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EFFECTS OF SUBDUCTION GROUND MOTIONS ON THE PROBABILITY OF COLLAPSE ON LOW-RISE BUILDINGS

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ABSTRACT: Hysteretic behaviour of reinforced concrete moment frame connections have been extensively studied, yet very little is known about the combined effects of ground motion duration and deterioration in the structural material. Following the general approach adopted in the Seismic Retrofit Guidelines 2nd Edition (SRG II), incremental dynamic analysis is conducted to investigate discrepancies in the probability of drift exceedance for certain building types under both crustal and subduction ground motion records. These ground motions are selected and scaled to match the 2015 uniform hazard spectrum of Victoria, B.C. A two-degree-of-freedom shear wall model is first examined to generalize the effects of long duration ground motions. A similar study on reinforced concrete building is then conducted to confirm these generalizations. Observations from this paper will be helpful in understand the effect of long duration ground motion.

1. Introduction

Long duration subduction ground motions have been found to be more likely to cause collapse of structures. Results presented in this paper are consistent with findings reported by Raghunandan, Liel, and Luco (2014) for the United States of Geological Survey, that it is likely to take a less intense subduction ground motion to achieve the same probability of collapse than a crustal one. The discrepancy might have been caused by: (i) the spectral shape of the ground motions, thus frequency contents, and (ii) the duration of the ground motions, thus the number of loading reversals. The overall ductility of the structural system also plays a key role in the determination of collapsing probability, and it seems to be more influencing on modern ductile systems than non-ductile ones.

The academic software OpenSees (2013) is the main tool used in this study. Material models capable of simulating monotonic and cyclic strength and stiffness degradation are incorporated into two prototype models, representing shear wall and moment frame respectively, which are then subjected to incremental dynamic analysis. Analysis results are presented in the form of fragility curves. The vertical axis is the probability of drift exceedance, and the horizontal axis is the scaling level of the ground motions.

2. Assessment of Seismic Performance

2.1. Seismic Retrofit Guidelines 2nd Edition (SRG II, 2013)

The SRG II is part of the British Columbia Ministry of Education program to reduce overall seismic risk of public school buildings. In light of performance-based design methodology, the philosophy is to prevent loss of lives by reducing the probability of collapse, rather than preventing damages from occurring. As such, interstorey drift ratio is chosen to be the indicator of building performance, hence adopted in the study presented in this paper. Following the state-of-the-art procedure for simulating dynamic building responses, multiple nonlinear time history analyses are conducted on each building system to establish the probability of exceeding the deformation limit state. The purpose of nonlinear analysis in SRG II is to determine an appropriate level of lateral strength, expressed as some portion of the structural weight, such that the probability of drift exceedance at a life safety drift limit is kept low at 2% in 50 years.

2.2. Material Hysteretic Degradation

The capability of a hysteretic model to capture different forms of deterioration is crucial in seismic collapse assessment (Ibarra, et.al., 2005). Through careful calibration against experimental results, Ibarra (2005) has developed three material models that address both monotonic and cyclic deterioration. These models are subsequently modified by Lignos and Krawinkler (2012) and become the uniaxial material model “Bilin”, “ModIMKPeakOriented”, and “ModIMKPinching” in OpenSees. Figure 1 illustrates schematically the deterioration capability of the OpenSees “Bilin” model used in this study.

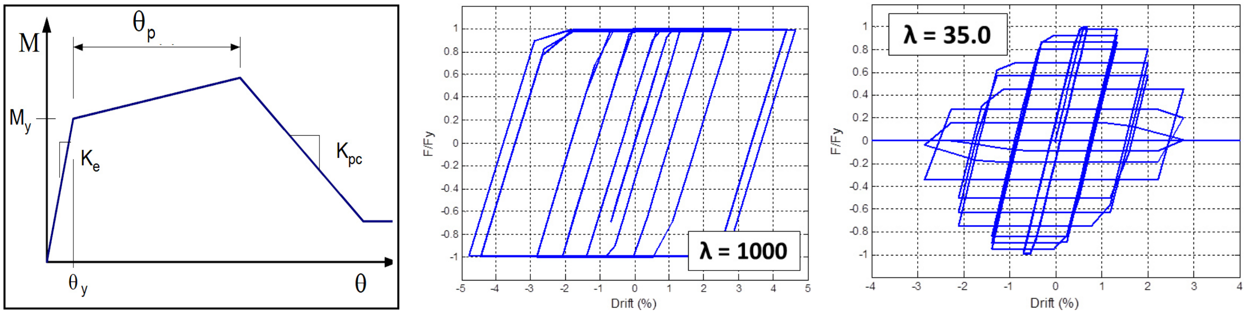


Fig. 1 – Schematic Representation of the Material Hysteretic Degradation Behaviour

