SELECTION OF GROUND MOTIONS FOR THE SEISMIC RISK ASSESSMENT OF LOW-RISE SCHOOL BUILDINGS IN SOUTH-WESTERN BRITISH COLUMBIA, CANADA

F. E. Pina[1], C.E. Ventura[2], G. Taylor[3] and W. D Liam Finn[4]

ABSTRACT

The estimation of seismic risk to life safety in the low-rise school buildings in British Columbia (BC) is being conducted as part of a major seismic mitigation project. Incremental nonlinear dynamic analysis is used to estimate the risk to life safety. The input motions for the analyses are representative of the three main types of earthquakes that dominate the seismic hazard in the highly populated areas of south-western BC; crustal, subcrustal and subduction earthquakes. The input motions have been selected from many sources with tectonic settings similar to the ones in Southwestern BC. A preliminary selection of records is focused on the specific combinations of moment magnitudes and hypocentral distances that contribute most to the seismic hazard. The selected records are then scaled to match target demands given by the uniform hazard spectrum of each type of earthquake. The final selection of records is based mainly on spectral shapes, scaling values, diversity on both earthquakes and recording stations. This paper describes how preliminary and final selection of records were selected and how they were modified to match target spectra How these selected records are used in the seismic risk assessment tool is briefly introduced in this paper.

Introduction

The seismic risk to damage of low-rise school buildings in British Columbia (BC) is being conducted as part of a major seismic mitigation project. Incremental non-linear dynamic analysis is the tool adopted to estimate damage. One of the basic and probably more cumbersome tasks is the definition of a suite of ground motions that is representative of the earthquake hazard at the building site. A representative sample of expected ground motions at the site is required to define properly the most probable structural damage scenario. This task is divided into two processes: selection and modification of motion records (Bommer 2004).

[1]Graduate Research Assistant, Dept. of Civil Engineering, The University of British Columbia, 2002 - 6250 Applied Science Lane, Vancouver, BC, V6T 1Z4
[2]Professor, Dept. of Civil Engineering, The University of British Columbia
[3]P. Eng, TBG Seismic Consultant Ltd., 1945 Llewellyn Place, North Saanich, BC, Canada
[4]Emeritus Professor, Dept. of Civil Engineering, The University of British Columbia

The selection of records is based on ground motion parameters and on geophysical parameters. Most of ground motion parameters (e.g. spectral acceleration ordinates) are fair estimates of the structural performance, which can narrow the selection process substantially. On the other hand, geophysical parameters (e.g. moment magnitude, hypocentral distance, site conditions, etc) capture the likelihood of the earthquake hazard but with minimum correlation to the expected structural behavior. Although some extra work is required, records selected using both types of parameters will be more representative of the expected seismicity in the region.

Selected ground motion candidates are then modified to match a certain target demand. The matching of the input record spectral ordinates to a code-based design spectrum or to a uniform hazard spectrum is a recurrent matching procedure (Shome et al. 1998). The spectral matching can be as simple as a linear scaling of the motion to match a single spectral ordinate or as complex as the modification of part or the entire original signal (time, frequency and/or phase angle content) to match a wider range of ordinates of the target spectrum. In this project, we have used a simple linear scaling procedure in order to keep most of the original records intact.

The seismic hazard in this part of the province is dominated by three different types of earthquakes located in the subduction zone of Cascadia: crustal (shallow), subcrustal (deep) and subduction earthquakes. Geophysical parameters and the responses in structural systems can be substantially different amongst these types of earthquakes. The definition of individual seismic hazards (seismic demand) for each type of earthquake is thus an important and key stage for the selection of ground motions in this seismic risk assessment project.

