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INFLUENCE OF GROUND MOTION SELECTION AND SCALING TO THE SEISMIC RESPONSE OF BUILDINGS

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ABSTRACT

This paper presents an on-going study addressing the selection and scaling of ground motion records for use in non-linear time-history seismic analysis of buildings. Historical or simulated acceleration records selected for such analysis should be representative of the type of earthquakes expected at building location and compatible with the uniform hazard design spectrum. The study was carried out for Vancouver for class C site conditions. 120 simulated and 10 historical acceleration records were initially selected based on the dominant magnitude-distance (M-R) scenarios. To investigate the influence of the reduction of database of simulated acceleration records, two subsets of ten accelerograms were defined using two selection methods. Several calibration strategies, all based on the spectral compatibility, were then applied to the selected records. Characteristic parameters of ground motion records were calculated and compared. The impact of different approaches to scaling and selection of acceleration records was evaluated by observing the inelastic response of 4-storey concentrically braced steel frame of conventional category. Results demonstrate that the characteristic parameters of historical and simulated records are similar. The median inelastic deformations of diagonals are also similar for all sets of acceleration records studied regardless the scaling method selected. More variability is observed when 84th percentile response values are compared. The closest resemblance is achieved when the simulated records are chosen so that their spectra fit well the NBCC design spectrum without any calibration.

Introduction

Non-linear time-history analyses are frequently used nowadays to study the behaviour of buildings under seismic loads. The results can be used to evaluate seismic response and validate current seismic design criteria, or they can be incorporated directly into the design process. The appropriate selection and scaling of ground motion records appears essential for such analysis to represent adequately seismicity at the design location and anticipated earthquake loads. There is however very little scientific evidence about the impact that different approaches to select and

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calibrate earthquake records may have on non-linear response of building structures.

For Western North-American locations, ground motions are usually selected from well establish databases of historical recordings. For Eastern North-American sites, where earthquakes rich in high frequencies are anticipated and very few historical recordings are available, the simulated acceleration records are often the only option. Using the stochastic finite-fault method, Atkinson (2009) has generated earthquake time histories that may be used to match the 2005 NBCC UHS for a range of Canadian sites both in Western and Eastern Canada. A large number of simulated records is available for site Classes A, C, D and E and different magnitude-distance (M-R) scenarios. For practical purposes, it would be desirable to conduct analysis for the smaller set of representative records likely to induce structural response similar to that observed under historical records. It is thus of interest to establish if the subsets of simulated acceleration records derived from the same larger set produce response similar to that obtained for the larger set itself. On the other hand, to gain confidence in using solely simulated records for seismic studies conducted for Eastern Canada, it is of interest to demonstrate that in western Canada historical and simulated records yield comparable inelastic structural response.