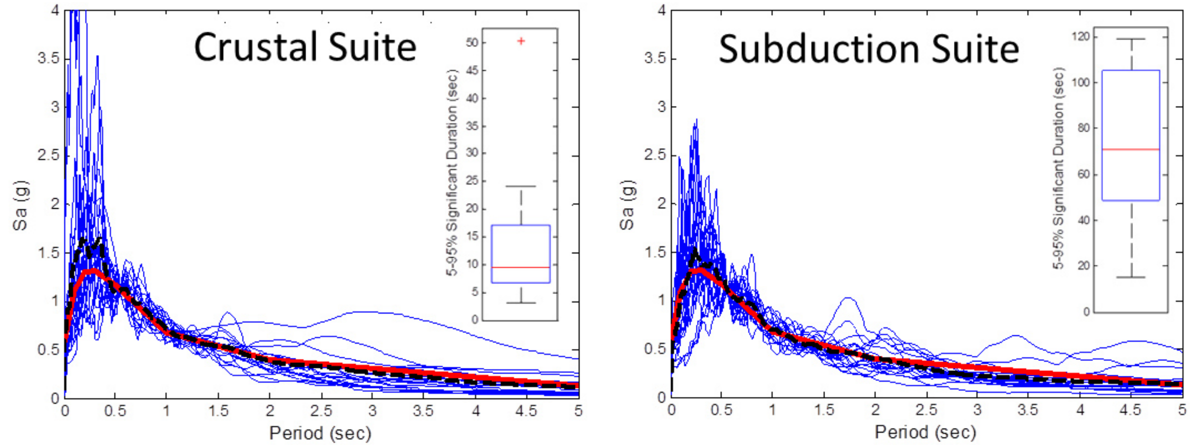
Monotonic deterioration refers to strength loss in one single cycle. The negative post-capping stiffness on the element backbone curve best exemplifies such deterioration. This negative stiffness is critical for seismic collapse simulation (Ibarra et. al., 2005). Pushover analysis is a common tool to study the monotonic deterioration properties of a structural component.

Cyclic deterioration refers to strength loss in subsequent cycles of loading while the tangent stiffness remains positive. Physically, this behaviour is the result of the element disintegrating under multiple reversing cycles, such as concrete spalling off or fastenings pulling out. This paper follows the material deterioration assessment and nonlinear modeling recommendations found in Chapter 2 of the PEER/ATC-72-1 Report. Cyclic displacement loading is an effective way to experimentally quantify the amount of cyclic deterioration on structural components. In the OpenSees “Bilin” material model, the amount of deterioration is controlled by four λ parameters that dictate the percentage drop of strength and stiffness dictated by a series of empirical relationships (Lignos and Krawinkler, 2012).

2.3. Ground Motion Selection and Scaling

Ground motion records are selected and scaled to the 2015 uniform hazard spectrum (UHS) of Victoria, B.C. In South-western British Columbia, including Vancouver and Victoria, the seismic hazard is made of two primary types: shallow crustal events and subduction zone events. Crustal earthquakes occur from slips along faults in the Earth's crust, typically less than 35km deep. Crustal earthquakes are the most common worldwide and have been recorded during many strong shaking events. Subduction (or interface) earthquakes are major shaking events caused by slip between subducting tectonic plates. Subduction regimes have been responsible for the most intense earthquakes ever recorded.

Using the S2GM database (Bebamzadeh et al., 2015), two suites of 20 ground motions are selected for crustal and subduction earthquakes respectively. The selection algorithm filters out ground motion records that deviate the least from the mean response spectrum, which is scaled to match with the UHS, from 0.2 to 1.5 times the fundamental period, as shown in Figure 2. The 2015 Victoria UHS is highlighted in red, and the black dashed line represents the mean response spectrum of the selected records. The insert summarizes the distribution of their significant durations. The crustal suite has an average significant duration of 10 seconds, and 70 seconds for the subduction suite.



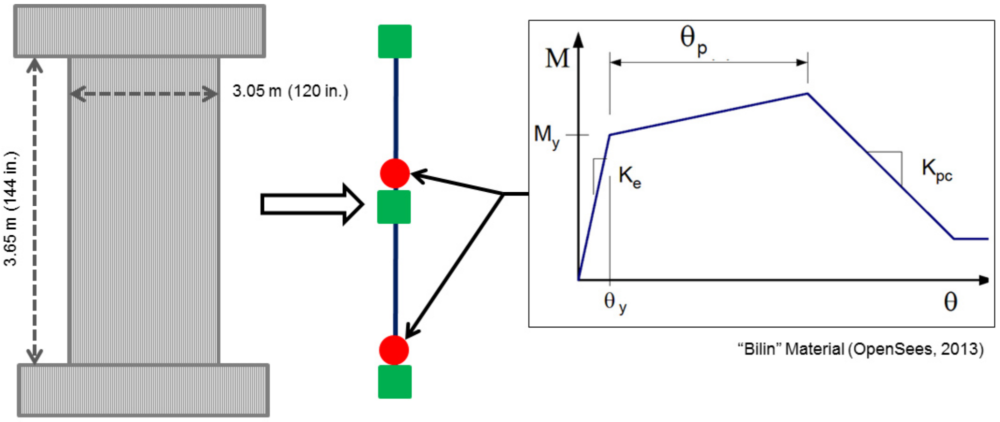
(a) **(b)**

Fig. 2 – Acceleration Response Spectra for the Selected Ground Motion Records after Scaling for the (a) Crustal and (b) Subduction Suites

