State-of-the-Art Review of Moisture Content Sensor Deployment in Mass Timber Construction

Dorothy Johns[1]; Yash Vyas[2]; and Russell Richman, Ph.D., P.Eng.[3]

Abstract: Mass timber is gaining popularity in the North American architectural, engineering, and construction (AEC) industry as a viable and sustainable building material. Owing to the water storage potential of mass timber, durability is of concern as a result of long-term exposure to moisture during building construction and service. The importance of monitoring mass timber subjected to moisture degradation during construction and occupancy of a building is critical in determining the longevity and viability of mass timber products. In situ moisture monitoring deployment techniques are currently inconsistent across building case studies. The objective of this review is to investigate: (1) relevant types of moisture content (MC) sensors and their applications in mass timber construction; and (2) practices for deploying MC sensors in mass timber construction. Cross-laminated timber (CLT), nail-laminated timber (NLT), and glue-laminated timber (Glulam) are typical mass timber products, each of which varies in thickness, manufacturing processes, and species composition. In addition, MC sensors have a range of applications, installations, and accuracies. The variability of mass timber products and MC sensors lead to multiple combinations of moisture monitoring techniques. Mass timber moisture monitoring installation and deployment practices have been recommended based on the literature review and case study analysis performed. **DOI: 10.1061/JAEIED.AEENG-1638**. *© 2024 American Society of Civil Engineers*.

Introduction

Developed in the early 1990s, mass timber has recently become a construction material of significant interest in the North American construction industry. Increasing popularity in the use of mass timber is predominantly due to its sustainable characteristics compared with construction materials such as concrete and steel (Brandner et al. 2016). In addition, mass timber construction has positive influences with regards to construction time, potential to improve building envelope thermal performance, and an inherent natural aesthetic that has been proven to be broadly appealing and beneficial to occupant comfort, health, and productivity (Fanella 2018; Karacabeyli and Gagnon 2020). Mass timber is prefabricated offsite and assembled onsite with no required curing or welding time, this results in faster onsite building erection times in comparison with structural products such as concrete and steel (Singh et al. 2019). Despite numerous benefits, mass timber construction has been limited in scale due to fire and durability concerns (Pei et al. 2016). These limitations are beginning to be addressed through evolving mass timber technologies and building code amendments in many countries (Brandner et al. 2016). Consequently, mass timber construction has been more widely adopted by the North American market in recent years with potential for further growth in the future.

The current climate crisis requires sustainable and renewable building materials to be manufactured and implemented as standard, prevalent materials in the construction industry. Considering the global efforts toward reducing carbon emissions, mass timber is an engineering wood product that is at the forefront of replacing traditional structural building materials such as concrete and steel due to its low carbon footprint (Karacabeyli and Gagnon 2020), carbon sequestration properties (FPL 2010), aesthetic desirability, and recent code amendments allowing for mass timber buildings to be constructed to taller heights in much of North America (Karacabeyli and Lum 2022; NRC 2020). However, there are specific technical complexities in the use of mass timber as a common building material that must be monitored and addressed.

Wood is a hygroscopic material that capable of absorbing water. Wood's absorptive characteristics can lead to material degradation through growth of mold fungi (Dietsch et al. 2015a; Schmidt et al. 2018). Traditionally, mass timber buildings have been built on sites with low risk of moisture deterioration; however, owing to technological advancements in mass timber manufacturing, there are more buildings being constructed in areas with higher risks of moisture degradation (Gradeci et al. 2017). As a result, it is important to manage moisture and identify localized areas of moisture degradation concerns (Baas et al. 2021; Cappellazzi et al. 2020; Fast et al. 2017; Gradeci et al. 2017; Kordziel et al. 2019, 2018; Schmidt et al. 2019).

Mass timber moisture performance can be evaluated through analytical and empirical methods. Analytical hygrothermal evaluation can be completed using computer simulation software such as WUFI. Lab and field hygrothermal monitoring of mass timber can be conducted to obtain empirical data. Hygrothermal evaluation of mass timber components in buildings is typically conducted through analysis of data collected from the localized deployment of moisture content (MC) sensors. Because mass timber is an

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[1] Ph.D. Candidate Building Science, Faculty of Engineering and Architectural Science, Dept. of Architectural Science, Toronto Metropolitan Univ., 350 Victoria St., Toronto, ON M5V 2K3, Canada (corresponding author). ORCID: https://orcid.org/0000-0002-6706-176X. Email: dorothy.johns@torontomu.ca

[2] Ph.D. Candidate Building Science, Faculty of Engineering and Architectural Science, Dept. of Architectural Science, Toronto Metropolitan Univ., 350 Victoria St., Toronto, ON M5V 2K3, Canada. Email: yash.p.vyas@torontomu.ca

[3] Professor & Associate Chair Graduate Studies Building Science, Faculty of Engineering and Architectural Science, Dept. of Architectural Science, Toronto Metropolitan Univ., 350 Victoria St., Toronto, ON M5V 2K3, Canada. Email: richman@torontomu.ca

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emerging construction material in North America, it is important to understand the dynamic evolution of the technology and take strategic steps to evaluate the long-term durability (Brischke et al. 2013; Singh et al. 2019). The aim of this paper is to identify the importance of moisture monitoring on the prediction of long-term durability of mass timber components, to investigate and define current moisture monitoring technologies, and to critically analyze current field moisture monitoring strategies of mass timber buildings.