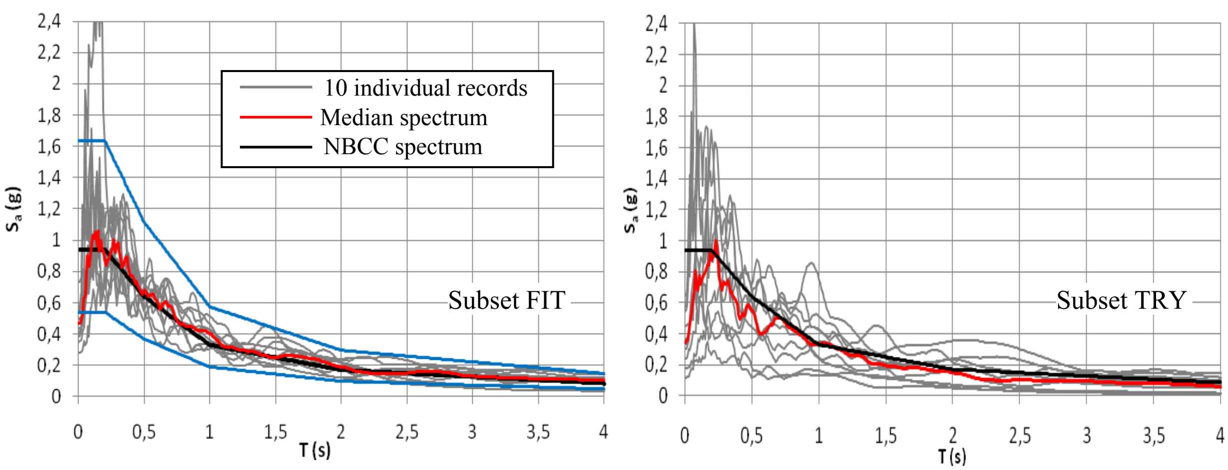
The study presented in this paper was conducted with the objective to evaluate different approaches to selection and scaling of ground motion records. This was done by comparing the characteristic parameters of different ground motions and by investigating the impact on non-linear structural response. The study was carried out for Vancouver. Sets of 120 simulated records and 10 historical acceleration records were initially selected based on the magnitude-distance (M-R) scenarios considering the types of the soil and peak ground acceleration at the location. Two methods of calibration are employed; the two based on the compatibility of the acceleration spectral intensities between response and design spectra over the range of periods of interest. To investigate the influence of the reduction of acceleration database, two subsets of ten simulated records are selected. Characteristic parameters of ground motion records, such as peak horizontal acceleration and peak horizontal velocity, Arias intensity, Trifunac-Brady duration, number of zero crossing, duration and intensity of pulses, etc, are calculated and compared. The inelastic response of 4-storey concentrically braced frame to selected sets of records calibrated using described procedures is then studied by examining the inelastic axial deformation of braces.

Selection and scaling of earthquake records

Simulated records

Simulated records used for this study were selected from the database developed by Atkinson (2009). Five M-R scenarios were considered for Vancouver class C site: M 6.5 with R equal to 10 and 20 km and M 7.5 with R equal to 20, 30 and 50 km. These M-R combinations contribute the most significantly to the seismic hazard at the site (Haltchuk and Adams 2008). For each scenario, 24 records were selected (3 trials x 8 azimuths) giving a total of 120 record. Two approaches were considered to match the spectra of selected records to target design spectrum. In the first approach, the spectral compatibility is achieved by equating the spectral intensity over the range of periods from 0.2 to 2.0 s. This calibration is denoted in the text by IND as the calibration is done for each individual record independently. In the second approach, a procedure similar to that described in ATC-63 (2009) is employed. The calibration is a two-step procedure. Each record is first scaled by the ratio of the median peak ground velocity (PGV) of the whole ensemble and the PGV of individual record. The second factor, the same for all the records, is then applied to obtain the compatibility of the median acceleration spectra of all records and NBCC design spectra between 0.2 and 2.0 s. Note that the calculation of the second factor is different from the one used in the original ATC method where the compatibility of median and target spectra is sought at the building fundamental period.

To investigate the influence of the reduction of database of simulated acceleration records, two subsets of ten ground motions were defined using two selection methods. In many modern seismic design codes, the use of 7 or more acceleration records in analysis is suggested to obtain more realistic dispersion of results. The first set was selected on basis of best "natural" fit between the spectra of a candidate record and target design spectra. This selection method is denoted as FIT. To decide if the spectra of candidate records are close to target spectrum, the upper and lower limit are traced by multiplying the NBCC spectral ordinates by the value A and 1/A. The resulting lines are shown in blue in Figure 1(a). The constant A is not initially fixed; in fact its value is adjusted until the spectra of 10 acceleration records fall within the defined limits over the targeted range of periods (0.2 to 2.0 s.). To insure that the variability of the records is maintained, each M-R scenario was represented by at least one acceleration record. The spectra of unscaled accelerogrammes of the subset FIT are shown in Figure 1 (a). In the further analysis, FIT records scaled using procedures IND and ATC were also considered. The main advantage of this method is that the acceleration records are not significantly amplified or reduced to match NBCC spectra. In fact, calibration factors are all very close to the one which is expected due to the nature of the selection process. Note that the ATC scaling procedure resulted in somewhat higher variability in the scaling factors compared to the IND procedure.



