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Assessing the effectiveness of cross-laminated timber (CLT) roof assembly moisture control and mitigation strategies: A field laboratory

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ABSTRACT

Exposure to moisture and wetting is a concern in mass timber construction and service. Understanding the moisture conditions and the drying response of mass timber during construction and service can impact durability of the building material and occupant health because of the potential for biological degradation and mould growth, respectively. Cross-laminated timber (CLT) used in roof assemblies is particularly susceptible to high moisture loading from exposure to driving rain and extended periods of ponding and water retention on roofs during construction. The field research conducted in this study utilises a purpose-built CLT test facility in Toronto, ON to test and assess the impact of three specific moisture control strategies towards both mitigating moisture and increasing the dry-out rate of CLT used in roof assemblies. The moisture control strategies tested were: (1) the integration of an air cavity directly above the CLT within the roof assembly, (2) the protection of CLT during exposure and moisture loading periods on site, and (3) the permeability of membranes installed in the roof assembly and during site exposure. The CLT roof panels underwent four months of exposure to exterior environmental conditions followed by two months of bulk water inundation at the CLT test facility site immediately prior to installation and enclosure. Moisture content was monitored at evenly distributed depths in the CLT panels throughout exposure and inundation periods and for one year of simulated service conditions, post-enclosure. Comparative analysis of the moisture control strategies tested during this field laboratory demonstrate that the presence of an air layer above the CLT in the roof assembly consistently doubled the dry-out rate compared to the assemblies without an air cavity. The results also found that unprotected CLT panels took approximately 2.5 times longer to dry-out to below 15 % MC than protected panels and finally, that in comparing the results of using impermeable vs. permeable air/vapour barrier membranes on the surface of exposed CLT, that the impermeable membrane slowed the dry-out rate of wetted CLT by approximately 20 %. The results of this research support the implementation of specific moisture mitigation and control strategies during design and construction towards promoting rapid dry-out of CLT in roof assemblies in service.

1. Introduction

1.1. Importance of dry-out period in CLT roof assemblies

Cross-laminated timber (CLT) is a prefabricated, engineered wood product composed of orthogonally glued lumber which must be manufactured to meet ANSI/APA PRG 320 Standard for Performance-Rated Cross-Laminated Timber [1] in North America. Because wood is a hygroscopic material the absorptive characteristics of CLT can lead to occupant health concerns and material degradation through growth of mould and decay fungi, respectively [2–5]. As a result, it is important to manage moisture and identify localised areas of moisture degradation concerns [6–12].

CLT used in exterior horizontal assemblies (e.g., roofs) is at an increased risk of high moisture content compared to vertical applications (e.g., walls) due to large areas of exposed CLT surfaces to environmental conditions including rain, the potential for standing water (flooding and ponding), and subsequent gravimetric moisture and bulk water uptake. This research focusses on the impact of moisture mitigation and control strategies used in the design and construction of CLT flat roof assemblies on the drying response of the CLT roof deck during service.

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In North America, it is required that CLT products maintain a moisture content of < 15 % - < 16 % during service, depending the building's location [1,13]. The Canadian CLT Handbook as well as FPL's (Forest Products Laboratory) Wood Handbook [14,15] both suggest multiple methods towards improving the drying response and performance of CLT during construction and in service. Increasing the dry-out rate of CLT drastically reduces the potential for aesthetic, physical, and biological degradation during construction and in service [6–12,15].

The field testing performed in this research is based on recommendations provided in the Canadian CLT Handbook [15] and FPL's Wood Handbook [14], as well as moisture monitoring and mitigation strategies recommended by North American mass timber manufacturers. The aim of this research is to quantify the impact of several recommended moisture mitigation and control strategies by field testing these strategies methodologically and analyzing the resulting moisture content data to quantify any observed reductions in the dry-out period of the CLT and consequently in the potential for mould growth.

1.2. *Moisture content monitoring of CLT*

Moisture content influences the durability of wood by increasing the risk for mould and decay as indicated in Fig. 1. Moisture content variations can impact the dimensional stability of the material through shrinkage and swelling, because the outermost layers of wood are impacted by variations in interior and exterior climate conditions first, the resulting moisture gradient will lead to internal stresses in the cross-section of the CLT. As an adhered product, these stresses often lead to pronounced cracking in the glue lines of the CLT prior to checking of the wood itself [2,16,17].

Quantifying the moisture content of CLT over time therefore provides a strong indication of the presence of mould as a health risk to occupants, and of mould as a proxy to decay as a risk of biological and structural degradation of the material impacting the durability of the building's structural system. As quantifying moisture demands a measurement of the sample in its (oven) dry state, [18] oven-drying [19] cannot be completed in the field, nor can it be completed on adhered timber products due to the resulting evaporation of chemical wood treatments and adhesive layers which can impact the structural capacity of the product as well as the accuracy of moisture readings. Therefore, moisture content sensors are used for measuring the moisture content of mass timber in-situ.

There are two primary types of conductance (resistance) moisture content sensors: pin-type, and pinless. A pin-type moisture sensor has two or more metal pins (probes) that penetrate the material, whereas a pinless moisture sensor uses electromagnetic wave technology to measure the MC of a material. Modern moisture sensors can be as accurate as ± 1 % MC for manufacturer provided operable temperatures. The accuracy of electrical moisture content readings are dependent on the calibration of the moisture sensors based on the localised wood structure and environment (eg. species, density, grain orientation, thickness, MC, and temperature) [18,20–22]. It should also be noted that above 30 % moisture content, the typical fibre saturation point of wood, conductance-type (resistance-type) moisture content sensor readings lose accuracy exponentially, making readings above 30 % moisture content unusable in this research.

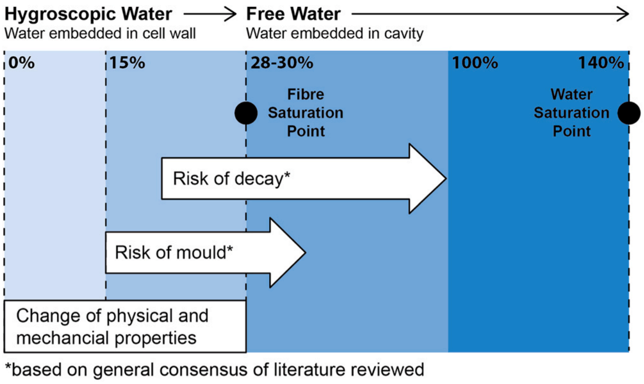


Fig. 1. Range of wood MC influence on its properties and vulnerability, adapted and modified from [2].

This field experiment has been conducted using pin-type moisture content sensors which are installed to take moisture content measurements at evenly distributed depths through each CLT specimen, see Fig. 2. This monitoring strategy provides a moisture distribution profile through each CLT specimen as well as the opportunity to analyze the temporal moisture behaviour including absorption, desorption, moisture loading, and dry-out periods through the wood layers of each specimen. This moisture monitoring strategy also reflects those successfully used in previous laboratory and field studies [2,6,12,23–28].

As discussed, moisture is a deterioration mechanism in almost every building material [29]. Therefore the ability of a building material and an enclosure assembly to dry, store moisture, and its resistance to wetting are very important in assessing the vulnerability of the assembly to biodeterioration and moisture-related damage [29]. The moisture content of wood is impacted by several types of moisture transport in buildings materials, including vapour diffusion (absorption and desorption), advection (adsorption), capillary action, and liquid transport (bulk water movement).

Based on the literature reviewed, a moisture content in wood of 16 % is suitable to initiate growth of *some* fungi, but most fungi require sustained moisture levels above 30 % to cause fungal decay and therefore structural concerns in mass timber construction [30–35]. Results of this study are not within the range of decay, therefore the focus of the analysis will be to conservatively estimate mould risk as described in Sections 1.3, and 4.2, and as summarised in Table 6.

1.3. *Occupant health in mass timber buildings*

The health impacts of mould are well documented in medical papers, journals, and regulations [36–40]. Mould is of particular concern to individuals with compromised immune systems or with known allergies. Occupants exposed to high fungal spore loads may also become sensitised and develop allergic responses to mould. Because wood is be susceptible to mould, it is important to consider the impact of the drying response of mass timber on occupant health.

2. Research objectives

The primary objectives of this research are: (1) to characterise and compare the initial drying response of CLT in roof assemblies after building enclosure based on specific moisture control and mitigation strategies, and (2) to conservatively assess the surfaces of CLT within roof assemblies for mould based on the implemented moisture control and mitigation strategies. These objectives are largely defined by the following research question: What are the impacts of moisture control and mitigations strategies implemented during design and construction on the initial dry-out behaviour of CLT in roof assemblies?

The research objectives and question defined above are based on observed site conditions, current areas of concern in the construction industry, and from the literature reviewed. The experimental research performed in the literature reviewed primarily studies the performance and moisture content of mass timber in wall (vertical) assemblies [24–26,41–43] as opposed to roof (horizontal) assemblies. This is a notable gap in research that must be addressed particularly as horizontal assemblies are inherently prone to proportionately larger areas of bulk water exposure as well as the potential for standing water, potentially leading to conditions appropriate for the development of mould and decay.

