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Hygrothermal Performance of CLT Subjected to Rain Loads during Construction in Belgium

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Abstract. *As the use of CLT is increasing, it is important to understand how to deal with moisture during construction. Throughout the construction phase it is often not feasible to shield every component and detail from direct rain impingement. This paper investigates what happens to CLT, and spruce wood in general, when it is exposed to rain events, and how fast it dries out afterwards. Subsequently, the implications of incorporating a wetted component into a finished wall system is also investigated. The moisture behaviour of both plain spruce and CLT samples that are exposed outdoors is investigated using the continuous moisture measurement (CMM) setup at the UGent Woodlab in combination with hygrothermal simulations in Delphin 6. Pieces of solid wood and CLT are mounted on load cells that record the weight every 5 minutes, to study the wetting and drying behavior. Hygrothermal simulations are done in Delphin 6 using a climate file that is made from the recorded weather data. This way, the CMM experiments can be recreated in simulations. The goal here is to understand what is happening in the simulations and to look at what influence different parameters have on the moisture content of the samples. Risks of mould and wood decay are investigated, and recommendations are made concerning practical moisture management and risk mititagion for these types of constructions.*

Keywords: *CLT; Hygrothermal; Moisture; Construction Phase; Mould; Experimental*

1 Introduction

Cross laminated timber (CLT) is an engineered timber product consisting of layers of timber bonded to each other, typically in perpendicular direction. Mostly softwoods such as spruce, pine, or fir are used, although using hardwood for CLT is being researched and already being used in some specific cases. Standard adhesives are polyurethane (PUR), but increasingly melamine-urea-formaldehyde (MUF) adhesives are adopted. The main arguments mentioned for the increasing popularity of using CLT are aesthetics, reduced carbon footprint, higher construction speed, reduced weight, and low thermal conductivity. If the timber is sourced from sustainable forests, CLT has some environmental advantages. The wood stores CO2 over its entire use in the building. At the end of its life, it releases the carbon back into the air either through natural decomposition where the wood becomes a nutrient source in the soil or by burning it as a fuel for heat recovery. The impact of this carbon sequestration is subject to considerable debate, with significant differences between static and dynamic LCA approaches

(Sutton et al., 2011; Gustafsson, 2019). The most prominent technical problem with using CLT today is moisture (Kukk et al., 2022). As it is typically made of untreated softwoods, it is very susceptible to both mould and wood rot. The main problems are (i) wetting of the CLT during the construction phase, especially when the CLT is encapsulated into a construction before it could dry out, and (ii) internal condensation due to diffusion or convection when the construction is poorly conceived or executed. As the use of CLT is increasing, it is important to know how to deal with moisture during construction. In practice, it is not feasible to omit every single risk of rain impingement during construction. This implies that increased initial moisture contents should be considered as an inherent aspect of CLT design and construction. This paper investigates what happens to CLT and spruce wood when it rains and how it dries out afterwards. Subsequently, mitigating actions for damage control afterwards are evaluated.

2 Wood and Wood Decay

The moisture content (MC) is the most important factor for fungal growth. A lot of research has been done on the moisture content criteria for fungal growth. An important distinction that is made is between without moisture and nutrient source available and with moisture and nutrient source available. Without moisture and nutrient source, the MC threshold is related to the fiber saturation point (FSP), which is generally between 22 – 30% (Vanpachtenbeke, 2019). Viitanen found the threshold to be a minimum relative humidity of 94 – 96% RH and a minimum MC of 25 – 28% (Viitanen, 2011). Saito et al. (2012) found no degradation below FSP, and Brischke et al. (2017) found a minimum moisture content of ±33% at 96% RH. If moisture and nutrient source are available much lower MC thresholds were found. Meyer & Brischke (2015) found 16% MC for Scots pine sapwood, 15% MC for beechwood. The Swedish CLT Handbook (Gustafsson, 2019) prescribes 18% MC as a maximum moisture content to avoid fungal growth. The moisture content of the wood is an important factor for the decay of wood, but even more import is the time of wetness. Viitanen (1996) adopted the time of wetness concept developed by Adan (1994), and made time of wetness criteria for both mould growth (TOW 20/5) and wood rot (TOW 25/10). A moisture content above 20% with a temperature above 5°C, should not occur more than 720 hours per year to avoid mould growth. Similarly, a combined 25% MC and 10°C should not exceeded for 168 hours a year to avoid wood rot. The updated VTT mould model extended the original VTT mould model, which only applied to pine and spruce, to other building materials and improved the mould prediction in unfavourable conditions. As this model is one of the most detailed mould prediction models and easy to use with hygrothermal simulations, it is used in this paper to investigate the risk of mould growth. The VTT mould model uses a mould index to indicate the amount of mould that is predicted.