(a) (b)

Figure 1. Spectra of unscaled acceleration records (a) subset FIT; (b) subset TRY.

The second subset of 10 records, named TRY, was obtained following a different selection approach. Using the IND scaling method described above, scaling factors were first obtained for each of the 24 acceleration records chosen within one M-R scenario from the complete data set of 120 accelerogramms. The mean value of scaling factor was then calculated for each M-R scenario and two records with the individual scaling factor the closest to the mean values were retained. The spectra of the selected records are shown in Figure 1(b). Similarly to what was done with the FIT subset, the records were scaled using IND and ATC procedures and used along with the unscaled values in further analysis. The main advantage of this selection method is the fact that all relevant M-R scenarios are evenly represented. For this same reason, compared to the results obtained for subset FIT, a larger variability of the scaling factors is observed.

Figure 2 shows the median spectra obtained for all sets of records. The NBCC design spectrum is also indicated. Overall, in spite of the small differences, all selection methods and calibration procedures gave similar results within the range of periods of interest. With two exceptions, where up to 22% difference was observed between the median spectral acceleration and spectral ordinate of NBCC spectrum at characteristic periods (0.2, 0.5, 1.0 and 2.0 s), the median spectral acceleration for all series of acceleration records studied were within 10% difference range.

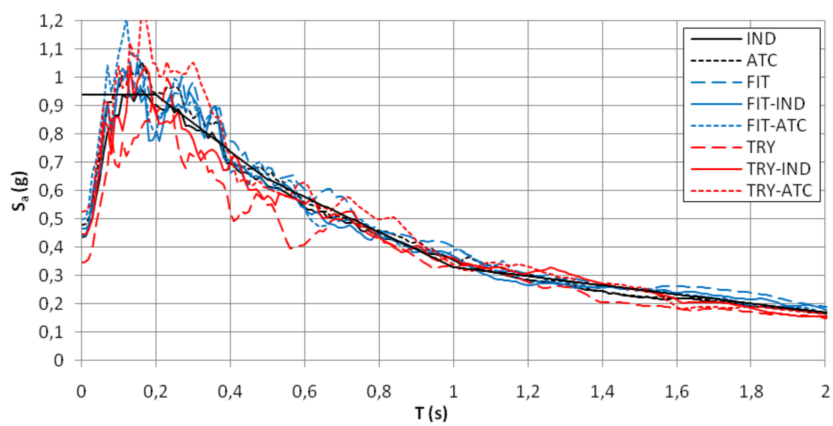


Figure 2. Comparison of median spectra of selected simulated ground motion sets.

Historical records

The historical records from the PEER database (PEER 2006) were used in previous studies by Bara (2007). The selection is done considering the dominat M-R scenarios, the site category (site C) and the peak ground acceleration at the site. The 10 records selected are shown in Table 1. With one exception, the elastic acceleration spectra of selected records are all bellow the target NBCC spectra, and therefore calibration was necessary. In addition to the two scaling procedures previously discussed (IND and ATC), two other scaling approaches were introduced. The two approaches differ from IND method in the way that the range of periods for which the compatibility is achieved is determined. In the first method, the range of periods is determined by the analyst based on the best visual fit between the two spectra. The second method, described in Rozon (2008) builds on the previous subjective approach by scaling the record such to achieve equal area under two spectral curves. These two methods are denoted as H1 and H2.

Table 1. Summary of selected historical records.

