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Dry-out behaviour of cross-laminated timber (CLT) edge conditions in roof assemblies: A field study

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ABSTRACT

Exposure to wetting is a concern during mass timber construction and in service. Mass timber roof assemblies are susceptible to moisture intrusion and sustained loading as surface ponding. Because wood is hygroscopic, cross-laminated timber (CLT) panels absorb and store moisture when exposed to bulk water. Moisture is rapidly absorbed parallel to the direction of wood grain, making the edge of CLT panels particularly vulnerable to sorption. This field study monitors the moisture of CLT panel edges to assess distribution patterns and dry-out behaviour. Field data was collected for 11 months from a mass timber building under construction in Toronto, ON. CLT roof assembly data was collected at ten locations, each location measuring the following data points: relative humidity (%) and temperature (°C) at the interior surface of the CLT, and moisture content (%) and temperature (°C) at three depths in each CLT panel: the interior wood layer, the center wood layer, and the exterior wood layer. The results of this field study demonstrate the volatility of the moisture behaviour at CLT edge conditions in mass timber roof assemblies, including: the impact of exposure to moisture prior to the direct application of an impermeable membrane to the exterior surface of the CLT. Two major outcomes of this research are: 1) the comparative analysis of dry-out rates based on MC monitoring location within the CLT panels (interior, center, or exterior wood layer), and 2) the observation of moisture sorption within the center layer of a CLT panel during the monitoring period. The results of this research demonstrate a significant increase in the dry-out period of any wood layer measuring above 15 % MC, particularly at the exterior wood layer where the measured dry-out rates (%MC/hr) are on average approximately 1.5–2.5 times slower than those measured at the center and interior wood layers. An exception to this outcome was noted at the center wood layer of one of the monitoring locations where a positive dry-out rate was determined based on the collected data - indicating moisture sorption at this location during the monitoring period.

1. Introduction

The durability of mass timber roof assemblies is a concern when exposed to moisture and wetting during construction. Research shows that once wood roof decks are wet, it takes months for them to dry out below 15 % moisture content ([24]; J. [34]). The drying capacity of contemporary, high efficiency building envelope assemblies and systems is negatively impacted by the increased thermal performance requirements and subsequent increased insulation thickness or by the combined use of membranes and/or insulation materials with low vapour permeance (e.g. polyisocyanurate, extruded polystyrene, and closed-cell polyurethan spray foam) required to meet new air tightness and energy performance requirements and standards ([24]; B. [33]; J. [34]). Excessive wetting of mass timber products, particularly during construction, can lead to issues such as staining, mould, or decay, where staining and mould growth affect occupant health and building aesthetics, and decay can compromise the structural integrity of the material and building ([3]; J. [34]). It is therefore important to understand the moisture behaviour and drying response in mass timber assemblies that have been exposed to wetting prior to enclosure. Interpretation of moisture conditions observed on site towards predicting the dry-out period of mass timber roof enclosures will impact the future design and construction of such assemblies, namely the impact of implemented moisture control and mitigation strategies.

Another important consideration when dealing with moisture and wetting during the construction of CLT roof assemblies is the vulnerability and behaviour of the CLT panel edges. CLT panel edges are highly susceptible to moisture uptake due to the exposed end grain of the

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lumber, enabling rapid moisture uptake parallel to the wood grain [5]. The industry has reported a large quantity of end-grain water absorption at CLT panel edges, particularly where the end grain is not exposed to dry, warm air [17]. Joints between CLT roof panels are therefore at high risk of wetting as well as sustained elevated moisture content (MC > 19 %) because there is little to no opportunity for dry-out within the joint and towards the exterior of the CLT roof panels due to impermeable exterior materials [18], refer to Fig. 1. Horizontal assemblies, such and roof and floor assemblies, are also at greater risk of exposure to standing water during construction and several field monitoring studies have indicated that critical MC occurred after single rain events – suggesting that an accelerated construction schedule is not sufficient to mitigating moisture ingress in mass timber particularly where wood end grain is exposed [17].

The field monitoring conducted for this research investigates the moisture and dry-out behaviour at panel edges in CLT roof assemblies by measuring at multiple depths in the CLT panel at each monitoring location to generate data representative of moisture distribution and transport through the panels. Given the moisture issues observed on this site, described in Section 2, this data is invaluable in assessing the dry-out period of the CLT roof panels based on their adjacent assembly and construction conditions. The permanence of the monitoring equipment on site will also provide further insight into the moisture behaviour in the CLT roof panels once the building is occupied.

Ultimately, the data collected and analyzed in this field study will contribute to the development of site- and environment-specific CLT roof assembly design and construction standards to improve drying response and decrease the drying period of CLT in roof assemblies in cold climates. These strategies are critical in reducing the potential for mould and/or structural instability and decay in CLT roof assemblies.

2. CLT field study site, building description, and construction chronology

The Toronto and Region Conservation Authority's (TRCA) new administrative headquarters building, located in North York, Ontario, is a four-storey, approximately 7300 m^2 (GFA) mass timber building. The building design features CLT elevator and stair cores as well as CLT stairs as opposed concrete cores typically used in mass timber hybrid super-structures in North America. This site provides a unique opportunity for field testing and monitoring to measure both construction and 'as built' (i.e. in service) performance and behaviour of CLT roof panels. This study focuses on the construction period and early initial dry-out period, for a total of eleven months of monitoring to date, with future planned in-service monitoring and analysis.

Initially the CLT and GLT (glue-laminated timber) wall assemblies were instrumented for monitoring, however, it became clear during construction that further monitoring of the roof assemblies was required based on several moisture-related setbacks which occurred during construction and installation of roof assembly membranes on the CLT deck. Due to unforeseen delays in the construction schedule as well as sizeable, unexpected weather events, the CLT roof panels were exposed to moisture and wetting for a much longer period than anticipated. Furthermore, the initial application of the vapour retarder directly to the CLT roof deck was not successful (Fig. 3), moisture in the wood caused the vapour retarder adherence to the CLT roof deck to fail. The CLT required drying prior to the installation of a new vapour retarder, several drying methods were tested during this period – the most effective method was to tent and mechanically vent the entire roof surface while also forcing warm air under tarps at specific vulnerable locations and areas where surface MC readings were consistently reading well above 30 %, refer to Fig. 4.