In this paper, we will present a comprehensive procedure for the selection, modification and use of strong ground motions for the seismic risk assessment of BC school buildings. The vast majority of BC schools are low-rise buildings located in a multi-earthquake hazard region. The input motions for the analyses are representative of the three main types of earthquakes that dominate the seismic hazard in the highly populated areas of south-western BC; crustal, subcrustal and subduction earthquakes. The preliminary selection of earthquakes and recording stations takes into account earthquake magnitudes and source-to-site distances for each type of earthquake. Selected records are linearly scaled to a target demand representative of the earthquake-type hazard for several school structural systems. The final selection of records is based on both spectral shapes and diversity of earthquakes.

Seismicity of South-western British Columbia

Tectonic setting

The tectonic setting of South-western British Columbia is influenced mainly by the subduction of the oceanic Juan de Fuca plate beneath the North America continental plate occurring about 100km west of Southern Vancouver Island (Ristau 2004). Mega-thrust earthquakes may occur at the interface of these two plates. There are other two types of earthquakes occurring at either of these two plates. Crustal or shallow earthquakes have been recorded at depth not longer than 20km in the continental North America plate. Subcrustal or deep earthquakes have been also recorded in this region at depth longer than 50km in the subducting Juan de Fuca plate. There is no clear understanding about the type of faulting of these two types of events, but there is solid evidence that either of them may occur.

Seismic Hazard

Seismic hazard data for each type of earthquake has been generated by using EZ-RISK (Risk Engineering 2008). The data, in turn, has been verified by comparison with the open source data provided by the Geological Survey of Canada; the GSC report (Adams and Halchuk 2003). Using the same approach as GSC, crustal and subcrustal data has been treated probabilistically and subduction data deterministically. The GSC report has been used to select the seismic sources and attenuation relationships. Probabilities have been assigned to subduction hazard data to treat the three types of earthquakes uniformly.

The SHA calculates the probability of exceeding the spectral acceleration at many periods. We have chosen to work with the spectral velocity derived from the spectral acceleration as the exceeding parameter in this study. Figure 1a shows the pseudo-velocity spectra for crustal subcrustal and subduction earthquakes for a soft rock site (Site Class C) in Vancouver with a probability of exceedance of 2% in 50 years (2500-year return period earthquake). The spectral velocity of subduction earthquakes for the city of Victoria, the second largest city in BC, has also been included in Figure 1a. Most of the seismic hazard comes from both crustal and subcrustal events in Vancouver, which have been defined as the reference high-to-moderate seismic hazard data in BC for these two types of earthquakes. Subduction spectrum has larger ordinates for Victoria compared to those for Vancouver, and it has been adopted as the target demand for this type of event in BC. The robust spectrum derived from the current hazard data available for Vancouver (UHS-Vancouver) has been added in Fig.1a for comparison with the new measures of hazard.

Target hazard (target demand)

One recurrent scaling procedure in the literature is the matching of selected records to a target demand given by the spectral value at the structure fundamental period. Scaling at the structure fundamental period reduces the dispersion of the structural inelastic response for a selected suite of motions (Shome et al. 1998). However, the matching at the fundamental period does not account for the softening (inelastic deformations) of the structural systems due to progressive damage of earthquake loading (Lestuzzi et al. 2004, Naoumoski et al. 2004, Elenas 2002). For that reason, we have scaled records to closely match the spectral demand in a period range that is developed by progressive structural softening.

The period range of interest was determined by conducting a statistical analysis of the characteristic range of periods for typical school buildings undergoing nonlinear response. Three range defining periods were considered; the period at yielding ($T1$), the period at 50% of the drift limit ($T_{eff}2$) and the period at the drift limit (T_{eff}). The period at yielding may be an approximation to the fundamental period, while $T_{eff}2$ and T_{eff} may be an estimation of the periods of inelastically deformed rigid and flexible systems, respectively. The distribution of these results is shown in Figure 1b. On the basis of these results, the period range of interest for more flexible buildings (wood frame, moment frame, rocking) has been selected to be 1.0s to

2.0s. The period range of interest for stiffer buildings (braced steel frame, concrete and masonry shear walls) has been set at 0.5s to 1.0s.