3. Study of a 2-DOF Concrete Shear Wall

3.1. Model Idealization

A two-storey reinforced concrete shear wall is idealized as a lumped plasticity two-degree-of-freedom (2-DOF) model as shown in Figure 3. Dimension and loading condition of the shear wall are determined in light of Birely (2012) analysis on specimen PW1, however the backbone curve and hysteresis parameters are selected based on the SRG II Prototype C-6 Shear Wall. The fundamental period is 0.18 seconds.



"Bilin" Material (OpenSees, 2013)

Fig. 3 – Idealization of the SDOF Concrete Shear Wall

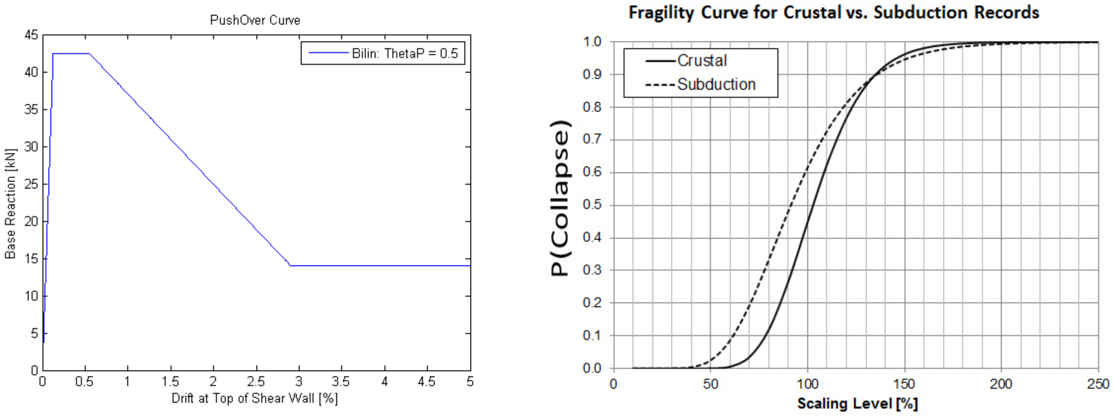
3.2. Analysis Procedure

The plastic deformation capacity of the lumped hinge, θ_P, directly contributes to the overall structural ductility. At each θ_P, the shear wall ductility is examined using pushover analysis. The model is then subjected to the two sets of 2015-Victoria-UHS-matching ground motion records. Each of the ground motion record is multiplied by a constant factor to simulate 10% to 250% of the original intensity. For each ground motion record, the intensity at which collapse is first detected is recorded. Collapse is defined as the drift level where the incremental dynamic analysis curves become flat and small changes in ground motion scaling cause extreme changes in drift. Then for each set of ground motion, the average and standard deviation of the intensity are computed. By assuming a lognormal distribution, the cumulative probability of drift exceedance at increasing intensity level can be established. Such plot is termed fragility curve in this paper.

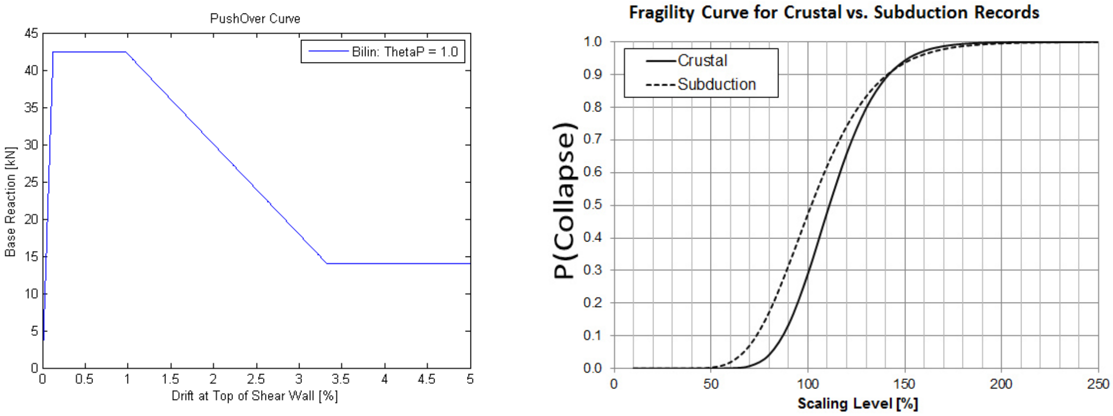
The degradation controlling parameter, λ, equals 35.0 for all four modes of degradation (Liel and Raghunandan, 2013).

