How monitoring CLT buildings can remove market barriers and support designers in North America: an introduction to preliminary environmental studies

Como a monitorização de edifícios CLT pode remover barreiras de mercado e apoiar o seu dimensionamento na América do Norte: resultados preliminares de um estudo de impacto ambiental

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Abstract

Currently, design of tall wood buildings is generally accomplished in the USA through the so-called alternate means process, with requires extensive testing, engineering analysis, and a stringent peer review process. As it pertains to cross-laminated timber (CLT), it is critical to develop effective performance prediction models, through laboratory testing elaborating on material behaviors (e.g. hygrothermal, vibrational, etc.) as well as monitoring data on the mid- to long-term performance of timber structures in situ. This paper presents the scope and preliminary outcomes of a project aiming to cross reference laboratory research and in-situ monitoring to establish a holistic performance-monitoring protocol for mass timber buildings; this protocol can later serve to define standards for mid- to long-term monitoring as well as to develop guidelines for the design of mass timber structures.

Keywords: CLT / Cross laminated timber / Hygrothermal performance / Monitoring / Structural health / Wood-water relationship

Resumo

Nos Estados Unidos da América, bem como em muitos outros países do globo, uma vez que não existem regras de dimensionamento regulamentadas que permitam o dimensionamento de edifícios altos em madeira, o processo de dimensionamento é realizado com auxilio a ensaios em laboratório, modelos computacionais avançados, e um rigoroso processo de revisão de projeto por peritos externos. No que diz respeito a edifícios que usem "Cross-laminated Timber" (CLT), para além dos ensaios laboratoriais, ainda existe um numero limitado de edifícios monitorizados in-situ que permitam a caracterização do comportamento higrotérmico e vibracional deste tipo de edifícios. Este artigo apresenta resultados preliminares de um projeto de investigação que visa cruzar ensaios laboratoriais com dados recolhidos num programa de monitorização in-situ de médio e longo prazo, a fim de estabelecer um protocolo de monitorização do desempenho de edifícios altos em madeira e apresentar diretrizes para o projeto no futuro.

Palavras-chave: Monitoramento / Comportamento higrotérmico / CLT / Relação madeira-água

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1 Introduction

Engineered wood products are increasingly incorporated as structural elements into mid- and high- rise construction in Europe and North America as incentives and initiatives align with technology and awareness. Specifically, cross-laminated timber (CLT) has gained traction over the last few decades, primarily in Europe, as its use in wall, floor, and roof assemblies has allowed for the scale and size of mass timber buildings to increase. In North America, Federal initiatives and incentives are emerging to support research for the use of CLT and mass timber products, but tall wood building construction is still inhibited by a general lack of awareness, understanding, acceptance, and coherent incorporation of design standards into the building code.

Currently a body of mixed research is emerging on CLT and mass timber performance that is elucidating important design parameters, including those pertaining to engineering mechanics, connection and fastener behavior, moisture adsorption/desorption, fire, and vibration performance [e.g. 1, 2]. Valuable information that informs design standards and practices is gained both from laboratory testing of materials and systems, as well as from measuring as-built performance of structures. These two forms of analysis are complementary, as controlled experimentation forms the basis for element analysis and modeling, while in situ analysis provides data on the actual performance of these elements and systems within the context of a complex global structure and relative environment over time. Due to the complexity of building systems at the global scale, and the dynamic nature of behavior of wood in situ/over time, further development of research at the building scale is necessary to complement and augment laboratory research. Structural health monitoring, via continuous sensor output, can efficiently give reliable real-time performance data on various engineering metrics in timber structures, while simultaneously allowing for a more comprehensive assessment of various parameters and their interactions studied at the laboratory level. The acquisition of mid- to long-range data sets can serve to directly validate design assumptions or give important cues as to why assumptions are violated. In addition to providing research-oriented data to support design standard development and numerical model optimization, continuous monitoring has pragmatic maintenance, service, and rating applications. Structural health monitoring can also contribute to the safety and service life of a building by serving as an early indicator for dangerous service conditions such as localized high moisture contents. In situ inspections and maintenance efforts can thus be coordinated with performance values and early warning indicators.

