Moisture Monitoring of a CLT Structure in a Southern Climate

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Abstract: Understanding moisture behavior in cross-laminated timber (CLT) is critical to the widespread use of CLT in construction in the United States. Currently, very little data exist on the long-term impact of moisture on CLT in real structures. The objective of this research was to collect data regarding the long-term moisture variation in the CLT panels at the University of Arkansas student residential building, named Adohi Hall. The climate of Northwest Arkansas is different from those of previously monitored buildings, mostly located in the Pacific Northwest. Comparatively, Northwest Arkansas has a warmer climate with higher average annual precipitation. Moisture sensors were installed in 45 locations throughout the building to provide a comprehensive evaluation of the building. Results indicate that for the interior floors of the building, i.e., not the roof, CLT panels have not encountered moisture intrusions. At the roof level, moisture intrusions during construction were trapped in the CLT panels by waterproofing. This trapped moisture resulted in slower drying to below acceptable levels of moisture. **DOI: 10.1061/(ASCE)AE.1943-5568.0000527**.

Introduction

Cross-laminated timber (CLT) is a manufactured product consisting of layers or plies of lumber boards glued orthogonally to each other (APA—The Engineered Wood Association 2019). In traditional CLT production, glue is applied to wide faces to adhere plies together, but the edges of the boards do not necessarily need to be glued within a ply (Gagnon et al. 2013). The thickness of a panel depends on each board as well as the number of plies. Panel length and width is limited by the manufacturer's production bed size and transportation considerations for width and length (Gagnon et al. 2013). CLT panels are commonly three to seven, or more, plies thick with an odd number of plies for structural stability. A typical CLT cross section is shown in Fig. 1.

Unlike other engineered timber materials and traditionally used timber products, CLT does not yet have defined reference strength values in the National Design Standard Supplement (NDSS) (AWC 2018a). The absence of reference design values is due to the variability in manufacturing, specifically in the thickness and number of plies.

CLT is relatively new and is gaining popularity as a renewable alternative to concrete or steel for mid-rise construction in particular (Gagnon et al. 2013). Mid-rise projects using CLT can reach completion rapidly, since CLT elements have a high level of prefabrication and do not require large cranes or specialized equipment to erect (Gagnon et al. 2013). Also, because CLT elements are lighter than their concrete or steel counterparts, foundation size may be decreased (Gagnon et al. 2013). CLT can be used for longer floor spans, shear walls, gravity walls and is more strong, durable, and fire-resistant than light-frame wood construction (Dagenais et al. 2013; Gagnon et al. 2013). There are still enduring questions about its performance, however, and its resistance to moisture is one of the most important considerations (Zelinka et al. 2019).

Importance of Moisture in CLT Structures

Major factors that impact the durability of wood structures include decay, termites, marine borers, and fire (Breyer et al. 2019). While marine borers are not a concern for an inland structure, and other factors such as termites and fire may be controlled similarly to regular light-frame wood buildings, decay is possible in CLT buildings. Decay occurs when fungi feed on wood products and becomes possible when the following conditions are met: MC > 20%, availability of food (in the form of cellulose or lignin), air exposure, and favorable temperatures (Breyer et al. 2019). For most CLT structures, maintaining a moisture content below 20% in all layers of the panels would be ideal for preventing decay.

Another reason to maintain low moisture in CLT structures is to maintain the design strength values. CLT reference design values are applicable without a wet use factor modification when used in dry service applications, MC < 16% (AWC 2018b). When used outside of dry service conditions, a reference design value reduction factor is applied to bending, tension parallel to grain, shear parallel to grain, rolling shear, and compressive strengths, as well as modulus of elasticity and minimum modulus of elasticity (AWC 2018b). While there is not a defined reduction for CLT (reference design values and adjustment factors are determined by the manufacturer), reduction factors for glulam (another laminated timber product) range from 0.53 to 0.875 (AWC 2018a, 2018b). Therefore, reductions in strength may be required if CLT structures are regularly used in wet service conditions, MC > 16%.

Impetus for Study

At the Second North American Mass Timber Research Needs Workshop in 2018, moisture was a common theme. In the category "durability and building physics," moisture performance of CLT in southern climates was ranked as the 5th most pressing research

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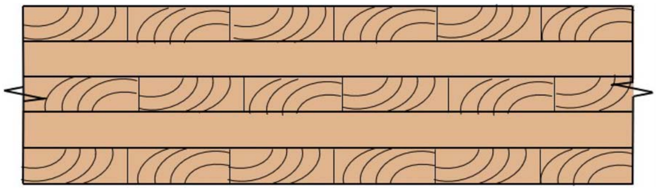

Fig. 1. 5-Ply CLT cross section.

