Field Measurement of Vertical Movement and Roof Moisture Performance of the Wood Innovation and Design Centre

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Contract Report

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Disclosure for Commercial Application: If you require assistance to implement these findings, please contact FPInnovations at info@fpinnovations.ca

SUMMARY

Two of the major topics of interest to those designing taller and larger wood buildings are the susceptibility to differential movement and the likelihood of mass timber components drying too slowly after they become wet during construction. The Wood Innovation and Design Centre in Prince George, British Columbia provides a unique opportunity for non-destructive testing and monitoring to measure the ‘As Built’ performance of a relatively tall mass timber building. Field measurements also provide performance data to support regulatory and market acceptance of wood-based systems in tall and large buildings. This report covers vertical movement and roof moisture performance measured from this building for about three and a half years, with sensors installed during the construction.

The report first describes instrumentation. The locations selected for installing displacement sensors for measuring vertical movement comprised of the following: glued-laminated timber (glulam) columns together with cross-laminated timber (CLT) floors on three lower floors; a glulam column together with a parallel strand lumber (PSL) transfer beam on the first floor; and a CLT shear wall of the core structure on each floor from the second up to the top floor. Sensors were also installed to measure environmental conditions (temperature and relative humidity) in the immediate vicinity of the components being monitored. In addition, six locations in the timber roof were selected and instrumented for measuring moisture changes in the wood as well as the local environmental conditions. Most sensors went into operation in the middle of March 2014, after the roof sheathing was installed.

The monitoring showed that the wood inside the building reached an average moisture content (MC) of about 5% in the winter heating seasons and about 8% in the summer, from an initial MC of about 13% during the construction. Glulam columns were extremely stable dimensionally given the changes in MC and loading conditions. With a height of over 5 m and 6 m, the two glulam columns monitored on the first floor showed very small amounts of vertical movement, about 2 mm (0.04%) and 3 mm (0.05%), respectively, over a period of about three years and a half. Assuming the two monitored columns are representative of the other columns along the column line, the cumulative shortening of the six glulam columns along the height of the building would be about 12 mm (0.05%), not taking into account deformation at connection details or effects of reduced loads on upper floors. The CLT wall was found to be also dimensionally stable along the height of the building. The measurements showed that the entire CLT wall, from Floor 1 to Floor 6, would shorten about 19 mm (0.08%). The PSL transfer beam had a reduction of about 12 mm (1%) in the depth, i.e., along the building height. The CLT floor panels also showed considerable vertical movement of about 5 mm (3%) in the thickness direction. All the differential movement was expected and taken into consideration in the design and construction of the building.

In terms of the roof performance, two locations, both with a wet concrete layer poured above the plywood sheathing, showed wetness during the construction but continued to dry afterwards. The satisfactory drying performance can be attributed to the interior ventilation function designed for the roof assemblies by integrating strapping between the sheathing and the mass timber beams below.

Table of Contents

List of Figures

List of Tables

1 OBJECTIVES

- Measure vertical movement at representative glulam columns and cross-laminated timber walls
- Monitor moisture performance at selected locations in the roof

2 BACKGROUND

In the last decade, there has been increased interest worldwide in using engineered wood products to build modern wood buildings. In Canada, recent efforts to relax the height and area limits for wood construction have amplified the interest in taller and larger mass timber buildings within the design and construction community. To help architects, engineers, code consultants, developers, building owners, and Authorities Having Jurisdiction to assess the solutions unique to such timber buildings, FPInnovations developed and published a Technical Guide for the Design and Construction of Tall Wood Buildings in Canada by working with a large multi-disciplinary team of professionals (Karacabeyli and Lum 2014). Chapter 9 of this guide includes general technical information on testing and monitoring of tall wood buildings to measure important aspects of building performance using non-destructive methods. Testing and monitoring of initial and in-service performance of tall wood buildings is needed to document actual performance, refine design assumptions, and make designs more cost effective in future buildings. Two major topics of interest to those designing taller and larger wood buildings are 1) the susceptibility to vertical differential movement among gravity load-bearing members and 2) the rate of drying of mass timber components after they are wetted during construction or in service.

The Wood Innovation and Design Centre (WIDC) in Prince George, with a total height of 29.5 metres was the tallest modern mass timber building in Canada when it was completed in 2014 (Figure 1). The building greatly showcases the applications and capacities of various wood products as well as good design and construction practices. This building structure has a cross-laminated timber (CLT) core structure for the elevator shaft and staircases, CLT floor and roof diaphragms, and glued-laminated timber (glulam) columns as major members to bear gravity loads, together with parallel strand lumber (PSL) transfer beams (Figure 2; Figure 3). Laminated veneer lumber (LVL) columns and structurally insulated panels are used in the exterior walls. At each floor, CLT panels are staggered vertically to provide ceiling chases for accommodating building services and other assembly materials (e.g., insulation). At the roof level, the underside of the roof structure in the interior is vented by creating an air space between the CLT roof panels and the plywood roof sheathing using plywood strapping (see the components in Figure 2). It was recognized during the design stage that this building would provide a unique opportunity for non-destructive testing and monitoring to measure the ‘As Built’ performance of a mass timber building in a cold climate in British Columbia. Field measurements were also expected to provide performance data to support regulatory and market acceptance of wood-based systems in tall and large buildings.

Figure 1 The Wood Innovation and Design Centre in Prince George, British Columbia

Figure 2 Mass timber roof structure integrated with an interior ventilation cavity between plywood roof sheathing and CLT panels below (Courtesy of Michael Green Architecture)

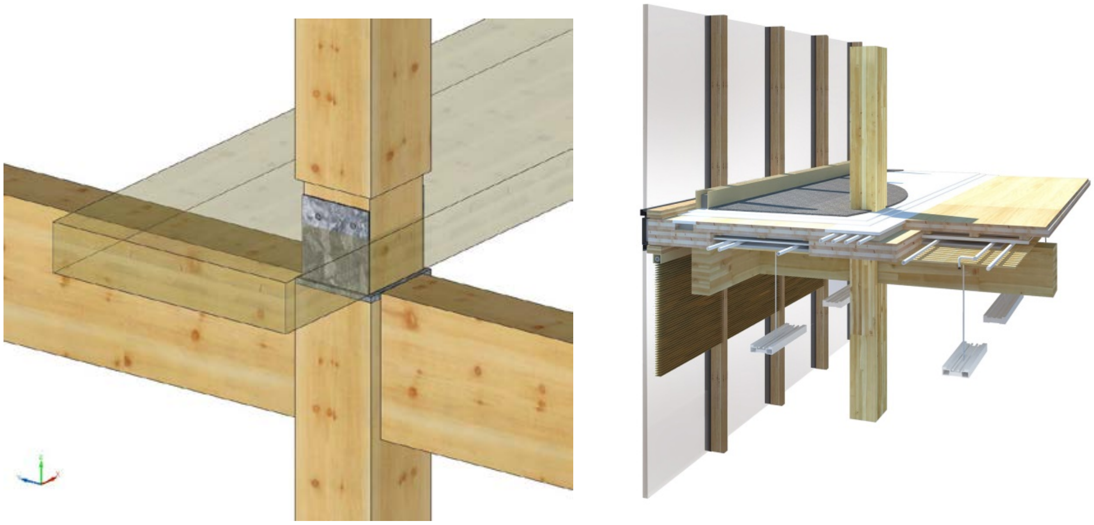

Figure 3 Left: Support of CLT floor slab with glulam column and beam (Courtesy of Equilibrium Consulting); Right: Vertically staggered CLT floor panels for providing chases to accommodate building services (courtesy of Michael Green Architecture)

Working closely with the architect, the engineers, and the contractor involved, FPInnovations carried out testing and monitoring in this building to assess the vertical movement and the moisture performance. Sensors were installed during the construction stage to measure vertical movement of selected columns, beams, and walls and moisture performance of the roof; this activity was reported previously (Wang 2015; Wang *et al.* 2016). This updated report covers the initial instrumentation and the monitoring of vertical movement and roof moisture performance for a period of three years and a half since the completion of the building.

3 INTRODUCTION

3.1 Vertical Movement of Wood under Compression

Vertical differential movement among columns and walls, interior or exterior, resulting from different materials, connection methods, and environmental conditions is an important consideration in design. Special attention to detailing may be required to prevent potential adverse impacts due to the cumulative and varying nature of vertical differential movement.

Vertical movement of wood members is primarily associated with dimensional changes due to moisture content (MC) changes below the fiber saturation point. Wood is known to have much larger shrinkage / swelling amounts in transverse orientations (from tangential to radial) than in the longitudinal direction (FPL 2010). In addition, instantaneous and time-dependent deformation (i.e., creep) when wood is compressed and building settlement that is simply the closing of construction tolerance gaps both contribute to vertical movement. Differential movement is typically a larger concern for platform frame construction due to the use of stacked members, such as wall plates, than for post and bean and mass timber constructions. That is why the major wood design books in North America only provide methods for estimating shrinkage of dimension lumber wall plates and floor joists in the gravity load path (CWC 2005; Breyer *et al.* 2006; APEGBC 2011; CSA 2014). Moreover, while most members are typically kiln-dried dimension lumber (marked “S-Dry”) in wood-frame construction, their initial MC will generally be higher than the initial MC of engineered wood products at manufacture[1]. FPInnovations has been collecting vertical movement data from both wood-frame (Wang and Ni 2012; Wang *et al.* 2013; Wang 2016a; Wang 2017a) and mass timber buildings (Munoz *et al.* 2012) in recent years to assist in the development of mid-rise and taller buildings. In addition to validating movement estimation methods, field measurements are helpful to assess the impact of materials, design and fabrication methods, and construction and service conditions.

When predicting vertical movement, the effect of (gravity) loads is generally ignored in North America. This is based on the fact that wood has a high modulus of elasticity parallel to the grain; therefore deformation caused by compression parallel to grain, such as that in axially loaded studs and columns is negligible. However, wood members loaded perpendicular to grain may undergo considerable amounts of instantaneous compression followed by creep, particularly when the wood has a high MC or experiences large MC changes. For example, creep is most pronounced where wood members are subjected to high levels of sustained loads in an environment with large fluctuations in humidity, or under continuously wet conditions. Research shows that there is a need to consider instantaneous compression and creep, in addition to wood shrinkage, when predicting vertical movement. Based on a laboratory test (Wang and King 2015) conducted using a wood-frame structure, where the wood dried from an initial MC of about 20% to a final MC of about 7% and was under a dead load that could be experienced by the bottom floor of a six-storey wood-frame building, wood shrinkage accounted for approximately 70% of the entire vertical movement of the structure. The remaining 30% was contributed by load-induced movement including settlement, instantaneous compression, and creep. Instantaneous compression and building settlement mostly occur with increases in loads and typically can be accommodated during construction; however, deformation due to creep after construction (particularly those contributing to differential movement) may result in movements that exceed acceptable construction tolerances. European design provisions (CEN 2004) recommend that creep of solid timbers, glulam and LVL should be estimated at 0.6 times the instantaneous deformation caused by dead loads for members under typical indoor living conditions[2]. For applications in damp environments, creep may be estimated to be twice as much as the instantaneous deformation caused by dead loads. There are no provisions in North America on how to address such load-induced vertical deformation in any type of wood

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[1] The wood used in engineered wood products generally require a lower initial MC to facilitate bonding with adhesives. This includes the lumber used to manufacture mass timber elements, such as CLT and glulam.

[2] It means without long periods of elevated humidity levels and with the average MC in most softwoods not exceeding 12%.

construction. Measuring long-term vertical movement from selected columns, CLT walls, and beams in the WIDC building aims to generate more information related to design of mass timber buildings.

3.2 Moisture Performance of Roof

Questions about durability performance of wood roofs often arise when a roof is built with structural composite and mass timber products, such as CLT, LVL, PSL, and laminated strand lumber (LSL) in thick and wide panels, particularly when they are exposed to moisture during construction. Research has shown that once wood roof decks (e.g. plywood, OSB, CLT, LVL, nail-laminated timber) get wet[3], it will take months to dry out under the coastal climatic conditions (Wang 2014; Wang 2016b; Wang 2017b). The drying capacity of building envelope assemblies in modern buildings is often made worse because of the increased insulation levels needed to meet more stringent energy efficiency requirements, or the combined use of membranes or insulation materials with low vapour permeance (e.g., polyisocyanurate, extruded polystyrene, and closed-cell polyurethane spray foam). Excessive wetting can lead to issues, such as staining, mould, and ultimately decay (Wang 2016c). Staining and mould growth mostly affect appearance, and decay can compromise the structural integrity.

