A Conceptual Approach for Developing Guidelines to Prevent Drying Cracks in Mass Timber

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Abstract. Surface checks, cracks, and splits can occur in wood when it dries out too rapidly. Wood expands and contracts with changes in moisture content in the hygroscopic range. Spatial differences in wood moisture content cause internal stresses, and cracks form when these moisture-induced stresses exceed the tensile strength of the material. Large moisture gradients may occur in mass timber products, such as glue-laminated timber (glulam) and cross-laminated timber (CLT), at multiple points during and after exposure to moisture during the construction process, followed by abrupt changes in the indoor environment related to startup of building heating, ventilation, and air-conditioning equipment. Drying cracks in mass timber products are aesthetically undesirable when they are intended to provide a finished surface inside the building. In addition, if more severe cracks develop from repeated wetting and drying cycles, structural capacity might be degraded. There is currently a lack of detailed guidance on temperature and humidity setpoints for preventing drying cracks. In this paper we propose an approach toward the development of practical guidance for indoor temperature and humidity conditions in mass timber buildings following the construction process. We suggest that drying cracks can be minimized by maintaining conditions that limit the moisture gradient near the wood surface. We illustrate how hygrothermal simulations can be used for assessing moisture gradients for different levels of built-in moisture and different indoor humidity conditions.

Keywords: Mass Timber · Wood · Moisture · Drying Cracks · Hygrothermal Simulation

1 Introduction

Mass timber buildings are a relatively new type of construction that utilize engineered wood composite panels as floor, wall, or roof components, including CLT, mass plywood panels (MPP), nail-laminated timber (NLT), or dowel-laminated timber (DLT). These buildings often feature engineered wood columns and beams as well, including glulam,

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laminated veneer lumber (LVL), or other types of structural composite lumber (SCL) [1, 2]. Mass timber buildings are gaining popularity for their environmental sustainability, biophilic nature, aesthetics, and speed of construction [3–5].

Mass timber members are manufactured from kiln-dried lamination stock under controlled environmental conditions, typically in the 10% to 15% moisture content (MC) range. In some cases, members may be wrapped in a protective layer for delivery to the jobsite. In one study where glulam and CLT had a protective wrap, the MC remained between about 8% and 14% during transport and storage [6]. However, once the mass timber elements are installed, they can be exposed to precipitation, sunlight, and other environmental loads until the building is enclosed. Moisture contents are generally in the 15–20% range for unwetted mass timber elements during construction; MC levels of 20–30% are indicative of wetting during construction, and MC levels above 30% can occur where water is ponded for some length of time or impermeable layers prevent drying [6–10]. This 30% MC value is significant because it corresponds with the approximate transition from the hygroscopic range, where water is primarily located in the wood cell walls, to the over-hygroscopic range, where capillary water exists in the pore structure [11].

Wood expands and contracts with changes in moisture content in the hygroscopic range. Spatial differences in wood MC cause internal stresses, and surface checks, cracks, and splits can form when these moisture-induced stresses exceed the material's tensile strength. Large moisture-induced stresses may occur in mass timber elements under five different scenarios:

1. Repeated cycles of wetting and drying from exposure to precipitation during construction with natural drying.
2. Wetting during construction followed by fast drying from exposure to sun.
3. Wetting during construction followed by fast drying using mechanical equipment (fans, dehumidification, heating, etc.).
4. Exposure to the outdoor elements, increasing the MC of the mass timber elements during construction, followed by an abrupt change in the MC of the mass timber elements during the enclosure of the building and the commissioning of the heating, ventilation, and air-conditioning (HVAC) equipment.
5. After commissioning, low MC levels in mass timber elements resulting from low indoor relative humidity (RH) levels. Examples include heated buildings with low occupancy during winter in cold climates, or buildings with low occupancy in dry climates.

This paper focuses on scenarios 4 and 5 above.

The formation of drying cracks in mass timber has been studied with laboratory measurements and modeling. Kukk et al. looked at surface cracks and gaps between adjacent boards in CLT panels as the relative humidity (RH) in a conditioning chamber was decreased stepwise from 75% to 15% [12]. Fortino et al. used a hygrothermal-mechanical model to examine moisture gradients and internal stresses in glulam bridge elements exposed to outdoor temperature and humidity fluctuations [13]. Their simulations show that moisture-induced stresses perpendicular to grain exceed the strength design values. A similar approach was taken by Autengruber et al. to assess the extent of crack formation in solid timber and glulam [14]. Even though both studies excluded liquid water absorption, the simulations showed the possibility for cracks to form because of outdoor RH fluctuations.