Table 1. Annual weather data for Fayetteville, Arkansas, and Portland, Oregon

Location	Average summer high dry bulb temperature (°F)	Average winter low dry bulb temperature (°F)	Average annual precipitation (in.)
Fayetteville, Arkansas	90.2	27	48.51
Portland, Oregon	81.8	36.1	36.03

Source: Data from NOAA (2010, 2020).

need out of 29 topics and the 23rd out of 117 topics overall (Zelinka et al. 2019). This research appears, therefore, to be timely for addressing concerns of the mass timber research community about CLT structures in southern climates. Additionally, this work aims to supplement previous research, which also included moisture monitoring of a mass timber structure but focused on monitoring moisture at a different phase of building construction/occupancy and in a different climate.

Currently, little data exist on the long-term impact of moisture on mass timber structures (Kordziel et al. 2019; Schmidt and Riggio 2019). Moisture in CLT panels is a primary durability concern because excess moisture gained during construction or by uptake from the environment can lead to mold or even degradation of physical properties (Carll and Wiedenhoeft 2009). Additionally, CLT is designed and manufactured to be used in dry service conditions at a moisture content (MC) below 16% (APA—The Engineered Wood Association 2019).

Construction of mass timber buildings in the United States has mainly occurred along the coasts, especially the Pacific Northwest (WoodWorks Wood Products Council 2020). Previous studies investigated the changes in moisture inside CLT panels in Portland, Oregon (Kordziel et al. 2019). According to the Köppen-Geiger climate classification (Kottek et al. 2006), Portland has a warm temperate climate with dry, warm summers.

CLT is becoming a popular material in other regions which specific climates may result in different moisture movements inside such a material. A new student residential building on the University of Arkansas (UA) campus in Fayetteville, Arkansas (Adohi Hall) constructed mostly of CLT provided an opportunity to monitor the moisture in a CLT structure located in a different climate. Fayetteville, Arkansas, is in a humid subtropical climate zone that tends to have more constant high humidity than the Pacific Northwest. Annual averages for high temperature, low temperature, and annual precipitation are shown in Table 1.

The hypothesis of this study is that mass timber construction, specifically construction with CLT panels, is feasible in a warm, humid southern climate, specifically in the context of panel performance given its elevated moisture conditions brought on during construction.

The objective of this research was to collect data on the long-term changes in moisture within the CLT panels at the UA Adohi Hall to understand better the CLT structures' sensitivity to

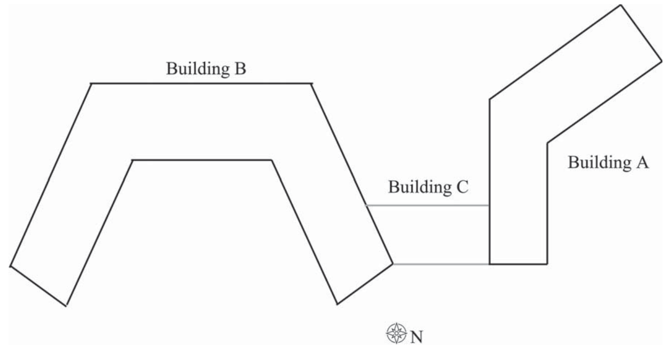

Fig. 2. Building footprint.

moisture in a southern climate. Long-term monitoring was achieved by installing moisture sensors inserted into the CLT panels throughout the building.

Structure Description and Experimental Methods

Structure Description

Adohi Hall, located on the UA campus in Fayetteville, Arkansas, is a student residence designed to US Green Building Council's LEED Silver standards (Univ. of Arkansas 2020) and is primarily constructed of mass timber elements. Adohi Hall was the largest CLT building in the United States at the time it was constructed, in summer 2019. The hall consists of three interconnected buildings, containing 708 beds for students and faculty in the form of suite and pod student rooms, faculty apartments, as well as study lounges, kitchens, laundry rooms, community rooms, and workshop spaces. The building footprint for Adohi Hall was generalized and recreated based on construction drawings and is shown in Fig. 2 (Leers Weinzapel Associates et al. 2017). Building A and Building B are the main dormitory buildings and are each five stories. Covered with a green roof, Building C has a shared space that connects Buildings A and B.

Most columns and beams in the building are glulam, and the floors are built with CLT panels (except for the first story concrete podium level). Spruce CLT panels were obtained from a European manufacturer for the construction of the building. Mass timber floor/ceiling elements were left exposed in most areas for aesthetic purposes but are covered by a drop ceiling or gypsum board in hallways, bathrooms, community rooms, and kitchens. A sound mat and gypsum floor underlayment were placed on top of panels before final carpeting was installed to improve acoustic footfalls and vibrations in the building. Sample cross sections for interior exposed and enclosed CLT ceiling conditions are shown in Fig. 3.

Roof design, regardless of material, aims to prevent three intrusions into a building: water, vapor, and heat. The roof design at Adohi, as shown in Fig. 3, is similar to the conceptual roof design found in the CLT Handbook (Gagnon et al. 2013; Glass et al. 2013). For the panels used in Adohi Hall, MC upon delivery of the Spruce CLT panels was 10% ± 2%, regardless of panel size (binderholz 2019). Typically, panels would be protected from outside moisture until the structure is fully enclosed, but in practice this can be difficult to achieve.

