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Experimental analysis of moisture uptake and dry-out in CLT end-grain exposed to free water

K Kalbe¹, A Annuk², A Ruus² and T Kalamees¹

¹ Tallinn University of Technology, nZEB Research Group, Tallinn, Estonia

² Tallinn University of Technology, Tartu College, Tartu, Estonia

E-mail: kristo.kalbe@taltech.ee

Abstract. This paper presents the results of a series of laboratory tests of CLT end-grain moisture uptake and dry-out. We put CLT test details (TDs) in direct water contact from the end-grain edge and then left the TDs to dry for two weeks in the laboratory and in an outside shelter. Half of the TDs had their wet sides attached to another CLT detail. Fibre saturation point was quickly reached in the bottom part of the TDs during the seven-day water contact. A tendency of increasing moisture content (MC) was up to 90 mm from the wet edges, but we did not record MC levels above the critical level at that height. However, MC exceeded critical levels at 60 mm from the water level. The measured water absorption coefficient A_w was $3.51 \times 10^{-3} \text{ kg/m}^2 \cdot \text{s}^{0.5}$. Drying was negligible for the TDs which were in contact with another CLT detail. Thus, moisture dry-out is very complicated in joints where the CLT end-grain is covered, such as the exterior wall to foundation or intermediate ceiling connection. The dry-out of CLT is not expected in a cold and humid outdoor environment once the CLT end-grain has absorbed moisture even with wet edges exposed to air.

1. Introduction

Wetting of timber structures can have a harmful effect on their durability [1-3] and could lead to adverse health effects due to microbial growth [4–7]. Pasanen et al. [8] brought out that capillary absorption of water in wood-based materials results in rapid fungal contamination and that mould growth is abundant when the moisture content (MC) is above 20%. Olsson [9] reported that the probability of mould growth is very high when timber is exposed to free water. In a more recent study, Olsson indicated that it is very probable that cross-laminated timber (CLT) will get wet and develop mould growth if constructed without weather protection [10]. Olsson observed that "water does not easily absorb into the perpendicular fibres or through glued layers" thus indicating that the wetting of end-grain is more critical. Kalbe, Kukk and Kalamees observed the construction of a CLT building in Estonia and identified that the most critical areas of CLT regarding wetting are the joints where the end-grain portion is exposed [11]. Niklewski et al. [12] studied the moisture conditions of rain-exposed glue-laminated timber members and measured the highest MC in exposed end-grain details. It is thus evident that the end-grain parts of timber details are the most vulnerable due to moisture. However, CLT panel cut edges differ from the end-grain sides of typical glue-laminated timber members due to there being both end-grain and tangential wood faces which could have cracks and gaps between them. This could affect the moisture uptake and dry-out characteristics of wetted CLT panels. Previous studies have described the hygrothermal characteristics of CLT, but have concentrated

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on moisture transport perpendicular to grain [13–15]. Öberg and Wiege discuss that end-grain water uptake is crucial for wood and CLT panels, but state that end-grain water intrusion was not part of their calculations [16].

This paper presents the laboratory measurements of water uptake in the end-grain of CLT panels and subsequent drying under laboratory and outdoor conditions considering dry-out limiting factors which may occur in intermediate ceiling or foundation joints. Knowledge about these characteristics help to design better solutions for moisture-safe CLT construction.

2. Methods

2.1. Test details

Twelve test details (TDs) were prepared from a five-layer CLT panel obtained from a local producer in Estonia. The panel was produced in a controlled environment and had an initial MC of $\approx 12\%$ upon delivery. The TDs had a width and height of 400 mm and a thickness of 100 mm. Three edges of the TDs were covered with a liquid-applied membrane coating to prevent moisture transfer through these edges. The side surfaces were left untreated. Thereby, one TD corresponds to one 400 mm by 400 mm portion of a larger uninsulated CLT wall panel where the three end grain edges would be in contact with timber (i.e., with surrounding parts of the larger panel, rather than air) and the side surfaces would not yet be covered. The bottom end grain edge was left untreated (Figure 1). This mimics a scenario where the CLT panel is installed on site and is open to water contact from the bottom connection (e.g., exterior wall to foundation connection) and insulation or any other layers are not yet installed providing a possibility of moisture dry-out through the sides. The TDs were left to stabilise for two weeks in a controlled environment before the wetting started.

