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Field Measurement of Vertical Movement and Roof Moisture Performance of the Wood Innovation and Design Centre: Instrumentation and 1st Year's Performance

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By:

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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 slowly after they are wetted 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 first describes instrumentation to measure the vertical movement of selected glulam columns and cross-laminated timber (CLT) walls in this building. Three locations of glulam columns and one CLT wall of the core structure were selected for measuring vertical movement along with the environmental conditions (temperature and humidity) in the immediate vicinity. The report then describes instrumentation to measure the moisture changes in the wood roof structure. Six locations in the roof were selected and instrumented for measuring moisture changes in the wood as well as the local environmental conditions.

All sensors and instrumentations, with the exception of one, were installed and became operational in the middle of March 2014, after the roof sheathing was installed. The other instrumentation was installed in July 2014. This report presents performance of the building during its first year as measured from topping out of the structure. In the end, the one-year period covers six months of construction and six months of occupancy. This is the first year of a planned five-year monitoring.

The first year's monitoring showed that the wood inside the building had reached moisture content (MC) of about 4-6% in the heating season, from an initial MC of 13% during construction. Glulam columns were extremely dimensionally stable given the changes in MC and loading conditions. With a height of over 5 m and 6 m, respectively, the two glulam columns measured in this study showed very small amounts of vertical movement, each below 2 mm. The cumulative shortening of the six glulam columns along the height of the building would be about 8 mm, 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 14 mm. The CLT floors, however, had considerable shrinkage in the thickness direction, and therefore should be taken into consideration in the design and construction of components, such as curtain walls, which are connected to the floors. In terms of the roof performance, two locations, both with a wet concrete layer poured above the plywood sheathing, showed wetness during construction but dried slowly afterwards. The good drying performance must be attributed to the interior ventilation function designed for the roof assemblies by integrating strapping between the sheathing and the mass timber beams below. Overall this monitoring study shows the differential movement occurring among the glulam columns and the CLT wall is small and the wood roof has good drying performance.

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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 recent decade there has been increased interest in using engineered wood products to build modern tall wood buildings. A number of buildings, with the height ranging from 7 to 10 storeys, have been built worldwide. In Canada, recent efforts to relax the height and area limits for wood construction has amplified the interest within the design and construction community to better understand the performance of taller and larger wood buildings. To help architects, engineers, code consultants, developers, building owners, and Authorities Having Jurisdiction to assess the solutions unique to tall wood 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 confirm actual performance, refine design assumptions, and make designs more cost effective in future buildings. 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 slowly after they are wetted during construction.

The Wood Innovation and Design Centre (WIDC) in Prince George, is currently the tallest modern wood building in Canada, with a total height of 29.5 metres. This building greatly showcases the applications and capacities of various wood products as well as good design and construction practices. This building includes a cross-laminated timber (CLT) core structure of an elevator shaft and staircases, glued-laminated timber (glulam) columns, CLT floors and roof structure, parallel strand lumber (PSL) transfer beams, and laminated veneer lumber (LVL) columns and structurally insulated panels in the exterior walls. An example of good design practices is the interior vented roof structure, installed with an air space between the CLT roof panels below and the plywood roof sheathing above by using plywood strapping. The CLT roof panels are staggered vertically to provide roof ceiling chases for accommodating building services and other assembly materials. This building provides a unique opportunity for non-destructive testing and monitoring to measure the ‘As Built’ performance of a mass timber building in British Columbia. Field measurements can also provide performance data to support regulatory and market acceptance of wood-based systems in tall and large buildings.

With major construction taking place in the winter/spring of 2013-14, the building was instrumented in the middle of March, 2014 to measure vertical movement of selected columns, beams, and walls and moisture performance of the roof, after the roof sheathing was installed. The construction was completed around September, 2014 and the building was gradually occupied after that. This progress report describes the instrumentation and the building performance during the first year. The monitoring study is expected to last for five years and future reports will be provided periodically. In addition to this monitoring study, tests for vibration and acoustic performance were also conducted and are reported in a separate document (Hu *et al.* 2015). FPInnovations is well placed to set up and see through this type of long-term monitoring because of our highly-trained permanent staff and our experience with the documentation requirements of long-term field testing and service trials.

3 INTRODUCTION

3.1 Vertical Movement of Wood Under Compression

Post and beam construction and mass timber construction are important construction types for wood buildings. Mid-rise post and beam buildings were commonly built in North America around 100 years ago with large solid sawn wood posts and beams, and many of those buildings are still being used today. There has been renewed interest in mid-rise mass timber construction using innovative engineered timber products in recent years. 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 nature of differential movement.

Vertical movement of wood members is primarily associated with dimensional changes due to moisture content (MC) changes below the fiber saturation point. In addition, instantaneous and time-dependent deformation (i.e., creep) when wood is compressed and building settlement that is simply the closing of the construction tolerance gaps all contribute to vertical movement. Compared with post and beam and mass timber construction, differential movement is typically a larger concern for tall platform frame construction due to the use of stacked horizontal members, such as wall plates. Moreover, while members are typically kiln-dried dimension lumber (marked “S-Dry”), their initial MC will generally be higher than the initial MC of engineered wood products at manufacture[1]. That is why the major wood design books in North America only provide methods for estimating shrinkage of wall plates and floor joists in a load path (CWC 2005; Breyer *et al.* 2006; APEGBC 2009). FPInnovations has been collecting vertical movement data from both wood-frame (Wang *et al.* 2013; Wang and Ni 2014) 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. Wood has a high modulus of elasticity (MOE) parallel to the grain; therefore deformation caused by compression parallel to grain, such as that of studs and columns, is very small. However, wood

[1] The wood used in engineered wood products need a lower initial moisture content to facilitate bonding with adhesives.

members loaded perpendicular to grain may undergo considerable amounts of instantaneous compression and 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 may be 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% while under a dead load that could be experienced by the bottom floor of a six-storey wood-frame construction, 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 increase in loads and typically have little consequence in construction; however, creep may make considerable contributions towards vertical movement. European design provisions (Eurocode 5 2004) recommend that creep of solid timbers, glue-laminated timbers and LVL should be estimated at 0.6 times the instantaneous deformation caused by dead loads for members used under typical indoor living conditions (i.e., without long periods of elevated humidity levels and with the average MC in most softwoods not exceeding 12%). 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 construction. Measuring long-term vertical movement from selected columns and CLT walls in this building aims to generate more information related to design of mass timber buildings.

3.2 Moisture Performance of Roof

Questions about the durability performance of wood roofs often arise when a roof is built with structural composite and timber products, such as CLT, LVL, PSL, and laminated strand lumber (LSL), in long 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) get wet, it will take months to dry out under the coastal climate conditions (Wang 2014). The drying capacity of building envelope assemblies in modern buildings is 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) (Wang 2011). Excessive wetting can lead to issues, such as staining, mould, and ultimately decay. Staining and mould growth affect appearance and decay can compromise the structural integrity.

It was suggested by the design team to monitor the long-term durability performance of the roof of this building since there was a concern about the drying performance of such a timber roof. Based on 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 gets wet before roof membranes are installed. The design team revised and improved the roof design after learning the importance of drying capability for roof assemblies (Wang 2014), not long before the roof was built. Plywood strapping was 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 (see the built roof in Figure 8). Knowing this improved design would greatly improve the drying capacity and reduce the moisture risk, we proceeded with the planned roof monitoring study. Six locations in the roof, covering different orientations and moisture risks, were selected for instrumentation to measure the long-term moisture performance.

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 Engineering (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 continuously for five years. Field measurements are always more complex and often present unique challenges compared with laboratory testing. One of the reasons is that once an instrument is installed and subsequently covered by building elements, it becomes very difficult or even impossible to access it 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. One of the key sensors, the draw wire displacement sensors for measuring vertical movement, were first tested and compared with other products in a mock-up structure 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). 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 in the building.
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 of roof	Moisture pins, a resistance type	Small screws (pins)	Each sensor compensated for temperature and wood species
Detecting liquid water in roof	Moisture tape, based on measurement of electrical resistance	Thin metal tape	Indicating presence of liquid water when the measured electrical resistance is under a threshold 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 measures RH and temperature of the environment

5.2 Instrumentation Planning

A plan of instrumentation for measuring vertical movement along columns and walls, 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 1 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. 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. Data was recorded and transmitted hourly using a computer and internet in the building.

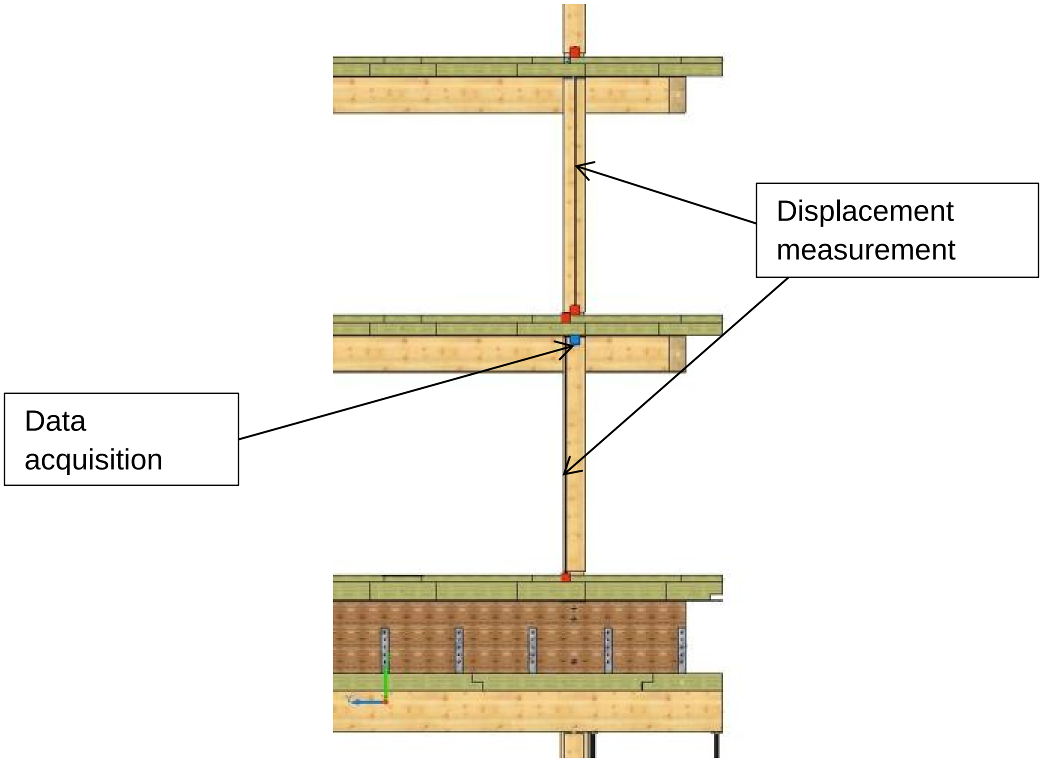

Figure 1 Locations of two displacement sensors (red, along the glulam column) and one data acquisition box (blue) for measuring vertical movement at Location 3

5.3 Vertical Movement

It was very challenging to identify appropriate locations along columns or interior load-bearing walls to make the measurements of vertical movement representative of the building design. A major issue was how to conceal each instrument using existing building elements. Adding other elements to conceal or mask an instrument was generally not recommended for aesthetical reasons. This building primarily uses glulam columns for bearing gravity loads and has an elevator shaft and staircases built with CLT as the core structure. Unlike wood-frame construction, wood elements in this building, 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, 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 WIDC were built to be rental spaces for future tenants and therefore exposing any instrument becomes more inadvisable. It was therefore decided to focus on the lower three floors for measuring vertical movement of glulam columns. Being supportive of this, research showed that measuring vertical movement at lower floors was generally more important due to the effect of loads on vertical movement (Wang *et al.* 2013; Wang and Ni 2014; Wang and King 2015). Three locations of glulam columns: at GL C and GL 6.5 on Floor 1, at GL 6.7 and GL B on Floors 2 and 3, and at GL B and GL 4 from Floors 1 to 3 based on the drawings of the building, were finally identified to be reasonably suitable for measurements. Instruments were therefore installed to measure the vertical movement along with service environmental conditions (Tables 2 and 3). These locations would allow comparing the vertical movement of glulam columns at two locations and assessing the effects of CLT floors as well.