Mass Timber Material Characteristics

Mass timber is an engineered wood product, composed of dimensional lumber adhered or fastened together using adhesives, nails, or dowels (Karacabeyli and Gagnon 2020). Currently in North America, mass timber is manufactured according to the ANSI/APA PRG320 (APA – The Engineered Wood Association 2019) standard and shipped to site for erection. Common mass timber products include cross-laminated timber (CLT), glue-laminated timber (GLT), nail-laminated timber (NLT), and dowel-laminated timber (DLT). The combined use of CLT and GLT has increased significantly in the 21st century (Schmidt et al. 2018). In particular, CLT panels have become a preferred mass timber product as they support two-way spans for building components such as roofs, floors, and walls due to the orthogonal placement of the dimensional lumber in the manufacturing of the panels (Karacabeyli and Gagnon 2020; Riggio et al. 2020). CLT panels may be oriented horizontally to be used as structural roofs and floors, and vertically, with the outer longitudinal dimensional lumber oriented parallel to the gravitational force vector, when constructing shear walls and/or building enclosure assemblies. Conversely, GLT provides high one-way strength and is typically used for beams and columns in mass timber structures. GLT can also be manufactured in one-way curved forms making it an ideal structural material for large spans. Mass timber buildings are often constructed using a combination of both CLT and GLT products. In addition, because CLT and GLT include adhesive layers that impact the permeability of the products, this review focuses on the moisture monitoring of CLT and GLT as common adhered mass timber products.

CLT is composed of at least three layers of dimensional lumber adhered orthogonally. CLT products are typically fabricated with an odd number of layers with three to seven layers being common; however, more layers are often used depending on required spans and loads. This thickness of individual lumber boards can vary between 16 and 51 mm (5/6 and 2.0 in.) and the width of the boards may vary between 60 and 240 mm (2.4 and 9.5 in.) (Karacabeyli and Gagnon 2020). The lumber in the outer layers of CLT wall panels are normally oriented parallel to gravity loads to maximize vertical load capacity. Similar to CLT, GLT is also composed of adhering multiple layers of dimensional lumber together. GLT must consist of at least two layers of dimensional lumber glued parallel to its length. The maximum wood layer thickness of GLT is also 51 mm. Ultimately the length, depth, and overall dimensions of both CLT and GLT are limited by the manufacturing, transportation, and structural requirements of the products.

Mass timber components are also dependent on the grade of lumber required during the manufacturing process. In the case of both CLT and GLT, the grade of dimensional lumber used throughout a single component and/or member can vary. Using varying grades of lumber can result in reduced material costs and a reduction in the waste of lumber during manufacturing. If varying grades of lumber are used in a single product, higher-grade lumber is placed at the outer layers of the members and panels where higher stress occurs and lower grade lumber is placed within the laminations where less stress occurs. The material characteristics of mass timber are therefore dependent on both the properties of the lumber itself and the manufacturing processes used.

Importance of Moisture Monitoring in Mass Timber

Wood is an organic material that is susceptible to material degradation due to moisture (Karacabeyli and Gagnon 2020). This degradation can occur as physical damage (e.g., wood delamination, wood cracking) and/or biological deterioration (e.g., fungi and bacteria growth, insects). Advancements in engineered wood construction have led to the development of CLT and GLT; however, these products are still susceptible to material degradation as a result of sustained moisture exposure (Baas et al. 2021; Brischke et al. 2013; Cappellazzi et al. 2020; Dietsch et al. 2015a, b; Gradeci et al. 2017; Karacabeyli and Gagnon 2020; Schmidt et al. 2019). It is therefore necessary to clearly characterize the potential modes and conditions of mass timber failure related to moisture exposure. Owing to the relatively new introduction of this structural material in the North American construction industry, long-term moisture monitoring of mass timber is an area of research that requires further consideration and study and is a critical component to educated design and engineering practices. Current long-term moisture monitoring of mass timber will also lead to a robust data set to be utilized for the prediction of both durability and potential failures of mass timber components. The collection of this data set will ultimately remove industry barriers such as a concern for the structural integrity and overall lifespan of mass timber products with respect to durability related to moisture cycling (Johns et al. 2022). In turn, it will also increase the perceived viability of mass timber construction and lead to the development of standardized moisture monitoring protocols to improve the performance and longevity of mass timber buildings in the future.