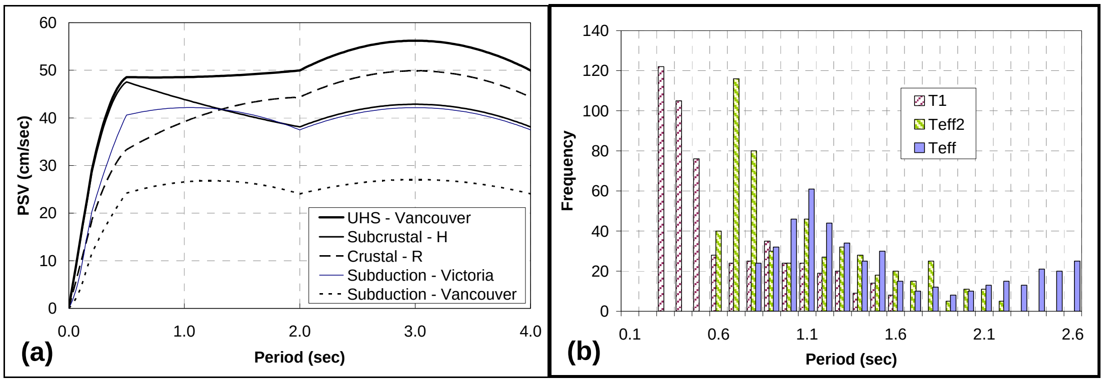

Figure 1. (a) Spectral 5%-damping pseudo-velocities for the aggregated sources (UHS – Vancouver) and for each earthquake type and (b) distribution of elastic and effective (equivalent inelastic) periods of a pool of low-rise building systems in BC.

Selection of ground motions

Preliminary selection of records

There are thousands of instrumented stations recording hundreds of earthquakes around the globe. We have limited the search for earthquakes and stations by geophysical considerations, such as site conditions, magnitudes and source-to-site distances. We have selected earthquakes that have occurred in a similar tectonic setting mainly at the interface of plates in subduction zones, in the overlaying crust and in the subducting plate. These similar settings were found in Japan, Northern Pacific of USA, the West coasts of Mexico and Central America, the West coast of South America and Southern Europe. Since there is no clear understanding on the mechanism expected of future earthquakes in this part of the province, we have selected earthquakes and the horizontal components of the records regardless the type of faulting and direction of the shaking. Near-source events were excluded.

The reference soil classification, Site Class C, adopted in the national building code of Canada, NBCC 2005 (NRCC 2005) was selected as the fundamental site condition for this study. A Site Class-C site is defined by an average shear wave velocity in the upper 30 m, Vs30, between 360 m/s and 760 m/s, and is considered to be dense soil or soft rock. Not all the stations have enough information regarding the soil underneath, and estimations of the Vs30 had to be conducted in those cases. In many Japanese stations, the shear wave velocity was measured in the upper 10 m only. The classification for these stations was obtained from the extrapolation method developed by Boore (2004).

The search for appropriate earthquake records is constrained by a range of magnitudes and distances to earthquake sources. Appropriate ranges were determined by the results of deaggregated probabilistic seismic hazard analyses using EZ-FRISK (Risk Engineering 2008). We selected modal values to define the ranges of magnitudes and distances of interest. The range of modal values for the combined magnitude and source-to-site distances are summarized in Table 1 for the three types of earthquakes. These values were defined for the deaggregated 2% in 50year probability of exceedance of the spectral accelerations at periods of 1.0s and 2.0s.

Table 1. Ranges of moment magnitude, depth and hypocentral distance for the preliminary selection of recording stations of crustal, subcrustal and subduction earthquakes.