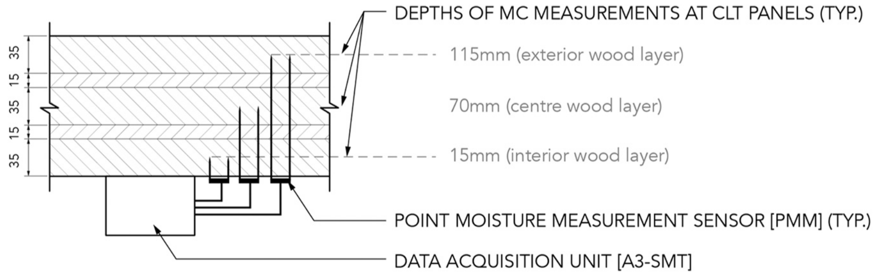


Fig. 2. Point moisture measurement sensor [PMM] distribution in 5-layer CLT panel.

3. CLT roof testing methodology

3.1. Moisture control and mitigation strategies

Three specific moisture control and mitigation strategies towards improving the dry-out capacity of CLT in service have been tested for this research in a controlled purpose-built field-laboratory setting. The moisture control and mitigation strategies tested are based primarily on strategies provided in the Canadian CLT handbook [15], mass timber manufacturer recommendations, and as a response to field conditions observed during the construction of multiple mass timber buildings in Ontario, Canada. The strategies selected for this research were presented to either completely avoid the uptake of moisture and bulk water during construction and/or to encourage higher dry-out rates and therefore decreased periods of high moisture in the CLT during construction and in service. These strategies include: (1) the integration of an air cavity directly above the CLT within the roof assembly, (2) the protection of CLT during exposure and moisture loading periods on site, and (3) the permeability of membranes installed in the roof assembly and during site exposure.

To test the three selected moisture control and mitigation strategies, eight CLT roof assembly specimens were designed. Each specimen was configured to monitor specific independent moisture control and mitigation variables described in Table 1. Table 2 lists the independent variables applied to each CLT specimen using established nomenclature from Table 1.

3.2. CLT specimen preparation and instrumentation

All eight CLT roof assembly specimens have the following attributes:

- CLT panel dimensions: 610 mm x 610 mm
- CLT panel composition: 5-layer SPF (Spruce/Pine/Fir) CLT
  - o Wood species set to 'undefined' for the purpose of data analysis, as the composition of SPF in the CLT used in this study is unknown but is likely to be predominantly Black Spruce in combination with Jack Pine based on the manufacturer's primary mill location in Northern Ontario

Table 1
Summary of independent variables.

Variable	Description	Option	Identifier
Moisture Protection	Protection or exposure of CLT during exposure and inundation periods	Protected Unprotected	**PR** **UR**
Vapour Retarder	Use of one of the following vapour retarders: • Permeable – Class III @ 1658 ng/ Pa s m2 (29 perms) • Impermeable – Class I @ 1.8 ng/ Pa s m2 (0.031 perms)	Permeable Impermeable	**PM** **IM**
Air Cavity	Presence (decoupled) or absence (coupled) of a 25 mm air cavity on the exterior side of the CLT Note: air cavity is not vented.	Coupled Decoupled	**CC** **DC**

Table 2
Specimen list.

Panel #	Name
Panel 1	**1 - DC/PR/PM**
Panel 2	**2 - CC/PR/PM**
Panel 3	**3 - DC/PR/IM**
Panel 4	**4 - CC/PR/IM**
Panel 5	**5 - DC/UR/IM**
Panel 6	**6 - CC/UR/IM**
Panel 7	**7 - DC/UR/PM**
Panel 8	**8 - CC/UR/PM**

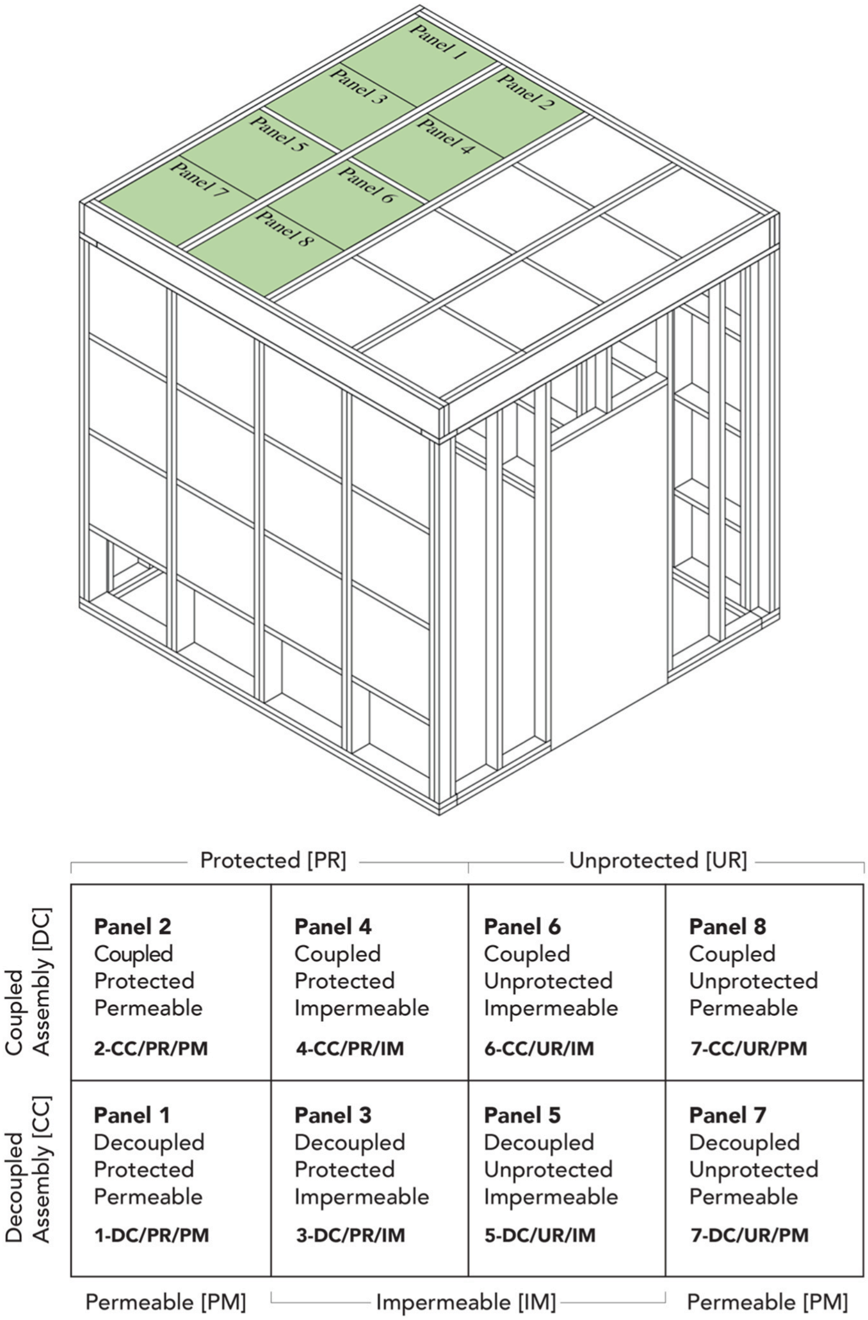
- CLT wood layer thicknesses (Fig. 2):
  - o Layers 1, 3, and 5 = 35 mm
  - o Layer 2 and 4 = 15 mm
- CLT specimen edge treatment: liquid-applied asphaltic waterproofing membrane (Fig. 3)
- Exposure period: four months (Fig. 3).
- Inundation period: two months (Fig. 3).
- Monitoring period: during exposure and inundation periods, and for one year following enclosure.
- Monitoring frequency: all measurements are taken hourly during the monitoring period.
- Monitoring equipment (per CLT specimen):
  - o 1 data acquisition device (wireless data acquisition unity) measuring temperature (°C) and relative humidity (%) at the location of the logger (interior surface of CLT).
  - o 3 point moisture measurement (PMM) devices connected to insulated probes with exposed tips, measuring temperature (°C) and moisture content (%) (via electrical resistance readings at exposed probe tips) at three depths in the CLT: the interior wood layer (15 mm from interior surface), the centre wood layer (70 mm from interior surface), and the exterior wood layer (115 mm from interior surface), see Fig. 2

Treatment of the PMMs and probes is critical to obtaining accurate moisture content readings. The probes are insulated along their length with an exposed tip allowing for electrical conductance to occur only at the end depth of the exposed tip. Using wood species correction coefficients, the electrical conductance (resistance) measured hourly is converted to moisture content and temperature readings based on the Garrahan equation [44]. The PMMs are also sealed to the interior (unexposed) face of the CLT specimens to ensure moisture (liquid or vapour) cannot travel into and within the core drilled for the installation of the PMM probes from the interior side of the CLT specimens.

During the exposure and inundation testing the data loggers and moisture content sensors were protected from bulk water by being mounted on the underside of the CLT specimens and raised from the exposure surface - which in the case of this field laboratory was a flat roof assembly as shown in Fig. 3.

Typical coupled (no air cavity) and decoupled (with air cavity) specimens are illustrated in. The eight CLT specimens, per Table 2, were configured in Toronto Metropolitan University's CLT test facility as

Fig. 3. 4-month exposure period (left), and 2-month bulk water inundation period (right).



