FPInnovations
2665 East Mall
Vancouver, British Columbia V6T 1W5

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Quantifying the Impacts of Moisture and Load on Vertical Movement in a Simulated Bottom Floor of a 6-Storey Platform Frame Building

by

Jieying Wang
Senior Scientist
Durability & Building Enclosure Group

Luke King
British Columbia Institute
of Technology

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Jieying Wang
Project Leader

Paul Morris
Reviewer

Erol Karacabeyli
Research Manager

Summary

Vertical movement of wood frame buildings has become an important consideration in recent years with the increase of building height in Europe, North America, and Asia up to 6-storeys. This movement is composed of wood shrinkage and load-induced movement including initial settlement and creep. It is extremely difficult to identify the relative contributions of these components while monitoring full size buildings. A laboratory test was therefore designed to do this under controlled environmental and loading conditions. Two identical small-scale platform frame structures with dimensional lumber floor joists were designed and constructed, with built-in vertical movement and moisture content monitoring systems. The two structures were first conditioned in a chamber to achieve an initial moisture content (MC) about 20% to simulate typical MC on exposed construction sites in wintertime in Coastal BC. After the two structures were moved from the conditioning chamber into the laboratory environment, using a unique cantilever system, Structure No. 1 was immediately loaded to measure the combined shrinkage and deformation in the process of drying. Structure No. 2 was not loaded until after the wood had dried to interior equilibrium moisture content to observe the shrinkage and load-induced movement separately. The load applied on the two structures simulated a dead load experienced by the bottom floor of a six-storey wood frame building. The vertical movement and MC changes were monitored over a total period of six months. Meanwhile, shrinkage coefficients were measured by using end-matched lumber samples cut from the plate members of the two structures to predict the shrinkage amounts of the horizontal members of the two structures.

The results suggested that a load must be applied for movement to "show up" and occur in a downward direction. Without loads other than the wood weight, even shrinkage could show as upward movement. Monitoring of Structure No. 1 appeared to separate the contributions of wood shrinkage, initial settlement (bedding-in movement), and creep reasonably well. The entire movement amount reached about 19 mm after six months, which was comparable to the vertical movement measured from the bottom floor of a 4-storey wood-frame building in BC. Shrinkage accounted for over 60% of the vertical movement, with the other 40% contributed by load-induced movement including initial settlement and creep (when elastic compression was neglected); the magnitude of creep was similar to the initial settlement amount. Structure No. 2 showed less vertical movement but an increased settlement amount at the time of loading, indicating the presence of larger gaps between members when the wood was dry (with an estimated MC of 11%) before loading. Depending on construction sequencing, such settlement should occur with increase in loads during construction and can therefore be ignored in design. However, this test suggested that there may be a need to consider the impact of creep, in wet climates in particular, in addition to wood shrinkage.

This laboratory test will be maintained for a longer period to observe any further vertical movement and the relative contributions of shrinkage and creep. Similar tests should be conducted for structures built with engineered wood floor joists, given the fact that most mid-rise platform buildings use engineered wood floor joists instead of lumber joists.

Acknowledgements

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FPInnovations would like to thank its industry members, Natural Resources Canada (Canadian Forest Service); the Provinces of British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, Nova Scotia, New Brunswick, as well as Newfoundland and Labrador and the Government of Yukon for their guidance and financial support for this research.

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1 Objectives

- Estimate the relative contributions to vertical movement from wood shrinkage and load-induced movement including initial settlement and creep using a laboratory test.

2 Introduction

Platform wood frame construction is a dominant construction type for residential houses and buildings in North America. Vertical movement over the height of wood frame buildings has become an important consideration in recent years with the increase of building height in Europe, North America, and Asia. 5 to 6-storey wood frame buildings (sometimes over 1 or 2 storeys of concrete) have been built for several years in a few European countries, such as Sweden, and a few states of the U.S., such as California, Oregon, and Washington. In British Columbia (BC), Canada, wood-frame residential construction is permitted to be built up to 6 storeys as of April 6, 2009. During the past three years following the code changes, dozens of 5- and 6-storey buildings have been planned and designed across the province and several have been completed. A few other Canadian jurisdictions have showed interest in such code amendments. A large research project has been undertaken by the National Research Council of Canada (NRC) to assess the design requirements for mid-rise wood construction to possibly integrate it into the National Building Code of Canada.

Vertical movement of wood-frame walls is mainly caused by dimensional changes due to moisture content (MC) changes (shrinkage or swelling when the MC is below fiber saturation point). In addition, instant compression, time-dependent deformation (creep), and building settlement resulting from simply closing of the construction tolerance gaps between building members also result in vertical movement (Wang and Ni 2010). In the major design books in North America, only wood shrinkage is taken into consideration for predicting vertical movement (Canadian Wood Council 2005; Breyer *et al.* 2006). In Europe, it was recommended by Grantham and Enjily (2003) that the amount of deformation due to creep be considered equal to the elastic compression for the total dead load and imposed load. This was later integrated into the Eurocodes. The “settling effect” was noticed during the perpendicular-to-grain compression of multiple member wood assemblies, simulating the bottom chord of a truss resting on the top plate of a shear wall, and chords of a shear wall resting on the bottom plate (Basta *et al.* 2012). Overall there are very few data available regarding impacts of loads on vertical movement in wood-frame construction.

The design community identified differential movement as one of the major concerns for mid-rise wood frame construction during the code amendment in BC (Association of Professional Engineers and Geoscientists of British Columbia and Architectural Institute of British Columbia 2008). The APEGBC Technical and Practice Bulletin (APEGBC 2009, 2011) provided general design guidance and recommended the use of engineered wood products and dimension lumber with low MC to reduce differential movement in five and six-storey wood frame buildings. To help assist in the design and construction of mid-rise wood frame buildings, FPInnovations conducted an extensive literature review and a survey in the industry to summarize existing knowledge and experience, and identify critical knowledge gaps (Wang and Ni 2010; 2012). Work was then started in 2010 to collect vertical movement data from residential wood-frame buildings in BC to validate the movement estimation methods, and assess the impact of material use, fabrication methods, and construction sequence. The field monitoring of vertical movement indicated that the increase of vertical movement was contributed not only by wood shrinkage, but was also associated with the increase in loads resulting from installation of exterior cladding and interior finishes, and occupancy (Wang *et al.* 2013). The measured movement amounts of the bottom storeys of a four-storey building were generally higher than those of the upper storeys, and the two interior walls showed higher amounts of movement than the exterior wall, probably resulting from higher loads and slightly lower MC in service (Wang *et al.* 2013). To complement the field measurement, a laboratory test was designed to assess the relative contributions of shrinkage and load-induced movement to vertical movement of platform frame structures under controlled environmental and loading conditions.

3 Staff

Jieying Wang	Senior Scientist, Durability and Building Enclosure, Project Leader
Luke King	RDH Building Engineering Ltd. (then studying at BCIT)
Chun Ni	Principal Scientist, Structure Performance
Conroy Lum	Research Leader, Structure Performance
Tony Thomas	Senior Instrumentation Technologist, Structure Performance
Paul Symons	Senior Engineering Technologist, Structure Performance
Phil Eng	Senior Technologist, Structure Performance
Paul Morris	Research Leader, Durability and Building Enclosure
Dave Minchin	Senior Technologist, Durability and Building Enclosure
Janet Ingram	Senior Technologist, Durability and Building Enclosure
Alan Matsalla	Carpenter

4 Materials and Methods

The overall strategy of this work was to design and build two identical small-scale wood platform frame structures, monitor and compare the vertical movement, loaded before wood drying and loaded after wood drying.

4.1 Design and Construction of Two Structures

The two structures were designed to simulate the vertical load transfer in platform frame buildings using dimensional lumber joists, but scaled down and simplified for the lab testing purpose. Each structure consisted of two walls, each including two bottom plates (nominal 2 in. by 6 in. dimension lumber, with actual dimensions of 38 mm by 140 mm), four studs (nominal 2 in. by 6 in. lumber, about 430 mm high), and four top plates (nominal 2 in. by 6 in.). The two walls were bridged with four lumber floor joists and two rim joists (all nominal 2 in. by 10 in., with actual dimensions of 38 mm by 240 mm), plus one layer of ¾ in. thick plywood subflooring as the top surface of the structures. As shown in Fig. 1, to make it easier to load the structure, four top plates were built together to simulate the two top plates and two bottom plates used for a typical floor of a multi-storey wood frame building in BC. The studs and joists were initially planned to be at 400 mm on centre with the outside studs and floor joists bear directly on the end of each plate. But each of the outside studs and floor joists was moved 38 mm (1.5 in.) in from the end of the plate before the conditioning to minimize the end effect that may occur when it was loaded. End effect can significantly reduce lumber resistance to compression in the transverse grain orientation. The studs were sheathed with ¾ in. thick plywood for lateral resistance.