This review paper will cover current and prospective moisture monitoring techniques in mass timber buildings to create a foundation for understanding the durability of mass timber products during manufacturing, construction, and service. This paper recommends specific state-of-the-art moisture monitoring techniques as best practice supported by an in-depth literature review and case study analysis. The literature review establishes current mass timber moisture monitoring techniques, technologies, and hardware, which are further analyzed through case studies.

MC Monitoring of Mass Timber

MC influences the durability of wood for several reasons; the first of which is due to its effect on the risk for insect and fungal decay as indicated in Fig. 1. An additional effect of wood MC variations is associated shrinkage or swelling of the material. Since the outermost fibers of the wood cross section adapt faster to the climatic conditions (Johns et al. 2023; Vyas et al. 2023), the resulting moisture gradient and the associated shrinkage or swelling will lead to internal stresses in the cross section (Dietsch et al. 2015a). A prevalent type of damage is pronounced cracking in the glue lines and lamellas of adhered mass timber products due to these internal stresses, which can lead to a reduction in the structural integrity of the material (Dietsch et al. 2015a; Sikora et al. 2016).

Quantifying the MC of wood can be a rationale to justify a failure in mass timber construction (Schmidt et al. 2018). MC is defined as the weight of the moisture contained in the wood expressed as a percentage of the oven-dry weight of the wood. Consequently, the MC may range from zero, for oven-dry wood, to over 100%, for a supersaturated wood material (James 1998).

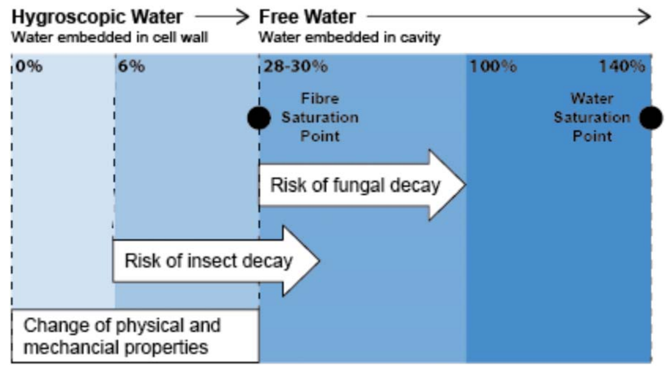

Fig. 1. Range of wood MC and influence on its properties. (Data from Dietsch et al. 2015a.)

Oven drying wood is the most accurate method of achieving dry MC; however, this test cannot be completed in the field. In the case of mass timber, the wood has been treated with chemicals, and the composition of CLT and GLT relies on adhesive layers. Oven drying CLT and GLT can result in the evaporation of these substances and can result in weight loss misinterpreted as the evaporation of water (James 1998). Many researchers believe that the loss in chemicals will not impact the MC readings. However, a larger difference in MC occurs due to the ease of bulk water movement and moisture transfer between the boards of dimensional lumber in gaps and openings created by a lack of continuous adhesive. The impact of oven drying on the error of MC readings between field and lab testing has yet to be studied and published for CLT and GLT products.

Currently, the manufacturing standard for mass timber products requires manufacturers to monitor the MC of the wood in their mass timber products (APA – The Engineered Wood Association 2019); however, the determination of the MC of the wood relies on the manufacturer's own assessment methods – this has yet to be standardized. Most current mass timber manufacturers only take surface MC measurements of their mass timber components onsite using probe MC readers. To obtain accurate and repeatable readings, standard laboratory test standards such as ASTM D4442-16: Standard Test Methods for Direct Moisture Content Measurements of Wood and Wood-Based Materials (ASTM Standard D4442; ASTM 2016) should be used. This standard uses an oven-dry method to determine the MC in wood samples and then compares the oven-dry results to the measurements taken on the wood samples from the sensors prior to oven drying (ASTM Standard D4442; ASTM 2016). However, as previously mentioned, oven drying CLT or GLT can lead to ambiguities in MC readings. An alternative distillation method is provided in ASTM D4442 as an option only if the primary oven-drying method is not justifiable. As such, the most appropriate method for quantifying the MC of wood in the field and for a prolonged period before, during, and after construction is the indirect conductance method using field-installed MC sensors.

MC Sensors

Pin versus Pinless Moisture Sensors

Pin and pinless are the two primary categories of moisture sensors. A pin-type moisture sensor has two or more metal pins that penetrate the material, whereas a pinless moisture sensor uses electromagnetic wave technology to measure the MC of a material. Modern-day moisture sensors can be as accurate as ± 1% MC for manufacturer-provided operable temperatures. ASTM D4442 standard test methods for direct MC measurement of wood and wood-based materials can be used to determine the accuracy of the moisture sensor (ASTM Standard D4442; ASTM 2016).

