PREDICTING THE FUNDAMENTAL PERIOD OF LIGHT-FRAME WOOD BUILDINGS

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ABSTRACT: This research project deals with dynamic testing of wood shear wall buildings in view of their seismic assessment. The primary objective of this investigation is to evaluate the National Building Code of Canada (NBCC) formula for estimating the light wood frame building's fundamental period, through field testing and numerical modelling, and propose a simplified rational approach as an alternative. Several ambient vibration (AV) field tests have been conducted on thirty multiple-storey wood buildings around Canada. Modal parameters of measured buildings, such as natural frequency, mode shapes and equivalent structural damping, were then obtained from Frequency Domain (FD) analysis of ambient motion records. The paper provides insight about the ambient vibration testing procedures of four wood frame buildings and explains the protocol adopted for the current research program.

1. Introduction

Light wood frame construction represents a large share of the construction industry in North America. The majority of construction type is low-rise residential and commercial occupancies, and the governing design criterion is that the safety of occupants be preserved in the event of natural catastrophes such as extreme wind storms and earthquakes. While the light-frame buildings have performed well in such natural disasters, extensive earthquake damage causing financial and social disturbance has been observed over the years, as reported by Kircher et al. (1997). In wood buildings, the lateral load resisting system, essentially comprised of shear walls, is generally used to provide lateral stiffness and strength. Precise predictions of the seismic behavior of wood shear walls are required to have a better understanding of the level of safety in existing wood buildings. Several studies have been conducted on wood shear walls and light-frame wood buildings to assess their dynamic properties using ambient vibration, forced vibration and full-scale testing (Reynolds et al. (2014), Christovasilis et al. (2008), Mosalam et al. (2008), Filiatrault et al. (2010), Camelo (2003), Filiatrault et al. (2002), Mosalam (2002) and Kharrazi (2001)).

In some Canadian provinces, the building code revision has allowed the construction of wood buildings up to six storeys, which has accentuated the need for reliable base shear estimation for seismic design of wood shear wall buildings. The limited literature on field testing of wood buildings prompted the current research to explore the seismic performance of wood buildings, by studying their dominant dynamic characteristics that have been identified as critical in seismic design. In the current study a series of ambient vibration tests have been performed on wood based buildings, with aim to establish a database of their dynamic characteristics. To date, the subset count of the database is thirty engineered and non-engineered, regular shape and L- shape multiple-storey buildings, located in different regions of the country. Some of the buildings have also been measured at different construction stages. Field testing is still in progress to grow the size of this database, and subsequently, regression analysis will be performed to obtain a reliable approach for approximating the fundamental period of wood building.

This paper addresses selected fieldwork conducted on light wood framed buildings. A summary of the testing procedure and analysis approach implemented on multiple storey wood-based buildings is provided, and a detailed numerical model is discussed. A comparison is also drawn between field results and the fundamental periods calculated according to the National Building Code formula.

2. Shear wall Period Equation $(\mathbf{T_a})$

The fundamental period equation is provided in the National Building Code of Canada (NBCC, 2010) as $T_a = 0.05{h_n}^{3/4}$, for shear walls and other structures, where h_n is the building height above the base in meters. This code provision does not distinguish between shear walls of different materials, such as concrete, steel and wood. Research by Gilles (2011), Farsi and Bard, (2004), Lee et al. (2000), Morales (2000), Goel and Chopra, (1998) and Lagomarsino (1993) has been undertaken to evaluate the applicability of this period equation for concrete buildings.