3 Materials and Methods

3.1 Vapour Diffusion

The water vapour diffusion resistance of the adhesive layer is investigated using the cup test according to EN ISO 12572 (2016). This is done by measuring the water vapour diffusion resistance of a sample without an adhesive layer and that of a sample with an adhesive layer and comparing the two results. The samples have a diameter of 90 mm and a thickness of 6 mm. The wood is spruce, and the adhesive is a melamine-urea-formaldehyde (MUF) adhesive.

3.2 Continuous Moisture Measurement

The Continuous Moisture Measurement (CMM) setup is an outdoor setup where samples are exposed outdoors in Ghent, and their weight is continuously measured. The CMM setup is from the UGent Woodlab and consists of single point load cells that are connected to a Delta-T DL2e data logger. The table on which the load cells are fastened is positioned in a 173° direction, corresponding to the high S-W wind driven rain load in Belgium. The load cells have a precision of 1 g and a maximum loading capacity of 1000 g. On top of the load cells, T-shaped holders bent in a 45° angle are mounted on which the samples are installed. The datalogger records with an interval of 5 min. The calibration of the load cells is done by placing calibrated weights on each loadcell. The conversion from mass of the sample to the moisture content in mass percent is made by using the dry weight. The dry weight is determined by drying the samples for 48 hours at 103±2°C at the end of the experiment. The spruce samples had a thickness of 35 mm, width of 85 mm and height of 250 mm, the CLT samples measured 20 mm x 137 mm x 137 mm. The CMM experiment on is done on several different CLT samples. CLT 1, 2, and 3 are samples with a 1 cm top layer and a 1 cm bottom layer with the edges, that are end-grain, sealed with a silicone-based paint. CLT 4, 5, and 6 are also samples with a 1 cm top layer and a 1 cm bottom layer, but with open end-grain. CLT 7 is the same as CLT 1, 2, and 3, but has an edge between two boards in the top layer. CLT 8, 9, and 10 are samples with a 3 mm top layer and sealed edges. CLT 11 and 12 are POM plastic samples to check the impact of adhering rain, wind pressure, and changes in resistance of wires to the datalogger. All samples are under a 45° angle on the CMM setup, except CLT 12 which is under a 0° angle. Next to the CMM setup a weather station is installed. The weather station consists of a solar radiation sensor, a tipping bucket rain gauge, a relative humidity probe, a thermometer, an anemometer and a wind vane.

3.3 Hygrothermal Simulations

Delphin 6 is a simulation program for combined heat, air, moisture, and pollutants simulations (CHAMPS) in porous building materials. As no pollutants are studied here, the abbreviation HAM simulation can be used. In this paper, only one-dimensional (1D) simulations are done as the simulated configurations mainly consist of planar elements. Boundary conditions are applied to the construction, for simulating the CMM setup this entails that an outdoor climate is applied to the top and bottom surface of the construction (for the latter, without WDR and adjusted radiation). The adhesive layer is modelled as a layer with the properties of the adhesive material. The adhesive used by Stabilame (supplier of the CLT panel used in this study) is the BASF Kauramin Glue 690 Liquid with Kauramin Hardener 1690 Liquid, which is a melamine-urea-formaldehyde (MUF) adhesive. BASF prescribes a maximum adhesive film thickness of 0.3 mm. Hass et al. (2010) found the typical adhesive film thickness when bonding wood with a similar adhesive to be 0.25 mm. The adhesive layer is modelled as a layer with a thickness of 0.25 mm. Li et al. (2014) looked at water absorption of plywood using CT scanning and found that a MUF glue line has a large liquid water resistance, so no liquid water transport is modelled in the glue layer. The water vapour diffusion resistance is taken from the cup testing results. The sorption isotherm for a MUF adhesive layer is taken from Wimmer et al. (2013). The specific heat capacity is 1000 J/kgK. The thermal conductivity is approximately the same as for wood and is 0.13 W/mK (Uysal et al., 2019). The density of the MUF adhesive layer is 1000 kg/m³ (Svensson Tengberg and Hagentoft, 2021).