Since pin-type moisture sensors only measure a localized region, they are known to have low accuracy when considering the entire MC of a material component. A moisture profile can be obtained through several pin-type moisture sensors installed at various depths in one direction of a material component or sample. Furthermore, previous literature shows a range of opinions regarding the impact of density on MC readings. Work completed by Smith (2020) shows that density does not have a major impact on MC, whereas James (1998) and Crean (2017) indicate that pin-type moisture sensors are significantly impacted by density. The research completed by Smith (2020) assumes that because the pins are situated in proximity of each other, the conductance values will not differ; however, Smith overlooks the impact of various MCs at high densities. As indicated by James (1998) and Crean (2017), at high densities the radius of wood cavities will decrease and can be filled with moisture even at relatively low MC values. Therefore, according to James (1998) and Crean (2017), wood density can impact the MC readings.

Pinless MC sensors send and receive electrical waves at a specific frequency. The different between electromagnetic waves is correlated to a MC reading. Pinless moisture sensors read the MC of wood under the sensor's pad. The depth of measurement can vary significantly between different types of pinless moisture sensors (James 1998). Unlike pin-type moisture sensors, all previous literature states that when using a pinless moisture sensor, the density significantly impacts the MC readings (Crean 2017; James 1998). A benefit of pinless moisture sensors is that they are nondestructive, which is one of the primary reasons for these sensors to be used in mass timber manufacturing plants and onsite.

Electric Moisture Sensors

Electric moisture sensors measure conductivity between two points to interpolate the MC of a material. Conductance-type, capacitance-type, and power-loss are the three types of electrical moisture sensors. In specific wood products, the conductance increases with an increased in MC because water has a higher conductivity than air. This is measured using a conductance-type moisture sensor. A capacitance-type moisture sensor measures the relationship between the dielectric constant of wood and MC. Lastly, a power-loss moisture sensor measures the relationship between the dielectric loss factor of wood and MC.

Ohm's law is used to determine the magnitude of conductance through a medium (material). The electric moisture sensors typically have two pins and the electric current runs from the positive pin to the negative pin. The voltage drop is used to measure the magnitude of conductance that is used to determine the MC. The readings taken by electric moisture sensors are affected by MC, temperature, and grain angle. Typically, there is a log–log relationship between electrical current and MC (FPL 2010; James 1998). However, the log–log relationship is very poorly correlated with MC higher than the fiber saturation point (FPL 2010). In addition, as the temperature rises, the conductance of wood also increases (FPL 2010). Furthermore, the conductance increases when it is parallel to the direction of the wood grain as compared with being perpendicular (FPL 2010). Although this is intuitive, as parallel wood grains provide ease of energy transfer, this point has been argued to be less significant compared with the type of species of this wood (James 1998; Smith 2020; Wengert and Bois 1997).

The dielectric constant is described as "the ratio of the capacitance of a capacitor, using the material as the dielectric, to the capacitance of the same capacitor with a vacuum (in practical usage, air) as dielectric. In principle, the dielectric constant is a measure of how much electric potential energy is stored in the material when it is placed in a given electric field" (James 1998). Furthermore, the dielectric constant depends on MC and temperature. Change of grain direction and species of wood do not significantly impact the dielectric constant, whereas change in MC and density of wood have a significant impact on the dielectric constant (James 1998; Wengert and Bois 1997). An increase in wood density creates a higher contact between wood cells, which increases the electric transfer and leads to an increase in the dielectric constant.

In general, conductance-type moisture sensors are battery operated and precalibrated to read MC readings. These sensors can be directly connected to WiFi to be used for remote moisture monitoring. The pin-type moisture sensor has the following varieties: surface-contact electrodes, pin-type electrodes, four-pin electrodes, insulated-pin electrodes, veneer electrodes, and permanent electrodes. The surface-contact electrodes cannot be paired with a conductance-type sensor as the surface will be drier or wetter than the core of the material and will skew the MC readings. Pin-type electrodes are driven into the wood and MC readings are taken from a small section of the wood along the length of the driven pins. The four-pin electrodes are also driven into the wood to measure MC from the specific section of the wood between which they are driven. Insulated-pin electrodes and veneer electrodes are isolated and only measure MC from the exposed tip of the pin. Permanent electrodes are installed within a wood panel and can be of any type of electrode discussed previously.

The accuracy of electrical MC readings is dependent on the calibration of the moisture sensors. The moisture sensors are calibrated by the manufacturer in a laboratory; however, the uncertainty of sample size and specimen type that are tested to create the calibration curves used are not disclosed and could therefore lead to inaccurate readings and analysis. Furthermore, the accuracy of MC readings is also impacted by the localized wood structure and environment (e.g., species, density, grain orientation, thickness, MC, temperature) (James 1998; Wengert and Bois 1997).