ID	Event	M	R (km)	Station	Comp. (°)	PGA (g)	PGV (m/s)
V11	Jan. 17, 1994 Northridge	6.7	44	Castaic, Old Ridge Rd	90	0.568	0.53
V12	Jan. 17, 1994 Northridge	6.7	30	Santa Monica City Hall	360	0.369	0.251
V13	Jan. 17, 1994 Northridge	6.7	34	Los Angeles Baldwin Hills	360	0.167	0.176
V14	Fev. 9, 1971 San Fernando	6.6	31	Castaic, Old Ridge Rd	291	0.268	0.259
V15	Jan. 17, 1994 Northridge	6.7	26	Pacific Palisades-Sunset	280	0.197	0.149
V16	Avr. 25, 1992 Cape Mendocino	7.0	52	Eureka - Myrtle & West	90	0.178	0.283
V17	Oct. 18, 1989 Loma Prieta	7.0	54	Stanford Univ.	360	0.29	0.28
V18	Oct. 18, 1989 Loma Prieta	7.0	100	Presidio	90	0.200	0.34
V19	Avr. 13, 1949 West.Wash.	7.1	76	Olympia, Test Lab	86	0.28	0.17
V20	Juin 28, 1992 Landers	7.3	93	Barstow	90	0.135	0.258

Figure 3 compares median spectra of calibrated historical records to NBCC target spectra. Regardless of the scaling method, the median spectral accelerations at characteristic periods (0.2, 0.5, 1.0, and 2.0 s) were, in general, very close to NBCC spectral ordinates (± 10% difference).

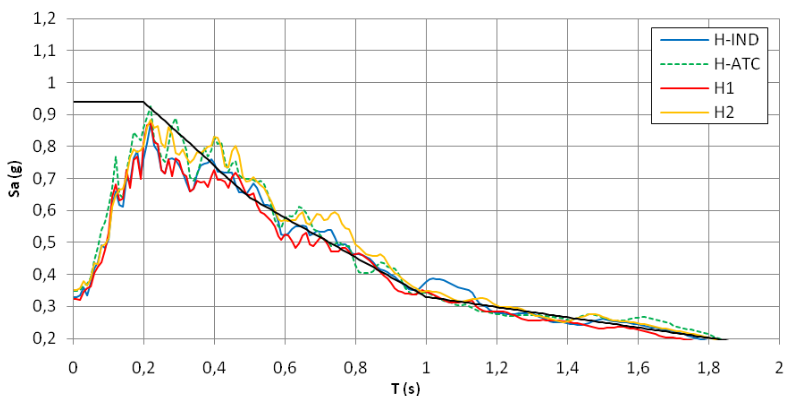


Figure 3. Comparison of median spectra of selected historical ground motion set.

Comparison of ground motion characteristics

In order to compare historical records and two subsets of simulated records chosen, several characteristic parameters of ground motion records were calculated. These included: peak horizontal acceleration (PGA), peak horizontal velocity (PGV) and their ratio (PGA/PGV), Arias intensity (I_A), Trifunac-Brady duration (t_d), number of zero crossing (NZC), cumulative absolute velocity (CAV) and incremental velocity (v_{incr}). Mean results are given in Table 3. On average, the PGA, PGV and PGA/PGV for records from subsets FIT matched better the values observed for historical records compared to accelerograms from the subsets TRY. The Areas intensity for subset TRY records was much higher compared to historical records. No significant difference between historical and simulated records was observed relative to the duration of strong shaking. The number of zero crossing calculated for Trifunac-Brady duration was consistently higher for simulated records indicating possible absence of longer acceleration pulses which may result in the less significant inelastic demand on the structure. The incremental velocity that represents the size of a pulse, was comparable for the historical and subset FIT records, but higher for TRY records indicating the potential for more serious inelastic demand induced by TRY records.

Table 3. Mean values of characteristic ground motion parameters (historical and simulated records)

	Simulated records						**Historical records**			
	FIT	**FIT-IND**	**FIT-ATC**	**TRY**	**TRY-IND**	**TRY-ATC**	**H1**	**H2**	**H-IND**	**H-ATC**
PGA (g)	0.47	0.43	0.44	0.60	1.01	1.22	0.32	0.35	0.34	0.35
PGV (m/s)	0.45	0.41	0.41	0.45	0.63	0.74	0.33	0.36	0.36	0.34
PGA/PGV	1.1	1.1	1.1	1.3	1.3	1.3	1.0	1.0	1.0	1.0
t_d (s)	16	16	16	16	16	16	14	14	14	14
I_A (m/s)	2.81	2.26	2.55	3.32	10.03	15.17	1.34	1.69	1.50	1.73
NZC	226	226	226	157	157	157	82	82	82	82
CAV (cm/s)	1.53	1.38	1.45	1.17	1.53	1.73	1.04	1.14	1.11	1.15
v_{incr} (m/s)	0.21	0.19	0.20	0.28	0.44	0.54	0.23	0.25	0.25	0.23