The design team suggested monitoring the moisture performance of the roof in the WIDC building to ascertain the drying performance of timber roofs. In the original design, 19-mm thick plywood roof sheathing would rest on sloped sleepers placed on staggered CLT panels. Although this solution would provide some air space to improve the drying performance compared with a common practice of directly installing plywood sheathing on CLT panels, there would still be some locations with poor drying capacity, particularly when the plywood is wetted before the roof membranes are installed. The design team revised and improved the roof design not long before the roof was built. Plywood strapping was instead installed between the CLT beams below and the plywood sheathing above in most areas of the roof to introduce an air cavity for interior ventilation (Figure 2; see the built roof in Figure 12). Knowing this improved design would greatly improve the drying capacity and reduce the moisture risk, interest remained in seeing how well the new system would perform. Six locations in the roof, covering different orientations and moisture risks were therefore selected for instrumentation to measure the moisture performance.

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[3] Field measurements in the 18-storey UBC Brock Commons building showed that the average MC in the surface of the CLT floor panels (built with Spruce-Pine-Fir) was below 20% even in rainy days of the construction, confirming only a limited amount of moisture penetrated into the wood after rain (Wang and Thomas 2016).

4 PROJECT TEAM

FPInnovations:

Jieying Wang	Senior Scientist, Project leader
Tony Thomas	Principal Instrumentation Technologist

PCL (Contractor):

Chad Kaldal	WIDC Project Manager
Lloyd Church	Site Superintendent
Daniel Lynch	Project Coordinator

Michael Green Architecture (Architectural design):

Michael Green	Architect
Mingyuk Chen	Architect

Equilibrium Consulting (Structural design):

Eric Karsh	Structural Engineer
Daniel Thomi	Structural Engineer

RDH Building Science (Building envelope consultant):

Graham Finch	Building Science Research Specialist

5 INSTRUMENTATION

This field monitoring study requires installing instruments during construction and then measuring the performance for multiple years. Field measurements are always more complex and often present unique challenges compared to laboratory testing. One of the reasons is that once an instrument (including sensors and data loggers) is installed and subsequently covered by building elements, it becomes very difficult or even impossible to access if there is a need for maintenance or repair. The guidelines provided in Chapter 9 of the Technical Guide for the Design and Construction of Tall Wood Buildings in Canada were generally followed to develop the instrumentation plan for this building (Karacabeyli and Lum 2014).

5.1 Instruments

Instruments selected for this monitoring study had all been tested and applied in a number of field and laboratory testing projects with proven performance. For example, the key sensors including the draw wire displacement sensors for measuring vertical movement and the RH/T sensors for measuring ambient relative humidity (RH) and temperature were all tested in the FPInnovations laboratory and later used in multi-year field measurements, along with the data collection systems (Wang *et al.* 2013; Wang and Ni 2014; Wang 2016a; Wang 2017a). Table 1 lists the major instruments used for monitoring vertical movement and roof moisture performance in this building.

Table 1 Major Instruments Selected for Measurements

Purposes	Instrument	Shape and Size	Note
Measuring vertical displacement	Displacement sensor, a draw wire type	Box: 90 mm × 125 mm × 64 mm (3.5 in × 5 in. × 2.5 in.)	Measurement range: 50 mm; Linearity max.: 0.1 mm Metal conduit, ½ in. in diameter, was used to protect the wire of each displacement sensor.
Measuring environmental RH and temperature	RH/T sensor	Small probe	RH resolution: 0.5%; Accuracy: ±3% to ±5% (in the range of 10-95%) Temperature tolerance: 1%; Resolution: 0.1℃; Accuracy +/- 1℃
Measuring wood MC in the roof	Moisture pins, a resistance type	Small screws (pins)	Each sensor was compensated for temperature and wood species
Detecting liquid water in the roof	Moisture tape, based on measurement of electrical resistance	Thin metal tape	Indicating presence of liquid water when the measured electrical resistance was under a threshold of around 100K ohms
Collecting and transferring data (wirelessly)	Data acquisition unit “A3”	Box: 125 mm × 125 mm × 64 mm (5 in × 5 in. × 2.5 in.)	Each unit also measured RH and temperature of the environment

5.2 Instrumentation Planning

A plan of instrumentation for measuring vertical movement along columns, walls, and beams, and moisture performance of the roof was discussed among the project team based on the building design. Each instrument was integrated into drawings of the building in advance (as shown in Figure 4 as an example; see 5.3 and 5.4 for instruments at each location) to facilitate discussion and approval, with each location verified at site. It was known that the batteries of the data loggers would last approximately two years. Efforts were made to place the data loggers at accessible locations, whenever possible. The instruments were installed in the building from March 11 - 15, 2014 after the roof structure was installed. This timing was expected to allow protection of the instruments from weather, to capture the performance that is of interest and will address design concerns, and to allow the installation of the major instruments on one trip to reduce cost. Afterwards, data was recorded and transmitted hourly using a computer and internet in the building.

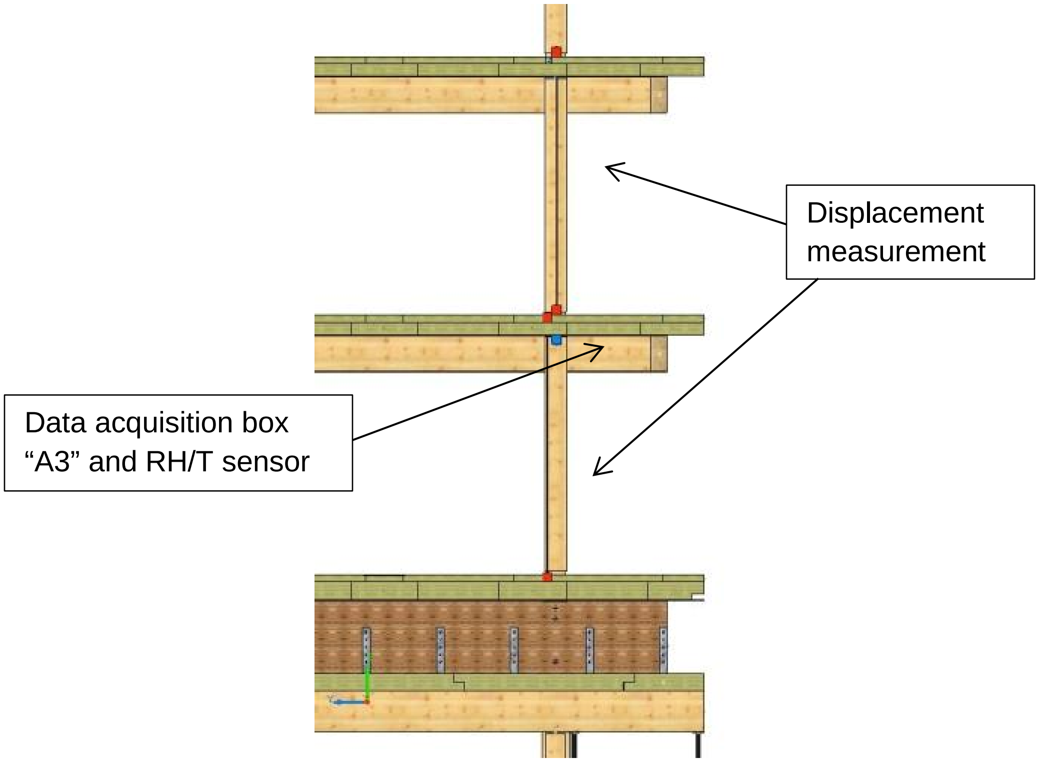

Figure 4 Locations of two displacement sensors (red, along the glulam column) and one data acquisition box together with an RH/T sensor (blue) for measuring vertical movement at Location 3

5.3 Vertical Movement

It was very challenging to identify appropriate locations along columns or interior load-bearing walls to make meaningful measurements of vertical movement that were also representative of the building design. A major issue was how to conceal each instrument using existing building elements. Adding extra elements to conceal or mask an instrument was generally not recommended for aesthetical reasons. This building primarily uses glulam columns and beams for bearing gravity loads. It has an elevator and staircase core and an adjacent interior shear wall built with CLT. Unlike wood-frame construction, many timber members, such as glulam columns, are designed to be exposed to the interior space to showcase the appearance of wood. There are spaces provided by the staggered CLT panels in each floor structure and dropped ceiling (Figure 3, right), but very few cavities or gaps were available between floor and ceiling to accommodate instruments. In comparison, stud cavities would be readily available for concealing instruments in a wood-frame building. Moreover, the top three floors of the building were built to be rental spaces for future tenants, with little finishing provided when the building was completed; exposing any instrument therefore became less advisable. It was therefore decided to focus on the lower three floors for measuring vertical movement of glulam columns. Research showed that vertical movement was generally higher on lower floors due to the effect of gravity loads (Wang *et al.* 2013; Wang and Ni 2014; Wang and King 2015; Wang 2016a; Wang 2017a). Three locations (labelled as Location 1, 3, and 4 in this paper) were finally identified to be reasonably suitable for measurements[4]. Instruments were subsequently installed to measure the vertical movement together with the environmental conditions in service (Figure 5; Figure 6; Figure 7; Table 2; Table 3). These locations would allow comparing the vertical movement of glulam columns and assessing the movement of CLT floors at a few locations as well as of a massive LSL transfer beam.

Figure 5 A displacement sensor (its metal conduit in left photo, and a closer image of the sensor box which is adjacent to the column base) at Location 1 for measuring vertical movement of the glulam column

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[4] These are Location 1 at GL C and GL 6.5 on Floor 1, Location 3 at GL 6.7 and GL B on Floors 2 and 3, and Location 4 at GL B and GL 4 from Floors 1 to 3 based on the drawings of the building.

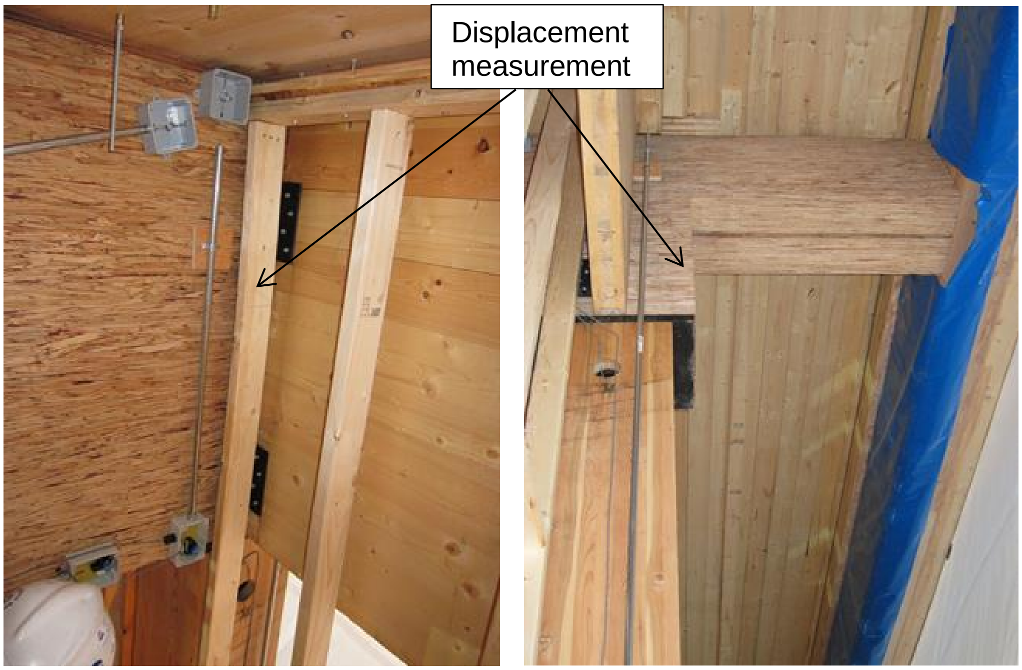

Figure 6 Left: A displacement sensor measuring a PSL transfer beam; Right: a displacement sensor measuring the movement of both PSL transfer beam and glulam column at Location 1