4 Results

4.1 Water Vapour Diffusion Resistance

It was found that the adhesive layer had a water vapour diffusion equivalent air layer thickness *s*'' of 0.104 m for the wet cup and 0.842 m for the dry cup. As expected, the vapour diffusion resistance is higher for the dry cup than for the wet cup. When assuming that the MUF adhesive layer has a thickness of 0.25 mm, the water vapour diffusion resistance μ (-) is 416 for the wet cup and 3368 for the dry cup. This is in line with what was found in literature (Volkmer et al., 2012).

4.2 Moisture Behaviour of Plane Spruce

The moisture behaviour of plain spruce is investigated by hygrothermal simulations on spruce materials and analyzing the CMM. From the CMM it can be concluded that during drying days, the moisture content is 8 – 15%. During longer dry periods, the moisture content stays below 12%. The daily variations in moisture content are around 4% between day and night. During a rain event, the moisture content quickly rises above 15% and goes up to a maximum of 20% during this experiment.

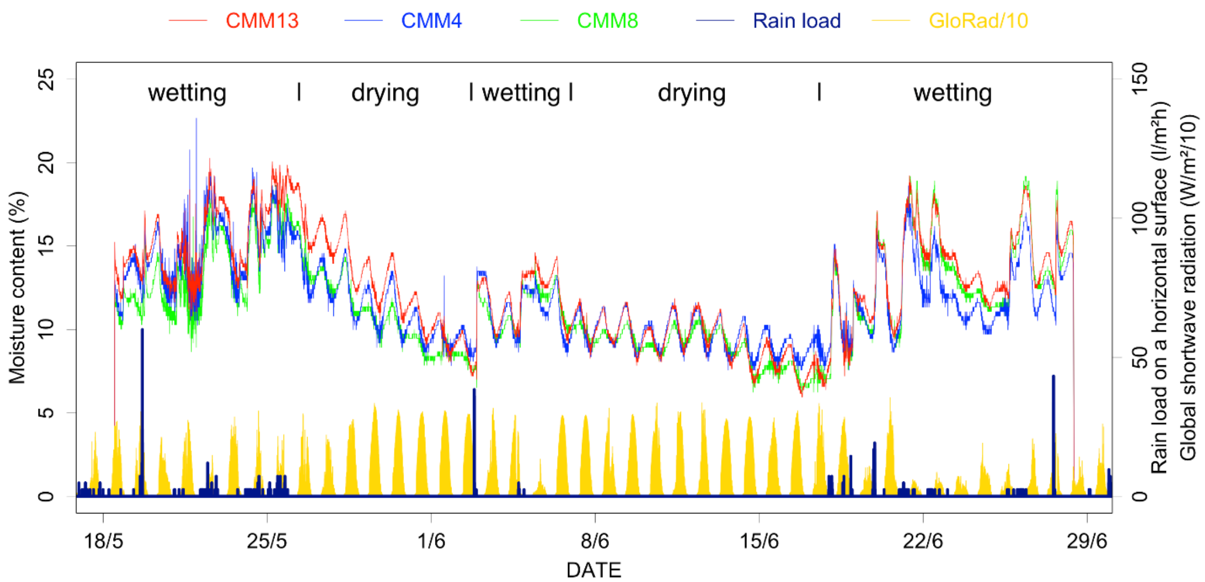

Figure 1: CMM results for the plain spruce samples

From the hygrothermal simulations in Delphin (Figure 2) it can be concluded that the "Spruce SW" materials with the high water absorption coefficients do not match the CMM results well. Most of the other spruce materials that were simulated gave a relatively close match, with especially "Spruce tangential (from Saxony) [713]" giving a good match. Looking at the influence of the vapour diffusion resistance of the wood, a small effect was seen on the moisture content when simulating a typical range of vapour diffusion resistances of wood. The small influence was attributed to the short time span of the dry periods, with in turn little second drying phase. The difference between the lowest and highest water uptake coefficient found in the Delphin 6 material database for spruce wood is a factor 25. It was found that a higher water uptake coefficient results in a higher moisture uptake, but also in faster drying, causing the peaks to be larger, but the moisture contents to converge as drying progresses. When precipitation was excluded in the simulations, the moisture content still showed (damped) peaks with the base simulation during periods of rain due to an elevated relative humidity. The calculated equilibrium moisture content also matched the base simulation quite well. As expected, a higher longwave sky radiation increased the moisture content, whereas a higher shortwave absorption coefficient decreased the moisture content. Increased wind velocity and associated vapour diffusion exchange coefficient significantly increases the drying flux in the first drying phase, resulting in lower moisture contents during wet periods. Finally, it was concluded from measurements and simulations that the impact of rain intensity was capped: a rain intensity above 5 l/m²h did not increase absorption.