Recently, research and educational institutes have initiated programs to promote the use of innovative and sustainable timber structures, which include the construction of new facilities made of mass timber and the development of research programs for monitoring the structural performance and the indoor climatic conditions of these buildings. Among these monitored structures, we can cite the extension of the ESB – École Supérieure du Bois, in Nantes [3,4], the House of Natural Resources at the Swiss Federal Institute of Technology in Zurich (ETHZ), Switzerland [5], the Wood Innovation and Design Centre at the University of Northern British Columbia (UNBC), Prince George, Canada [6], the Brock commons at the University of British Columbia (UBC) in Vancouver, Canada [7], and the Arts and Media building in Nelson, New Zealand (NZ) [8]. In all cited cases, the monitoring program plays a central role in promoting the constructive systems adopted and aims to analyze these systems for their effectiveness in the mid- to long-term.

Construction and in-service risks of mass timber buildings include water events, which can severely affect durability and serviceability performance of the timber systems [9, 10]. Thus, in all monitoring plans of mass timber buildings, control of moisture content (MC) in CLT panels and other structural timber elements is mandatory.

Fortunately, modern sensor technology increasingly allows for efficient and reliable quantification and correlation of environmental conditions and wood MC over time and subsequently for correlation to other critical design parameters [11].

To date, only a small number of research projects have been conducted directly on CLT samples or in situ, as it pertains to wetting/drying potential, stability, and crack formation [e.g. 12]. In addition to elaborating on these important material properties, laboratory work can help develop and implement strategies for collecting rich data derivable from monitoring CLT in situ.

In this paper, we present results of a preliminary laboratory campaign, finalized to define a strategy for the control of MC-related parameters on site.

2 The Smart-CLT project

The SMART-CLT research project, whose formal title is "Structural Health Monitoring and Post-Occupancy Performance of Mass Timber Buildings", aims to measure various performance indicators of CLT assemblies, both within a controlled laboratory setting and within selected case-study buildings. Through measurement of structural efficiency and serviceability, durability and maintainability, and thermal performance, the goal is to identify the interdependence of various indicators in an effort to generate monitoring protocols for this building type, and ultimately define performance standards for the CLT systems. Using physical sensor measurement of vibration, moisture content, ambient and material temperature, relative humidity (RH), air velocity, and thermal resistance, the project aims to collect significant performance data and use these to track design outcomes and define principles for future design iterations.

The following sections describe a preliminary laboratory activity, whose aim is twofold: (1) begin collecting observational data on various moisture-related performance parameters of CLT (adsorption/desorption, stability, checking), and (2) define a methodology for onsite monitoring.

2.1 Materials and methods

Accelerated weathering tests were carried out to evaluate the hygrothermal performance of CLT panels. To this end, the Multi-Chamber Modular Environmental Conditioning (MCMEC) System at the Green Building Materials Lab, Oregon State University, was used. The MCMEC consists of three (3) separate chambers, which can be set to individual environmental conditions. The temperature range is –30 to 40°C (-22 to 104°F) and the relative humidity range is defined by -20°C dew point and up to 95%. A mobile spray rack can be positioned in each of the chambers to simulate rain at a spray rate of up to 5 liters per minute. A two (2) kilowatt metal-halide lamp solar array can be used to simulate sun exposure up to 1200 W/m^2.

In this study, the samples were exposed to two (2) wetting/drying cycles over the course of 52 days, as described in Figure 1. The first cycle consisted of: two (2) days spray-wetting, at 95% RH followed by two days no-wetting at 95% RH and finally by thirteen days dry at 30% RH. Spray-wetting consisted of two overhead emitters spraying at a rate of (2.2 L/min) for two (2) hours at a time, four (4) times a day. The second cycle consisted of two (2) days wetting at 95% RH followed by seventeen days (17) dry at 30% RH and another fourteen (14) days dry at 45/65% RH. The temperature was kept constant at 20°C for the two cycles, and slightly lowered (18°C) during the last fourteen (14) days of the second cycle.

The test material described in this paper consisted of two CLT specimen types (sealed and unsealed) made of five (5) plies of mixed-species woods (*Pseudotsuga menziesii*, *Abies concolor*, *Pinus ponderosa*). These samples utilized a water and weather resistant melamine resin (MF) adhesive. The panels, conditioned at 20°C, 60% RH were of approximately the same volume and mass (90 cm X 30 cm X 18 cm and 20 kg). Specimen "A" was left unsealed and specimen "B" had all its edges with exposed end-grain sealed with putty and marine grade epoxy resin to prevent adsorption through end-grain in order that diffusion through plies was more clearly delineated.