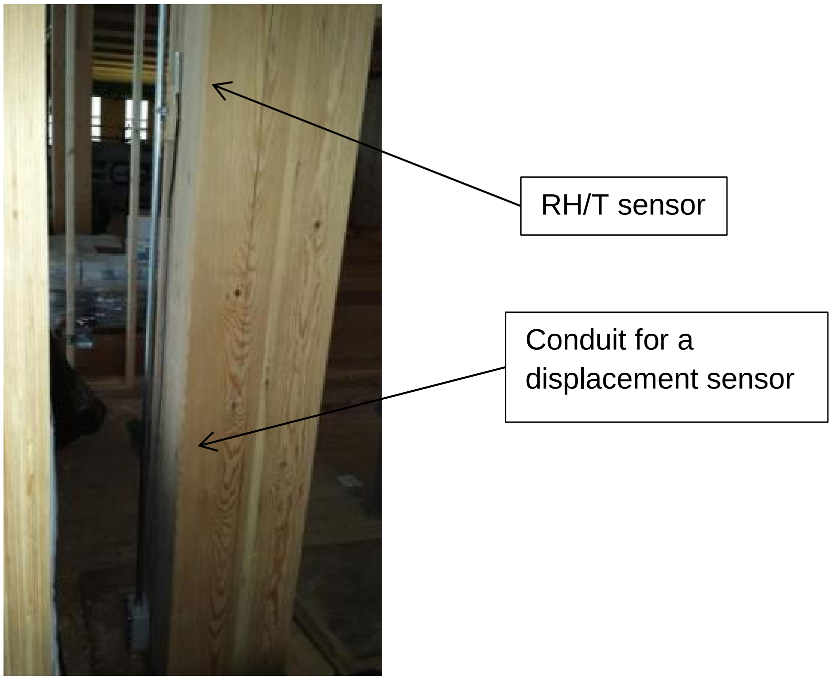

Figure 7 A displacement sensor and an RH/T sensor for measuring the glulam column on Floor 3 at Location 4

Regarding CLT walls, the CLT shear wall outside the staircase shaft appeared to be able to accommodate instruments, since one side of the wall was to be covered with gypsum boards supported with 38 mm by 90 mm (2 in. by 4 in.) framing. The exception would be the first floor, where the wall was to be exposed to the interior. The portion of wall adjacent to the staircases and the elevator may experience a high level of vibration resulting from foot traffic and operation of the elevator, which would consequently cause a high level of noise for movement monitoring. Considering all these factors, Location 5[5] from Floor 2 to Floor 6 was identified for measuring vertical movement (Figure 8; Figure 9; Figure 10; Figure 11; Table 2; Table 3). However, it was found during instrumentation that a LSL ledger fastened to the CLT wall close to the ceiling would affect the measurement on Floors 2, 3, and 5 (a LSL ledger seen in Figures 8-10). It would be complicated and time-consuming to drill holes through those ledgers to install displacement sensors and to run conduits. Therefore on these three floors, instruments were installed to measure vertical movement of the CLT wall from the floor only up to the ledger. On Floors 4 and 6, where the ledger was not in the way, the displacement sensors were installed to measure movement from the floor up to the ceiling. The original distance (gauge length) covered by each displacement sensor was measured to estimate the ratio between vertical movement and gauge length, and consequently the movement of the entire CLT wall.

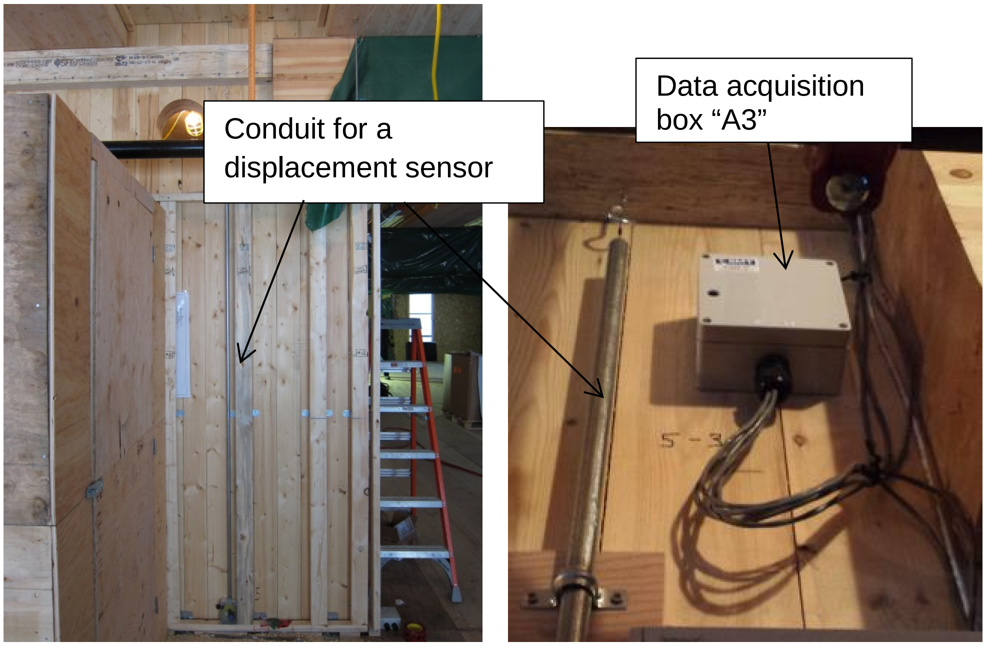

Figure 8 A displacement sensor (left photo) and a data acquisition box A3 (right photo) on Floors 2 and 3 at Location 5

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[5] Location 5 was at GL E between GL 4 and GL 5, facing GL F (i.e., not on the staircase side) in the drawings.

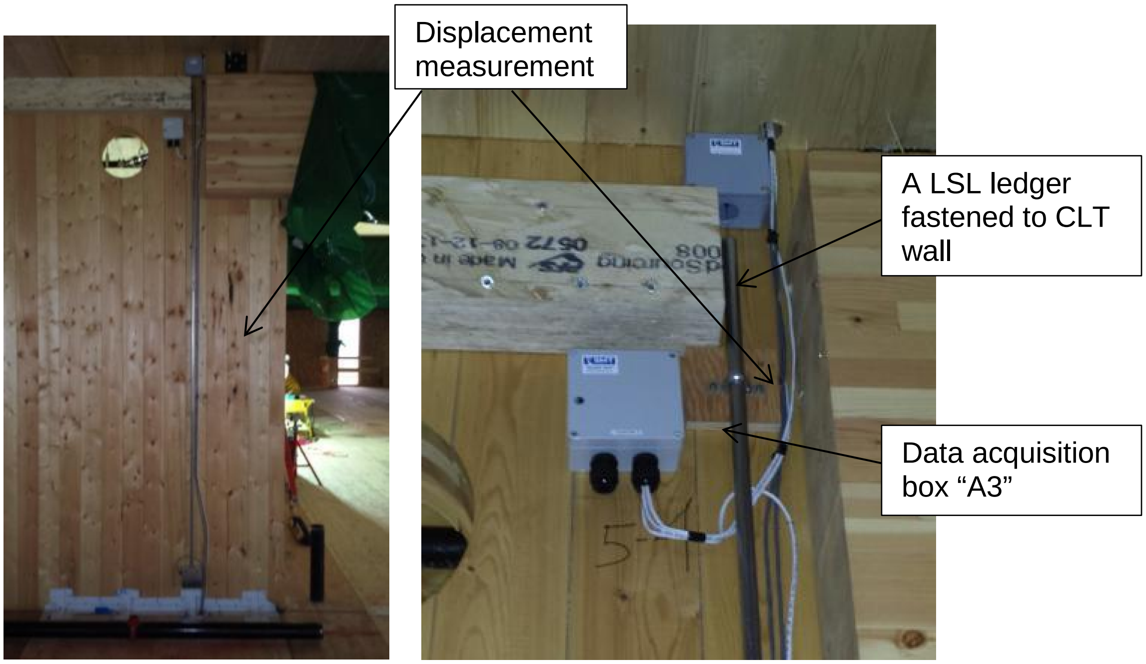

Figure 9 A displacement sensor and a data acquisition box A3 on Floor 4 at Location 5

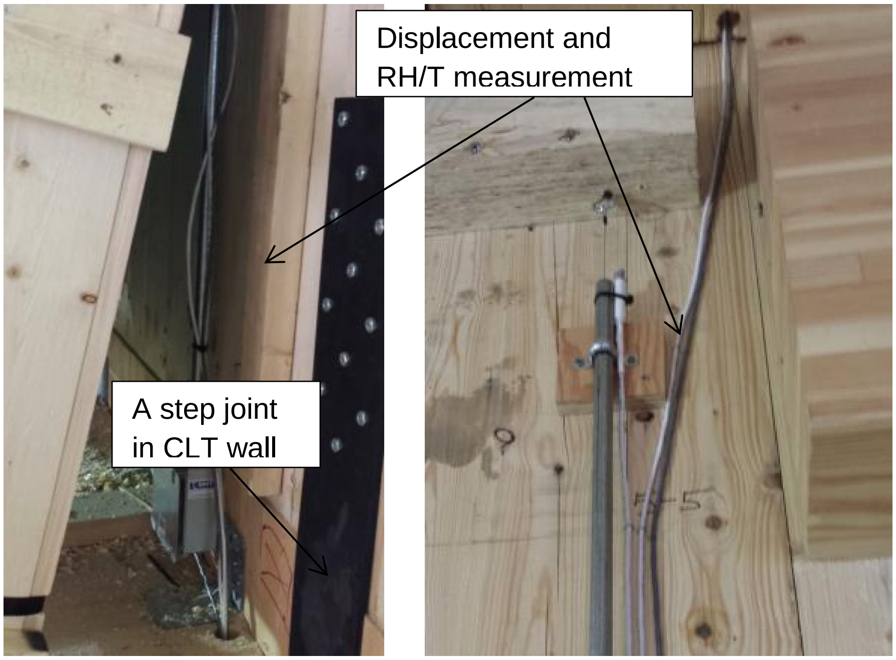

Figure 10 A displacement sensor covering a horizontal step lap joint in CLT wall (left photo) together with an RH/T sensor (right photo) on upper wall on Floor 5 at Location 5

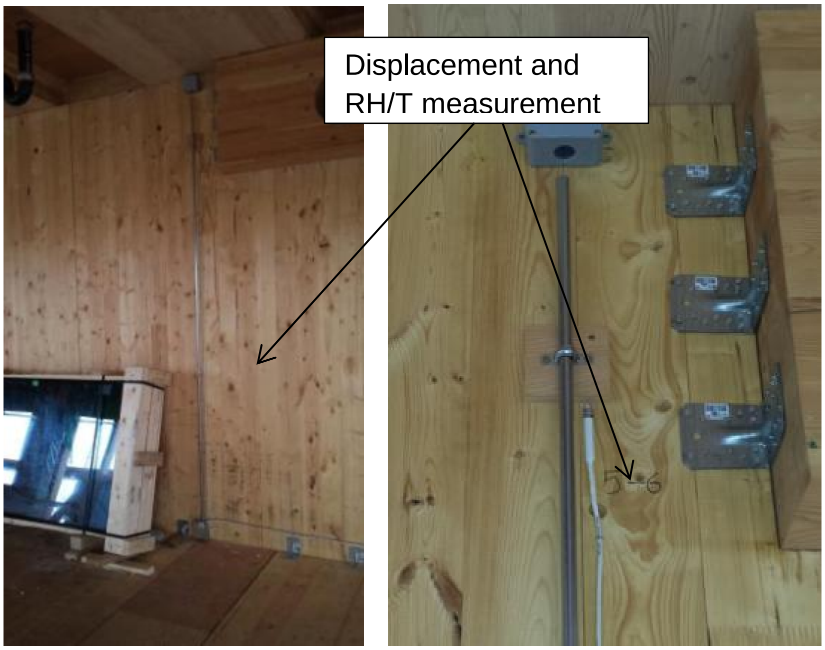

Figure 11 A displacement sensor together with an RH/T sensor on Floor 6 at Location 5

To summarize, measuring the vertical movement of a continuous vertical component over the entire height of the building from the ground to the roof was not possible at any location in this building. However, the installed displacement sensors were expected to provide key information about vertical movement of glulam columns, the CLT shear wall, a LSL transfer beam, and CLT floor panels under given environmental conditions in service.

