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LONG DURATION EFFECTS ON WOOD SHEARWALLS

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Abstract

Over the past 10 years, a significant effort to retrofit schools in the Province of British Columbia has been undertaken. A central part of this work has been on the development of a set of Seismic Retrofit Guidelines, which are a performance based tool to provide engineers the basis for retrofit. For the 3rd Edition of guidelines (2016), which includes the new 2015 ground motions from the National Building Code of Canada, there is an increased focus on long duration shaking and their effects. The aim of this study was to investigate the effect of ground motion duration on the collapse probability of wood shearwalls. First several physical tests were performed in which full-scale wood shearwalls were subjected to long duration ground motion. A numerical model was then calibrated to these test results and used to run incremental dynamic analysis using two suites of ground motions including long and short duration. The results indicated that near the code shaking level (ground motions with a 2% in 50 year probability of exceedance) there was little difference between the two record sets. At higher shaking levels, the difference between the two record sets became more apparent, with the median collapse shaking level becoming lower for the long duration suite. At these high shaking levels more damage and cyclic degradation was observed in the models. This implies that while duration has little impact on the collapse capacity of wood shearwalls near code shaking levels, the margin against collapse is significantly lower when this type of system is subjected to long duration motions.

Keywords: long-duration; wood shear-walls; incremental dynamic analysis

1. Introduction

Over the past 10 years the Ministry of Education in the province of British Columbia has implemented a Seismic Retrofit Program for public schools. As part of this program, the Ministry collaborated with the Association of Professional Engineers and Geoscientists BC (APEGBC) and the University of British Columbia (UBC) to develop a set of performance-based Seismic Retrofit Guidelines (SRG) which are based on a program of experimental testing and state-of-the-art nonlinear analysis [1].

Concurrently, the 2015 edition of the National Building Code of Canada is featuring an updated seismic hazard model with an updated earthquake catalogue, including probabilistic treatment of the Cascadia subduction zone and the resulting use of long-duration ground motions [2]. The most recent version of the SRG (3rd Version, September 2016) has emphasis on the long-duration effects both in the experimental program and in the ground motion selection and analysis. Limited long-duration testing has been performed on URM walls, wood shear walls, and an upcoming test program (Fall 2016) will feature testing on a single storey wood frame structure.

This paper focuses on the analysis of single wood shearwalls designed as per standard building practice and the SRG blocked shearwall prototypes. A limited shake-table test program was performed on these walls using a long duration record. The numerical model was run with the same conditions and compared to the test results. The numerical model was then subjected to a series of long and short duration records to assess the duration effect.

2. Long Duration Effects

The influence of ground motion duration on the performance of structures is not well understood. It is difficult to isolate duration effects from the other shaking parameters (i.e. magnitude, frequency content); often higher magnitude earthquakes correspond with longer duration ground motion. Furthermore, up to 10 years ago, prior to the Tohoku 2011 and Maule 2010 earthquakes, it was challenging to produce significant results due to the limited database of available ground motion records. There also has not been good agreement between scientist on how to define 'duration' itself. More recently the tendency is to use the duration definition related to the amount of energy released during the shaking, such as 'significant duration'. Current seismic design practice and loading protocols for component tests do not explicitly consider the effect of duration. Performance based engineering methodologies can implicitly consider duration through the qualitative ground motion selection for a given location. In geological locations where crustal and subduction earthquakes have a significant hazard, such as found in south-western British Columbia, Canada, the effect of duration may be a cause for concern in regardss to significant damage and collapse (i.e. in Victoria, B.C. at 1sec period structure subduction, subcrustal and crustal contributes to 60%, 22% and 17% of the total hazard, respectively).

A study by Chandramohan et al. [3] found that the probability of structural collapse is higher for long duration ground motions compared to short duration ground motions considering spectrally equivalent sets of records for a ductile steel moment frame building. Spectrally equivalent set of records were used to isolate the event of duration from other shaking parameters. A similar study [3] was conducted on a reinforced concrete bridge pier and the effect of duration was quantified as a 17% decrease on collapse capacity when considering the long duration set rather than the short suite of ground motion. An additional study by Chanadramohan et al. [4] found that the mean annual frequency of collapse of the same steel moment frame building was underestimated by 29%, 59% and 7% for Seattle, WA, Eugene, OR, and San Francisco, CA, respectively, when using typical-duration ground motions from the PEER NGA-West2 database (as compared to ground motions selected using source-specific probability distributions of the durations of the ground motions anticipated at the site). The probability of collapse was more significantly underestimated for sites where subduction earthquake sources govern the hazard.