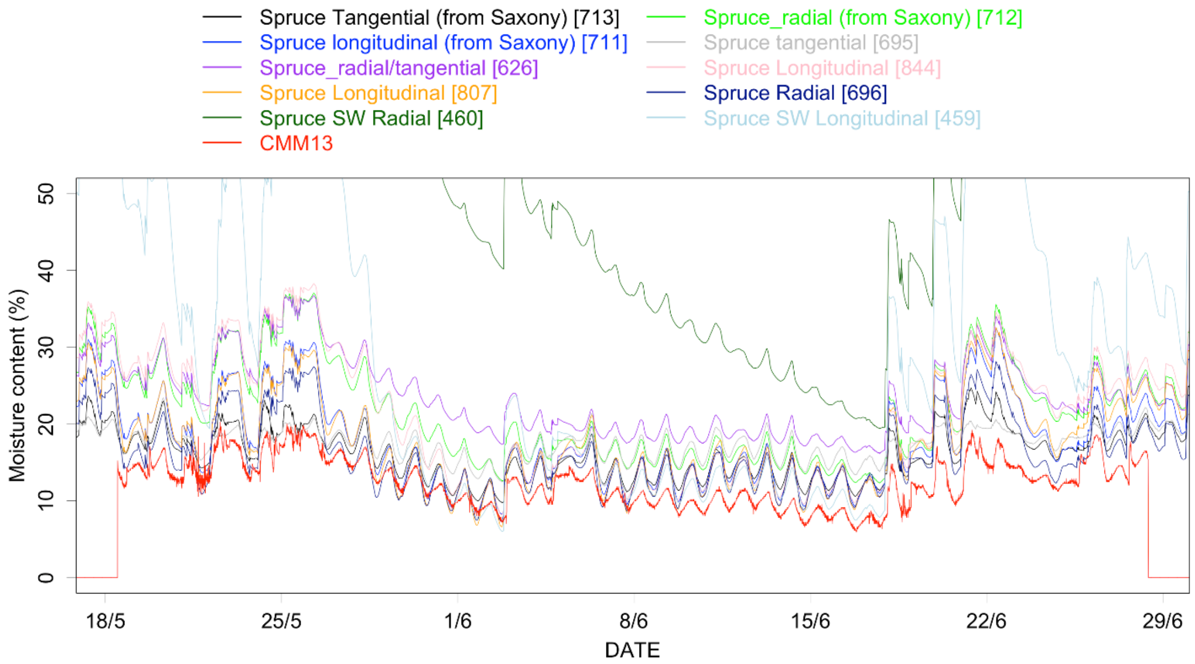

Figure 2: Plot of all spruce materials in the Delphin 6 material database

4.2 Moisture Behaviour of CLT

The results of the CMM experiment show that the moisture contents are very similar during dry periods, and variations between the samples mainly exist during a rain event. The daily variations on days without rain are determined by the equilibrium moisture content of the wood and show variations of 8 – 10% MC over a day. During wetting, the highest peak moisture contents of 30 – 35% MC are recorded for the samples with open end grain (CLT 4, 5, and 6), the lowest peak moisture contents of 20 – 25% MC are recorded for the sealed samples with 10 mm top layer (CLT 1, 2, 3, and 7), and in between are the samples with the 3 mm top layer (CLT 8, 9, and 10) with peak moisture contents of ±27% MC. All samples dry out to below

18% MC in about two days. As can be seen in Figure 3, the simulations reasonably match the real moisture behaviour as seen in the CMM experiment well, making it a good tool to investigate the moisture behaviour and investigate if problems are to be expected. However, this is only feasible when right material properties have been selected, and accurate local RH and rain data are available. It should be noted that the reliability of the simulations decreases during longer wetting periods. The simulations systematically overestimate the absorption of rain, and underestimate the drying in the first drying phase.