Table 2 Locations of Displacement Sensors and Their Measurements

Location	Sensor Label	Vertical Distance Covered by Displacement Sensor	Initial Gauge Length (m)
Location 1 (GL C and 6.5, Floor 1, along a glulam column)	L1 F1 Glulam column	Measuring a glulam column, from its bottom to the top	5.01
	L1 F1 Column+Beam	Measuring a glulam column and a PSL beam. There are 2 beams side by side with a small gap between; each beam is 1220 mm deep (i.e., height) and 178 mm wide.	6.33
	L1 F1 Transfer beam	Measuring a PSL beam, not including its top and bottom surfaces.	1.12
Location 3 (GL 6.7 and B, Floors 2-4, along a glulam column)	L3 F2 Column+CLT 2-3	Measuring from the bottom of a glulam column to the CLT floor above, including both column and CLT floor. The CLT panel has a thickness of 169 mm.	3.29
	L3 F3	Measuring the bottom of a glulam	3.19

Location	Sensor Label	Vertical Distance Covered by Displacement Sensor	Initial Gauge Length (m)
	Column+CLT 3-4	column to the CLT floor above, including both column and CLT floor. The CLT panel has a thickness of 169 mm.	
Location 4 (GL B and GL 4, Floors 1-4, along a glulam column)	L4 F1 Column	Floor 1, measuring a glulam column, from its bottom to the top	6.16
	L4 F1 Column+CLT 1-2	Floor 1, from the bottom of a glulam column to the CLT floor above, including both column and CLT floor. The CLT panel has a thickness of 169 mm.	6.48
	L4 F2 Column+ CLT 2-3	Floor 2, from the bottom of a glulam column to the CLT floor above, including both column and CLT floor. The CLT panel has a thickness of 169 mm.	It was not measured, but should be close to the corresponding gauge length at Location 3, i.e., about 3.29 m.
	L4 F3 Column+CLT 3-4	Floor 3, from the bottom of a glulam column to the CLT floor above, including both column and CLT floor. The CLT panel has a thickness of 169 mm.	It was not measured, but should be close to the corresponding gauge length at Location 3, i.e., about 3.19 m.
Location 5 (GL E and GL 4 and 5, facing GL F, Floors 2 to Roof)	L5 CLT F2	Floor 2, from floor to bottom of ledger	2.87
	L5 CLT F3	Floor 3, from floor to bottom of ledger	2.86
	L5 CLT F4	Floor 4, from floor up to ceiling	3.01
	L5 CLT F5	Floor 5, from floor to bottom of ledger	2.89
	L5 CLT F6	Floor 6, from floor up to ceiling	3.00

Table 3 Sensors for Measuring Relative Humidity and Temperature along with Displacement Sensors

Location	RH/T or A3	Instrument Label	RH/T or A3 Locations
Location 1 (GL C and 6.5, Floor 1, beside Glulam column)	A3 (with RH/T)	L1 F1 RH sensor 2, L1 F1 T sensor 2	Interior wall of the projector room, at eye height
	RH/T	L1 F1 RH sensor 1, L1 F1 T sensor 1	
Location 3 (GL 6.7 and B, Floors 2-	A3 (with RH/T)	L3 F2 RH, L3 F2 T	Floor 2, close to CLT floor
	RH/T	L3 F3 RH, L3 F3 T	Floor 3, along the column, at

Location	RH/T or A3	Instrument Label	RH/T or A3 Locations
4, beside Glulam column)			eye height
Location 4 GL B and GL 4, Floors 1-4, beside Glulam column	RH/T	L4 F2 RH sensor 1, L4 F2 T sensor 1	Floor 2, along the column, at eye height
	A3 (with RH/T)	L4 F2 RH sensor 2, L4 F2 T sensor 2	Floor 2, in the ceiling chase
Location 5 GL E and GL 4 and 5, facing GL F, Floor 2 to Roof	RH/T	L5 F2 RH, L5 F2 T	Floor 2, on upper CLT wall
	A3 (with RH/T)	L5 F3 RH, L5 F3 T	Floor 3, on upper CLT wall
	A3 (with RH/T)	L5 F4 RH, L5 F4 T	Floor 4, on upper CLT wall
	RH/T	L5 F5 RH, L5 F5 T	Floor 5, on upper CLT wall
	RH/T	L5 F6 RH, L5 F6 T	Floor 6, on upper CLT wall

5.4 Moisture Performance of the Roof

The measurement in the roof generally aimed to monitor its drying capacity through measuring wood MC and ambient conditions in both the vented cavities, created by strapping between the CLT panels and the plywood roof sheathing above, and the ceiling chases, created by staggered CLT panels at several location (see instruments in Table 3). Such monitoring is not expected to serve as a leak detection system for the entire roof nor to replace normal roof inspection and maintenance. Compared to measuring vertical movement in the building, making an instrumentation plan and installing sensors in the roof was relatively straightforward. Being a conventional roof, rigid insulation and roofing membranes (SBS) etc. were to be installed above the plywood sheathing when the instruments were installed. The roof top was designed to have a low slope towards drains through the use of tapered expanded polystyrene (EPS) boards. A layer of concrete topping was to be installed between the plywood and the EPS above in the central area, i.e. around the mechanical penthouse. This was to improve acoustic performance by reducing sound transmission from the mechanical room and the outdoor mechanical units to the living space below.

Six locations in the roof, varying in orientation and roof assembly, were chosen for instrumentation. See Table 4 for their locations, assemblies, and the sensors installed. Five locations (Roof 1, 2, 3, 5, 6 in Table 4) were instrumented in March 2014 (The sensors installed at Roof 3 shown in Figure 12). The two moisture sensors at each location were first both installed in the plywood sheathing. One was then moved to the top layer of the CLT panel below about one month later. The moisture sensors installed on CLT and plywood sheathing[6] were calibrated for lodgepole pine since the wood products were made with “Spruce-Pine-Fir”, which was predominantly lodgepole pine. The sensors installed on glulam were calibrated for Douglas fir. In addition to moisture sensors and RH/T sensors for measuring the ambient environment,

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[6] The adhesive in plywood may have effect on MC readings; it typically increases the MC readings, particularly at high MC conditions (Wang and Thomas 2018). This effect was ignored in this study.

several moisture tapes were installed on the CLT panel at each location and around drains at Locations 2, 3, and 5 to detect water leakage. The other location (Roof 4) was not accessible for installing sensors in March due to construction activities in that area. Sensors at this location were instead installed in early July 2014. When sensors were installed, there was no timeline to finish the top floor (space for future tenants) and the roof was entirely accessible for instrumentation. However, a couple of years later the top floor became occupied with the roof finished and closed. The data loggers installed in the roof then became inaccessible for changing batteries.

Table 4 Locations of sensors in the roof for measuring moisture performance and environmental conditions

Location No.	Sensor	Sensor Label	Sensor Location
Roof 1 (at southeast corner, conventional roof, maximum insulation thickness)	RH(T)	R1 T sensor 1, R1 RH sensor 1	Vented cavity
	A3 (with RH/T)	R1 T sensor 2, R1 RH sensor 2	Ceiling chase
	Moisture pin 1	R1 PIN1 Roof T, R1 PIN1 Roof MC	In plywood sheathing
	Moisture pin 2	R1 PIN2 Beam T, R1 PIN2 Beam MC	In plywood sheathing in the first month, and in the top layer of CLT afterwards
	Moisture tape	R1 Tape	On CLT
Roof 2 (close to the core, in southeast direction, close to a roof drain, conventional roof, minimum insulation thickness)	RH(T)	R2 T sensor 1, R2 RH sensor 1	Vented cavity
	A3 (with RH/T)	R2 T sensor 2, R2 RH sensor 2	Ceiling chase
	Moisture pin 1	R2 PIN1 Roof T, R2 PIN1 Roof MC	In plywood sheathing
	Moisture pin 2	R2 PIN2 Beam T, R2 PIN2 Beam MC	In plywood sheathing in the first month, and in the top layer of CLT afterwards
	Moisture tape	R2 Tape1	Surrounding a pipe
	Moisture tape	R2 Tape2	On CLT
Roof 3 (close to the core, in southwest direction, close to a drain, with a concrete layer above sheathing, minimum insulation thickness)	RH(T)	R3 T sensor 1, R3 RH sensor 2	Vented cavity
	A3 (with RH/T)	R3 T sensor 2, R3 RH sensor 2	Ceiling chase
	Moisture pin 1	R3 PIN1 Roof T, R3 PIN1 Roof MC	In plywood sheathing
	Moisture pin 2	R3 PIN2 Beam T, R3 PIN2 Beam MC	In plywood sheathing in the first month, and in the top layer of CLT afterwards

Location No.	Sensor	Sensor Label	Sensor Location
	Moisture tape	R3 Tape1	Surrounding a pipe
	Moisture tape	R3 Tape2	On CLT
Roof 4 (close to the exterior wall, in west direction, with a concrete layer above sheathing, maximum insulation thickness) The sensors were installed in early July 2014.	A3 (with RH/T)	R4 T sensor 2, R4 RH sensor 2	Ceiling chase
	Moisture pin 2	R4 PIN2 Roof T, R4 Plywood sheathing	Into plywood sheathing
	Moisture pin 1	R4 CLT 1	Into CLT beam
	Moisture pin 3	R4 CLT 2	Into CLT beam close to exterior wall
	Moisture pin 4	R4 Glulam beam	Into glulam beam
	Moisture tape	R4 Tape 1	Below CLT and above glulam
	Moisture tape	R4 Tape 2	Below CLT and above glulam
Roof 5 (close to the core, in northwest direction, close to a drain, conventional roof, minimum insulation thickness)	RH(T)	R5 T sensor 1, R5 RH sensor 1	Vented cavity
	A3 (with RH/T)	R5 T sensor 2, R5 RH sensor 2	Ceiling chase
	Moisture pin 1	R5 PIN1 T, R5 PIN1 MC	In plywood sheathing
	Moisture pin 2	R5 PIN2 T, R5 PIN2 MC	In plywood sheathing in the first month, and in the top layer of CLT afterwards
	Moisture tape	R5 Tape1	Above CLT panel
	Moisture tape	R5 Tape2	Above CLT panel
Roof 6 (at northwest corner, conventional roof, maximum insulation thickness)	RH(T)	R6 T sensor 1, R6 RH sensor 1	Vented cavity
	A3 (with RH/T)	R6 T sensor 2, R6 RH sensor 2	Ceiling chase
	Moisture pin 1	R6 PIN1 T, R6 PIN1 MC	In plywood sheathing
	Moisture pin 2	R6 PIN2 T, R6 PIN2 MC	In plywood sheathing in the first month, and in the top layer of CLT afterwards
	Moisture tape	R6 Tape	Above CLT panel

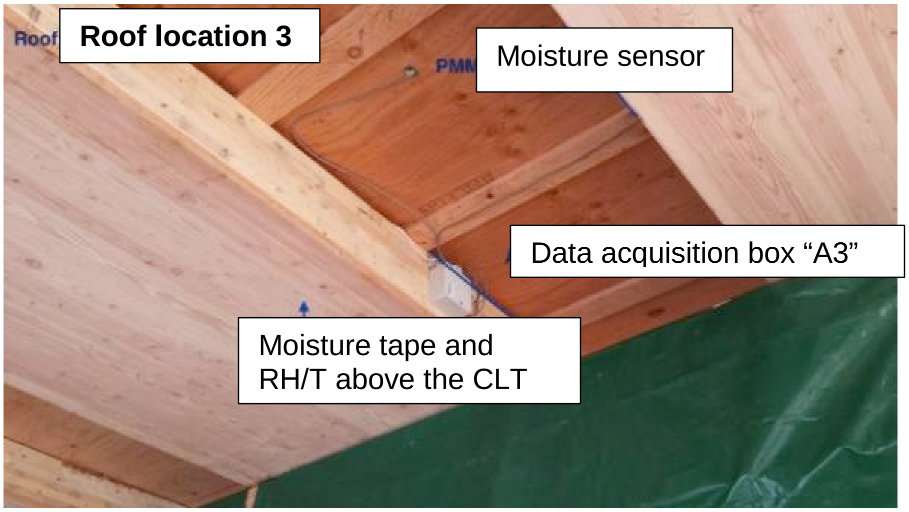

Figure 12 Instruments installed in the roof at Location 3 (R3) to measure wood moisture content and environmental conditions