Thermoplastic polyolefin (TPO) membrane and cover board provide moisture control and bulk water removal. Poly-iso insulation provides thermal control to the interior of the building. A vapor retarder sheet and underlayment provide vapor control and secondary moisture control.

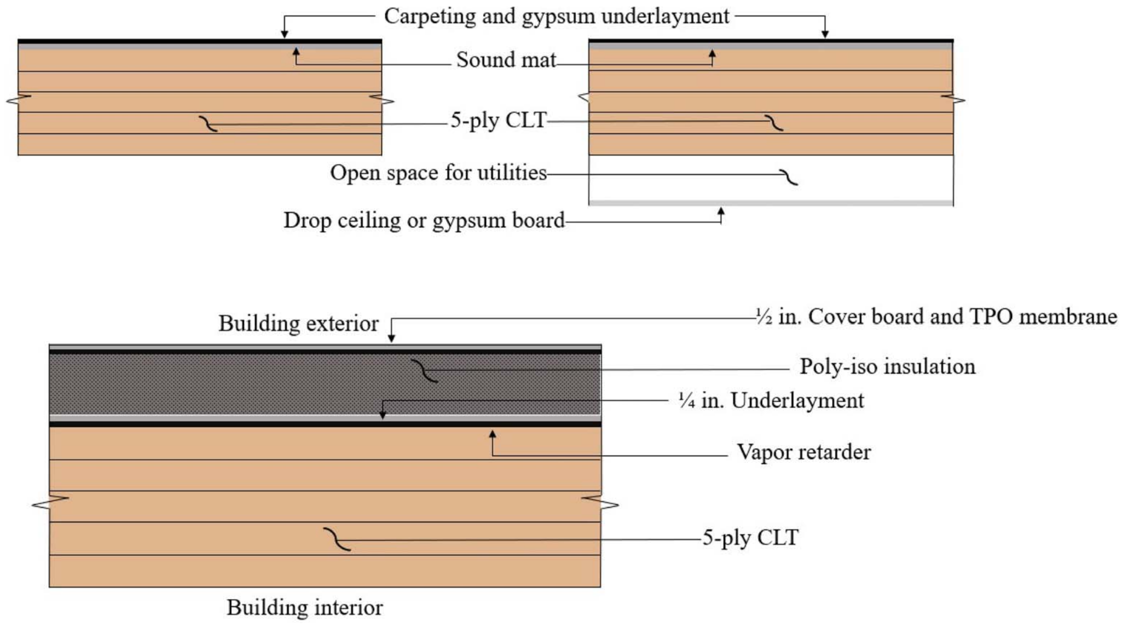

Fig. 3. Ceiling and roof sections.

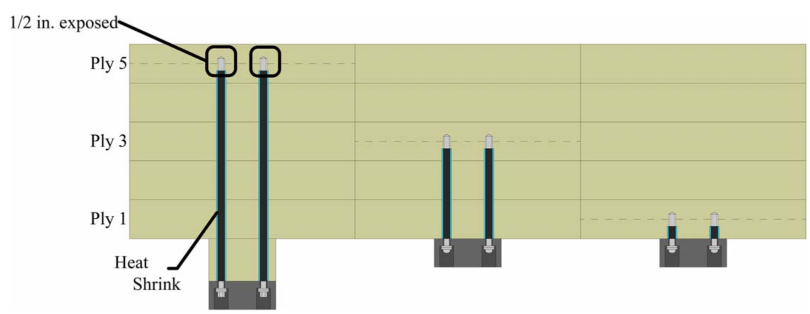

Fig. 4. Pin depth and typical cluster layout.

Experimental Methods

Pin-type sensors, such as those outlined and used in previous research, were selected since specific depths could be targeted for monitoring (Kordziel et al. 2019). Pin-type sensors used a battery to create a current, which travels down one pin, across the sample medium, and into the other pin. The resistance encountered in the sample was used to calculate wood moisture equivalent (WME) in the CLT sample (James 1988). Calibration of conversion for WME to MC was determined by oven drying testing according to ASTM D4442-16: *Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood Based Materials* (ASTM 2016).

As designed, Omnisense S-160 pin-type moisture sensors penetrate only 2 in. into a sample material, where the current is isolated to the portion of the screw extending past the plastic legs. Since this research targeted depths more than 2 in., the protective legs were entirely removed.

Without the legs, the current passed through the area of highest moisture, i.e., the area of least resistance, regardless of screw length. Heat shrink tubing was applied to isolate the path of current to only the targeted depth. The use of heat shrink tubing allowed for uniform thickness and, therefore, for consistent current resistance continuously down the length of the covered screw shank. The last ½ in. of each screw was left exposed, as shown in Fig. 4. Stainless steel screws of various lengths were chosen to target different depths in CLT. Since measurements were taken at depths reaching the center of first, third, and fifth ply, appropriate screw lengths were selected, also shown in Fig. 4. Sensors were placed in groups of three, or clusters, to target different plies in the same panel area. These ply locations were selected to establish the moisture gradient in the panels and determine if there was any greater moisture at surfaces close to the envelope or to conditioned spaces compared to the panel interior.