	Protected [PR]		Unprotected [UR]	
Coupled Assembly [DC]	**Panel 2** Coupled Protected Permeable **2-CC/PR/PM**	**Panel 4** Coupled Protected Impermeable **4-CC/PR/IM**	**Panel 6** Coupled Unprotected Impermeable **6-CC/UR/IM**	**Panel 8** Coupled Unprotected Permeable **7-CC/UR/PM**
Decoupled Assembly [CC]	**Panel 1** Decoupled Protected Permeable **1-DC/PR/PM**	**Panel 3** Decoupled Protected Impermeable **3-DC/PR/IM**	**Panel 5** Decoupled Unprotected Impermeable **5-DC/UR/IM**	**Panel 7** Decoupled Unprotected Permeable **7-DC/UR/PM**
	Permeable [PM]	Impermeable [IM]		Permeable [PM]

Fig. 4. Test facility layout of CLT specimens with moisture control and mitigation strategies implemented.

indicated in Fig. 4.

3.3. Exposure and inundation testing

Prior to installation and enclosure in the CLT test facility, the CLT specimens were sealed at the perimeter edges and equipped with data acquisition units and point moisture measurement devices, following which they were exposed to environmental conditions for four months (late May 2022 – late September, 2022) followed by two months (late September 2022 – late November 2022) of inundation in Toronto, Canada.

There is no standardised test method for liquid water absorption by inundation. However, the test performed in this study was modelled on the liquid water absorption by partial immersion test [45] revised to effectively flip the panels horizontally and therefore to contain water on the top side of the panel allowing for absorption relying primarily on gravimetric water transport mechanisms as opposed to water absorption by only capillary forces. The inundation apparatus and period included in this study was modelled on the water absorption by inundation test performed by [46], the testing apparatus for Kordziel's test required a reservoir constructed on the top (exposed/exterior) side of the CLT panels to contain the liquid water for an extended period against the surface of the CLT. To isolate the surface of the CLT, the edge conditions of each panel were sealed using a liquid-applied asphaltic waterproofing membrane, except at edges where splines would be later installed. The liquid-applied asphaltic waterproofing membrane proved resistant to moisture uptake during concurrent material characterisation laboratory testing, therefore, this method was mirrored during the experimental research performed in this study.

Sealing the CLT edges is a critical step in the experimental set-up as the edge conditions of CLT expose the end grain of the wood layers to surrounding environmental conditions. Because moisture travels more quickly parallel to wood grain compared to perpendicular, exposed CLT edges are vulnerable to rapid moisture uptake [47]. 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 [48], joints such as spline conditions are therefore at high risk of wetting as well as sustained elevated moisture conditions because there is little to no opportunity for dry-out within a joint condition. The liquid-applied asphaltic waterproofing is used to isolate for the moisture control and mitigation strategies being tested and to simulate a continuous (adiabatic) moisture boundary condition assuming a much larger scale of CLT panels typical on site.

Like Kordziel's test, the inundation testing apparatus for this experiment was installed on site using an acrylic dam sealed to the waterproofed sides of the CLT specimens using neoprene caulking as well as waterproof tape for structural support. This varies from Kordziel's test only in the location of the dam perimeter, where in this test the installation adhered to the sides of the CLT panel rather than the top (as in Kordziel's study), this allowed for the full exposed face of the CLT to be in contact with liquid water. Moisture monitoring in each panel was continuous during both the exposure and inundation periods. Ultimately, the purpose of the exposure and inundation periods in this research was to elevate the moisture content of the wood layers from the exterior side of the CLT panel to simulate standing water conditions often observed on mass timber construction sites prior to roof assembly enclosure.

3.4. CLT test facility

Monitoring the dry-out period of the CLT roof assembly configurations required an enclosed, conditioned space to simulate CLT assembly enclosure conditions during construction and in-service. The CLT test facility used in this study was constructed for the purpose of this research in Toronto, Canada. The CLT test facility is an approximately 2.7 m × 2.7 m enclosed, conditioned space with no openings aside from the entry door. The roof has been sloped 2 % to accommodate required water run-off towards the North side of the building. Each 610 mm × 610 mm CLT roof panel was installed within the lightwood framing of the building as illustrated in Fig. 4. The CLT test facility is continuously insulated using mineral wool insulation for the wall assemblies (nominal RSI = 3.52), and polyisocyanurate for the roof assembly (nominal RSI = 7.04).

Fig. 5 demonstrates the conditions observed at the interior surface of the CLT specimens prior to and post-enclosure in the CLT test facility. It is evident that the interior conditions during the service period monitoring still fluctuated based on exterior environmental conditions despite efforts to maintain consistent temperature and relative humidity.

4. Results and discussion

All eight CLT specimens were monitored: (i) during exposure, (ii) during inundation testing, and (iii) for approximately one year after enclosure in the CLT test facility. The exposure and inundation periods were defined and executed to simulate typical conditions observed on mass timber construction sites in North America, and to allow sufficient time for quantification and comparison of the initial in-service dry-out period between all moisture control and mitigation strategies implemented in each specimen. The results will analyze and compare the initial dry-out behaviour (rate, time, and distribution) and subsequent mould risk based on current industry standards.

4.1. Initial results

Table 3, Table 4, and Table 5 summarise the findings of each moisture mitigation and control strategy tested as described in Section 3.1. Critical measurements for analysis of this data include the peak moisture content reached at the time of enclosure at the test facility as well as the number of hours required for the panels to dry-out from peak moisture content (MC) to ≤ 11 % MC.

Each graph illustrates the initial dry-out period at each moisture monitoring location from the time at which the CLT panels were enclosed at the test facility. The data presented has been normalised using a moving average of 49 hours to remove sharp fluctuations in the moisture content readings which indicate measurement uncertainty. The precise cause of measurement error is unknown, however, several known causes of measurement error for electrical resistance pin-type moisture metres include: (1) leakage down the length of the moisture content probes (unlikely here due to installation of the probes occurring from the underside of the panels), (2) condensation on PMM bolts protruding from the exterior side of the sensor (unlikely here because after panel installation the PMM bolts were protected by sealant), or 3) electrical noise on all inputs on the data loggers from the direct connection of the PMM sensors to the building which can occur when using electrical resistance-type moisture metres (again, unlikely as the test facility is lightwood framed). As such, the most likely cause of measurement error is a result of variable connection/contact between the tip of the moisture content probes and the wood within the drilled cores. Variable contact in this case could be caused by fluctuating moisture content in the wood causing dimensional instability – where, diminishing moisture content in wood can cause shrinkage, thereby resulting in periods of disconnection between the tip of the moisture content probes and the wood generating error in the electrical resistance measurements. This type of measurement error was obvious for up to a 24-hour period, therefore the use of a 49-hour (2 day) moving average in the data analysis is justified in improving the accuracy of the data analyzed.

4.1.1. Protected vs. unprotected panels

Specimens 1–4 were protected during exposure and inundation periods, and specimens 5–8 were unprotected (exposed) during the same

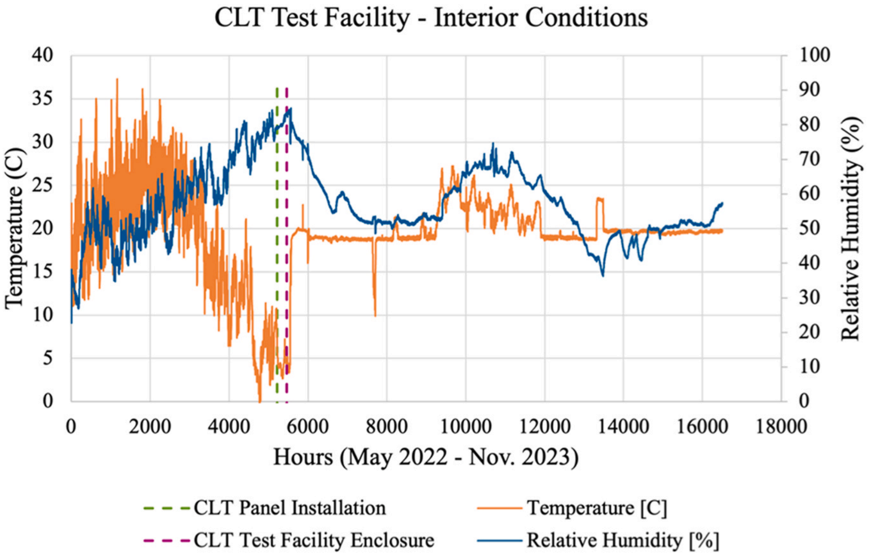


Fig. 5. Interior Temperature and Relative Humidity of CLT Test Facility.

periods (refer to Fig. 4).

It is evident from the graphs in Table 3 that unprotected CLT panels show both higher initial peak moisture content readings and moisture loading in the exterior wood layers of the CLT panels, prior to drying out.

4.1.2. *Permeable vs. impermeable membranes*

Specimens 1 and 2 were protected using permeable membranes which remained installed during envelope enclosure and specimens 7 and 8 had permeable membranes installed after the inundation period during envelope enclosure. Similarly, specimens 3 and 4 were protected using impermeable membranes which remained installed during envelope enclosure, and specimens 5 and 6 had impermeable membranes installed after the inundation period during envelope enclosure (refer to Fig. 4).