As a result of the moisture-related issues observed during construction of the roof on this site, additional moisture content measurement devices were installed from the underside of the CLT roof deck specifically at the edges of the CLT roof panels where visual and measured surface moisture content data indicated high (> 25 %) moisture content. Two moisture content measurement devices were also installed in areas showing "typical" (≤ 16 %) moisture content for comparison. The primary purpose of these moisture content measurement devices was to monitor the dry-out behaviour of the panels exposed to typical levels of moisture vs. those exposed to high levels of moisture as defined above and to define their dry-out behaviour.

The CLT roof assemblies monitored in this study consist of either 7-layer 220 mm or 7-layer 260 mm CLT roof deck panels, refer to Fig. 5. From interior to exterior, the exterior assembly consists of: the CLT roof deck per structural drawings, 1 mm vapour barrier modified bituminous peel and stick membrane, sloped rigid insulation up to 260 mm thick (avg. RSI 1.76), 6 mm underlay board, 10 mm 2-ply modified bituminous membrane roofing, 150 mm rigid insulation (min. RSI 5.28), membrane protection and root barrier, drainage panel and filter fabric, and 38 mm gravel, Fig. 5.

Monitoring of the CLT roof panels on site focusses on the CLT edges where measured moisture content taken from the panel surfaces indicated values above 25 % for prolonged periods and where visual indications of moisture intrusion were evident.

3. Moisture content monitoring at CLT roof panels

3.1. In-situ instrumentation

The CLT roof assemblies were equipped with a total of ten moisture content data acquisition devices, each of which was connected to three point moisture measurement devices (PMM). Each point moisture measurement device is made up of a pair of insulated moisture content probes connected by the PMM device itself, measuring the electrical resistance between the probes at the uninsulated tips, refer to Fig. 6. Three depths in the CLT panel were measured using PMMs at each data acquisition device (based on CLT panel thicknesses of either 220 mm or 260 mm) as follows: 1) the interior surface wood layer at 15 mm deep, 2) the center wood layer at 120 mm deep, and 3) the exterior wood layer at either 205 mm or 215 mm deep depending on the thickness of the CLT roof panel.

All monitoring equipment was obtained from SMT Research Ltd. The

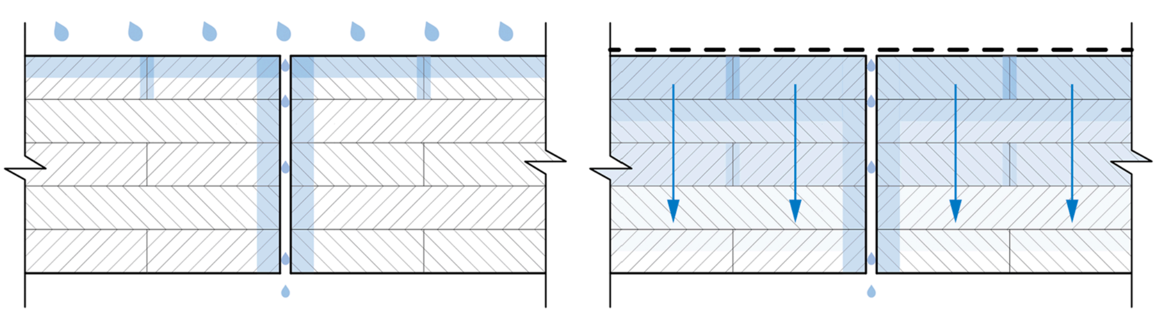

Fig. 1. Water uptake at CLT panel edge and roof surface, adapted from [19].

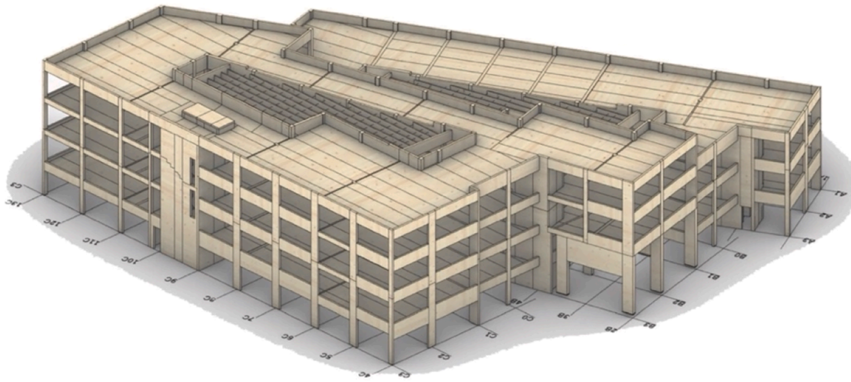

Fig. 2. Toronto and Region Conservation Authority (TRCA) administrative headquarters - Mass timber superstructure axonometric drawing [8].

Fig. 3. TRCA site photos – failed vapour retarder membrane (at protruding beams)

Fig. 4. TRCA site photo – tented roof with fans and tarps on high MC area

proprietary name of the data acquisition devices is “SMT-A3 – 8 Channel Wireless Data Acquisition Unit”, which communicates wireless sensor readings to the “SMT Building Intelligence Gateway (BIG)”. The A3 devices convert the measured raw electrical resistance data received from the connected PMM sensors in ohms (Ω) to the intended output. The proprietary name of the moisture content sensors is “Point Moisture Measurement Sensor (PMM)”, which is used to perform a direct contact measurement of moisture content in hygroscopic materials. The design of the PMM ensures moisture probes are spaced apart consistently and contains an integrated temperature sensor (°C) for temperature correction of moisture content readings. Moisture content readings are also corrected based on wood species, based on regression coefficients, [9]. In this field study, the CLT is composed of SPF (Spruce-Pine-Fir), though the exact proportion and composition of these species within the CLT is unknown. Therefore, the wood species was required to be set to “unknown”, which is an average calibration setting for data processing from the sensor and monitoring device manufacturer (SMT Research Ltd.). Accuracy of the A3 devices in measuring electrical resistance (Ω) is ± 1 % for the range of the data collected in this field study. However, it is important to consider the wood species, unless exact wood species is known, this is an additional uncertainty of ± 3 % MC [14,15,26,36,4], with less uncertainty at lower MC values (<12 %) and increasing uncertainty as MC values increase (>15 %). The majority of data loss and uncertainty using these moisture monitoring devices are therefore in the installation of the device itself and in knowledge of the exact species composition of the CLT.