3.3. Fragility Curve Results

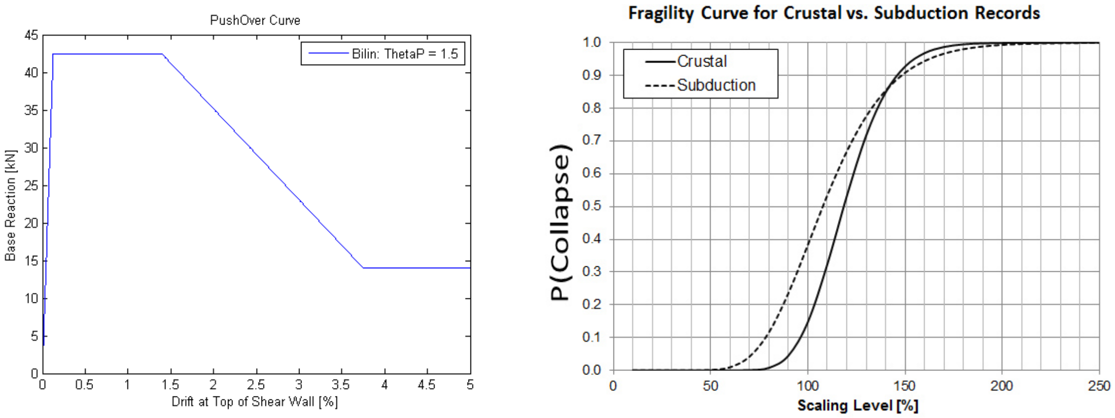
A range of θ_P values was selected from 0.5 to 3.0 at a 0.5 increment. The fragility curves from incremental dynamic analysis are presented in comparison Figure 4 (a) through (i).



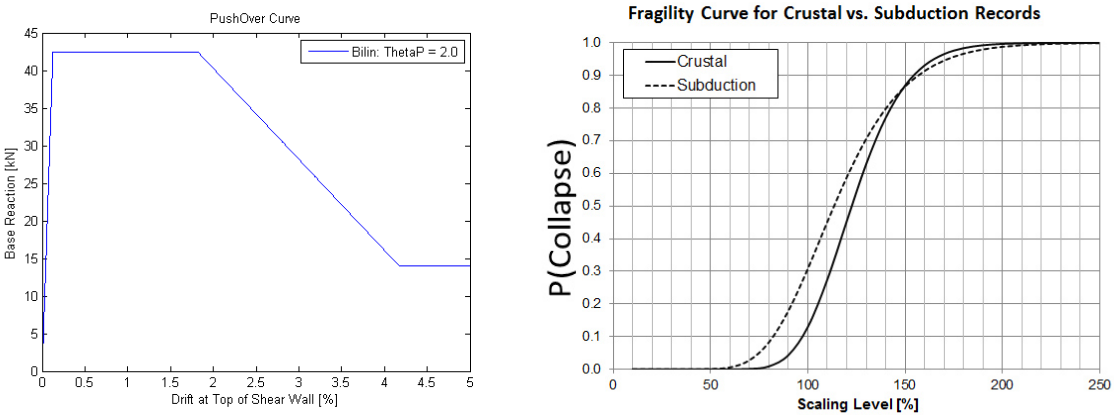
(a)



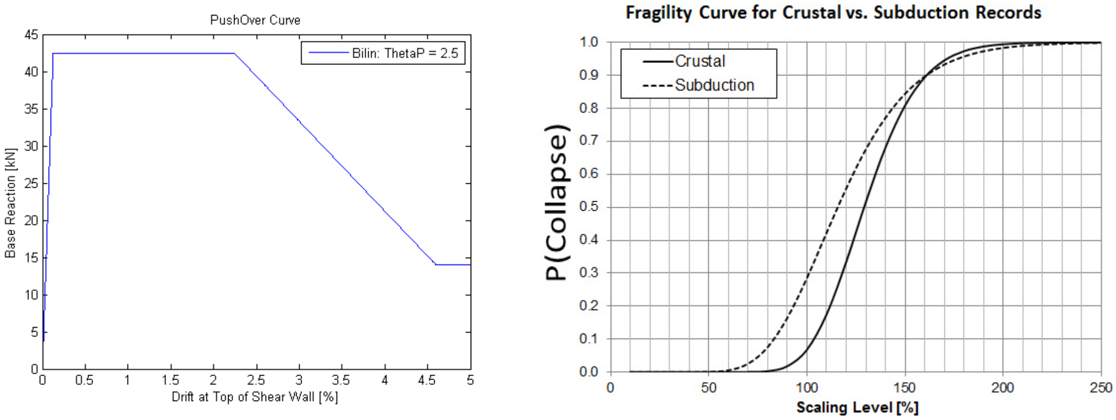
(b)