The two structures were made as identical as possible by using end-matched materials (cut from the same lumber or panels for each member of the structure) and similar assembling methods. The lumber was "S-Dry" S-P-F (Spruce-Pine-Fir), with a grade No. 2 and better, purchased from a local building supply store. This commodity is heavy to Lodgepole pine (*Pinus contorta*) in BC due to the heavy logging of Mountain Pine Beetle-killed pine. All framing was connected with 3 ¼ in. common nails using a pneumatic coil nailer. The plywood subflooring and wall sheathing was installed using 2 in. specialized flooring screws. The nailing and fastening patterns generally followed the design criteria outlined in the 2005 National Building Code of Canada. The entire structure was about 1200 mm (48 in.) long, 600 mm (24 in.) wide, and 900 mm (36 in.) high. The table size of 1200 mm by 600 mm was mostly decided by the size of the steel plates to be used as loads (see 4.4.2). The steel plates were slightly longer (1370 mm (54 in.)), but had the same width with the structures below.

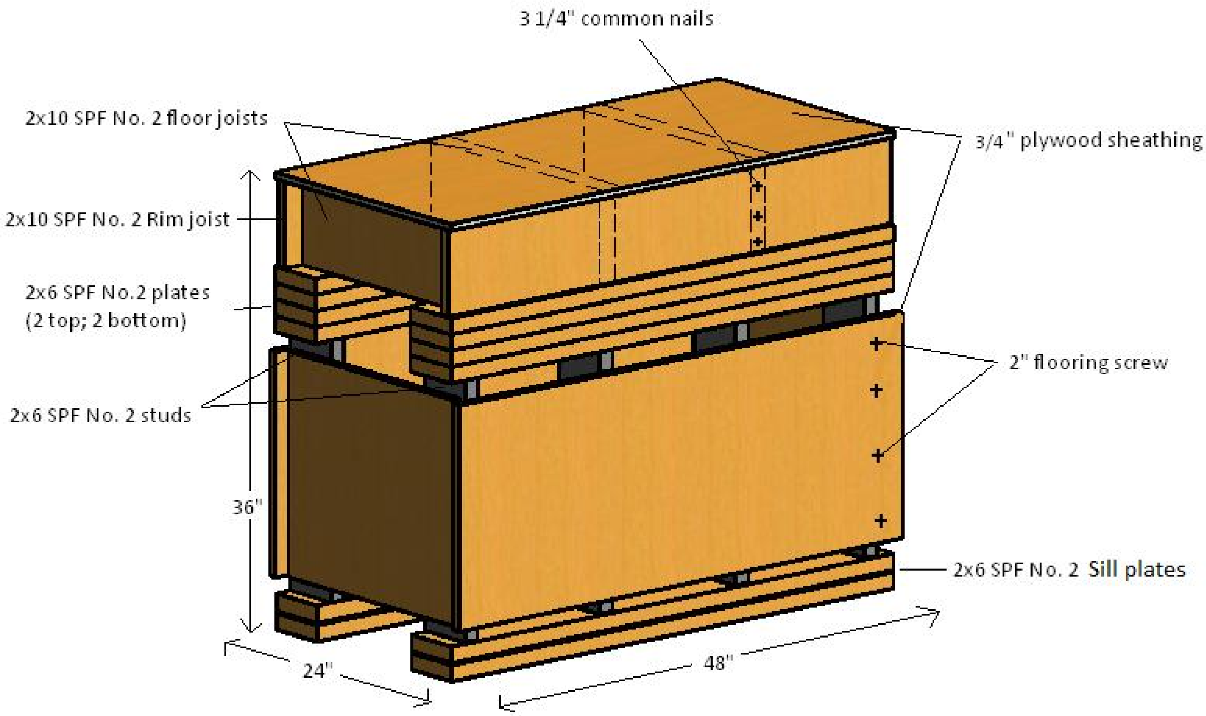

Figure 1 Schematic of the structure built for testing (Fig. 6, King 2012)

4.2 Preconditioning

The two structures were kept in a conditioning chamber for two months to increase the MC and achieve relatively consistent MC throughout (Fig. 2). Targeting an initial MC of about 20% to simulate a typical MC before building enclosure on construction sites in wintertime in Coastal BC (Wang *et al.* 2013), the conditioning chamber was set at a RH of 90±3% and a temperature of 20ºC. This condition corresponds to wood equilibrium moisture content (EMC) about 21% (FPL 2010). The two structures were separated from the metal floor of the chamber using small wood strips. They were covered with spare sheets of OSB on the top to reduce potential wetting caused by dripping of condensed moisture under such a high RH condition. A small load of about 200 pounds in total was placed on each structure (above the spare OSB sheet) to minimize potential gaps resulting from swelling. The load consisted of four 50-pound weights, one at each corner and was roughly 2% of the calculated dead load (see 4.4). Although this load may introduce a small amount of settlement, it was considered negligible. The lumber MC was occasionally measured with a portable capacitance-based moisture meter (Wagner Digital Recording Moisture Meter, Model L 610) to monitor the MC changes.

Figure 2 Conditioning the two structures under a small load in a conditioning chamber

4.3 Instrumentation for Measuring MC and Vertical Movement

Resistance-based MC pins, which were coated except at the tips to measure the MC of wood in direct contact with the tips, were installed at 12 lumber members of each structure. The pins were driven perpendicularly into the face of the selected floor joists, rim joists, studs, and the edges of the plates. Located in the middle of each member in the longitudinal direction, the tip of each MC pin was controlled to reach a depth of 1/3 of the lumber depth (i.e. 1/3 of the width of a plate and 1/3 of the thickness of each floor joist) to estimate the average MC of the whole member. A displacement sensor (Duncan 9610) with a range of 25 mm (1 in.) was used to monitor vertical movement during testing. After calibration, eight sensors were installed in three groups; two at diagonal corners and one in the middle along the length of the structure, to measure the vertical movement of the entire height, the floor joists (composed of four top plates and lumber joists), and the bottom plates of each structure (see Fig. 3, 4). Each installed MC pin and displacement sensor was then connected individually by SMT Research Ltd. using single-pair stranded and shielded cable to the data acquisition units (called “WiDAQs”, provided by SMT) located on the two structures. The WiDAQs were programmed to log and transmit data to the SMT data server when a computer running Building Intelligence Gateway (BiG) software was in proximity. The data can then be graphed directly online or exported into Excel from the SMT data server.

The installation of the instrumentation was mostly completed in the conditioning chamber (Fig. 5) in order to start the measurement of MC and vertical movement once the two structures were moved into the Structural Performance Laboratory (before drying could occur). In total, 12 MC pins, eight displacement sensors and three WiDAQs were installed on each structure. Table 1 and 2 list the sensors for each structure and their target purposes. The two structures were moved into the Structural Performance Laboratory on July 4 2012. Structure No. 1 was loaded immediately (see 4.4). With a dedicated computer running BiG software sitting beside the two structures, data were collected every 5 minutes in the beginning and every 30 minutes after three weeks. A few WiDAQS were found to malfunction in the beginning of the test, which must have been caused by exposure to the high humidity of the conditioning chamber. They were later repaired or replaced by SMT.

The MC or displacement of the plywood subflooring was not measured to simplify the instrumentation as well as the comparison with the predicted movement (see 5.3), given the small contribution of plywood or OSB subflooring to vertical movement of real buildings. More details of instrumentation were provided by King (2012).

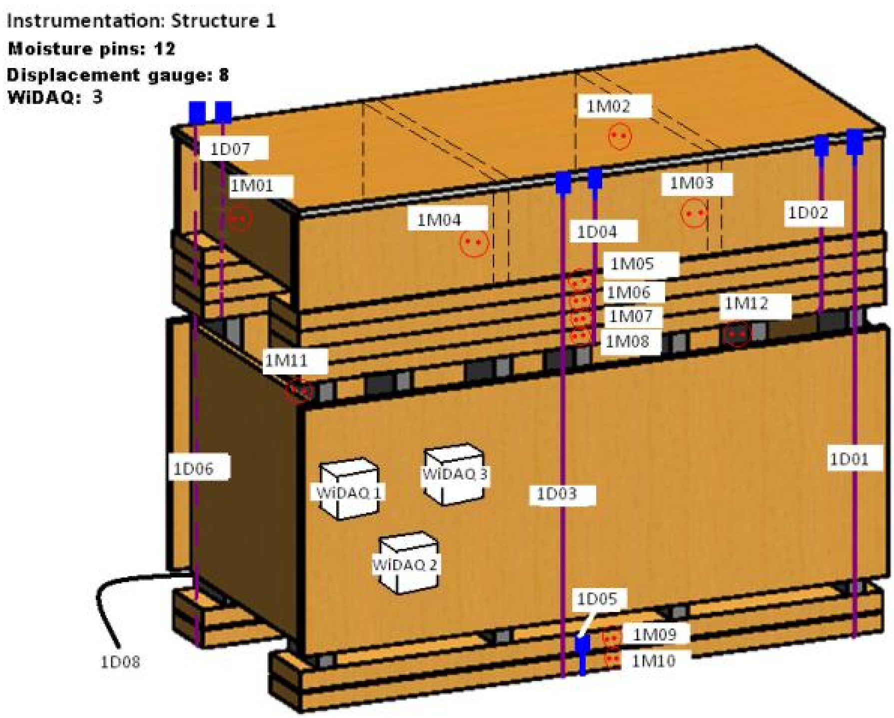

Figure 3 Schematics of MC pins, displacement sensors, and WiDAQs on Structure No. 1 (Fig. 8, King 2012)