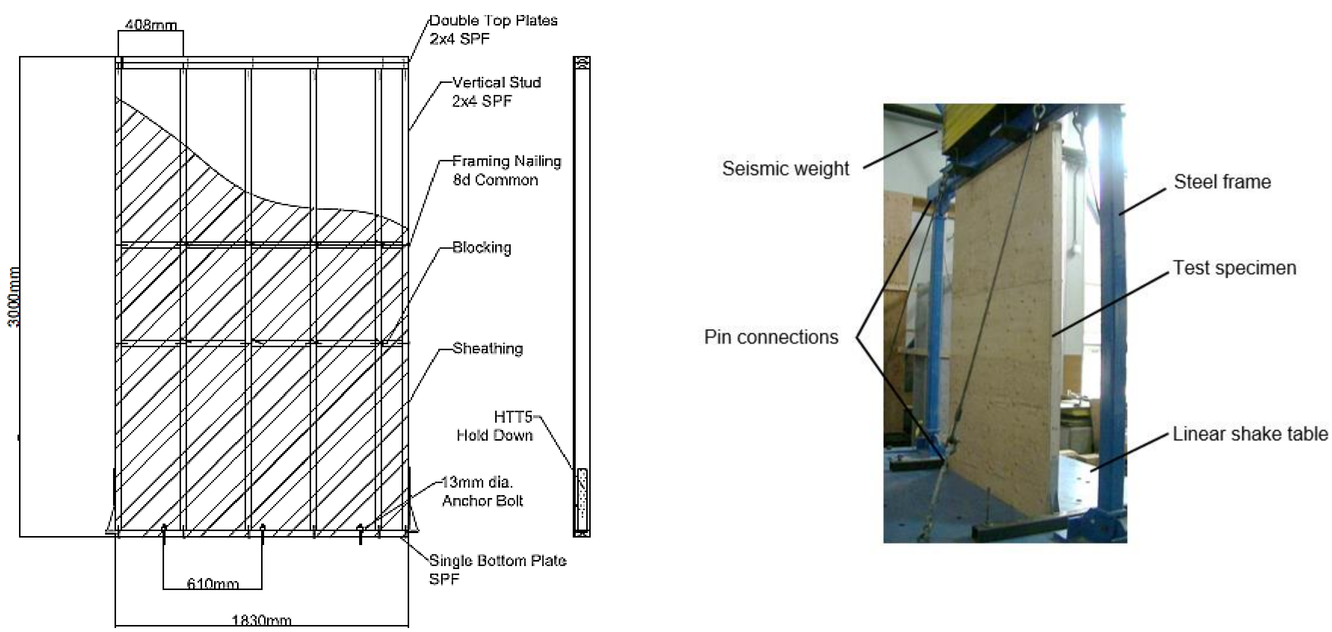
There has been little research in determining the effect of duration and subduction earthquakes on light frame wood structures. After seismic events, such as the Northridge earthquakes, the research was focused on addressing the deficiencies observed in the post-earthquake evaluations. The earthquakes were crustal strike-slip, as common to California, and as a result, the cyclic-testing protocols developed better represent the characteristics of crustal seismic events. In this paper, an experimental and numerical study was completed to investigate the effect of the duration of ground motions on the performance of light-frame wood structures, as well as to have a better prediction of the response of the structure in a subduction earthquake with a large magnitude (Mw ~ 9).

3. Experimental Testing

For the development of the BC Public School Seismic Retrofit Guidelines, an extensive experimental testing program has been undertaken. The testing that was done prior to the release of the Second Edition of the guidelines was primarily monotonic and cyclic testing on in-plane and out-of-plane prototype specimen. The current program of testing focuses on the dynamic response of prototype specimens; planning for shake-table test of a single story retrofitted woodframe school block is planned for late 2016. The purpose of the testing is to examine post-earthquake response techniques and long-duration effects on these types of structures. Prior to the full-scale test, two single blocked wood shear walls were tested on the shake-table with a long-duration record. This was a very limited test program, and was performed with the intention of i) evaluate methods to compute drift from acceleration measurements; ii) examine how well the previous cyclic tests were at representing the dynamic behaviour and iii) examining the effects of long duration shaking on these walls.

The fully-blocked shear wall specimens were constructed in accordance to the Canadian Wood Design Manual 2010 [5] and as described by a W1 Prototype as per SRG2 (Fig. 1). The test specimens were 3.0m height and 1.8m length as shown in the wall schematic in Fig. 1. Simson Strong Tie holddowns (HTT5) at each end and ½" diameter anchors bolts were used to ensure full anchorage of the wall. Vertical studs, top and bottom plates were 2x4 SPF and 8d common nails were used for the framing and sheathing connections for both test specimens. The sheathing nails were spaced at 100mm on the panel edges and 300mm on the interior. OSB (12.5mm) and plywood (12.5mm) was used for the sheathing in the first and second test, respectively.