Unlike previous research moisture monitoring of CLT panels, notches in the CLT were not necessary to conceal the sensors (Kordziel et al. 2019). Instead, pilot holes were drilled ½ in. short of final depth on the underside of the panel. The use of pilot holes protected the heat shrink tubing from damage during installation and ensured the only portion of the screws in firm contact with CLT was the exposed portion. This method was considered advantageous since it maintained the original cross section of the panels.

Locations were selected to capture a variety of moisture and temperature conditions throughout the building, especially areas near the envelope or where water was expected. Many student rooms were instrumented. All student rooms were located next to the building envelope, and sensor clusters were placed in the ceiling directly next to the windows. Areas near building plumbing and drains were also instrumented, specifically communal kitchens and bathrooms, as well as laundry rooms. Two additional internal locations for the sensors' placement were identified and were not expected to have extremes of moisture, one with climate control and a dropped ceiling, the other without climate control and an exposed CLT ceiling. These interior locations were both far away from the building envelope. Hallway sensors provided the most insulated readings, as they were in an enclosed dropped ceiling farthest away from the building envelope. Several areas of the building were not air-conditioned, such as trash rooms, utility rooms, and storage closets. These internally located environments are enclosed by the building envelope and were monitored for comparison to the HVAC-controlled spaces. All five floors in Adohi Hall contained a combination of these conditions, and a typical layout of sensors (on the second floor of building A) is shown in Fig. 5. Successful sensor cluster installation was dependent on availability and free surface areas in the plenum space and on the varying ceiling layouts respective to each floor; therefore, the exact sensor location varied slightly from floor to floor. Some additional sensor locations were selected during the installation and were not repeated on every floor, such as locations near bathrooms, a janitorial closet, an HVAC air handler room, and under a green roof.

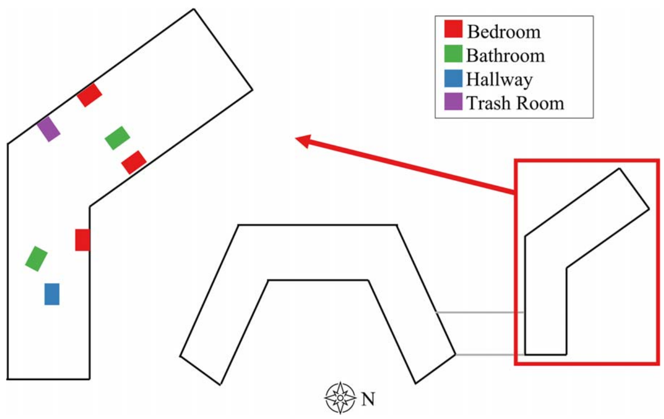

Fig. 5. Building A typical sensor locations.

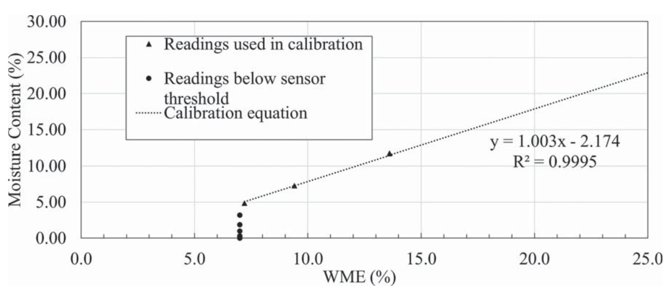

Fig. 6. Calibration results.

The installation procedure for the sensors included the following steps: the pilot hole locations were marked on CLT using a template, pilot holes were drilled, and sensors were installed in a cluster of three (to monitor the first, third, and fifth ply). A total of 45 locations were instrumented with 134 sensors. In one location, under the green roof, only two sensors were possible due to installation limitations from a different ceiling detail. All sensors were installed after the panels were erected, while the building was already enclosed but prior to the operation of the HVAC system. Since data were collected before full occupancy of the building, any panels with an MC above $10\% \pm 2\%$ resulted from exposure to moisture during construction. This is because the panels were delivered to the site in sealed plastic at a design MC of $10\% \pm 2\%$.