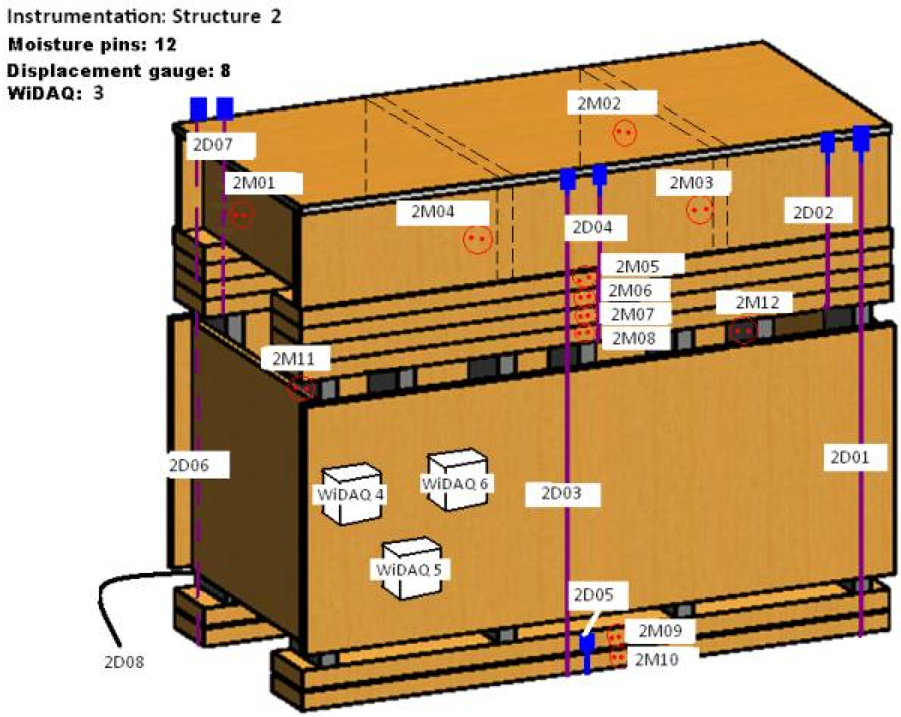

Figure 4 Schematics of MC pins, displacement sensors, and WiDAQs on Structure No. 2 (Fig. 9, King 2012)

Figure 5 Luke King installing sensors in the conditioning chamber

Table 1 Summary of sensors on Structure No. 1, their location and intended purposes (Table 2, King 2012)

Structure 1 instrumentation summary

	Structure 1		
	Sensor ID	Wood member description and ID in which MC pin is installed	Purpose of sensor
Moisture Content	1M01	Joist - JA1	Measure MC within floor joist
	1M02	Joist - JC1	Measure MC within floor joist
	1M03	Rim joist - RJA1	Measure MC within rim joist
	1M04	Rim joist - RJA1	Measure MC within rim joist
	1M05	Top plate - TPE1	Measure MC within top plate
	1M06	Top plate - TPF1	Measure MC within top plate
	1M07	Bottom plate - TPG1	Measure MC within bottom plate
	1M08	Bottom plate - TPH1	Measure MC within bottom plate
	1M09	Sill plate - BPC1	Measure MC within sill plate
	1M10	Sill plate - BPD1	Measure MC within sill plate
	1M11	Stud - S6	Measure MC within studs
	1M12	Stud - S17	Measure MC within studs

	Sensor ID	Displacement sensor location	Purpose of sensor
Displacement	1D01	North east full height	Measure vertical displacement of the entire structure: Floor/rim joists, 2 top plates, 2 bottom plates, studs and 2 sill plates
	1D02	North east top half	Measure vertical displacement of the top portion of the structure: Floor/rim joists, 2 top plates, 2 bottom plates
	1D03	East full height	Measure vertical displacement of the entire structure: Floor/rim joists, 2 top plates, 2 bottom plates, studs and 2 sill plates
	1D04	East top half	Measure vertical displacement of the top portion of the structure: Floor/rim joists, 2 top plates, 2 bottom plates
	1D05	East sill plates	Measure vertical displacement of the 2 sill plates
	1D06	South west full height	Measure vertical displacement of the entire structure: Floor/rim joists, 2 top plates, 2 bottom plates, studs and 2 sill plates
	1D07	South west top half	Measure vertical displacement of the top portion of the structure: Floor/rim joists, 2 top plates, 2 bottom plates
	1D08	West sill plates	Measure vertical displacement of the 2 sill plates

Table 2 Summary of sensors on Structure No. 2, their location and intended purpose (Table 3, King 2012)

Structure 2 instrumentation summary

	Structure 2		
	Sensor ID	Wood member description and ID in which MC pin is installed	Purpose of sensor
Moisture Content	2M01	Joist - JD2	Measure MC within floor joist
	2M02	Joist - JB2	Measure MC within floor joist
	2M03	Rim joist - RJA2	Measure MC within rim joist
	2M04	Rim joist - RJA2	Measure MC within rim joist
	2M05	Top plate - TPA2	Measure MC within top plate
	2M06	Top plate - TPB2	Measure MC within top plate
	2M07	Bottom plate - TPC2	Measure MC within bottom plate
	2M08	Bottom plate - TPD2	Measure MC within bottom plate
	2M09	Sill plate - BPA2	Measure MC within sill plate
	2M10	Sill plate - BPB2	Measure MC within sill plate
	2M11	Stud - S3	Measure MC within studs
	2M12	Stud - S4	Measure MC within studs

	Sensor ID	Displacement sensor location	Purpose of sensor
Displacement	2D01	North east full height	Measure vertical displacement of the entire structure: Floor/rim joists, 2 top plates, 2 bottom plates, studs and 2 sill plates
	2D02	North east top half	Measure vertical displacement of the top portion of the structure: Floor/rim joists, 2 top plates, 2 bottom plates
	2D03	East full height	Measure vertical displacement of the entire structure: Floor/rim joists, 2 top plates, 2 bottom plates, studs and 2 sill plates
	2D04	East top half	Measure vertical displacement of the top portion of the structure: Floor/rim joists, 2 top plates, 2 bottom plates
	2D05	East sill plates	Measure vertical displacement of the 2 sill plates
	2D06	South west full height	Measure vertical displacement of the entire structure: Floor/rim joists, 2 top plates, 2 bottom plates, studs and 2 sill plates
	2D07	South west top half	Measure vertical displacement of the top portion of the structure: Floor/rim joists, 2 top plates, 2 bottom plates
	2D08	West sill plates	Measure vertical displacement of the 2 sill plates

4.4 Loading of Two Structures

4.4.1 Load Calculation

In order to determine a load that would be representative of the dead load of the bottom floor of a six-storey platform frame building, two methods were used for calculation. The first method was based on ultimate limit states design to calculate the maximum acceptable factored load without exceeding the corresponding factored resistance (CWC 2010; CSA 2005). The calculated load was 5,350 kg (11,770 pounds). The load experienced by real buildings should not exceed this. The second method was calculating the dead load that was expected to be transferred through the load bearing walls to the bottom floor of a six-storey wood-frame building, based on recommendations found in wood engineering books (March 2006; Thompson 2010). The result was 5,364 kg (11,800 pounds). The two results were remarkably close. The load that was decided to apply on the two structures was therefore 5,357 kg (11,785 pounds), an average of these two numbers. Table 3 and 4 list the detailed calculation, with more details provided by King (2012).

