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MOISTURE MONITORING AND MODELING OF MASS TIMBER BUILDING SYSTEMS

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ABSTRACT: The use of mass timber structural products in tall building applications (6–20 stories) is becoming more common around the world including North America. A potential concern is the environmental wetting of mass timber products during construction because such products may dry out more slowly than light-frame structural lumber, and wood, as an organic material, is susceptible to deterioration at elevated moisture contents. In order to better understand the moisture conditions present in high rise timber constructions, a long-term moisture monitoring program was implemented on an eight story, mixed-use, mass timber framed building in Portland, Oregon. The building was monitored with an array of moisture meters to track moisture content throughout the building's construction and operation. This paper presents data covering a period just over one year starting from the manufacture of cross-laminated timber (CLT) panels. Hygrothermal properties of CLT samples of the same type used in the building were measured in the laboratory, and wetting and drying experiments on representative CLT samples were conducted. Simulated moisture contents using a one-dimensional hygrothermal model compared reasonably well with laboratory experiments and building site measurements.

KEYWORDS: Cross-Laminated Timber, Moisture Monitoring, Building Enclosure, Hygrothermal Modeling

1 INTRODUCTION

Massive engineered wood products, such as glue-laminated timber (glulam) and cross-laminated timber (CLT), have recently gained use in high rise buildings in North America. This market has traditionally been dominated by steel or concrete framing systems, but the low carbon footprint, construction efficiency, and economic competitiveness of "mass timber" products have made them viable alternatives to conventional steel and concrete framing systems [1–3]. While structural and fire behaviour of mass timber building systems have received considerable study, little is known about the moisture performance of mass timber buildings during construction and building operation. Moisture management during the construction process is important for all building types but is especially so for those that use timber structural members. Elevated moisture levels can cause dimensional instability, cracking, microbial attack, and fastener corrosion. Understanding the range of moisture levels that can be expected in North American mass timber buildings is necessary for informed design.

Recent studies in North America ranging from laboratory measurements [4, 5] to field tests and computer simulations [6, 7] have provided insight into CLT moisture performance. McClung *et al.* [6] monitored the drying performance of various CLT wall assemblies from a wet initial condition and found that walls dried fairly rapidly except for certain cases in which an impermeable membrane was placed on the exterior or interior of the CLT panel. Simulations based on CLT hygrothermal properties [4] and water uptake and drying behavior [5] measured in the laboratory generally agreed well with measured data at levels below about 25% moisture content (MC), although simulations tended to over-predict moisture levels in the center of the panels. The simulation approach, however, required an unusual modification of the moisture transfer properties in order to achieve agreement between measured and simulated MC [5–7]: the coefficient for liquid water redistribution had to be adjusted by over 10 orders of magnitude. This situation may leave designers lacking confidence in the ability of conventional models to predict drying behavior of mass timber or to evaluate the moisture performance of different building envelope designs.

The studies mentioned above provide some indication as to how CLT might respond in the real world, but CLT moisture performance cannot be fully understood without monitoring actual buildings. Recent studies have included on-site moisture measurements in two mass timber buildings in British Columbia [8, 9]. Because CLT can take a long time to dry out if it gets wet, it is

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critical to characterize moisture exposure on the jobsite, moisture content of CLT panels when the building is enclosed, and the rate of drying after enclosure, particularly for assemblies in which CLT has an impermeable membrane on one side [6].

This paper describes parts of a multiyear study to obtain moisture monitoring data in mass timber buildings across several different climate zones in the US. The goal is to fully characterize the wood moisture content from the factory to occupancy of the building. The focus of this paper is moisture monitoring of CLT panels in an eight story, mass timber building located in Portland, Oregon. The measurements are compared with hygrothermal simulations of the drying of the panels after exposure to record-setting precipitation during construction.

2 METHODOLOGY

2.1 BUILDING MOISTURE MONITORING

The building has a primary structural system of glulam columns and beams in conjunction with CLT floor slabs. A braced steel framing system is integrated with the mass timber gravity system to resist lateral seismic and wind loads. Lightweight wood-frame stud walls are installed for exterior walls and interior partition walls. CLT panels provide the structure for a low-slope roof. An isometric view of the building’s framing and photograph are shown in Figure 1.