Fig. 7 shows a typical installation of the data acquisition device and the three associated PMMs inserted into the CLT and mounted to the interior (underside) surface of the CLT roof deck at a panel edge condition – in this case the panel edge is also adjacent to a GLT column and beams.

The ten locations measured were determined based on areas of high and low moisture observed using surface moisture content probes on site, eight sensor locations were installed at high moisture locations (30 %+ MC), and two sensor locations were installed at consistently low (≤16 % MC) to allow for comparative analysis in the moisture distribution and dry-out behaviour based on peak (and initial) moisture content. In total, three locations were measured at the third floor (lower) roof, and seven locations were measured at the fourth floor (top) roof. One of data acquisition devices at the fourth floor roof malfunctioned and did not collect data during the monitoring period, therefore a total of nine locations in the roof have been monitored and analyzed in this research.

3.2. Data collection

As described in Section 2, the schedule of site-specific conditions, roof treatments, and dry-out during construction is critical when analyzing the moisture monitoring data. Installation of all ten roof monitoring locations occurred in early July 2023, one month after the application of the new vapour retarder on the CLT roof decks. The monitoring therefore did not capture the impact of the roof tenting and mechanical dry-out using fans, heat, and isolation of specific high-moisture roof areas. Instead, the monitoring period commences effectively at the start of what is intended to be the dry-out period. After the failure of the first vapour retarder application, the intention was for the entire roof deck(s) to be dried to at minimum below 19 % MC. It is

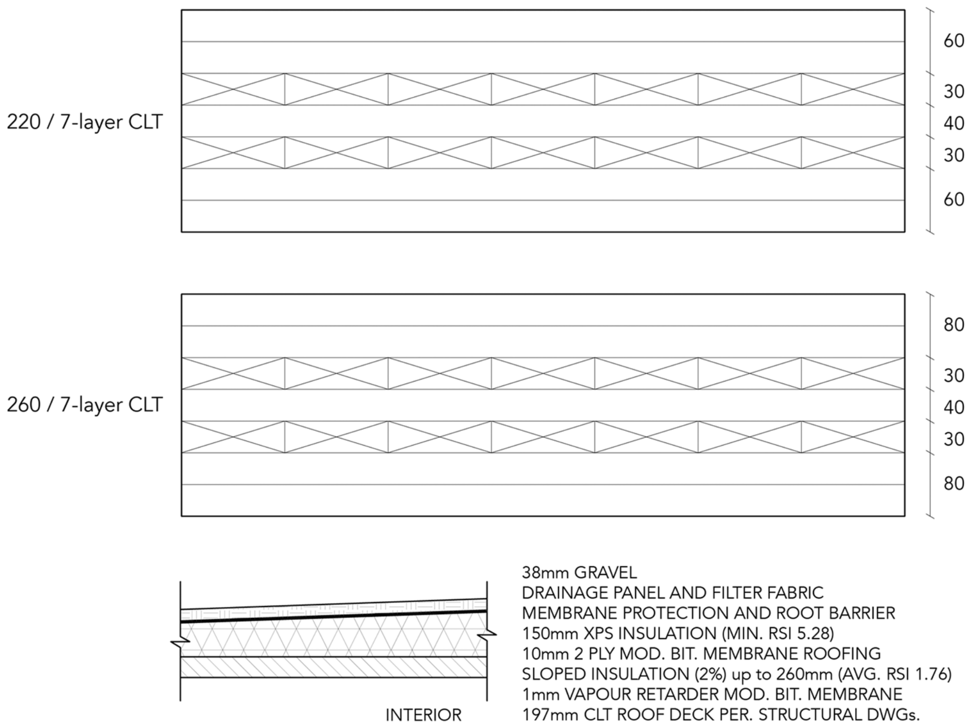

Fig. 5. Typical CLT roof panels (above) and assembly (below) – adapted from TRCA [8].

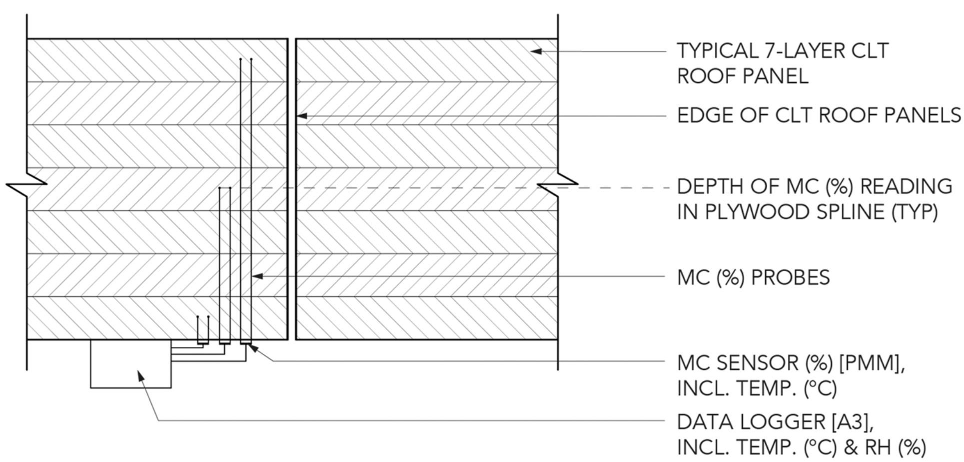

Fig. 6. Typical moisture content measurement instrumentation diagram.

important to note that 19 % MC is still above the industry standard of 15 % MC in-service based on the field study's location [1], however, 19 % MC was accepted as the threshold on site to be achieved prior to enclosure (application of any additional membranes/roof assembly materials) as it was assumed the CLT would continue drying to reach the in-service standard threhold within the first year of service. However, several of the monitored locations indicate moisture in the CLT consistently higher than 19 % prior to and after application of the new vapour control layer (impermeable membrane) and subsequently the rest of the exterior roof assembly layers. This indicates that moisture monitoring and management protocols used on site must be further developed and refined to demonstrate an accurate assessment of the moisture conditions of the CLT. The high MC areas measured were at locations showing visual signs of moisture exposure including wood staining, as expected. The start of the monitoring period in this research aligns with the installation of the exterior roof assembly.