Table 3 Maximum applicable load using limit states design (Table 5, King 2012)

Maximum load calculations				Applied pressure (kN/m^2)		Mass in Kg
					184	10700
Modification factors						
K_D	Load duration factor	1	K_{zcp}	Size factor for bearing (joists)		1
K_L	Lateral support factor	1		Size factor for bearing (studs)		1
K_T	Treatment factor	1	$K_{Zb/v}$	Size factor for bending and shear		1.1
K_H	compression parallel to grain	1.1	$K_{SE/c}$	Service condition factor		1
	Bending/Long shear	1.4	K_B	Length of bending factor (joists - end of member)		1
				Length of bending factor (studs - end of member)		1
	b (mm)	d (mm)	L (mm)	Spacing (mm)	Tributary width (m)	S (mm^2)
SPF Floor joists (mm)	38	240	610	400	0.4	364800
Studs (mm)	38	140	432	400	0.305	
Specified strengths	f_b	f_v	f_c	f_{cp}	E	
SPF No. 2 (Mpa)	11.8	1.5	11.5	5.3	9500	
Criteria 1 - Bending moment of joists				Criteria 2 - Shear resistance of joists		
$F_b = f_b(K_D K_H K_{sb} K_T)$ (Mpa)		16.5		$V_f = w_f L/2*(1 - 2d/L)$ (kN)		4.79
$M_r = \phi F_b S K_{zb} K_L$ (kNm)		5.97		$F_v = f_v(K_D K_H K_{sv} K_T)$(MPa)		2.10
$M_f = w_f L^2/8$ (kNm)		3.43		$V_r = \phi F_V 2/3 A_n K_{zv}$ (kN)		12.6
$M_r \geq M_f$		acceptable		$V_r \geq V_F$		acceptable
Criteria 3 - Deflection of joists				Criteria 4 - Bearing capacity of floor joists (perpendicular to grain)		
$\Delta_{limit} = L/360$ (mm)		1.7		$Q_f = w_f L/2$ (kN)		22.5
$E_s I = E(K_s K_T) I$		4.16E+11		$Q_r = \phi F_{cp} A_b K_B K_{zcp}$ (kN) (A includes area of rim joist)		80.9
$\Delta_{max} = 5w(L^4)/(384 E_s I)$ (mm)		0.32		$F_{cp} = f_{cp}(K_D K_{sc} K_T)$(MPa)		5.3
$\Delta_{max} \geq \Delta_{limit}$		acceptable		$Q_r \geq Q_F$		acceptable
Criteria 5 - Compression strength in studs (parallel grain)				Criteria 6 - Compression strength of plates (perpendicular)		
$P_{rd} = \phi F_c A K_{zcd} K_{cd}$ (kN)		69.9		$Q_r = \phi F_c A$ (kN)		22.6
$P_{rb} = \phi F_c A K_{zcb} K_{cb}$ (kN)		65.5		$\phi F_c = \phi f_c K_D K_{scp} K_T K_B K_{zcp}$		4.2
$\phi F_c = \phi f_c K_d K_H K_{sc} K_T$ (Mpa)		10.1		$Q_f = w_f L/2$ (kN)		22.5
K_{zcd} = 1.3	K_{zcb} =	1.3				
C_{cd} = 3.09	C_{cb} =	11.4				
K_{cd} = 1.00	K_{cb} =	0.94				
$P_f = w_f L/2$ (kN)		22.5				
P_{rd} or $P_{rb} \geq P_f$		acceptable		$Q_r \geq Q_F$		acceptable

Table 4 Expected dead loads in real buildings (Table 6, King 2012)

Expected real building dead loads in pounds per square foot	
Roof dead loads	
Roofing	6.5 psf
5/8” Sheathing	1.9 psf
2x4 strapping @ 24” o/c	0.7 psf
2x10 joists @ 24” o/c	1.9 psf
5/8” GWB Ceiling	2.8 psf
Insulation/miscellaneous	1.2 psf
Total roof design dead loads	15 psf

Per storey dead loads	
Carpet	1.5 psf
1 ½” Concrete topping	18.0 psf
5/8” Plywood sheathing	1.9 psf
2x10 joists @ 16” o/c	2.8 psf
5/8” GWB	2.8 psf
Total floor design dead loads	27 psf
Partition design dead load	13 psf
Total per storey design dead load	40 psf

4.4.2 Loading Two Structures

Steel plates, 1350 mm (54 in.) by 600 mm (24 in.), and a thickness of either 19mm (3/4 in.) with a weight of 114 kg (250 pounds) or 38mm (1 ½ in.) with a weight of 227 Kg (500 pounds), were used to load the two structures. The height of the steel weights alone would have been about 900 mm (36 in.) if they had been directly stacked on top of the structure, which could be a large concern of safety. Based on suggestions from Conroy Lum, a lever system was designed and assembled by Paul Symons, Luke King and Tony Thomas to achieve the target load. This placed the steel plates close to the floor and reduced the weight needed from 5,357 kg (11,785 pounds) to 2050 Kg (4,500 pounds) due to the use of the lever (see Fig. 6; The actual load achieved on the structures was 5,182 kg (11,426 pounds), slightly below the target value). Large efforts were made during the assembling of the lever system to achieve uniform vertical load distribution in the two structures (King 2012).

When Structure No. 1 was loaded on July 4 2012 the wood had a MC slightly over 20% (see 5.1). Structure No. 2 was loaded on November 13 2012, about four months after the loading of Structure No. 1, when the wood had an estimated MC about 11% (see 5.1).

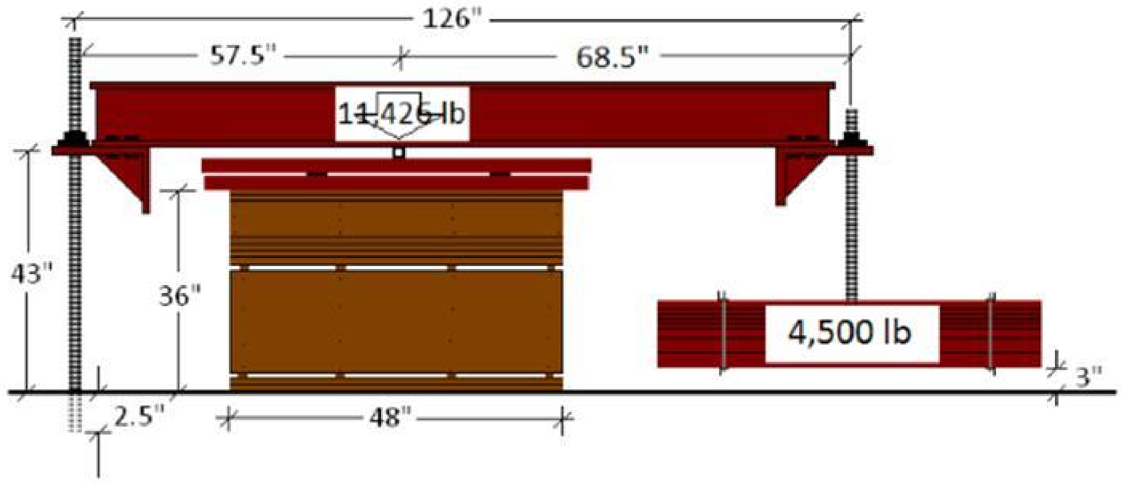

Figure 6 A lever system to apply the load on the two structures (Fig. 24, King 2012)

Figure 7 Two structures under loads

4.5 Estimating Wood Shrinkage Coefficients

Wood dimensional change (when the MC is below fiber saturation point) is the major cause of vertical movement of wood-frame buildings, and shrinkage coefficients are very important for designers to predict shrinkage of wood construction. Wood varies in shrinkage or swelling due to different species, grain orientations, density, and other factors (FPL 2010). Shrinkage coefficients of 0.20 or 0.25% per 1% change in MC are recommended in wood design books for horizontal lumber members of platform frame construction (CWC 2005; Breyer *et al.* 2006; NIST 2010).

It was decided to estimate the shrinkage coefficients of the horizontal members based on the real dimensions and the same grain orientations used in the load path of the two structures. Four to six end-matched clear blocks, about 30 mm in the longitudinal direction, were cut from each lumber used for the plates and joists of the two structures. The dimensions were measured in the direction of interest and four points were marked on each sample to provide an average of the measured dimensions. The samples were all exposed to three ambient conditions including the highest RH of 90% (using the same conditioning chamber for conditioning the two test structures, shown in Fig. 2). They were kept for three to four weeks under each condition, and their weights were checked to ensure that equilibrium had approximately been achieved. At the end, the samples were dried in an oven at a temperature of 103ºC. The changes in both dimension and weight were monitored in the process to calculate wood MC changes and shrinkage coefficients. This method was simplified and different from the ASTM standard method (ASTM, 2009), partially due to the time and budget constraints of this study.

5 Results

5.1 Lab Conditions and Wood MC Changes

Fig. 8 shows the recorded RHs and temperatures from the Wood Engineering Lab, where the indoor temperature was mostly controlled around 20°C but the RH was left fluctuating with temperature and season. The temperatures rose to 25°C and occasionally higher in the summer. Some data were missing from December to January due to power outages in the lab. EMC of wood is primarily determined by the RH of the environment when the temperature fluctuates within a small range (FPL 2012). To simply estimate wood EMC at different stages, it was assumed that the average RH was 55% in the summer, 45% in the fall, and 35% in the winter in the lab. Table 5 provides the estimated wood EMC based on such assumed environmental conditions (FPL 2010).