Figure 1: *Eight-story mass timber building structural schematic and photograph during construction*

The majority of CLT panels in the building consist of one layer of Douglas-fir (DF) on the exposed underside and four layers of western Canadian spruce-pine-fir (SPF). CLT floor panels are overlaid with insulation, cover board, polyethylene film, lightweight concrete topping, acoustic damping, and finish flooring. CLT roof panels are overlaid with vapour barrier/air barrier membrane, rigid insulation, cover board, and roof membrane (Figure 2).

An array of wireless sensors (OmniSense LLC, Ladys Island, SC, USA) was installed in various components of the building to monitor wood moisture content over time. A summary of sensor quantities and locations is presented in Table 1. The sensors measure the electrical conductance between two stainless steel screws embedded in the wood, which is calibrated to moisture content [10]. For this study a laboratory calibration was conducted using DF and SPF specimens from CLT panels of the same type monitored in the building; the calibration yielded root-mean-square errors of 1.6% MC and 2.1% MC, respectively, relative to gravimetric moisture content measurements over the range from 7% MC to 25% MC [11]. Twenty sensors with data logging capability were installed at the CLT production facility in November 2016 to record MC during storage and transport to the building site. The remaining sensors were installed on the jobsite at two different construction stages.

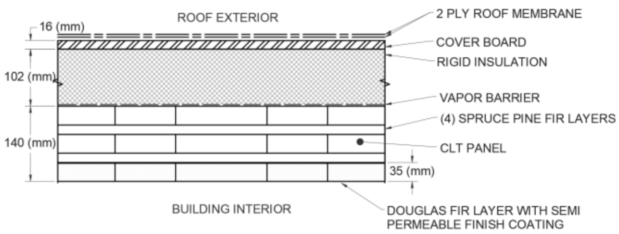

Figure 2: *Roof assembly detail*

Table 1: *Sensor locations and quantities*

Location	CLT	Glulam	Stud Wall	Total
Floor 1	0	12	0	12
Floor 2	0	0	8	8
Floor 4	10	1	8	19
Floor 8	0	2	8	10
Roof	33	0	0	33
Total	43	15	24	82

The sensors were located in three main assemblies: (1) glulam columns and beams near the concrete foundation and near beam/column connections; (2) CLT floor and roof panels; and (3) fire-retardant-treated wood stud walls. The building owner preferred that sensors be hidden from view, so it was not possible to install sensors in CLT panels from the underside. Instead, sensors were installed from the top side and located within a small notched pocket that was subsequently covered with waterproofing (Figure 3).

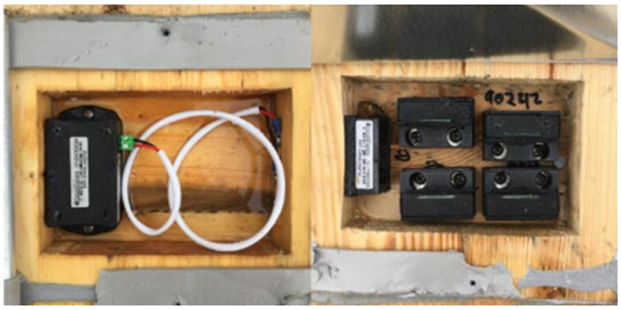

Figure 3: *Sensors located in pockets notched in CLT panels*

The first installation of sensors on the jobsite occurred after the fourth floor framing was completed (Jan. 6, 2017). Shortly after this installation the project site was subjected to frequent precipitation including a rare blizzard. During this time the timber components were exposed to bulk water, and many of the sensors were damaged. The second installation of sensors on the jobsite occurred after the primary mass timber structural system was completed, including the roof (Feb. 10, 2017). At this time damaged sensors installed previously were removed and replaced. All sensors placed in notched pockets on the top side of CLT panels were covered with metal flashing and sealed with foam gasketing and silicone caulk.