Regarding CLT walls, the walls outside the staircases appeared to be able to accommodate instruments, since one side was to be covered with gypsum boards, with 38 mm by 90 mm (2 in. by 4 in.) framing between the finishing drywall and the inside CLT walls. The exception would be the 1st floor, where that side was to be exposed to the interior space. The CLT walls adjacent to the staircases or the elevator may experience a high level of vibration resulting from foot traffic, which would consequently cause a high level of noise for movement monitoring. Considering all these factors, a location at GL E between GL 4 and GL 5, facing GL F (not on the staircase side), from Floor 2 to Floor 6, was selected for measuring vertical movement (Tables 2 and 3). However, it was found during instrumentation that a LSL ledger installed on the CLT wall below the CLT floor would block the measurement on Floors 2, 3, and 5. It would be very complicated and time-consuming to drill holes through the ledgers to install displacement sensors and run conduits. Therefore on these three floors, instruments were installed to measure the vertical movement of the CLT wall from the floor 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 CLT 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.

To summarize, continuous measurement of vertical movement 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 and CLT walls, together with sensors installed for measuring service ambient conditions. Figures 2-7 show installed instruments.

Table 2 Locations of Displacement Sensors and Their Measurements

Location	Sensor Label	Vertical Distance Covered	Initial Gauge Length (m)
Location 1 (GL C and 6.5, Floor 1, beside glulam column)	L1 1C Column	Measuring glulam column, from bottom to top	5.01
	L1 1B Column+Beam	Measuring glulam column and PSL beam. There are 2 beams together at each location, with a small gap between; each beam is 122 cm deep (i.e., height) and178 mm wide.	6.33
	L1 2V Beam	Measuring PSL beam, not including the top and bottom surface areas.	1.12
Location 3 (GL 6.7 and B, Floors 2-4, beside glulam column)	L3 F2 Column+CLT 2-3	Measuring from bottom of column to upper CLT floor, including both column and CLT floor. The CLT panel has a thickness of 169 mm.	3.29
	L3 F3 Column+CLT 3-4	Measuring from bottom of column to upper CLT floor, including both column and CLT floor. The CLT panel has a thickness of 169 mm.	3.19
Location 4 (GL B and GL 4, Floors 1-4, beside glulam column)	L4 F1 Column	Floor 1, from bottom to top of a column	6.16
	L4 F1 Column+CLT 1-2	Floor 1, bottom of column to upper CLT floor, 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, bottom of column to upper CLT floor, including both column and CLT floor. The CLT panel has a thickness of 169 mm. The CLT panel has a thickness of 169 mm.	Not measured, but should be very close to the corresponding gauge length at Location 3, about 3.29 m.
	L4 F3 Column+CLT 3-4	Floor 3, bottom of column to upper CLT floor, including both column and CLT floor. The CLT panel has a thickness of 169 mm.	Not measured, but should be very close to the corresponding gauge length at Location 3, 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, bottom of CLT floor to bottom of ledger	2.87
	L5 CLT F3	Floor 3, bottom of CLT floor to bottom of ledger	2.86
	L5 CLT F4	Floor 4, bottom of CLT floor up to ceiling	3.01
	L5 CLT F5	Floor 5, bottom of CLT floor to bottom of ledger	2.89
	L5 CLT F6	Floor 6, bottom of CLT floor up to ceiling	3.00

Table 3 Sensors for Measuring Relative Humidity and Temperature together 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 Unit RH, L1 Unit T	Interior wall of the projector room, at eye height
	RH/T	L1 RH, L1 T(RH)	
Location 3 (GL 6.7 and B, Floors 2-4, beside Glulam column)	A3 (with RH/T)	L3 F2 Unit RH, L3 F2 Unit T	Floor 2, close to the CLT floor
	RH/T	L3 F3 RH, L3 F3 T(RH)	Floor 3, along the column, at eye height
Location 4 GL B and GL 4, Floors 1-4, beside Glulam column	RH/T	L4 F2 RH, L4 F2 T(RH)	Floor 2, along the column, at eye height
	A3 (with RH/T)	L4 F2 Unit RH, L4 F2 Unit T	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(RH)	Floor 2, at top of the CLT
	A3 (with RH/T)	L5 F3 Unit RH, L5 F3 Unit T	Floor 3, at top of the CLT
	A3 (with RH/T)	L5 F4 Unit RH, L5 F4 Unit T	Floor 4, at top of the CLT
	RH/T	L5 F5 RH, L5 F5 T(RH)	Floor 5, at top of the CLT
	RH/T	L5 F6 RH, L5 F6 T(RH)	Floor 6, at top of the CLT

Figure 2 A displacement sensor (its metal conduit in left photo, and a closer image of the sensor box which is just above the column base metal connector) at Location 1 for measuring vertical movement of the glulam column

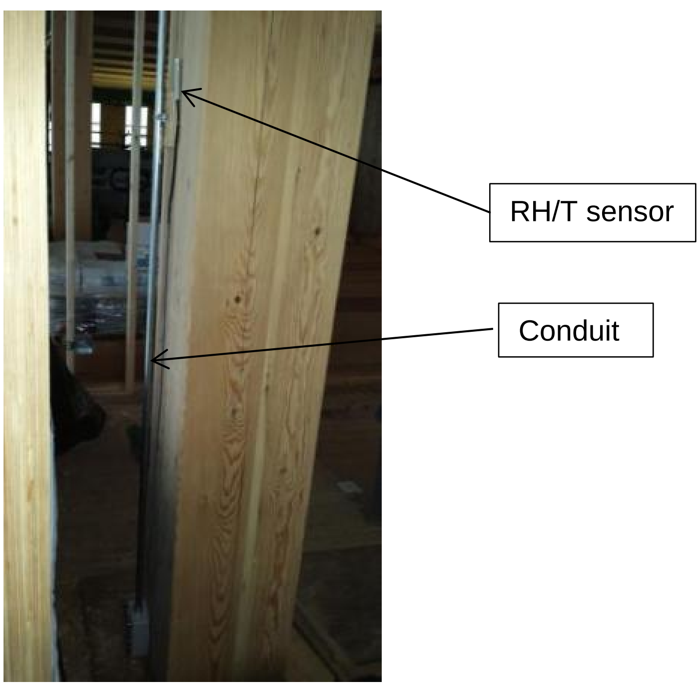

Figure 3 A displacement sensor at the bottom and an RH/T sensor in the middle of the height of the glulam column on Floor 3 at Location 4

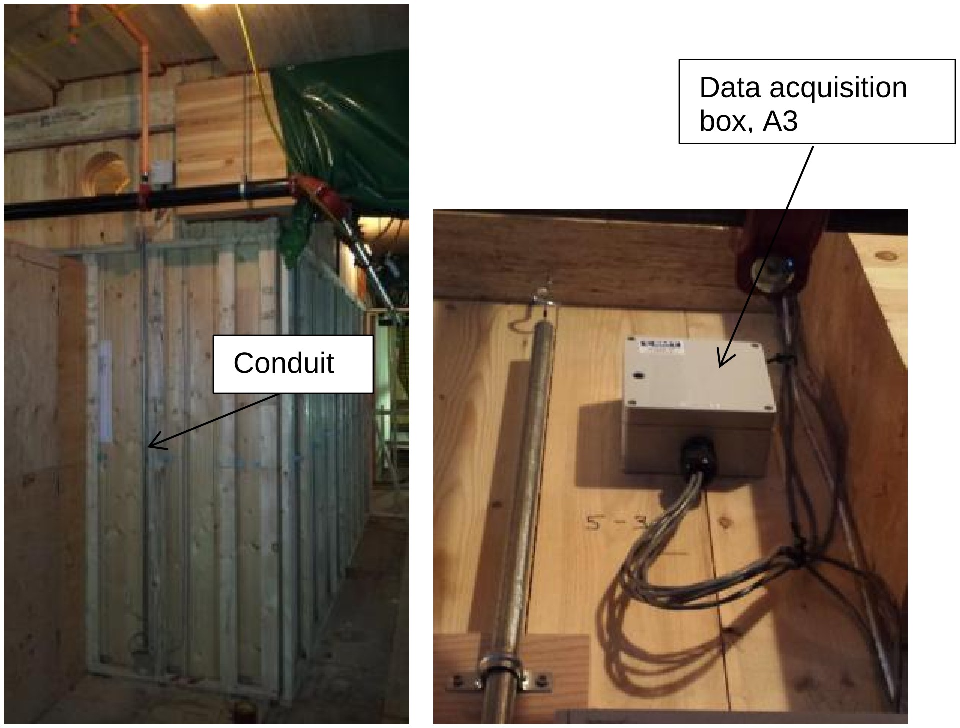

Figure 4 A displacement sensor (left photo) and a data acquisition box A3 (right photo) on Floor 2 and 3 at Location 5

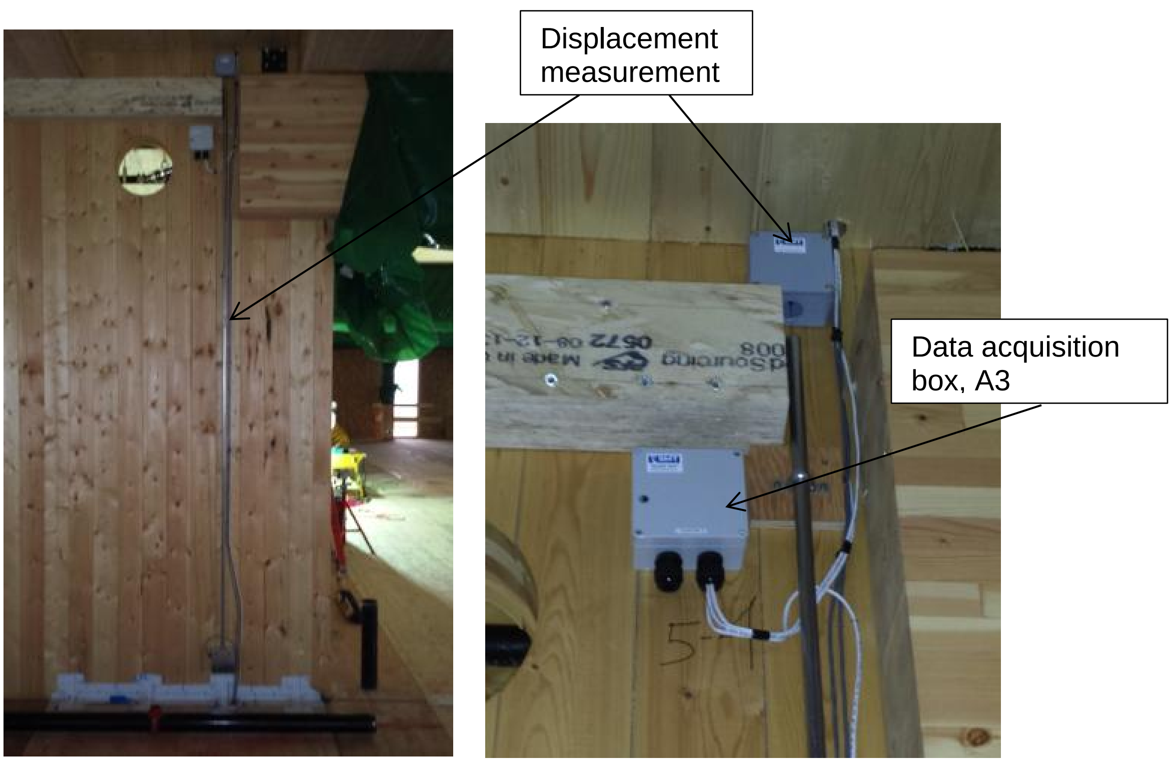

Figure 5 A displacement sensor and a data acquisition box A3 on Floor 4 at Location 5