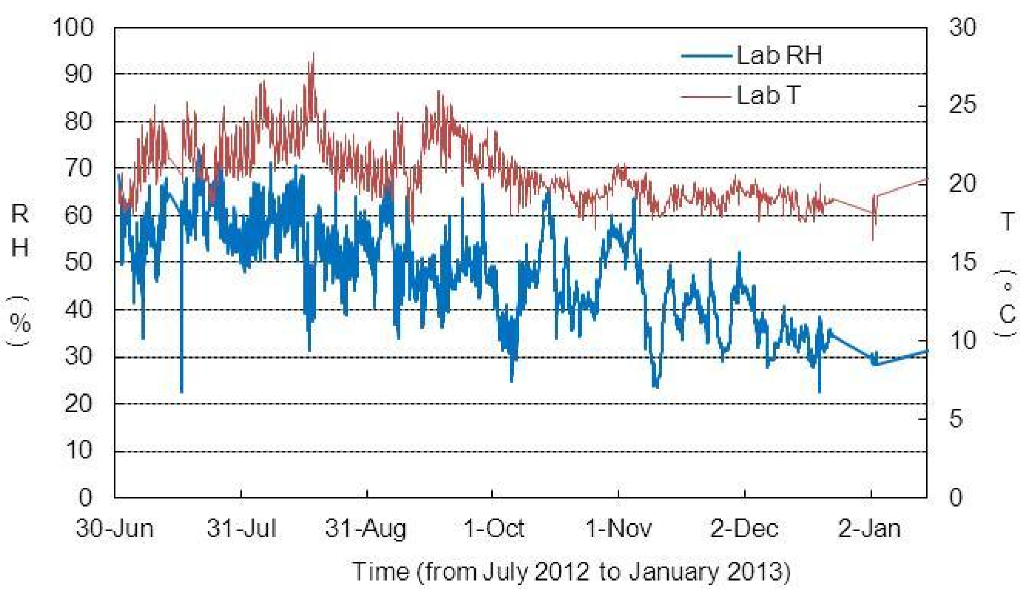

Figure 8 RH and temperature in the Wood Engineering Lab

Table 5 Estimated average RH and the theoretical wood EMC in different time periods

Time Periods	Average RH (%)	Theoretical EMC @ 20°C (%)
July-August, summer	55%	10
September-October, fall	45%	9
November-January, winter	35%	7

*The initial MC was about 20% when Structure No. 1 was loaded on July 4 2012. Structure No. 2 was loaded on November 13 2012.

The wood varied in the initial MC, ranging from 18% to 23%, based on the readings of the MC pins installed at different locations (Fig. 9 and 10). For simplicity in predicting wood shrinkage, it was assumed that each member had a MC of 20% to start with. The wood also varied in MC between members (locations) after they were moved to the Structural Performance Laboratory. The MC readings showed a trend of drying. Wood tended to dry more quickly when it was standing alone, such as the joists and studs than when built-up, such as top and bottom plates. Unfortunately, the malfunction of the WiDAQs in the beginning of the test probably resulting from exposure to high RH in the conditioning chamber caused large fluctuations (and sudden drops) of MC readings in July 2012 (Fig. 9 and 10). Loosening of MC pins in wood resulting from drying could also have had an effect. This was all repaired when noted. The resistance-based MC measurement system had a lower MC limit of 11.2% based on the calibration for Lodgepole pine. When the MC gets too low, the resistance in wood becomes too high to measure accurately. The MC of most wood members of these two structures dropped below this limit by the end of August, except for a few built-up members (i.e. the top and bottom plates). Given the fact that wood varies between members in time to reach EMC under a certain environmental condition, an adjustment was made to the theoretical EMC under each environmental condition (Table 5) to predict the shrinkage amounts below. It was assumed that all of the wood members had a uniform MC of 20% when Structure No. 1 was loaded on July 4 2012; they had a MC of 11% when Structure No. 2 was loaded on November 13 2012, and the average MC reached 9% by January 30 2013 (5.3.2).

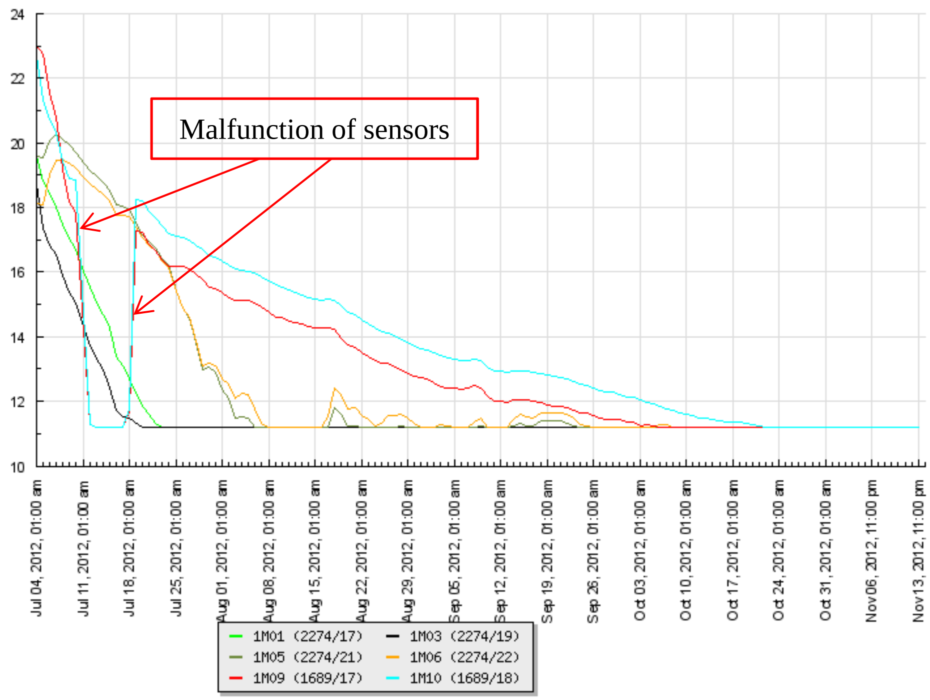

Figure 9 MC readings from the pins installed at different locations in Structure No. 1

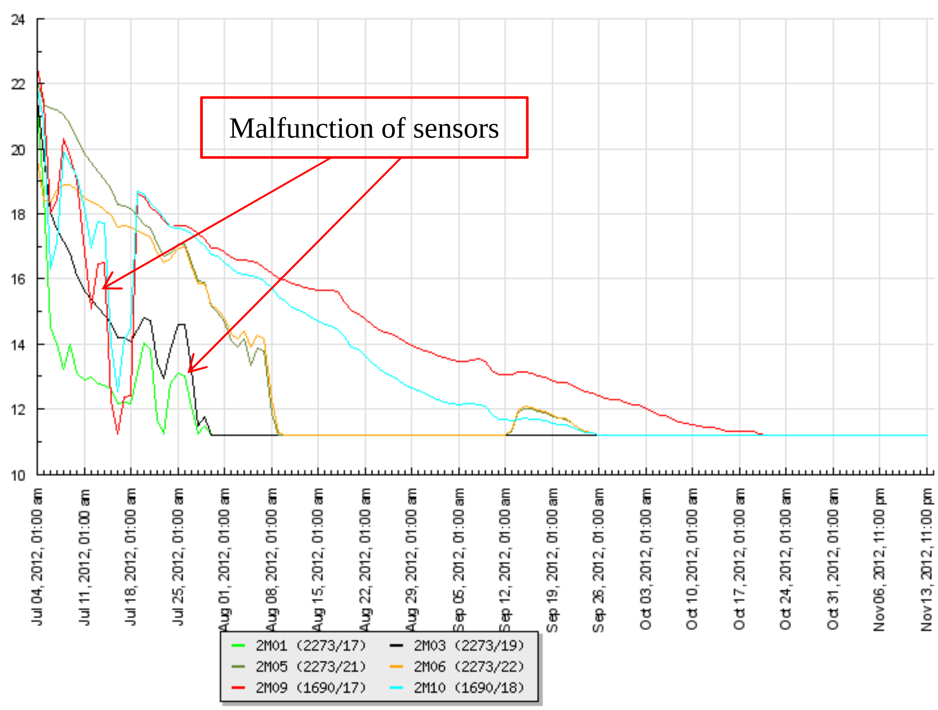

Figure 10 MC readings from the pins installed at different locations in Structure No. 2

5.2 Estimated Wood Shrinkage Coefficients

Based on the measured weights and dimensions (in the same direction as the vertical movement of each matched member in the structure) of each small wood block under the four moisture conditions, the relationship between dimension and MC was plotted using Excel (shown in Fig. 11 as an example). It was found that the dimensional measurement for the joist members, with a large dimension, about 240 mm (nominal 10 in.), using a caliper, was not able to assess true shrinkage, mostly due to cupping and warping that occurred during the process. It was relatively consistent to measure the dimensional changes of the plate samples, with a small dimension (about 38 mm, nominal 2 in. thick) in the loading direction. As a compromise, the average shrinkage coefficient of all of the plate samples was taken as the shrinkage coefficient of the joist members given their similar transverse grain orientations (Table 6).