The moisture monitoring plan was developed based predominantly on observed site conditions and for the benefit of future post-occupancy research. Two monitoring locations were selected based on their consistently low MC ($\leq$16 %) as well as their location within washrooms which will allow for future testing related to high humidity indoor environmental conditions. The remaining eight monitoring locations were dispersed proportionately in the lower (third floor) and upper (fourth floor) roof assemblies to capture variations in their locations including: exposure and adjacency to structure and/or building enclosure. Each roof monitoring location at the TRCA is described using the nomenclature in Table 1 and listed in Table 2.

Devices 1 and 2 are the 'dry' monitoring locations during construction per the site inspection's daily moisture probe readings. They are both also in washrooms, located approximately 10 feet from the East exterior envelope assembly. In this building, the washrooms have the potential to have higher relative humidities compared to the adjacent office spaces, they may also be set to different relative humidity and temperature setpoints to test moisture response in the CLT after building

Fig. 7. Instrumentation installation at underside of CLT roof deck at panel edges

Table 1
Data Acquisition Device Description and Nomenclature.

Description	Option	Identifier
Data acquisition device number (A3)	####	**####**
A3 device roof level	L3	**L3**
	L4	**L4**
A3 device exposure direction in building	North	**N**
	East	**E**
	West	**W**
A3 device general location in building	Near envelope	**ENV**
	Near center	**CTR**
	Above washroom	**WC**
A3 device nearest gridline location (not required for the purpose of this paper)	Number + Letter	**###**

Table 2
Data Acquisition (A3) Device List.

Device #	Device Name	Floor	Exposure	Relative Device Location
1	**1 – 9675_L4_E_WC**	**4**	**East**	**Baseline (“Dry”) at W/C**
2	**2 – 9677_L4_E_WC**	**4**	**East**	**Baseline (“Dry”) at W/C**
3	**3 – 9597_L3_W_CTR**	**3**	**West**	**Center of structural bay**
4	**4 – 9696_L3_W_CTR**	**3**	**West**	**Adjacent to exterior wall**
5	**5 – 9685_L3_N_ENV**	**3**	**North**	**Adjacent to exterior wall**
6	**6 – 9583_L4_W_CTR**	**4**	**West**	**Center of structural bay**
7	**7 – 9678_L4_E_CTR**	**4**	**East**	**Center of structural bay**
8	**8 – 9682_L4_W_ENV**	**4**	**West**	**Adjacent to exterior wall**
9	**9 – 9703_L4_W_CTR**	**4**	**West**	**Center of structural bay**
10 *	**10 – 9706_L4_S_ENV**	**4**	**South**	**Adjacent to exterior wall**

* Removed from study, data unavailable due to sensor malfunction

enclosure and while the building is not occupied.

Most of the remaining “wet” monitoring locations are located on the West side of the building on both the lower (L3) and upper (L4) roofs, with five total located on the West side, one on the East (aside from the “dry” monitoring locations) and one on the North side. The intent was to have monitoring locations evenly distributed between center and envelope adjacent conditions, however due to the failure of Device 10 as well as site-specific conditions, there were only two successful envelope adjacent “wet” monitoring locations at Devices 5 and 8. Based on the scope including the quantity of data points measured and period of monitoring, the data collected is large in terms of industry standards and is representative of the environmental conditions and the associated construction and observed material conditions on site. However, three of the monitored locations on the West side of the building at the upper roof level (L4) indicated much higher moisture values from the measurements taken in this study than the spot checks taken on site using largely surface conductance and surface pin readings, refer to Section 4.

4. In-situ moisture content monitoring results and discussion

The results of this research focus on the moisture distribution and dry-out behaviour of the monitored locations at the TRCA building site. Based on the linear dry-out models developed, the dry-out period is also predicted where applicable. Moisture distribution is observed through comparative analysis of the moisture measurements taken at each of the three measured depths in the CLT roof panels at each monitoring locations. The three depths at the interior, center, and exterior wood layers enable observation of the transport of moisture through the panel based on environmental conditions and adjacent materials and therefore the direction and quantity/rate of dry-out and/or absorption. The moisture content distribution results are particularly significant in addressing the impact of an impermeable membrane applied to the exterior side of the CLT on the drying response of each position in the CLT based on initial moisture content (i.e. “wet” vs. “dry”).

Moisture behaviour refers more generally to moisture transport in the material as well as moisture exchange between wood and air depending on the relative humidity and temperature of the surrounding conditions as well as the simultaneous moisture content in the wood. Moisture distribution and moisture behaviour can both impact the physical and mechanical properties of wood itself and therefore of mass timber products including dimensional stability (i.e. swelling, shrinkage, warping, checking, splitting) [12], delamination of wood layers within adhered mass timber products [13], and the potential for mould growth and/or biological degradation and decay [21,31,32,6].

4.1. Dry CLT roof panel results

The two “dry” panels monitored are located on the East side of the building. These panels are noted as dry because throughout the entire monitoring period the moisture content at all measured depths in both monitoring locations did not exceed 12 % - this is not only within the construction standard of 19 % for this site, but it also meets the ANSI/APA PRG 320–2019 standard [1] which governs CLT manufacturing conditions and processes in North America. These two panels show no moisture measurements above the device baseline threshold of 8.8 % in the interior wood layers. In both monitoring locations, the exterior wood layer shows some moisture fluctuations between 8.8 – 12 % between the initial 0–3000 hours, which is approximately the first four months of monitoring from early July 2023 through early November 2023. The center wood layer in both monitoring locations fluctuates consistently between approximately 9 – 11 % MC during this period, which is also indicative of dry conditions. Any initial dry-out period observed in both monitoring locations is negligible (see Fig. 8 and Fig. 9) as such, additional dry-out behaviour was not conducted for these panels.

The dry CLT roof panel results are provided to illustrate the consistent moisture content behaviour of CLT below 12 % MC, where fluctuations in MC are minor, and a drying response was not expected since the wood is already considered dry below this threshold. However, for other monitoring locations where higher moisture content was observed, subsequent dry-out behaviour analysis is required.