Completion of the roof assembly was delayed for two months after sensor installation, and CLT roof panels were exposed to extremely high levels of precipitation prior to application of the roof membrane. During this period, several of the sensor pockets had ponding water and the sensors were damaged (despite efforts at waterproofing). Further details are reported in other publications [11, 12]. A temporary protective enclosure was built above the CLT roof, and fans were operated to dry the roof panels for one week before completion of the roof enclosure in April 2017.

2.2 LABORATORY MEASUREMENTS

Hygrothermal properties of CLT were measured using specimens cut from the same type of panel used in the building. Measurements included bulk density, thermal conductivity, moisture storage function, water vapour diffusion resistance factor, and liquid water absorption coefficient. Density and saturated moisture content (under vacuum-soak) were measured according to the method described by Zelinka *et al.* [13]. For the moisture storage function in the hygroscopic range, specimens were conditioned at five different relative humidity (RH) levels at room temperature using environmental chambers [14], both from a dry and wet initial condition. Literature data for pine were used for the over-hygroscopic (capillary) range, although pressure plate measurements [15] were nearly complete at the time of writing. The water vapour diffusion resistance factor was measured with the desiccant method (dry cup) and water method (wet cup) [16]. The liquid water absorption coefficient was measured by partial immersion [17]. Further details on the materials and measurement methods are given by Kordziel [18].

In addition, two wetting and drying experiments were conducted with larger CLT specimens having full panel thickness (139 mm) and dimensions of 600 mm by 600 mm. In both experiments the SPF surface was wetted (rather than the DF surface), corresponding to the exposure to precipitation during construction. The four sides of each specimen were coated with a liquid-applied membrane that is water and vapour impermeable. In the first experiment, hereafter referred to as "partial immersion", the panel was lowered into a water container with the SPF surface under water, similar to the tests done by Lepage [5]. In the second experiment, hereafter referred to as "inundation", a dam was constructed to hold liquid water on top of the panel (SPF surface up), simulating a roof exposed to rain during construction, as depicted in Figure 4. After a sufficient wetting period, the water was drained and the top surface was covered with 0.15 mm polyethylene film (only for the inundation experiment), which prevented drying of the wetted surface, similar to the CLT roof panels being covered with an impermeable membrane. In both experiments the DF surface was uncovered, and the wetting period was followed by drying at laboratory conditions of 23–25° C and 45% RH (±5% RH). Specimens were weighed periodically to determine the total amount of moisture in the panel over time. Additionally the wood moisture content at various locations through the panel thickness was continuously monitored with the same pin-type wireless sensors described previously.

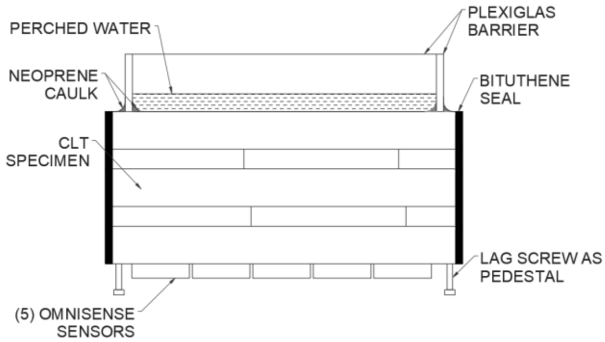

Figure 4: *Setup for top side water inundation experiment*

2.3 HYGROTHERMAL MODELING APPROACH

The moisture content of CLT in the roof assembly of the monitored building and the water uptake in the laboratory wetting and drying experiments described above were simulated using WUFI® software for one-dimensional transient heat and moisture transfer [19, 20].

Material properties of CLT measured in the laboratory in this study were used in the simulation software in conjunction with literature data for the moisture storage function in the over-hygroscopic region, as described by Kordziel [18]. Properties of other materials in the roof assembly were taken from manufacturer data or from the software material database.