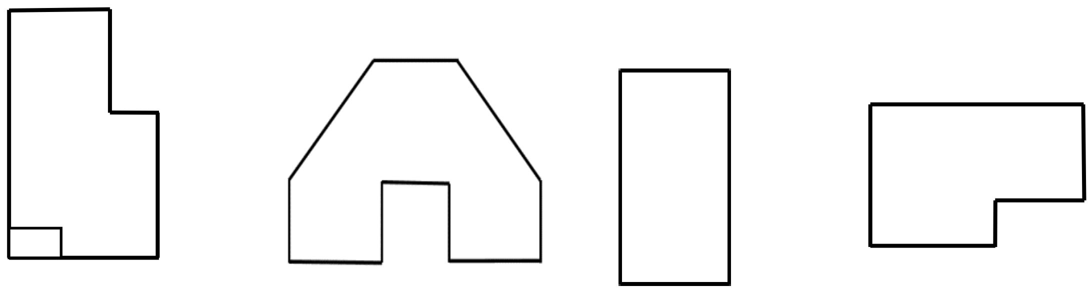
Goel and Chopra, (1998) evaluated the code equation for concrete shear wall buildings based on field measurements, where the fundamental period was measured during strong ground motions. The study found large scatter in the measured data when compared with that obtained by code equation. An improved method was suggested by the authors that was not limited to the wall height only, but also incorporated other shear wall dimensions. Morales (2000) evaluated the code period formula for concrete shear walls and frame buildings and proposed an equation that accounted for the moment of inertia (equivalent second moment of area) and height of the building. The alternative equation was derived from a data base of buildings where the fundamental periods were measured during strong earthquake motions by California Strong Motion Instrumentation Program (CSMIP), and by National Oceanic and Atmospheric Administration (NOAA). The equation was linear with building height but non-linear with moment of inertia, and showed good correlation with measured periods. Very limited studies proposing a period equation for wood buildings have been undertaken. Camelo (2003) proposed a period equation as a function of height to estimate the fundamental period of wood buildings. His study used the data base of dynamic characteristics of wood frame buildings developed through analysis of recorded earthquake response obtained from three sources: 1) California Strong Motion Instrumentation Program (CSMIP), 2) force vibration response measurements, and 3) shake table testing of one to three storeys wood houses. The proposed formula was derived from low amplitude shaking at low drift level (less than 0.1%). Camelo's research suggested that the proposed formula represents the behavior of wood frame buildings more accurately than Uniform Building Code (UBC, 1997) formula and perhaps is more realistic than the FEMA – 273 period formula.

3. Research Goal and Methodology

The main goal of this investigation is to evaluate the adequacy of the NBCC formula for estimating the fundamental period of wood-based buildings and suggest an improved expression to yield more reliable period estimates for seismic design. The study also aims to investigate the effect of the presence of non-structural components on the fundamental period of wood based-buildings. The research methodology begins with ambient vibration field-testing followed by signal processing of the recorded ambient measurements, where the extraction of modal parameters was performed using Enhanced Frequency Domain Decomposition (EFDD). Appropriate assumptions are adopted for stiffness calculation of lateral load resisting system and numerical models were developed for individual tested shear wall buildings to validate the proposed procedure.

4. Structural Details of Selected Tested Buildings

The tested buildings were located in high to moderate seismic zones of Canada. All of them are typically of residential occupancies. Schematic plans of the buildings are shown in Fig.1 while the geometric coordinates and available structural details are provided in Tables 1 and 2, respectively. The ground floor of building B1 has high ceiling and concrete walls for commercial occupancy. Letters W, C and B in the storeys column in the table represent wood, concrete and basement.



a) B1 b) B2 c) B3 d) B4

Fig. 1 – Schematic Plans of Four Tested Buildings

Table 1 – Geometric details of tested buildings

Building Id	**Location**	**Storeys**	**Height above ground floor (m)**	**Plan dimensions (m x m)**
B1	Kamloops, BC	5W +1C+B	17.4	44.0 x 16.5
B2	Ottawa, ON	4W+B	14.9	65.0 x 33.0
B3	Ottawa, ON	3W+B	10.1	12.0 x 15.0
B4	Ottawa, ON	2W+B	6.4	20.0 x 7.6