6 RESULTS AND DISCUSSION

6.1 Vertical Movement

6.1.1 Columns, Beams, and CLT Floors

The charts below were created based on data collected from the monitoring systems installed in the building. There were varying degrees of data loss in each chart, caused by loss of power to the data loggers due to difficulty in accessing closed assemblies for changing batteries. A displacement sensor measures all movement in the target direction at the moment data is recorded. Its readings, therefore, include not only the true movement of a member or members covered, but also various measurement noises. The true movement of a wood member for the intended measurement results from MC changes and loading, such as shrinkage or swelling due to MC changes and load-induced deformation (Wang and Ni 2012). For the structural members monitored in this study, instant (or elastic) deformation resulting from loading as well as the majority of settlement, i.e., closing of gaps between members, should have occurred not long after their installation, i.e., before the instrumentation was installed. Extraneous signals, for example, could be caused by localized vibration resulting from construction and occupant activities. Localized vibration should be mostly on a temporary basis and was unlikely to be all recorded given the fact that the monitoring system collected data hourly. It is reasonable to assume that the measurements over the duration of this study show wood shrinkage resulting from drying and time-dependent deformation, i.e., creep, of the structural members. Both shrinkage and creep in normal building service are slow movements and do not cause sudden changes or large fluctuations in vertical movement measurements. As observed in the previous monitoring studies (Wang and Ni 2014; Wang 2016a), it was noticed that the readings from a number of displacement sensors started drifting with highly fluctuated readings after the sensors were in service for over one year or longer. Such fluctuations were considered to be electrical noise probably resulting from loosening of the wire in the displacement sensor. These high frequency components are not taken into consideration in the discussions that follow.

The results from the displacement sensor installed at Location 1, labelled “L1 F1 Glulam column”, show that the glulam column was extremely stable under compression and seasonal environmental conditions, with the maximum shortening amount of about 2 mm after three years and a half in service (Figure 13; Figure 14). The sensor labelled “L1 F1 Column+Beam”, covering the entire glulam column and the PSL beam above (with a metal connector between them), showed a shortening amount of about 14 mm. The sensor (“L1 F1 Transfer beam”) measuring the PSL beam but excluding the two loading surfaces (i.e., excluding the contact areas with the CLT floor above and the glulam column below) showed a movement amount of about 11 mm. These measurements indicate that the PSL beam was a major contributor to the vertical movement at this location, with an estimated movement amount of 12 mm from itself alone. Apparently movement including wood shrinkage and deformation resulting from compression occurred along the entire depth of the beam. From the two sensors installed over the PSL beam and showing the largest movement amounts observed in this study (i.e., “L1 F1 Column+Beam” and “L1 F1 Transfer beam”), the movement increased over time; the increases were the fastest in the first year (including the first heating season). It appears that the movement amounts levelled off after about two years after the second heating season in service.

At Location 4, the behaviour of the glulam column measured by the sensor “L4 F1 Column” was consistent with the glulam at Location 1, with the maximum shortening amount of about 3 mm based on over two years’ monitoring (Figure 15; Figure 16). This glulam extends two floors, including the ground and the mezzanine level above. It is over 6 m tall and about 1 m taller than the glulam at Location 1. Wood is known to have the highest stiffness, strength, and dimensional stability in the longitudinal grain orientation (FPL 2010). The measurements of these two columns demonstrate that glulam columns are highly stable under loading in the longitudinal direction. Neither MC changes nor sustained loading led to considerable movement. The good dimensional stability of wood in the longitudinal direction was certainly utilized in this building with glulam columns connected end-to-end using metal connectors along the height of the building. This detail eliminated the insertion of horizontal wood members in the gravity load path, a practice common in wood-frame construction.

Because of the good correlation to the seasonal heating and cooling cycles of the building, the changes in movement was attributed to changes in the indoor environment and consequently the MC of wood. When the field monitoring started in March 2014, the average MC of the timbers being installed was estimated to be 13%[7] based on on-site measurements using a portable capacitance moisture meter. After the building was occupied, the temperature inside

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[7] The CLT panels have a MC of 12±2% at time of production based on information from the manufacturer (http://structurlam.com/products/cross-laminated-timber/).

the building was controlled around 20℃, with the indoor RH mostly remaining seasonal depending on exterior environmental conditions as well as the amount of heating and ventilation (i.e. air exchanges) provided (Figure 14; Figure 16). Indoor environment tends to be dry under heated conditions in such a cold and dry climate (typical of Prince George)[8], unless the humidity is specifically controlled (e.g. by using humidifiers). The humidity in this building was found to fluctuate between 20% and 30% and sometimes even lower in the wintertime heating seasons. Wood would achieve an average MC of approximately 5%, which is very dry (FPL 2010). The amount of wood shrinkage was therefore the largest in the winter. By comparison, the humidity in the building was higher, being around 40%, corresponding to a wood MC of about 8% in the summer.

Assuming a change in MC of 8% from construction to service (the same for CLT below) and a shrinkage coefficient of 0.005% per 1% change in MC for the longitudinal direction (FPL 2010), the calculated shrinkage amounts for these two glulam columns were close to the measured movement (Table 5). The total shortening would be expected to be approximately 12 mm based on the measurement, accounting for a total height of 24.5 m for the connected glulam columns from Floor 1 to Floor 6. This did not take into consideration any potential settlement or deformation at connections between glulam columns, or effects of reduced loads on top floors. Such a vertical movement amount is obviously much lower than those observed in light wood-frame buildings (Wang *et al.* 2013; Wang and Ni 2014; Wang 2016a; Wang 2017a), but comparable with the measured movement from other mass timber buildings (Munoz *et al.* 2012; Mustapha *et al.* 2017).

Mechanical and other properties of wood are sensitive to its MC. Maintaining a low MC reduces not only instant deformation and time-dependent deformation (i.e., creep) (Bodig 1966; Wolcott *et al.* 1989), but also avoid durability concerns. However, extremely low MC or large moisture gradients resulting from fluctuating environment humidity conditions can lead to other issues, such as checking (Jonsson and Thelandersson 2003; Winter *et al.* 2014). MC changes that cause large dimensional changes, particularly in large cross-section members that are restrained, for example, by heavy metal connector plates may compromise the structural performance of the connection. A safety factor for accounting for potential checking development is required by the Eurocode (CEN 2004). Measures may be taken during building operation to allow the wood to adjust to the service conditions slowly (e.g., through humidity control), particularly in the first year of service to reduce check development. Alternatively, connections can be detailed to accommodate this movement.

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[8] It is Climate Zone 6 based on the National Energy Code of Canada for Buildings (NRC 2011) and climate Dfb according to the Köppen-Geiger climate classification.

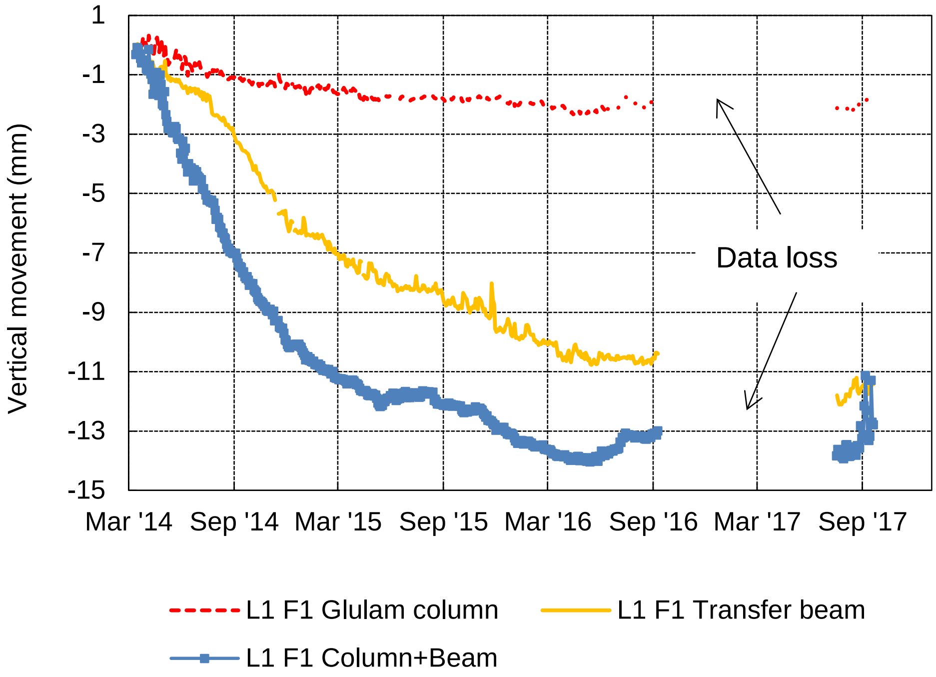

Figure 13 Vertical movement of a glulam column, a PSL transfer beam, and the combined column and beam at Location 1

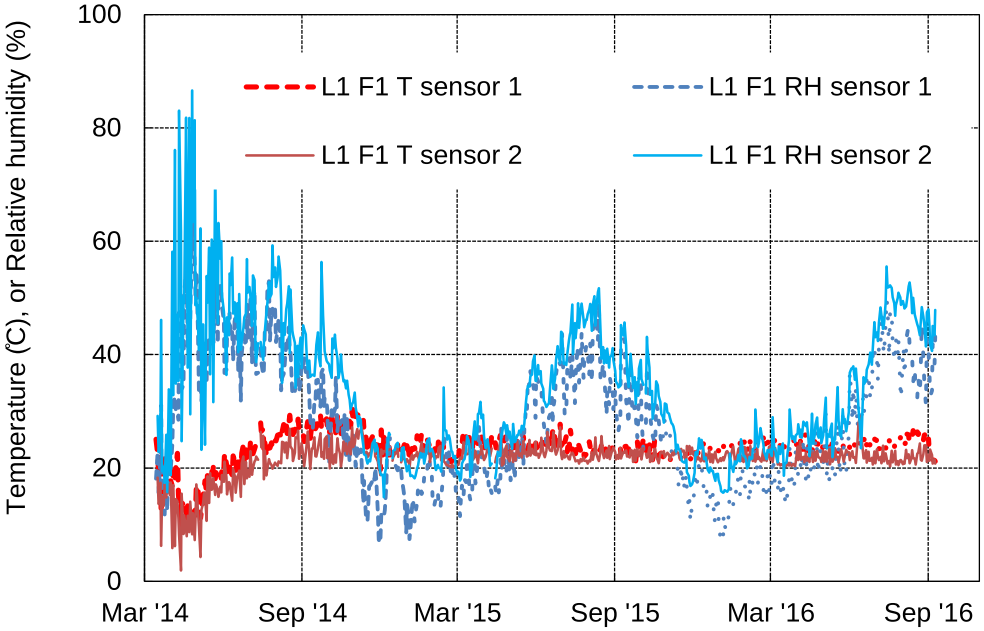

Figure 14 Relative humidity (RH) and temperature (T) on the 1^{st} floor (F1) at Location 1 (L1)