Testing was performed on the linear shake-table of the Earthquake Engineering Research Facility at the University of British Columbia. The table is capable of displacements of up to +/- 450mm. The wall was mounted in a steel in-plane test frame, with steel plates used as seismic weights attached at the top (Fig. 1b). The walls are tested in shear only as the axial load was taken by the steel test frame. The seismic weight on the first and second test specimen was 22kN and 40kN, respectively. This was chosen to result in peak drift values of 1.5 and 3.0%.



(a) (b)

Fig. 1 – (a) Details of test specimen (b) Photograph of test setup prior to testing

The Shiroishi (MYG016) record from the 2011 M_w = 9.0 Tohoku, Japan earthquake [6] was selected for the shear walls tests for three main reasons: i) the spectra matched the Victoria uniform hazard spectra well; ii) the motion was very long in duration ($D_{s5-95} = 107s$); and iii) the record had multiple peak accelerations which is a distinctive characteristic of subduction ground motions. Fig. 2 presents the spectrum of the Tohoku MYG016 compared to the target Victoria subduction 2% in 50 year spectrum, the acceleration time history of the record, and the Husid Function for the record which shows the D_{s5-95}. For the first test, since a lower seismic weight was used, the record was run at three increasing intensities (100%, 120% and 160%) to achieve higher drift levels. For the second test with higher seismic weight, the test was repeated three times at 100% intensity.

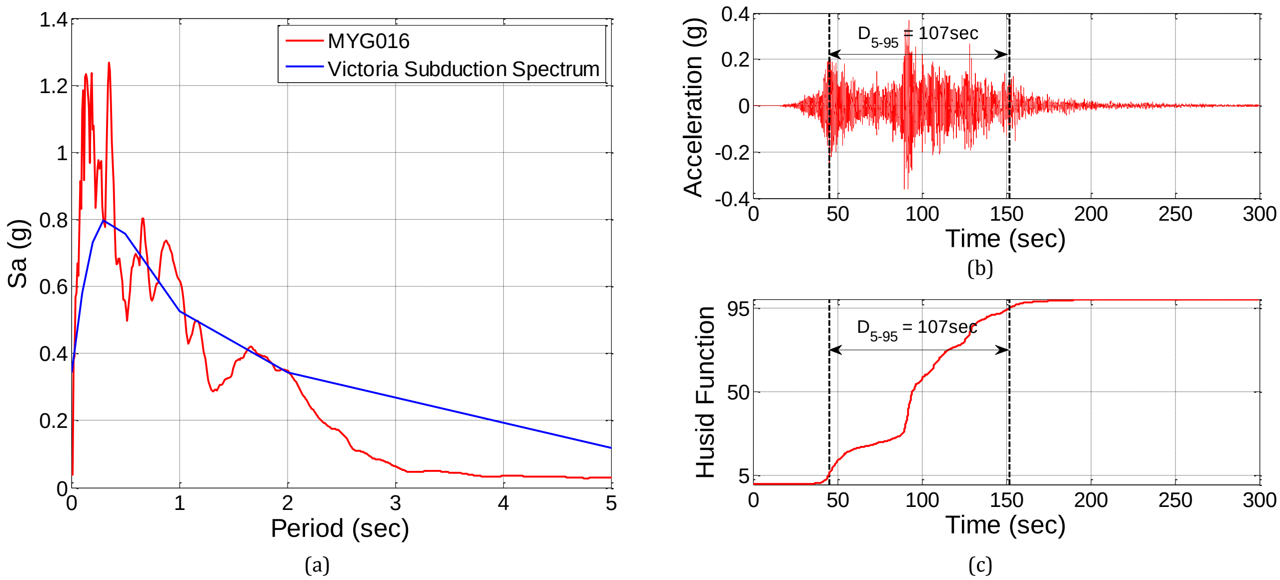


Fig. 2 – Tohoku MTG016 (a) Spectra (b) Acceleration time history (c) Husid Function

4. Numerical Modeling

A single-degree-of-freedom model was used to further investigate the performance of light-frame wood walls subjected to long-duration ground motions. The parameters of model were based on the results of the cyclic UBC tests on blocked shear walls [7]. The evolutionary parameter hysteretic model (EPHM) by Pang et al. [8] was matched to the experimental results and linearly scaled to adjust for the length of the wall. A plot of the hysteretic behaviour is shown in Fig. 3. The values for parameters used in the model are comparable to the parameters presented in the literature [8]. The EPHM model was developed to capture the behaviour of light-frame wood shear walls at high drift levels where stiffness and strength degradation is significant. The model is defined with: i) tracking indices, ii) evolutionary parameters, iii) a backbone curve and iv) loading/unloading rules. An initial and degraded backbone curve is defined in the model. In-cyclic and cyclic deterioration of strength and stiffness is included in the model which according to Ibarra et al. (2005) and Chandramohan et al. [3] makes the model suitable for studying the influence of duration of ground motion on collapse. It should, however be noted that a full-scale model including P – Δ effects would provide a more conclusive study and will be the focus of future work.