4.2. Example dry-out behaviour analysis at Device 5

There are three monitoring devices located in the L3 roof. Device 5 shows dry-out behaviour aligned to initial expectations where the exterior and center wood layers both begin with higher peak moisture content measurements compared to the interior wood layer which is protected during construction. The average dry-out rates of both the center and the exterior wood layer monitored by Device 5 were analyzed based on normalized data using a moving average of 49 hours or two full days, inclusive, and the assumption that once a moisture content of 15 % or lower is measured for two weeks or more, the (PMM) monitored location in the CLT panel can be considered “dry”, refer to Fig. 10 indicating the slope of the average dry-out rates in both layers indicated. The two-week period was established during analysis of the data based on observed fluctuations to generate a conservative estimate of the time required for wood to equilibrate at the “dry” monitored environmental and moisture conditions.

As illustrated in Fig. 10, the peak MC value in the center wood layer at Device 5 was 19.33 % and it took 1735 hours, or just over 72 days to reach $\leq$ 15 % over a minimum of two weeks. The peak MC value in the exterior wood layer at the same device (5) was a very similar 19.77 % but it took 6819 hours, or almost 8.5 months to “dry” as previously described. Evidently, this created variation in the dry-out rates, where

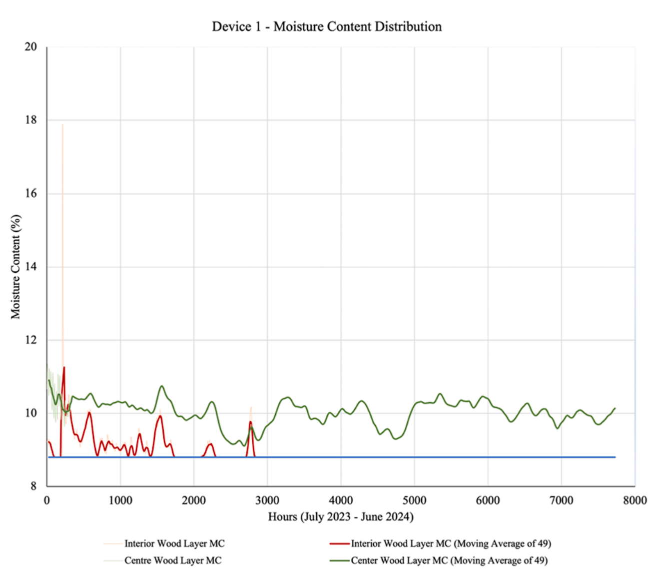

Fig. 8. Moisture Content Distribution in Baseline ("Dry") CLT Panel for Device 1.

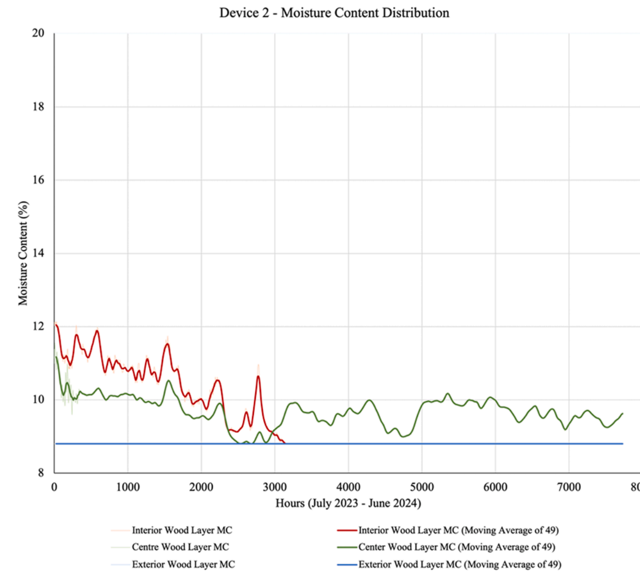

Fig. 9. Moisture Content Distribution in Baseline (“Dry”) CLT Panel for Device 2.

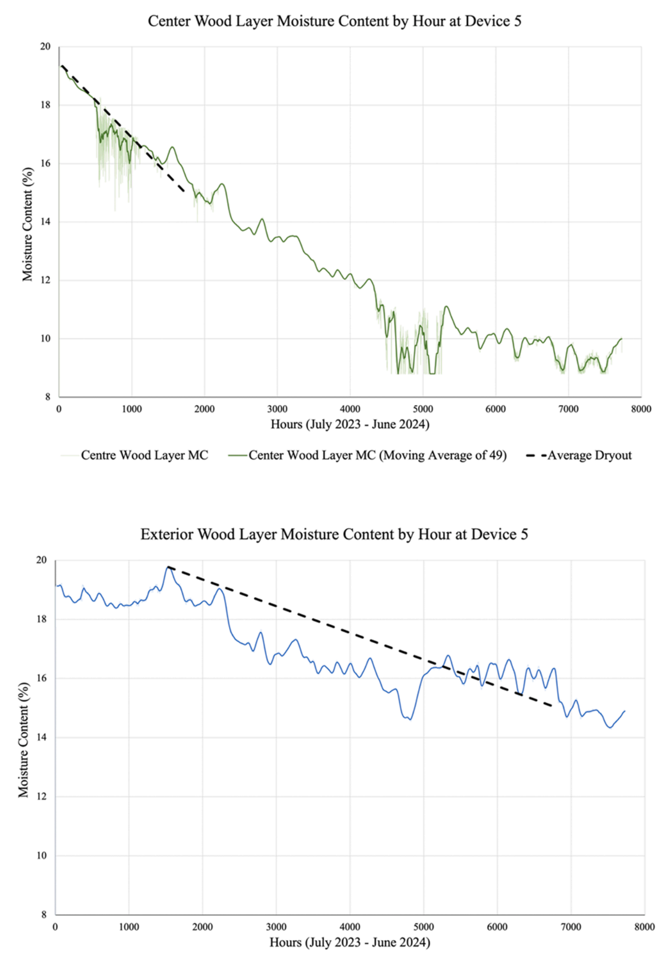

Fig. 10. Centre (above) and exterior (below) wood layer dry-out behaviour at Device 5.

the center wood layer was drying at a rate of −0.0616 % / day and the exterior wood layer above dried at the slower rate of −0.0217 % / day as illustrated by the linear average dry-out models indicated in Fig. 10. The center wood layer's linear regression model has a coefficient of determination (R^2) of 0.92, whereas the exterior layer has an R^2 of only 0.57. The slower and more volatile conditions at the exterior wood layer, as indicated by the calculated dry-out rate and the R^2 value respectively, are likely a result of the application of the impermeable membrane directly to the CLT prior to reaching MC below 19 % inhibiting drying towards the exterior of the CLT panel.