Sensors used in this research were designed to detect moisture in a variety of construction materials, rather than just wood. For this reason, raw data collected directly from the sensors were reported in terms of WME, an approximation of what the moisture content would be if the sensor were installed in an unspecified wood sample (James 1988). Sensor calibration was performed using ASTM D44412-16, and results are summarized in Fig. 8. The actual MC was determined by mass while drying CLT samples in an oven. Comparisons indicate a nearly linear relationship between MC and WME and a 2.17% difference between MC and WME. This comparison is not applicable at $MC < 5\%$, as the lower threshold for sensor readability is 7% WME. Based on the calibration of the sensors, a conversion of WME to MC followed the equation in the following, from the calibration results in Fig. 6. Readings below $MC = 5\%$ were reported as 5% in this paper since the actual MC could not be determined.

$$MC = WME - 2.17\% \tag{1}$$

Results and Discussion

First-Floor Locations

First-floor locations were of interest because of the differing floorplan, as shown in Fig. 7. In lieu of a wing for additional bedroom

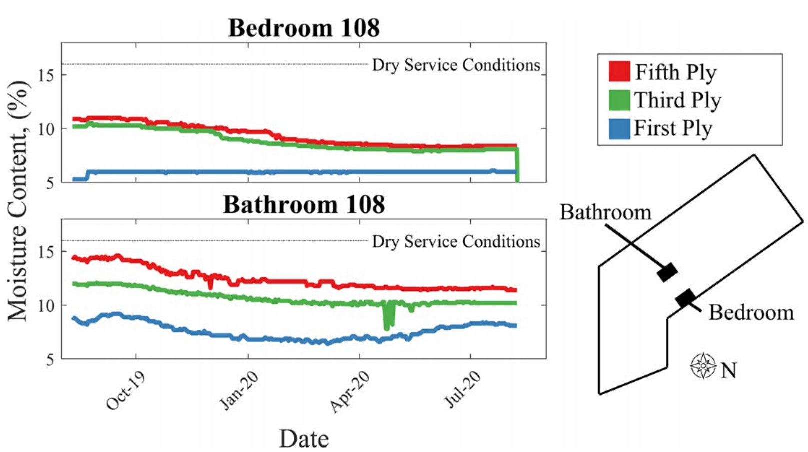

Fig. 7. First-floor results.

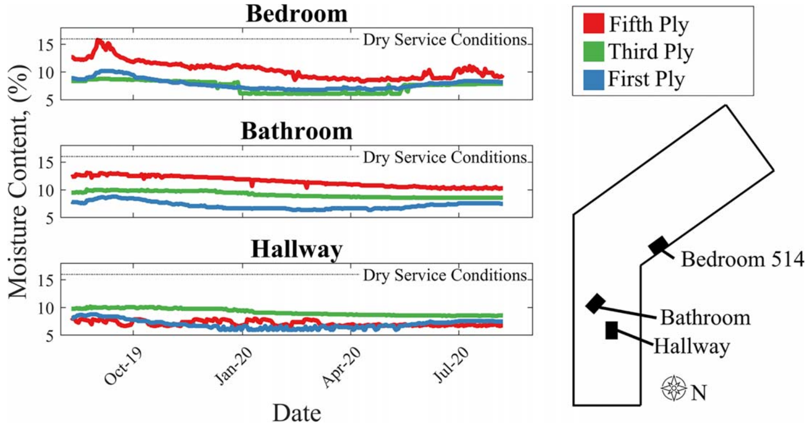

Fig. 8. Third-floor results.

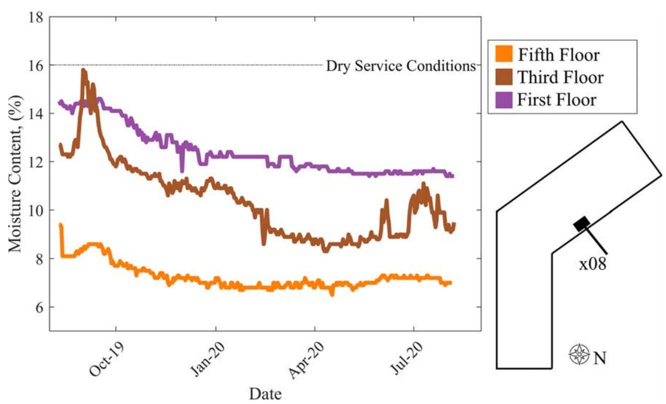

Fig. 9. Selected bedroom results.

and bathrooms, the southeast wing includes large doors for entry and exit of goods from the building. Despite the infiltration of humidity and heat from exterior doors, first-floor locations remained dry, as shown in Fig. 7. Sensors of highest and lowest values are shown in this paper to highlight the extremes of moisture activity on the floor. The bedroom location, near the building envelope, provided the highest moisture content on the floor but remained in dry service conditions throughout the monitoring. Values below 5% are artificially shown as 5%, the lowest value that could be accurately measured. The bathroom location, near the hallway which leads to the exterior doors, recorded a relatively constant moisture level, implying that the frequent opening and closing of exterior doors had little effect on the CLT panel. A trend of decreasing MC is apparent. It is possible (based on results from other floors) that the MC in these panels was higher when the panels were erected and were exposed to the elements. Clearly, now that the panels have been enclosed for a year, the MC has stabilized to acceptable levels.