Mass timber buildings often include exposed elements as a design feature, and therefore, surface cracks are aesthetically undesirable (Fig. 1). Cracks, splits, and gaps in structural members may be problematic for several reasons. The sound of timber splitting may be disconcerting for occupants. Visible cracks range in width and severity, from unsightliness to an appreciable decrease in load carrying capacity. Other gaps may open and compromise the airtightness of sealed joints intended to resist smoke and flame penetration in the event of a fire. Given the variety of concerns related to cracks, splits, and gaps, it is reasonable to ask if it is possible to minimize or even eliminate crack formation in exposed mass timber elements. Because cracks develop in-place, primarily from construction site conditions, efforts to minimize construction wetting events (or rapid drying from solar radiation) may be the most important steps to prevent cracks. It is advisable to develop a Moisture Management Plan with the project consultant and construction team during the project's design phase to prevent such wetting and drying events as much as possible [15]. Another important factor for reducing crack formation is the drying rate after the building is enclosed.

Fig. 1. Cracks in glue-laminated timber elements: diagonal brace (left) and beams supporting CLT floor panels (right).

Several mass timber providers have general guidelines for turning on HVAC systems to minimize cracking, but they do not give specific protocols. On the other hand, Finnish Standard SFS 5978 [16] specifies interior building temperature and humidity conditions that reduce the wood MC by no more than 6% from measured values and specifies multiple phases of drying if the MC difference exceeds 6%. However, the duration of such phases is unclear, the meaning of the measured MC is unclear (mean value or maximum?), and in the case of high measured MCs, this guidance may result in prescribing humidity conditions above 75% RH, which may be conducive to mold growth.

In summary, there is a need to develop simple and practical tools for assessing the risk of crack formation and commissioning protocols that minimize drying cracks in mass timber elements. Different protocols may be needed for each of the five different scenarios listed previously. In this paper, we propose an approach toward the development of guidance for indoor temperature and humidity conditions in mass timber buildings following the construction process. We suggest that drying cracks can be prevented by maintaining conditions that limit the moisture gradient near the wood surface. The approach relies on a combination of laboratory measurements, field data, and hygrothermal simulations. We illustrate how hygrothermal simulations can be used for assessing moisture gradients for different levels of built-in moisture and different indoor humidity conditions.

2 Proposed Approach

Our approach rests on the hypothesis that drying cracks can be minimized when the rate of change in RH with time is sufficiently slow that moisture gradients stay below a critical value. Moisture gradient refers to the derivative of moisture content, u (mass of water expressed as a percentage of dry wood mass), with respect to position, x ($\mathrm{d}u/\mathrm{d}x$, expressed in % mm^{-1}).

We initially considered using data on the kiln drying of wood to identify safe moisture gradients. Kiln drying schedules were developed with the twin goals of drying the wood as fast as possible while minimizing defects such as cracks [17]. Moisture gradients have been measured, for example, during kiln drying of Norway spruce lumber using X-ray computed tomography [18]. Moisture gradients perpendicular to grain were between 0% and 3% mm^{-1} for boards with a cross section of 47×150 mm, and checking was not observed for several different kiln schedules ranging from traditional to aggressive, meaning higher temperature and lower humidity.

However, there are several differences between kiln drying lumber and commissioning mass timber buildings. The strength properties and moisture transport properties of wood vary with temperature. In addition, the kiln drying process itself can aspirate the bordered pits in softwoods, thus altering the moisture transport properties [11], so the wood used in making glulam and CLT is not the same as green wood. Furthermore, the adhesive bonds in mass timber elements introduce constraints on shrinkage such that these composites behave differently from individual boards. For example, wood shrinkage along the grain is much less than shrinkage perpendicular to grain, so the crosswise laminations in CLT limit the extent of dimensional changes within the plane of the panel. Additionally, the manufacturing of CLT varies between suppliers; some may perform edge gluing (adding adhesive to the side of the lamella and pressing the lamellas together), while others may not.

Instead of relying on kiln drying data, we propose new laboratory measurements using mass timber elements in conjunction with hygrothermal simulations to determine the critical moisture gradient and possible lower limits on MC. Samples that incorporate edge gluing and samples that do not would be placed in a conditioning chamber, starting with a uniform initial moisture content, and then monitored for cracking under exposure to different changes in relative humidity. These laboratory experiments, together with measured hygrothermal property data, would serve to calibrate the simulations and identify conditions that exceed the critical moisture gradient. Guidelines would then be developed based on simulations for various scenarios and tested in practice by monitoring conditions in mass timber buildings and documenting the presence or absence of cracks. Below we provide illustrations of moisture gradients from hygrothermal simulations.