Study of inelastic response

Building studied

A four-storey building located in Vancouver on a class C site was selected for the study. In each orthogonal direction, the lateral loads are resisted by a pair of Split-X braced frames of conventional category located along the perimeter of the building. The building plan view, the frame elevation and the design gravity loads are shown in Figure 4. The design was performed using the commercially available Graitec Advanced Design-America software (2008) in accordance with NBCC 2005 (NRCC 2005) and CSA S16-01 standard (CSA 2001).

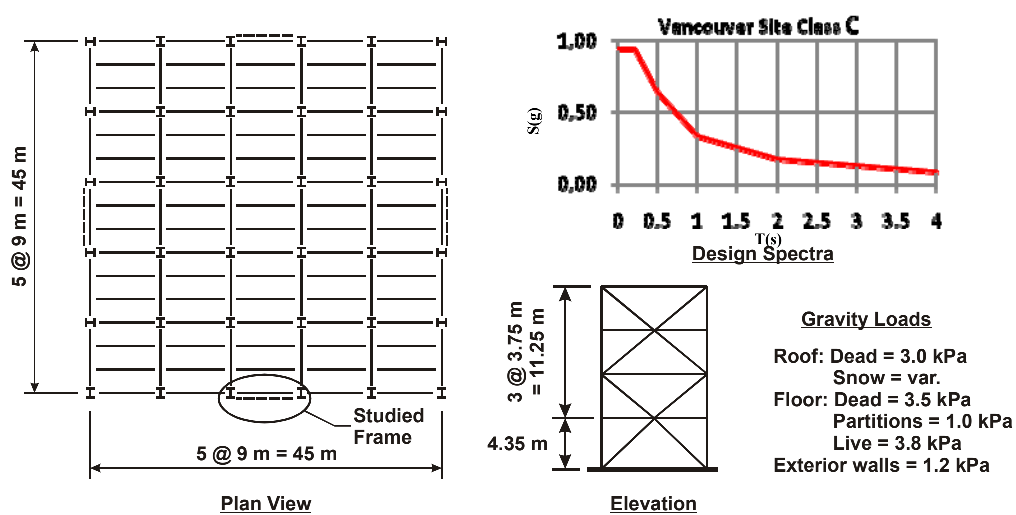


Figure 4. Building geometry and design loads.

The response spectrum spectrum analysis method was used to determine earthquake effects. The seismic base shear from dynamic analysis, $V_d = 7432$ kN, was compared to 80% of design base shear, V, calculated by equivalent static method, as specified in NBCC 2005 for regular buildings. V is taken as the elastic base shear, $V_e = S(T_a)\ M_v\ I_E\ W$, divided by the product of ductility- and overstrengh-related force modification factors, R_o and R_d. In this expression, $S(T_a)$ is the design spectral acceleration for the given site given at the fundamental building period, T_a, M_V is a factor accounting for higher mode effects, I_E is the importance factor, and W is the seismic weight. In this study, T_a= 0.78 s, $S(T_a)$ = 0.487 g, M_v = 1.0, I_E = 1.0, W = 35230 kN, R_o = 1.3 and R_d = 1.5, resulting in V = 8792 kN. Because the base shear obtained from dynamic analysis was greater than 0.8V, the former was used in design. All relevant load combinations were considered and P-Delta effects were included. The selected frame sections are given in Table 4.