PushOver Curve
Bilin: ThetaP = 1.5
Base Reaction [kN]
Drift at Top of Shear Wall [%]
0
5
10
15
20
25
30
35
40
45
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Fragility Curve for Crustal vs. Subduction Records
Crustal
Subduction
P(Collapse)
Scaling Level [%]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
50
100
150
200
250

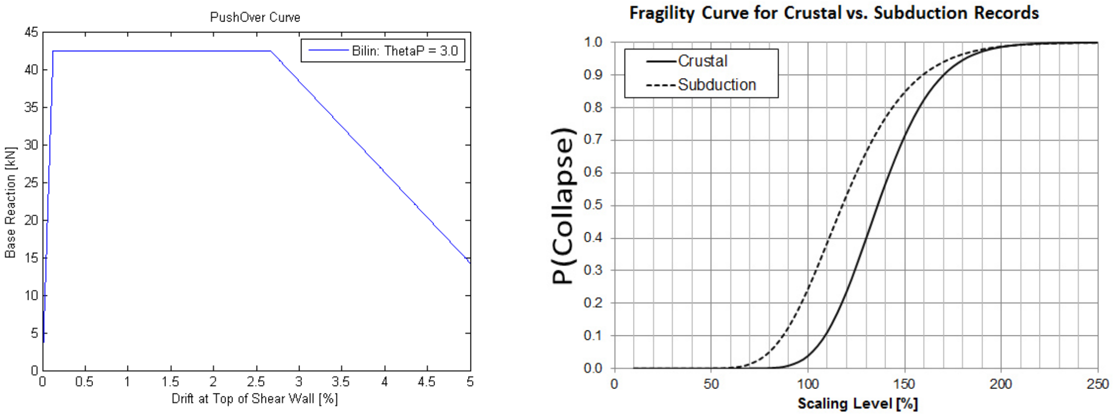
(c)


PushOver Curve
Bilin: ThetaP = 2.0
Base Reaction [kN]
Drift at Top of Shear Wall [%]
0
5
10
15
20
25
30
35
40
45
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Fragility Curve for Crustal vs. Subduction Records
Crustal
Subduction
P(Collapse)
Scaling Level [%]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
50
100
150
200
250

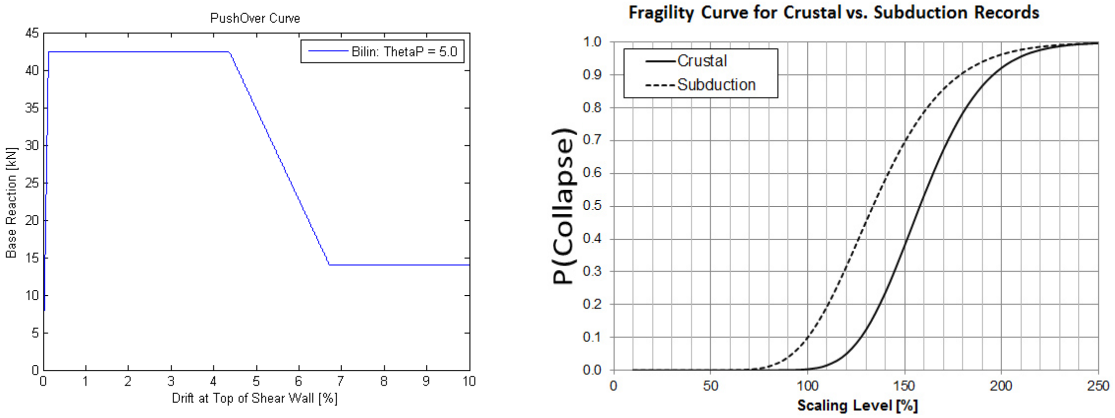
(d)


PushOver Curve
Bilin: ThetaP = 2.5
Base Reaction [kN]
Drift at Top of Shear Wall [%]
0
5
10
15
20
25
30
35
40
45
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Fragility Curve for Crustal vs. Subduction Records
Crustal
Subduction
P(Collapse)
Scaling Level [%]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
50
100
150
200
250

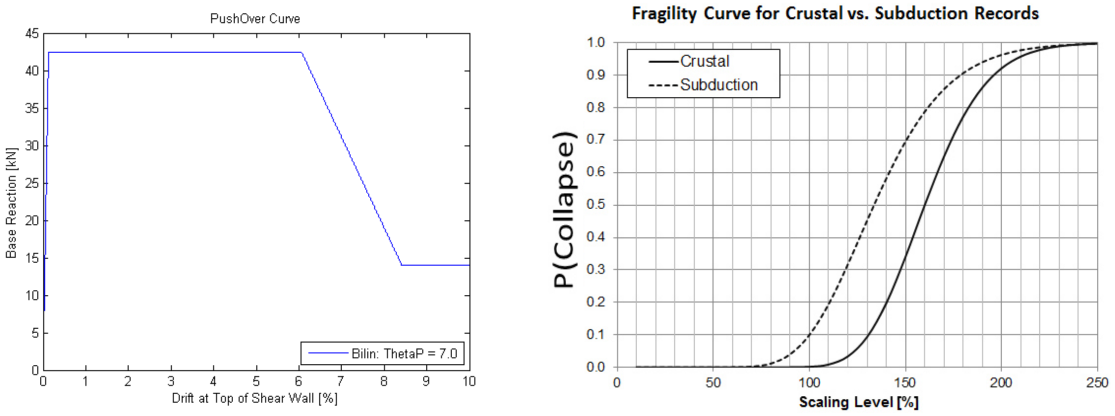
(e)