Continuous material moisture data were collected during the cycles using a resistance-type moisture monitoring device from Scanntronik [13]. The system additionally measures and stores climate data such as relative humidity, room temperature and material temperature at the location of moisture measurement. Insulated electrodes were placed towards the center of each specimen and moisture content (MC) readings were conducted in three (3) different plies: the bottom-most ply (PLY 1), and the two plies above it (PLY 2 and PLY 3).

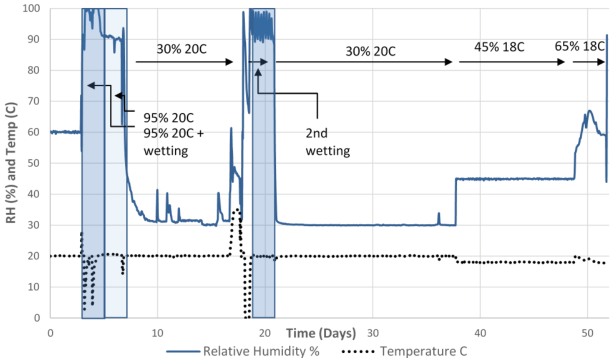

Figure 1 Climate conditions over the course of the 52-day experiment

In addition to collecting continuous MC readings during these cycles, the samples were removed from the chamber on a biweekly basis and measured for weight, and dimensional change, as well as photo-scanned for surface cracking. While MC readings were carried out along the entire duration of the cycles (52 days), the other measurements were terminated at the 41st day of the test.

2.2 Results and discussion

Results related to sorption/desorption cycles and dimensional changes consequent to the accelerated weathering tests are presented in this section. Due to the quantity of dimensional data, only select (and representative) surfaces were chosen for discussion.

Figures 2 and 3 below show MC curves of the unsealed and sealed panels, respectively. MC readings in specimen B (sealed) indicate that, in exposure conditions simulating wetting of a roof or floor CLT panel from above (long faces), the interior plies have a very low wetting potential. Conversely, without a sealant (specimen A) the wetting potential is higher for the interior. Furthermore, moisture collected from a few days wetting takes a few months to dry out (an estimated two months at dry conditions to equilibrate to pre-wetting levels). This signifies that proximity of moisture sources to an edge, and edge/face ratio could strongly affect interior wetting and drying potential. It was also found that adsorption/desorption rates were exaggerated during the 2nd cycle, indicating that exposure and environmental conditions can potentially affect the behavior of this material over the short and long term, due to different factors affecting the peculiar sorption hysteresis behavior of this material [10].

Figure 4 above shows mass variation of the two specimens along the first 41 days of exposure. Mass change is an indirect indicator of MC variations in the specimens; Figure 3 confirms a more pronounced absorption and desorption phenomenon during the second cycle.

Figures 5 and 6 below (for specimens A and B, respectively) each display climate-dependent dimensional variations of two surfaces as measured by 3 points along each surface (one point at each end of the surface and one in the center). The "lower face" graph for each specimen indicates the % change of width across the bottom most facial surface, while the consecutive "end condition" graph for each indicates the % change in thickness across an edge surface. These chosen surfaces are representative of behavior for analogous surfaces, i.e. thickness change was similar across all edge surfaces, while width and length changes were similar across all surfaces. These results verify that the thickness of the specimens (out of plane) was the least dimensionally stable and exhibited an average deformation during the 2nd cycle of about 2% in the unsealed specimen and a more subdued value of about 0.5% for the sealed specimen. The max change in width at the surface was close to 0.5% for both specimens, and the change in length was on average less than 0.025%. These results confirm in field observations of the monitored CLT floor slabs in the Wood Innovation and Design Centre, as reported by Wang *et al*. 2016 [6]. Wood, in fact, is generally stable only longitudinally (along the grain) and has significantly higher deformation rates across the grain. By merit of the fact that CLT is comprised of layers of length-wise members laminated orthogonally, moisture-dependent deformation in CLT is limited in the planar directions by the restraining action of consecutive plies. Dimensional stability is also increased as the cross-section increases in a wooden member [14,15]. This is related to the restraining action of the stable core, or "passive" zone [16] that is less prone to environmental flux (MC variation), as confirmed by readings in the different plies in the two specimens (Fig.2). The resultant MC "lag", or insulatory effect of the interior makes it difficult for CLT to gain and lose moisture deep within [17, 18, 19], and when combined with hysteresis/desorption behaviors [10], possibly more difficult to lose. Work by Alsayegh indicates that moisture uptake values (A-values) through the cross section of CLT panels are smaller than for standard lumber, due to moisture inhibition at lamination lines [14]. This insulatory effect means that, like for all wooden members (if not more), CLT is most susceptible to environmental flux and resultant deformations at the surfaces/surface plies.