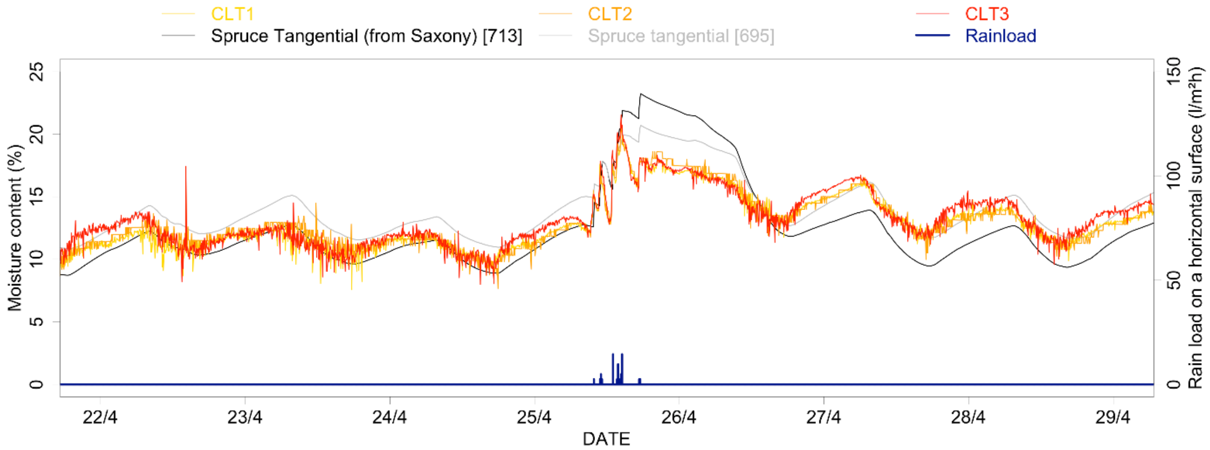

Figure 3: Plot of MC over time for measurements and simulations of CLT 1, 2 and 3.