It is difficult to visually assess a clear distinction in peak moisture content, moisture loading, and moisture dry-out periods between the permeable vs. impermeable specimens shown in Table 4. However, in the exterior wood layer it is evident that specimen 6 – which had an impermeable membrane installed after inundation and between the exterior assembly layers – has a slower dry-out rate than the exterior wood layer in Panel 8 which mimics the conditions of specimen 6 except for the use of a permeable membrane installed after inundation. Specimens 6 and 8 also have very similar initial/peak MC values – 18.14 % and 17.50 %, respectively – at the time of building enclosure including application of membranes on the exterior wood layer which was exposed during inundation for both specimens. Further comparison of specimens 6 and 8 will therefore be performed to assess the impact of permeable vs. impermeable membranes under very similar MC conditions. Initial results from specimens 6 and 8 also indicate minimal measurement error compared to all other monitored, this enables further analysis of the moisture distribution gradient and movement of moisture through the CLT panel.

4.1.3. *Coupled vs. decoupled assemblies*

Specimens 1, 3, 5, and 7 were assembled during enclosure to include a 25 mm air cavity (decoupled assembly) on the exterior (top) side of the CLT, and specimens 2, 4, 6, and 8 were assembled with exterior membranes and insulation installed directly on the CLT with no air cavity (coupled assembly).

From the graphs in Table 5, coupled assemblies clearly demonstrate higher moisture in the centre and exterior layers after enclosure as well as longer dry-out periods.

4.2. *Linear and phased linear analysis of dry-out*

The following analysis has been completed to address the primary goal of this research - to quantify and compare the impact of each moisture mitigation and control strategy on the drying response of the CLT conditions and subsequently, to conservatively assess the impact of these strategies on the potential for mould using current industry standards. This analysis has been completed by comparing moisture content measurements over time and using the a linear regression model to determine the average dry-out rate to predict the time each assembly will take to dry-out from the initial peak moisture content to below the established 15 % moisture content mould risk threshold and finally to below 11 % MC to be considered dry based on mass timber manufacturing standards. Refer to Fig. 6 illustrating the analysis performed for each monitoring location in all specimens, where the average dry-out rate can be calculated using the general slope formula.

Where,

PMC = peak moisture content [%]

DMC = dry moisture content [%]

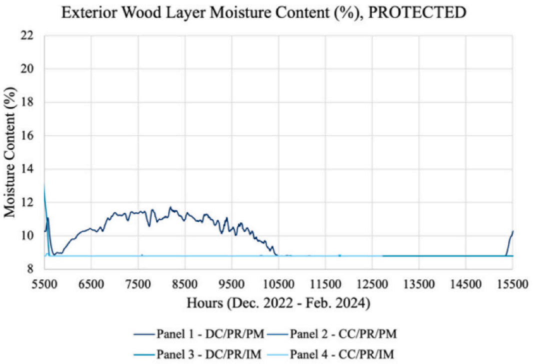
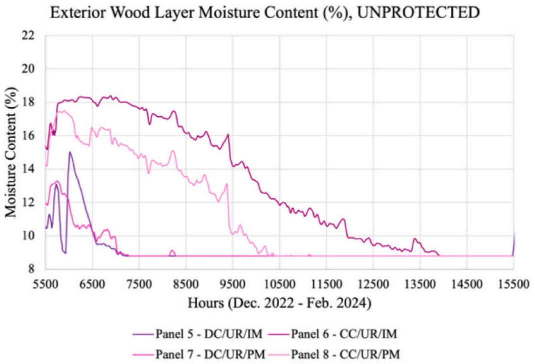
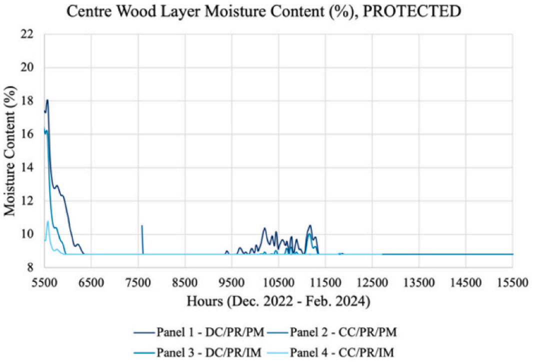
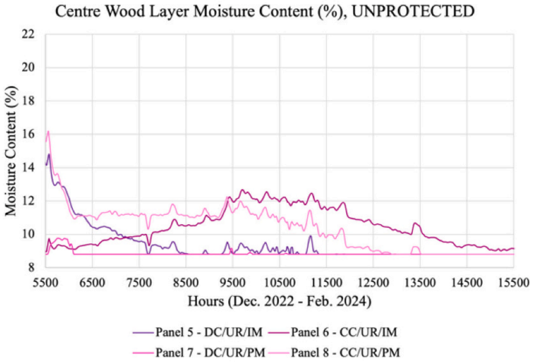
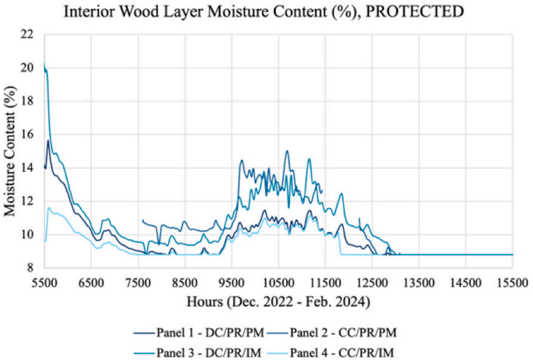
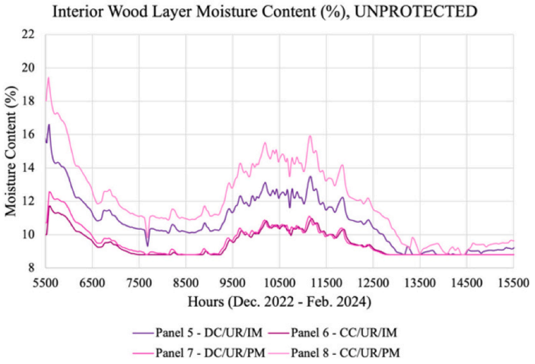
Additionally, the accuracy of the simplified linear predictive models will be compared to the readings using a coefficient of determination (R^2). Using basic algebraic methods with peak moisture contents above 15 % and the associated dry-out rate, the amount of time can be determined until the panel is not at risk of mould growth by isolating for time using the following equation:

$$15\% = \text{PMC} - (\text{rate of dryout}) * \text{time}$$

Fig. 6 illustrates the linear regression analysis performed and Table 7 and summarise the results of this analysis for all moisture content readings taken adjacent to surfaces where the potential for mould growth exists, including: the interior and exterior wood layers of the CLT specimens.

Within this investigation additional phased linear analyses were conducted to measure the dry-out response of the CLT panels within three distinct ranges of moisture content associated with the dry-out rate as well as the peak moisture content measured within each assembly, refer to Table 6. The “mould risk range” upper limit is based on the results from the CLT panels which did not exceed 29 % MC. The upper limit of the “typical moisture range” is based on current industry standards which requires the equilibrium moisture content (EMC) of wood in mass timber in service to be < 15 % MC over one year without

Table 3
Moisture content of protected vs. unprotected CLT specimens.

Depth	Protected [PR]	Unprotected [UR]
Exterior 115mm	 Exterior Wood Layer Moisture Content (%), PROTECTED	 Exterior Wood Layer Moisture Content (%), UNPROTECTED
Centre 70mm	 Centre Wood Layer Moisture Content (%), PROTECTED	 Centre Wood Layer Moisture Content (%), UNPROTECTED
Interior 15mm	 Interior Wood Layer Moisture Content (%), PROTECTED	 Interior Wood Layer Moisture Content (%), UNPROTECTED