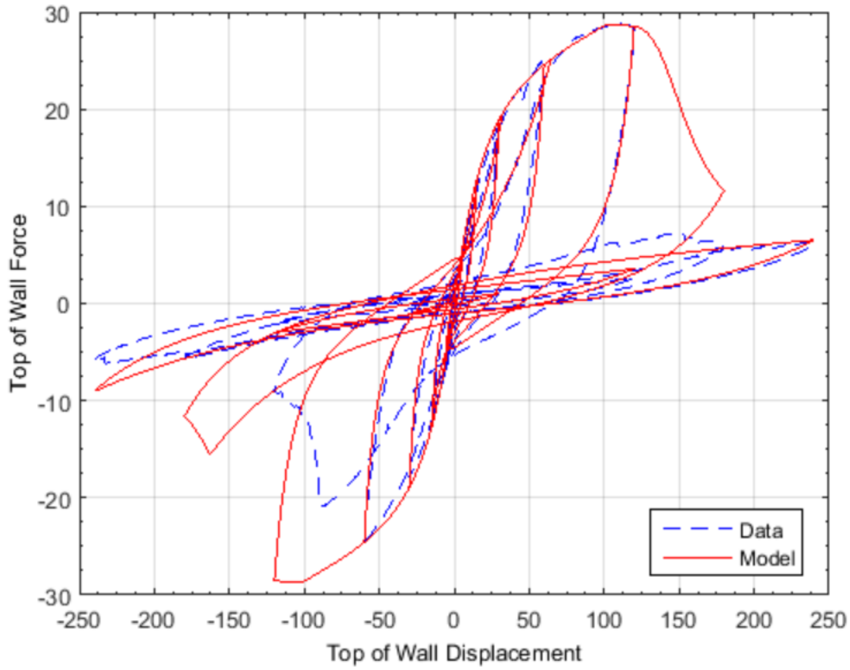


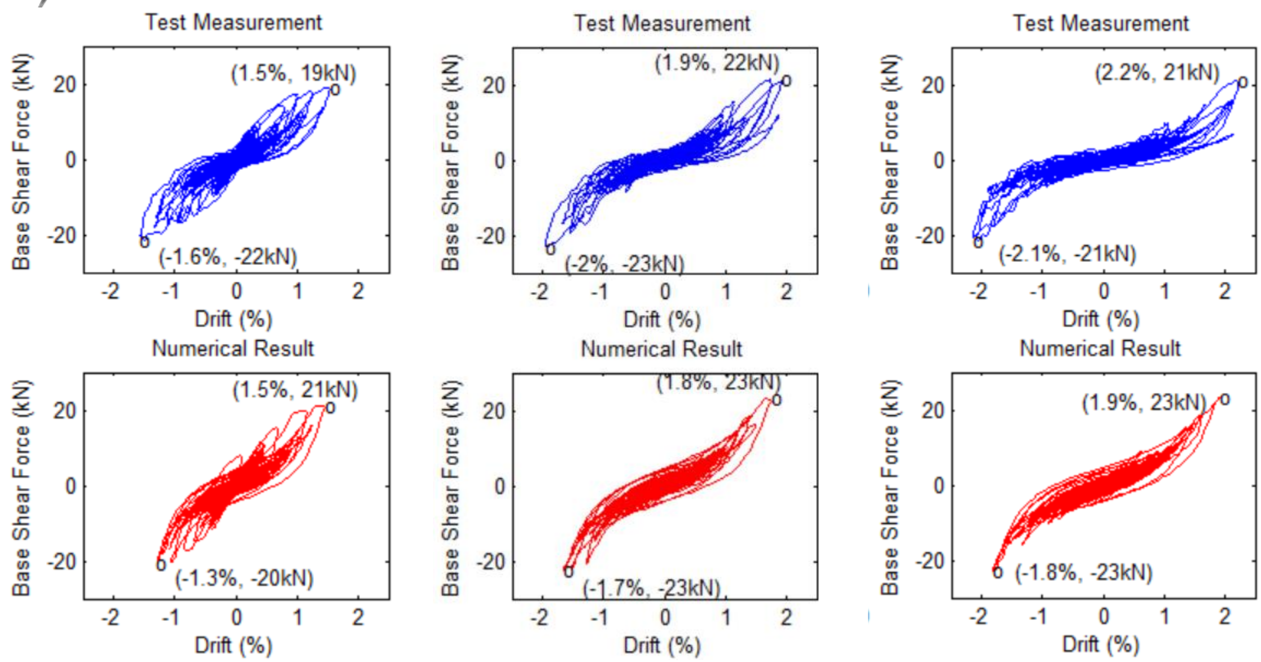
Fig. 3 – Hysteretic loops of the altered experimental cyclic results and SDOF EPHM fit