2.2. Test setup for moisture uptake and subsequent drying

A moisture uptake test was prepared where the untreated bottom end-grain edges of the TDs were held in constant water contact throughout seven days (Figure 2). A similar situation could occur on the construction site if the CLT panels had been installed without weather protection and rainwater had accumulated under the CLT edge. Such occurrences have been documented by Kalbe, Kukk, and Kalamees [11].



Figure 1. Dimensions of a test detail (TD). Location of the moisture measurement points (red dots) shown on a diagram of the TD.



Figure 2. Test detail suspended above water with $\approx 2 \text{ mm}$ in water contact.

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Water level was kept constant at about 1 mm to 2 mm above the bottom level of the TDs (Figure 2) by regularly adding small amounts of water to the container. Special care was taken to ensure that the water contact remained constant and that the TDs would be level regarding the water surface. Blunt pins were used under the TDs to maximise the water contact and eliminate possible surface effects. Blue dye was added to the water to better illustrate the moisture transport in the CLT structure. The TDs were cut in half after the drying sequence and the moisture ingress was further inspected visually.

The TDs were held in water contact for 168 h at indoor conditions and thereafter numbered (TD13–TD24) and divided into four groups for the drying sequence: 1) TDs in indoor air with the wet surface exposed, 2) TDs in outdoor air with the wet surface exposed, 3) TDs in indoor air with the wet surface against another CLT detail that inhibits moisture dry-out and 4) TDs in outdoor air with the wet surface against another CLT detail.

The TDs, which were connected to other CLT details, describe a situation where the wetted area exhibits moisture trapping conditions. This is similar to exterior wall to foundation or exterior wall to intermediate ceiling connection where the end grain edge is on the foundation construction or intermediate ceiling slab [11]. If there is a hydro-insulation layer on top of the foundation structure or a moisture barrier on top of the intermediate ceiling slab and water had gotten between this layer and the CLT panel on top, the moisture dry-out would be rather limited. In this sense, the CLT detail that was connected to the TDs in this study is a rather modest moisture barrier, because timber absorbs some water and thus pulls away moisture from the TD. However, the timber still exhibits vapour retarding properties (compared to freely drying surfaces that are open to ambient air). This approach was chosen because it will establish a base value and if more vapour retarding materials are used on the connection, the moisture dry-out would be even slower than described in this study.

The air temperature and relative humidity (RH) in the laboratory and in the outdoor shelter were measured with a Hobo UX100-023 data logger with its external sensor about .5 m from the TDs. The average ambient air temperature in the laboratory during the drying sequence was +21.6 °C (standard deviation, s = 0.8 °C) and the average RH was 28.6% (s = 5%). The water vapour pressure in the room was thus between 580 Pa and 910 Pa. Assuming an RH of ≈ 100 % at the wet TD edge, the corresponding water vapour pressure at the wet CLT surface was ≈ 2600 Pa. The difference in the water vapour pressure between the surrounding indoor air and the wet surface describes a situation with good ambient drying potential. The average air temperature in the sheltered but ventilated outdoor environment was +2.1 °C (s = 2.7 °C) and the average RH was 92% (s = 5%). The corresponding water vapour pressure was between 500 Pa and 830 Pa. The water vapour pressure at the wet CLT surface in the outdoor conditions was between 580 and 860 Pa, being often times equal to the ambient air water vapour pressure. The drying potential was thereby marginal.

2.3. Measurements

Moisture content measurements were made according to the EN 13183-2:2002 standard [17]. A calibrated Logica Holzmeister LG9 NG electrical resistance-based wood moisture meter was used. The expanded uncertainty was 0.8 % upon calibration for MC values between 12% and 22%. This increases notably when timber cell walls are completely saturated with water (fibre-saturation point $\approx 30\%$ MC), however, in this paper we have opted to report the measurements as is. The high values that indicate a MC over the fibre-saturation point help to describe the extent of wetting (e.g., just about at fibre-saturation point or certainly exceeding it). Nevertheless, if the structure has wetted to fibre-saturation point, there is a large risk of damage due to microbial growth or swelling and shrinkage.

All MC measurements were done with 60 mm long Teflon insulated pins that were attached to a ram-in electrode. The pins had 10 mm long uninsulated peaks that made it possible to

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measure the MC at different depths, depending on how far the electrodes were rammed in. MC was measured on every TD at two depths: 5 mm and 50 mm from the surface at five height levels from the bottom of the TD (at 30 mm, 60 mm, 90 mm, 120 mm and 150 mm from the water level (Figure 1). Thus, a total of ten MC measurements were made per one TD. The 5 mm deep measurement points describe MC in the outer ply of the CLT and the 50 mm deep measurement points describe the conditions in the inner (3rd) ply of the CLT (5 layers in total). Both timber board layers were in the same direction and had the end-grain part exposed to free water. The measurements were done daily throughout the test period from wetting to drying.