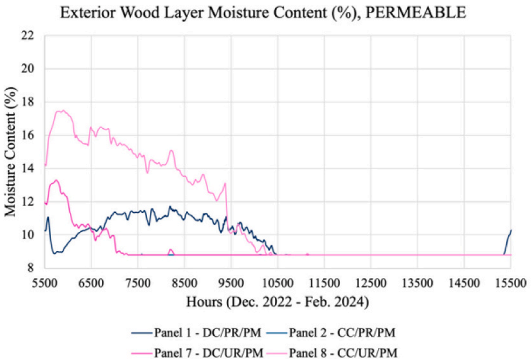
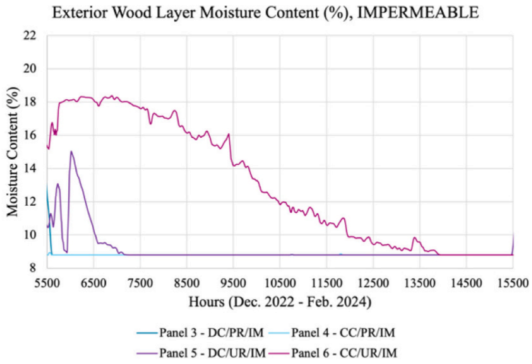
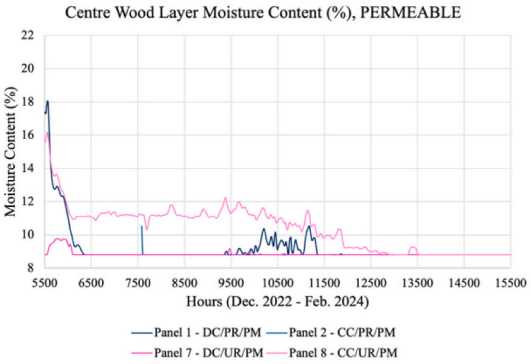
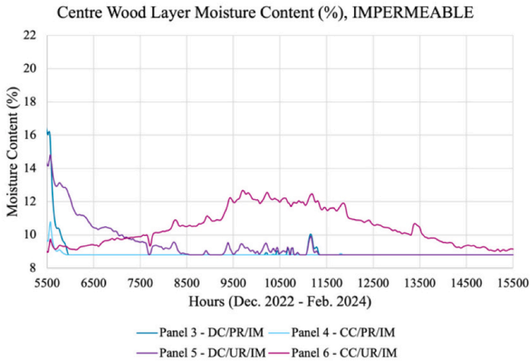
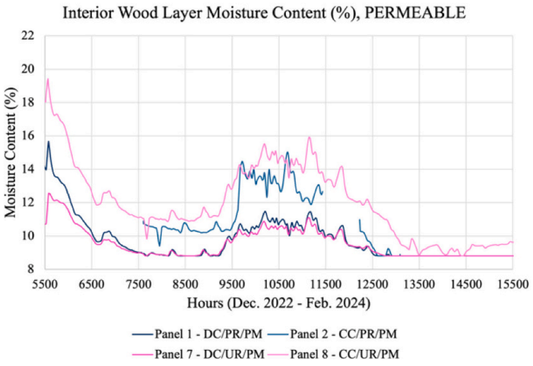
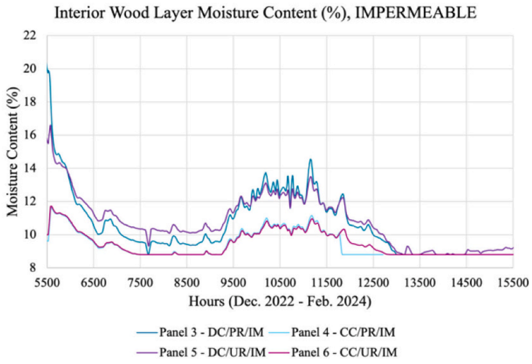
exceeding 19 % in Canada, and < 16 % in the United States [1], the AWC National Design Specifications for Wood Construction reflect the PRG 320 standard, stating the MC of CLT in service must be less than 16 %. The upper limit of the “typical moisture range” has therefore been conservatively set to 15 % MC. The upper limit of the “dry range” is representative of mass timber manufacturing standards which require wood to be 11 % ± 3 %, and the lower limit of the “dry range” is based on the lower limit of the PMM devices used for this study which cannot differentiate MC values below 8.8 % when set to an undefined wood species, see Fig. 7. This limitation varies by ± 2 % MC depending on the wood species defined for data acquisition and processing. The purpose of the phased linear analysis was to look for a relationship between the actual moisture content and the dry-out rate, and to generate linear regression models within these ranges that fit the data more accurately than the simplified linear models.

The “mould risk’ range has been simplified and defined for this research as moisture content values above 15 %, based on the current industry standards described above. Many empirical mould models exist to quantify mould risk, mould growth, and/or to assess for the initiation of conditions required for mould (germination) [34,39,49–53]. Because the purpose of this research is primarily to quantify and compare the impact of specific moisture control and mitigation strategies on the drying response of CLT in roof assemblies, 15 % MC is used as a conservative threshold to associate the significance of the observed drying response and dry-out period to its potential impact on occupant health.

4.3. *Mould risk analysis*

To assess the risk of mould growth, the average dry-out rate was analyzed using simple linearization of dry-out as illustrated in Fig. 6. Because mould growth occurs only on the surfaces of bio-based materials such as wood, mould risk was only assessed at the exterior and interior wood layers of each CLT specimen, where moisture conditions in the wood and subsequently the adjacent environmental conditions (eg. equivalent relative humidity and temperature) contribute to mould potential. By determining the initial peak moisture content after

Table 4
Moisture content of permeable vs. impermeable CLT specimens.

Depth	Permeable [PM]	Impermeable [IM]
Exterior 115mm		
Centre 70mm		
Interior 15mm		

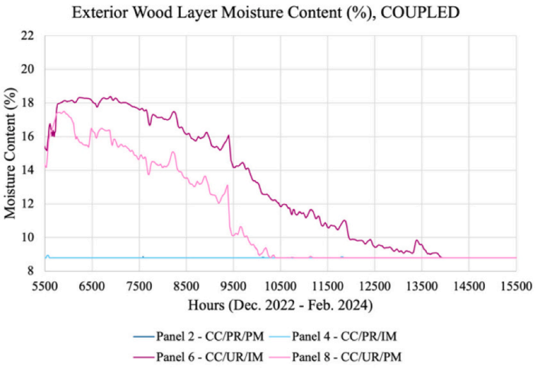
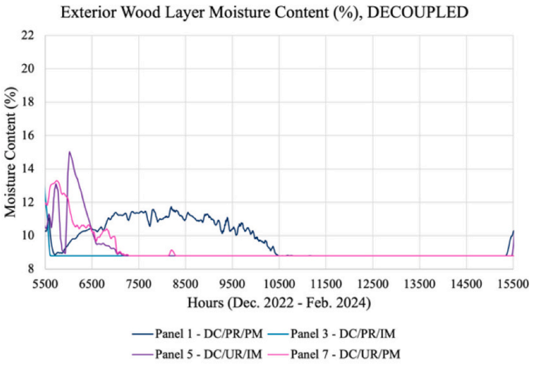
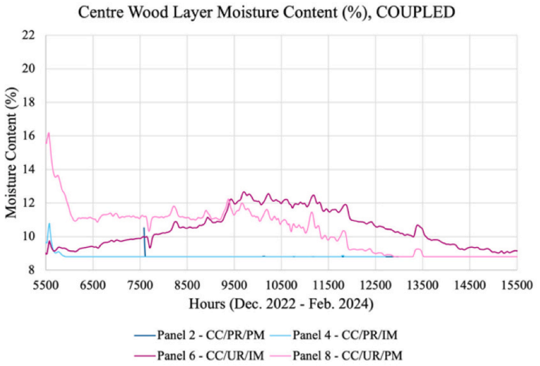
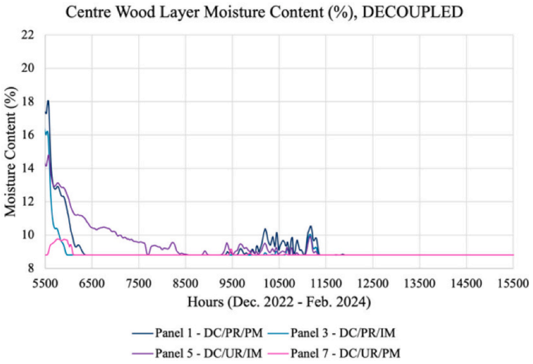
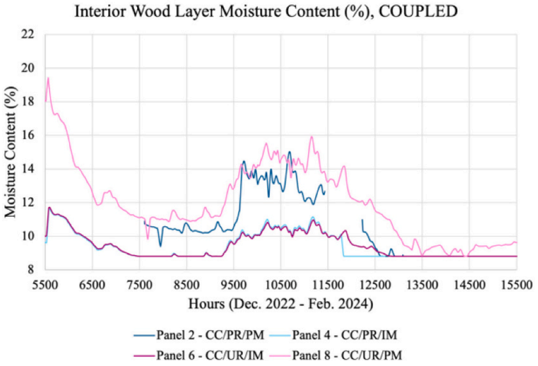
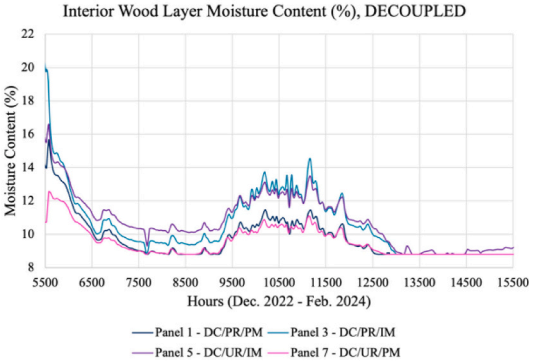
installation and enclosure of the specimens in the CLT test facility, any specimens that are immediately at risk of mould growth can be determined by observing whether the peak moisture content is above 15 % (the conservative limit defined for this research as described in Section 4.2). After identifying which assemblies are vulnerable, the average rate of change (slope) from the linear approximation of the function was drawn. Both the average linear analyses and phased linear analyses were drawn for every specimen to study the impact of moisture content and the tested independent variables on the dry-out rate.

As discussed in Section 4.1, moisture content fluctuations have been normalised using moving averages based on data analysis techniques used in similar experiments [54] to minimise the impact of outliers without removing them entirely. Therefore, the average moisture content readings were normalised by calculating the average of the 24 hours before and after each reading (i.e. a moving average of 49). To calculate the average dry-out rate, the value of the peak moisture content after assembly enclosure was identified and recorded at the time which it occurred.

Because of the variability of the moisture content readings, this study defines ‘dry’ not as an instantaneous reading of 11 % or lower, but as when the average reading at a given time remains less than 11 % MC for the following two weeks or more. This reduces the impact of the localised minima on the dry-out rate. An important note that the dry-out rate cannot be calculated for specimen that reached a peak moisture content of less than 11 %, as they were already considered ‘dry’. Specimens with a peak moisture content of less than 15 % have no hours in the mould risk zone.

