TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Materials and Environmental Technology

CAPILLARY MOVEMENT OF WATER IN A RADIAL DIRECTION AND MOISTURE DISTRIBUTION IN A CROSS-SECTION OF CLT PANEL

VEE KAPILLAARNE LIIKUMINE RADIAAL SUUNAS JA NIISKUSE JAOTUMINE CLT PANEELI RISTLÕIKES

MASTER THESIS

Student: Raina Lipand

Student code: 182537KVEM

Supervisor: Villu Kukk, Early Stage Researcher

Co-supervisor: Targo Kalamees, Professor

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(*On the reverse side of title page*)

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Department of Materials and Environmental Technology

THESIS TASK

Student: Raina Lipand, 182537KVEM

Study programme, KVEM12/18 - Technology of Wood, Plastic and Textiles

Main speciality: Wood technology

Supervisor: Villu Kukk, Early Stage Researcher, Tel:6202402, villu.kukk@taltech.ee

Co-supervisor: Targo Kalamees, Professor, Tel: 6202403, targo.kalamees@taltech.ee

Thesis topic:

(in English) Capillary movement of water in a radial direction and moisture distribution in a cross-section of CLT panel

(in Estonian) Vee kapillaarne liikumine radiaal suunas ja niiskuse jaotumine CLT paneeli ristlõikes

Thesis main objectives:

1. Measuring moisture content in the three first layers in CLT panel with two methods
2. Finding water uptake coefficient
3. Carrying out visual evaluation

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Beginning of tests	19.12.2020
2.	Collection of results and materials for literature review	25.02.2021
3.	Analysis of results – comparison of measurement mythologies	04.03.2021
4.	Analysis of results – laboratory tests	11.03.2021
5.	Description of methodology	18.03.2021
6.	Discussion – conclusions from the results	25.03.2021
7.	Discussion – comparison with other works	01.04.2021
8.	Literature review part 1	08.04.2021

9.	Literature review part 2	15.04.2021
10.	Introduction, summary and other	06.05.2021
11.	Thesis draft ready	09.05.2021

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Student: Raina Lipand ………………………………. "......" 2021

/signature/

Supervisors: Villu Kukk ………………………………. "......."..................2021

/signature/

Co-supervisors: Targo Kalamees ………………………………. "......."..................2021

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Head of the study programme: Jaan Kers ……………………. "......."................2021

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PREFACE

This work was carried out in Taltech Near Zero Energy Building (nZEB) and Laboratory of Wood Technology. The topic of this thesis was proposed by Villu Kukk, whose PhD research coincides with this subject. The study was assisted by my supervisors, Villu Kukk and Targo Kalamees, also by Neeme Takis and Margus Kangur.

First, I would like to express my gratitude to my supervisors Villu Kukk and Targo Kalamees, who have motivated and helped me with this study. I also would like to thank Neeme Takis for Uniflex Systems OÜ for helping configure the Onmisense system in the Near Zero Energy Building and Margus Kangur from Laboratory of Wood Technology for helping me prepare specimens for tests. Finally, I would like to thank all my coursemates for keeping up the positive spirit during the COVID-19 pandemic.

The main objective of this study was to investigate the impact of waterproofing of cut edges and cracks on the water absorption properties of the CLT surface and moisture content distribution in the cross-section of the CLT panel. In addition, it was important to find a suitable measurement method for measuring the moisture content of CLT under both laboratory and outdoor conditions (construction site). This study found that when deciding on the electrodes and measuring system, the reliability and ease of use should be considered. The water absorption from the CLT cut edges without waterproofing dominates the water absorption of the entire panel. The CLT in contact with water (standing water, rain, snow) only the surface saturates with water, filling the cell voids, and moisture inside the panel is distributed by liquid conductivity and water vapour diffusion along the cell walls, achieving equilibrium moisture content.

Keywords: CLT, cross-laminated timber, moisture content, water uptake coefficient, visual evaluation, moisture distribution, master's thesis

List of abbreviations and symbols

Abbreviations

CLT – Cross-laminated timber

EMC – Equilibrium moisture content

FSP – Fibre saturation point

LVL – Laminated veneer lumber

MC – Moisture content

MS – modified silicon

RH – Relative humidity

Symbols

A_w – water uptake coefficient [kg/m^2·s$^{0.5}$]

d – diameter [mm]

m – mass [g]

MC – moisture content [%]

P_c – capillary pressure

R – electrical resistance [10logΩ]

T – temperature [°C]

INTRODUCTION

Cross-laminated timber (CLT) is becoming more widely used as a construction material due to its many advantages like excellent static, mechanical and insulation properties. As wood is susceptible to moisture, it is essential to ensure the proper approaches of moisture safety management on the construction site to keep the structural integrity of CLT elements. When developing the moisture safety plan, it is crucial to understand how moisture distributes in CLT panels, especially in the surface layer open to the environmental factors.

Many previous studies [1]–[7] on measuring CLT moisture content have measured moisture content in specific depths of the panel but not explored the topic of moisture distribution. Those studies have found that the moisture content of CLT panels open to the outside environment for a long-term period will reach the fibre saturation point, which is 30%. Whereas during the short-term period, the moisture content reaches 20%. Both of those measurements are favourable conditions for the formation of mould and rot on the wood [2]. However, these results do not show how the moisture moves on the surface of the panel and in each layer of the CLT panel. Hence the reason for choosing this research topic.

The objective of this study was to investigate the impact of waterproofing of cut edges and cracks on the water absorption properties of the CLT surface and moisture content distribution in the cross-section of the CLT panel. In addition, to find a suitable CLT moisture content measurement methodology that would be applicable for both laboratory conditions and use on construction sites. In order to fulfil that objective, the following tasks were done. Moisture content (MC) in the first three layers of the CLT panel was measured with the electrical resistance method based on EN 13183-2 standard and oven-dry method based on EN 13183-1 standard. The water uptake coefficient of the CLT panel was determined with a partial immersion test based on ISO standard 15148:2002. Visual evaluation of water absorption in the CLT panel was carried out using red dye in water.

The results gathered from this study will give a better understanding of how the moisture is distributed throughout the three first layers of the CLT panel and help make better choices while planning moisture safety on the construction site. Since the moisture content of the CLT panel is a topic that has not been covered in great depth, there is a possibility of further research.

1. LITERATURE REVIEW

1.1 CLT use in construction

Cross-laminated timber (CLT) is an engineered wood panel product made by glueing together layers of solid-sawn lumber (usually made from spruce wood). Each layer of boards is positioned perpendicular to neighbouring layers and glued on the wide face of each board (Figure 1.1). Most commonly, an odd number of layers are used (3 to 9 layers); however, there are also even-numbered panels. Whichever the configuration of the layers, the outside layers and middle layer are symmetrically placed; this kind of assembly will give the panel better structural rigidity in all directions.

It was first developed in Europe in the early 1990s, yet the product was not commonly used until the 2000s thanks to green building, which was developing at that time. CLT was only introduced into the International Building Code in 2015. [8]

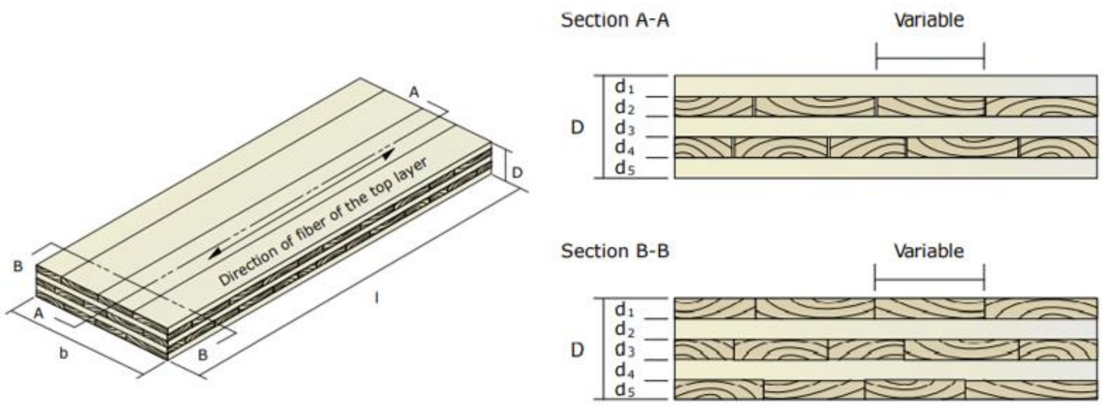

Figure 1.1 Five-layer CLT panel with two cross-sections

CLT as a material is on the rise in the construction industry because of its many advantages (Table 1.1). It is lightweight yet strong, good acoustic, fire, seismic and thermal performance and because of this, CLT is being used in place of concrete, masonry, and steel in the construction of residential, industrial, and commercial buildings. CLT resists high racking and compressive forces and can be cost-effective for multi-storey and long-span applications like bridges. Due to its dimensional stability and structural properties, this product is well suited for floors, walls, ceilings, roofs, and even stairs (Table 1.2). It can also be used together with any other building material like brick, render or composite panels. Initially, CLT was utilized to construct low and mid-rises, but in recent years, it has become a trend where high-rises, up to 18 storeys (Voll Arkitekter's Mjøstårne, Brumunddal, Norway) are being made. [1]

Table 1.1 Advantages and disadvantages of CLT

Advantage	Disadvantage
Sustainable consumption of raw material used for its production	More expensive than traditional construction materials (steel, concrete)
An energy-efficient production process, which makes the material environmentally friendly	Code restrictions on timber building heights
Superb static, mechanical and insulation properties	Costs of electrical, plumbing and other services can increase
Lightness, which makes the building structure incomparably lighter than other structures made of conventional materials	There can be higher architectural/design costs
The possibility of producing prefabricated elements, which result in a short time of completion of the whole building regime	A higher material transportation cost (relatively few manufacturing plants)
The possibility of combining with other building materials (steel, glass, plastic, etc.), resulting in maximum freedom of architectural design	Less long-term flexibility (future renovations)
CLT panels have fire resistance due to their structure	