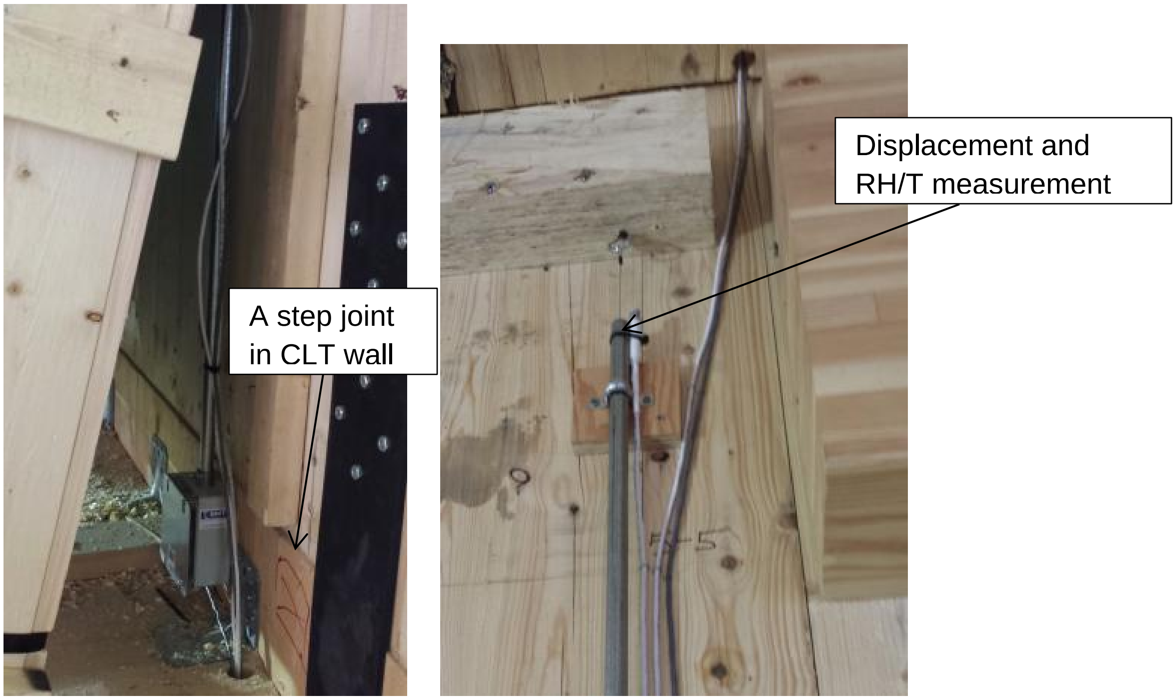

Figure 6 A displacement sensor covering a horizontal step lap joint in CLT (left photo) together with an RH/T sensor (right photo) on Floor 5 at Location 5

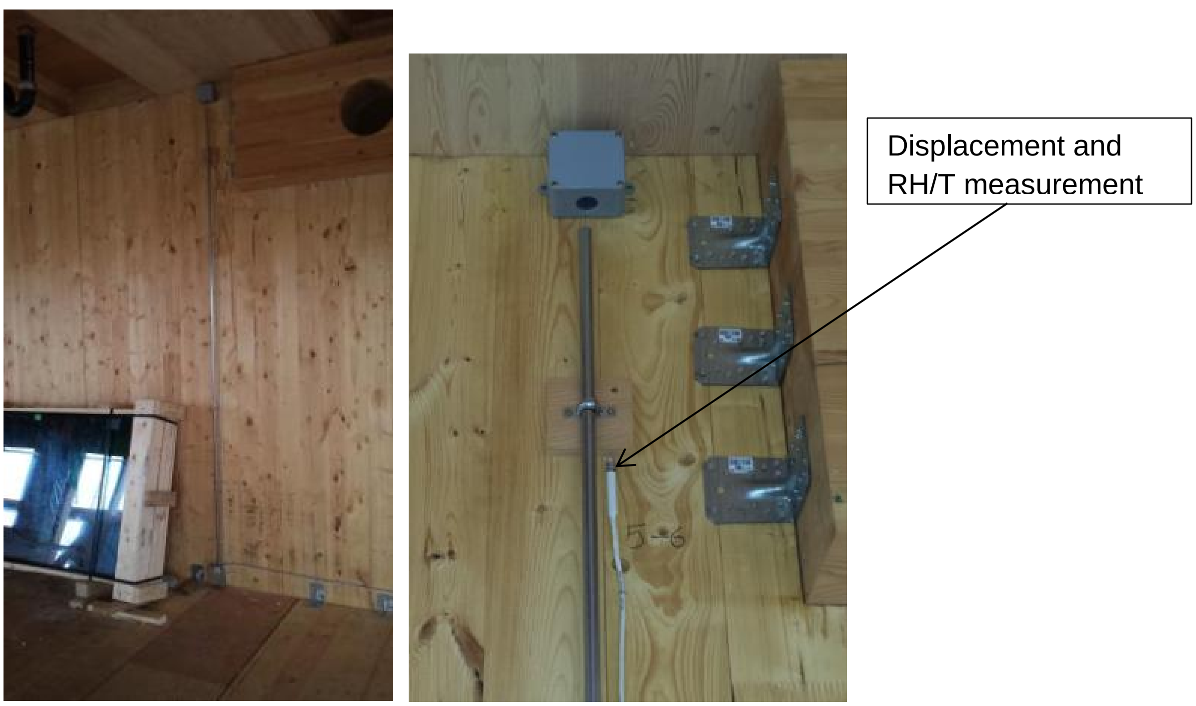

Figure 7 A displacement sensor together with an RH/T sensor (right photo) for measuring environmental conditions on Floor 6 at Location 5

5.4 Moisture Performance of the Roof

It was relatively easy to decide an instrumentation plan and install sensors in the roof, compared with the measurements of vertical movement in the building. Being a conventional roof, layers of rigid insulation and roofing membranes (SBS) etc. were to be installed above the plywood roof sheathing when the instruments were installed. The top surface of the roof was designed to be sloped by using tapered expanded polystyrene (EPS) boards above the plywood sheathing, leading to varied thicknesses of insulation in the roof. In addition, a layer of concrete topping was installed between the EPS and the plywood sheathing in the central area of the roof, i.e. around the mechanical penthouse. This was to improve acoustic performance and prevent sound transmission from the mechanical room and the outdoor mechanical units to the living space below. Six locations in the roof, with different orientations and slightly varied roof assemblies, were chosen for measurement. The general objectives of the measurement was to monitor wood MC and ambient conditions in both the vented cavities, created by strapping between the CLT panels and the plywood roof sheathing, and the ceiling chases, created by staggered CLT panels (see instruments in Table 3). Five locations in the roof were instrumented in March 2014. When first installed, the two moisture sensor pins at each location were both installed in the plywood roof sheathing. One of them was moved to the top layer of the CLT panel about one month later (on the trip for vibration tests). In addition to moisture sensor pins and sensors for measuring environmental humidity and temperature, several moisture tapes were installed on the CLT panels (at each location) and around drains (at Locations 2, 3, and 5) to detect potential water leakage. The sixth location (Roof 4) was not accessible for installing during construction due to other activities in that area. Sensors were instead installed in early July 2014.

In general the instrumentation was intended to primarily measure wood MC and the drying ability of the designed roof assemblies at these selected locations, instead of detecting leaks for the entire roof. Periodic inspections are still needed for other areas of the roof. Related to measuring wood MC, calibration of the sensors and data acquisition systems used in this building will be conducted in the laboratory and readings may be corrected in future reports once the calibration is completed.

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)	RH(T)	R1 T(RH), R1 RH	Vented cavity
	A3 (with RH/T)	R1 Unit T, R1 Unit RH	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)	RH(T)	R2 T(RH), R2 RH	Vented cavity
	A3 (with RH/T)	R2 Unit T, R2 Unit RH	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	On pipe
	Moisture tape	R2 Tape2	On CLT
Roof 3 (close to the core, in south-west direction, close to a drain, with a concrete layer above sheathing, minimum insulation)	RH(T)	R3 T(RH), R3 RH	Vented cavity
	A3 (with RH/T)	R3 Unit T, R3 Unit RH	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
	Moisture tape	R3 Tape1	On 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) The sensors were installed in early July 2014, later than other sensors.	A3 (with RH/T)	R4 Unit T, R4 Unit RH	Ceiling chase
	Moisture pin 2	R4 PIN2 Roof T, R4 PIN2 Roof MC	Into plywood sheathing
	Moisture pin 1	R4 PIN1 CLT MC R4 PIN1 CLT T	Into CLT beam
	Moisture pin 3	R4 PIN3 Exterior CLT	Into CLT beam close to exterior wall

	Moisture pin 4	R4 PIN4 GluBeam MC	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)	RH(T)	R5 T(RH), R5 RH	Vented cavity
	A3 (with RH/T)	R5 Unit T, R5 Unit RH	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)	RH(T)	R6 T(RH), R6 RH	Vented cavity
	A3 (with RH/T)	R6 Unit T, R6 Unit RH	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

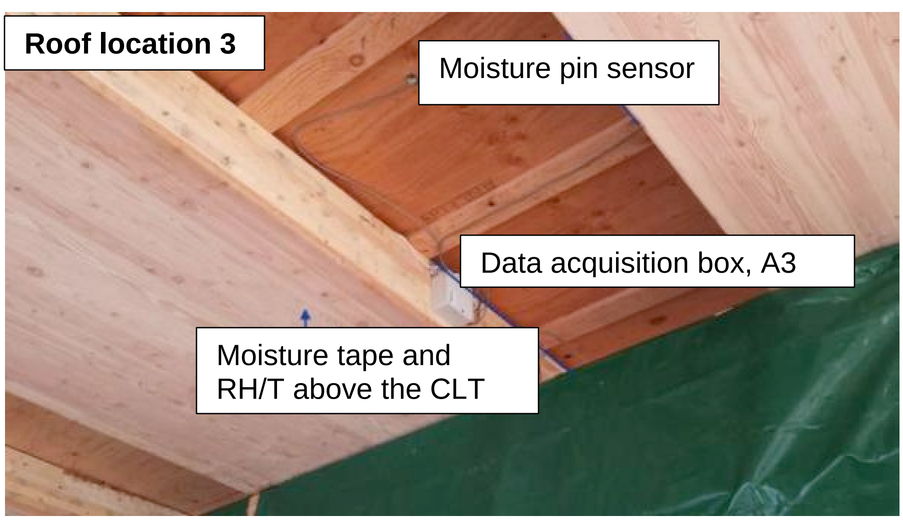

Figure 8 Instruments installed in the roof at Location 3 to measure wood moisture content and environmental conditions

6 RESULTS AND DISCUSSION

6.1 Vertical Movement

6.1.1 Columns, Beams, and CLT Floors

The first year's monitoring covers both construction and occupancy, about six months for each. All charts below were created based on readings from sensors, without any filtering or processing. A displacement sensor measures any movement in the target direction. Therefore a reading includes not only the true movement of a member or members covered, but also data sampling error and measurement noise. The movement of a wood member results from MC changes and loading, such as shrinkage or swelling depending on the MC changes and load-induced deformation (Wang and Ni 2012). Extraneous signals, for example, could be caused by localized vibration resulting from construction or occupant activities. In addition, there is always a potential for errors when using electronic devices (i.e., electrical noise). For the structural members monitored in this study, any 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. Localized vibration is mostly on a temporary basis and is unlikely to be all recorded since the monitoring system collects data hourly. Therefore, the measurements over the duration of this study primarily show wood shrinkage resulting from drying and time-dependent deformation, i.e., creep, of the structural members.