Based on these findings, multiple specimens were found to be at risk of mould growth. Generally, time in the mould risk zone at the interior layer trends with interior relative humidity conditions of the test facility and based on the time noted, is only within the mould risk zone for up to 18 days, except for specimen 8. Specimen 8 shows mould risk in all PMM depths through the panel and for extended periods of time compared to all other panels. Specimen 6 also shows the longest period in the mould risk zone at the exterior wood layer of any other PMM location indicating over three months of moisture measured above 15 % MC.

Table 5
Moisture content of coupled vs. decoupled CLT specimens.

Depth	Coupled [CC]	Decoupled [DC]
Exterior 115mm		
Center 70mm		
Interior 15mm		

4.4. Comparative analysis of moisture control and mitigation strategies

To compare the overall results of each moisture control and mitigation strategy tested, the number of hours above 15 % MC observed at all monitored depths of all specimens are summarized in Fig. 8 for each independent variable (moisture control and mitigation strategy) tested.

The longest period of mould risk observed occurred in unprotected panels and coupled panels at the exterior wood layer. Notably, centre and interior layers showed very little time in the mould risk range across all independent variables. As expected, decoupled specimens showed a much smaller (shorter) mould risk period than coupled at the exterior wood layer. The air cavity allows some natural ventilation even though no forced air was introduced, it also provides a space for moisture ingress to escape the CLT through vapour diffusion based on pressure equalisation across the CLT. Comparing the observed data between coupled and decoupled assemblies the presence of an air layer above the CLT in the specimens tested consistently doubled the dry-out rate compared to specimens with not air cavity – where exterior assembly layers were installed directly on the CLT panels.

Also as expected, the unprotected specimens showed a much greater (longer) mould risk period than protected specimens. This is analogous with similar studies discussed in Section 5. The unprotected specimens consistently show higher peak moisture content measurements at the exterior wood layer compared to the protected specimens, impacting the dry-out period. The centre wood layers in two of the unprotected specimens demonstrate both moisture loading as well as stagnant moisture content after enclosure where evidence of drying does not occur until approximately 4000 hours after enclosure. This initial period without evidence of drying at the centre wood layers could be a result of liquid moisture movement from the exterior wood layer towards the centre of the panel between cracks and unsealed portions of the CLT, some of which would dissipate during transport though the wood layers via vapour diffusion and liquid transport along gluelines and within wood layers parallel to the wood grain. The slower dry-out rate of the

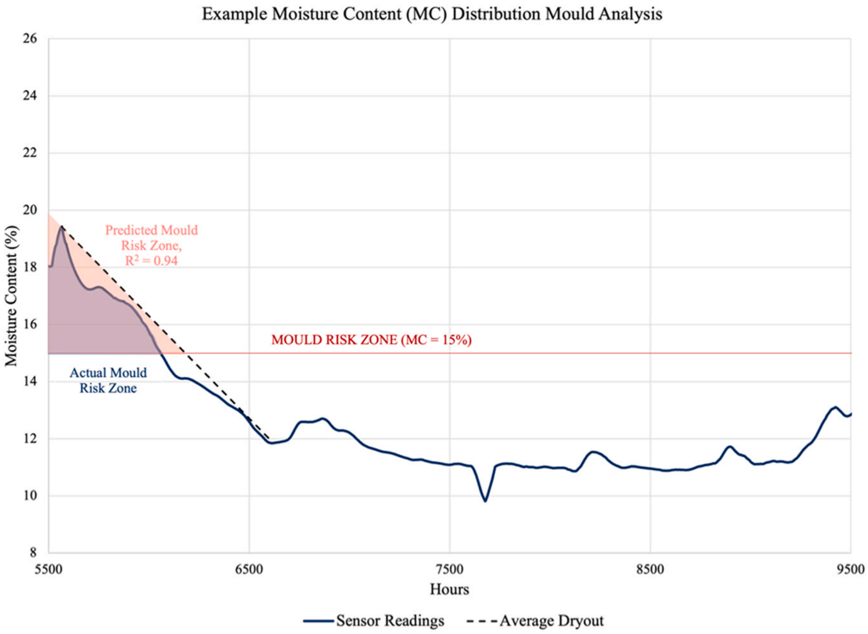


Fig. 6. Sample Moisture Content Distribution Analysis for Mould Risk.

Table 6
Phased linear analysis moisture content ranges.

Description	Moisture Content Range (%)
Mould Risk Range	15–29
Typical Moisture Range	11–15
Dry Range	8.8–11

centre wood layers can also be attributed to the relatively low permeance of the adjacent wood layers of the CLT which restrict vapour diffusion.

The permeable vs. impermeable test did not generate expected results. Fig. 8 shows that at the exterior wood layer, the impermeable specimens are above 15 % MC for less than half the time of the permeable specimens. Further analysis was performed to understand these results.

Notably, the results illustrated in Fig. 8 are based on the summation of all observed data above 15 % MC from all specimens within each category indicated. These results therefore consider all moisture monitoring locations, several of which showed evidence of measurement error and uncertainty outside of the 49-hour moving average. This measurement error is therefore skewing the summarized results, particularly for the permeable vs. impermeable variable comparison. To assess the impact of the permeability of the air/vapour retarder membrane on the dry-out of CLT that has been exposed to bulk water, specimens 6 and 8 will be analyzed further. In addition to demonstrating clear results at all moisture monitoring depths in the CLT, without indication of measurement error outside of the moving average,

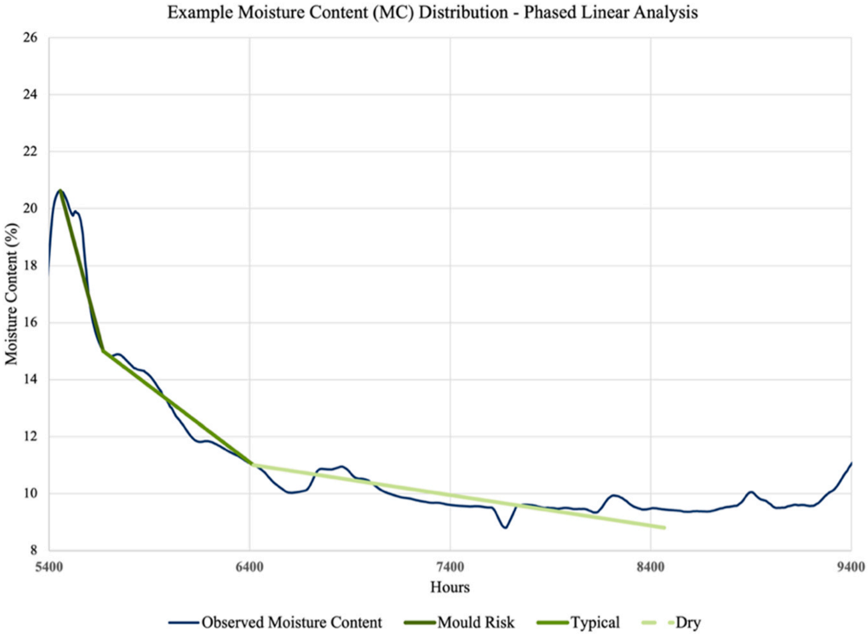


Fig. 7. Phased linear analysis of sample moisture content distribution.

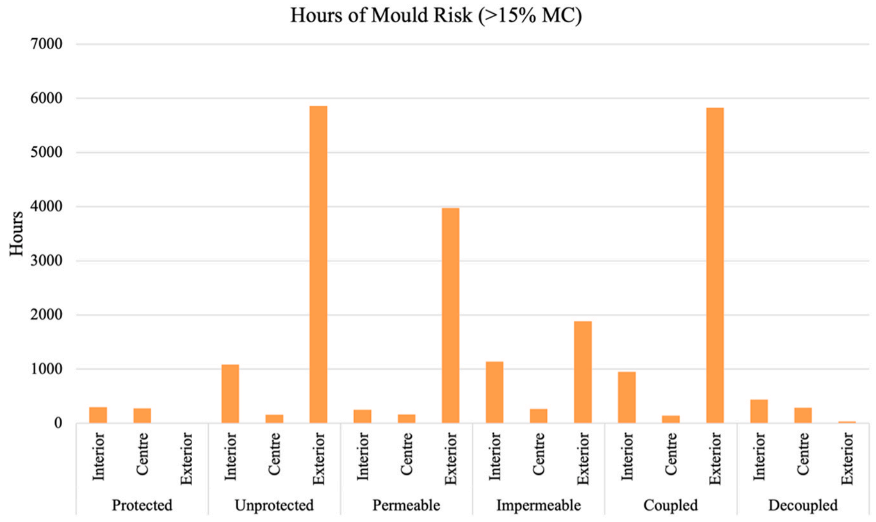


Fig. 8. Mould Risk Summary by Moisture Control and Mitigation Strategies Tested.