Table 1.2 Applications of CLT

Type of element	Applications of CLT
Wall elements	Loadbearing single and compartment wall leafs
	External walls – either loadbearing of infill panels
	"Balloon-framed" walls with joisted floors
	Non-structural partitions with and without linings
	Parapet walls formed from balloon-framed wall panel elements
	Curved loadbearing wall structures
	Shafts and towers
	Shear walls
Floor (ceiling elements)	Floor slabs – either one-way or two-way spanning
	Flat roof slabs
Roof elements	Room-in-the-roof sloping panels – either as couple roof or supported by purlins
	Flat roof slabs
Other elements	Bridge elements
	Stair flights
	Furniture

CLT structures are generally built using a platform frame technique, where walls are temporarily braced with raking props before floor panels are lowered onto them end fixed. The completed floor construction offers the "platform" for building the wall panels to the following storey (Figure 1.2). There is also a balloon-frame technique where floor structures are supported inside the CLT wall panels (Figure 1.3). [9]

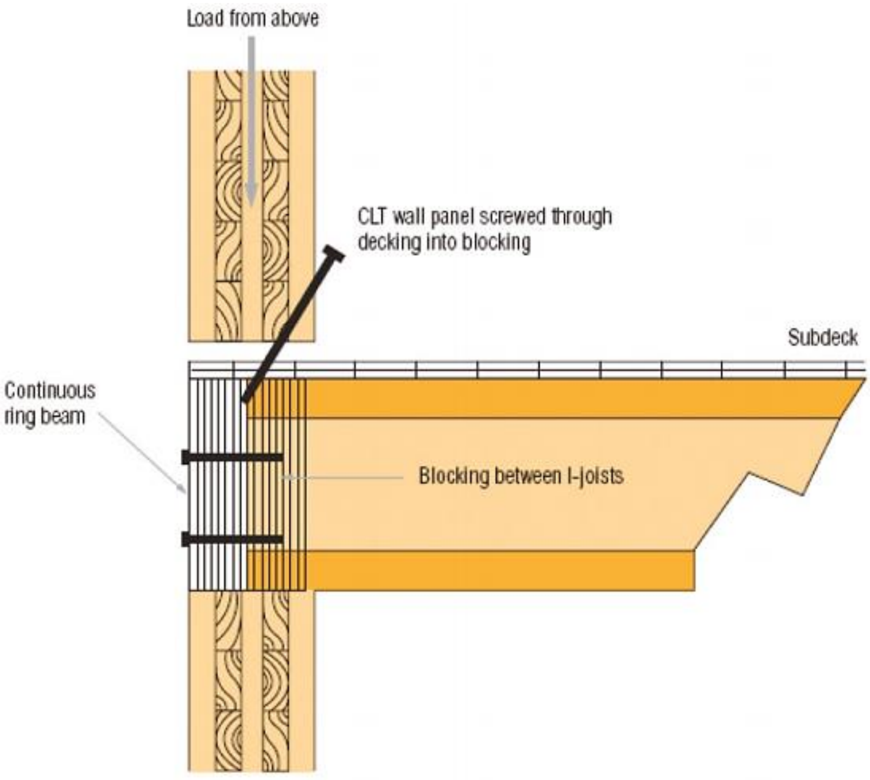

Figure 1.2 Wall-joist detail - platform-frame method [9]

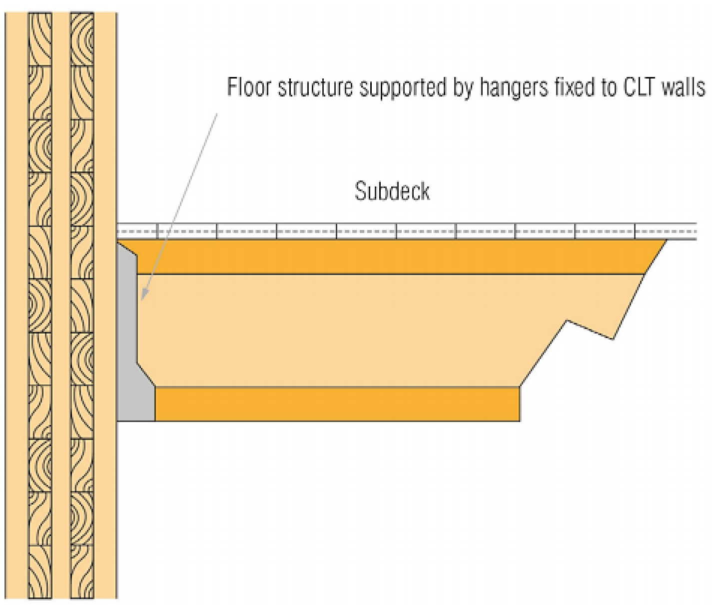

Figure 1.3 Wall-joist detail - balloon-frame method [9]

1.2 Moisture in wood

Wood is a hygroscopic material, and it takes moisture from the surrounding environment. The amount and direction of moisture exchange (gain or loss) with air depend on the relative humidity, air temperature and the current amount of moisture in the wood. The physical and mechanical properties, resistance to biological deterioration, and dimensional stability of wood are all affected by the amount of moisture present. It is important to understand the nature of water in wood and how it related to wood microstructure. [10]

Water can get into the wood in three ways: through the cell lumens as liquid (capillary pressure) and vapour, and through the cell walls as molecular diffusion. Moisture content in wood is explained through the relationship between the mass of water in the wood and the mass of the timber without the water. Newly sawn wood usually has a moisture content of 40-200 %. In regular use, the moisture content of wood can vary from 8% to 25% by weight, and it is dependent on the relative humidity of the surrounding air. [11]

Water in wood can be in two forms: free water situated as a liquid in pores and vessels and bound water trapped within the cell walls (Figure 1.4). At first, when green wood starts to lose moisture, it does not change its dimensions because the fibres are still entirely saturated with bound water. Once all the free water has been lost, the wood will reach the fibre saturation point (FSP). This can range from 20% to 40%, but it is taken to be 30% (percentage of the oven-dry weight of wood) for practical reasons. From a practical standpoint, if the wood moisture content is above the fibre saturation point, the mechanical and physical properties of the wood do not change. Only below 30% of the moisture content of wood properties start to change, and wood enters a drying state. [12], [13]

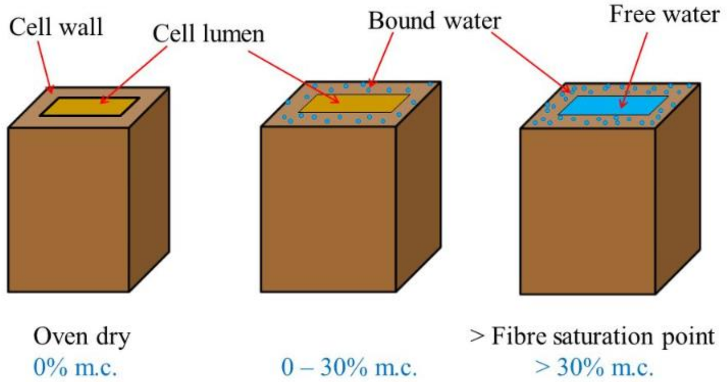

Figure 1.4 Different water forms in wood

1.2.1 Hygroscopic moisture

At the saturation point, the cell walls are saturated with moisture. Such moisture is called bound cell wall moisture or bound water, or hygroscopic moisture.

As the moisture content of wood drops below the fibre saturation point, it will continue to lose moisture until it stabilizes at a commensurate value with the surrounding moisture in the air. This phenomenon is known as the point of equilibrium moisture content (EMC). Equilibrium moisture content will change based upon the changing relative humidity and temperature of the surrounding air. The curve connecting the EMC of wood to relative humidity at constant temperature is called sorption isotherm. This isotherm obtained when the wood is loosing moisture (desorption isotherm) does not coincide with the isotherm when the wood is gaining moisture (adsorption isotherm) (Figure 1.5). This phenomenon is called hysteresis. [12], [13]

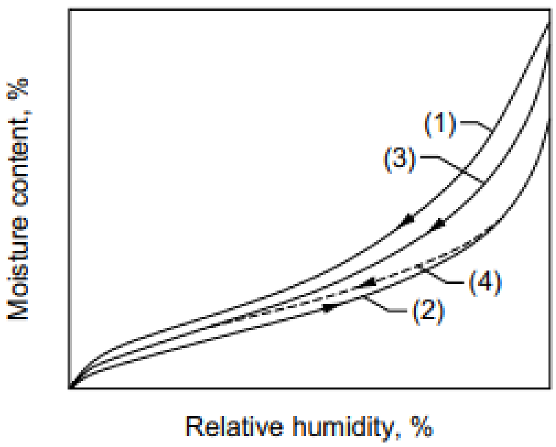

Figure 1.5 Schematically drawn sorption isotherms for wood; 1 - initial desorption isotherm, 2 - adsorption isotherm, 3 - secondary desorption isotherm [13]

Sorption is a physical and chemical process by which one substance, usually gas or liquid, becomes attached to another. This term is commonly used when talking about adsorption/absorption and desorption. There are specific cases of sorption happening in the wood. The bound water within the cell wall is held by adsorption forces that are mainly hydrogen bonds. Absorption, however, results from surface tension and capillary forces in the wood. Adsorption involves the attraction of water molecules to hydrogen-bonding sites present in cellulose, hemicellulose, and lignin. [10]