The results from the displacement sensor installed at Location 1, labelled "L1 1C Column", show that the glulam column was extremely stable under compression, with the maximum shortening amount of about 1.5 mm (Figure 9). The sensor labelled "L1 1B Column+Beam", covering the entire glulam column and the PSL beam above (with a metal connector between them), showed a shortening amount of about 11 mm. The sensor ("L1 2V 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 7 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 9 mm for this beam alone. Apparently deformation resulting from compression occurred not only at the surface loading areas, but also 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 1B Column+Beam" and "L1 2V Beam"), the movement increased over time; but it appears that the increases were faster before December 2014; both slowed down after that. Such changes should be attributable to changes in the indoor environment and consequently the wood MC. While the temperature inside the building was controlled around 20℃ after the building was occupied, the RH change is mostly seasonal depending on the exterior conditions as well as the amount of heating and ventilation (i.e. air exchanges). Indoor environment tends to be very dry under heated conditions in such a cold and dry climate, unless the humidity is specifically controlled (e.g. by using humidifiers). The humidity in the building was found to become particularly low after mid-December, fluctuating between 20% and 30% and sometimes even lower (Figures 12, 14, 15). Such ambient conditions correspond to wood MC of approximately 4-6%, i.e., very dry (FPL 2010).

The attention given to the service environmental conditions is justified because of the effect of MC on the mechanical properties of wood. 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, and may affect the structural performance (Jonsson and Thelandersson 2003; Winter *et al.* 2014). This becomes particularly important for large cross-section members, especially when free shrinkage is hindered by means, such as fastening. 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.

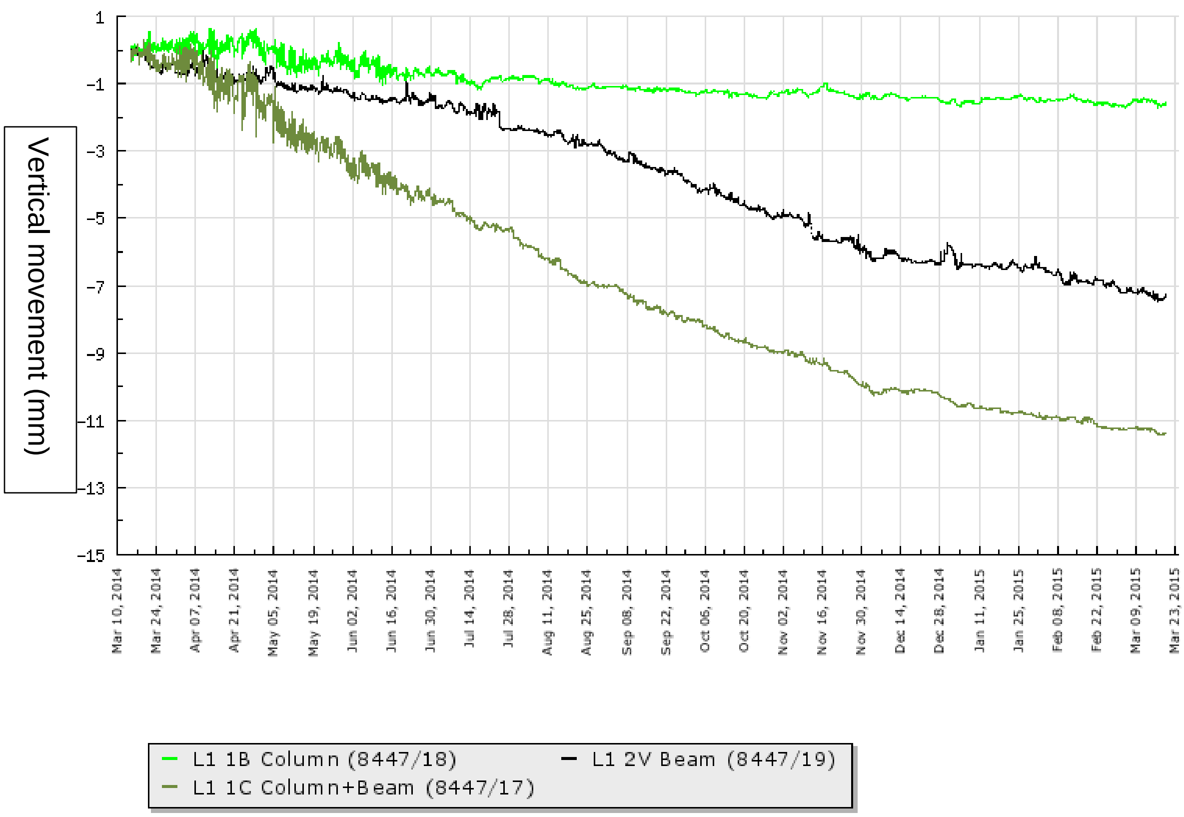

Figure 9 Vertical movement of glulam column, PSL beam, and combined column and beam at Location 1

At Locations 3 and 4, the behaviour of the glulam column measured by the sensor “L4 F1 Column” was very consistent with the glulam at Location 1, with the maximum shortening of about 1.8 mm (Figures

10, 11). 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), and the measurements of these two columns demonstrate that glulam columns are highly stable when loaded in the longitudinal direction. Neither MC changes nor sustained loading led to considerable movement. When a small shrinkage coefficient, 0.005% per 1% change in MC (FPL 2010), was used to estimate wood shrinkage, the calculated shrinkage alone would have slightly exceeded the entire movement measured (shrinkage plus all other potential components) (Table 5). 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, eliminating horizontal wood members in the load path. The total shortening would be expected to be approximately 8 mm based on the measurement, accounting for a total height of 24.5 m for 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 the top two floors. This amount is certainly much lower than the vertical movement observed in light wood-frame buildings (Wang *et al.* 2013; Wang and Ni 2014), but comparable with the measured movement from a similar six-storey mass timber building in Quebec City (Munoz *et al.* 2012).

When a measurement covered a glulam column, a CLT floor, and the connection between them, the movement amount increased greatly (Figure 10, Table 5). 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. The glulam beams were supported by glulam columns using dovetail connections. It is believed that the beam should have a minor contribution to the vertical movement measurement since its vertical movement (including shrinkage) is restrained by the column and the connection. Being 5-ply and 169 mm thick, the bottom CLT panel was included in the corresponding measurement with a displacement box installed to sit on this 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 there should be no cumulative deformation resulting from compression. Similarly, the panels may deflect under loads, particularly over a large span, but that would not contribute to any vertical movement measured in this study. Shrinkage of the CLT panel (out-of-plane) resulting from drying must therefore be a major reason for the measured movement at each location. It was mentioned above that the sensor labelled “L4 F1 Column” showed a shortening amount of 1.8 mm. For comparison, the displacement sensor labelled “L4 F1 Column+CLT 1-2” showed a total shortening of 7.3 mm. 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, and part of the glulam beam). This indicates that the difference of 5.5 mm between these two measurements was primarily caused by shrinkage of the CLT floor panel. The shrinkage for out-of-plane CLT can be estimated when the MC change and shrinkage coefficient are known. 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/). When the field monitoring started in March 2014, the average MC of the panels was estimated to be 13% based on measurements using a portable capacitance moisture meter at the site as well as sensors installed in the building. Assuming that the MC dropped to 6%, a very conservative MC, in March 2015 based on the RH and temperature measurements, and CLT has a composite shrinkage coefficient of 0.25% per 1% change in MC in its thickness, i.e., the transverse grain orientation of wood (Wang and King 2015), these 5-ply CLT panels should have a shrinkage amount of about 3 mm. This estimation was much lower than the amount indicated by the measurement. Apparently the shrinkage amount of the CLT floor panel must be considerably larger than the shrinkage of the glulam column in the longitudinal direction (Table 5). Not relevant to the movement monitoring in this study, the upper 3-ply CLT panels (99 mm thick) of the floors would have incurred shrinkage of another 2 mm under these conditions. Therefore the total shrinkage amount would exceed 5 mm when these two panels are stacked. This magnitude of movement could be significant if the floor was, for example, supporting equipment that had rigid service connections attached to the walls or columns, or directly connected to other building components, e.g., curtain wall. Therefore out-of-plane shrinkage as well as deflection of CLT floors may need to be taken into consideration in design and installation of such components or equipment.