Third-Floor Locations

Third-floor locations represent perhaps the most insulated areas of the building since they are two floors away from the ground level's exterior doors as well as the fifth floor's roof system. In addition to protection from the building exterior, the third floor also has the most spacious plenum area. With fewer water, sewer, etc., pipes and smaller HVAC routing, the third-floor CLT panels are also exposed to less moisture in the form of condensation and steam. Sensors with the highest, average, and lowest readings are shown in Fig. 8 to represent the typical conditions on the third floor. Only one sensor approached the threshold for dry service conditions but that area quickly dried to well below dry service conditions. As mentioned in the discussion of the first floor, it is likely that these locations were moister during construction but have since dried to acceptable levels. For both bedroom and bathroom locations, the fifth ply had the highest MC compared to the third and first plies.

Comparison of Floors

Bedroom 08 is an area that was monitored on each floor. Fig. 9 shows results from the first, third, and fifth floors. To improve figure readability, these sensors were selected to represent the building as a whole and provide a general view of typical conditions on each floor. Fig. 9 shows the results from the fifth ply, which almost always had the greatest MC. All sensors remained within dry service conditions, despite their proximity to the building envelope.

The CLT panel which functions as the ceiling of the fifth floor also acts as the roof for the entire building. For this reason, locations on this floor were of the greatest concern because rain and snow resulted in roof moisture. Proper drainage and waterproofing must be provided to protect the panels.

Building A, where most sensors were located, was constructed last. The protective sheets covering the CLT panels for delivery were removed to install the panels. The exposure of these panels to water and moisture during the period between removal of this protective sheet and when the building is fully enclosed can lead to high MC. The common approach is to cover the CLT during construction, but this is difficult in practice. In addition to preconstruction moisture in some panels, roof panels were exposed to rain and moisture prior to waterproofing. During installation, locations were observed where moisture intrusion had caused staining, especially close to the edges of the building and around connection locations, as shown in Fig. 10. Obviously, moisture affected the panels during construction; therefore, the internal moisture measurements were important to determine if this moisture dissipated once the building was occupied. The fifth-floor sensors provided useful information about the change in moisture from construction to occupancy since these panels were last installed.

Fig. 11 shows only the fifth ply (closest to the exterior) measurements from selected locations on the fith floor. Three locations were outside of dry service conditions, and one was above the threshold for possible decay at the time the fifth-floor sensors were installed. These locations are in an area with standard waterproofing and roofing insulation between the CLT panel and the outside of the building. Locations under the concrete topper remained within dry service conditions and provided similar results to those on the first or third floor. All sensors have shown a trend of decreasing MC over time. Because the sensors were installed, however, those in the hallway and bathroom locations appear to be drying at a slower rate at the time these data were collected (one year of sensor readings).

Examination of Locations with Elevated MC

Although the roof locations included plies that were above dry service conditions, it is important to emphasize that the entire cross section was not at this same level of elevated moisture.

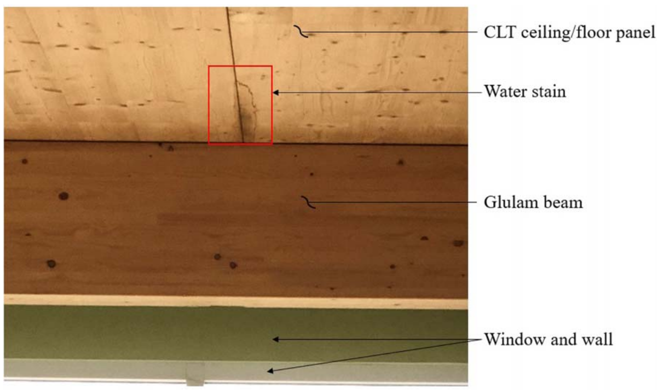

Fig. 10. Water stain on the CLT panel.

As shown in Fig. 12, the first and third plies remained within dry service conditions during the first year of monitoring. In fact, the first ply for all three locations was nearing the lower threshold of sensor readability, MC = 5%.

Because two exposure conditions existed in Adohi Hall, the relationship between MC and absolute humidity (AH) was compared. In all locations, the top face, i.e., the face at the fifth ply, is covered with a sound mat and gypcrete. The variable exposure condition is at the bottom face, i.e., the face at the first ply. These conditions are either exposed or concealed in a drop ceiling.

Pearson's correlation coefficient was calculated using Eq. (2) to evaluate the correlation between *MC* and *AH*.

$$\rho = \left(\sum_{(i=1)}^{N} = \left((AH)_i - (\overline{AH})\right)\left((MC)_i - (\overline{MC})\right)/N \right) \Big/ (\sigma_{AH}\ \sigma_{MC}) \tag{2}$$

where N = number of samples; and σ = standard deviation.

Three representative locations were selected for analysis. These locations are a third-floor bedroom, third-floor hallway, and a fifth-floor bathroom. The location and MC progression may be referenced in Fig. 8 for third-floor locations and Fig. 12 for the fifth-floor location.