1.2.2 Capillary moisture

Free moisture or water, or capillary moisture, is defined as the moisture (liquid and vapour) to which water accumulates in the voids (pits, lumens, cell wall cavities) within and between cells. Free water is transported through cell lumens and pits above the fibre saturation point by capillary pressure difference. As the capillary radius of wood decreases, the capillary pressure increases (Figure 1.6). Free water flow is a bulk flow described as permeability. Permeability is a measure of how fluid flows through a porous material driven by pressure difference. There the moisture moves as a liquid in narrow spaces in opposite to external force like gravity. It occurs because of intermolecular forces between the liquid and surrounding solid surfaces. As the diameters of wood lumens and cavities are tiny, the combination of surface tension (caused by cohesion within the liquid) and adhesive forces between the liquid and wood surface act to propel the liquid. [14], [15]

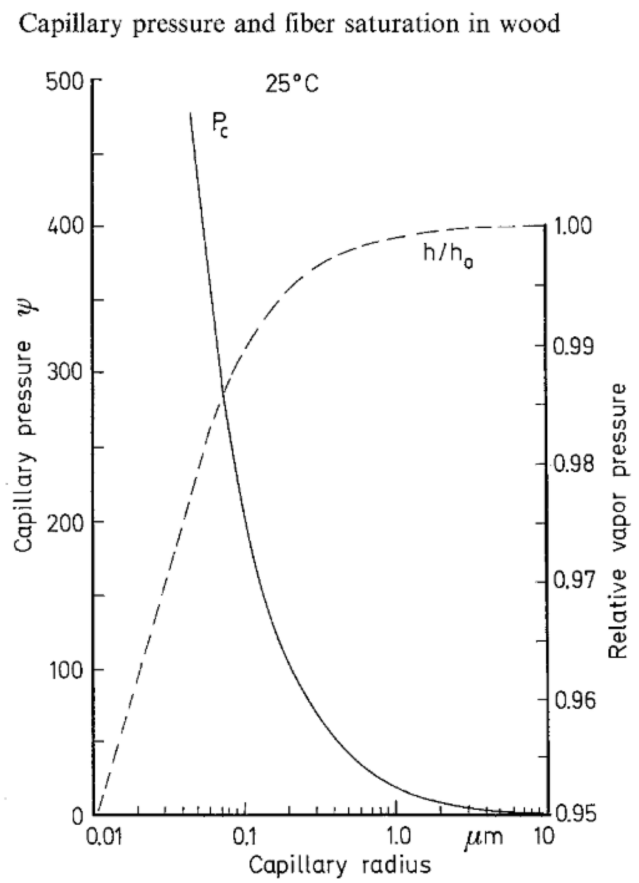

Figure 1.6 Interrelationship of capillary pressure (P_c), capillary radius and relative vapour pressure (h/h_0) [15]

The mechanism of water absorption is called capillary action or wicking. Water engages strongly with the wood cell wall and forms a concave meniscus, i.e. curved surface within the lumen. This interaction, combined with the water-air surface tension, creates a pressure that draws water up the lumina. The rate of absorption is quickest in the longitudinal direction. Methods for measuring water absorption rate are described by international standards ASTM C1794-19 [16] and ISO 15148:2003 [17]. These standards give instructions on how to find the water uptake coefficient.

1.3 Methods for wood moisture content measurements

1.3.1 Standard methods

Three standards describe how to measure moisture content in wood:

1. EN 13183-1 determination by oven dry method;
2. EN 13183-2 estimation by electrical resistance method;
3. EN 13183-3 estimation by capacitance method.

The oven-dry method is the European Standard method and is considered as the reference method. It applies to sawn timber and timber which has been planed or mechanically surfaced by other means. [18]

Apparatus needed for this method is a balance accurate to 0.1g if the mass of the test slice could be more than 100g in an oven-dry state or a balance accurate to 0.01g if the mass of the test slice is less than 100g in an oven-dry state and equipment for drying wood. [18]

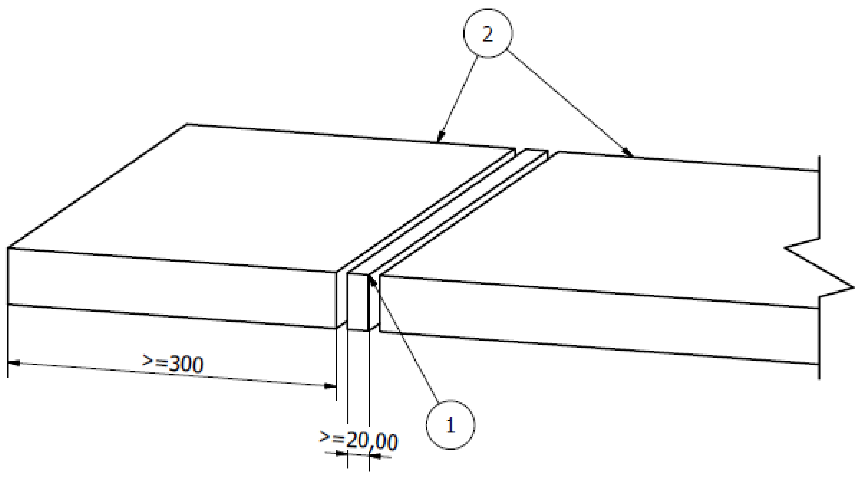

Figure 1.7 Position of the test slice; 1 - test slice, 2 - test piece [18]

The procedure goes as follows; a test slice is cut from the wood of the whole cross-section and a minimum of 20 mm dimensions in the direction of the grain at a point by 300 mm from either end of the test piece, or at the midpoint if the piece is less than 600 mm long (Figure 1.7). It should be free of resin wood, bark, knots and resin pockets. The test slice has to be weighed immediately after cutting. Then drying of the weighed test slice at a temperature of 103 ± 2°C is done until the difference in mass between two successive weighings separated by an interval of 2 hours is less than 0.1%. If immediate weighing is not possible, the test slice is kept in a sealed container and weighed within 2 hours. The dry weight measurement is carried out immediately after taking the test slice out of the oven. [18]

To calculate the moisture content, as a percentage by mass, the following equation is used:

$$MC = \frac{m_1 - m_0}{m_0} \cdot 100, \qquad (1.1)$$

Where m_1 is the mass of the test slice before drying, in grams;

m_0 is the mass of the oven-dry test slice, in grams;

MC is the moisture content, in per cent.

Results are expressed nearest to 0,1 percentage point moisture content. [18]

The electrical resistance method, which is also European Standard, defines a non-destructive method for estimating the moisture content of a piece of sawn timber using an electrical resistance moisture meter. It applies to sawn timber and timber which has been planed or mechanically surfaced by other means. This method is suitable for timber having a moisture content between approximately 7-30%. Some type of preservative, flame retardant, heat or chemical treatments will affect the accuracy of the measurements and require special calibration of the instrument. [19]

For this method, an electrical resistance moisture meter equipped with insulated electrodes is needed. It can graduate up to 30% in units of maximum 1% moisture content. Before taking measurements, the electrical resistance moisture meter shall be checked accordingly. [19]

Measurements are taken in the direction of the grain or at right angles to the grain if specially requested in the instrument manual. Insulated electrodes with undamaged insulation are used to get the correct measurement. The electrodes are driven into one face of the piece at a point at least 300 mm from either end of the piece (or at the midpoint of pieces less than 600 mm long) and at a distance of 0.3 times the width from one edge (Figure 1.8). The tips of the electrodes should penetrate to a depth of

0.3 times the thickness of the piece. The area must be free of resin wood, bark, knots, resin pockets. Reading should be taken after it has been displayed for 2-3 seconds. [19]

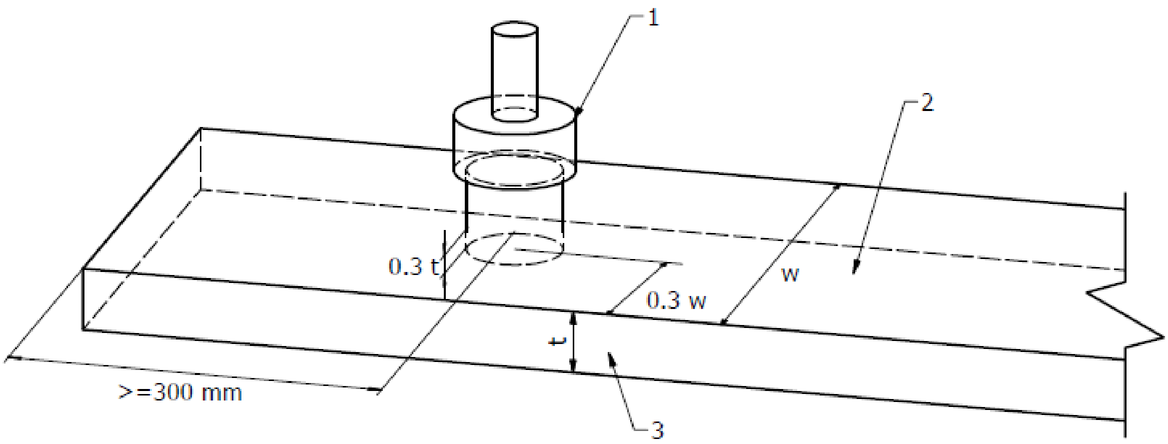

Figure 1.8 Place of measurements; 1 - Hammer electrode, 2 - Face, 3 - Edge, t - thickness, w – width [19]

Table 1.3 Sampling and testing frequencies [19]

Number of tested pieces	Number of measurements per test piece*
1	3
2	3
3	2
4	2
5	2
>5	1
* Measurements should be taken at random along the length, excluding 300 mm at each end (or at the midpoint of pieces less than 60 mm long). All results of measurements should be noted.	