Table 2 – Structural details of tested buildings

Building Id	**Wall type**	**Wall studs**	**Structural sheathing**
B1	Partition wall	2 walls 2x4 @16” to 8” from bottom to top floor level	½” plywood on exterior side nails to studs with 2 ½”, .128” dia. @ 4” min at edges and 12” intermediate
	Corridor wall	2x4 @ 8” to 4” Staggered	
	Interior wall	2x4 @ 16” to 8”	
	Exterior wall	2x4 @ 16” to 8”	
	Shear wall	Double stud at panel edges and staggered panel edges	½”plywood 2 1/2”, Nails 0.131” dia, and 0.128” dia.
B2	Partition wall	2x6 @ 8” c/c	½” OSB, 3” common nails @ 4” panel edges and 12” intermediate

	Corridor wall	2x6 @ 16” c/c	3/4” OSB ,3” common nails @ 4” panel edges and 12” intermediate
	Exterior wall		
B3	Exterior wall	2x6 @ 16” c/c	7/16” OSB sheathing
	Interior wall	2x4 @ 24” c/c, 2x6 @ 24” c/c	7/16” OSB sheathing
	Shear wall	2x6 @ 16” c/c	½” OSB sheathing, 3” nails @4” (edges) and 12” panel support

5. Experimental Investigation

Ambient vibration testing has become a popular experimental method for measuring the dynamic characteristics of full-scale structures as of its non-obtrusive nature allows measuring structures in their fully operational or as-built condition. Furthermore, no artificial cumbersome excitation methods and equipment are required as the building motion is induced by ambient dynamic sources such as wind, traffic and human/operational activities. Since, the exact input forces driving the building vibrations are unknown, records processing to extract the dynamic properties of structure assumes the excitation is stationary Gaussian white noise equally exciting all building frequencies.

For the research undertaken, an experimental program was established to perform (AVT) on wood-based buildings, and testing was organized in two phases; Phase 1: where the buildings were measured during construction, having all structural components installed (ideally) without application of any finishing material and Phase 2: where the measurements were taken once all non-structural (architectural) elements (gypsum walls and exterior finishes) were attached externally and internally to the building. Of course, existing buildings could only be tested in Phase 2 conditions.

5.1. Measurement Method

The selected buildings discussed in this paper were tested during construction (Phase 1), when the lateral load resisting system was completely built. Multiple acceleration/velocity sensors were used to measure the ambient motion of the buildings in three orthogonal directions (two horizontal and vertical). The sensors have compact portable size (100mm x 140mm x 8mm) and weight (1.1Kg) which allow keeping them in position without any anchorage to the floor. The sensors work through radio communication for record synchronization and their acquisition frequency range is 0.1- 256 Hz, which include all significant natural frequencies of the building structure. Multiple sensors were used for each test set-up, and several set-ups were used for each building, thus requiring a reference sensor typically located at the highest possible level to record a strong signal. The roving sensors were moved to the pre-identified locations determined by studying building plans and access considerations. The roving sensors were located in such a way to measure maximum floor translational motion, though the torsional mode shapes and frequencies that may be important in L-shaped buildings are not included in this study. Typically, the buildings’ response was recorded for eight consecutive minutes per each measurement setup at the sampling frequency of 128 Hz. The recorded signals are the velocity time histories of the reference and roving sensors for each measurement.

5.2. EFDD Analysis

The ambient response of the buildings due to external random excitation is often contaminated with specific noises at the time of measurement. The recorded signal is therefore pre-processed to eliminate the episodes deemed erroneous or non-representative. The synchronized data set (pre-processed time-history signals), together with the geometric layout of the tested points, were analyzed in the frequency domain using the ARTeMIS Extractor software (Structural Vibration Solutions A/S, 2010a). The software allows signal extraction of modal parameters such as natural frequencies, mode shapes and approximate equivalent internal damping ratios using a technique called enhanced frequency domain decomposition (EFDD). The EFDD technique is an enhancement of the more classical frequency domain decomposition (FDD) technique which uses reliability analysis to reduce the uncertainty on frequency peak signal identification. EFDD requires estimation of the spectral density function (SDF) of each time record, which describes the distribution of energy with respect to frequency. FFD utilizes the well-known signal processing concept of Fast Fourier Transform (FFT) of recorded time velocity histories to yield power spectral density (PSD) matrices. Each (PSD) matrix is Hermitian and at a specific frequency, its elements represent the spectral density between two degrees-of-freedom (measurement points) - (DOF) row & (DOF) column. The spectral density, Gxy(ω), between two time history records, x(t) and y(t), having corresponding Fourier transforms X(ω) and Y(ω) is given in Equation 1;