4.3. High MC CLT roof panel results

From the four "wet" (high MC) monitored locations at the L4 CLT roof deck, Device 7 did not reach MC readings above 11 % at any of the monitored layers and therefore will not be further analyzed in this study aside from noting that this was the only monitored location on the East side of the building aside from the "dry" sensor locations. The other three "wet" monitored locations at the L4 CLT roof deck were on the West side of the building where most roof ponding and water retention was observed on site during the erection of the mass timber structure and CLT roof deck. These three devices show the highest moisture content readings from this study aligning with the moisture-related issues observed on site and spot-checked moisture readings taken during construction. These three monitoring location were at areas which required protection and additional mechanical drying previously described. Fig. 13 shows the moisture content distribution and behaviour in each of the monitoring locations. A moving average of 49 hours (2 days) was used to analyze the remaining data, as originally presented in Fig. 10. The use of this moving average removed sharp fluctuations in the moisture content readings which indicate measurement uncertainty. The exact cause of measurement error in the data collected is unknown, however, several known causes of error for electrical resistance pin-type moisture meters include: 1) leakage down the length of the MC probes, 2) condensation on the PMM bolts protruding from the CLT panel, 3) electrical noise on inputs in the data loggers from direct connection of the PMM sensors to the building, and finally the most likely cause in this case 4) dimensional instability of the CLT/wood layers caused by fluctuating moisture conditions causing disconnection between the probe tips and the wood. In most cases, measurement error was obvious for periods less than 24 hours, making the use of a 49-hour moving average justified in improving the accuracy of the data analyzed. Where large gaps in the data exist, the linear dry-out rate analysis is performed either after the gap as shown in the exterior layers of Devices 6 and 9 (Fig. 11 and Fig. 13, respectively), or if possible the gap is interpolated. Interpolation of the moisture content data at the exterior wood layer at Device 8 is described below and illustrated in Fig. 14.

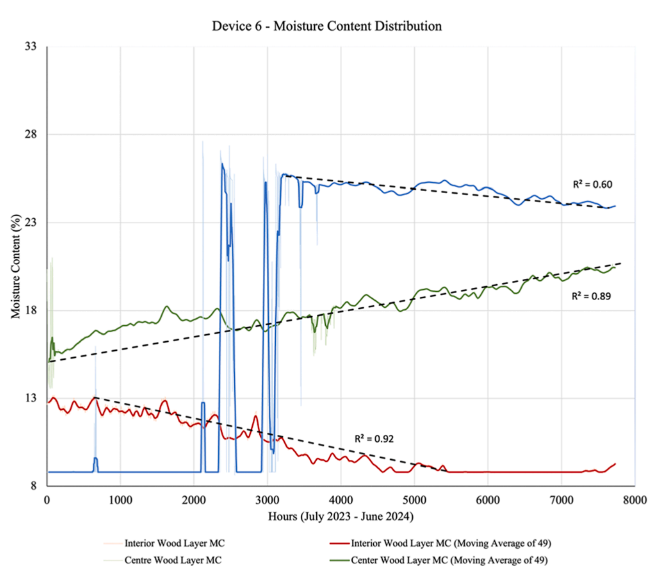

Fig. 11. Moisture content distribution in "wet" CLT roof panels at Device 6.

Fig. 12. Moisture content distribution in "wet" CLT roof panels at Device 8.

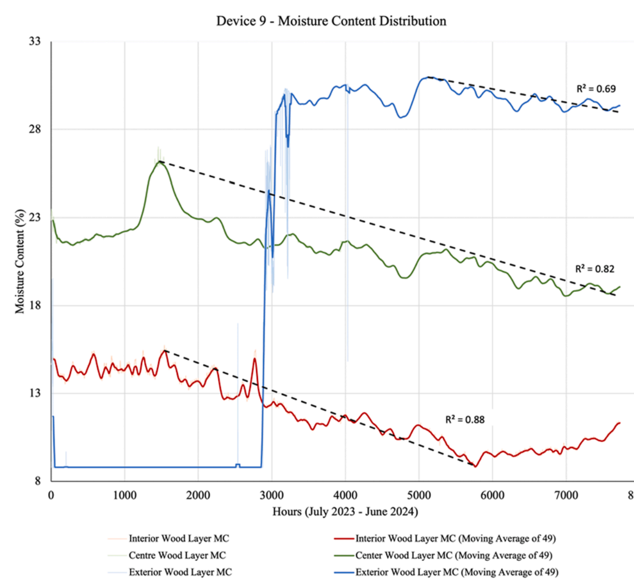

Fig. 13. Moisture content distribution in "wet" CLT roof panels at Device 9.

The implications of the large gaps observed in the data has either required data omission from the field study analysis or a reduction in the extent of the data analyzed per wood layer at each measurement device, as described. Evidently, further development of the instrumentation process and potentially of the instruments themselves is required to address data loss. In particular, a method to address connection failure between the probe tips and the wood would likely show a significant reduction in data loss.

Device 8 is missing periods of data from the exterior wood layer, however given the slope and pattern of this data, the missing hours between approximately 4000 and 6700 can be interpolated and assumed to fluctuate between the data points on either side of the gap, which would be around 24 % MC consistently, refer to Fig. 14. Given this

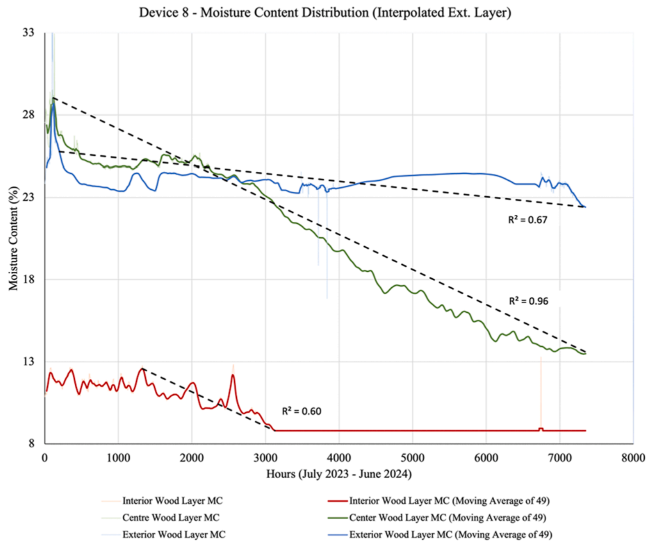

Fig. 14. Device 8 moisture content distribution including interpolated exterior wood layer data.