The capacitance method is a non-destructive method for estimating the moisture content of a piece of sawn timber. The standard applies to sawn timber and timber that has been planed or surfaced by other means. This method is suitable for timber having a moisture content between approximately 7-30%. Some type of preservative, flame retardant, heat or chemical treatments will affect the accuracy of the measurements and require special calibration of the instrument. [20]

A hand-held capacitance moisture meter equipped with a flat shaped condenser plate surface, surface spring electrodes, or special non-invasive measuring probes is needed for this method. Normally capacitance moisture meters are equipped with a setting for correction for density and are applicable or adjustable for different thicknesses. Density correction may also be carried out by using special tables or formulas provided by the supplier of the instrument. [20]

The capacitance moisture meter shall be checked accordingly and will be adjusted for the density of the wood. If the actual density is unknown, and average density for species may be selected from the operating manual of the instrument. It must be ensured that the instrument is adjusted for the thickness of the timber being measured. Air gaps or insufficient contact between the condenser plates and the wood surface must be avoided. Measurement area should be free of bark, knots, resin pockets, wetted surface or checks. Measurement is taken at a point 300 mm from one of the pieces ends and for pieces less than 600 mm long, at mid-length. [20]

1.3.2 Methods of measuring moisture content of wood used in different researches

Fredriksson [3] introduced a method of small resistive moisture content sensors. Those sensors will help to measure moisture content at different depths in points close to each other. Contact between the electrodes and the wood is ensured by glueing electrodes to wood with electrically conductive adhesive.
Sensors are made of capillary tubing (outer diameter 1.6 mm, inner diameter 1 mm), an electrically conductive adhesive (EPO-TEK E4110, Epoxy Technology) and copper wire (d = 0.5 mm). In the process of putting sensors to the wood, a hole with a diameter of 1.6 mm must be drilled to the depth of the measurement. The capillary tube is then inserted until it reaches the bottom of the hole, and then it is pulled out about 1 mm to give room for the adhesive. The electrically conductive adhesive is inserted through the capillary tubing using a non-silicon-treated syringe. Finally, a copper wire with a gold-plated crimp contact pin soldered on the upper end is inserted.

For measurements, a logger with the range 0.001-200 μS and applied voltage of 2 V is built. Specimens are circular with a thickness of 10 mm and a diameter of 60 mm. Four holes (diameter 1.6 mm, depth 5 mm) are drilled at the centre of the specimens, and four moisture content sensors are placed in each specimen. By measuring the conductance between these four sensors, four determinations of conductance could be made in each specimen: two in the fibre direction and two crosswise.

Brischke et al. [21] used Scanntronik measuring devices for long-term (2 years) measurement of moisture content in building cladding and a wooden bridge with glued electrodes. Devices used from Scanntronik were Materialfox Mini data logger to record moisture content and Mygrofox mini data logger to collect relative humidity and air temperature. The research found that the selected measuring system was suitable for long-term measurement, and in combination with an alarm device, an irregular moisture accumulation can be detected at an early stage.

In Kalbe et al. [2] study, moisture content was measured using wood moisture meter Gann Hydromette LG 3, which consists of a measuring device and a ram-in electrode pair (Teflon insulated pins). This moisture meter is most commonly used to get the readings during the measurements and is not suitable for continuous long-term measurements

Kordziel et al. [6] measured moisture content during partial immersion test with electrical-conductance-type sensors (Omnisense Model S-2). Electrodes of stainless-steel screws were installed in the specimens from the non-wetted Douglas-Fir surface to different depths. Screw threads were ground off except the tip, and shafts were insulated so that measurements showed results near the tips.

1.4 Measuring moisture content in CLT – Case studies

In Kalbe et al. [2] study analysed the construction works of a CLT building to determine the most critical joints of CLT construction and propose a set of activities to help to avoid moisture ingress during the installation of CLT panels. The observed construction site was exposed to precipitation, and protective measures were used partially. As there was no moisture safety management implemented, the timber structure was suitable to determine the critical joints of precipitation exposed CLT construction.

The moisture content of CLT structures was measured according to the EN 13183:2002 [18] standard of electrical resistance method using a wood moisture meter, Gann Hydromette LG 3 with 60 mm long Teflon insulated pin electrodes. Twenty measuring points were selected around the perimeter and three points on the intermediate ceiling to the intermediate wall, and two points on the intermediate ceiling to window connections (measured from end-grain). The results were measured at the height of 30 mm from the lower edge of the CLT panel and at a depth of 30 mm.

The first measuring showed an average of 21% MC, which rose to 29.5% during the first-floor concrete pouring. As concrete pouring is moisture intensive task, the rise in

MC was presumable. After that, the MC decreased, and by the end of the test period, the average moisture content of CLT panels was 16.5%. The first results of the intermediate ceiling and wall connections were between 11% and 14%, and the last results stayed below 13%. The study found that the most critical places were the junctions of the exterior wall to the foundation. The panels were not covered, and water was absorbed to the CLT panel longitudinal to the wood grain. However, the connections of intermediate ceiling and wall that were weather protected stayed below 17% throughout the testing period. It can be concluded that the edges of CLT elements should be covered, and proper moisture safety management is crucial.

In the case study by Kuus et al. [1], the moisture content of CLT elements was monitored on a construction site using a pin electrode moisture meter Extech MO290 with short pins of 10 mm for external layers and long pins of 80 mm to get the internal results. Measuring was done during the 8-week installation, and the measuring points selected were the most critical positions for moisture. Also, in this study, no proper moisture safety plan was implemented on the site.

Parallel polygon test with reduced size of vertical and horizontal CLT elements was done near the construction site. The test was done to compare the moisture content of unsealed and covered CLT elements with unsealed and uncovered elements in a real-life building. Three conditions were tested: elements unsealed and exposed to all weather exposure, elements unsealed but under protective cover, and elements sealed in the factory and kept unopened.

Horizontal elements showed a higher moisture content throughout the test period than the horizontal-vertical joints. The moisture content of horizontal elements stayed in the range of 13% to 16 % and horizontal-vertical in the range of 7.5% to 115. Uncovered and exposed horizontal CLT elements in the polygon test had moisture content over 25%, and covered CLT elements had MC under 17%. Vertical elements had similar results, but moisture content was about 10% lower. This study showed that it is crucial to cover the CLT elements from environmental factors because the extended direct contact with water can result in high moisture content that will be difficult to dry out.

Wang et al. [7] measured the moisture content of the CLT panels, plywood and laminated veneer lumber (LVL) in laboratory conditions and an outdoor environment. Specimens used were 3-ply CLT panels of Spruce-Pine-Fir with polyurethane adhesive, 13-ply LVL, and 19 mm thick Spruce-Pine-Fir softwood plywood. The panels were sprayed hourly for 5 seconds for 18 days (delivering approx. 35 L of water per specimen) in the laboratory. In the natural weather, the panels were kept for two month period in Vancouver, British Columbia, Canada.

The plywood MC increased from less than 10% to 70% under both conditions, and the LVL MC increased from 6% to 30%. The moisture content of CLT panels increased from 12% to 24%, which was a much smaller increase than plywood and LVL. That shows that LVL and plywood act as lath checks and channel humid air and water into the inner plies, leading to fast wetting. The findings for moisture content of outdoor and laboratory test of CLT panel were similar – laboratory test showed average moisture content of 24% and an outdoor test of 22%. The gap between the laboratory and the outdoor test was small, only 2 %. From that, it can be concluded that the results of moisture content of CLT panels with constant contact with water and ones in an outdoor environment have a minimal difference.

Kordziel et al. [6] researched hygrothermal characterization of CLT in building envelope. For this, water absorption was measured with two different methods: one where panel specimens were partially immersed in water and the other where ponded water was on top of the CLT panel. Six different five-layered CLT panels were obtained for the testing: four layers were from the Spruce-Pine-Fir group and one layer of Douglas-fir. All four sides were coated with an impermeable liquid-applied membrane. The water uptake was measured perpendicular to the wood grain. Specimens of Spruce-Pine-Fir (SPF) had a measured water uptake coefficient of 0.0025 and 0.0028 $kg/(m^2 \cdot s^{0,5})$. Moisture content sensors embedded in the CLT panel indicated that the liquid water did not reach the electrodes 38 mm from the wetted surface during the 30-day duration of the partial immersion test. Also, water absorption measured using a method with ponded water gave a higher rate of water uptake than the partial immersion test.

All these studies address moisture content in CLT panels, but only in a certain depth. That being said, none of them discusses how moisture is distributed in the CLT panel when exposed to the weather. Especially on the surface of the panel perpendicular to the wood grain. That indicates that the moisture distribution in the CLT panel has not yet been studied in depth. This topic is novel and needs to be explored to improve the management of moisture safety in construction sites.

2. MATERIAL AND METHODS

2.1 Method development

This study's development of measuring method took several small tests with two different types of electrodes and measuring systems. Two types of electrodes were insulated copper wires and insulated screws. Scranntronik and Onmisense systems were used for measuring equipment. The selection for the equipment was based on the availability of laboratory inventory.

2.1.1 Different devices

Scanntronik measuring system equipment consists of Scanntronik Mugrauer GmbH Thermofox Universal data logger and Thermofox Material Moisture Gigamodules (extension modules) (Figure 2.1), MC and temperature sensors and wire cables. Moisture content sensors are connected with extension modules by cables, and the extension module is connected with the universal data logger that saves all the results.