4.3 Moisture Tolerance of CLT

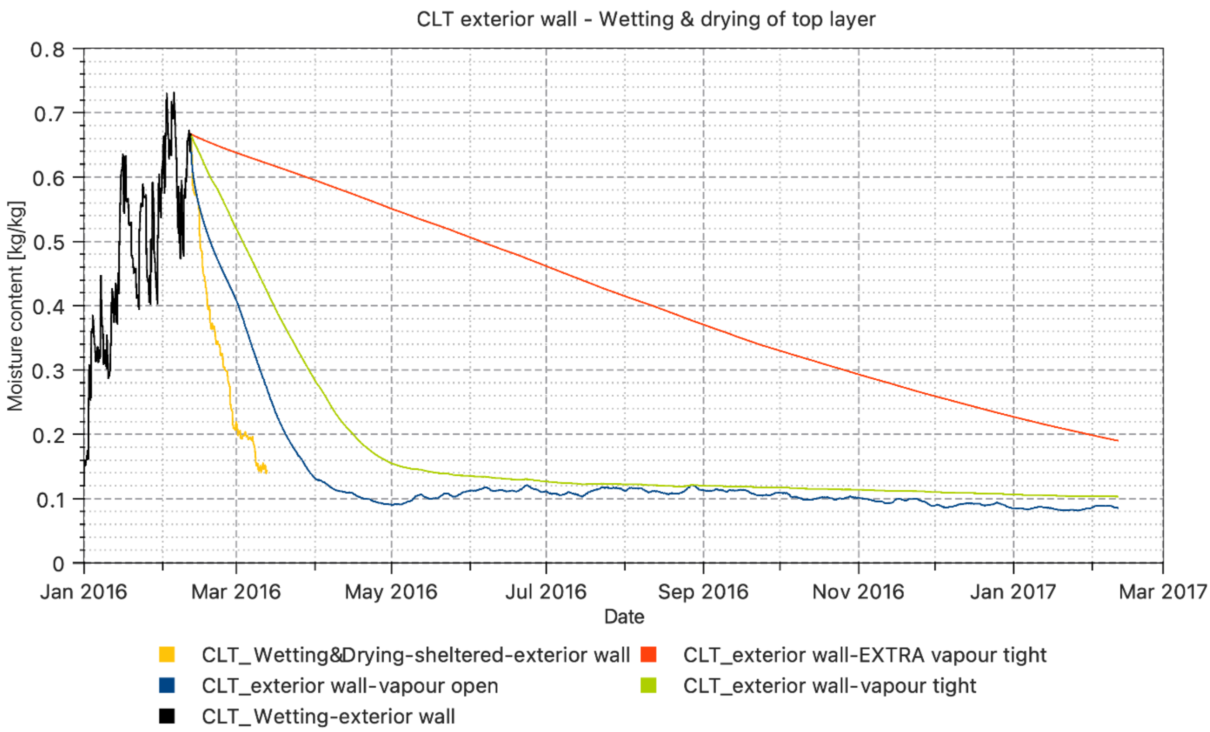

Figure 4: MC in the top layer of a CLT exterior wall element. Wetting for 42 days in critical conditions (black), drying afterwards for 30 days while sheltered (yellow) / vapour open construction (dark blue) / high permeability VB (light green) / low permeability VB (red).

In practice, interior floor elements, interior wall elements and roof elements are often exposed for 2 weeks and exterior wall elements for 6 weeks [20]. Horizontal elements exposed for 2 weeks to critical conditions (return period 3 years) reached ±80% MC and exterior wall elements exposed for 6 weeks reached ±70% MC. Evidently, this is not an average or typical condition. It is then investigated how fast the CLT elements dry out to 18%MC, which should be a safe upper limit for the 'initial' moisture content before encapsulation [20]. Different drying techniques are assessed: drying while sheltered by the floor above, drying while in an indoor climate, and drying using a building dryer. To investigate how and if wall and roof elements dry out in a construction, simulations are done with as initial conditions the moisture content profile of the element right after wetting. Vertical elements are facing in a Southwest (225°) direction. Drying while sheltered works well to dry out CLT elements taking only 3 weeks for floors (Figure 4) and about 1 month for exterior walls to dry below 18%MC. The mould index stayed below 1 for the wetting and drying of a CLT floor element while sheltered. Encapsulating a very wet CLT element into a construction without letting it dry out always gives problems and no construction is vapour open enough to facilitate fast enough drying. Drying in a vapour open wall construction entails a maximum mould index of 3.5 and a TOW 25/10 = 810 h (<168 h to avoid wood rot), whereas drying in the most vapour tight wall construction almost gave the maximum mould index of 6 and a TOW 25/10 = 7290 h. For flat roofs similar results are found. It is important to note that only simulations using very critical conditions were done here. To put this into perspective, the CMM experiments showed that even for a full day of rain, moisture contents do not go that high and dry out fast.

5 Conclusions

- It was found that the adhesive layer had a water vapour diffusion-equivalent air layer thickness *s*" of 0.104 m for the wet cup and 0.842 m for the dry cup, which for a 0.25 mm adhesive layer is a water vapour diffusion resistance $\mu = 416$ for the wet cup and $\mu = 3368$ for the dry cup.
- The moisture behaviour of plain spruce and CLT showed to be strongly dependent on the relative humidity, with daily variations around 4%MC and MC's between 8 – 15% for the experiment on plain spruce samples and daily variations around 8 – 10% MC and MC's between 8 – 20% for the experiment on CLT samples. During a rain event, the moisture content then quickly rises above 15% and goes up to a maximum of 20% during the experiment on plain spruce samples.
- For the CMM experiment on CLT, the highest peak moisture contents during a rain event of 30 – 35% MC are recorded for the samples with open end grain, and the lowest peak moisture contents of 20 – 25% MC are recorded for the sealed samples with a 10 mm top layer. All samples dried out to below 18% MC in 1 – 2 days.
- Encapsulating a very wet CLT element into a construction without letting it dry out always entails problems and no construction is vapour open enough to facilitate fast

enough drying. Roof and exterior wall constructions which do not get time to dry out showed to be problematic. Protecting the CLT from rain when the element is exposed to the outdoor climate is always a good idea, as the less moisture enters the wood, the less moisture must dry out.

- Finishing the roof or exterior wall right after a rain event shows to be problematic as the MC will be the highest at that time. Letting the CLT elements dry out for a short while (days to weeks) in open air will result in much lower MC's when built in, and by consequence this entails a reduced risk for wood rot afterwards.
- Only 1D simulations were adopted. No absorption through end-grain was studied, nor any leakage paths between boards of the CLT or through shafts. These are often the places with the most potential for severe problems as these are hard to protect and should remain points of attention during construction. The simulations showed very sensitive to the accurate material selection, wetting is often overestimated, and drying is often underestimated, which may render the output too conservative.