	Bin I **Crustal EQses**	**Bin II** **Subcrustal EQs**	**Bin III** **Subduction EQs**
Moment Magnitude (Mw)	6.5 – 7.5	6.3 – 7.6	8 – Max
Depth (km)	0 – 30	30 – 90	0 – 50
Hypocentral Distance	0 – 80	30 – 100	120 – 250

Database and data processing

Most crustal earthquakes were downloaded from the PEER-NGA database (Chou et al. 2008). None of these records requires further signal processing and the information regarding site conditions is properly reported. Japanese earthquakes were downloaded from the K-NET (Kinoshita 1998) and KiK-net (Aoi et al. 2000). The Japanese database contained all three types of earthquakes. Subcrustal earthquakes were mostly downloaded from the COSMOS database (Archuleta et al. 2006). The majority of subcrustal records and subduction records required the reformatting of the information. Details of selected records are listed in Table 2.

Excluding PEER-NGA database records, many time histories required further data processing. Those records were baseline corrected (BC) using a lineal function and then filtered with a 4-th order band-pass Butterworth filter with cut-off frequencies of 0.10 Hz and 25 Hz (cut-off periods of 10s and 0.04s). In several cases, records were filtered in a different range of cut-off frequencies and larger filter orders (6-th to 8-th) were used. Once filtered, the 5%-damping velocity spectra were obtained for each record. The average spectral pseudo-velocities, Sv*, of the period range 1.0 to 2.0 s were computed for each record. The scaling factor (SF) is then calculated as the ratio of these average spectral pseudo-velocities to the one for the target demand.

Selection Criteria

The selection criteria of the scaled records adopted in this work were as follows: select only records above 70% of the target for the scaling period range (1.0s to 2.0s); give preference to those that fall above 80 or 90% the target; the average of the final suite must be above the 90% the target within the whole matching period range; select those motions recorded from different earthquakes rather than records from the same earthquake; and, select one record per station.

Final selection of records

By following the criteria described above, suites of motions for each type of earthquake were defined. The suites correspond to the 2% in 50yr hazard level. Table 3 lists the selected motions for Vancouver (crustal and subcrustal) and Victoria (subduction). This table provides earthquake names, dates, station names, moment magnitudes (Mw), hypocentral distances (D), peak ground accelerations (PGA) of recorded motions, the average spectral velocities in the 1.0s to 2.0s period range ($PSV^*_{1\text{-}2}$) and the scaling factors (SF).

Table 2. Summary of earthquakes and number of stations preliminary selected.

Crustal				
Number ID	**Earthquake Name**	**Date yyyy/mm/dd**	**Mag. Mw**	**Stations No**
1	Kern County	21-Jul-52	7.4	2
2	Parkfield	28-Jun-66	6.2	1
3	San Fernando	09-Feb-71	6.6	4
4	Friuli, Italy-01	06-May-76	6.5	2
5	Gazli, USSR	17-May-76	6.8	1
6	Santa Barbara	13-Aug-78	5.9	1
7	Tabas, Iran	16-Sep-78	7.4	1
8	Imperial Valley-06	15-Oct-79	6.5	2
9	Mammoth Lakes-01	25-May-80	6.1	1
10	Victoria, Mexico	09-Jun-80	6.3	1
11	Irpinia, Italy-01	23-Nov-80	6.9	2
12	Irpinia, Italy-02	23-Nov-80	6.2	2
13	Coalinga-01	02-May-83	6.4	5
14	Morgan Hill	24-Apr-84	6.2	2
15	Nahanni, Canada	23-Dec-85	6.8	2
16	N. Palm Springs	08-Jul-86	6.1	1
17	New Zealand-02	02-Mar-87	6.6	1
18	Whittier Narrows-01	01-Oct-87	6	6
19	Loma Prieta	18-Oct-89	6.9	22
20	Manjil, Iran	20-Jun-90	7.4	1
21	Cape Mendocino	25-Apr-92	7	2
22	Landers	28-Jun-92	7.3	1
23	Landers	28-Jun-92	7.3	1
24	Northridge-01	17-Jan-94	6.7	34
25	Kobe, Japan	16-Jan-95	6.9	2
26	Kocaeli, Turkey	17-Aug-99	7.5	1
27	Chi-Chi, Taiwan-03	20-Sep-99	6.2	7
28	Chi-Chi, Taiwan-04	20-Sep-99	6.2	1
29	Chi-Chi, Taiwan-06	20-Sep-99	6.3	2
30	Hector Mine	16-Oct-99	7.1	1
31	Duzce, Turkey	12-Nov-99	7.1	1
32	E. Honshu, Japan	13-Jun-08	6.8	13
Sub-Crustal				
Number ID	**Earthquake Name**	**Date yyyy/mm/dd**	**Magnitude Mw**	**Stations No**
1	Nisqually, WA	28-Feb-01	6.8	20
2	Guerrero, Mexico	10-Dec-94	6.6	3
3	Michoacan, Mexico	11-Jan-97	7.1	2
4	El Salvador	13-Jan-01	7.6	1
5	S. Honshu, Japan	24-Mar-01	6.4	11
6	Miyagi_Oki, Japan	16-Aug-05	7.2	4
7	Olympia, WA	13-Apr-49	6.9	1
8	Puget Sound, WA	29-Apr-65	6.7	1
Subduction				
Number ID	**Earthquake Name**	**Date yyyy/mm/dd**	**Magnitude Mw**	**Stations No**
1	Tokachi_Oki, Japan	25-Sep-03	8	15
2	Valparaiso, Chile	03-Mar-85	8	1
3	Southern Peru	23-Jun-01	8.4	5
4	Tarapaca, Chile	13-Jun-05	8	1
5	Michoacan, Mexico	19-Sep-85	8.1 (Ms)	7