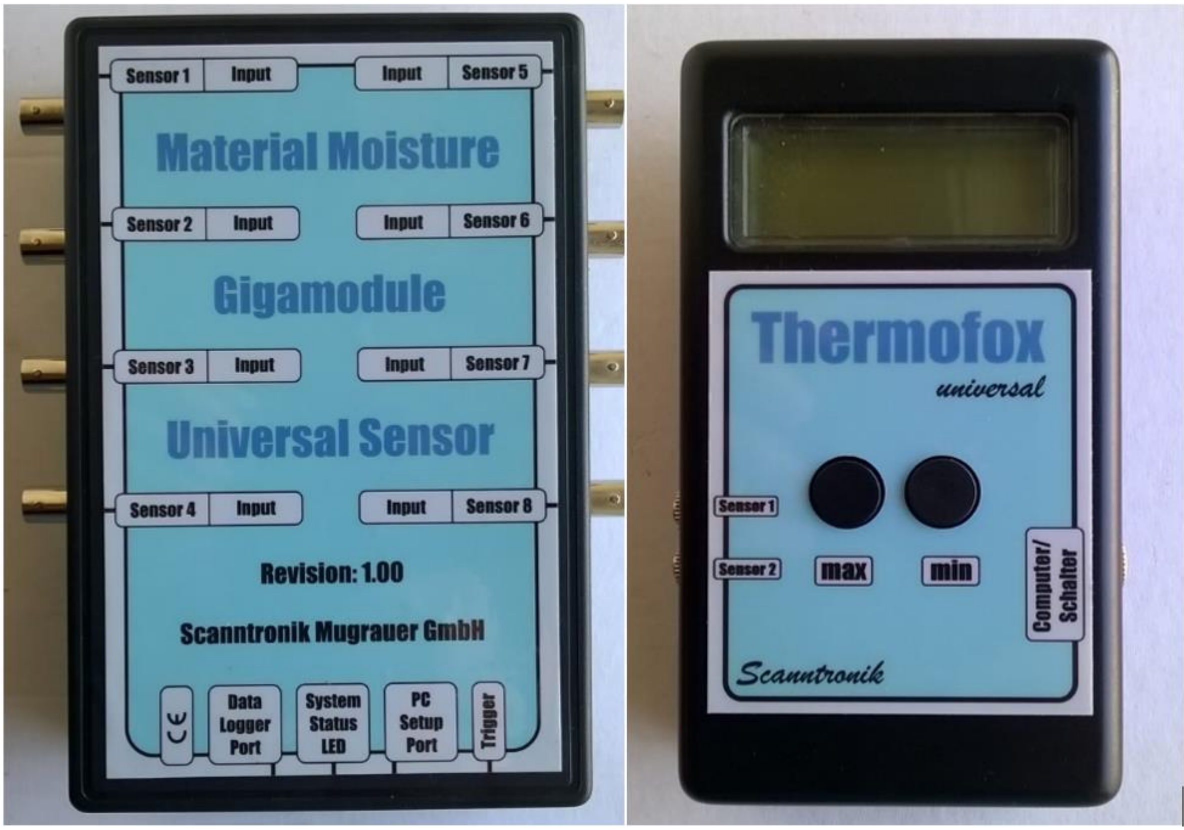

Figure 2.1 Thermofox data logger's modules, left - Material Moisture Gigamodule for MC sensors; right - Thermofox Universal data logger

Results gathered with this system are given as electrical resistance (ohm), and these have to be converted into MC (%). Conversion is made by following Equation 2.1:

$$MC(R;T) = \left((a \cdot T) + b\right) \cdot e^{\left((c \cdot T) + d\right) \cdot R + \left((e \cdot T) + f\right)} + (g \cdot R^2) + \left((h \cdot T) + i\right) \qquad (2.1)$$

Where T is the wood temperature (°C),

R is electrical resistance (10logΩ),

a, b, c, d, e, f, g, h, i are material-specific variables found through the experimental tests.

Values for Norway spruce specific variables are shown in Table 2.1. [22]

Table 2.1 Norway Spruce specific variables and their values

Material specific variables	**Values**
a	0.236692988
b	7.749631087
c	-0.001432786
d	-0.094496422
e	0.034216745
f	6.181685367
g	-0.001428117
h	-0.064431994
i	25.13030002

Omnisense system is located in TalTech near-zero energy test building, and it is web-based remote maintenance, monitoring and data collecting system. Sensors and transmitters that will be used in thesis testing are part of the test building monitoring system. The system consists of:

- Data capture module or gateway (located in the test building and currently stationary) – it is connected to the network and sends information to a web-based user interface from which data can be view and downloaded;
- Data transmission modules or transmitters (Figure 2.2) (black boxes to which sensors (electrodes) are connected – they send readings to the data capture module wirelessly and must be close to the said module (approximately 10 m);
- Sensors or electrodes, in this case, are made from screws that are isolated with hear-shrinking wrap and will measure the moisture content in wood – are connected to the transmitter with special plugs.

Transmitters are located in test room 8 and 7, and both rooms have 20 transmitters that are already working on another test. Nonetheless, this does not affect this thesis testing or vice versa. Omnisense transmitters use two 0.7 millisecond pulses of the same polarity with a 3 V amplitude at 1-second intervals to measure wood moisture. This repeats every 75 seconds, and the effect of temperature is 0,2% per degree.

Figure 2.2 Transmitter used in Omnisense system

There are several disadvantages to the Scanntronik system compared to Omnisense one. Scanntronik system uses two different devices to gather the results – one is the Gigamodule that measures the results and the other datalogger which would log the data. To get the information from the datalogger, it had to be disconnected from the Gigamodule and connected to the computer via USB cable and specific software is needed to download the results. The Omnisense system has one gateway in the building that sends all the information obtained from the transmitters to the web, and the data is accessible from the Omnisense website. The Omnisense system is much easier to use, and it is accessible through the network. However, the reliability of the Scanntronik system was better than Omnisense one because transmitters used in the latter system could be faulty and give wrong results or would not work at all.

2.1.2 Different electrodes

During the development of the measuring method, two options for electrode were considered. The first material for electrodes was PVC insulated copper wire (Figure 2.3), and the second option was screws insulated with heat-shrink tubes (Figure 2.4). Copper wire was the cheaper option; however, it needed extra work to prepare and install electrodes in the wood. Also, contact with wood was insufficient because of a lack of mechanical force and a need for conductive adhesive. Insulated screws proved to be better suited for measuring the moisture content due to mechanical force between wood and screw. Moreover, the preparation and installation of screw electrodes were easier than wire electrodes.

Figure 2.3 Insulated copper wire electrodes

Figure 2.4 Insulated screw electrodes with plastic and spring washers

2.1.3 Selected system

The selected measuring equipment consisted of insulated screw electrodes and an Omnisense system. The main reason for electrode selection was their good contact with wood, which would give better results. Choice in favour of the Omnisense system came from its ease of use and accessibility.

The relationship between the moisture content and electrical resistance is important for the improved accuracy of the resistance-type moisture meters for wood. In the study by Samuelsson [23], the measurements on that relationship were made on Scotch pine and Norway spruce. The results of curve fitting with software Statgraphics are shown in Figure 2.5. The curve shows that the resistance of wood decreases with increasing moisture content.

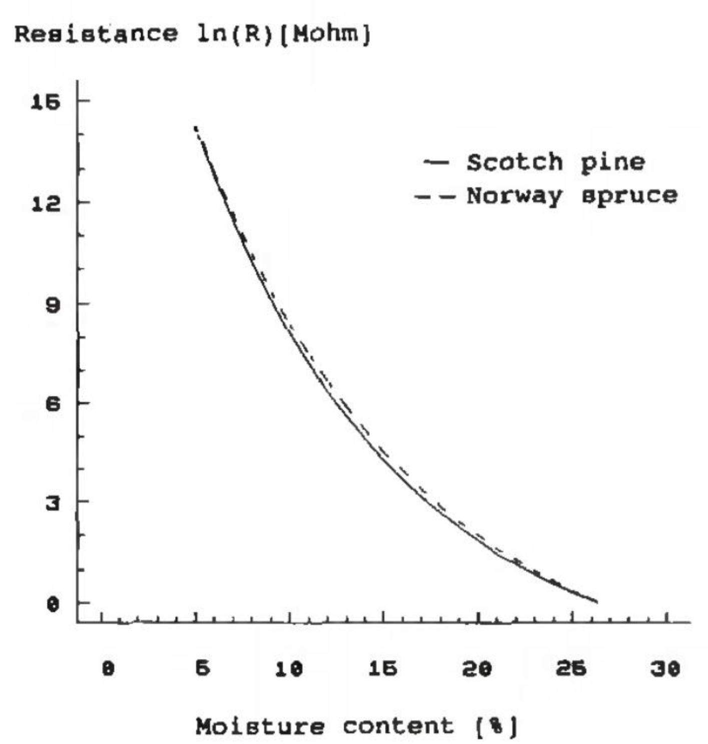

Figure 2.5 Calibration curved for Scotch pine and Norway spruce [23]

2.2 Laboratory measurements

Laboratory measurements for this study were done in TalTech near-zero energy test building during two and half month period of 19.12.2021 – 01.03.2021.

2.2.1 Test specimens

There were three different test variation:

1. CLT panel with cut edges made waterproof – 3 pieces
2. CLT panel with incisions made with a saw (width 4 mm) between surface layer solid-sawn lumber, cut edges made waterproof – 3 pieces
3. CLT panel without waterproof mastics on cut edges – 3 pieces

Panels were made of Norway spruce (*Picea abies*). CLT panels used for tests were with dimensions 400 x 400 x 100 mm. Specimens were conditioned in atmospheric conditions (last month's average RH 85% and temperature 3 °C) to simulate the same conditions as on the construction site. Cut edges of six specimens were made waterproof with IKOprotect MS Detail, a solvent-free and odour-free single-component coating based on the flexible MS polymer, and a vapour barrier sealing tape by Tesa was also used to give extra protection (Figure 2.6).

Figure 2.6 Specimen with previously applied IKOprotect mastics and unfinished taping of vapour barrier sealing tape

2.2.2 Target results

Moisture content in the first three layers was found with the electrical resistance method, oven-dry method. Both the electrical resistance method and oven-dry method were based on European standards previously mentioned in paragraph 1.3.1.

To measure moisture content with the electrical resistance method, the previously prepared specimens (with attached electrodes and cables) were placed into a plastic case with dimensions 780 x 560 x 180 cm, where black plastic dashboard supports were attached to the bottom to keep the CLT panels in a stationary position (Figure 2.7). Cases were filled with water, and Eosin Yellowish dye was added.