References

Adan O.C., *On the fungal defacement of interior finishes*, PhD-Thesis, Technische Universiteit Eindhoven, 1994.

Brischke C., Soetbeer A., Meyer-Veltrup L., *The minimum moisture threshold for wood decay by basidiomycetes revisited. A review and modified pile experiments with Norway spruce and European beech decayed by Coniophora puteana and Trametes versicolor*, Holzforschung, vol. 71, no. 11, pp. 893–903, Oct. 2017, doi: 10.1515/hf-2017-0051.

EN ISO 12572, *Hygrothermal performance of building materials and products - Determination of water vapour transmission properties – Cup method*. European Committee for Standardization, 2016.

Gustafsson A., *The CLT Handbook*, Svenskt Trä, 2019.

Hass P., Wittel F.K., McDonald S.A., Marone F., Stampanoni M., Herrman H.J., Niemz P., *Pore space analysis of beech wood: The vessel network*, Holzforschung, vol. 64, no. 5, Aug. 2010, doi: 10.1515/hf.2010.103.

Li W., Jan den Bulcke J., Mannes D., Lehmann E., De Windt I., Dierick M., Van Acker J., *Impact of internal structure on water-resistance of plywood studied using neutron radiography and X-ray tomography*, Construction and Building Materials, vol. 73, pp. 171–179, Dec. 2014, doi: 10.1016/j.conbuildmat.2014.09.095.

Kukk V., Kaljula L., Kers J., Kalamees T., *Designing highly insulated cross-laminated timber external walls in terms of hygrothermal performance: Field measurements and simulations*, Building and Environment, vol. 212, p. 108805, Mar. 2022, doi: 10.1016/j.buildenv.2022.108805.

Meyer L., Brischke C., *Fungal decay at different moisture levels of selected European-grown wood species*, International Biodeterioration & Biodegradation, vol. 103, pp. 23–29, Sep. 2015, doi: 10.1016/j.ibiod.2015.04.009.

Saito H., Fukuda K., Sawachi T., *Integration model of hygrothermal analysis with decay process for durability assessment of building envelopes*, Build. Simul., vol. 5, no. 4, pp. 315–324, Dec. 2012, doi: 10.1007/s12273-012-0081-8.

Sutton A., Black D., Walker P., *An introduction to low-impact building materials*, BRE IP, no. 17/11, p. 6, 2011.

Svensson Tengberg C., Hagentoft C.E., *Risk Assessment Framework to Avoid Serial Failure for New Technical Solutions Applied to the Construction of a CLT Structure Resilient to Climate*, Buildings, vol. 11, no. 6, p. 247, 2021, doi: 10.3390/buildings11060247.

Uysal B., Kurt S., Ozcan C., *Thermal conductivity of laminated veneer lumbers bonded with various adhesives and impregnated with various chemicals*, BioRes 4(2), p. 16, May 2009.

Vanpachtenbeke M., *Timber frame walls with brick veneer cladding: reliability to fungal decay*, PhD-thesis Ghent University 2019. http://lib.ugent.be/catalog/rug01:002807530

Viitanen H.A., *Modelling the Time Factor in the Development of Brown Rot Decay in Pine and Spruce Sapwood - The Effect of Critical Humidity and Temperature Conditions*, Holzforschung, vol. 51, no. 2, pp. 99–106, 1997.

Viitanen H.A., *Factors affecting the development of mould and brown rot decay in wooden material and wooden* *structures. Effect of humidity, temperature and exposure time*, PhD-thesis, The Swedish University of Agricultural Science, Uppsala, 1996.

Volkmer T., Schmidt J.A., Kranitz K., Niemz P., *Untersuchungen zum Einfluss der Klebstoffart auf den Diffusionswiderstand von Holzverklebungen*, Bauphysik, vol. 34, no. 2, pp. 55–60, Apr. 2012, doi: 10.1002/bapi.201200006.

Wimmer R., Kläusler O., Niemz P.,*Water sorption mechanisms of commercial wood adhesive films*, Wood Sci Technol, vol. 47, no. 4, pp. 763–775, Jul. 2013, doi: 10.1007/s00226-013-0538-7.