The SDOF dynamic time history analysis, as part of Pang et al. [9] software, was used to predict the response of the shear wall that was tested on the shear table. The model was able to closely predict the response of the walls, as well as the degradation from the tests; the comparison between the maximum absolute drift observed in the experimental tests and numerical results is shown in

Table 1. The three ground motions were run consecutively in the analysis (as done with the experimental testing) to capture the cyclic and stiffness degradation of the wall due to each run. The viscous damping was assumed to be 1.0% of critical damping; most of the damping can be accounted for through the hysteresis. The period of the model was found to be 0.37s. The hysteresis of the test measurements and model results are shown in Fig. 4. The model was able to give an accurate prediction of the cyclic behaviour of the wall, with the stiffness and strength degrading after each run and the maximum drift increasing.

Table 1 – Absolute maximum drift: Numerical Model vs. Test Data

Test Specimen/Seismic Weight	**Test Number and Intensity Level**	**Numerical Result**	**Test Measurement**
1 (22kN)	1 (100%)	0.7	0.7
1 (22kN)	2 (120%)	1.0	0.9
1 (22kN)	3 (160%)	1.5	1.7
2 (40kN)	1 (100%)	1.5	1.6
2 (40kN)	2 (100%)	1.8	1.9
2 (40kN)	3 (100%)	1.9	2.2



(a) (b) (c)

Fig. 4 – Hysteretic loops for test measurements and numerical results for Test 2 (a) Run 1, (b) Run 2, (c) Run 3

5. Ground Motion Selection and Scaling

The main parameter of interest for the selection of the ground motions used in this study was the significant duration, which is defined as the 5-95% of the accumulation of the integral [3]:

$$D_{s5-95} = \int_0^{t\_max} a(t)^2 dt \quad (1)$$

where a, the acceleration time history of the record and . Long duration ground motions are defined in this study as a ground motion with a significant duration longer than 30s. Thirty long duration ground motions were selected out of a suite of 50. The number was reduced to avoid event bias and preference was given to ground motions with a better match to the Victoria uniform hazard spectra. Long duration motions on soft soil (Vs<180m/s) were not selected; the effects of the soft soil were beyond the scope of the study.

The intention of this study was to compare the effects of long duration vs short duration motions; in order to best perform the comparison a series of spectrally matched, short and long duration pairs were created. For each long duration record, a spectrally equivalent short duration ground motion was then selected based on minimizing the sum of the squares errors between to the two response spectra. The distribution of significant duration for the long and short duration ground motions is displayed in Fig. 5. The median significant duration is 15.3s and 39.5s for the short and long motions, respectively. All ground motions were scaled from 0.1s – 2.0s to match the uniform hazard spectra in Victoria, Canada. An example comparison of the response spectra and time history for the short duration and long duration pair is shown in Fig. 6.