3 Methods

Moisture gradients are simulated in a one-dimensional segment through the center of a glulam beam (perpendicular to grain) for several scenarios involving different initial MCs and different interior RH conditions. An initial value of $u = 12\%$ represents a scenario where the material remains close to the factory condition during the construction process, and $u = 20\%$ represents a scenario where the MC increases appreciably during the construction process. Interior RH conditions are selected for illustration to be constant values of either 10% as an extreme value for a low occupancy building in a cold climate or 50% as a moderate value. RH levels as low as 10% can be justified as follows. At 21 °C, 10% RH corresponds to a dew point temperature of –12 °C. In buildings with no internal moisture generation, the indoor dew point temperature tracks the outdoor dew point temperature (neglecting moisture buffering, which smooths out short-term fluctuations) [19]. A dew point of –12 °C is not uncommon for winter cold spells in the northern U.S. or in many parts of Canada. For reference, the January mean outdoor dew point temperatures in Minneapolis and Duluth, Minnesota, are –11 °C and –13 °C, respectively [20].

A one-dimensional segment through the center of a 184-mm-wide Douglas-fir glulam beam was simulated using WUFI Pro software [21]. The material properties are from Glass et al. [22]. The temperature was constant at 21 °C. The surface heat transfer resistance was set to 0.125 $m^2\ K\ W^{-1}$. Radiation was excluded. The effect of a surface coating on moisture transfer was omitted here, but this is an important variable that will be explored in future work. The RH was constant at either 10% or 50% after a linear decrease over 24 h from an initial value corresponding with the initial wood MC. The numerical grid was set with 1,840 linearly spaced elements to facilitate the calculation of moisture gradients, which were based on 1 mm increments.

4 Results and Discussion

Moisture profiles are plotted in Fig. 2 for the different scenarios at various points in time. In all cases the moisture gradient is greatest after one day and decreases thereafter. As expected, the scenario with the largest moisture gradient (lower left) is for an initial MC of 20% and interior RH of 10%. The scenario with the smallest gradient (upper right) is for an initial MC of 12% and interior RH of 50%.

These examples are simply for illustration. At this point the critical moisture gradients for different mass timber products such as glulam and CLT are not known. However, laboratory tests will provide a way to monitor whether cracking occurs under exposure to different changes in relative humidity and corresponding moisture gradients.

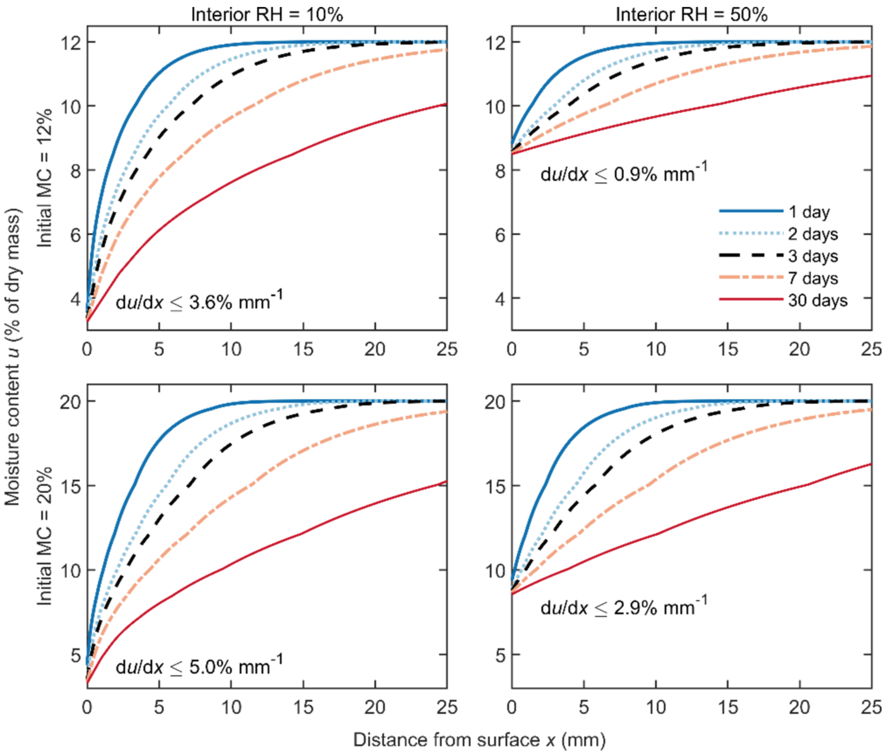

Fig. 2. Simulated moisture content vs. distance from the surface of a 184-mm-thick Douglas-fir member, with initial MC of 12% (top row) or 20% (bottom row) exposed to interior RH of 10% (left column) or 50% (right column). Maximum moisture gradients are indicated in each plot.

5 Conclusion

This paper discusses the problem of drying cracks in mass timber elements and the need for practical tools to assess the risk of crack formation and for guidance on indoor temperature and humidity levels to mitigate the problem. We propose a combined approach including laboratory measurements, hygrothermal simulations, and field monitoring toward this end.

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