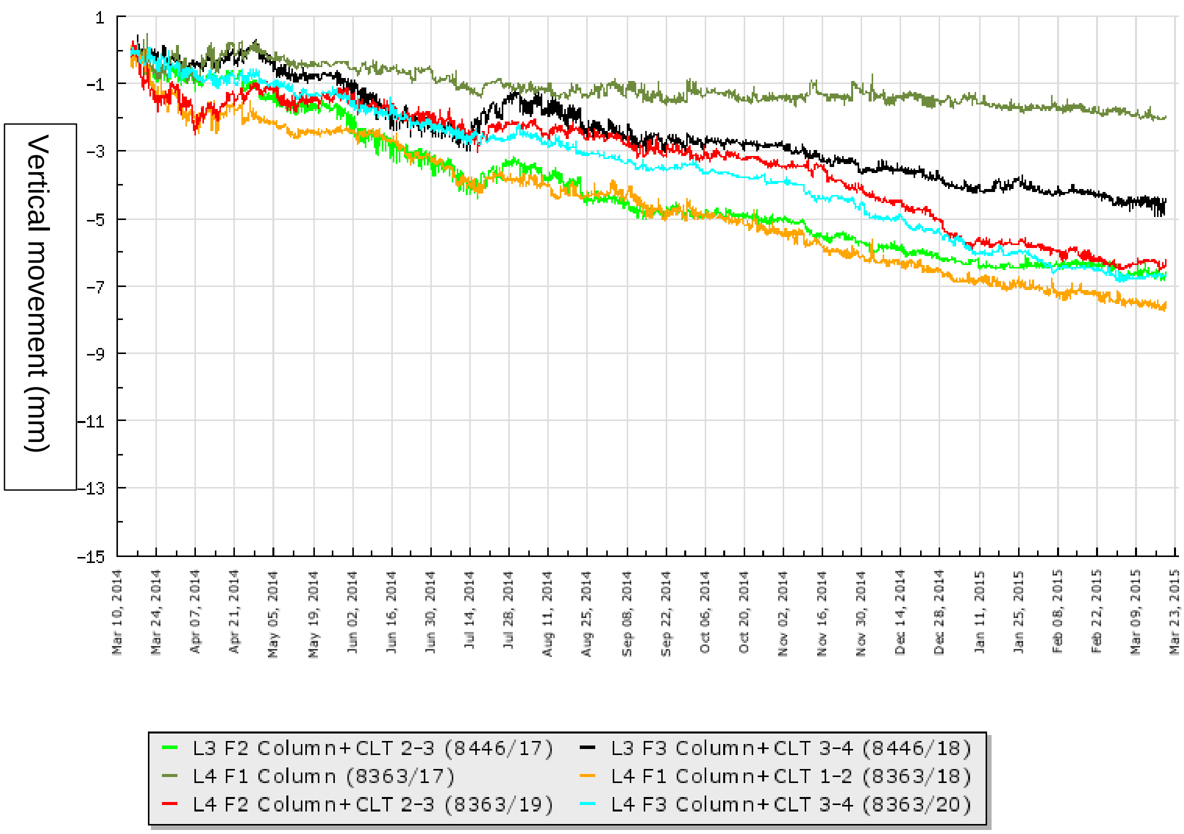

Figure 10 Vertical movement of glulam column and combined column and CLT floor at Locations 3 and 4

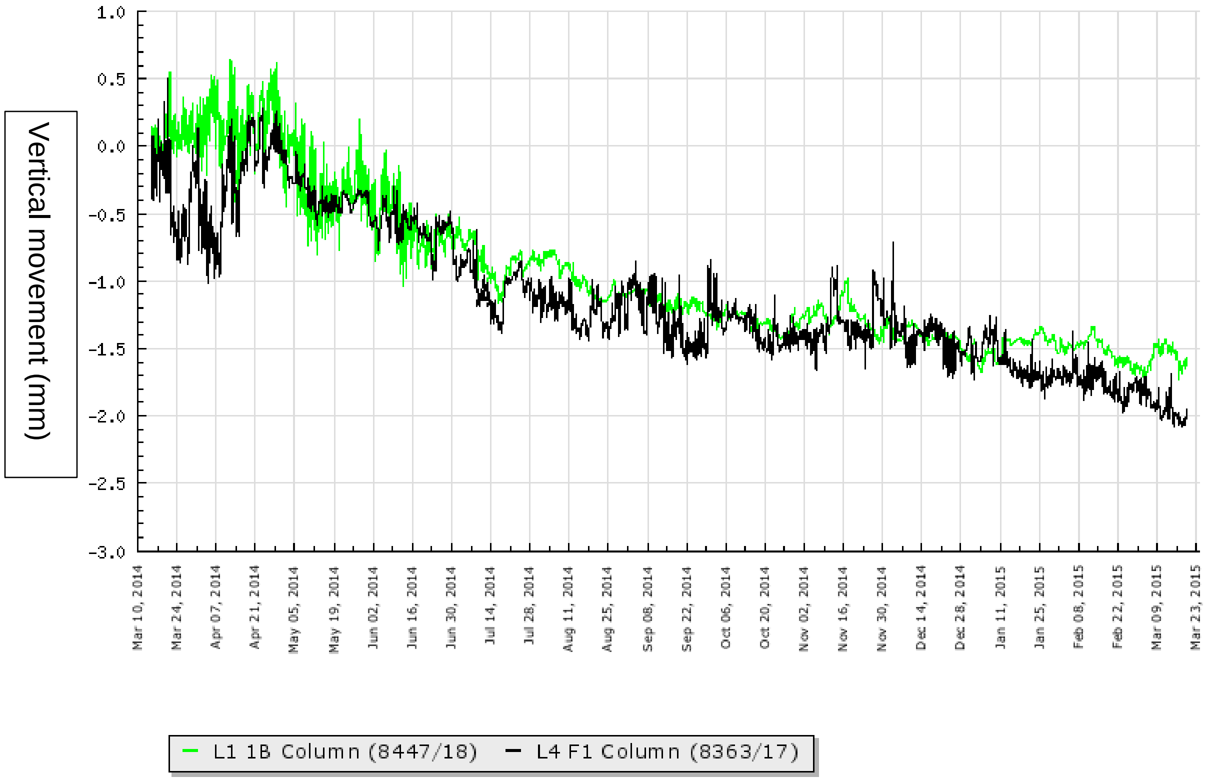

Figure 11 Vertical movement of two glulam columns at Locations 1 and 4

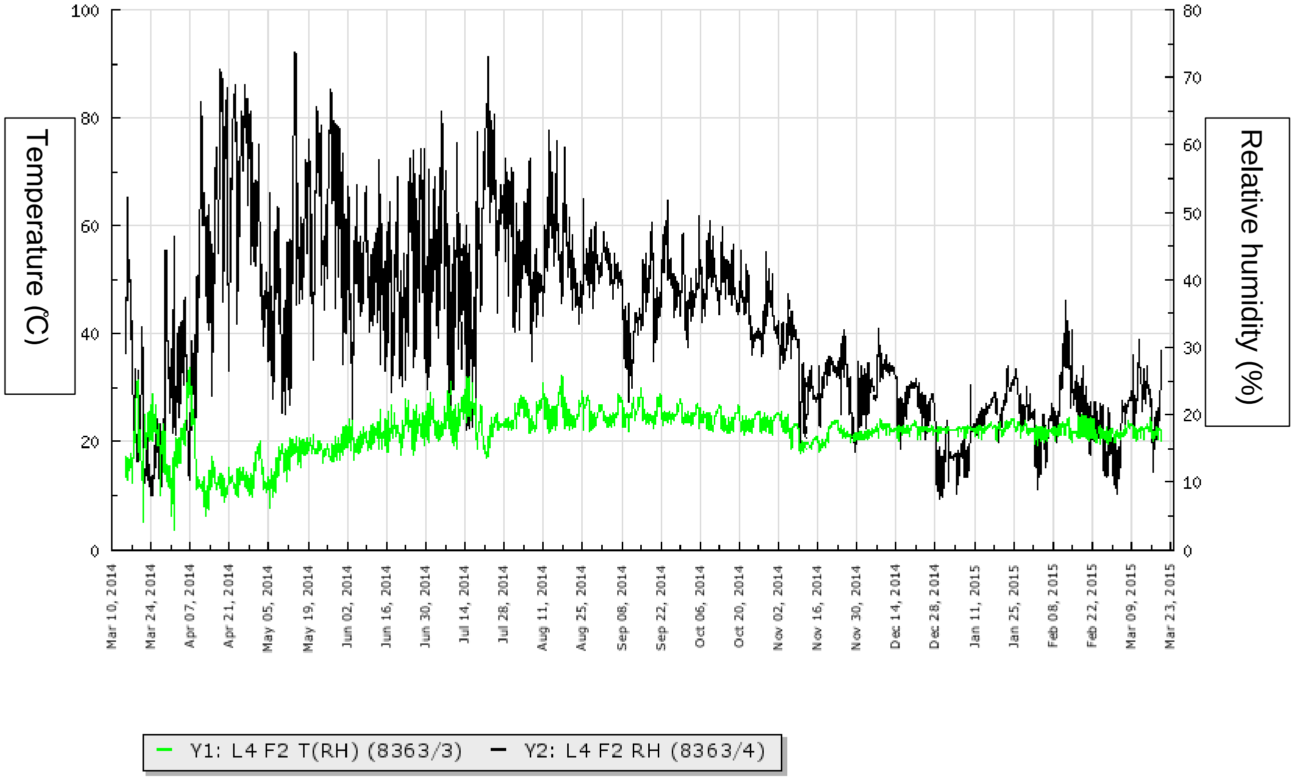

Figure 12 Relative humidity and temperature on the 2nd floor at Location 4

6.1.2 CLT Walls

According to the drawings, the CLT walls in this building have a height of 24.5 m, with two horizontal step joints. 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 1.3 mm to 2.3 mm on each floor (Figure 13, with the service environmental conditions shown in Figures 14 and 15). The measurements in this study confirmed that CLT was also highly dimensionally stable in its plane direction. Assuming that wood shrinkage and load-induced deformation were uniform along the height on each floor, and the movement amounts were proportional based on of the heights of the wall, the measurements showed that the total shortening of the CLT wall, from Floors 1 to 6, would be about 14 mm. This is larger than the vertical movement of a glulam line under the same indoor environment but the differential movement is quite small for such a building.

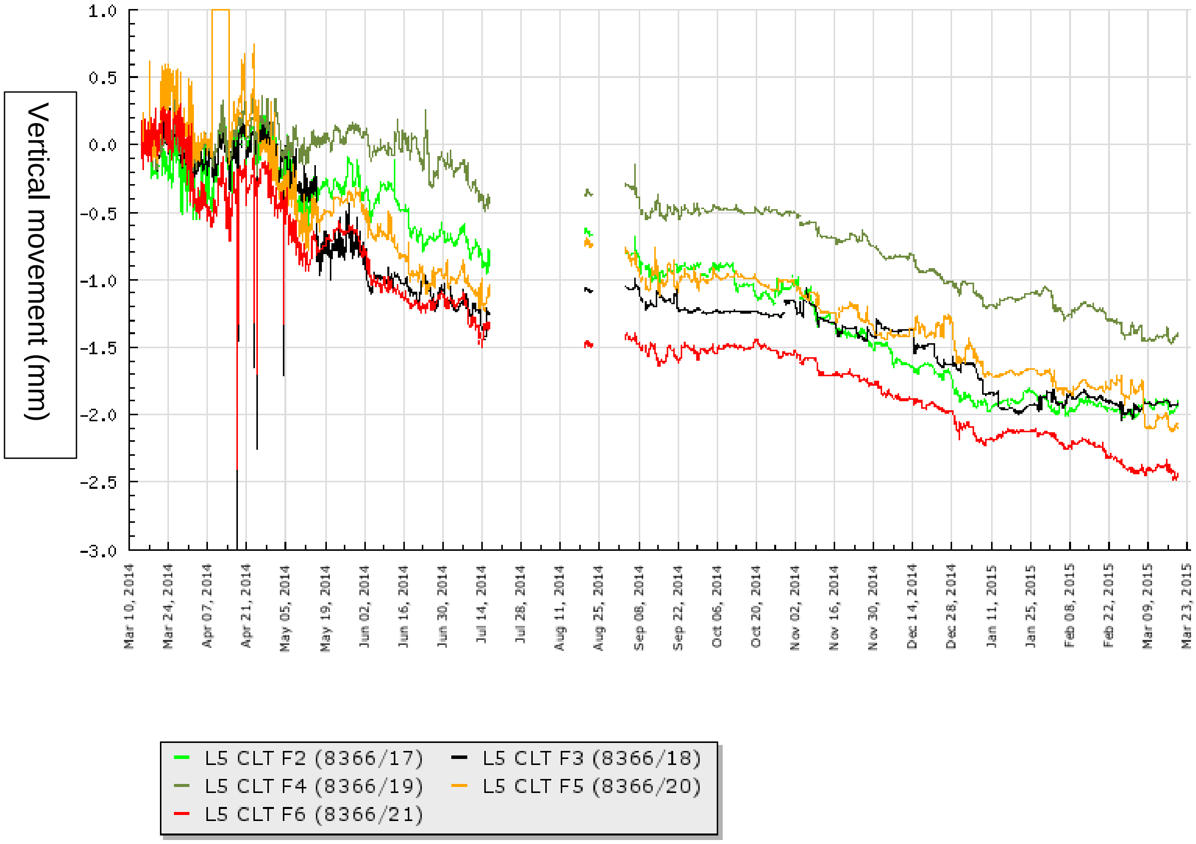

Figure 13 Vertical movement of CLT wall from Floors 2 to 6 at Locations 5

(Note: some data was lost between July and September 2014 due to a wireless transmission issue)

