limits on scaling", Soil Dynamics and Earthquake Engineering, Vol. 26, No. 5, pp. 477-482.

WOOD, Richard., and HUTCHINSON, Tara, "Effects of ground motion scaling on nonlinear higher mode building response", Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering, Toronto, 2010.