interpolation of the data, the dry-out behaviour of Device 8 emulates the dry-out behaviour observed in the baseline "dry" monitoring locations observed on the East side of the building except at much higher MC values and with much longer dry-out periods and consequently slower dry-out rates. In fact, the exterior wood layer only began to show signs of drying approximately 500 hours (21 days) prior to the end of the period illustrated, which was approximately 10.5 months after the data collection began and almost one year after the exterior roof assembly was installed on the CLT roof deck.

Device 9 indicates very consistently high levels of moisture in the exterior wood layer as well as consistent moisture content in both the center and interior layers, with minimal to no indication of any dry-out occurring during the data collection period. The rapid spike in MC in only the exterior wood layer at around 3000 hours is indicative of a sensor malfunction prior to the spike and it can be assumed that the MC was consistent around 30 % prior to the spike, for the entire data collection period and illustrated in Fig. 13. The concern at this monitored location is that there is no indication of dry-out in the exterior wood layer in the first 11 months of monitoring, and that the center wood layer shows indication of very slow dry-out only. In Device 6, the concern is that the center wood layer is showing signs of further wetting/moisture loading over the period monitored and the exterior wood layer is also only indicating very slow dry-out.

Average linear dry-out models as demonstrated in Fig. 10, were drawn for each monitored depth at the three monitoring location with the highest sustained moisture content values: Device 6, 8, and 9, see Fig. 13. Table 3 summarizes the results of these models in%/hr and %/day rates allowing for the prediction of the overall dry-out period for these monitored locations (at each monitored depth). Table 4 summarizes the results of the dry-out analysis in days and years based on the previously determined %/day dry-out rates.

The MC/day (%) rate from Table 3 is illustrated in Fig. 15. This clearly demonstrates the consistently slower dry-out rates at the exterior wood layer compared to the center and interior wood layers. It also indicates the positive rate of the center wood layer at Device 6 which indicates moisture absorption, not dry-out. It is possible that the moisture loading observed at the center wood layer is a result of the impermeable membrane applied to the exterior wood layer which could be inhibiting dry-out towards the exterior thereby changing the direction of moisture transport towards the interior of the CLT. This would mean moisture was being transported from the higher MC exterior layer through the CLT to center wood layer. However, given that the other two

Table 3
CLT dry-out behaviour analysis at high MC monitoring locations.

Device	Wood Layer	Peak MC (%)	Min. MC (%)	Dry-out Rate (%/Hr)	Dry-out Rate (%/Day)	C.O.D. (R2)
6 – 9583_L4_W_CTR	Interior	13.05	8.80	−0.0008	−0.0192	0.92
8 – 9682_L4_W_ENV	Interior	12.58	8.80	−0.0021	−0.0504	0.60
9 – 9703_L4_W_CTR	Interior	15.44	8.86	−0.0016	−0.0373	0.88
6 – 9583_L4_W_CTR	Center	20.67	15.08	0.0007	0.0173	0.89
8 – 9682_L4_W_ENV	Center	29.04	13.49	−0.0021	−0.0504	0.96
9 – 9703_L4_W_CTR	Center	26.18	18.54	−0.0012	−0.0295	0.82
6 – 9583_L4_W_CTR	Exterior	25.62	23.84	−0.0004	−0.0097	0.60
8 – 9682_L4_W_ENV	Exterior	28.69	22.39	−0.0009	−0.0209	0.67
9 – 9703_L4_W_CTR	Exterior	30.97	28.99	−0.0008	−0.0182	0.69

Table 4
CLT dry-out behaviour analysis at high MC monitoring locations.

Device	Wood Layer	Days to 19 % MC	Days to 15 % MC	Years to 15 % MC
6 – 9583_L4_W_CTR	Interior	*n/a*	*n/a*	*n/a*
8 – 9682_L4_W_ENV	Interior	*n/a*	*n/a*	*n/a*
9 – 9703_L4_W_CTR	Interior	*n/a*	11.77	*n/a*
6 – 9583_L4_W_CTR	Center	*no dry-out occurring*		
8 – 9682_L4_W_ENV	Center	199.12	278.47	0.76
9 – 9703_L4_W_CTR	Center	243.25	378.72	1.04
6 – 9583_L4_W_CTR	Exterior	679.51	1090.09	2.99
8 – 9682_L4_W_ENV	Exterior	465.15	657.20	1.80
9 – 9703_L4_W_CTR	Exterior	658.57	878.72	2.41

wet monitoring locations do not show the same trend at the centre wood layer it is more likely that there is out-of-plane liquid water movement through the CLT that is being captured at this particular location. A prevalent type of damage in CLT panels is pronounced cracking in the gluelines and lamellas of adhered products due to swelling and shrinkage of wood layers caused by moisture fluctuations [7].