The TDs were also weighed regularly (every 2h for the first 6h and every 24h afterwards) with a Kern DS 30K0.1L platform scale with an expanded uncertainty of 0.8 g for loads up to 10,000 g. Every TD was also photographed from one side before it was put back into water contact. Water uptake rate and water absorption coefficient were calculated on the basis of these measurements. The test was performed largely according to the European standard EN ISO 15148 [18], which provides the procedure to determine the water absorption coefficient of a building material by partial immersion. The difference with our test and the standard procedure was that the standard requires coating of all sides, but we coated only the end-grain sides and top surface. This was necessary for the additional dry-out sequence of the test.

2.4. Critical moisture content

For the estimation of the criticality of MC, we used the limit value of 16% (mould growth initiation). Gradeci et al. made a systematic literature review about mould growth criteria and reported that the minimum RH requirements for mould growth initiation varied from 70% to 85%, while most reviewed studies indicated mould growth when RH was at least 80% [19]. The latter corresponds to a timber MC of $\approx 16\%$ [20] at temperatures $\approx 0-20$ °C. Mould growth is also affected by exposure time and temperature [21], but in this study we focused on the MC distribution and thus established only a critical MC level for the evaluation of results.

3. Results

During three weeks, a total of about 2800 MC measurements were done. Figure 3 summarises the results and several effects become evident. The upper five plots describe the MC conditions in the outer 5 mm surface layer of the TDs and the bottom plots describe the MC in the 50 mm deep middle layer of the TDs. Moisture content measurements taken from various heights from the water level are presented on separate plots (from 30 mm up to 150 mm, see Figure 1 for a graphical representation of the measurement points).

At 90 mm and above (from the water level), the MC decreased in the 5 mm deep (surface) measurement points during the wetting period due to the dry ambient air. This indicates that the moisture absorbed from below did not reach the measurement points at that level. Though, we observed some cases where moisture stains reached up to 130 mm adjacent to the measurement points. The trend of decreasing MC in the surface level continued for the TDs which were left to dry in the indoor environment. However, the TDs which were put to the outside environment started to absorb moisture from the ambient air and the MC increased above the critical level. The equilibrium MC was > 22% in the outside environment (calculated with the equation 4-5 given in [20] with the average outside temperature of ≈ 2 °C and RH 92 %). Thus, the increase in the surface MC was to be expected. This effect was not evident for the middle layer measurements taken 50 mm deep. However, the measurements indicated moisture redistribution in the middle layer up to 90 mm high, where a slight upwards trend of the MC levels was visible. The redistribution of moisture in the middle of the TDs was very clear for measurements up to 60 mm above the water level, where the MC had an increasing trend for all TDs regardless of conditions throughout the entire test period.

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Figure 3. Measured MC in the TDs over wetting and drying. The upper five plots describe the MC in the surface layer (5 mm deep) of the TDs in different heights (Figure 1) from the water level and the bottom five charts describe MC in the middle layer of the TDs (50 mm deep). Each colour represents a different TD.

Further analysis of the results showed that MC in the middle layer of the TDs, which had another CLT detail attached to the wet base, did not go below 20% even in the TDs that were left drying in the inside air conditions (Figure 4, left). MC did decrease in the surface layer (Figure 4, right), but only for the TDs that dried indoors.

The water uptake rate (average of every TD) was 200 g/(m²·h) for the first two hours, then decreased quickly to about 85 g/(m²·h) during the next four hours and then decreased gradually during the next 70 hours to about 20 g/(m²·h) where it stabilised (Figure 5). The water absorption coefficient A_w was 3.51×10^{-3} kg/m²·s^{0.5} (calculated as per EN ISO 15148 [18]).

The added blue dye illustrated moisture transport on the CLT surface. The results reflected the electrical resistance-based MC measurement adequately from the surface layer. Heterogenic properties of wood were also visible. Figure 6 shows photos of TD20 where the water level at MC measurement points was lower than just next to the measurement points. The main water level stain marks did not rise above 130 mm in any test detail during the seven-day wetting period, but there were few instances where small stain marks were visible higher up in cracks

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and ply joints. However, the stain line inside the TDs did not correlate with the measured MC in the middle layer. This was probably because the dye trapped in the lowest few millimetres of the TD and did not reach further. Thus, the visual inspection was impractical inside the TD.