The slope of each linear trendline of the relationship between dimension and MC of each plate sample, as shown in Fig. 11, was calculated and then averaged for the top plates and the bottom plates, respectively. Wood shrinkage is usually expressed as a percentage on the basis of green dimension, which is the dimension of “green wood” (freshly cut wood) achieved when the MC is above fiber saturation point (FPL 2010). Because the highest RH used for conditioning these samples, i.e. 90%, was not able to achieve the fiber saturation point, each of the above linear relationship was arbitrarily extrapolated to an EMC of 26% to estimate the green dimension of each sample. A figure of 26% was used instead of 28% or 30%, the fiber saturation point recommended in wood textbooks (FPL 2010, CWC 2005), mainly because the dimensional change of wood is not linear with the change in EMC when the EMC approaches the fiber saturation point (FPL 2010). The increased dimension resulting from such a small MC adjustment was found to be very small. The calculation of shrinkage coefficients is summarized in Table 6. The calculated values for the top and bottom plates were between 0.20 and 0.25% per 1% change in MC, which were recommended in wood design books for horizontal lumber members of platform frame construction (CWC 2005; Breyer *et al.* 2006; NIST 2010). The shrinkage coefficients of top plates, bottom plates, and joists (an average of top plates and bottom plates), as listed in Table 6, were used for predicting wood shrinkage in the following discussion (see 5.3.2).

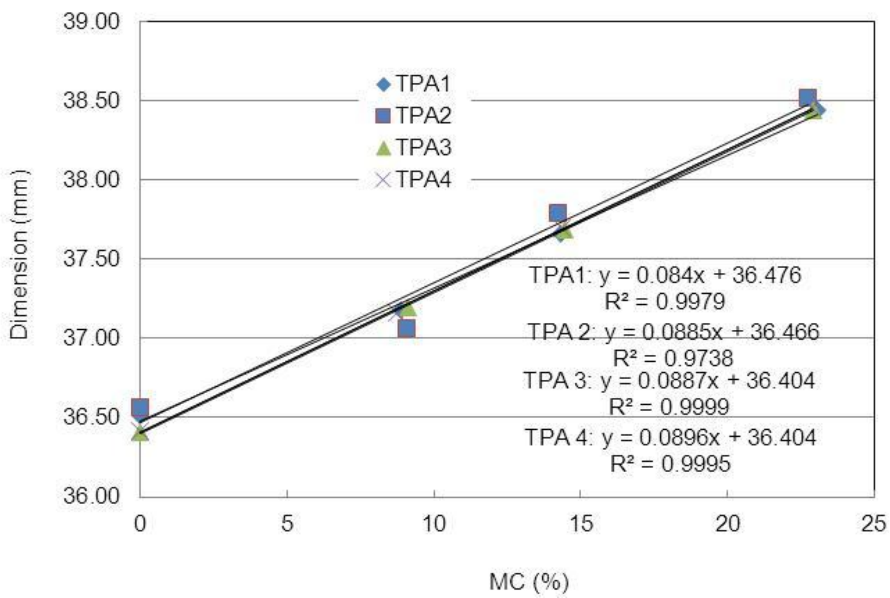

Figure 11 Dimensional change with MC change of the four block samples cut from the lumber used for one of the top plates (labeled as TPA, adopted from Fig. 7, King 2012)

Table 6 Average shrinkage coefficients of the horizontal members of the two structures

Members	Labels	MC after conditioning at 90% RH (%)*	Dimension after conditioning at 90% RH (mm)*	Average dimension change per MC change (% per % MC)*	Estimated average dimension at 26% (mm)	Calculated shrinkage coefficient (% per 1% MC change)	Shrinkage coefficient (% per 1% MC change)
Top plates	TPA	22.9	38.46	0.088	38.74	0.227	0.217
	TPB	21.2	38.65	0.072	38.99	0.185	
	TPC	22.3	38.57	0.054	38.77	0.139	
	TPD	23.2	38.70	0.090	38.95	0.231	
	TPE	22.5	38.40	0.080	38.68	0.207	
	TPF	22.0	38.66	0.093	39.03	0.238	
	TPG	22.7	38.73	0.097	39.05	0.248	
	TPH	22.2	38.59	0.100	38.97	0.257	
Bottom plates	BPA	22.3	38.82	0.090	39.15	0.230	0.228
	BPB	25.8	37.81	0.111	37.84	0.293	
	BPC	23.5	38.23	0.065	38.39	0.169	
	BPD	22.3	38.51	0.085	38.82	0.219	
Average of all plate samples (used for joists for shrinkage calculation)							0.220

*An average of 4 to 6 replicates under each condition

5.3 Vertical Movement of Wood Frames

5.3.1 Measured Vertical Movement

Two displacement sensors, 1D07 and 2D01, failed and their results were not included in the discussion below. Fig. 12 and Fig. 13 shows the vertical movement amounts measured by the sensors installed on Structure No. 1 and No. 2, with a graph for each structure directly output from the SMT server. The measurement was started at the time of loading Structure No. 1. on July 4 2012. The data were also exported into Excel and further processed to obtain an average movement amount for each of the following three groups: the two bottom plates, the floor including four top plates and floor joists, and the entire height including these two groups plus the studs (Fig. 14 and Fig. 16). A few obviously outlier data (caused by electrical noises etc.) were trimmed during the process. There were a few data gaps due to issues with data acquisition (Fig. 14 and 16). The results were expressed in Fig. 15 and 17 using X-axis of log (time) to better show the change rate of vertical movement with time. The movement amounts one hour after the loading of Structure No. 1 on July 4, immediately before and one hour after the loading of Structure No. 2 on November 13 2012, and the latest results on January 2013, respectively, were summarized in Table 7. One hour was given for each structure to "settle down" after the loading (Fig. 13 shows swings in movement at the moment of loading).

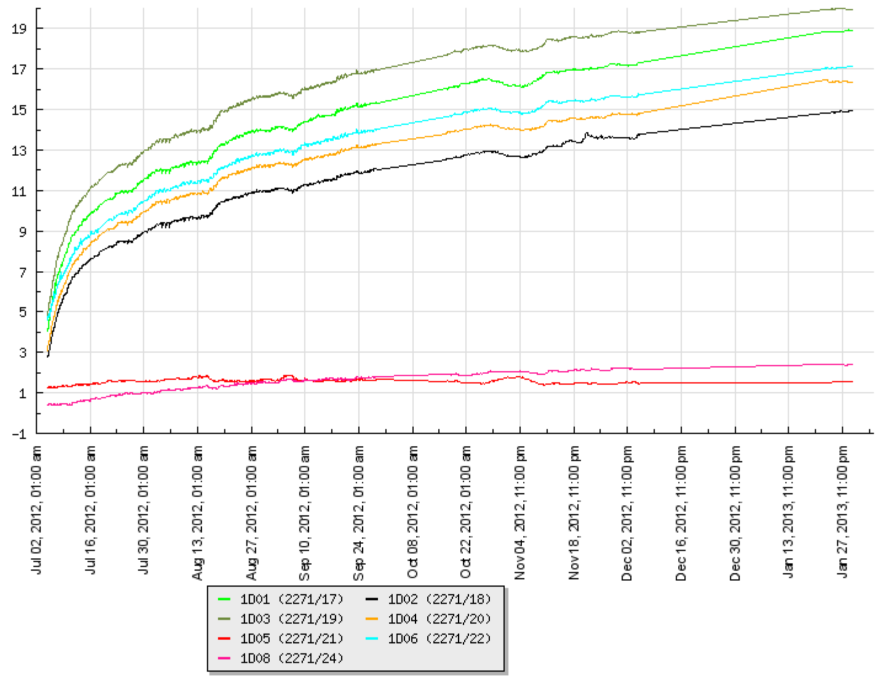

***Figure 12 Vertical movement amounts measured from Structure No. 1, directly output from the SMT data server** (Positive values mean downward movement and negative values mean upward movement)*

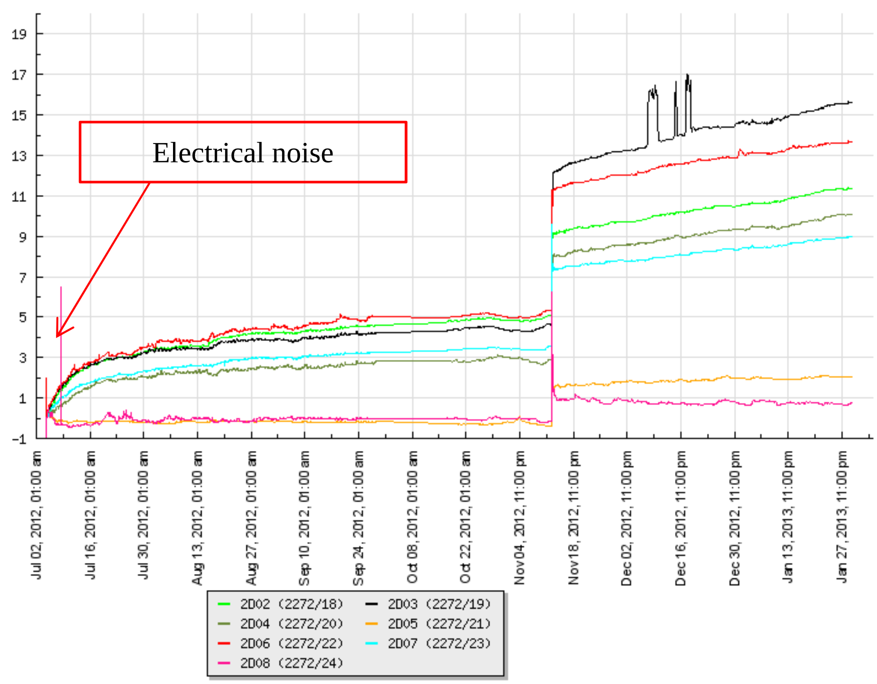

***Figure 13 Vertical movement amounts measured from Structure No. 2, directly output from the SMT data server** (Positive values mean downward movement and negative values mean upward movement. The large jump in readings reflects the loading of this structure.)*