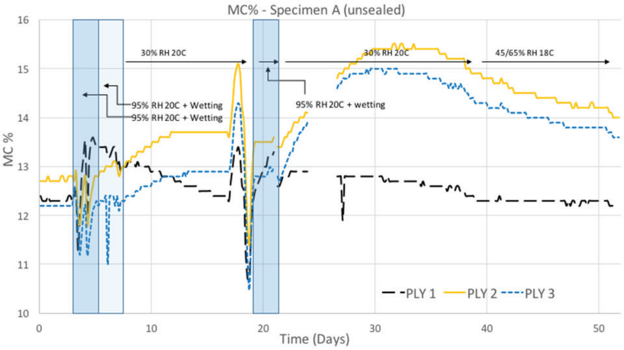

Figure 2 Moisture curves in the bottom-most ply (PLY 1), and the two plies above it (PLY 2 and PLY 3, respectively) of specimen A-unsealed over the duration of 52 days. *Note: values that deviate from 20°C are not temperature-corrected; anomalous spikes in MC can be directly correlated to temperature spikes in Figure 1*

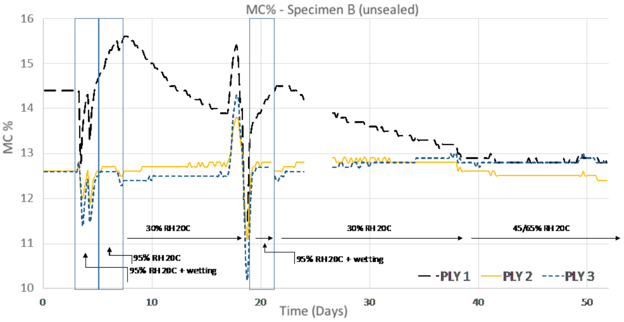

Figure 3 Moisture curves of specimen B-sealed over the duration of 52 days

Figure 4 above shows mass variation of the two specimens along the first 41 days of exposure. Mass change is an indirect indicator of MC variations in the specimens; Figure 3 confirms a more pronounced absorption and desorption phenomenon during the second cycle.

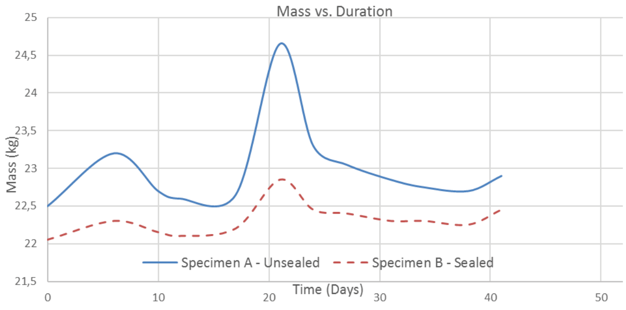

Figure 4 Mass of specimens over the duration of the first 41 days

Figures 5 and 6 below (for specimens A and B, respectively) each display climate-dependent dimensional variations of two surfaces as measured by 3 points along each surface (one point at each end of the surface and one in the center). The "lower face" graph for each specimen indicates the % change of width across the bottom most facial surface, while the consecutive "end condition" graph for each indicates the % change in thickness across an edge surface. These chosen surfaces are representative of behavior for analogous surfaces, i.e. thickness change was similar across all edge surfaces, while width and length changes were similar across all surfaces. These results verify that the thickness of the specimens (out of plane) was the least dimensionally stable and exhibited an average deformation during the 2nd cycle of about 2% in the unsealed specimen and a more subdued value of about 0.5% for the sealed specimen. The max change in width at the surface was close to 0.5% for both specimens, and the change in length was on average less than 0.025%. These results confirm in field observations of the monitored CLT floor slabs in the Wood Innovation and Design Centre, as reported by Wang *et al*. 2016 [6]. Wood, in fact, is generally stable only longitudinally (along the grain) and has significantly higher deformation rates across the grain. By merit of the fact that CLT is comprised of layers of length-wise members laminated orthogonally, moisture-dependent deformation in CLT is limited in the planar directions by the restraining action of consecutive plies. Dimensional stability is also increased as the cross-section increases in a wooden member [14,15]. This is related to the restraining action of the stable core, or “passive” zone [16] that is less prone to environmental flux (MC variation), as confirmed by readings in the different plies in the two specimens (Fig.2). The resultant MC “lag”, or insulatory effect of the interior makes it difficult for CLT to gain and lose moisture deep within [17, 18, 19], and when combined with hysteresis/desorption behaviors [10], possibly more difficult to lose. Work by Alsayegh indicates that moisture uptake values (A-values) through the cross section of CLT panels are smaller than for standard lumber, due to moisture inhibition at lamination lines [14]. This insulatory effect means that, like for all wooden members (if not more), CLT is most susceptible to environmental flux and resultant deformations at the surfaces/surface plies.