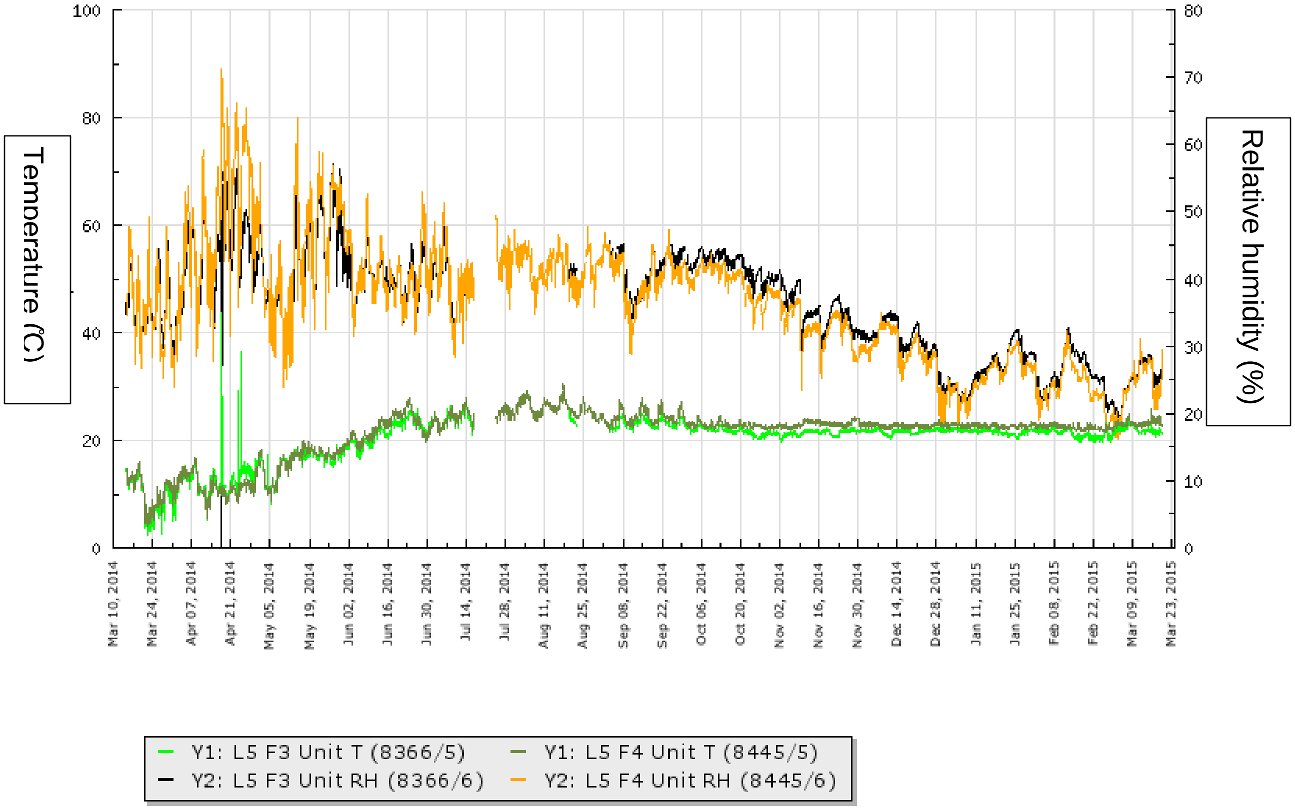

Figure 14 Relative humidity and temperature on the 3rd and 4th floor at Location 5

(Note: some data was lost in July 2014 due to a wireless transmission issue)

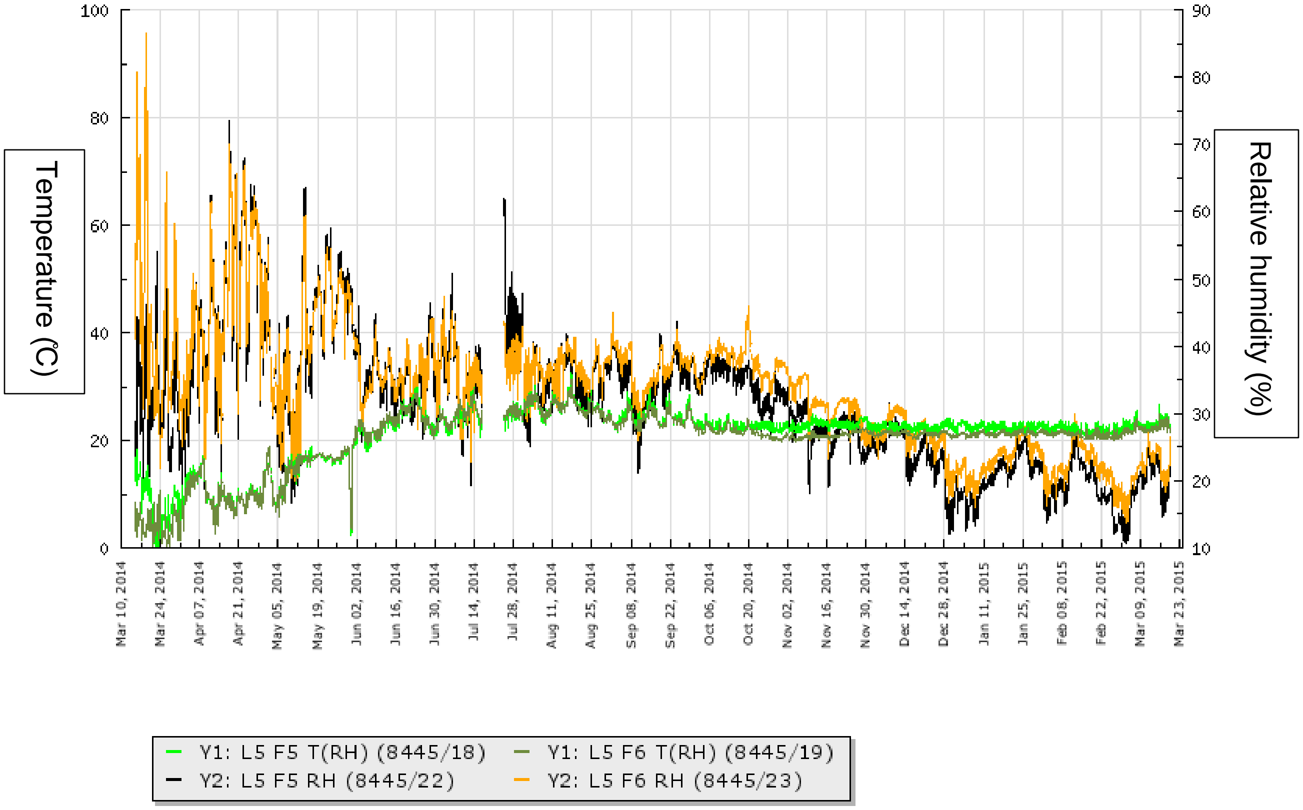

Figure 15 Relative humidity and temperature on the 5nd and 6th floor at Location 5

(Note: some data was lost in July 2014 due to a wireless transmission issue)

Table 5 Vertical Movement Readings from Displacement Sensors and Potential Contributions

Location	Displacement Sensor Label	Movement Reading on Feb 26, 2015 (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 1C Column	1.6	5005	1.8	0	1.8	-0.2
	L1 1B Column+Beam	11.3	6330	1.8	***	-	-
	L1 2V Beam	7.3	1120	-	***	-	-
Location 3	L3 F2 Column+CLT 2-3	6.6	3290	1.2	3.0	4.1	2.5
	L3 F3 Column+CLT 3-4	4.4	3190	1.1	3.0	4.1	0.3
Location 4	L4 F1 Column	1.9	6160	2.2	0	2.2	-0.3
	L4 F1 Column+CLT 1-2	7.5	6480	2.3	3.0	5.2	2.3
	L4 F2 Column+CLT 2-3	6.2	3290	1.2	3.0	4.1	2.1
	L4 F3 Column+CLT 3-4	6.7	3190	1.1	3.0	4.1	2.6
Location 5	L5 CLT F2	1.9	2870	1.0	-	1.0	0.9
	L5 CLT F3	1.9	2860	1.0	-	1.0	0.9
	L5 CLT F4	1.4	3010	1.1	-	1.1	0.3
	L5 CLT F5	2.1	2890	1.0	-	1.0	1.1
	L5 CLT F6	2.4	3000	1.1	-	1.1	1.4
	CLT total	9.7	14630	5.1	-	5.1	4.6

* An assumed composite shrinkage coefficient of 0.005% per 1% change in MC for longitudinal glulam and CLT and 7% in MC reduction for estimating shrinkage

** An assumed composite shrinkage coefficient of 0.25% per 1% change in MC for out-of-plane CLT;

***A lack of information for estimating shrinkage or load-induced deformation for PSL beam.

6.2 Moisture Performance of the Roof

The wood roof structure was generally very dry during this monitoring period. Figure 16 shows RH and temperature measured from Location R1 to represent environmental conditions in the roof area. Consistent with the ambient conditions measured from areas closer to the walls, most locations of the roof showed RH below 50% in the summer of 2014, and the humidity reached very low levels in December 2014. As a result of the dry indoor environment, both the plywood roof sheathing (Figure 17) and the CLT panels below (Figure 18) produced very low MC readings at these five monitoring locations (i.e., except R4). It should be noted that the resistance-based measurement systems showed a lower MC limit of 11% in this study, with calibration based on lodgepole pine (due to the use of “SPF” CLT and plywood sheathing). Therefore a reading of around 11% may not reflect the real wood MC. The electrical resistance becomes too high to be accurately measured when the wood MC is too low. The sheathing of a flat roof would be typically subjected to the highest risk when wetting occurs during construction, or the roof leaks in service. Thicker panels, such as double-layer of plywood or OSB sheathing, and mass timber products, such as CLT, all have reduced drying rates compared to the traditional one layer of roof sheathing upon wetting (Wang 2014). For the roof assemblies in this building, however, the interior ventilation function, which was achieved by installing strapping between the sheathing and the mass timber beams below, should enable the wood members to dry since they were exposed to the conditioned indoor environment, if they were wetted.