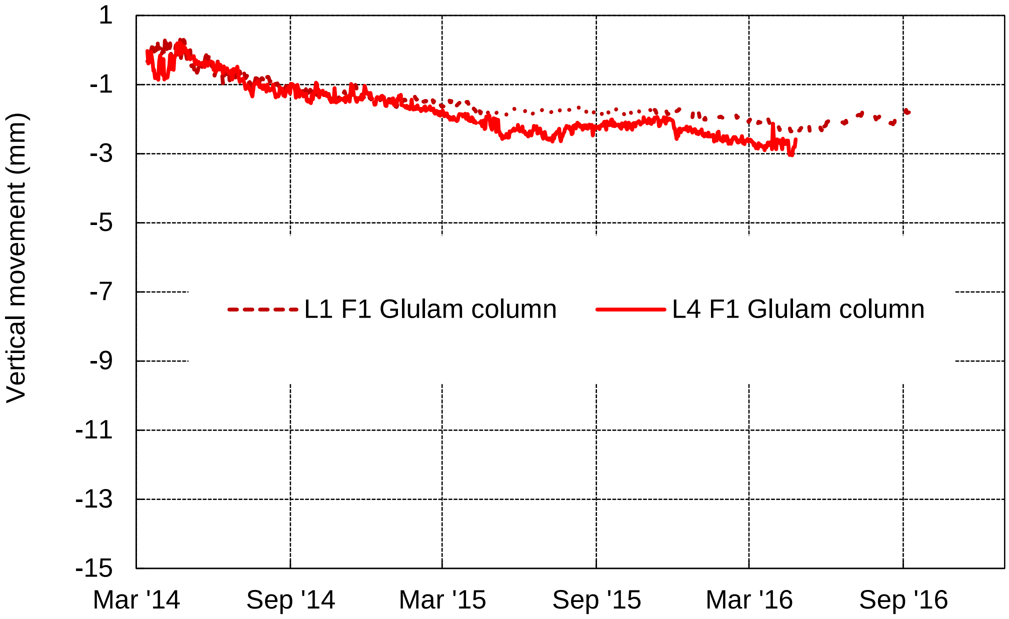

Figure 15 **Vertical movement of two glulam columns at Locations 1 and 4 (L1, L4) on the 1st floor (F1)**

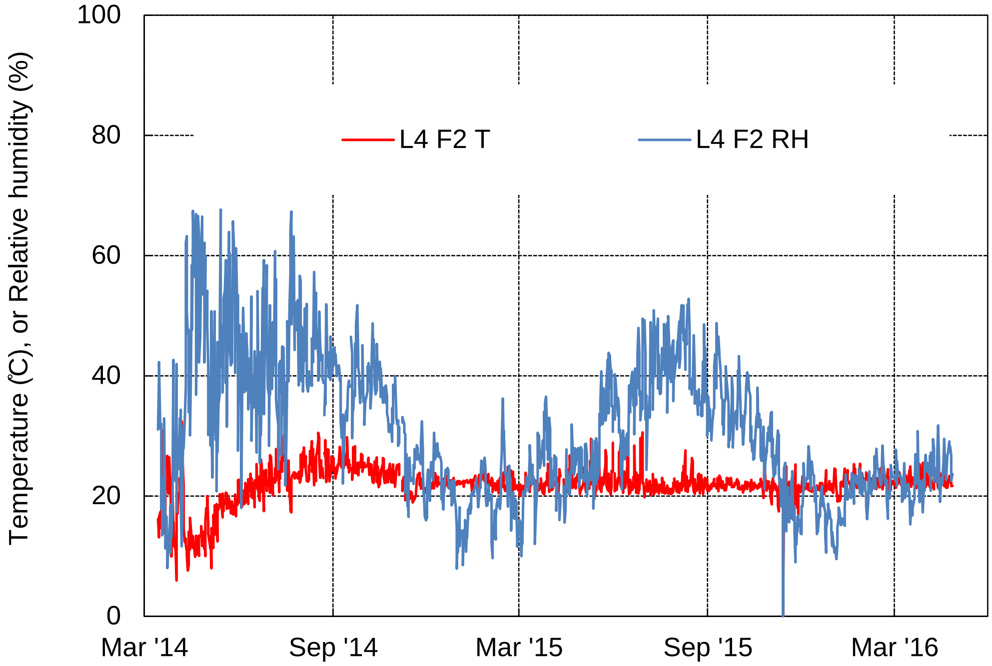

Figure 16 **Relative humidity (RH) and temperature (T) on the 2nd floor (F2) at Location 4 (L4)**

When a measurement included both the movement of a glulam column and the CLT floor slab above, larger movements were recorded (Figure 17). There were also more obvious seasonal changes, i.e., with the shortening amount being the largest at the end of a heating season and the smallest at the end of summer, compared to the glulam columns. The floors of this building were built with two layers of vertically staggered CLT panels, which were structurally supported by glulam beams at each end (Figure 3). The glulam beams were supported by glulam columns using dovetail connections. It is believed that the glulam beam has a minor contribution to the measured vertical movement since it is supported in a manner where changes in its overall member depth results in only small movements in the position of the CLT slab that it supports. Being 5-ply (169 mm thick), the lower CLT panel was included in the corresponding measurement with a displacement sensor box sitting on the panel (i.e., in the space created by the staggered CLT floor panels, right next to the supporting glulam column). The CLT panels are not major members for bearing gravity loads in this building and deformation resulting from compression is expected to be negligible. Similarly, the panels may deflect under loads, particularly over a large span, but that would not contribute much to the vertical movement measured. Shrinkage of the CLT panel (out-of-plane) resulting from drying must therefore be a major cause for the measured movement at each location. It was mentioned above that the sensor labelled “L4 F1 Column” showed a shortening amount of 3 mm. For comparison, the displacement sensor labelled “L4 F1 Column+CLT 1-2” showed a total shortening of 8 mm (Figure 17). These two sensors were installed from the bottom of the same glulam column, but the former ended at the upper end of the column (i.e., measuring only the glulam column) and the latter extended above the CLT floor (i.e., covering the glulam column, the CLT floor panel, and the connection). This indicates that the difference of 5 mm between these two measurements was caused by shrinkage of the CLT floor panel and settlement at the connection. The shrinkage for out-of-plane CLT can be estimated when the MC change and the shrinkage coefficient are known. Assuming that the CLT has a composite shrinkage coefficient of 0.2% per 1% change in MC in its thickness, i.e., the transverse grain orientation of wood (CWC 2005; CSA 2014) and a MC change of 8% from construction to service, these 5-ply CLT panels should have a shrinkage amount of 2.7 mm (Table 5). It was lower than the amount of 5 mm indicated by the measurement. This was the case for each measurement involving a CLT floor (Table 5). Apparently the real shrinkage of the CLT floor panel could have been larger than this estimation; there could also be contributions from other factors, such as loads and settlement. Not relevant to the movement monitoring in this study, the upper 3-ply CLT panels (99 mm thick) of the floors was estimated to incur shrinkage of about 1.6 mm based on the same assumptions. Therefore the total shrinkage amount of the CLT floors would exceed 4 mm since these two panels were stacked. This magnitude of movement could be significant if the floor is, for example, supporting equipment that has rigid service connections attached to the walls or columns, or directly connected to other building components, e.g., curtain wall (Figure 18). The out-of-plane shrinkage as well as deflection of CLT floors may need to be taken into consideration in the design and installation of such building components or equipment in order to accommodate the differential movement.

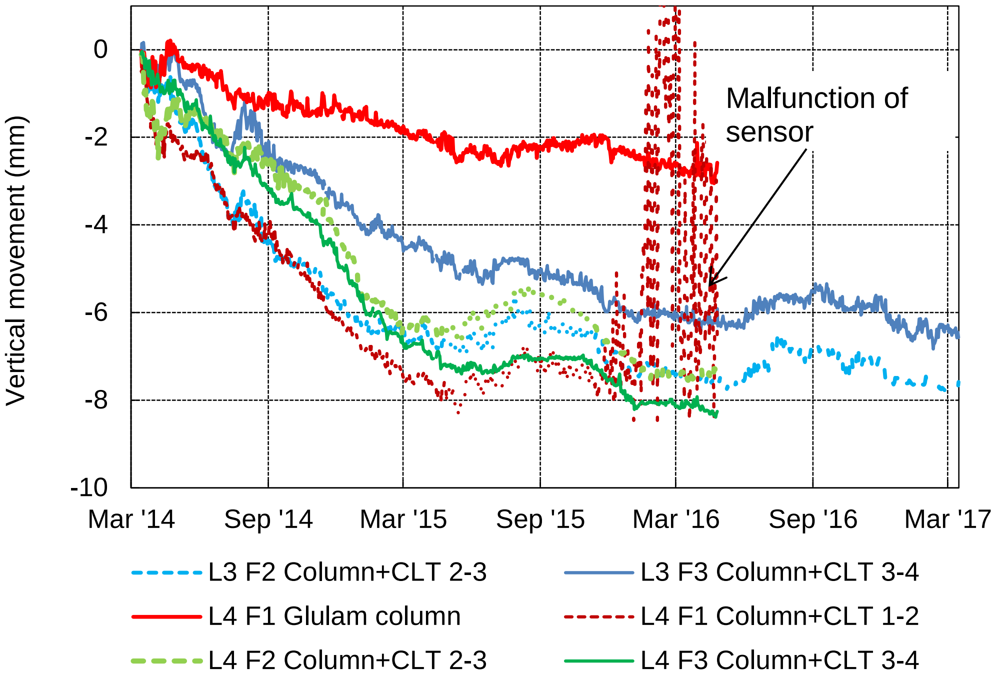

Figure 17 Vertical movement of glulam column and combined column and CLT floor at Locations 3 and 4 (L3, L4) on floor 1, 2 and 3 (F1, F2, F3)

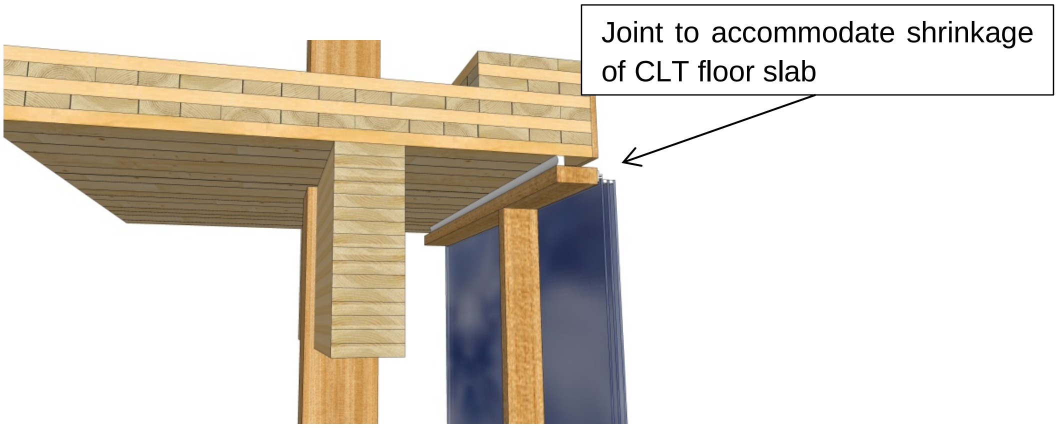

Figure 18 Joint provided between floor and wall to accommodate shrinkage of CLT floor slab (Courtesy of RDH Building Science Inc.)

6.1.2 CLT Walls

The CLT shear wall has a total height of 24.5 m including two horizontal step joints based on the drawings. The vertical movement was only partially monitored from the 2nd floor to the 6th floor, as described in Section 5.3. Similar to the measurements of the two glulam columns at Locations 1 and 4, the shortening amounts measured from the CLT wall were also found to be small, ranging from 1.5 mm to 3 mm on each floor (Figure 19, with the service environmental conditions shown in Figure 20 and Figure 21). The measurements confirmed that CLT was highly dimensionally stable in its plane direction. Assuming that wood shrinkage and load-induced deformation were uniform along the height and the movement amounts were proportional to the heights of the wall, the measurements showed that the maximum shortening of the CLT wall, from Floors 1 to 6, would be about 19 mm. This is larger than the vertical movement of a glulam line under the same indoor environment but the differential movement is considered to be small for such a building. It is understandable that a CLT wall would have a slightly larger vertical movement than a glulam column under similar service environments since CLT involves both longitudinal and transverse grain orientations with glued cross-laminated boards along its height. The shrinkage prediction would slightly underestimate the vertical movement of the CLT wall when the same shrinkage coefficient for the longitudinal direction is used (Table 5).