Sensor Install Practices

Sensor installation methods are largely dependent on the type of sensor being installed, the sensor location, and the desired moisture monitoring data output. The following should be considered when determining an appropriate installation method:

1. The measurement method must take place without damaging the structure or taking samples.
2. The accuracy and precision of the measurements must be consistent.
3. The system must enable mounting on the structure itself and allow for independent measurements and digital logging of the results at different locations of measurement.
4. Depending on the research, the chosen measurement method must enable the determination of timber MC in different depths of the cross sections to derive a moisture gradient.
5. The timber MC should be measured and recorded in equal time intervals (Dietsch et al. 2015b).
6. Climate data including relative humidity, room temperature, air speed, and material temperature are also recommended at or within proximity of the moisture measurement.
7. Data loggers are required to store measured values (Dietsch et al. 2015a).
8. Power in the form of a direct electrical connection or batteries is required, direct power supply is recommended for remote data transmission setup.
9. All data must be accessible remotely, therefore requiring integration within the building's wireless network.

Few sensor types can provide all the preceding requirements. The conductance-type (pin-type) sensors have the potential to fulfill all requirements if installed correctly, consistently, and without allowing for the surroundings environmental conditions to impact the microclimate in the mass timber being measured. The conductance-type method also features an acceptable accuracy (± 1% below $\mathrm{MC} = 20\%$) (James 1998), it is nearly nondestructive, and it enables measurements at multiple pairs of electrodes (pins) that can be installed at different locations and depth within the mass timber being measured. Owing to these characteristics of MC measurement and monitoring, the conductance (also known as resistance) method is widely accepted as the state-of-the-art technique (Brischke et al. 2008; Dietsch et al. 2015a, b; Fast et al. 2017; Kordziel 2018; Kordziel et al. 2018, 2019; McClung 2013; McClung et al. 2014; Schmidt et al. 2018, 2019; Smith 2020; Wengert and Bois 1997).

Nail-, screw-, and wire-type sensors can be used as electrodes for conductance-type sensors. Regardless of type, they should be Teflon-insulated to measure MC at clearly defined depths and, if possible, they should be installed perpendicular to the grain of the wood with typically 30 mm between each electrode of a pair and a minimum of 150 mm between pairs of electrodes where multiple points of measurement exist to avoid interference (Dietsch et al. 2015a, b). Electrodes must be installed tightly within the wood to avoid interference from heavy environmental flux and to avoid loss of contact with the wood (Schmidt et al. 2019). This can be achieved by gluing in the electrode or by predrilling with a slightly smaller diameter than the electrode between inserting and tapping in the electrode to ensure a tight fit with the wood (Brischke et al. 2008; Dietsch et al. 2015a; Schmidt et al. 2019). A drill guide should also be used to ensure electrodes are installed at the desired depth within the wood. The pin-type electrodes are connected to the data acquisition box by shielded coaxial cables and the connections between the electrodes and the cables should be fully insulated to avoid short-circuits in case of condensation (Dietsch et al. 2015a).

In addition to probes, data storage should be considered for continuous measurements. Data loggers are used to store the measured values. To prevent interference, each channel is actuated successively and separately during measurement, allowing for independent measurement and subsequent transmission to a digital data logger (Dietsch et al. 2015a). In order to obtain a robust measurement system, it will be necessary to reduce the number of connecting pieces, intermediate switches and other parts that are prone to interference or failure (Dietsch et al. 2015a). The measurement equipment and data loggers should be stored in an installation box with silica gel bags to prevent negative influence from accidental contact and/or impact, climactic fluctuations, or dirt (Dietsch et al. 2015a).

MC sensors are placed at specific depths within each layer of wood of the mass timber panels and/or members being monitored, as illustrated in Fig. 2. This configuration of sensors ensures precise monitoring at each surface of the panel or member where MC will be more sensitive to fluctuations relative to adjacent surface temperature and relative humidity conditions. The laboratory research performed by McClung (2013) utilized similar distribution and configuration of sensors within various wall assemblies.