For the R4 location, the instruments were not installed until July 2014 due to construction activities. Once the system was activated, the MC of the plywood sheathing at that location was found to be about 25%, the highest MC detected in this study since the monitoring program started. The high initial MC must have been caused by the pouring of the wet concrete layer above the plywood sheathing. 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. Also, the monitoring showed that the plywood sheathing gradually dried with the MC gradually dropped to 20% in September and to 15% in January 2015. In addition to this suspected leak at R4, it was found that the humidity level in the ventilation gap, i.e., between the roof sheathing and the CLT beam at the R3 location, reached almost 100% during the construction period in March 2014. Again the monitoring showed that the humidity readings gradually dropped and remained around 60% in June 2014. Coincidentally a concrete layer was also installed above the plywood sheathing at this location. In general, the roof showed good drying performance. The design also facilitated detection of water leaks. Both are important for the long-term durability of a mass timber roof.

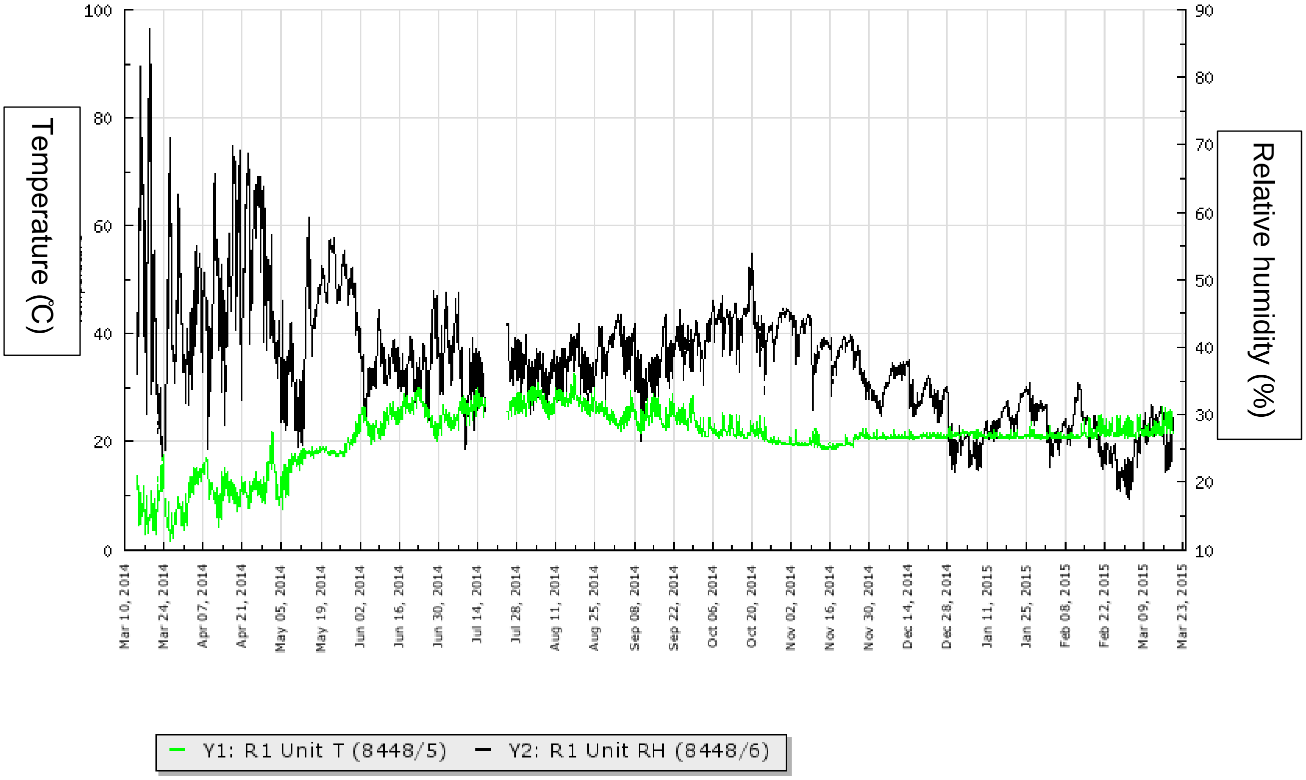

Figure 16 Relative humidity and temperature at Roof 1 location

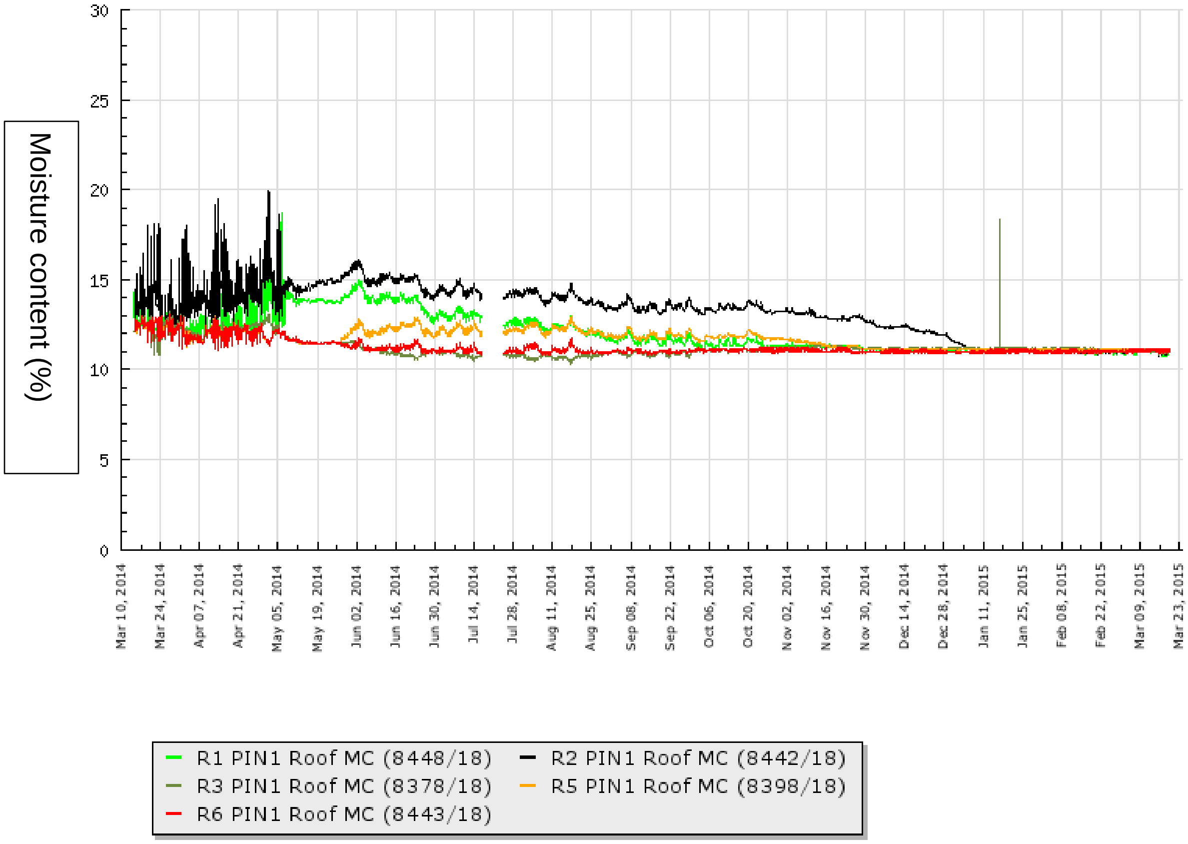

Figure 17 MC measured from plywood sheathing at five roof locations

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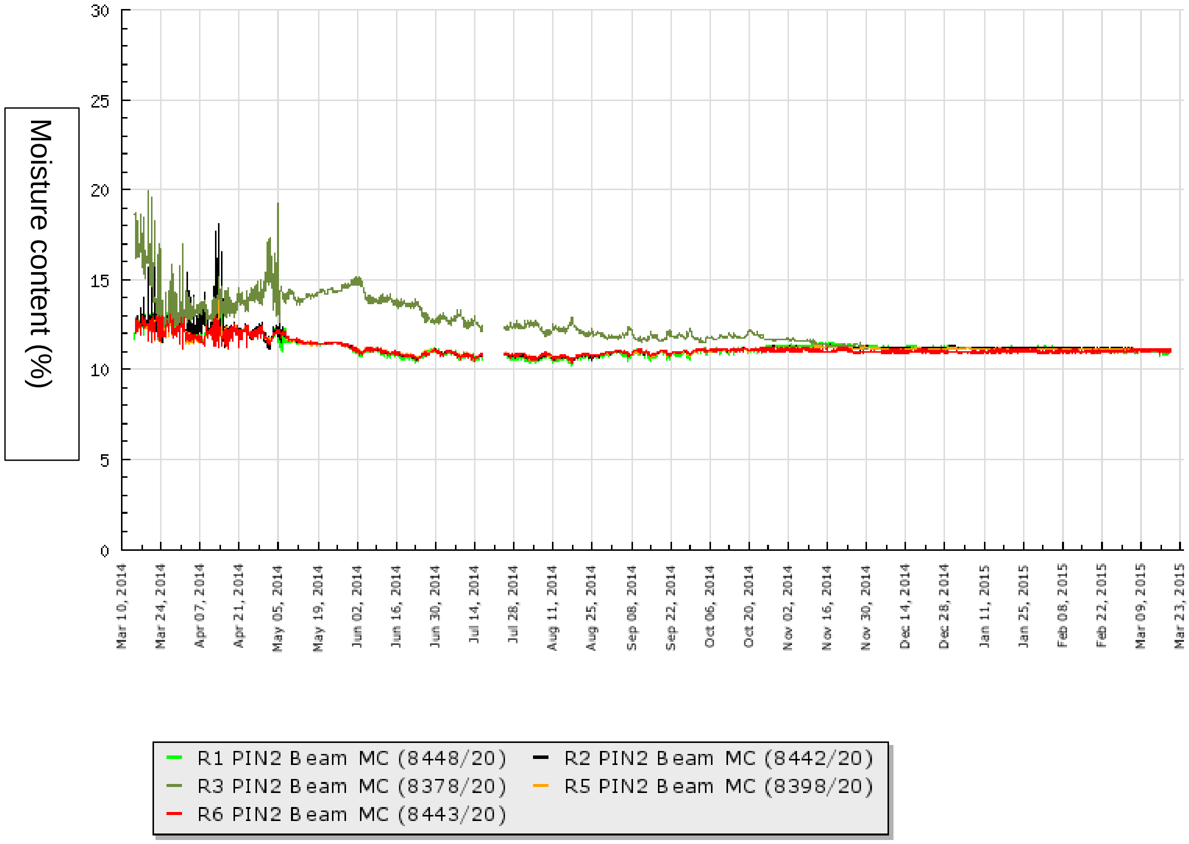