Figure 2 compares the spectral pseudo-velocities of the selected motions and average spectrum with the target spectrum. Differences amongst these three suites can be observed in terms of spectral shapes or period content. Crustal earthquakes have a clear short-period spectral content with a progressive decay for periods longer than 2 seconds. The same is true for the subcrustal suite, but with spectral values dominated at the scaled 1.0s to 2.0s period range only. We must add here, though, that most unselected subcrustal earthquake records have very high spectral values at periods shorter than 1 second. Many of these subcrustal earthquake records could not be selected because of the steep decay of the spectra at periods longer than 0.5 seconds. Subduction earthquake records have a better correlation with the target spectral values over the periods of interest.

Table 3. Summary of selected suites for Vancouver and Victoria.

Crustal Suite - Vancouver - Site Class C - R Model (PEER-NGA and K-Net database)							
Earthquake Name	**Date**	**Station Name**	**Mw**	**D km**	**PGA g**	**PSV^*_{1-2} cm/sec**	**SF**
Kern County	21-Jul-1952	USGS 1095 Taft Lincoln School	7.4	46.2	0.18	30.8	1.38
Tabas, Iran	16-Sep-1978	Stn: 9102 Dayhook	7.4	21.4	0.41	44.5	0.95
Irpinia, Italy-01	23-Nov-1980	ENEL 99999 Calitri	6.9	17.8	0.13	44.0	0.97
Nahanni, Canada	23-Dec-1985	Stn: 6098 Site 2	6.8	10.3	0.32	36.5	1.16
Loma Prieta	18-Oct-1989	CDMG 57007 Corralitos	6.9	18.9	0.64	51.8	0.82
		CDMG 57217 Coyote Lake Dam (SW Abut)	6.9	35.4	0.48	54.7	0.78
Cape Mendocino	25-Apr-1992	CDMG 89156 Petrolia	7.0	10.5	0.59	57.0	0.75
Northridge-01	17-Jan-1994	USGS 5108 Santa Susana Ground	6.7	22.8	0.29	33.2	1.28
Kobe, Japan	16-Jan-1995	CUE 99999 Nishi-Akashi	6.9	19.9	0.51	43.0	0.99