The third-floor bedroom, B308, is an exposed location that has remained within dry service conditions throughout the monitoring. As shown in Fig. 13, the greatest Pearson correlation, ρ, between MC and AH occurs in the first ply, which is the ply exposed to the ambient conditions inside the building. This strong correlation

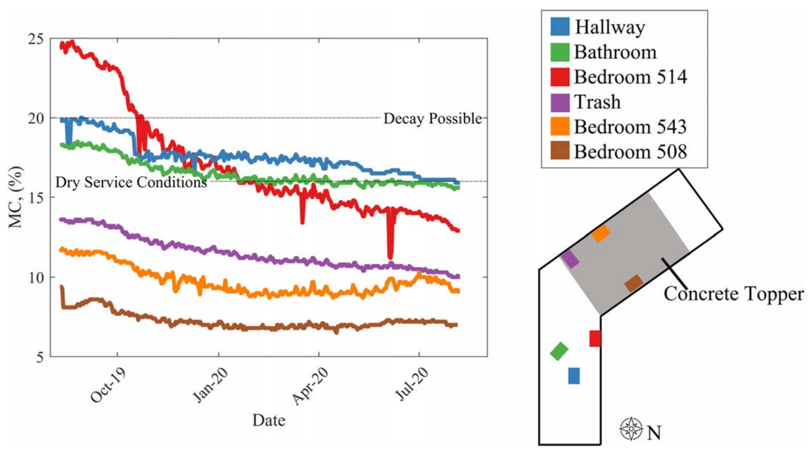

Fig. 11. Fifth floor, fifth ply results.

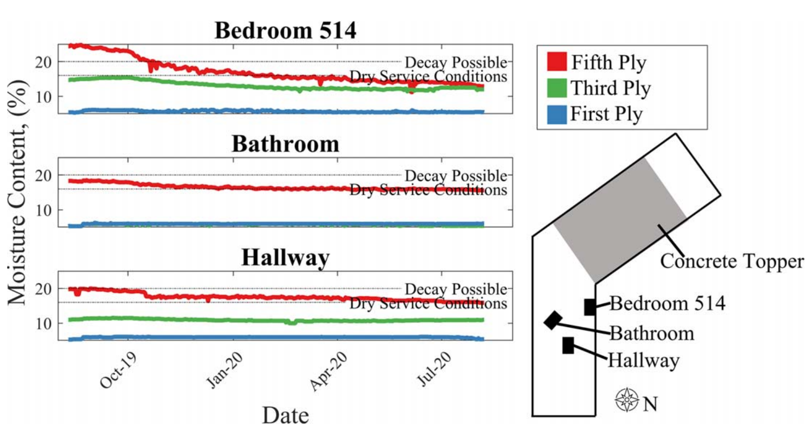

Fig. 12. Full depth examination of elevated MC clusters.

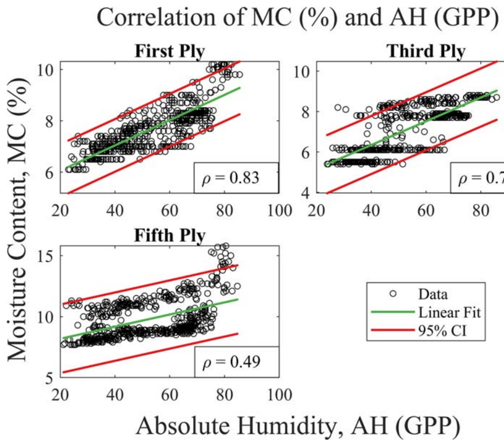

Fig. 13. Correlation of MC and AH for third-floor bedroom.

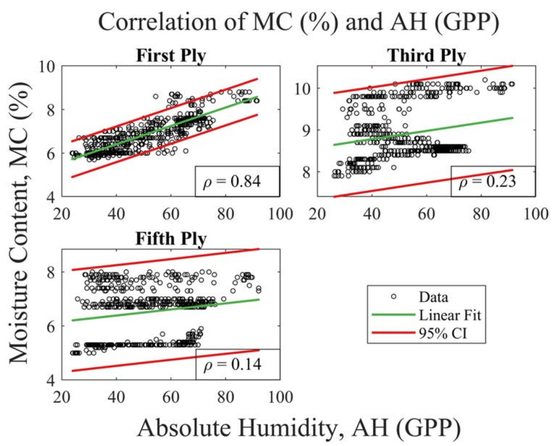

Fig. 14. Correlation of MC and AH for third-floor hallway.

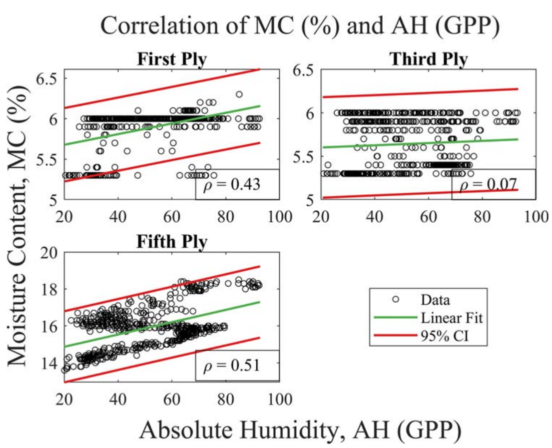

Fig. 15. Correlation of MC and AH for fifth-floor bathroom.

implies that for the first ply, changes in MC are strongly correlated to changes in AH. For the fifth ply, though, the decreased ρ implies that changes in MC are not strongly correlated to AH.