Because moisture uptake is more pronounced in end grain and longitudinally than in the transverse directions [10], and because consecutive plies will moisture-dependently-deform at varying rates relative to one another, internal stresses are generated between plies and within dimension lumber elements. In our experiment, adjacent plies were measured for width at the ends in the unsealed specimen and compared: it was found that the ply containing end grain swelled at a maximum of about 0.6% whereas the adjacent lengthwise ply swelled at each end by only 0.1-0.3% during the same period. By running one’s hands down the corner of the specimen, one could feel this differential in the form of a sinusoidal pattern.

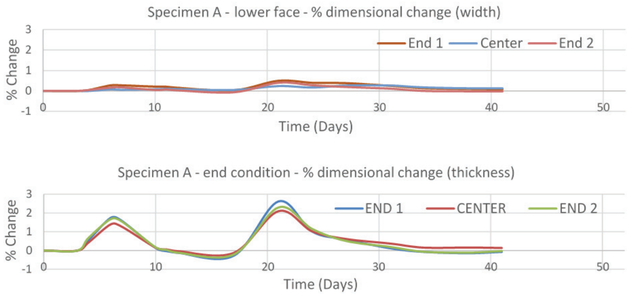

Figure 5 Specimen A – % dimensional change in width and thickness

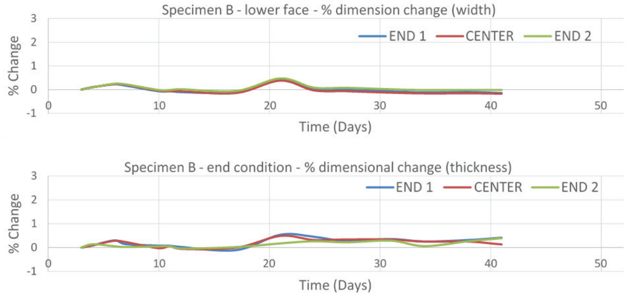

Figure 6 Specimen B – % dimensional change in width and thickness

Figure 7 Checking, gap widening, material defect, and delamination in edge condition Specimen A, day 42

This stress resulted in pronounced checking in specimen A (Figure 7 above) and sheared epoxy resin in specimen B. Thus, the same phenomenon that stabilizes CLT results in large boundary stresses across the surface, and in two directions (two grain orientations). This cross-lamination effect is similar to the effect of restraining deformation at connections described in Dietsch and Tannert [11]. Over time these checking discontinuities can extend further into the interior of the CLT: as stresses develop, relax, and cycle, a "zipper" effect will lengthen the checks to equilibrate stresses [20].

Delamination that occurred in specimen A (e.g. Figure 7) was less than the 5% maximum acceptable delamination of total lamination length on sawn faces as specified in the Cyclic Delamination Test protocol for glulam – AITC, 2007 [21] – which, should be noted, is not truly applicable in this case, as our materials and methods deviate from the standard. Other ostensible delaminations in these specimens are in actuality splits in the wood adjacent to bond lines, induced by hygrothermal stresses acting perpendicular to grain.

Stress induced checking and delaminations, as well as gaps resulting from lack of edge-gluing, manufacturing errors, and imperfections in elements (e.g. rounded corners) (Figure 6) are potentially significant access routes into CLT's interior for air and water, and may worsen over time with environmental fluctuation. McClung [19] observes that tests on smaller CLT samples minimize understanding of the potential for these cracks to increase water uptake into the interior, while Lepage [17] confirms preliminarily that discontinuities and checking do affect sorption behavior. Furthermore, Wang [18] confirms observationally that the resultant gaps from various manufacturing practices of CLT members allowed water to penetrate the edges and into the interior during his experiments.