$$G_{xy}(\omega)=E[X(\omega)\,Y(\omega)^*] \quad (1)$$

Where * (asterisk) means conjugate; the spectral density matrices are complex conjugate symmetric. Singular value (eigenvalue) decomposition (SVD) of each PSD matrix is performed giving n sets of singular vectors (eigenvectors) that represent an approximation of the building mode shapes while singular values represent individual natural frequencies. The singular values obtained from each of the n measured configurations are averaged by normalizing the area under the preceding singular value curve. The averaging operation is as shown in Equation 2 for each singular value ω (see Gilles (2011) for more detailed explanations).

$$\{S_i(\omega)\} = \frac{1}{n}\sum_{m=1}^{n} S_i(\omega, m) \quad (2)$$

Where i=1,2,3., m is measurement configuration (sensor setup). These averaged singular values are plotted against frequency to offer potential peaks for identification of the building's natural frequencies excited by ambient sources. A single-degree-of-freedom (SDOF) bell shaped function is produced for each measured configuration, by considering all frequencies in the vicinity of the resonance frequency (potential peak) and the modal parameters are identified using a range of frequencies (for this study: 0-20 Hz) in the neighborhood of the peak point (see Fig. 2) of the SDOF spectral bell shaped function. An estimate of the damping ratio for each identified natural sway frequency mode is obtained by converting the SDOF bell function to time domain using Inverse Fast Fourier Transform (IFFT) and calculating its logarithmic decrement according to the classical viscous damping assumption. It is noteworthy that this equivalent damping ratio is only a very rough approximation, considering the many signal manipulations leading to its determination and the fact that structural damping is not typically viscous.

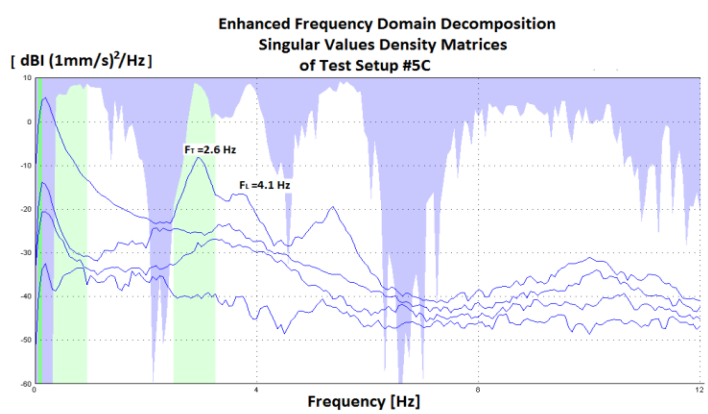


Fig. 2 – **Peaks Showing Frequency in Transverse and Longitudinal Direction for B3**

6. Results

Table 3 shows the fundamental frequencies and damping ratios obtained through ambient vibration tests performed on the selected four multiple-storey buildings. The corresponding sway modes in the transverse and longitudinal directions are shown in Figs. 3 to 6. For building B1 it was only possible to identify the frequency in the transverse direction. The mode shapes were extracted at 80% confidence level from multiple setup schemes for each building.