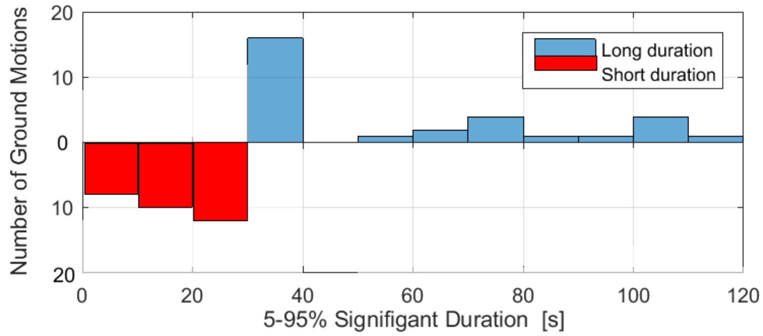
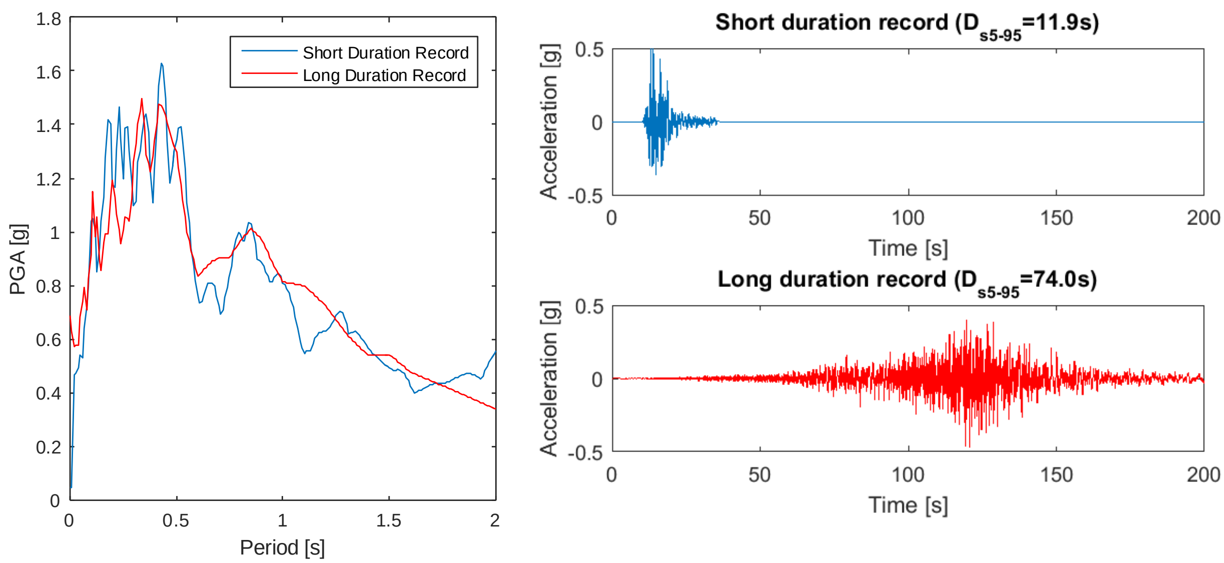


Fig. 5: Distribution of the significant duration of the short and long duration ground motion records



(a) (b)

Fig. 6: (a) Response spectra and (b) time history of short and long duration spectrally equivalent records [4]

6. Nonlinear Dynamic Analysis

Incremental dynamic analysis was performed on the model subjected to the long and short duration record sets; this was done of a range of 10 – 250% of the design earthquake for Victoria, Canada [10], where 100% refers to 2% in 50 years hazard. The short duration and long duration IDA curves are shown in Fig. 6(a) and Fig. 6(b), respectively. The fragility curve for the drift exceedance of 4% onset of collapse is given in Fig. 7. At the code level shaking (100% level), no significant difference between short and long duration motions is observed. However, as the intensity of the ground motions is increased, the difference between the two record suites becomes more apparent. Fig. 7 shows that the median of collapse for the short duration suite occurs at 140% of code level intensity, while the median of collapse for the long duration suite occurs at 120% of code level intensity for the long duration suite. This suggests that a long duration motion is expected to cause collapse at a lower ground motion intensity level than a spectrally equivalent short duration motion. In addition, it suggests that the collapse margin ratio, the ratio between median collapse level and 2% in 50 years ground motion, is reduced as the duration of ground motion is increased.

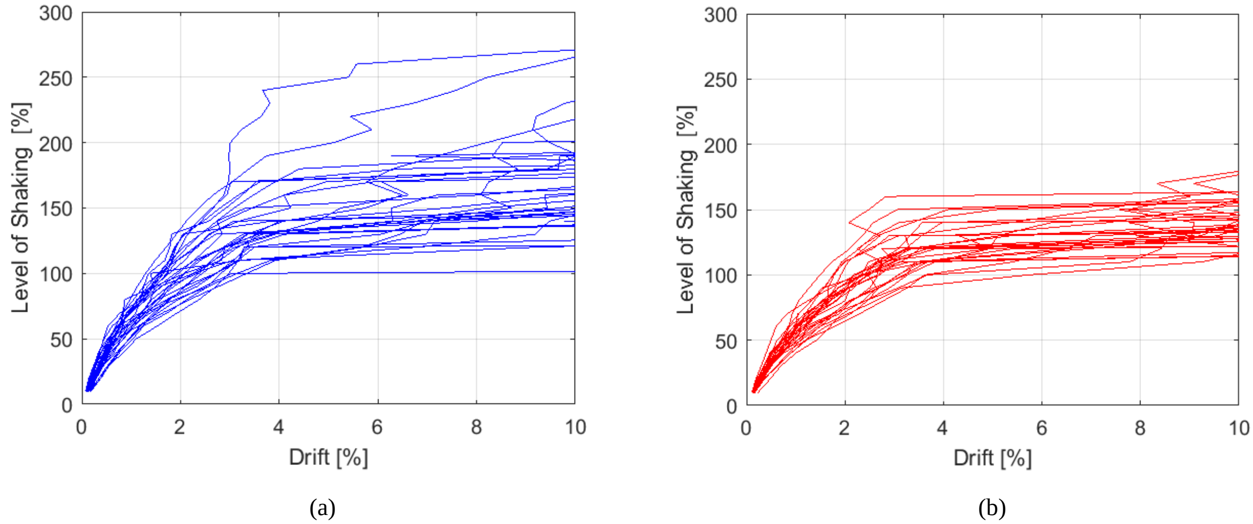


Fig. 7: IDA curves of model using (a) short duration and (b) long duration ground motion record sets