Table 4. Summary of selected shapes

Storey	Braces	Columns	Beams
4	HS203x203x8	W200x52	W250x58
3	HS254x254x9.5	W200x52	W200x52
2	HS305x305x8	W360x162	W360x51
1	HS305x305x11	W360x162	W360x51

Analysis and results

Non-linear time-history analysis was carried out using the SAP 2000 program (CSI 2008). For simplicity, inelastic behavior was modeled only for the brace members, assuming bi-linear response using two elements connected in series: an elastic truss element and a non-linear zero-length element with bilinear force-deformation curve. The yield strength is set equal to the value of the brace axial load from spectral analysis combined with the axial load introduced by gravity loads due to 1.0D+0.5L+0.25S. In this calculation, torsional effects were not considered in the spectrum analysis and $R_oR_d = 3.0$ was used to determine the seismic induced brace loads, such that sufficient inelastic deformations develop to accentuate the differences in demand from the ground motion ensembles. Strain hardening taken equal to 2% of the axial stiffness of the brace was assumed. The deformation of the inelastic element is zero until the elastic limit of the brace is reached. The use of such a simple inelastic model was justified by the objective of comparing the demand from different ground motion ensembles, not to assess the demand level by itself. Rayleigh damping based on 3% of critical damping in the first two modes was specified. P-Delta effects were included in the analyses.

The analyses were carried out for 12 sets of ground motions discussed in the previous section. These included: a full set of 120 simulated records calibrated by the IND and ATC methods, two subsets of 10 simulated records (FIT and TRY), unscaled and scaled motions using the IND and ATC procedures, and 10 historical records scaled using four scaling procedures IND, ATC, H1 and H2. The response of the frame is observed by tracking the maximum inelastic tensile deformations in each pair of braces at every storey. The horizontal component of this deformation is then normalized by the storey height, h_s, and the median and 84th percentile values are determined for each set of accelerograms.

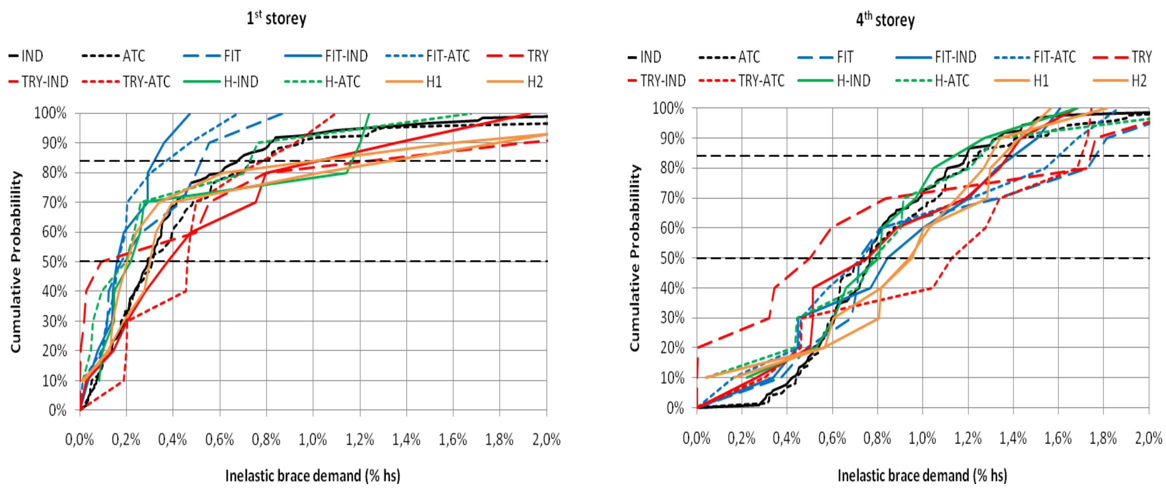
Table 5 presents the results obtained for each of the four storeys. Values of record-to-record variability, β_{RTR}, are also indicated. The demand on the diagonal bracing member at the first storey was dominated by first mode response, while the effects of the higher modes influenced the braces at the other levels. In general, median results obtained for simulated and historical records compare well. For 1st storey brace, the results obtained from the TRY subset were higher compared to the historical records and other groups of simulated records. In the majority of cases, the unscaled accelerograms from the FIT subgroup induced the non-linear response that compared most to that caused by historical records. Similar observations can be made for the 84th percentile results.