Table 3 – Modal parameters of tested buildings

Building Id	Frequency (Hz)		Damping ratios (%)	
	Transverse	Longitudinal	Transverse	Longitudinal
B1	3.2	-	1.5	-
B2	2.9	2.7	5.0	2.2
B3	2.6	4.1	3.7	3.0
B4	4.2	7.6	1.9	1.3

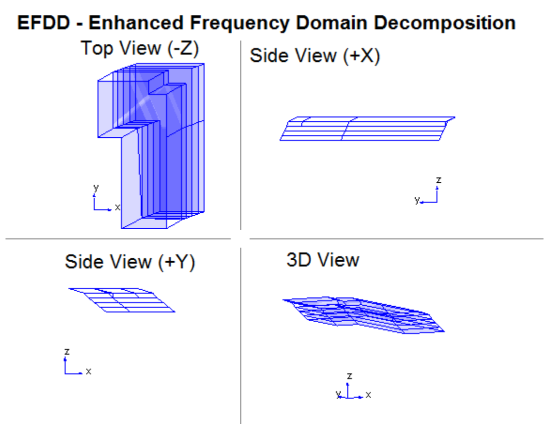
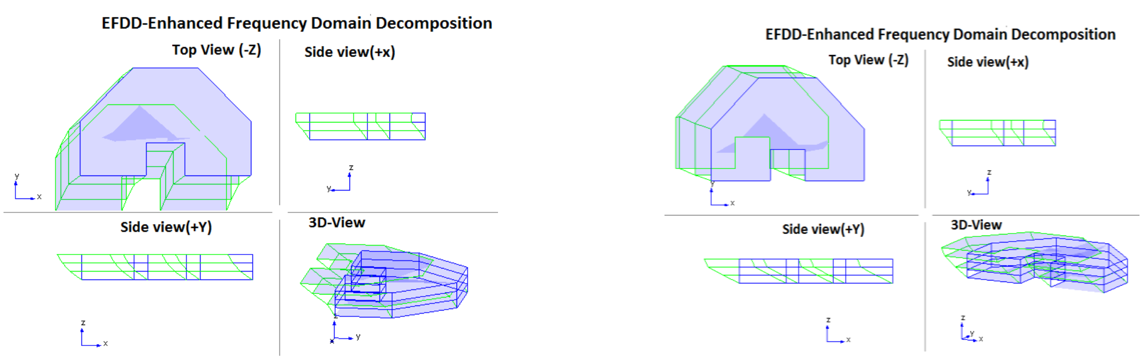
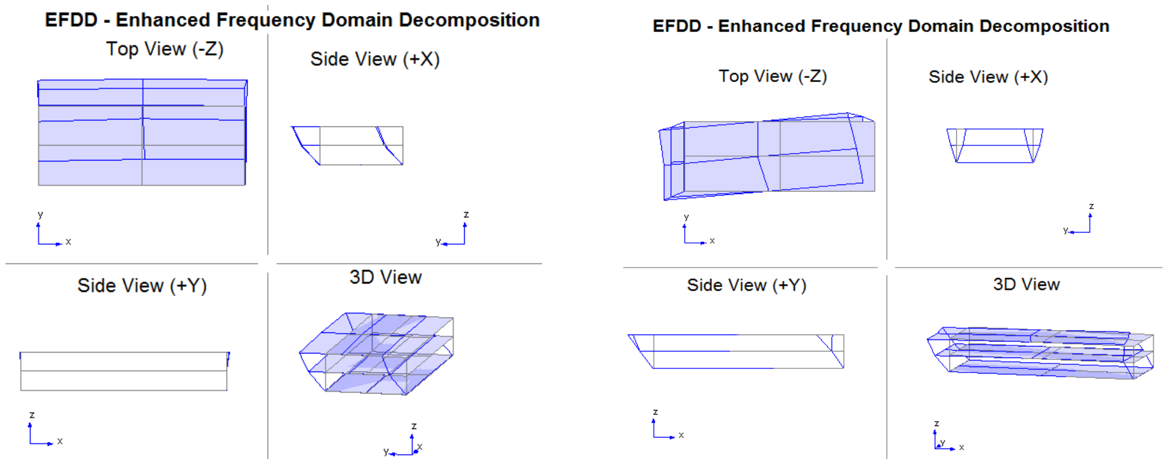