(f)



(g)



(h)

Fig. 4 – Comparison of Backbone and Fragility Curves at Various Plastic Hinge Deformation Capacities for θ_P = (a) 0.5, (b) 1.0, (c) 1.5, (d) 2.0, (e) 2.5, (f) 3.0, (g) 5.0, and (h) 7.0

3.4. Observation and Discussion

Each point on the fragility curve represents the probability of collapse when the ground motion intensity reaches a certain level. There are two key trends observed from these results: the decreasing probability of collapse as the plastic hinge deformation capacity increases, and the fundamental difference in probability of collapse between crustal and subduction ground motions at the same intensity level.

As the plastic hinge deformation capacity, θ_P, increases, so does the overall ductility of the structure. The enhanced capability in enduring larger deformation allows the structure to reach larger interstorey drifts before collapse while the plastic zone dissipates the input earthquake energy. Such enhancement is most evident at lower ductility levels where θ_P ranges from 0.5 to 3.0. Under the same hazard, or when the scaling level is 100%, the probability of collapse drops from 0.45, when θ_P equals 0.5, to 0.05, when θ_P equals 3.0. Therefore, enhancing the ductility of a structure may be one effective way to lower the probability of collapse. The trend of decreasing probability of collapse is less evident at larger ductility levels where θ_P ranges from 5.0 to 7.0. This is because of the cyclic deterioration in the models, which causes large strength losses before the entire ductility can be realized.

Another interesting observation is the difference between crustal and subduction records. At each plastic hinge deformation capacity level, it takes a less intense subduction ground motion to cause the same probability of collapse. One possible explanation is the higher number of cycles in the subduction records that may have exhausted the pre-defined deterioration capability of the material model, represented by the parameter λ. Notice that these fragility curves are generated using 20 ground motions for each type of earthquake. The authors intend to conduct a future study to encompass more records to examine the effect of statistical dispersion of the data.

4. Study of an MDOF Ductile Reinforced Concrete Moment Frame

4.1. Idealization of Concrete Moment Frame Model

This study makes use of a ductile concrete moment frame model developed by the American Technical Council (ATC, 2012). The five-bay-and-six-storey building was designed to satisfy detailing requirements in modern building codes. Figure 5 shows the schematic of the model. Beams and columns are modelled as lumped plasticity elements with rotational hinges forming at both ends. Each hinge is assigned with element specific monotonic and cyclic parameters as reported by ATC 2012. In addition, the *Joint2D* element is used to model the beam-column joint behaviour, and a leaning column is added to capture the P-Delta effect. The ATC Prototype 1 is adopted as the "base case" in this study. The first three modal periods are 1.59s, 0.56s, and 0.29s.