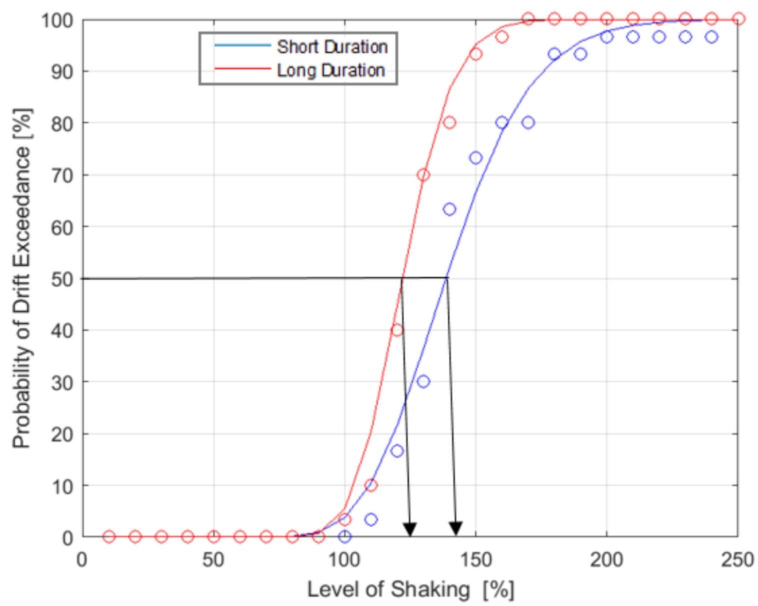
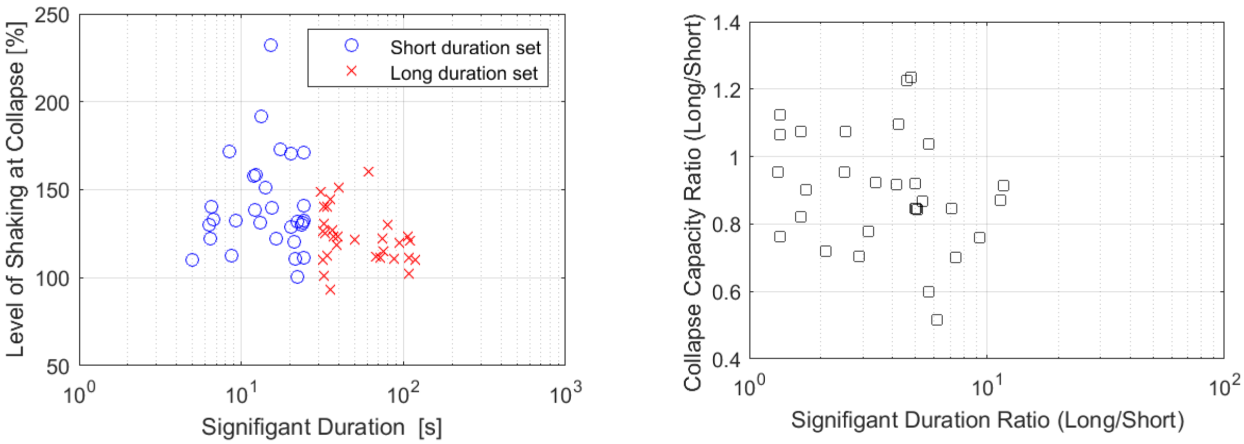


Fig. 8: Fragility curves for 4% conditional drift limit using the short duration and long duration record sets scaled to design earthquake for Victoria

A semi-log plot of the scaling level at collapse and the duration of the event is given in Fig. 9(a); the short duration set is shown in blue and the long duration set is shown in red. It can be observed that in semi-log space the data follows a negative linear trend, where the collapse scaling level decreases as the duration increases. A comparison of the ratio for the collapse scaling level vs. the ratio for significant duration of the long duration and short duration spectrally equivalent pairs is given in the semi-log plot in Fig. 9(b). In semi-log space a negative linear trend is observed, therefore for two ground motions with equivalent spectra collapse will occur on average at a lower intensity for the longer duration motion compared to the shorter duration motion. Further work and sensitivity analysis is required to investigate the feasibility of using a factor in code approach to account for duration effects in locations where it may be critical, such as areas where subduction earthquakes govern the hazard.