Figure 2.7 Plastic container with dashboard supports on the bottom

After that, the cables were connected with an Omnisense transmitter that would measure moisture content every hour throughout the test. The results of the electrical resistance method were given in per cent on the Onmisense webpage (https://ttytest.uniscada.eu/) and did not need any calculations. The results were downloaded as Excel files for each electrode pair to analyse the data further.

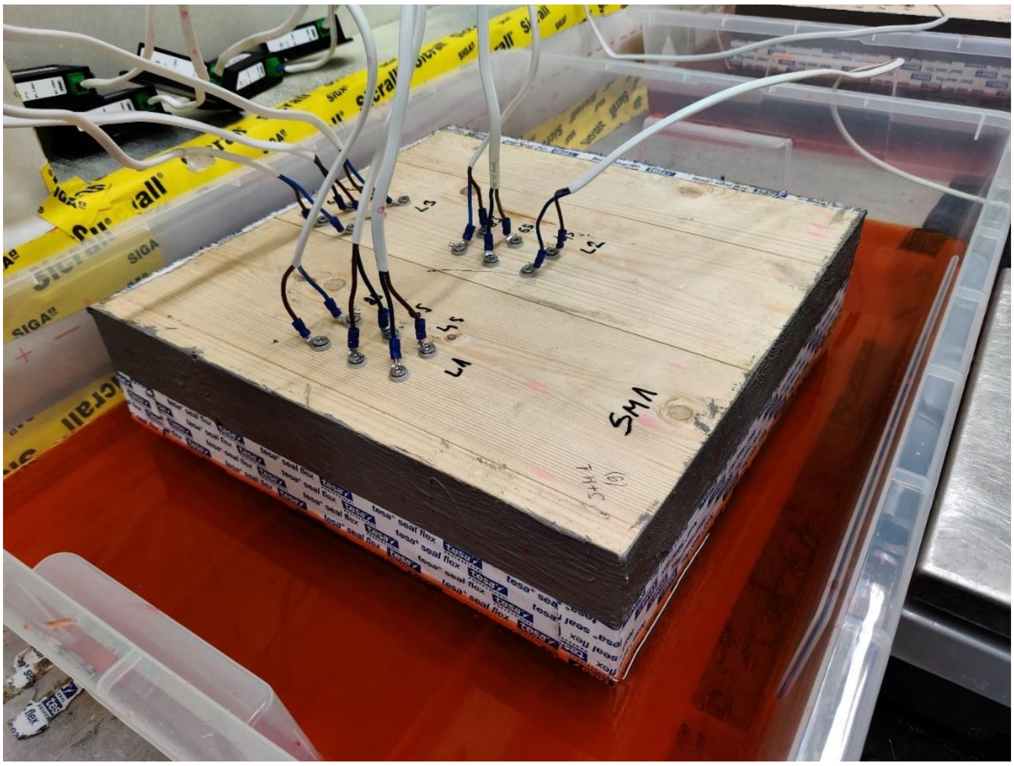

Figure 2.8 Measuring of moisture content of a sample with covered edges

When measuring moisture content with the electrical resistance method was over, the specimens were taken out of the water-filled cases. Small chips from each layer's measuring point were cut and weighed. Then those chips were placed into the oven at temperature 103 ±2 °C (Figure 2.9). After a week, the second weighing was done and the third one 2 hours after that to makes sure the difference in mass between two successive weighings were less than 0.1%. For weighing balance with an accuracy of 0.01 g was used. Oven-dry method results were then calculated based on Equation 1.1.

Figure 2.9 Test pieces placed in an oven

Water uptake coefficient measurements were gathered according to the standard EVS-EN ISO 15148:2003, which states the testing procedure and how to present the results. This standard gives a method for determining the short-term liquid water uptake coefficient by partial immersion with no temperature gradient. Each sample was placed in a water tank so that the sample base would be resting on the supports (black dashboard supports). The water level was kept constant during the test at 5±2 mm above the base of the samples. The specimens were weighed before placing them into water-filled cases using a balance with an accuracy of 0.1% of the mass of the specimen. The second weighing was done 5 minutes after the immersion. The base surface was blotted with a sponge to remove adhering water (Figure 2.10). Following weighings were done at 20 minutes, 1 hour, 2 hours, 4 hours, 8 hours, 16 hours, and 24 hours after the start of immersion. From there on, samples were weighed once every week (Figure 2.11). The weighings were done with cables and electrodes connected with specimens. The concern of weighing accuracy was analysed before the beginning of the test. The measurements were taken so that all cables were on balance while weighing or if that was not achievable, the cables had to be as stationary as possible to minimize the impact of cables. Special care was put into how the cables were situated during each weighing. Their placement was as similar to the previous weighing as possible, so it would not make a big difference in measured results.

Figure 2.10 Blotting of the excess water of the sample before weighing

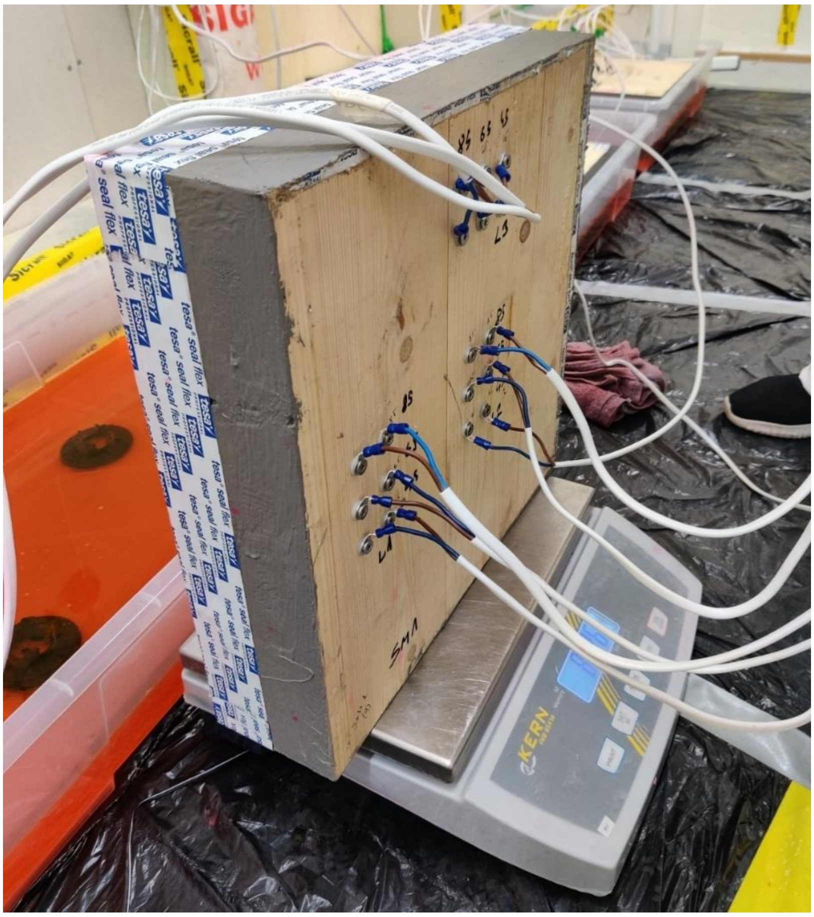

Figure 2.11 Weighing of a sample

As the method of calculating the results depends on the shape of the resulting curve, the difference between the mass at each weighing and the starting mass per area was calculated and plotted against the square root of the weighing times.
From there, the water uptake coefficient was calculated according to Equation 2.1:

$$A_w = \frac{\Delta m'_{tf} - \Delta m'_0}{\sqrt{t_f}}, \tag{2.1}$$

where A_w –

$\Delta m'_{tf}$ – value of Δm on the straight line at a time t_f (kg/m^2),

$\Delta m'_0$ – where graphs trendline cuts the vertical axis,

t_f – duration of the test (seconds).

A visual evaluation was done after measuring moisture content with the electrical resistance method and before the oven-dry method. In order to see how the water had moved in the CLT panel, Eosin Yellowish dye was added to the water (Figure 2.12). Smaller test pieces were cut out of the nine big specimens from the measuring areas (Figure 2.13). The absorbency of dyed water in test pieces was captured on images for later analysis (Figure 2.14). After that, smaller chips were cut out of those measuring area test pieces to get the exact place in the layer where the electrodes measured moisture content. The dye adhered to the wood, making it easy to see how much and how far the moisture had moved.

Figure 2.12 Left - measuring Eosin dye, right - dye added to the water

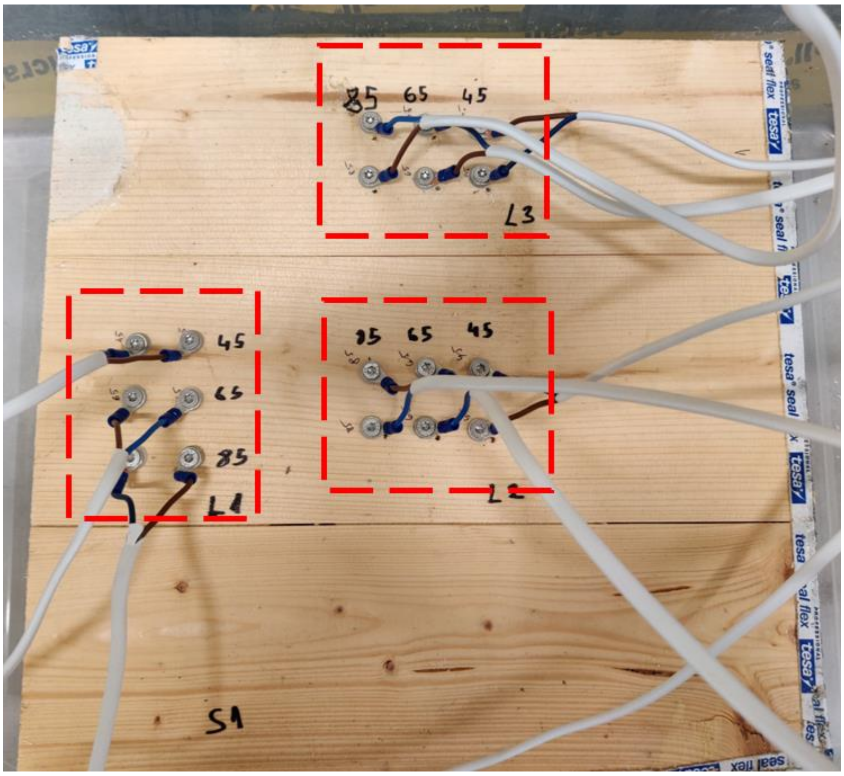

Figure 2.13 Prepared specimen with attached electrodes and cables, red lines show approximately where the smaller test pieces were cut

Figure 2.14 Smaller test piece that was cut out from measuring area

The equipment layout for measuring the moisture content with the electrical resistance method and measuring schema is shown in Figure 2.15 and Figure 2.16. Figure 2.17 shows the prepared cable with screw electrodes.