Figure 4. MC at 30 mm from the bottom of the TDs that had wet edges against CLT. Measurements from the middle (50 mm deep, left) and surface (5 mm deep, right) layer.



Figure 5. Water uptake rate during the test as an average of every TD.



Figure 6. Photos of TD20 at 2, 29 and 168 hours after the start of water contact. Water was dyed blue and left stains on the timber surface. Red dots mark the MC measurement points.

4. Discussion

Our findings show that the most vulnerable area to moisture damage leading from water ingress from under a CLT panel through the end-grain side is up to a height of 60 mm from the bottom of the panel. There is a tendency of rising MC in the middle layer of the TDs up to 90 mm high,

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but we did not record MC levels above the critical level at that height during the seven-day continuous wetting period and 14-day drying period afterwards. A greater risk to dampness related problems in the higher areas are on the surface and more due to outside environment conditions. However, in low temperature conditions, the probability of mould growth is low [19].

Measurements from the bottom area of the TDs (30 mm from the water level) indicate that fibre saturation point was quickly reached in the bottom part of the TDs in both surface and middle layers. During the two-week drying period, it became evident that there is no drying potential even with wet edges exposed to air in the cold and humid outside environment (t ≈ 2 °C and RH 92 %, which approximate to the February averages in the Estonian moisture reference year for mould growth criticality [22]). Drying was also negligible in the indoor environment for the TDs which were in contact with another CLT detail. This suggests that moisture dry-out is very complicated for construction joints where the CLT end-grain is covered, such as the exterior wall to foundation or intermediate ceiling connection. It is possible that moisture stays in the CLT panel bottom part until the construction process reaches stages where temperature around the panel is suitable for mould growth. These findings show that moisture redistribution is probable for up to 90 mm from the water contact surface. This implies that MC in the area could exceed the critical level well after the initial wetting incident and thus would be susceptible to mould growth. Moreover, Li and Wadsö reported that fungal activity is greater during moisture desorption process than absorption at the same RH levels [23]. Researchers have suggested to use whole site weather protection for timber buildings [24] and although this would help to minimise the risk of wetting, incidents might still occur. We propose to use endgrain protection on CLT panels regardless of site weather protection, because the poor dry-out characteristics and possible moisture trapping conditions in several end-grain joints.

Previous studies have measured the water absorption coefficient (A_w) of CLT, but have determined it with the CLT panel face in water contact and not for the end-grain cut edge in water contact. AlSayegh has reported that the A_w for the side surfaces of CLT is 1.6–1.7×10⁻³ kg/m²·s^{0.5} [14, 15]. The European CLT samples from a study by Lepage had an A_w \approx 1.1×10⁻² kg/m²·s^{0.5} [25]. In a recent study by Kordziel et al. A_w was also calculated for the side surfaces of CLT and was $\approx 2.5-2.8\times10^{-3}$ kg/m²·s^{0.5} [13]. Longitudinal moisture transport in wood is greater than moisture transport perpendicular to grain [20]. This is evident when comparing our results with the ones of Kordziel et al. and AlSayegh, where the A_w value we calculated was greater. However, Lepage reported higher values of A_w for moisture transport perpendicular to grain. This could be influenced by different wood species and glue formulas. Measured values of A_w for softwoods are in the range $\approx 1-1.6\times10^{-2}$ kg/m²·s^{0.5} in the longitudinal direction and $\approx 1-7\times10^{-3}$ kg/m²·s^{0.5} in the transverse directions [20]. It seems that regarding the moisture absorption coefficient, CLT end-grain acts more like the transverse direction in regular timber.

5. Conclusion

In this paper we characterised the water uptake and subsequent moisture dry-out of CLT panels from the end-grain edge. The measured water absorption coefficient A_w was $3.51 \times 10^{-3} \text{ kg/m}^2 \cdot \text{s}^{0.5}$.

Taken together, our results from the drying sequence suggest that if gotten wet, the CLT endgrain edges will not dry out in a timely manner, especially the parts of panels where moisture trapping conditions occur.

We suggest to protect the end-grain edges of CLT panels with a moisture barrier that also prevents water from getting between the CLT and the barrier itself. We reccomend to apply the barrier before the delivery of CLT panels on site and use the barrier regardless of other weather protection practices to minimise the risk of wetting in joints where moisture trapping conditions could occur.

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