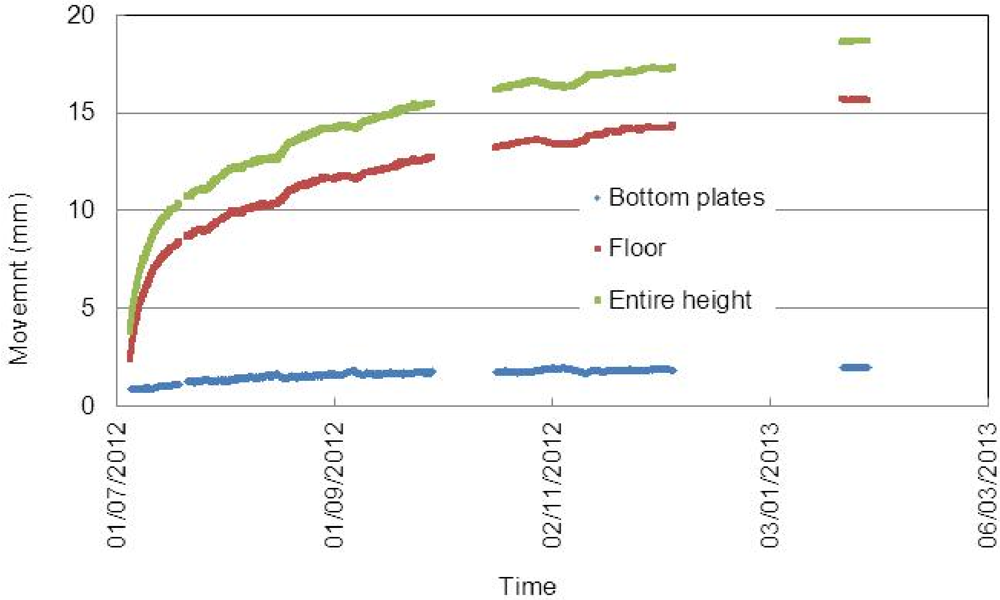

Figure 14 Average vertical movement amounts of three groups of Structure No. 1 over time (Positive values mean downward movement and negative values mean upward movement)

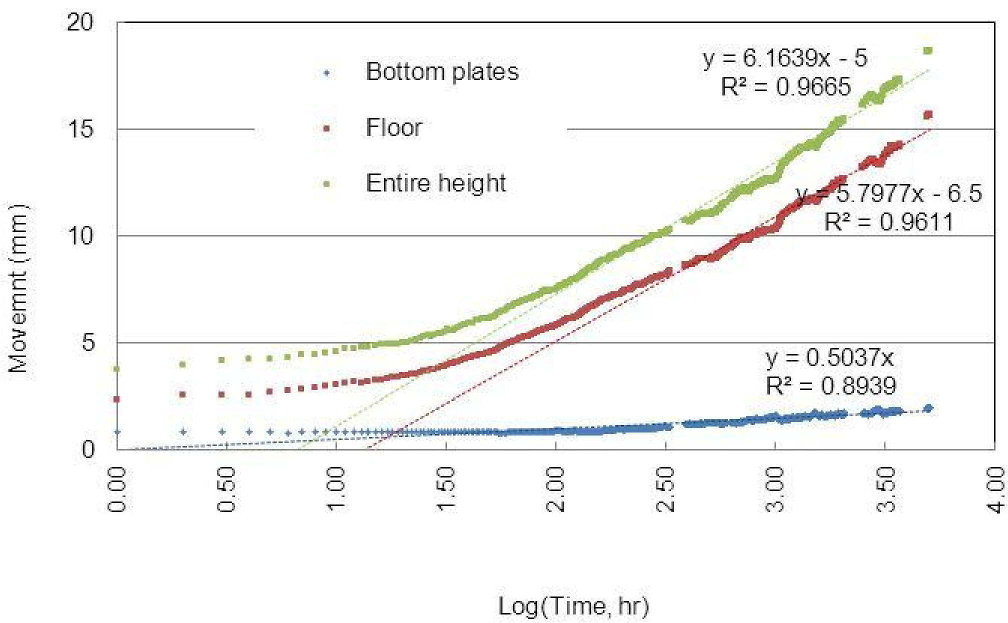

Figure 15 Average vertical movement amounts of three groups of Structure No. 1 over log (time)

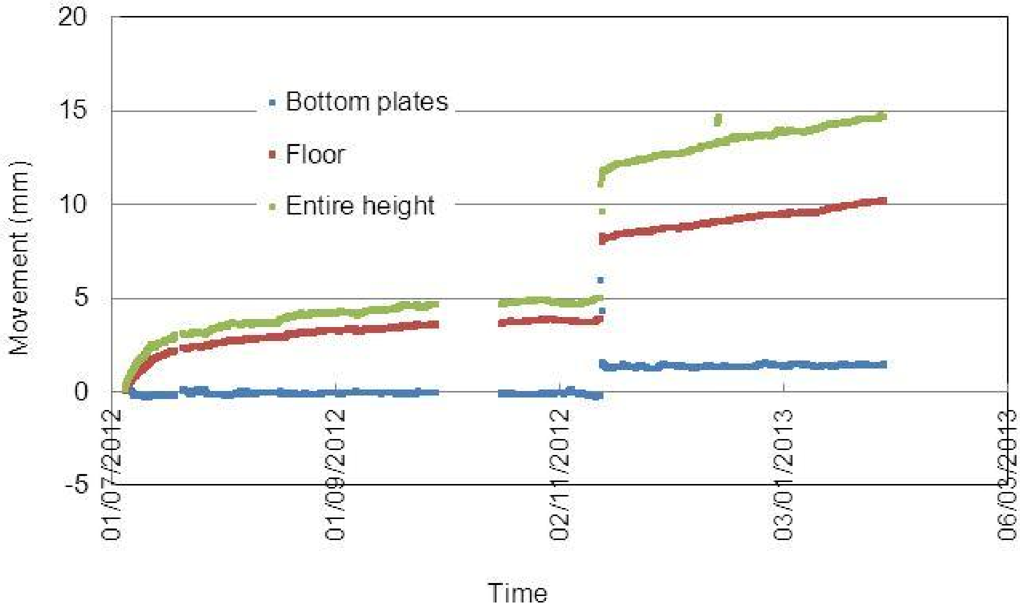

Figure 16 Average vertical movement amounts of three groups of Structure No. 2 over time (Positive values mean downward movement and negative values mean upward movement)

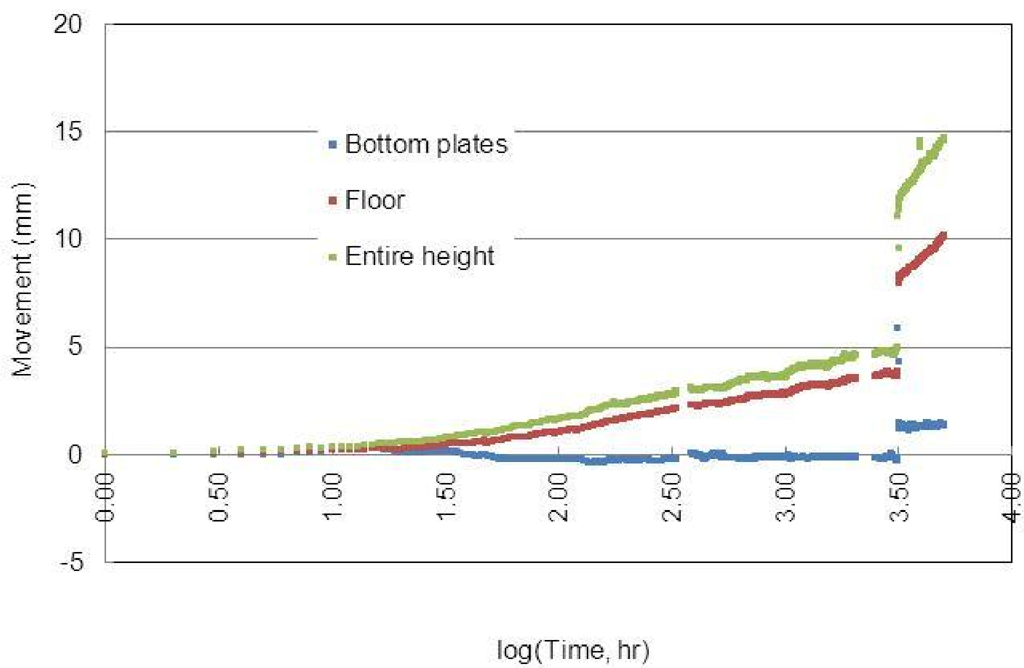

Figure 17 Average vertical movement amounts of three groups of Structure No. 2 over log (time)