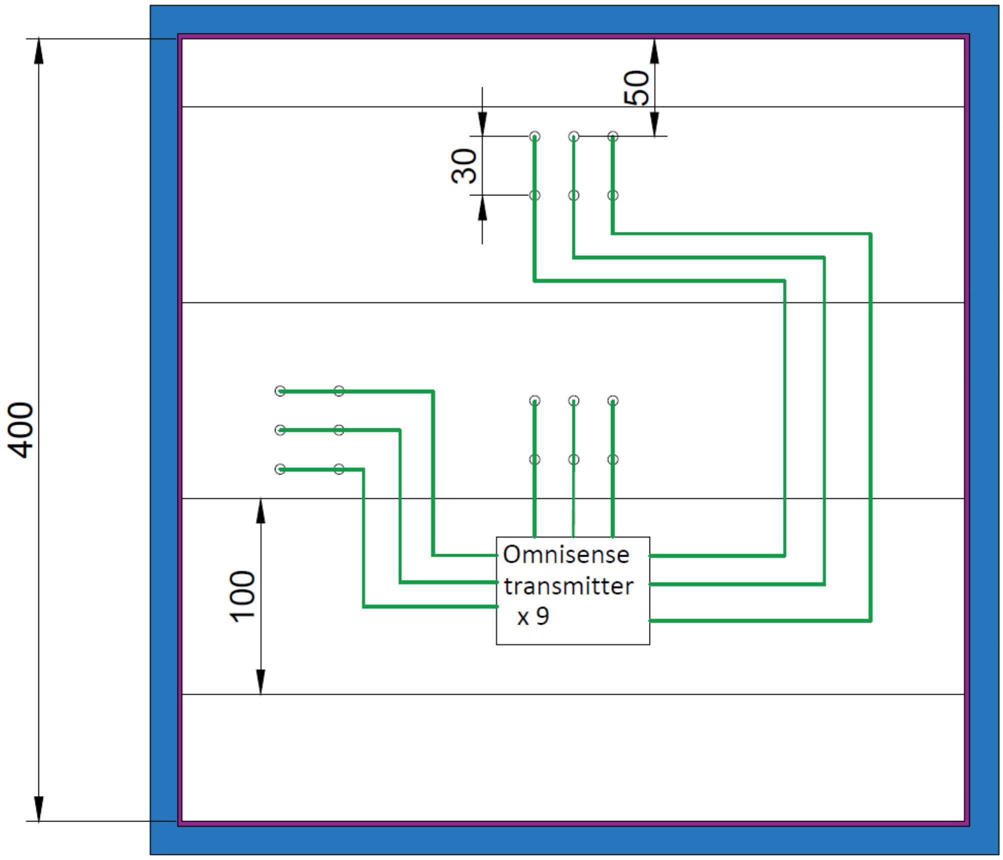

Figure 2.15 Measuring schema and equipment layout for samples with covered edges (top view); blue - water with dye, purple - waterproof mastic and tape, green - cables, measurements are given in mm

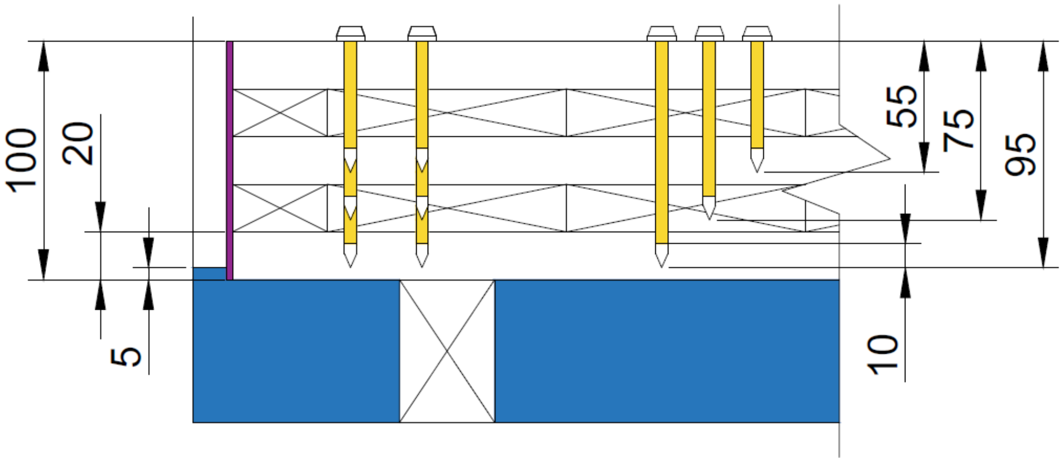

Figure 2.16 Measuring schema from the side; blue - water with dye, purple - waterproof mastic and tape; yellow - screw insulation (heat-shrink tube); measurements are given in mm

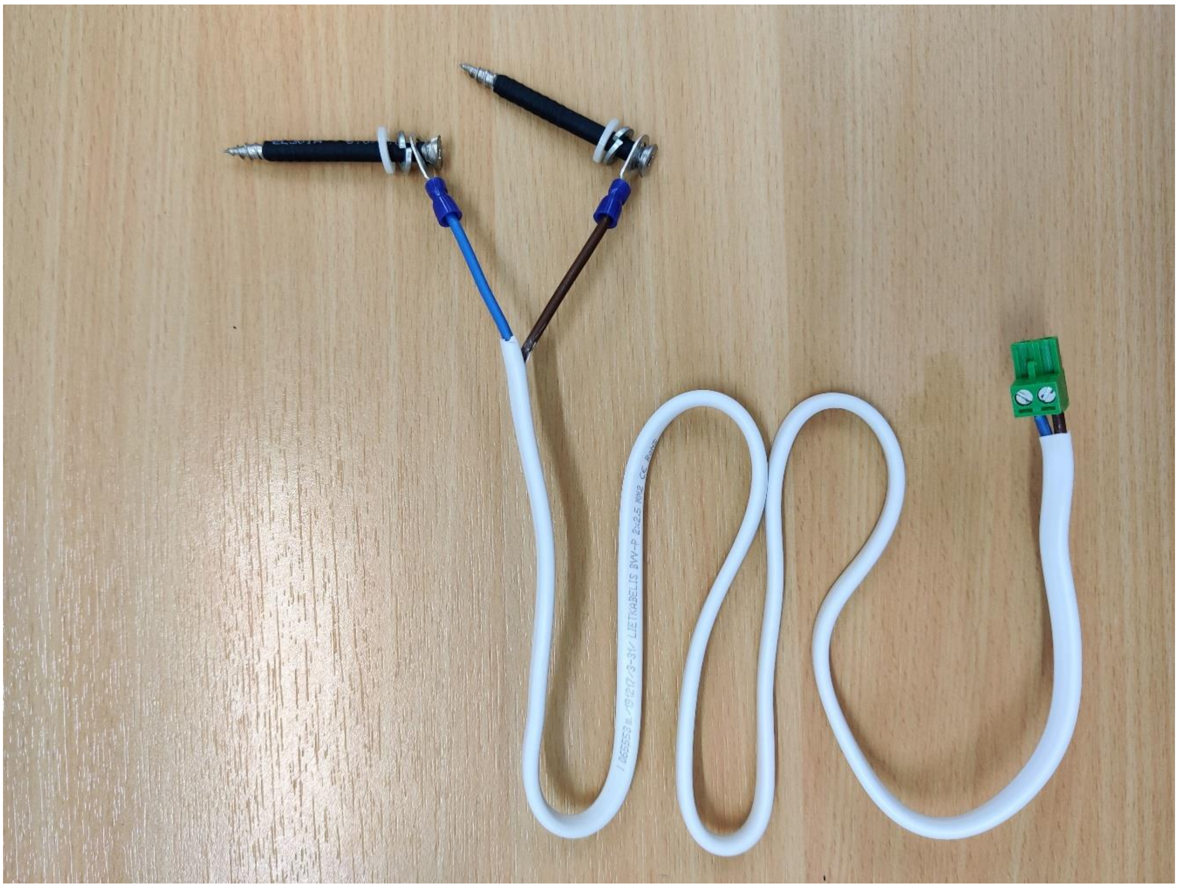

Figure 2.17 Previously prepared cable with insulated screw electrodes and washers

3. RESULTS

3.1 Suitable measurement method for wood moisture content

In order to find a suitable measurement method, different electrodes and systems were tested. Overview of two different types of electrodes is in Table 3.1. Preparation of isolated screws was relatively easy. The heat-shrinking tube was cut into the correct measurement based on the length of the screws and fixed with a hot air gun. Before installing the screws, two holes with different diameter and depth were drilled for each screw. Then plastic and metal spring washers were added, and screws were placed into the holes. Contact with wood was achieved with a mechanical force of winding the screws into the wood. It was essential to use plastic washers to isolate the screw head from the surface of the wood and metal spring washers for added mechanical force. However, for this laboratory test, spring washers were not a good choice because some of the screws became loose while testing.