(a) (b)

Fig. 9: (a) semi-log plot of level of shaking at collapse vs. significant duration ($D_{s5\text{-}95}$) with regression fit of data, (b) semi-log plot of scaling level at collapse ratio vs significant duration ($D_{s5\text{-}95}$) ratio of the long duration and short duration motions with regression fit of data

7. Conclusion

The aim of this study was to investigate the effect of ground motion duration on the collapse probability of wood shearwalls. First several physical tests were performed in which full-scale wood shearwalls were subjected to a long duration motion recorded in the 2011 $M_w = 9.0$ Tohoku, Japan earthquake. The tests established the dynamic response of these walls at drift levels of 1.5% and 3.0% during long-duration shaking.

A numerical model was then calibrated to these test results and used to run incremental dynamic analysis using two suites of ground motions: a long duration suite comprising 30 records, and a short duration suite with 30 spectrally equivalent records. The results indicated that near the code shaking level (ground motions with a 2% in 50 year probability of exceedance) there was little difference between the two record sets. This is likely due to the ground motion level not being high enough to significantly damage and cause degradation the models.

At higher shaking levels, the difference between the two record sets became more apparent, with the median collapse shaking level becoming lower for the long duration suite. At these high shaking levels more damage and cyclic degradation was observed in the models. This implies that while duration has little impact on the collapse capacity of wood shearwalls near code shaking levels, the margin against collapse is significantly lower when this type of system is subjected to long duration motions.

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References

[1] C. E. Ventura, A. Bebamzedeh, M. Fairhurst, G. Taylor and W. D. L. Fiam, "Updates to the British Columbia Seismic Retrofit Guidelines, 3rd Edition," in *11th Canadian Conference of Earthquake Engineering* , Victoria, Canada, 2015.

[2] J. Adams, S. Halchuck, T. Allen and G. Rogers, "Canada's 5th Generation Seismic Hazard Model, As Prepared for the 2015 National Building Code of Canada," in *11th Canadian Conference of Earthquake Engineering*, Victoria, Canada , 2015.

[3] R. Chandramohan, J. W. Baker and G. G. Deierlein, "Quantifying the influence of ground motion duration on structural collapse capacity using spectrally equivalent records," *Earthquake Spectra.*, in press.

[4] R. Chandramohan, J. W. Baker and G. Deierlein, "Impact of hazard-consistent ground motion duration in structural collapse risk assessment," *Earthquake Engineering & Structural Dynamics* , 2016.

[5] Canadian Wood Council, Wood Design Manual, Ottawa, ON: Canadian Wood Council, 2010.

[6] S. Kinoshita, "Kyoshin net (K-net)," *Seismological Research Letters,* vol. 69, no. 4, pp. 309-332, 1998.

[7] EERF, "Innovative retrofit strategies for wood frame walls, Technical Report, Seismic Retrofit Guidelines," Earthquake Engineering Research facility, University of British Columbia, Vancouver, 2009.

[8] W. C. Pang, D. V. Rosowsky, S. Pei and J. W. van de Lindt, "Evolutionary Parameter Hysteretic Model for Wood Shear Walls," *Journal of Structural Engineering,* vol. 133, pp. 1118-1129, 2007.

[9] W. Pang, E. Ziaei and A. Filiatrault, "A 3D model for collapse analysis of Soft-story Light-frame wood building,," in *World Conference on Timber Engineering*, Auckland, New Zealand, 2012.

[10] D. Vamvatsikos and C. A. Cornell, " Incremental dynamic analysis," *Earthquake Engineering & Structural Dynamics,* vol. 31, no. 3, pp. 491-514, 2002.

[11] CUREe, "CUREe-Caltech Woodframe Project Newsletter," 1998. [Online]. Available: http://www.curee.org/projects/woodframe/.

[12] C. Scawthorn, L. Kornfield, H. Seligson and C. Rojahn, "Estimated Losses from Scenario Earthquakes Affecting San Francisco: CAPSS – Part 2.," in *8th US National Conference on Earthquake Engineering*, San Francisco, CA, 2006.

[13] C. Ventura, W., L. Finn, T. Onur, A. Blanquera and M. Rezai, "Regional seismic risk in British Columbia — classification of buildings and development of damage probability functions.," *Canadian Journal of Civil Engineering*, p. 32(2):372–387, 2005.

[14] P. Bahmani, "Performance-Based Seismic Retrofit (PBSR) Methodology for Multi-Story Buildings with Full-Scale Experimental Validation," Colorado State University, 2015.

[15] ATC, "Here today—Here tomorrow, earthquake safety for soft-story buildings," Applied Technology Council, Redwood City, CA, 2008.

[16] S. Pei, "Loss Analysis and Loss Based Seismic Design for Woodframe Structures," Colorado State University, 2007.