The implementation of the moisture transfer coefficients in WUFI is not trivial. The program nominally partitions moisture transfer between vapour diffusion and capillary water transport, which includes a coefficient for suction (when directly exposed to liquid water) and a coefficient for redistribution. These coefficients can be generated by the software based on a measured water absorption coefficient A_w ($kg \cdot m^{-2} \cdot s^{-1/2}$) and a free saturation water content w_f ($kg \cdot m^{-3}$). The liquid transport coefficient for suction D_{ws} ($m^2 \cdot s^{-1}$) is approximated as a function of water content w ($kg \cdot m^{-3}$) as shown in Equation (1) below:

$$D_{ws} = 3.8 \cdot \left(\frac{A_w}{w_f}\right)^2 \cdot 1000^{\left(\frac{w}{w_f}\right)-1} \quad (1)$$

The liquid transport coefficients are implemented once the moisture content is above a reference MC, which is typically selected from the moisture storage function as the MC in equilibrium with 80% RH. This default method was used in this analysis. The measured water absorption coefficient and saturation water content were also used for this analysis.

Measurements for many hygroscopic materials show an increasing vapour permeability (decreasing vapour resistance factor) with increasing RH. For wood this can be attributed to combined vapour diffusion and bound water diffusion. The vapour diffusion resistance factor was assigned a constant value between 0% and 25% RH, corresponding to the measured dry cup value; an exponentially decreasing function of RH between 25% and 80% RH based on a fit to measurements; and a constant value between 80% and 100% RH to avoid double counting, as the model uses the liquid transport coefficients above 80% RH.

The factor of 3.8 in Equation (1) was adjusted to reach agreement between the measured water uptake and simulated water uptake in the laboratory immersion and inundation experiments. Hourly measured laboratory temperature and RH were used as boundary conditions.

Simulation of the CLT roof assembly used hourly weather data averaged from several Portland weather stations near the project site [21] and hourly interior temperature and RH measured in the building. The initial MC of each CLT layer in the model was set to the measured value.

3 RESULTS AND DISCUSSION

3.1 BUILDING MOISTURE MONITORING

The moisture content of CLT panels was between 9% and 15% from the time when sensors were installed at the production facility (Nov 2016) until the panels were unwrapped on the project site (Jan or Feb 2017). Thus the panels were not exposed to any unusual moisture loads during storage or shipping [11, 12]. After panel installation, however, the moisture content spiked following exposure to precipitation.

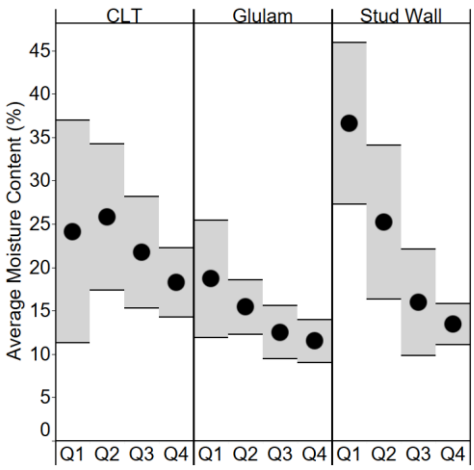

Figure 5: *Average moisture content of CLT, glulam, and stud walls over each quarter (Q) of 2017 with standard deviation*

The moisture levels in different wood products and different locations within the building were found to vary considerably, especially during the construction process. Figure 5 depicts moisture content in CLT panels, glulam columns and beams, and lightweight wood-frame stud walls for each quarter of 2017. As expected, the variability for CLT and glulam is most pronounced in the first quarter prior to enclosure of the building. This variability reflects differing exposure to precipitation. After the wall and roof envelope components were completed, the timber components gradually dried and the variability gradually decreased.

The CLT sensor locations remained at high moisture levels longer than the glulam columns and beams and stud walls. This may be a result of the horizontal orientation of CLT panels that exposed a larger area to rain wetting, longer uncovered wetting duration during construction, and the presence of an impermeable membrane on the top side of the CLT panels installed in April 2017. The glulam and stud wall locations were partially sheltered by overhead CLT floor and roof panels, and their drying was not impeded by any barrier.