Table 5. Median and 84th percentile values of the inelastic brace deformations (% h_s)

		Simulated records								Historical records			
		IND	**ATC**	**FIT**	**FIT-IND**	**FIT-ATC**	**TRY**	**TRY-IND**	**TRY-ATC**	**H1**	**H2**	**H-IND**	**H-ATC**
4th storey	**50th**	0.77	0.77	0.76	1.06	0.78	0.55	0.82	1.20	0.78	0.98	0.81	0.84
	84th	1.19	1.24	1.78	1.43	1.62	1.75	1.39	1.71	1.18	1.29	1.17	1.27
	β_{RTR}	0.46	0.45	0.60	0.56	0.75	1.62	0.59	0.64	0.97	1.02	0.56	1.04
3rd storey	**50th**	0.64	0.58	0.77	0.79	0.51	0.53	0.75	0.96	0.51	0.70	0.55	0.72
	84th	1.03	1.09	1.36	0.96	1.16	1.63	1.15	1.29	0.98	1.06	0.95	1.25
	β_{RTR}	0.56	0.53	0.52	0.41	0.67	0.90	0.68	0.54	0.75	0.76	0.60	0.79
2nd storey	**50th**	0.51	0.49	0.43	0.41	0.48	0.42	0.49	0.64	0.52	0.64	0.56	0.64
	84th	0.81	0.82	0.79	0.84	0.71	0.81	0.94	0.75	1.06	1.06	1.07	1.01
	β_{RTR}	0.56	0.52	0.46	0.45	0.52	2.57	0.57	0.45	0.80	0.88	0.48	0.79
1st storey	**50th**	0.60	0.69	0.61	0.48	0.49	0.85	0.93	0.89	0.47	0.51	0.53	0.49
	84th	1.03	1.16	1.13	0.65	0.81	1.90	1.69	1.26	1.42	1.47	1.74	1.39
	β_{RTR}	0.59	0.62	0.49	0.26	0.42	1.79	0.83	0.51	0.88	0.91	0.80	0.90

Note that the record-to-record variability obtained in this study is higher than the value of 0.4 reported in ATC (ATC 2009), particularly for subgroups TRY, H-ATC and H2. This may be attributed to the fact that peak inelastic deformation response may be more sensitive to the characteristics of a particular acceleration record. Similar observation was made for eccentrically braced frames in a previous study by Rozon (2008).

The cumulative probabilty of reaching a given value of inelastic brace deformation is illustrated in Figure 5 (a) and (b) for the first and fourth storey braces, respectively. Dashed lines are used for the median and 84th percentile level values to ease the comparaison.



(a) (b)

Figure 5. Inelastic brace demand : (a) 1st storey, (b) 4th storey

Conclusions

A study investigating the impact of the procedures used to select and scale earthquake records on the non-linear response of structures has been presented. The study compared the characteristic parameters of historical and simulated ground motions and their effects on structure. The effects of reducing the number of ground motions in a set were also examined. The results indicate that, in spite of differences in characteristic parameters, simulated and historical records induced similar inelastic demand on the braces of the frame studied. The reduction of the number of simulated records in a set does not appear to have any significant impact on the response. The results obtained for simulated ground motions whose spectra fit naturally the best the NBCC target spectra over the range of periods between 0.2 and 2.0 s showed the best concordance with the results obtained for historical records. No further calibration of simulated acceleration records is required when adopting this selection method. However, to ensure the adequate variability of acceleration records, it is recommended to include at least one acceleration record for each M-R scenario that contributes most significantly to the seismic hazard at the site.

Time history analysis was carried only on one structure that had specific dynamic and ductility characteristics. A similar study has recently been initiated for an 8-storey concentrically braced frame of the conventional construction category and preliminary results show similar trends. Nevertheless, the results presented herein should not be generalized until additional studies are carried out on other structural systems to extend the observations presented in the paper.

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