Similar moisture monitoring principles used on controlled laboratory environments are applied in building field testing. For example, moisture sensors were installed at an eight-story mass timber building in Portland, Oregon for just over one year (Kordziel 2018; Kordziel et al. 2018, 2019). Twenty sensors with data

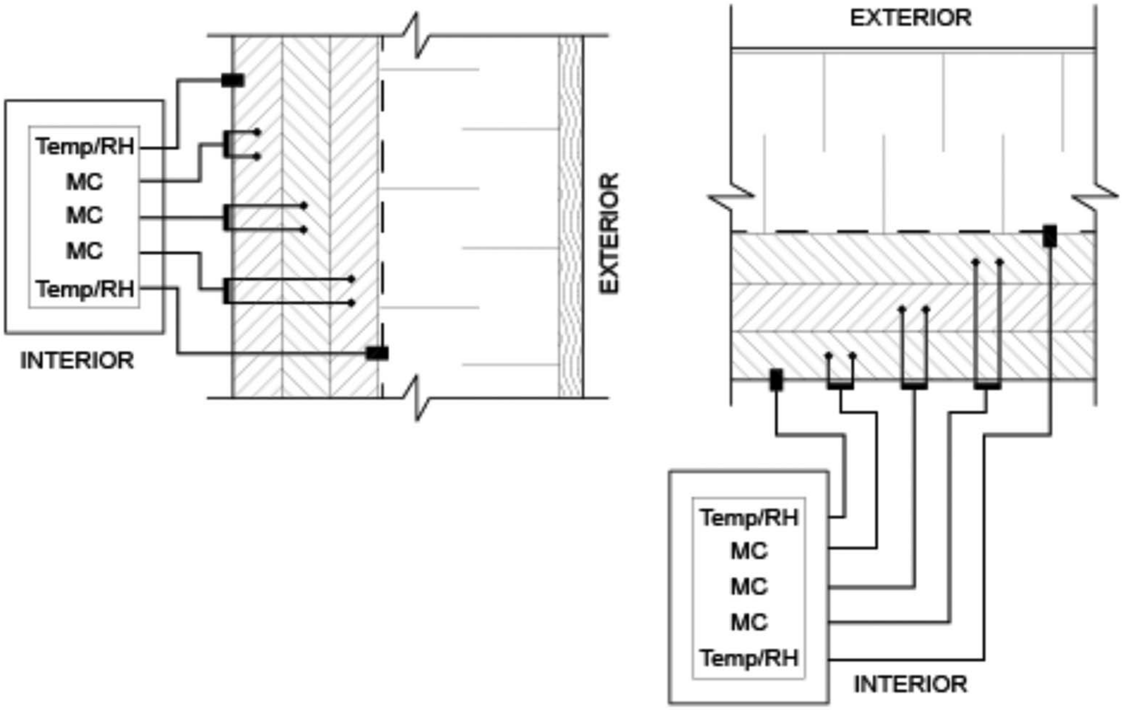

Fig. 2. Schematic of data acquisition device and CLT MC sensors (probes) based on the resistance method in a typical wall assembly and in a typical roof assembly, respectively.

logging capability were installed at the CLT production facility to record MC during storage and transportation to the building site. Approximately 60 (for a total of approximately 80) sensors were onsite during two different construction stages (Kordziel et al. 2018). Sensors were dispersed vertically and horizontally throughout the building, on floors 1, 2, 4, and 8 and on the roof (Kordziel et al. 2018). Sensors were installed in five primary assemblies: (1) Glulam columns near the wood/concrete foundation interface; (2) CLT sensors installed at the top with pins measuring half depth and full depth of the panel; (3) CLT sensors installed at the top with pins measuring each lamination (used only on the roof); (4) CLT sensors installed at the top with pins measuring the top lamination (used only on the roof); and (5) sensors installed in fire-retardant-treated (FRT) stud walls to measure the MC of the secondary structure (Kordziel et al. 2018). Sensors installed within the roof panels were notched in pockets on the top side of the CLT so that the sensors were not visible from inside the building. These notches were covered with metal flashing and sealed from foam gasketing and silicone caulking. After exposure to bulk water onsite, many of the sensors, including those located in the notched and sealed pockets, were damaged (Kordziel et al. 2018). Fig. 3 illustrates an exposed installation that, even if sealed, is not a feasible option for the installation of sensors susceptible to moisture damage.

Long-term measurements of timber MC, temperature, and relative humidity were taken in a total of 21 buildings consisting of seven different typologies (uses) in Munich, Germany. At each location of measurement, four pairs of Teflon-insulated electrodes were installed at two locations of the roof structure in each building with varying length pins to enable measurement of MC at clearly defined depths of the GLT's cross section (Dietsch et al. 2015b). The moisture sensor could read up to eight channels and measurements were taken every hour and subsequently transmitted to a data logger (Dietsch et al. 2015b). Climate data including temperature and relative humidity, as well as surface temperature of the material, were also logged to provide comparative data. The moisture monitoring of each of the 21 buildings individually was not as extensive as in the preceding example of the eight-story building in Portland, Oregon; however, the long-term occupancy data collection provided several conclusions and best practices pertaining to the hygrothermal performance of CLT and relevant occupancy climate control of mass timber building in order to increase the lifespan of the mass timber structure.