Only one group of five sensors installed to measure moisture content in each layer of CLT roof panels functioned continuously (without damage) through the monitoring period. These measurements are shown in Figure 6. The top layer is distinctly different from the others and has the highest moisture content, as expected from its direct exposure to precipitation. The bottom layer is also distinct in having the lowest moisture content. After the CLT was covered with an impermeable membrane in April 2017, the moisture content in the middle layers (2-4) generally increased, likely as a result of moisture transfer from the top layer downwards.

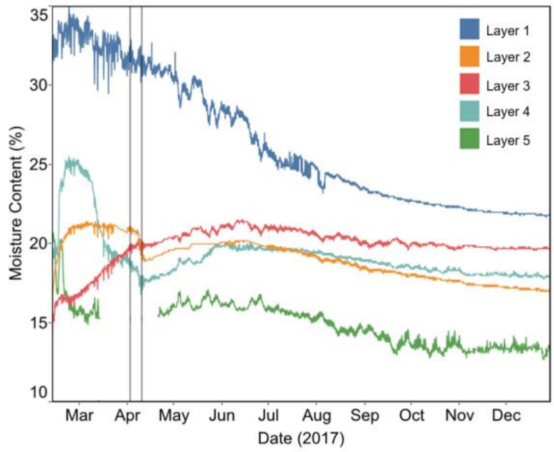

Figure 6: *Moisture content over time in each layer of a CLT roof panel (1: top layer; 5: bottom layer); vertical lines represent timing of tarped drying and the installation of impermeable membrane*

The slow drying of the CLT roof panel in Figure 6 is similar to one of the CLT wall configurations monitored by McClung *et al.* [6]. In that study, a western Canadian SPF CLT panel, initially soaked with water, was covered with an exterior impermeable membrane and exterior insulation and installed for monitoring in the wall of a test facility. The moisture content in this wall configuration remained above 20% for 12 months, similar to the top roof layer shown in Figure 6.

3.2 MODELING OF LABORATORY WETTING AND DRYING MEASUREMENTS

Measured water uptake versus the square root of time was linear for both partial immersion and inundation laboratory experiments (not shown). The water uptake data for the two panels under partial immersion are shown in Figure 7 (linear time axis), along with the uptake simulated with WUFI software. The liquid transport coefficient for suction was calculated according to Equation (1), but the constant was changed from 3.8 to 1.9 to improve the accuracy of the simulation. This reduction of the liquid transport was necessary because the RH-dependent vapour diffusion played a significant role in overall moisture transfer in the simulation; further details are given by Kordziel [18]. This method avoided the need to adjust the liquid transport coefficient for redistribution by 10 orders of magnitude as done by Lepage [5]. The simulation slightly under-predicted the water uptake at early time and under-predicted the drying rate (over-predicted the moisture content) after the panel was removed from the water (at about 720 h) and allowed to air dry in the laboratory.

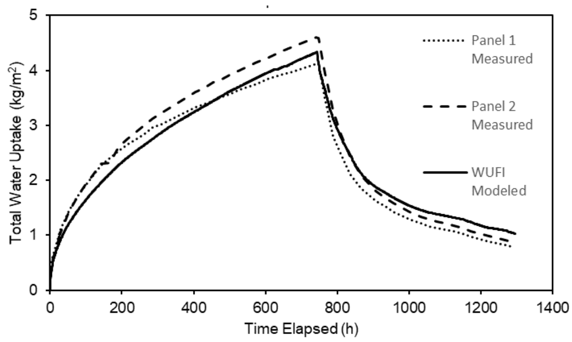

Figure 7: *Measured water uptake in partial immersion experiment for each panel and calibrated simulation*

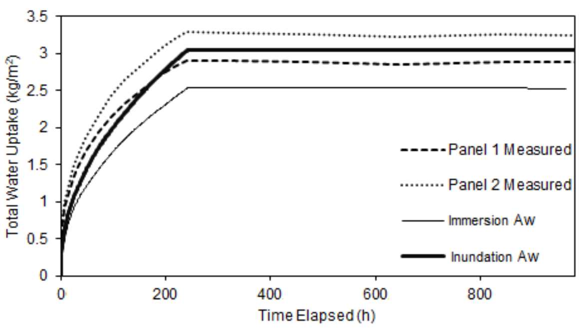

Figure 8: *Measured water uptake in inundation experiment for each panel and calibrated simulations*