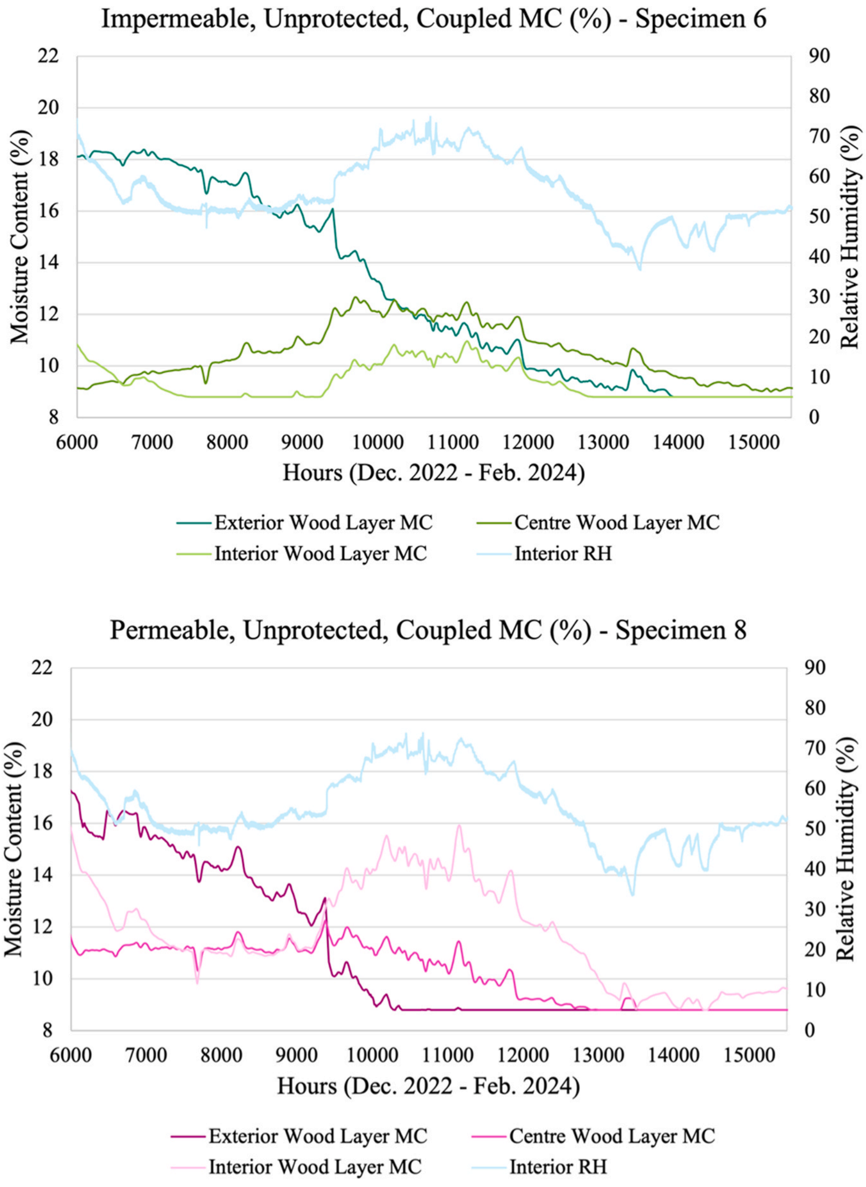


Fig. 9. Permeable vs. Impermeable MC analysis: specimens 6 and 8 results summary.

specimens 6 and 8 also both include coupled (no air cavity) assemblies above the installed membrane and they were both unprotected during the exposure and inundation periods. These two specimens therefore isolate the permeability of the membrane as the independent variable, and they also closely reflect typical assembly configurations in current mass timber design and construction practices. Fig. 9 illustrates the moisture content at each monitored depth in specimens 6 and 8 as well as relative humidity (%) collected from the interior surface of the CLT from the peak moisture content measurement observed prior to drying.

The observed moisture content at the exterior wood layer of the CLT has been further isolated to observe the drying behaviour of the exterior wood layer directly adjacent to the air/vapour retarder membranes in question. Furthermore, the exterior wood layer in both specimens show very similar observed peak moisture content values of 18.14 % at specimen 6 and 17.5 % at specimen 8, and also indicate the greatest period spent in the "mould risk" range, refer to underlined hourly values in Table 7. This enables a direct comparison between these two monitoring locations and the impact of the isolated independent variable: permeable vs. impermeable membrane applied to unprotected CLT. The linear regression models of the dry-out of both specimens are illustrated in Fig. 10.

The variation in dry-out rates as described in Fig. 10 aligns with expected results and industry recommendations to use vapour permeable membranes to increase the dry-out rate and potential of CLT in enclosure assemblies [15,55]. This analysis also demonstrates that the data summarized in Fig. 8 was acutely impacted by the measurement error observed in several specimens. Increased repeatability would improve the reliability of this comparative analysis. However, consistency was observed in the results comparing the other two independent variables (coupled vs. decoupled, and protected vs. unprotected). It is evident that protecting CLT during bulk water inundation and including an air cavity adjacent to the exterior side of the CLT have an almost equal impact on the number of hours spent above 15 % MC in the same monitoring period. In other words, protecting the assembly reduced the initial peak moisture content and decoupling the assembly increased the dry-out rate towards generating a similar impact on the overall moisture conditions observed between these two variables.

Table 7
Mould risk analysis of interior, centre, and exterior wood layers.

Exterior Wood Layer

Panel	Peak Moisture Content (%)	Dry-out Rate (%/Hr)	Dry-out Rate (%/Day)	C.O.D. (R2)	Mould Risk Zone Time (Hours)
1	11.08	−0.00346	−0.08303	0.98	0
2	8.80				0
3	14.36	−0.02708	−0.64993	0.99	0
4	8.94				0
5	14.43	−0.01308	−0.31381	0.97	0
6	18.14	−0.00136	−0.03259	0.92	2314.29
7	13.30	−0.00824	−0.19767	0.92	0
8	17.50	−0.00190	−0.04572	0.90	1312.23

Centre Wood Layer

Panel	Peak Moisture Content (%)	Dry-out Rate (%/Hr)	Dry-out Rate (%/Day)	C.O.D. (R2)	Mould Risk Zone Time (Hours)
1	18.07	−0.02647	−0.63535	0.65	115.90
2	8.82				0
3	16.66	−0.02815	−0.67566	0.84	58.92
4	10.79				0
5	14.81	−0.00677	−0.16247	0.86	0
6	9.74	N/A	N/A	N/A	0
7	9.76				0
8	16.19	−0.00282	−0.06760	0.45	422.98

Interior Wood Layer

Panel	Peak Moisture Content (%)	Dry-out Rate (%/Hr)	Dry-out Rate (%/Day)	C.O.D. (R2)	Mould Risk Zone Time (Hours)
1	15.67	−0.00873	−0.20958	0.92	76.94
2	18.00	−1.39971	−33.59314	1.00	2.14
3	20.62	−0.01235	−0.29639	0.86	455.10
4	11.62	−0.00433	−0.10403	0.88	0
5	16.60	−0.00441	−0.10590	0.90	363.47
6	11.72	−0.00446	−0.10694	0.82	0
7	12.57	−0.00425	−0.10200	0.89	0
8	19.42	−0.00474	−0.11378	0.88	933.24

5. Limitations and context of research

Measurement error and uncertainty is a limitation of this research. 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, translating the electrical resistance readings (Ω) taken by the PMM devices into moisture content (%) values requires species correction factors. The CLT samples obtained for this research were gathered from a mass timber construction site undergoing concurrent in-situ moisture monitoring, however, the species were only known to be SPF (Spruce-Pine-Fir), exact CLT panel configuration of these species or proportionate composition is unknown. Therefore, the wood species were set to "undefined" which is an average calibration setting for data processing. This is an important consideration in calibrating the data from the moisture metres used as studies have proven that wood species impacts resistance moisture content readings by ~2 – 5 % MC, or potentially more [9,21,56,57].

Repeatability is also a limitation of this research with respect to the comparative analysis of each independent variable tested. This was emphasised in this study by the amount of measurement error reported by the monitoring devices installed. Potential causes of measurement error typical in the use of electrical resistance moisture metres was discussed in Section 4.1. The most likely cause of measurement error in this research is variable contact between the wood and the exposed PMM probe tips.

The mould risk presented in this work is also limited, where > 15 % MC is used as a threshold for comparative analysis only. Additionally, moisture content is an indication of the conditions required for mould to occur, however relative humidity and temperature are the parameters typically used for evaluating mould growth in empirical mould models. The moisture content ranges established for this research were primarily based on maximum in-service moisture content set by national guidelines [1,13] and on the results of the observed data. Where quantification of drying response was also limited based on the relatively low (<19 %) peak moisture content. Additional work is required to improve inundation testing towards achieving higher peak moisture content values towards understanding drying response in very high moisture conditions.

Many recent case studies have demonstrated the importance of controlling and/or mitigating moisture and bulk water intrusion during construction of mass timber buildings [8,12,27,48,54,58–63]. The protection and drying response of roof assemblies have been a prevalent topic of discussion among mass timber case studies. A case study in Norway looking at 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 [64]. The results of this research support these findings.