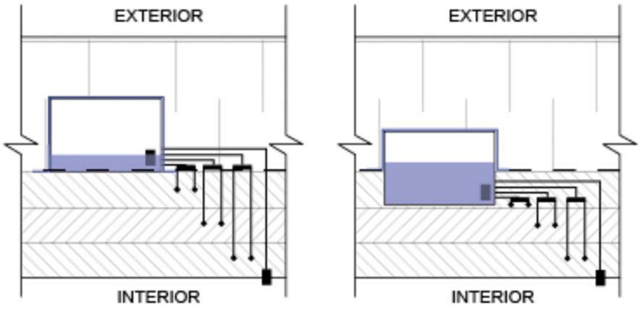

Fig. 3. Water damage of sensor installation in on exterior side of CLT roof panel and in notched pockets of CLT panels.

Based on the literature reviewed and cases studies, the installed of sensors and data acquisition boxes should be on the interior side of the envelope, similar to the schematic illustrated in Fig. 4. Further trial-and-error in the laboratory and in the field is required to develop functional and robust moisture monitoring field deployment techniques.

Recommended Installation Practices

Based on the literature and case studies reviewed, standard procedures, and recommendations of state-of-the-art sensor manufacturers,

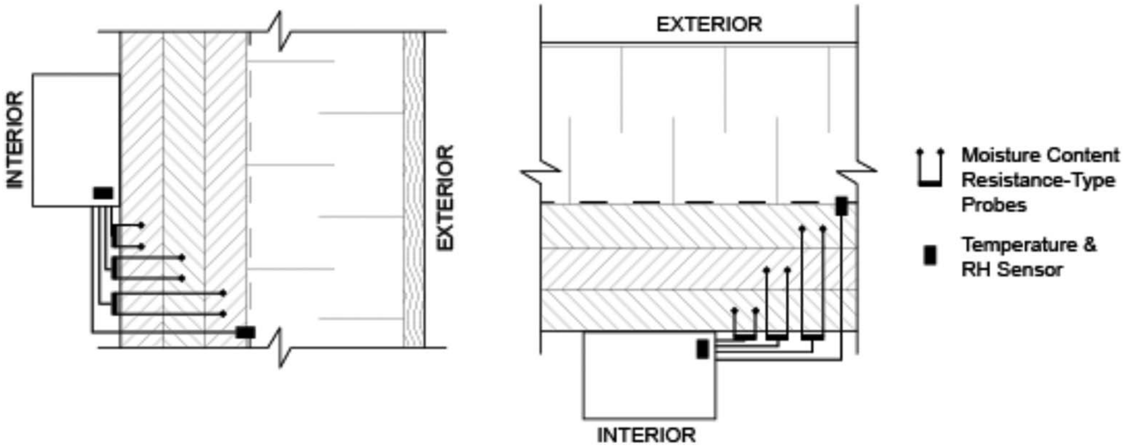

Fig. 4. CLT data acquisition device and moisture sensor configuration in a wall assembly and in a roof assembly, respectively.

the following section outlines recommended installation practices for deploying MC sensors in mass timber construction.

Scheduling, Location, and Distribution of Sensors

The MC sensor layout throughout a building and/or project should be planned during the construction documentation and systems coordination phase of the project, prior to site erection of the mass timber structure and during the rest of the building systems coordination. This enables all associated parties including the client, contractor, relevant engineers, and subtrades to review the location of the sensors and to determine if any coordination conflicts and/or issues exist. This also gives the contractor the opportunity to schedule the installation of the sensors appropriately within the building and/or project's overall schedule.

If sensors have not been preinstalled in the mass timber components offsite, they will be required to be installed onsite. Typically, even if some sensors are installed offsite to gather MC data during the transportation, storage, and construction of the project, additional sensors will still be required to be installed onsite during construction to gather data at critical and vulnerable details associated with the mass timber structure and envelope systems. For example, the Wood Innovation and Design Centre in British Columbia installed a series of MC sensors after the roof structure was installed to protect the instruments from weather and capture the performance of the structure during construction.

It should be noted that MC monitoring of a roof structure composed of mass timber elements, typically CLT, is not expected to serve as leak detection for the roof assembly. A leak detection system is still required to be installed as required by the client or owner, or to achieve warranties specific to the roof assembly system being installed. In the case of the Wood Innovation and Design Centre in BC, MC sensors were installed at multiple locations varying in orientation and roof assembly (Wang 2015). In addition, moisture tapes were installed on the CLT panels at each roof drain to monitor any additional moisture potential at those vulnerable locations compared with the rest of the roof assembly (Wang 2015).