4.4. Limitations and context of results

Measurement error and uncertainty are the primary limitations of this field study. In several cases, the measurement devices malfunctioned causing impractical measurement drops or spikes in the data. Additional measurement uncertainty is caused by the one-dimensional nature of the point measurement devices, which cannot capture out-of-plane movement of liquid water. Finally, accurately translating the electrical resistance readings (Ω) taken by the PMM devices into moisture content (%) values requires wood species correction factors as discussed in Section 3.1. Sensor malfunction further limited the repeatability of the data collected, where in some cases missing data from one of the PMMs at the same A3 device made analysis of moisture transport through the CLT panel unreliable to the point of omission. The collected data was therefore culled to the two "dry" and three "wet" locations discussed which could be further analyzed based on data

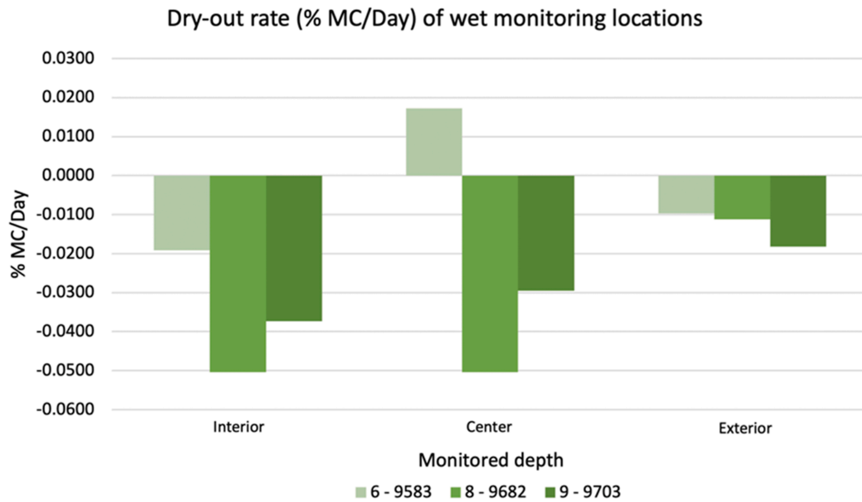

Fig. 15. CLT dry-out rates per measurement depth at 'wet' monitored locations.

availability and consistency at these locations.

The moisture sorption trend discussed at the center wood layer at Device 6 emphasizes a limitation in the point moisture content measurement method, which provides inherently one-dimensional results whereas CLT is three-dimensional material. Out-of-plane moisture transport is a known, prevalent issue mass timber construction and, as evidence by the results of this field study, can cause significant increase in moisture content even after enclosure of the assembly. Further research is therefore required to determine a conservative error range of one-dimensional moisture monitoring techniques in three-dimensional hygroscopic materials such as CLT - where liquid transport is often idealized in predictive models.

Many recent studies have demonstrated the importance of controlling and/or mitigating moisture and bulk water intrusion during construction and mass timber buildings ([10,16,17,23,25,27]; E. L. [28]; E. [29,30]; J. [34]; L. [35]). The protection and drying response of roof assemblies have been a prevalent topic of discussion among mass timber case studies. For example, a case study in Norway looking and fungal damages of mass timber elements states the primary cause of moisture intrusion during construction as insufficient protection from rainfall leading to the requirement for drying of assembly and structural components after the building is watertight [2]. Similarly, this field study observed substantial moisture intrusion during construction, which led to membrane damage and significant construction delays to dry the CLT roof panels prior to enclosure.

Based on the literature reviewed, one of the primary recommendations to avoid critical levels of moisture content in CLT is a rapid construction/installation process, however this is difficult to define. This goal is often idealized during design stages as there are numerous potential causes for delay during construction – namely, increasingly unpredictable and severe weather events causing high moisture and delayed work to allow for timber to dry. Ongoing research presented by ASHRAE [11], is studying the impact of moisture protection strategies for mass timber buildings based primarily on field studies. Finch's work [11] stresses the importance of this research in the context of all mass timber structures, specifically those that require specific wood encapsulation for fire protection during construction, where the risk for moisture entrapment between mass timber components and encapsulating materials is high – necessitating a higher degree of protection of the mass timber assemblies beyond current code requirements. This field study substantiates the prolonged drying response of CLT wetted prior to enclosure and prior to conditioning of the interior environment, particularly at trapped wood layers (i.e. exterior and core layers). These results are reflected in field studies performed by Schmidt (E. L. [28]), McClung [24], Lepage [22], and Kordziel [20], who all found that the rate of drying was considerably slower when the wetted wood surface was covered with an impermeable membrane (compared to being left exposed).

The chronology of the conditions on site also demonstrates the reality of damage to building materials adjacent to wetted mass timber. These results further indicate the need to develop site-specific, conservative moisture control and mitigation strategies for implementation during CLT roof assembly design and construction. Furthermore, the data collected from this field study could be used to conservatively predict the dry-out period of CLT in roof assemblies during construction and in-service based on the observed moisture conditions and measured dry-out rates.

5. Conclusions

The dry-out behaviour of the CLT roof panel edge conditions monitored in this case study demonstrates the need to address and implement consistent moisture control strategies during mass timber construction. The elevated moisture conditions (>19 %) found at several vulnerable locations in the CLT roof align with those required for mould growth to occur, particularly where elevated moisture was recorded for extended periods. The data collected reflected the conditions observed on site including visual assessment of water retention (ponding), wood staining at the interior side of CLT roof panels, and measured spot checks that were performed during construction as part of the on-site moisture management protocols.

This analysis also reveals the moisture transport and distribution through the panels, indicating that end-grain (CLT edge) wetting of CLT coupled with conditions that trap moisture (impermeable membranes) can significantly decrease the dry-out rate. This is clearly demonstrated by the considerably slower dry-out rates measured at the exterior wood layer, where the impermeable membrane is inhibiting drying towards the exterior and where the adjacent wood layers below the exterior layer are effectively slowing drying towards the interior as well – trapping moisture within the CLT roof assembly. On average, the dry-out rates at the exterior wood layer were 1.5 – 2.5 times slower than those measured at the center and interior wood layers. As observed on site during construction, application of adhered membranes directly to wet (>19 % MC) CLT surfaces can also result in rapid loss of adhesion and membrane uplift in addition to reducing the dry-out capacity of the CLT.

The data analyzed was collected during the construction period only, the building was not conditioned or occupied during this period aside from the tented roof structure which was mechanically ventilated and heated prior to the start of this monitoring period. Further research is required to investigate the continued dry-out behaviour of the CLT roof in service as well as the impact of occupancy conditions on the moisture behaviour and distribution in the CLT.

Mould modeling for occupant health and as a proxy for decay is also necessary to understand and predict the durability, performance, and potential health impacts of CLT in roof assembly applications. Additional research to quantify the impact of moisture control and moisture mitigation strategies including the use of vapour permeable membranes, the integration of ventilated air cavities, and the protection of CLT edges and surfaces from wetting during construction would benefit the development of high-performance, durable CLT roof assemblies.

CRediT authorship contribution statement

Dorothy Johns: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Russell Richman:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Russell Richman reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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