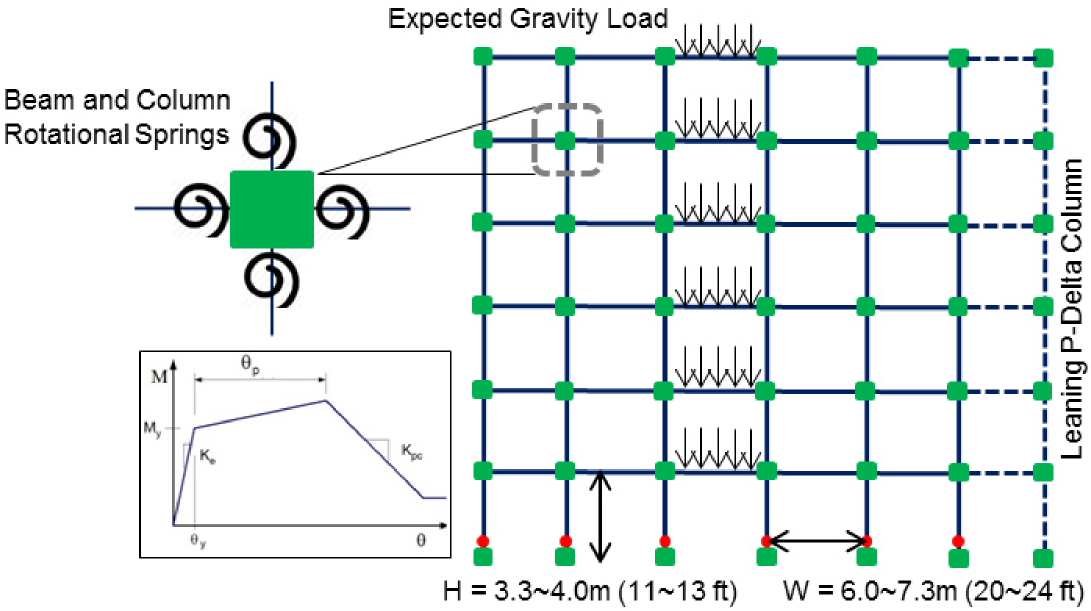


Fig. 5 – Schematic Representation of the MDOF Moment Frame Model

4.2. Fragility Curve Results

The fragility curves of the moment frame are generated for each type of ground motion. Pushover curve for the "base case" is presented in Figure 6, and the fragility curve results are summarized in Figure 7.

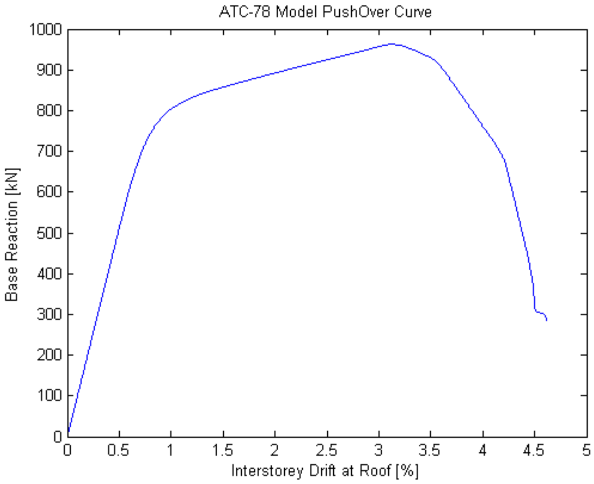


Fig. 6 – Moment Frame Pushover Curves for Base Case

As was the case with the shear walls, the moment frame also exhibits significant discrepancy between the probability of drift exceedance under crustal and subduction ground motions, as seen in Figure 7. Examination on the plastic hinge hysteresis data reveals that the energy dissipation capacity depletes more under subduction ground motion because of a higher number in load cycles.