Fig. 3 - Sway Mode Response in Transverse Direction, B1



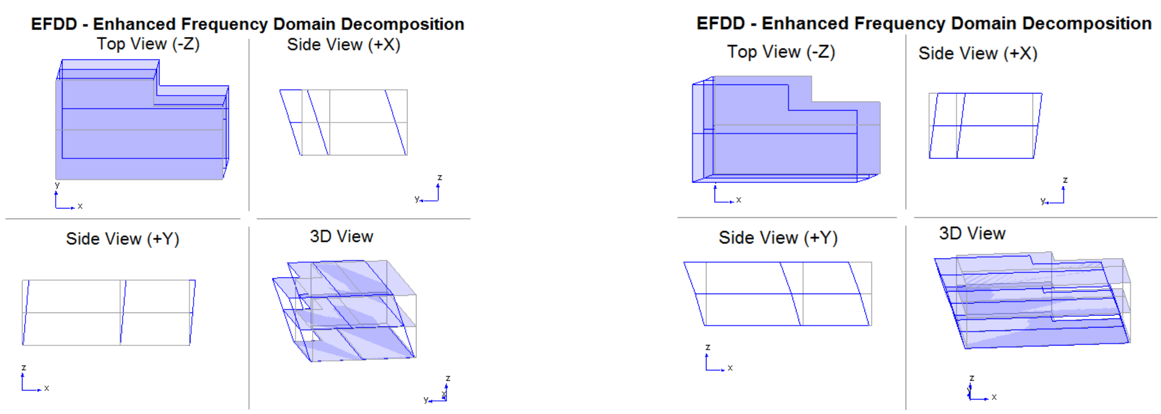
a) Transverse Direction **b) Longitudinal Direction**

Fig. 4 - Sway Mode Response, B2



a) Transverse Direction **b) Longitudinal Direction**

Fig. 5 - Sway Mode Response, B3



a) Transverse Direction **b) Longitudinal Direction**

Fig. 6 - Sway Mode Response, B4

Fig. 7 shows a comparison between the measured fundamental periods of the buildings and those calculated using the 2010 National Building Code of Canada (NBCC) period formula. The results show that the building code formula estimates are close to the measured values using AVT method. The fact that AVT results are close to the NBCC formula indicates that the code period formula is not suitable for wood light frame structures and that the code formula likely underestimates the building period during an earthquake. Considering that light frame shear walls are highly non-linear even at very low load levels and that non-structural components in wood buildings (especially architectural components) have a significant contribution to the natural period of the building, the behaviour of the structure is expected to be different under an actual earthquake relative to what is measured using AVT. Future modeling work involves inputs of varying level of stiffness degradation due to slight or major damage of non-structural and structural components.

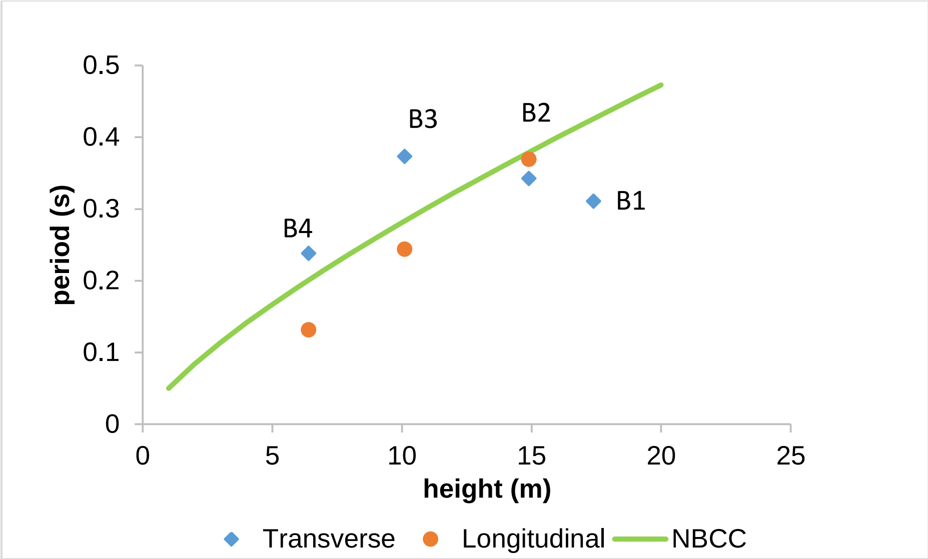
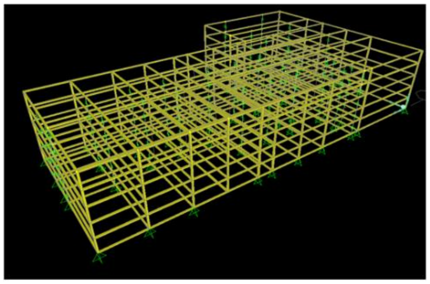