The Forest Science Complex case study in Oregon presented by Schmidt and Riggio [54] demonstrated moisture content readings in line with the data collected for this research, where horizontal CLT panels showed peak moisture content conditions of approximately 24 %-30 % on average at the time each monitored component was enclosed. The horizontal CLT panels in Schmidt and Riggio's research were floor panels as opposed to roof, but these floor panels showed drying

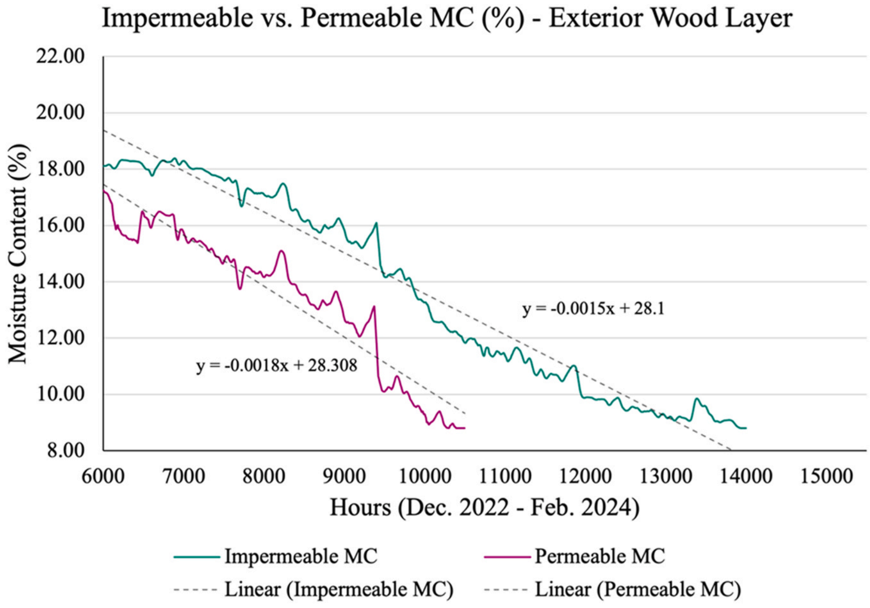


Fig. 10. Permeable vs. Impermeable MC Analysis: Specimen 6 vs. 8 Linear Regression Models at Exterior Wood Layer.

responses trending towards 15 % MC within the first 20 days of enclosure as described above. Within the context of this research that is a dry-out rate of −0.016 %/hr, conservatively, of which the most comparable results within the same order of magnitude from this research were found in Panel 5 [DC/UR/IM]. The drying response in most other monitored locations in this research are at least one order of magnitude slower than Schmidt and Riggio’s case study which is expected given the extent to which the roof is enclosed in materials of low permeability including membranes and insulation compared to floor assemblies which typically do not require hygrothermal control layers to separate interior spaces. It is therefore likely that a combination of moisture entrapment caused by impermeable exterior assembly layers and lower initial peak moisture content values inferring lower pressure gradients transporting moisture through the wood resulted in slower dry-out rates in this research compared to Schmidt and Riggio’s case study [54].

The same study by Schmidt and Riggio [54] also stated the importance of controlling and mitigating moisture, citing the excellent performance of two mass timber case studies; Limnologen in Sweden [58] and the ETH House of Natural Resources in Switzerland [59] both of which achieved near total elimination of moisture exposure by erecting canopies over the entire mass timber structures during construction, particularly at ETH, where monitored CLT panels did not exceed 11 % MC. However, this type of moisture control strategy would require substantial cost-benefit analysis based on the site and environmental conditions, building scale, occupancy type and many other factors.

In addition to the risk of mould and decay discussed in this research, moisture in mass timber building components can also cause schedule delays, dimensional instability and movement in the structural system. Moisture management protocols are typical of both manufacturers and contractors and typically include a risk review for the mass timber based on schedule and exposure, considerations for factory- and/or field-applied water repellant/water-shedding/waterproof coatings, various types of membranes, or other passive protection materials; shipping/storage protections methods, active daily site water management measures; passive/mechanical drying measures, and contingencies for drying and possible moisture damage remediation [55]. The research presented in this work aims to quantify the impact of several of the recommended moisture protection strategies presented in guidelines and moisture management protocols.

6. Conclusions, recommendations, and future work

Three moisture control and mitigation variables for CLT in roof assemblies were tested based on industry recommendations and moisture management issues observed on mass timber building sites. The primary findings from each variable tested are:

- Unprotected vs. protected: peak moisture content values were consistently higher in unprotected panels at all measured depths causing CLT panels to take 2.5 times longer to dry-out on average compared to protected panels.
- Permeable vs. impermeable membrane installation on wetted CLT: application of a permeable membrane on CLT with MC > 15 % can increase the dry-out rate by 0.01 %MC/day compared to the application of an impermeable membrane on CLT with MC > 15 %.
- Coupled vs. decoupled assembly: decoupling the exterior assembly from the CLT with a 20 mm air cavity consistently doubled the dry-out rate of the CLT roof panels.

Additional findings from this research include:

- The extent to which the protection of CLT during inundation mitigated moisture uptake and the extent to which the inclusion of an air cavity adjacent to the exterior surface of the CLT increased the dry-out rate resulted in a very similar quantity of hours observed above 15 % MC at all depths.
- All CLT panels dried quickly after enclosure in December, reaching below 15 % moisture content within the first month of enclosure except for the exterior wood layers of panels 6 and 8 both of which were unprotected during wetting (bulk water inundation) and both of which did not have an air cavity (coupled) above the CLT in the roof assembly.
- After the initial dry-out period of the CLT panels, moisture content fluctuations at the interior wood layer correlated to fluctuations in the interior relative humidity of the CLT test facility.
- In this study, the moisture content at the exterior layer of the CLT is primarily influenced by liquid water transport as a result of exposure to rainwater and extended periods of standing water, as a result, the exterior wood layer is also impacted by the outer enclosure layers of the roof assembly based on their configuration and permeability.

Based on this field laboratory study, the following recommendations should be considered for moisture control and mitigation based on the phase of the project.

1. Design
   a. Include an air cavity within the assembly adjacent to the CLT surface.
   b. Utilise vapour permeable air barrier system at CLT surface to increase dry-out rate.
2. Manufacturing
   a. Protect the CLT from moisture loading during transportation and construction using a pre-applied air/vapour barrier membrane.
3. Construction
   a. If using a pre-applied permeable air/vapour barrier membrane, ensure bulk water is actively cleared from surface to prevent absorption during construction.
   b. Protect CLT from all moisture sources particularly near exposed end grain.
   c. Review and monitor all horizontal CLT (floors and roofs) standing water and clear standing water rapidly from surfaces, particularly unprotected wood surfaces.
   d. Ensure CLT is below 15 % MC prior to installation of any membranes or materials that retard vapour and/or liquid water (including permeable and impermeable vapour retarders, waterproofing, water-resistive barriers, and low permeance insulation products).
   e. Ensure any wetted CLT above 15 % MC is protected from any additional moisture sources and is well-ventilated to promote drying.
   f. Monitor moisture using installed moisture metres at vulnerable connections including: exposed end grain, intersection of structural components, and intersection/connection of CLT panels, and based on visual assessment including: CLT where standing water is observed regularly, and where staining of the wood indicates consistent exposure to wetting, liquid water transport, and seepage.
   g. Install moisture metres at surface and core CLT layers to observe dry-out and to assess MC within primary structural layers of CLT.
   h. Using permanent/semi-permanent moisture metres provides temporal data including quantification of dry-out and they mitigate user error including skewed resistance measurements where surface moisture of wood may interfere with probe readings below wood surface using a hand-held type moisture metre for instantaneous readings only.
4. Service
   a. Continue moisture monitoring during the first year of building service.
   b. Extend monitoring period if MC remains above in-service limitations of the PRG 320 Standard which requires < 15 % EMC average over one year without exceeding 19 % in Canada [21]
   c. Review exposed CLT from interior of building for indication of moisture ingress and wetting including staining of wood.

Overall, exposure to moisture and bulk water must be avoided during transportation and construction as the initial moisture content significantly impacts the length of the dry-out period. This can be achieved through the use of water resistive or waterproof barriers with hydrophobic properties to also avoid water absorption. Standing water should be promptly cleared from protected and unprotected CLT surfaces. Furthermore, the introduction of an air cavity above CLT in a roof assembly has proven to consistently promote dry-out of the CLT. Finally, the use of vapour permeable air barriers applied to CLT with MC > 15 % do improve the dry-out rate – however, it is important to consider the absorption and adherence characteristics of the product which could impact quality of the installation and resilience of the membrane after installation and during service.

Future research and work to process the data presented using empirical mould models and to perform visual mould assessments would allow for direct correlation of the moisture control and mitigation strategies tested to the potential for and observed mould growth. Additional experimental research to assess the impact of introducing forced air movement (mechanical ventilation) in the air cavity has the potential to further increase dry-out rates from those observed and to diminish/eliminate mould risk. The development and calibration of predictive hygrothermal and mould models would enable simulation-based analysis of additional moisture control and mitigation strategies as well as the impact of possible water sources during building service (e.g. roof leaks). This would require additional laboratory testing to increase the repeatability of the tests performed in this study as well as a detailed comparative analysis of the limitations of hygrothermal modelling tools and current empirical mould models.

The research performed in this study supports the use of the tested moisture control and mitigation strategies using quantifiable metrics including dry-out rate, dry-out period, and moisture movement/distribution through CLT panels towards. These results further support the development of standardised moisture management plans for use during design, construction, and service.

CRediT authorship contribution statement

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

Declaration of Competing Interest

The authors 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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Data availability

Data will be made available on request.

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