Figure 18 MC measured from CLT beam at five roof locations

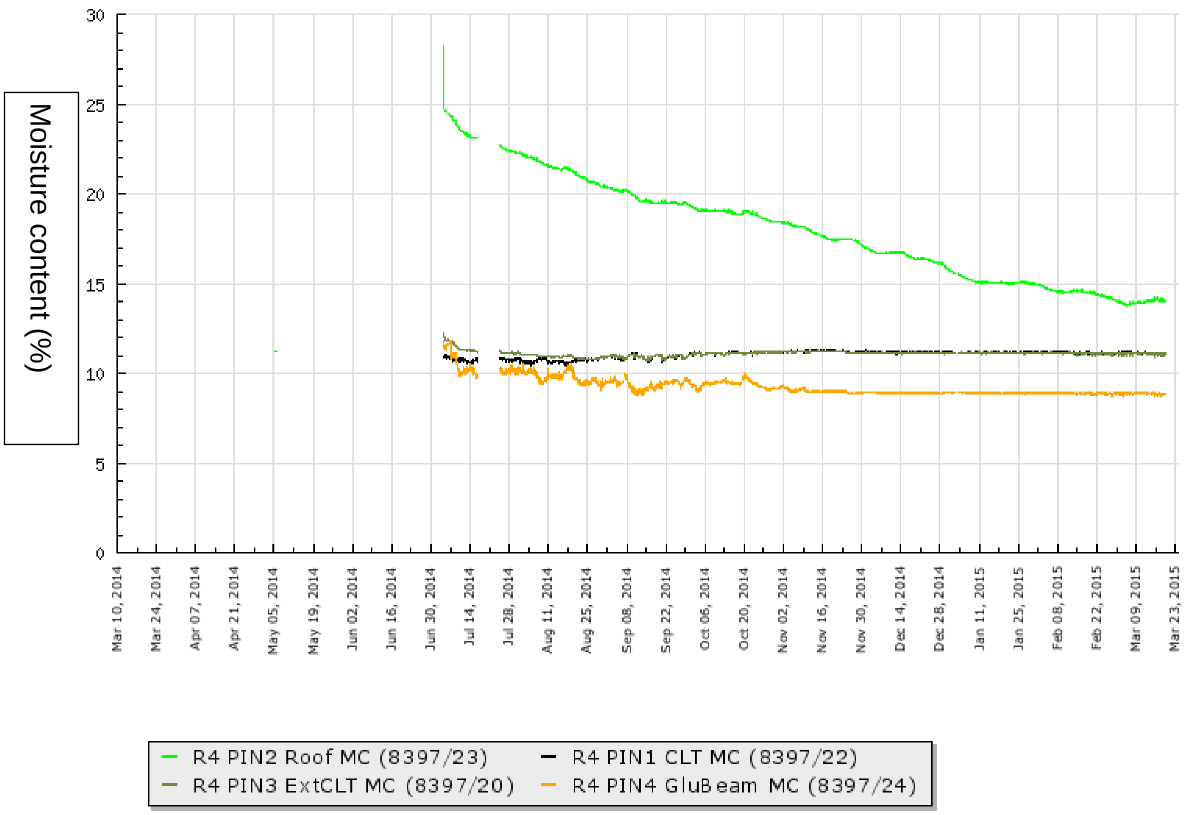

Figure 19 MC measured from CLT beam at five roof locations

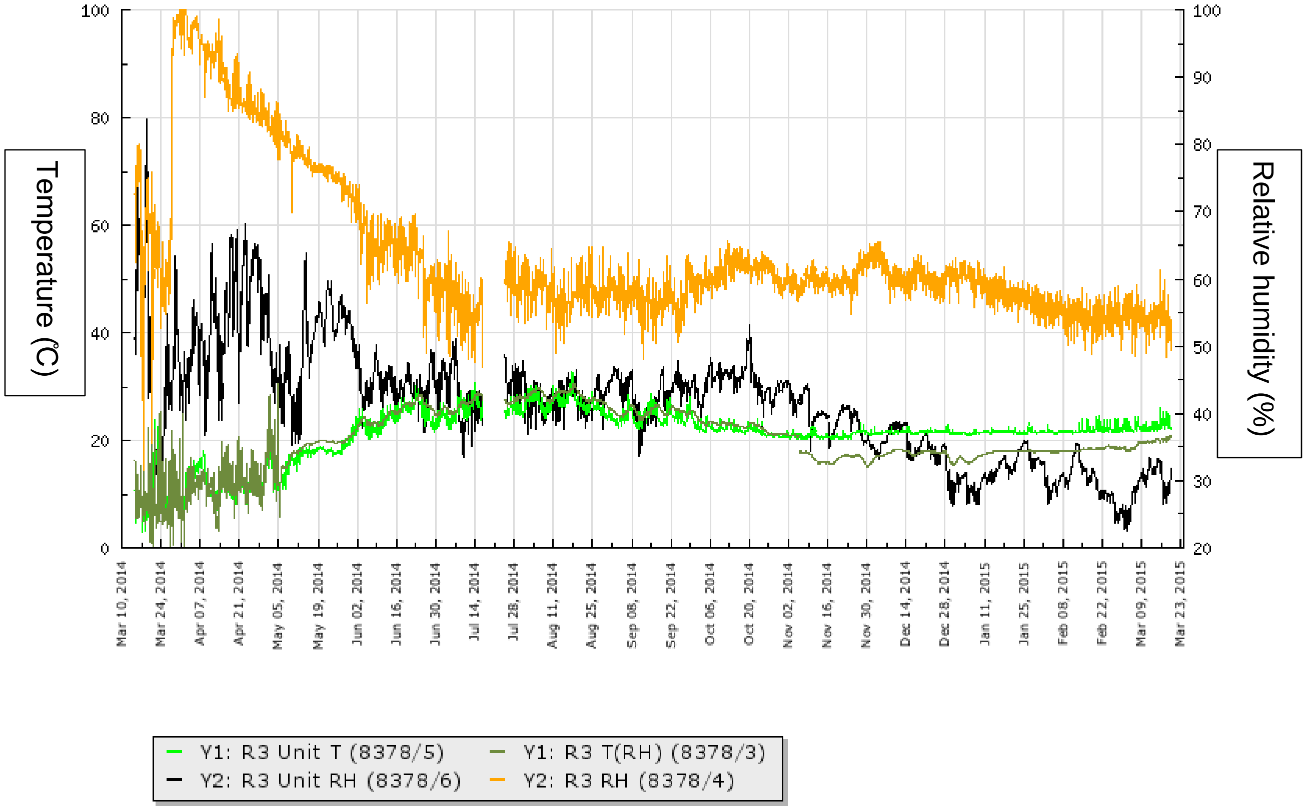

Figure 20 Relative humidity and temperature measured from Roof 3 location

7 CONCLUSIONS

The following conclusions can be drawn based on the monitoring so far:

- With an initial MC of 13% in construction, the wood inside the building was estimated to have reached an average MC of about 4-6% during the winter heating season, due to dry indoor conditions.
- With a height of over 5 m and 6 m, respectively, the two glulam columns measured in this study showed very small amounts of vertical movement, each below 2 mm. The cumulative shortening of the six glulam columns along the height of the building would be probably about 8 mm, not taking into account deformation at connections or effects of reduced loads on the top two floors.
- The CLT wall was found to be dimensionally stable 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 14 mm.
- CLT had considerable shrinkage in the out-of-plane (thickness) direction. It was estimated that the bottom floor panel, 5-ply and 169 mm in thickness, had a shrinkage amount of about 3 mm.

- The PSL beam monitored, with a total depth of over 1.2 m, showed a reduction of about 9 mm in the depth.
- Two locations in the roof, both with a concrete layer poured above the plywood sheathing, showed wetness during construction but dried slowly afterwards. The wood members at the other four locations were very dry during the duration of monitoring.

Overall the measured data in this study is consistent with the predicted performance based on the design of the building. The study shows that the glulam columns and the CLT walls are both dimensional stable under the moisture change and loading conditions of this building and the differential movement among them is small. Eliminating horizontal wood members in a gravity load path and avoiding compressing wood perpendicular to grain is important for a mass timber building. This monitoring also shows that mass timber roofs can dry and perform satisfactorily when properly designed. In this building the interior ventilation function designed for the roof assemblies by integrating strapping between the sheathing and the mass timber beams below ensures the good drying performance. It can also facilitate detection of water leaks in case it occurs.

8 RECOMMENDATIONS

Monitoring should be continued to assess the performance of the building on a longer term. The effects of indoor environmental conditions should be further assessed over seasonal changes.

Basic characteristics of engineered wood products, such as the PSL beams in this building, should be assessed to help building design.

9 REFERENCES

Association of Professional Engineers and Geoscientists of British Columbia (APEGBC). 2009. Structural, fire protection and building envelope professional engineering services for 5 and 6 storey wood frame residential building projects (Mid-rise buildings). APEGBC Technical and Practice Bulletin. Professional Engineers and Geoscientists of BC. Canada.

Breyer, D., Fridley, K., Cobeen, K., and Pollock, J.D. 2006. Design of Wood Structures. 6th ed. McGraw-Hill Professional. New York.

Bodig, J. 1966. Stress-strain relationship for wood in transverse compression. Journal of Materials 1(3): 645-666.

Canadian Wood Council (CWC). 2005. Introduction to Wood Design. Ottawa, Canada.

European Committee for Standardisation (CEN). 2004. Eurocode 5: Design of Timber Structures - Part 1-1: General - Common Rules and Rules for Buildings. The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC. Brussels, Belgium.

Forest Products Laboratory (FPL). 2010. Wood Handbook—Wood as an Engineering Material. Chapter 04: Moisture Relations and Physical Properties of Wood. Chapter 13: Drying and Control of Moisture Content. Wood. Gen. Tech. Rep. FPL-GTR-113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Hu, L., C. Pirvu, and R. Ramzi. 2015. In-situ testing at the Wood Innovation and Design Centre: floor vibration, building vibration, and sound insulation performance. FPInnovations report to Forest Innovation Investment (FII), Vancouver, Canada.

Jonsson J. and S. Thelandersson. 2003. The effect of moisture gradients on tensile strength perpendicular to grain in glulam. Holz als Roh- und Werkstoff 61: 342–348.

Karacabeyli, E. and C. Lum. 2014. Technical Guide for the Design and Construction of Tall Wood Buildings in Canada. FPInnovations Special Publication SP-55E, Vancouver, Canada.

Munoz, W., M. Mohammad, and S. Gagnon. 2012. In-situ monitoring of a 6-storey hybrid wood-concrete office building in Quebec, Canada. Proceedings of the World Conference on Timber Engineering, Auckland, New Zealand, July 16-19, 2012.

Wang, J. 2011. Vapour Condensation potential in insulated wood-frame building enclosure assemblies. FPInnovations report to the Canadian Forest Service, Natural Resources Canada. Vancouver, Canada.

Wang, J and C. Ni. 2012. Review and survey of differential movement in wood frame construction. Proceedings of the World Conference on Timber Engineering, Auckland, New Zealand, July 16-19.

Wang, J., C. Ni, and G. Mustapha. 2013. Monitoring of vertical movement in a 4-story wood frame building in Coastal British Columbia. Journal of Testing and Evaluation 41(3): 611-618.

Wang, J. 2014. Drying performance of experimental wood roof assemblies. FPInnovations report to the Canadian Forest Service, Natural Resources Canada. Vancouver, Canada.

Wang, J. and Ni, C. 2014. Monitoring of vertical movement in a 5-storey wood frame building in Coastal British Columbia. Proceedings of the World Conference on Timber Engineering, Quebec City, Canada, August 10-14, 2014.

Wang, J. and L. King. 2015. Impact of moisture and load on vertical movement in a simulated platform-frame wood structure. ASTM Journal of Testing and Evaluation 43(4).

Winter, S., A. Gamper, P. Dietsch, and M. Merk. 2014. Building climate – long-term measurements to determine the effect on the moisture gradient in timber structures. Report to Forschungsinitiative Zukunft Bau, Bundesamt für Bauwesen und Raumordnung.(Reference number: Z6-10.08.18.7-07.19/II2-F20-07-29). Germany.

Wolcott, M. P., B. Kasal, F. A. Kamke and D. A. Dillard. 1989. Testing small wood specimens in transverse compression. Wood and Fiber Science 21(3): 320-329.

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