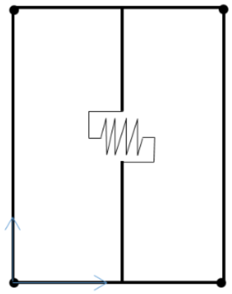
Fig. 7 – Fundamental Period of Tested Buildings

7. Finite Element Modeling of Test Buildings

Eigenvalue analysis is being performed on finite element models based on available structural information. The model for building B1is shown in Figure 8a as an example.. A simplified analytical model developed using assumptions proposed by (Källsner and Girhammer, 2009), and which was considered to be realistic for typical European wood shear wall buildings, is being investigated for its suitability for typical Canadian wood light-frame building construction. Careful attention was given to the orientation and location of the shear walls, which were modeled using horizontal linear elastic links (see Fig. 8b).



a) Model Geometry, B1



b) Typical Equivalent Shear Wall Model

Fig. 8 – 3D Model of B1

The shear wall models were pinned at the base with the assumption of rigid floor diaphragms. Stiffness and mass values were calculated for bare frame conditions to allow comparison with Phase 1 field test results. The in-plane lateral stiffness of the wood shear walls was estimated using the deflection attributed to the second and third terms of the nonlinear deflection equation provided in the Canadian timber design standard, CSA O86 *Engineering Design in Wood* (CSA, 2009), reproduced here as Equation 3.

$$\Delta_{sw} = \frac{2vH_s^3}{3EAL_s} + \frac{vH_s}{B_v} + 0.0025H_s e_n + \frac{H_s}{L_s} d_a \,, \qquad (3)$$

Where Δ_{sw} is the total lateral in-plane deflection, v is applied shear force per unit width length (N/mm), H_s is wall height (mm), E is the modulus of elasticity of end studs (MPa), A is the cross-sectional area of end studs (mm^2), L_s is the width length of shear wall segment (mm), B_v is the through-thickness shear rigidity of sheathing panel (N/mm), e_n is the nail slip at a particular load per nail (mm), and d_a is the horizontal deflection due to anchorage details such as rotation and slip at hold-down connections (mm). The first term of Equation 3, $\frac{2vH_s{}^3}{3EAL_s}$, represents the bending deflection of the framing elements and was disregarded in the analysis. The last term of Equation 3, $\frac{H_s}{L_s}d_a$, represents the horizontal deflection due to hold-down and is not included either in the stiffness calculation, as the buildings were excited through white noise (weak excitation) at very high initial stiffness and therefore does not trigger any significant vertical effects. Modeling results so far show that the model can reasonably well estimate the building period. In general the model overestimates the building period, which is expected as non-structural components, friction and other potential stiffening effects are not accounted for in the model.

8. Conclusion

This paper presents ambient vibration field testing of four multiple-storey regular and irregular shape wood frame buildings. The research work investigated the fundamental sway period formula for shear-wall buildings provided in the National Building Code of Canada for seismic design, through ambient vibration testing and finite element modeling of these buildings. The comparative study concluded that the NBCC formula underestimates the building period and needs to be revised for its implication on light wood frame buildings.

9. Acknowledgements

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