E. Honshu, Japan	13-Jun-2008	Ichinoseki (IWT010)	6.8	20.0	0.22	40.4	1.05
SubCrustal Suite - Vancouver - Site Class C - H Model (COSMOS database)							
Earthquake Name	**Date**	**Station Name**	**Mw**	**D km**	**PGA g**	**PSV^*_{1-2} cm/sec**	**SF**
Nisqually, WA	28-Feb-2001	Renton (RBEN)	6.8	73.1	0.11	21.1	1.94
		Seattle (BHD)	6.8	76.8	0.16	40.6	1.01
		Seattle (KIMB)	6.8	77.4	0.14	34.2	1.19
		Seattle (MAR)	6.8	77.6	0.13	13.2	3.08
		Poulsbo (KITP)	6.8	78.9	0.06	21.4	1.91
		Seattle (CRO)	6.8	79.4	0.09	18.4	2.22
		Seattle (EVA)	6.8	80.7	0.06	22.1	1.84
Guerrero, Mexico	10-Dec-1994	Zihuatanejo (AZIH)	6.6	76.6	0.06	11.3	3.61
Michoacan, Mexico	11-Jan-1997	Villita (VILE)	7.1	71.4	0.10	12.2	3.35
El Salvador	13-Jan-2001	Unidad de Salud, Panchimalco (PA)	7.6	95.7	0.19	17.9	2.28
Subduction Suite - Victoria - Site Class C - Deterministic Model (COSMOS 2008, K-Net 2008)							
Earthquake Name	**Date**	**Station Name**	**Mw**	**D km**	**PGA g**	**PSV^*_{1-2} cm/sec**	**SF**
Tokachi-oki, Japan	25-Sep-2003	Meguro (HKD113)	8.0	58.6	0.16	27.2	1.52
		Noya (HKD107)	8.0	126.4	0.09	38.0	1.09
		Obihiro (HKD095)	8.0	132.2	0.18	51.6	0.80
		Hombetsu (HKD090)	8.0	145.8	0.50	26.8	1.54
		Futamata (HKD087)	8.0	148.7	0.26	38.9	1.06
		Tsurui (HKD083)	8.0	163.4	0.19	35.8	1.16
Michoacan, Mexico *	19-Sep-1985	Caleta De Campos (CALE)	8.1	38.3	0.15	42.1	0.98
		Villita (VILE)	8.1	47.8	0.11	24.0	1.72
		La Union (UNIO)	8.1	83.9	0.17	34.3	1.21
		Zihuatanejo (AZIH)	8.1	132.6	0.10	34.9	1.18

* Local magnitudes were reported for this earthquake

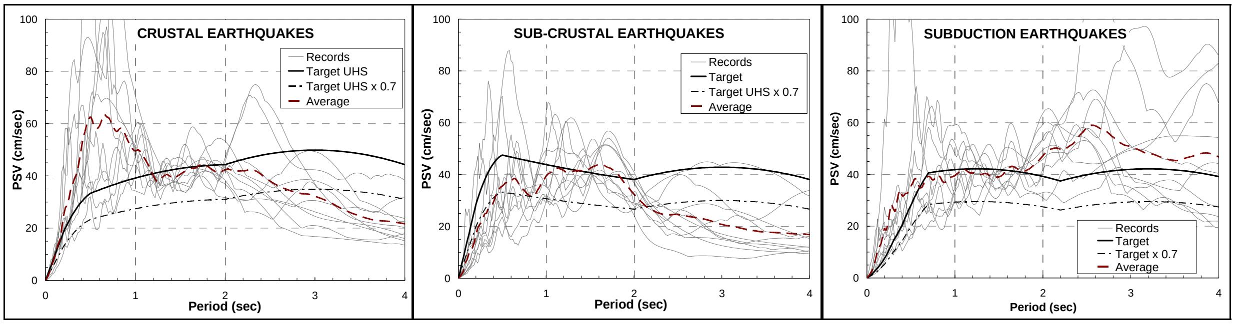

Figure 2. Spectral 5%-damping pseudo-velocities of selected/modified records and target Uniform Hazard Spectra (UHS) for crustal, subcrustal and subduction earthquakes.