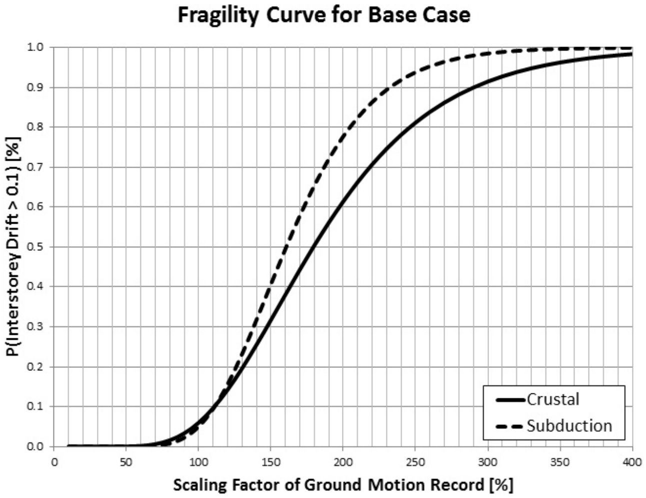


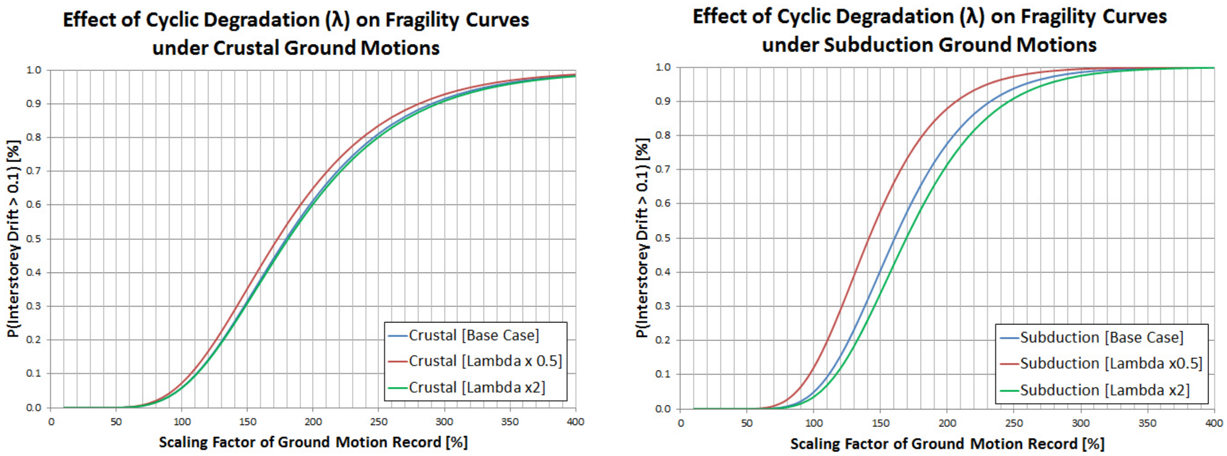
Fig. 7 – Fragility Curves for Base Case

4.3. Effect of Amount of Degradation

Material degradation does play a role in dictating the probability of drift exceedance. Recall the degradation parameter, λ, used in OpenSees. The higher the value, the less the degradation. Not surprisingly, a less deteriorating structural system (doubling λ) would have a lower probability of drift exceedance than an equivalent system prone to more deterioration (halving λ). What is interesting, however, is the influence of material degradation when facing subduction ground motions as opposed to crustal ones. With reference to Figure 9, the amount of degradation does not have much effect on the crustal ground motion suite, whereas the median collapse intensity reduces by almost 10% in the subduction case. The ground motion intensity corresponding to a probability of collapse of 10% and 50% (median) are summarized in Table 1. At lower probability of collapse, the ground motion intensities between crustal and subduction are reasonably close. At higher probability of collapse, however, the intensities deviate quite dramatically, especially in the case of high degradation.

Table 1 – Ground Motion Intensities Corresponding to 10% and 50% P(Collapse).

P(Collapse) =	10%		50% (Median)	
Case	**Crustal**	**Subduction**	**Crustal**	**Subduction**
"Base Case"	111%	111%	179%	161%
"λ x2"	111%	116%	181%	169%
"λ x 0.5"	106%	97%	173%	141%



(a) (b)

Fig. 8 – Effect of λ on Fragility Curves for (a) Crustal, and (b) Subduction Record Suites

5. Conclusion

In general, a building is more likely to collapse if shaken by a long duration ground motion. This observation is repeatedly seen from the shear wall and the moment frame studies, and is most evident when the building's ductility is high. At the same ground motion intensity, the probability of collapse is usually higher in the case of subduction ground motions than their crustal counterparts. Buildings in subduction regions around the globe, including the Cascadia subduction zone in the Northwest Pacific of North America, may be susceptible to large and long duration seismic events. This study has demonstrated that many buildings would be at a high risk if such event were to occur.

Though seismicity is usually considered in the design of modern buildings, effect of the ground motion duration is not explicitly accounted for. Results in this paper have shown that some discrepancies between the probability of collapse of crustal and subduction ground motions do exist and that the effect of the duration of motions may be important in structural design and assessment. Material degradation has been shown to significantly affect the probability of collapse, and therefore should be considered.

Another difference between crustal and subduction records may be in their frequency content and spectral shape. In this study, ground motions were selected and scaled to closely match a target spectrum, which removed this potential effect, so that the effect of duration could be studied independently. The effect of the difference in spectral shape between subduction and crustal ground motion records is another topic for future research.

References

Applied Technology Council, (ATC, 2012). "*Evaluation of the methodology to select and prioritize collapse indicators in older concrete buildings*," ATC-78-1 Report, ATC, Redwood City, CA.

BIRELY, A.C. (2012). "Seismic Performance of Slender Reinforced Concrete Structural Walls," Ph.D Thesis Dissertation, University of Washington, Seattle, WA.

BEBAMZADEH, A., VENTURA, C.V., FAIRHURST, M. (2015). "S2GM: Ground motion selection and scaling database," Annual Los Angeles Tall Building Design Council Meeting, Los Angeles, CA.

IBARRA, L.F., MEDINA, R.A., and KRAWINKLER, H. (2005). "Hysteretic models that incorporate strength and stiffness deterioration," *Earthquake Engineering and Structural Dynamics*, Vol. 34, pp. 1489-1511.

LIEL, A. and RAGHUNANDAN, M. (2013). "Investigation of Structural Collapse Risk in the Cascadia Subduction Zone," Final Report to U.S. Geological Survey, University of Colorado, Boulder, CO.

LIGNOS, D.G. and KRAWINKLER, H. (2012). "*Sidesway collapse of deteriorating structural systems Under seismic excitations*," Rep.No.TB 177, The John A. Blume Earthquake Engineering Research Center, Stanford University, Stanford, CA.

Open System for Earthquake Engineering Simulation (OpenSees) (2013). Pacific Earthquake Engineering Research Center, University of California, Berkeley, http://opensees.berkeley.edu/

PEER/ATC (2010). "*Modeling and acceptance criteria for seismic design and analysis of tall buildings*," PEER/ATC 72-1 Report, Applied Technology Council, Redwood City, CA, October 2010.

RAGHUNANDAN, M., LIEL, Abbie B., and LUCO, Nicolas. (2014). "Collapse Risk of Buildings in the Pacific Northwest Region due to Subduction Earthquakes". Earthquake Spectra In-Press.