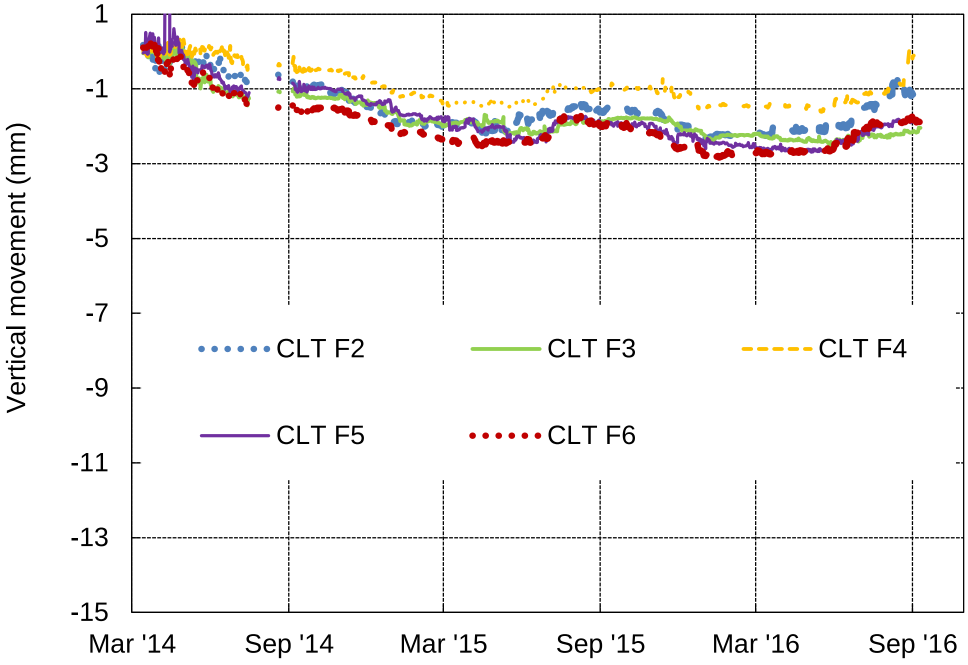

Figure 19 Vertical movement of CLT wall from Floors 2 to 6 (F2-F6) at Locations 5

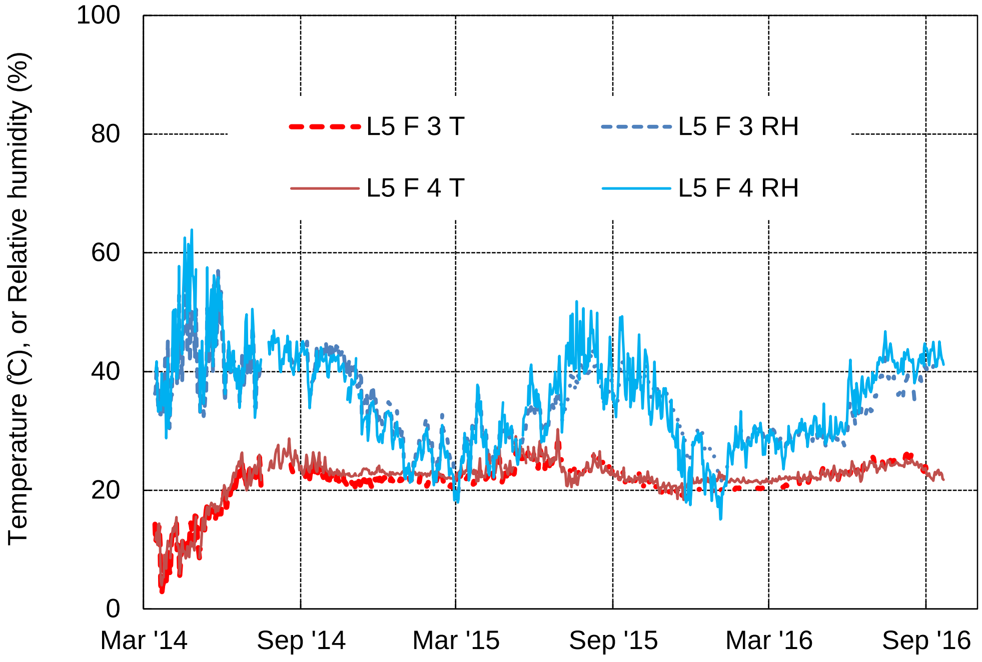

Figure 20 Relative humidity (RH) and temperature (T) on the 3rd and 4th floor (F3, F4) at Location 5 (L5)

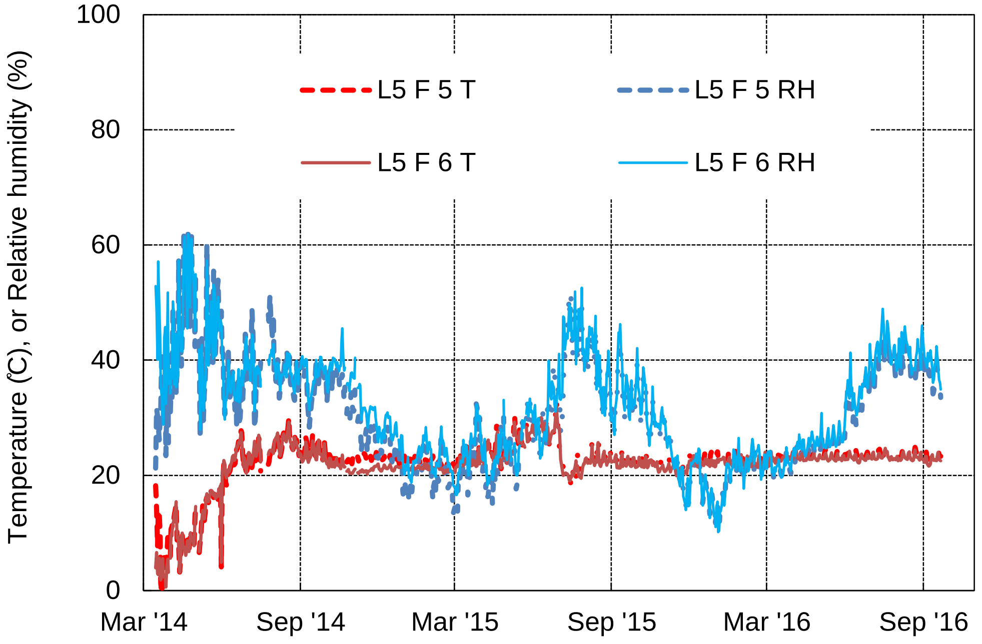

Figure 21 Relative humidity (RH) and temperature (T) on the 5th and 6th floor at Location 5 (L5)

Table 5 Measured Vertical Movement and Potential Contributions

Location	Displacement Sensor Label	Movement Reading on Mar 15, 2016 (mm)	Vertical Distance Measured (mm)	Estimated Longitudinal Shrinkage of Glulam Column or CLT Wall (mm)*	Estimated out-of-plane Shrinkage of CLT Wall (mm)**	Estimated Total Shrinkage (mm)	Estimated Movement Caused by Loading and Other Factors (mm)
Location 1	L1 F1 Glulam column	2.1	5005	2.0	-	2.0	0.1
	L1 F1 Column+Beam	13.8	6330	2.5	***	-	-
	L1 F1 Transfer beam	10	1120	-	***	-	-
Location 3	L3 F2 Column+CLT 2-3	7.4	3290	1.3	2.7	4.0	3.4
	L3 F3 Column+CLT 3-4	5.9	3190	1.3	2.7	4.0	1.9
Location 4	L4 F1 Column	2.8	6160	2.5	0.0	2.5	0.3
	L4 F1 Column+CLT 1-2	8	6480	2.6	2.7	5.3	2.7
	L4 F2 Column+CLT 2-3	7.4	3290	1.3	2.7	4.0	3.4
	L4 F3 Column+CLT 3-4	8	3190	1.3	2.7	4.0	4.0
Location 5	L5 CLT F2	2.2	2870	1.1	-	1.1	1.1
	L5 CLT F3	2.3	2860	1.1	-	1.1	1.2
	L5 CLT F4	1.5	3010	1.2	-	1.2	0.3
	L5 CLT F5	2.6	2890	1.2	-	1.2	1.4
	L5 CLT F6	2.7	3000	1.2	-	1.2	1.5
	Entire CLT wall	11.3	14630	5.9	-	5.9	5.4

* An assumed composite shrinkage coefficient of 0.005% per 1% change in MC for longitudinal glulam and CLT and 8% in MC reduction for estimating shrinkage

** An assumed composite shrinkage coefficient of 0.2% per 1% change in MC for out-of-plane CLT;

***A lack of information for estimating shrinkage or load-induced deformation for PSL beam. Some testing is currently underway at FPInnovations.

6.2 Moisture Performance of the Roof

The wood roof structure of this building in general remained dry during the entire monitoring period of time. Figure 22shows the RH and temperature measured from Location R1 to represent the overall service environmental conditions in the roof area. Consistent with the ambient conditions measured from lower floors, the RH was overall below 50% in the summer and reduced to 20% in the winter at most locations of the roof. As a result of the dry indoor environment, both the plywood roof sheathing (Figure 23) and the CLT panels below (Figure 24) showed MC readings close to 11% after the initial construction stage at five of the six monitoring locations (i.e., except R4). It should be noted that the resistance-based measurement systems has a lower MC limit of 11% when the calibration is based on lodgepole pine[9]. Therefore a reading of around 11% may indicate lower real MC.

At the R4 location, the instruments were not installed until July 2014. Once the monitoring system was activated, the MC of the plywood sheathing was found to be about 25% (Figure 25), i.e., the highest MC detected in this study since the monitoring study started[10]. The high initial MC must be attributed to the wet concrete poured on the plywood sheathing. The monitoring afterwards showed the plywood sheathing slowly drying with the MC decreasing to 20% by September 2014, and to 15% by March 2015. In addition to this suspected construction moisture issue at R4, it was found that the humidity level at a spot in the ventilation cavity, i.e., between the roof sheathing and the CLT beam at Location R3, reached almost 100% during the construction stage in March 2014 (Figure 26, RH/T sensor 1). Again the monitoring showed the humidity readings gradually decreasing and reaching the same level as other monitored locations by the summer of 2015. Like location R4, a concrete layer was also installed above the plywood sheathing at location R3.

The sheathing of a flat roof is typically subjected to the highest moisture risk when water leaks during construction or in service. Thicker roof panels, such as double-layer plywood or OSB, and mass timber products, such as CLT and nail-laminated timber, have reduced drying rates compared to the traditional single layer roof sheathing upon wetting (Wang 2014; Wang 2016b). The roof of this building showed satisfactory drying performance. The interior ventilation function, which was achieved by installing strapping between the sheathing and the mass timber beams below, likely assisted drying by being exposing the wetted surfaces to conditioned indoor air. If water leaks were to occur, such a design would also facilitate detection in service. Overall, good drying capacity and leak detection are both important for the long-term durability of a mass timber roof.

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[9] The lower limit was about 9% when the calibration was based on Douglas fir. The electrical resistance becomes too high to be accurately measured when the wood is too dry.

[10] This finding was immediately sent to the contractor as an alert; however, there should be no further moisture imposed on the sheathing after the roofing membranes were installed.