Application of selected motions

We may refer at this point to a companion paper (Ventura et al. 2010) for further details on the specific use of the three selected suite of motions in the seismic risk assessment procedure adopted in the school project. In this part, we will present the behaviour of a characteristic school building structural system under incremental intensities of the selected suites of motions.

IDA of a wood system

We have applied the selected motions to an unblocked plywood shear-wall 2-storey building, W-2, located in Vancouver and Victoria (further details of the structural system are given by Hanson et al. 2009). Crustal and subcrustal suites of motions have been linearly scaled to represent the respective target spectral demands of Victoria. Subduction suite of motion has been linearly scaled to represent the target demand of Vancouver.

The incremental dynamic curves for W-2 are presented in Figure 3 for the two cities. We can clearly see the different structural responses for these three events. Crustal earthquakes trigger the failure (flat line) at a much lower intensity levels than the other two in both cities. Failure occurs at very similar intensities to crustal earthquakes in Vancouver for subcrustal earthquakes, and in Victoria l for subduction earthquakes. Subduction earthquakes in Vancouver and subcrustal earthquakes in Victoria barely trigger nonlinear deformations in the structural system.

Remarks

This paper presents a comprehensive procedure for the selection of records for structural assessment of existing low-rise school buildings in British Columbia. The selection was primarily based on the likely magnitude-distance earthquake for the city of Vancouver separated into crustal and subcrustal earthquakes, and for the city of Victoria for subduction earthquakes. Selected records from these earthquakes were matched to corresponding earthquake hazard demands. The resulting suites of motions were used to run several IDA for a wood structural system located in Vancouver and Victoria.

Selected suites of motions for different types of earthquakes allows for a better understanding of the consequences of different earthquake demands and their possible damage scenarios in the structures of low-rise school buildings. Individual consequences will allow for a consistent and rational calculation of seismic risk from the contribution of each earthquake type.

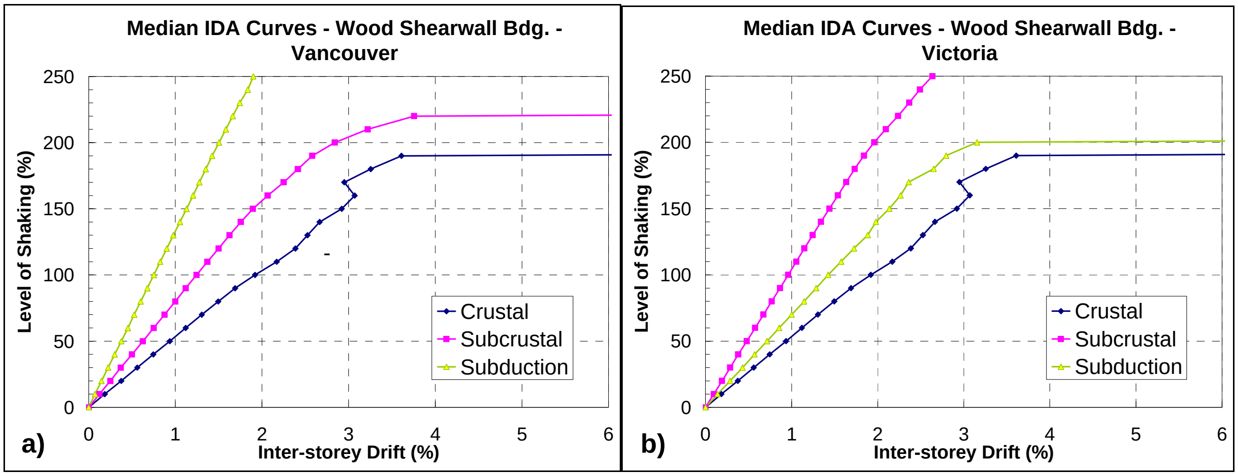

Figure 3. …Median IDA curves for a plywood shear-wall 2-storey building located in (a) Vancouver and (b) Victoria.

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