Our own observations lead us to suspect that there is a correlation between checking and the wetting potential of CLT's interior. This was illustrated by the fact that the mass, dimensions and interior ply MCs all increased more significantly for the unsealed specimen during the second cycle than during the first, despite an identical wetting exposure and even fewer high RH days (while the exterior ply – ply 1 – gained a similar amount of moisture during each cycle). Specifically, relative (comparing wetting cycles) mass increase was more than double for each specimen (Figure 3), relative dimensional deformation in depth, width and length at the surfaces nearly doubled (Figures 4-5) and relative MC increase of the interior plies more than doubled (while rate of MC change increased too) (Figure 2). There also is the possibility that defects in lamination were caused or exacerbated by cyclic environmental change [20] that allowed for higher rates of diffusion between plies (this, as well as micro-cracks in the edge sealant, could account for the higher mass gain in specimen B during the second cycle). Because checking is associated with moisture gradients from exposure, especially from the amount and rate of drying (exacerbated by rapid drying) [22] understanding exposure effects over the short and long term are important (i.e. exposure during construction through post-occupancy) to understanding sorption behaviors as well.

It is important to emphasize that checking can happen at any depth within CLT [23], as swelling/shrinking can elicit checking within the interior as well as the exterior [11]. This was possibly confirmed in our experiment, as output from one of the sensors was suddenly lost during the drying cycle and was regained during wetting. This is suggestive of an internal check that developed between electrodes as the wood shrank, and its subsequent closure as it swelled. This phenomenon reoccurred during the second drying cycle and a subsequent exposure to high RH. It should be noted that this, amongst other unpredictable interior phenomena (including anatomical anomalies such as knots) are challenges related to monitoring CLT with resistance-based electrodes.

3 Recommendations and conclusions

Results from our preliminary experimental campaign indicate that there are strong and interesting correlations between climate cycles, sorption/desorption rates, mass and dimensional changes, and checking in CLT panels. The effects will be further investigated onsite in full-size elements and assemblies. Also, the influence of these interrelated phenomena on other relevant performance indicators will be studied in the frame of the SMART-CLT project, specifically to analyze how (and if) the hygrothermal behavior can affect the dynamic properties of CLT panels (relevant for serviceability/vibrational performance of floors) and the thermal properties of CLT assemblies.

Our preliminary observations and literature confirm that environmental parameters can differently affect hygrothermal performance of CLT panels, depending on the exposed surfaces (i.e. end-grain, long face); the initial geometrical features of the panel (thickness – number of plies; planar extension; presence of gaps between dimensional lumber and in the glue lines, etc.).

It is also evident, that since the edges of CLT are the most sensitive to climatic flux and integral to interior wetting potential (and the resultant consequences), and at the same time are present in the most critical places (e.g. building envelope, connections and apertures), they require further attention, both in research and design.

Although testing of connections and joints was not specific to our preliminary research, their analysis associated to the analysis of the hygrothermal behavior of the panel is a point of importance and interest with regard to CLT. Connections are an important source of continuity and ductility in timber structures, and a natural point of sensitivity to deterioration due to cyclic loading (e.g. wind and seismic) [5] and moisture trapping. Koch, for example, found that an expansion joint of a mass-timber-element-end was prone to moisture trapping in a study on a mass timber bridge in Cologne, Germany, and exhibited higher than acceptable MC for serviceability [23]. Wherever CLT will be joined to another element, and wherever CLT will be opened with an aperture (e.g. a window or door), its edges will be exposed, and it (and importantly its interior) will be more vulnerable to climatic fluctuations, leaks, moisture trapping, and the resultant risks that are associated (decay, dimensional change, strength loss, etc.). This will be exacerbated by existing gaps from non-edge-glued panels, imperfections in layup and the tendency for an untreated end to check under climatic fluctuation. Edge treatment is a possible solution to reducing these effects and wetting potential to the interior.

Practically speaking, flaws in manufacturing, design and construction are inevitable and robust safety measures should be incorporated to account for this. Structural health monitoring can offer increased safety through continuous material observation, while a deeper understanding of long term material behavior at the global scale can be achieved, improving building safety and efficiency through performance assessment and design modifications.

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