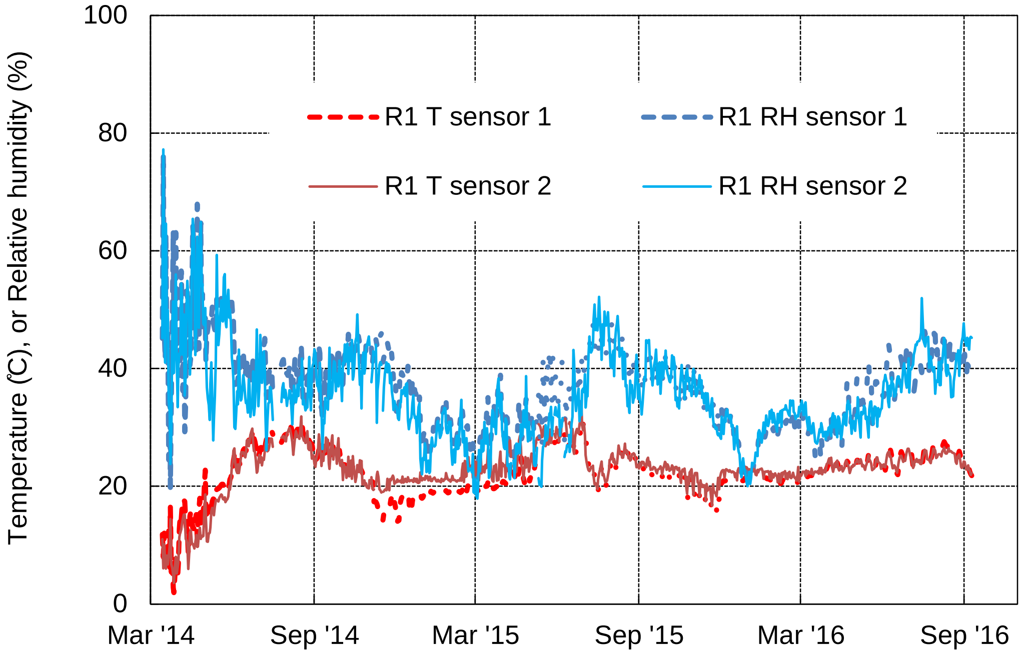

Figure 22 Relative humidity (RH) and temperature (T) at Roof 1 location (R1) measured with two RH/T sensors

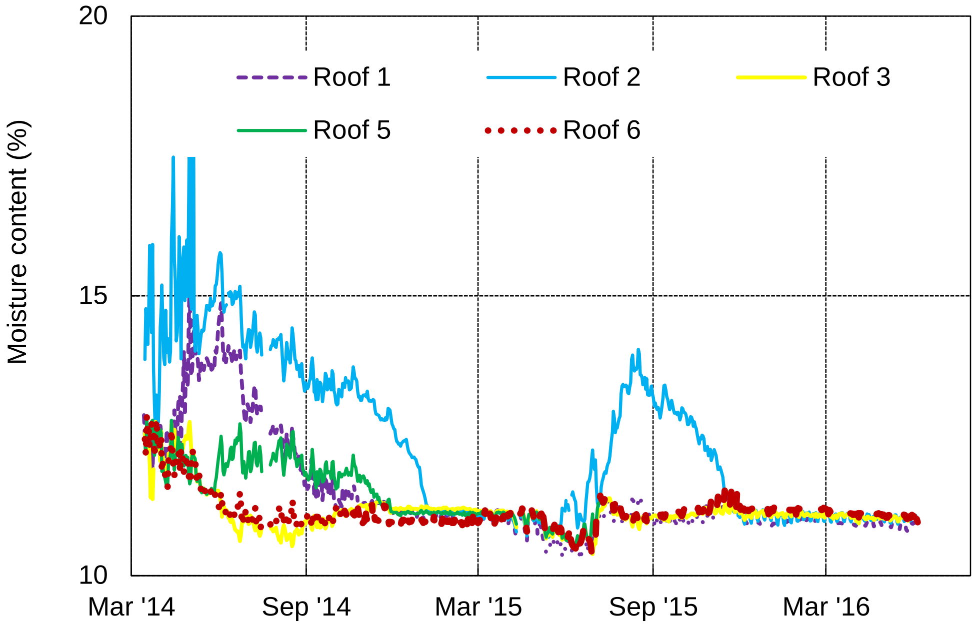

Figure 23 Moisture content measured from plywood sheathing at five roof locations

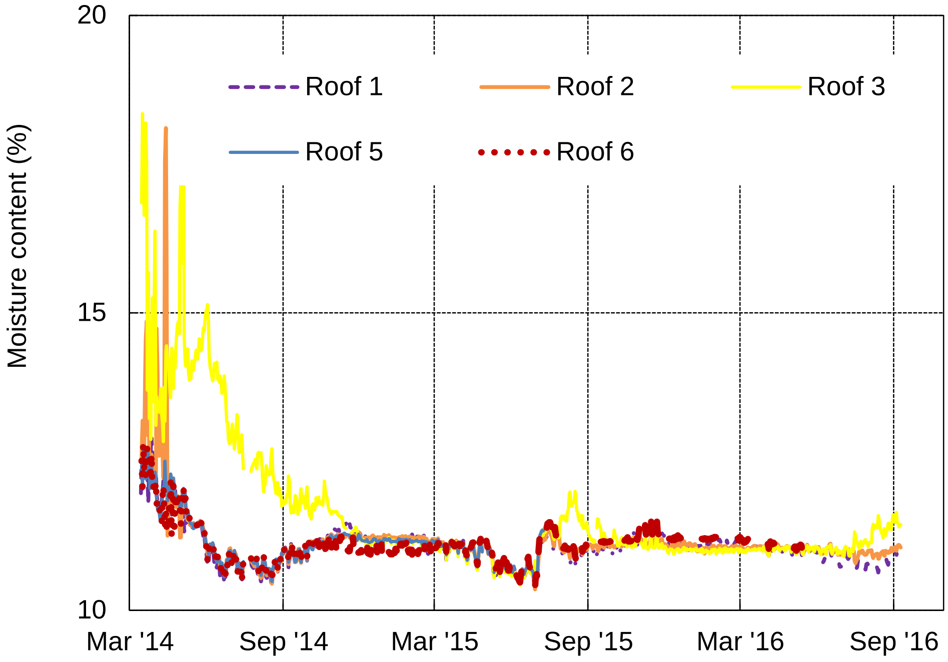

Figure 24 Moisture content measured from CLT beams at five roof locations

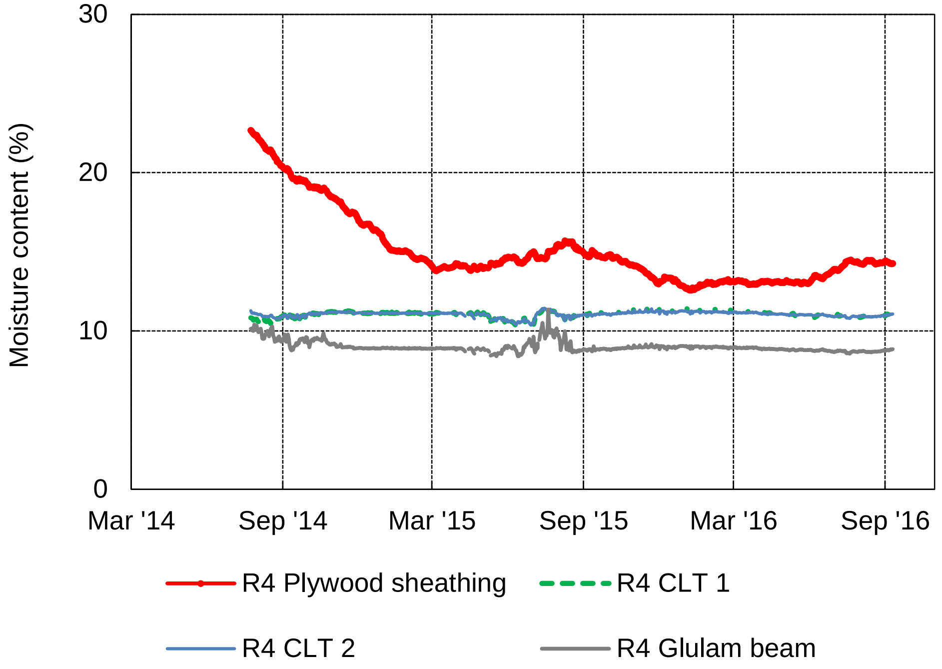

Figure 25 MC measured from plywood sheathing, two adjacent CLT beams, and one glulam beam at Roof 4 location (R4)

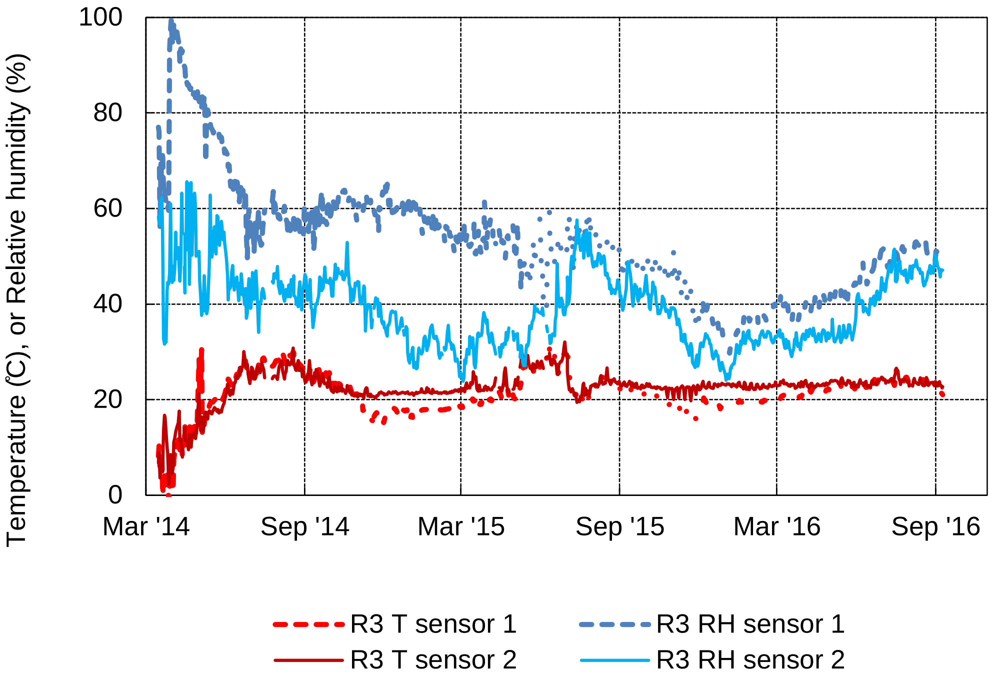

Figure 26 Relative humidity (RH) and temperature (T) measured from Roof 3 location (R3) with two RH/T sensors

7 CONCLUSIONS

The following conclusions can be drawn from the *in-situ* monitoring of the WIDC building over the past three and a half years, starting at the construction stage.

- With an initial MC of 13% during construction, the measurement of in-service environments indicated that the wood inside the building reached an average MC of about 5% during the winter heating seasons and an average MC of about 8% in the summer. The wood was too dry to be measured directly using resistance-based moisture sensors.
- With a height of over 5 m and 6 m, the two glulam columns measured at one storey showed vertical movement of about 2 mm and 3 mm, respectively. The cumulative shortening of six glulam columns along the entire height of the building would be about 12 mm (0.05%), not taking into account deformation at connections or effects of reduced loads on the top two floors.
- The CLT wall was found to not have much vertical movement along the height of the building. The measurements showed that the entire CLT wall, from Floor 1 to Floor 6 with a height of 24.5 m, would shorten about 19 mm (0.08%).
- CLT had considerable shrinkage in the out-of-plane (thickness) direction. The measurements indicated that the bottom floor panel, 5-ply and 169 mm in thickness, had a total vertical movement amount of about 5 mm (3%).

- The PSL transfer beam monitored, with a total depth of over 1.2 m, showed a reduction of about 12 mm (1%) in the depth, i.e., along the building height.
- Two locations in the roof, both with wet concrete installed above the plywood sheathing, showed wetness during the construction but eventually dried to match the MC at other locations. The wood members at the other four locations remained dry during the entire duration of monitoring.

Overall the measurement results in this study are consistent with the predicted performance by the design team of this building.

8 RECOMMENDATIONS

The study shows that the glulam columns and the CLT walls do not have large vertical movement and do not have substantial differential movement among them under the range of moisture changes and loading conditions of this building. This was primarily achieved by paying attention to eliminating or minimizing horizontal wood members in a gravity load path. Avoiding compressing wood perpendicular to grain is important to reduce vertical movement in a mass timber building. This monitoring also shows that mass timber roofs can dry and perform satisfactorily when properly designed. The interior ventilation function built into the roof assemblies of this building by integrating strapping between the sheathing and the mass timber beams below allowed drying to occur towards the interior. This detail would also facilitate more efficient detection of water leaks in case it occurs in service.

9 REFERENCES

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