Similar to the roof monitoring strategy used at the Wood Design and Innovation Centre as discussed previously, the MC monitoring of an entire building's mass timber structure should provide data for both empirical analysis as well as comparative analysis. This can be achieved by planning and locating sensors at regular intervals and locations throughout each level and elevation of the building, with additional sensors installed at locations in the building that are vulnerable to moisture penetration and accumulation. Such vulnerable locations could include but are not limited to: mass timber in proximity to envelope openings such as glazing, doors and drains; mass timber incorporated into predominantly exterior envelope conditions such as soffits; and mass timber exposed to interior spaces with high humidities such as washrooms and kitchens. Gathering data from across the entire building as stated, including vulnerable locations, provides an extensive scope of data to be used for empirical and comparative analysis.

In addition to locating the MC sensors within the building at a macroscale, the installation of sensors within the mass timber components, at a microscale, is also a critical component to the overall success in gathering holistic MC data. At this scale, it is important to discuss the installation of the conductance (pin) type probes within the mass timber components. Owing to the layered composition of mass timber products, particularly adhered mass timber components such as CLT and GLT, insulated MC probes should be installed to specific depths in the components to allow for MC readings to be taken from within each wood layer. This installation technique provides data to support the analysis of moisture transport across the mass timber component, which can indicate whether the assembly is performing as anticipated and whether there is potential for moisture degradation and/or biological deterioration to occur. For example, gathering MC data from the outermost later of wood within a wall assembly, where a vapor permeable or impermeable air barrier has been installed, will indicate whether moisture is accumulating in this layer of the mass timber component as a result of the adjacent air barrier membrane.

One final consideration when locating MC sensors in mass timber components is their proximity to wet, or initially wet, materials. For example, mass timber monitored in adjacency to cast-in-place concrete will likely impact the results of the collected MC data from within the mass timber and should also impact the location of the sensor in order to prevent damage while still enabling the collection of the data at this potentially vulnerable location.

Sensor Groups, Adjacencies, and Architectural Integration

MC sensors are required to be adjacent to a data acquisition box that then connects to the main data logger(s). Data acquisition boxes and any external wiring to the MC probes are the components of the monitoring system that are the most exposed to damage by the occupants during service of the building. These components of the monitoring system are also the most visible and therefore aesthetically obtrusive. Depending on the client, these components are likely to require coordination with the architect, contractor, and client to ensure appropriate integration with the occupancy, interior program and finishes, and potentially casework, millwork, and/or furniture arrangement. In the case of an office program, for example, it is likely that the data acquisition boxes and each of their associated MC probes could be installed below desk height at the sill of openings, or below or above floor or ceiling plenums if they are required to be completely concealed. However, these considerations will ultimately fall under project-specific coordination. In general, the probes of conductance (pin)-type moisture sensors should be installed in proximity to the data acquisition box to which they are connected via wiring. In some cases, the entire data acquisition box and MC sensor(s) could be encased in a protective cover; however, again this would fall under a project-specific consideration. Data loggers are to be installed in accessible locations, typically in server spaces, so they can be reached with minimal disruption to the occupants and direction connected to the building's servers if applicable.

Data Collection

Prior to the commencement of data collection, the sensors are required to be calibrated based on differing resistance characteristics of wood species. All data should be recorded at regular intervals, typically hourly, and collected and compiled regularly for analysis, typically monthly or quarterly. During construction, it is possible data will require collection onsite via wireless Bluetooth connection to the data acquisition boxes. However, ideally once the building server has been established, data will to be collected remotely at regular intervals. It is likely that throughout the overall data collection period of the project sensors will be damaged or may require adjustments, recalibration, or additional batteries. This should be completed in a timely manner to avoid gaps in the data collection and recorded accordingly.

Conclusions

The importance of long-term moisture monitoring of mass timber forms the foundation of this review. A robust data set can only be collected through the implementation of appropriate and proven data collection methods. Although it is likely that a small percentage of moisture monitoring instrumentation may fail, it is important to consider and account for this in the planning stages of the monitoring project. The combination of data collection from both general and repetitive locations as well as moisture-vulnerable locations throughout the mass timber building will provide a holistic data set from the building and/or project. Collecting data from manufacturing of the wood, through transportation to site, storage onsite, construction, and at minimum two years into the service of the building will provide a data set that encompasses periods of high moisture exposure as well as an in-service dry-out period and potentially some months of typical data from building service after the mass timber components have dried and largely equilibrated with interior moisture conditions. Because the exact dry-out period of the building is unknown, it is important to collect data at minimum until the MC of the mass timber components has equilibrated, and then ideally to continue collecting data during several years of service afterward to observe potential conditions that could cause material degradation during the early service life of the building and/or project.

The review conducted in this paper summarizes current moisture monitoring instrumentation, methods, and techniques used for mass timber moisture monitoring including field installation and data collection. The recommended practices methods described summarize the research and are based on empirical data as well as recent moisture monitoring case studies performed in North America. From this summary, further developments can be made toward gathering a robust data set of mass timber moisture conditions.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from corresponding author upon reasonable request.

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