The third-floor hallway sensors were on the underside of the CLT deck within the plenum space and, also, remained within dry service conditions throughout the monitoring. As shown in Fig. 14, the nearly identical ρ value for the first ply indicates that the exposure condition of the panel does not influence the correlation between MC and AH. Significantly decreased ρ values for the third and fifth plies also indicate a weak correlation between MC and AH.

The fifth-floor bathroom is extended with a plenum space, with a fifth ply that was above or near dry service conditions for the first year of monitoring. Unlike other locations, the first ply did not have a strong correlation between MC and AH, as shown in Fig. 15. This may be a result of the lack of change in MC throughout monitoring, as the range of MC in the first ply only varied by 1%. The weakest correlation occurred at the third ply, but like the first ply, the range of MC values was less than 1%. The ply of interest for this location is the fifth ply since it had elevated MC. Because the fifth ply had a similar correlation to that of the third-floor bedroom, it can be concluded that changes in MC for this location are not influenced more by AH than other locations. This supports the conclusion that locations with elevated MC are a result of external moisture intrusions (from the top of the panel), rather than a result of elevated AH inside the building.

Discussion of Results

Similar research performed in Portland, Oregon, found that throughout the manufacture and delivery process, panels remained stable at or near the manufacturer prescribed MC of 10%. During construction, however, panels were exposed to excess moisture prior to waterproofing application. When waterproofing was applied after panels were exposed to excess moisture in the top ply, it had the effect of slowing the drying of those plies compared to panels without waterproofing. At the time of the study, there was only one other published study containing real-world data on moisture in CLT panels (Kordziel et al. 2019).

The scope of this research was focused on the end of construction through the first year of building occupancy—this is the time when the most drastic changes in moisture are likely to occur. After 1 year of monitoring the CLT panels in Adohi Hall, moisture does not appear to be an enduring durability issue for the building. Moisture monitoring of other mass timber buildings should focus on the long-term effect of moisture intrusions from the construction phase, namely, in the first 5 years of building occupancy. In agreement with past work, this research indicates that waterproofing materials slow the drying of CLT, so this should be a point of emphasis in construction. If a panel is waterproofed, extra steps should be taken to protect it from moisture to prevent exposure to high moisture conditions for an extended period.

This study was limited to the climatic conditions encountered in Northwest Arkansas. Future research in other areas of the country will encounter other climatic conditions, and it is possible that moisture monitoring in those climates will yield different results.

Conclusion

The primary goal of this study was to collect long-term moisture monitoring data of CLT panels in a southern climate to determine the impact of moisture on CLT panel durability. Data collection was achieved through long-term monitoring of 134 sensors in 45 locations throughout different wings of Adohi Hall, a residential building on the UA campus.

The main findings from the study are as follows:

1. While there is currently no evidence of moisture increase within the building, moisture uptake from the construction process appears to have contributed to the elevated moisture content in certain areas of the building at the beginning of the monitoring

period. All locations below the fifth floor, which have only a sound mat and flooring on the top side of the panel, as shown in Fig. 3, were below dry service conditions. Since the sound mat and flooring materials are permeable to vapor, this likely resulted in a faster drying rate for interior panels.

2. Results from first-floor sensors indicated that temperature and humidity change from the proximity to exterior doors had little impact on MC in the panels. Results from all floors indicated that temperature and humidity change from proximity to the building envelope had little impact on MC in panels.
3. Third-floor locations provided similar results to first-floor locations. In all locations, all sensors remained under dry service conditions throughout the monitoring.
4. Installation of vapor barriers as part of the waterproofing system hase proved effective in blocking exterior moisture from entering the roof panels. However, the vapor barrier has also potentially inhibited the escape of initial moisture in roof panels. This drying inhibition has led to prolonged time with MC above dry service conditions and above the threshold for decay. It is also important to note that in areas with a different waterproofing system, i.e., where there is a concrete topper for an air handler, drying was not inhibited. These results are consistent with similar previous research, in which roof panels with a impermeable vapor membrane remained above 20% MC for nearly a year (Kordziel et al. 2019).
5. Throughout the building, changes in moisture content were only correlated to absolute humidity in the first ply.

Protecting roof panels from moisture intake before construction and application of waterproofing is recommended to reduce the probability of decay or reduced physical properties since drying occurs so slowly with the presence of waterproofing systems. Any steps that can be practicably taken to reduce moisture increases during construction (especially to the top surface of the panels) will prevent unwanted wetting, especially at the roof level.

Data Availability Statement

All data that support the findings of this study are available from the corresponding author upon reasonable request.

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