The water uptake data for the two panels measured in the inundation laboratory experiment are shown in Figure 8. The simulation was performed both with the water absorption coefficient (A_w) determined from the partial immersion experiment from Figure 7 (thin solid line in Figure 8) and the A_w value determined from the inundation measurements (thick solid line). The A_w value for the inundation experiment was greater than that for the partial immersion experiment, most likely as a result of water being able to fill gaps between boards when introduced from the top side in the inundation experiment. Any significant drying after removal of water from the top of the panel (at about 240 h) was prevented by impermeable polyethylene film placed on the top side of the panel. Redistribution of moisture downward through the panel and drying through the bottom side occurred, but at a relatively slow rate. Further details including sensitivity analysis and comparison of the simulations to the moisture contents measured with pin-type sensors at various depths are reported by Kordziel [18].

3.3 MODELING OF CLT ROOF ASSEMBLY

The measured and simulated moisture content in each layer of the CLT roof panel are compared in Figure 9, starting from the time when the CLT was covered with an impermeable membrane (April 2017). Layers 1, 3, 4, and 5 all show agreement generally within ±2% MC between measurement and simulation, although the drying rate of Layer 1 is under-predicted by the model (maximum difference of 3.5% MC). This under-prediction of drying rate (over-prediction of MC) is similar to the laboratory partial immersion experiment shown in Figure 7. In addition, McClung *et al.* [6] found that simulation under-predicted CLT drying rate in a western Canadian SPF CLT wall assembly in comparison to field measurements.

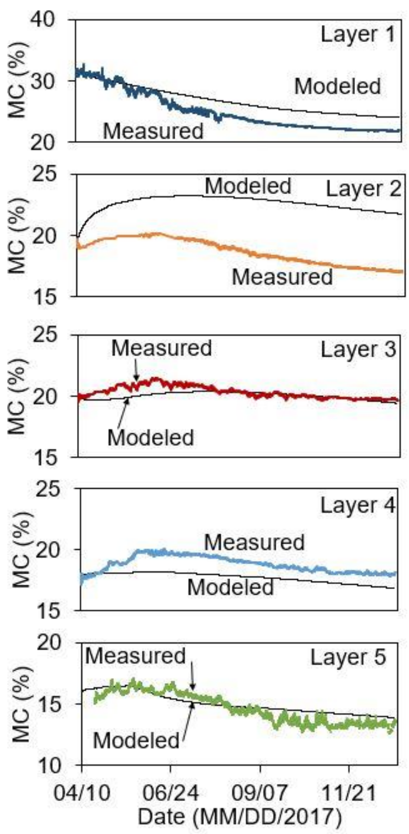

Figure 9: *Comparison of measured and simulated moisture content in each layer of the CLT roof panel*

The largest discrepancy in Figure 9 is Layer 2, which reaches a considerably higher moisture content in the simulation than in the measured data (maximum difference of 4.8% MC). The rise in moisture content in the simulation of Layer 2 comes from redistribution of moisture from Layer 1. The discrepancy may come from the sensor installation method, where a small pocket was notched in the top CLT layer for sensor placement. This air pocket above Layer 2 was not included in the model.

4 CONCLUSIONS

This paper presents one of the first sets of moisture monitoring data on a mass timber building in the US. Moisture levels were monitored from the time of CLT panel fabrication through transport, construction, and operation of an eight-story mass timber building in Portland, Oregon. While moisture levels were stable prior to construction, high moisture contents were measured in CLT, glulam, and stud walls during exposure to record levels of precipitation. The drying rate of CLT was reduced by application of impermeable membranes on the roof and floor panels, which limited drying to one direction. Calibrated hygrothermal simulations agreed reasonably well with laboratory and building site measurements, though CLT drying rates were slightly under-predicted by the simulations. Future research will include moisture monitoring of mass timber buildings in different US climates with refined instrumentation methods and further comparison with simulations.

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