Table 7 Summary of measured movement amounts with the changes of time and loading

Time	Structure No. 1				Structure No. 2			
	Bottom plates (mm)	Floor (mm)	Entire height (mm)	Difference (mm)[a]	Bottom plates (mm)	Floor (mm)	Entire height (mm)	Difference (mm)[a]
July 04 2012, after loading of Structure No. 1	0.9	2.3	3.8	0.6	0	0	0	0
November 13, before loading of Structure No. 2					-0.3	3.9	5.0	1.4
November 13, after loading of Structure No. 2	1.8	13.8	16.9	1.3	1.4	8.1	11.6	2.1
January 30 2012	2.0	15.6	18.7	1.1	1.4	10.1	14.7	3.1

*Positive values mean downward movement and negative values mean upward movement
[a]Difference = Entire height – Bottom plates –Floor

The measured movement of the entire Structure No. 1, contributed by drying and loading, reached 18.7 mm after six months. The movement of Structure No. 2, with the load applied when the wood was much drier, reached 14.7 mm in the same period of time. Related to this but measured from the four-storey wood-frame building in BC built with nominal 2 in. by 10 in. dimensional lumber floor joists with a similar initial MC of about 20%, the vertical movement amounts of the bottom floors ranged from 14 mm to 18 mm at three locations in a period of 18 months (Wang *et al.* 2013). It seemed that the laboratory testing results were overall comparable with the field measurement results.

Although these two structures eventually had the same amount of loading and went through a similar drying process, loading on dried wood did reduce the total vertical movement amount. This suggests that loading wood with a higher MC generated additional movement during MC changes. Most of the values in Table 7 were positive, which means downward movement. The only negative value of the two bottom plates of Structure No. 2 meant that its movement was upward before loading. It could be a result of wood warping and other dimensional changes when there was no additional load on the structure except for its wood weight.

5.3.2 Predicted Shrinkage

The wood shrinkage amounts were calculated based on the estimated shrinkage coefficients (5.2) and the MC changes (5.1). Wood is typically highly dimensionally stable in the longitudinal direction (FPL, 2010), which makes it difficult to precisely measure the shrinkage coefficient. A shrinkage coefficient of 0.0053% per 1% MC change was used in Table 8 based on the longitudinal shrinkage of 0.1 to 0.2% from green to ovendry state (FPL 2010; being consistent with the number used in previous reports (Wang and Ni 2010; Wang and Ni 2012)). The calculations showed that the entire height of the structure would have a shrinkage amount of 9.5% by November 13 2012 based on the assumption that the wood reached an average MC of 11%, and a shrinkage amount of 11.6% by January 30 2013 on the basis that the wood had an average MC of 9%.

Table 8 Estimated shrinkage of the major members

Members	Total dimension (mm)	Shrinkage coefficient (% per 1% MC change)	MC change (%) by November 13[a]	MC change (%) by January 30[a]	Shrinkage by November 13	Shrinkage by January 30
Studs	430	0.0053	9	11	0.2	0.3
Top plates, 4 pieces	152	0.216	9	11	3.0	3.6
Floor joists	240	0.220	9	11	4.8	5.8
Bottom plates, 2 pieces	76	0.227	9	11	**1.6**	**1.9**
Floor (including top plates and floor joists)					**7.7**	**9.4**
Entire height					**9.5**	**11.6**

[a]From an initial MC of 20% to a MC of 11% on November 13 2012, and to a MC of 9% on January 30 2013 based on Table 5.

5.3.3 Settlement and Creep

Based on the measured vertical movement (Section 5.3.1) and the predicted shrinkage (Section 5.3.2), the initial settlement (bedding-in movement) and the creep amount were estimated.

Table 7 shows the difference between the movement of the entire height (shown as "Entire height" in the figures and tables in this report) and the bottom plates, top plates and joists (shown as "Bottom plates" and "Floor" in the figures and tables) for each structure. Such a difference must be contributed by shrinkage of the studs, the interfaces between the studs and the top plates, and the interfaces between the studs and the bottom plates. Compared with Structure No. 1, Structure 2 showed higher differences for all the three member groups. The difference reached over 3 mm for the entire Structure No. 2 by the end of January 30 2013. While the shrinkage of the studs was expected to be very small (around 0.2 mm, Table 8) and not to vary much between these two structures, Structure No. 2 apparently had large gaps to close at these two interfaces during loading. This must be a result of wood drying and the consequent warping and other dimensional changes when there was no load.

Table 9 summarized the calculated load-induced movement including initial settlement and creep for the entire test period from July 4 2012 to January 30 2013. The vertical movement at the moment of loading is theoretically contributed by settlement, i.e. bedding-in movement, and elastic compression. Given the high modulus of elasticity of wood, the contribution of elastic compression was expected to be negligible (King 2012). Structure No. 2 showed larger amounts of settlement at the moment of loading, which was 6.61 mm for the entire structure, compared with 3.8 mm of Structure No. 1 (Table 9). As discussed above, this must have been caused by wood shrinkage and the associated dimensional changes, which increased the gaps between members (upward movement instead of the usually supposed downward movement). This was also the reason that the measured movement from Structure No. 2 did not reflect true shrinkage of wood, particularly before the load was applied. Therefore the calculated values for "Time dependent (shrinkage + creep)" and "Creep" for Structure No. 2 had no practical implication (Table 9, some values were negative). On the other hand, the calculations should be sound for Structure No. 1 since all movement was downward due to the high load applied from the beginning. The calculations in Table 9 showed that Structure No. 1 had a high time-dependent contribution. When the shrinkage component was removed from this time-dependent movement, the time-dependent compression, i.e. creep, was about 3.3 mm for the entire structure in a period of six months. Wood has complicated transverse compression behaviors depending on wood species, micro- and macro- structures, density, and MC (Bodig 1965; 1966; Kunesh 1966; Wolcott *et al.* 1989). MC is one of the most important factors which affect such behavior. MC reduces modulus of elasticity and wood with a high MC tends to show more "plastic" strain during transverse compression.

The calculation indicated that among the entire vertical movement amount of 18.7 mm from Structure No.1, 11.6 mm was contributed by wood shrinkage (62%), 3.8 mm was contributed by initial settlement when it was loaded (20%), and 3.3 mm was contributed by creep over time (18%). The shrinkage was expected to change slightly resulting from seasonal MC changes and creep may increase with time. However, the good linearity of the vertical movement over log(time, hr) (Fig. 15) after the initial test period indicated that the movement had been stable during the past few months. The creep amount had been increasing but had not been increasing dramatically when the wood became drier. Further observation was needed. Settlement should occur with increase in loads during construction and can be ignored in design, however, this test suggested that there may be a need to consider the impact of creep, in wet climates in particular, in addition to wood shrinkage.

Table 9 Differences between measured movement and estimated shrinkage

Contributors to vertical movement (mm)	Structure No. 1			Structure No. 2		
	Bottom plates	Floor	Entire height (percentages of entire movement)	Bottom plates	Floor	Entire height
Measured entire movement	2.0	15.6	**18.7 (100%)**	1.4	10.1	14.7
Predicted shrinkage	1.9	9.4	**11.6 (62%)**	1.9	9.4	11.6
Movement during loading[a]	0.9	2.3	**3.8 (20%)**	1.7	4.2	6.6
Time dependent movement (shrinkage + creep)[b]	1.1	13.3	**14.9 (80%)**	-0.3	5.9	8.1
Estimated creep[c]	-0.8	3.9	**3.3 (18%)**	-2.2	-3.5	-3.5

[a]The vertical movement occurred at the moment of loading, on July 4 2012 and November 13 2013, respectively
[b]The difference between the "Measured entire movement" and the "Movement during loading"
[c]The difference between the "Time dependent (shrinkage + creep)" and the "Predicted shrinkage"

6 Conclusions

1. A load must be applied for movement to "show up" and occur in a downward direction. Without loads even shrinkage could show as upward movement.
2. This test appeared to separate the contributions of wood shrinkage, initial settlement (bedding-in movement), and creep reasonably well. Based on the results gained from Structure No. 1, loaded when the wood had an initial MC about 20%, the entire movement amount reached about 19 mm in a period of six months. Within this amount of movement as the wood reaches an equilibrium moisture content, shrinkage accounted for over 60% of the vertical movement, with the remaining 40% attributed to load-induced movement including initial settlement and creep (when elastic compression was neglected); the magnitude of creep appeared to be similar to the initial settlement amount.

3. The use of dry wood generally reduced the total vertical movement amount. Drier wood also tended to have larger gaps between members, but such gaps should close almost instantaneously with increase in load during construction.

7 Recommendations

It was recommended that this test setup should be maintained for a longer period to observe any further vertical movement and the contributions of shrinkage and creep.

Similar tests should be conducted for structures with engineered wood floor joists, given the fact that most mid-rise platform buildings use engineered wood floor joists instead of lumber joists.

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