Preparation of isolated copper wires needed a bit more work than screw electrodes because the isolation had to be stripped at a certain length from the wire and, after that, bent to the correct depth of the measuring point. Contact with wood was achieved with the added conductive adhesive that had to insert into the previously drilled holes with a needle. It was important to place the wire electrode into the hole quickly before the adhesive had time to dry, which it did pretty quickly. After that, the wire was fixed with a stapler to the wood to add stability.

Screw electrodes were more reliable than wire electrodes because of the direct contact with wood and mechanical force. Also, the ease of use was much better with screws because it was quicker and less messy than using the wire electrodes.

Table 3.1 Overview of the isolated screw and isolated copper wire characteristics

Characteristics	**Isolated screws**	**Isolated copper wires**
Preparation	Needs heat-shrink tubing to isolate the screws; easy to measure and cut needed isolation	It needs a wire stripping tool or any other sharp tool to cut the isolation; hard to measure and cut the length of the non-isolated part of the wire.
Contact with samples (wood)	Good contact is achieved with the mechanical force of inserting the screw into the wood; needs plastic and metal (spring) washers to isolate the metal head of the screw	Contact with wood is achieved with conductive adhesive and fixing the wire with staplers; no mechanical force and washers

Characteristics	Isolated screws	Isolated copper wires
Installation	Two holes with different diameter and depth have to be drilled for each screw; must use washers	One hole with a specific depth and diameter has to be drilled for each wire; adding conductive adhesive is a must
Ease of use	Preparation and installation are pretty quick and easy	Preparing and installation takes much time and is messy because of the need to add adhesive
Reliability	More reliable than wires because of the mechanical force and direct contact with wood	Less reliable than screws because of no mechanical force and no direct contact with wood
Advantage	Mechanical force and direct contact with wood	Cheaper what screw electrodes
Disadvantage	Needs plastic washers	No direct contact with wood

Overview of two different systems used for testing is in Table 3.2. Scanntronik system used two different devices to gather testing information – one the Gigamodule that measured the results and the datalogger which would log the data. To get the information from the datalogger, it had to be disconnected from the Gigamodule and connected to the computer via USB cable and specific software needed to be used to download the results. The Omnisense system had one gateway in the building that sent all the information gathered from the transmitters to the web, and the data was accessible from the Omnisense website. The Omnisence system was easier to use because the test results were easy to access from anywhere. However, the reliability of the Scanntronik system was better than Omnisense one because transmitters use in the latter system could be faulty and give wrong results or would not work at all.

Table 3.2 Overview of Scanntronik and Omnisense system characteristics

Characteristics	Scanntronik system	Omnisense system
Setting up	Devices must be configured based on the wanted results	Cables connecting electrodes and transmitters had to be made by hand
Ease of use	To get the data device must be connected to the computer via USB cable, and data has to be downloaded	User-friendly system – all measurements are available on the Omnisense website anytime in the form of graphs or table
Reliability	Problems that could occur would be that the batteries would die, or the configuration before the test were set wrongly	Transmitters might not work all the time or be faulty
Advantage	Reliability	Ease of use and accessibility
Disadvantage	Tedious to get results from the device and no visual output	Unreliability of transmitters

3.2 Laboratory measurements

Laboratory measurements were done with nine samples divided into three different categories: samples without covered edges, samples with mastic and tape covered edges, samples with mastic and tape covered edges and incisions on the bottom surface. Measurements for moisture content (MC) were taken hourly, and samples weights were taken every week for 75 days to see how much water they obtained.

3.2.1 Water uptake coefficient

Water uptake coefficient measurements were gathered according to the standard EVS-EN ISO 15148:2003, which states the testing procedure and how to present the results. An overview of the test procedure is written in paragraph 2.2.2, where the calculation instructions are also given. The trendline of samples without covered edges included only results gathered in the first 24 hours of the test. For other samples, the trendline included all the results gathered.

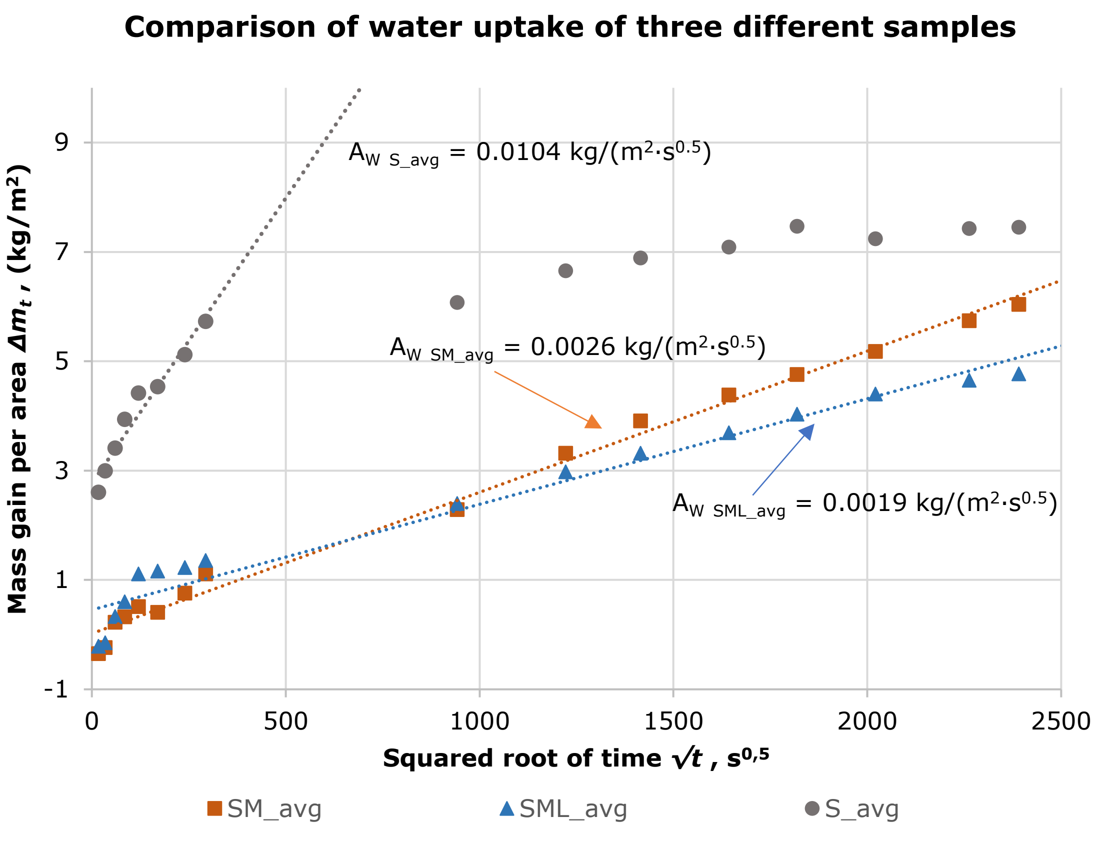

Figure 3.1 Comparison of average water uptake of three different samples: A_w – water uptake coefficient, S – samples without covered edges, SM – samples with mastic and tape covered edges, SML – samples with mastic and tape covered edges and incisions

The water uptake coefficient shows how many kilograms of water test samples absorbed per face area and per square root of time. Figure 3.1 shows the average water uptake coefficient of three different samples. The average water uptake coefficient was calculated for each type of samples by finding the average of all three sample's difference between the mass of each weighing. Samples without coverage had water uptake coefficient from 0.0070 kg/(m^2·$s^{0,5}$) to 0.0122 kg/(m^2·$s^{0,5}$), samples with covered edges had coefficients from 0.0019 kg/(m^2·$s^{0,5}$) to 0.0036 kg/(m^2·$s^{0,5}$), and samples with covered edges and incisions had coefficients from 0.0018 kg/(m^2·$s^{0,5}$) to 0.0020 kg/(m^2·$s^{0,5}$). $A_{w\ S\_avg}$ present the average water uptake coefficient of samples without any coverage on the edges and thus is the highest, 0.0104 kg/(m^2·$s^{0,5}$). The lowest average coefficient, 0.0019 kg/(m^2·$s^{0,5}$), is of samples with mastic and tape covered edges and incisions on the bottom surface, displayed on the figure as $A_{w\ SML\_avg}$. Average water uptake coefficient $A_{w\ SM\_avg}$ of samples with mastic and tape covered edges resides in between those results as 0.0026 kg/(m^2·$s^{0,5}$). The standard deviation of samples without covered edges was 0.0024, samples with covered edges 0.0007 and samples with covered edges and incisions 0.00009.

The trendline goes right up for samples without covered edges and only consisted of results gathered in the first 24 hours. It was caused by the quick absorption of water from the cut edges. The water absorbed until the surface was saturated, and then the absorption slowed down. Other samples had a trendline consisting of all results gathered, and there the weighings were linear throughout the testing period.

3.2.2 Moisture distribution in a cross-section of CLT

Moisture content (MC) measurements were carried out using two different standard methods: the electrical resistance method and the oven-dry method. The electrical resistance method will only give results up to 30-35%. The oven-dry method gives the most accurate results and will show moisture content that is even over 30%, which is fibre saturation point (FSP) in wood. Moisture content was measured in the three first layers of the CLT panel. The first layer is the bottom one with direct contact with water, the second layer is on top of that and so forth. Results of moisture content displayed in Figure 3.2 is of samples without covered edge, on Figure 3.3 of samples with mastic and tape covered edges and on Figure 3.4 of samples with mastic and tape covered edges and incisions on the bottom surface.

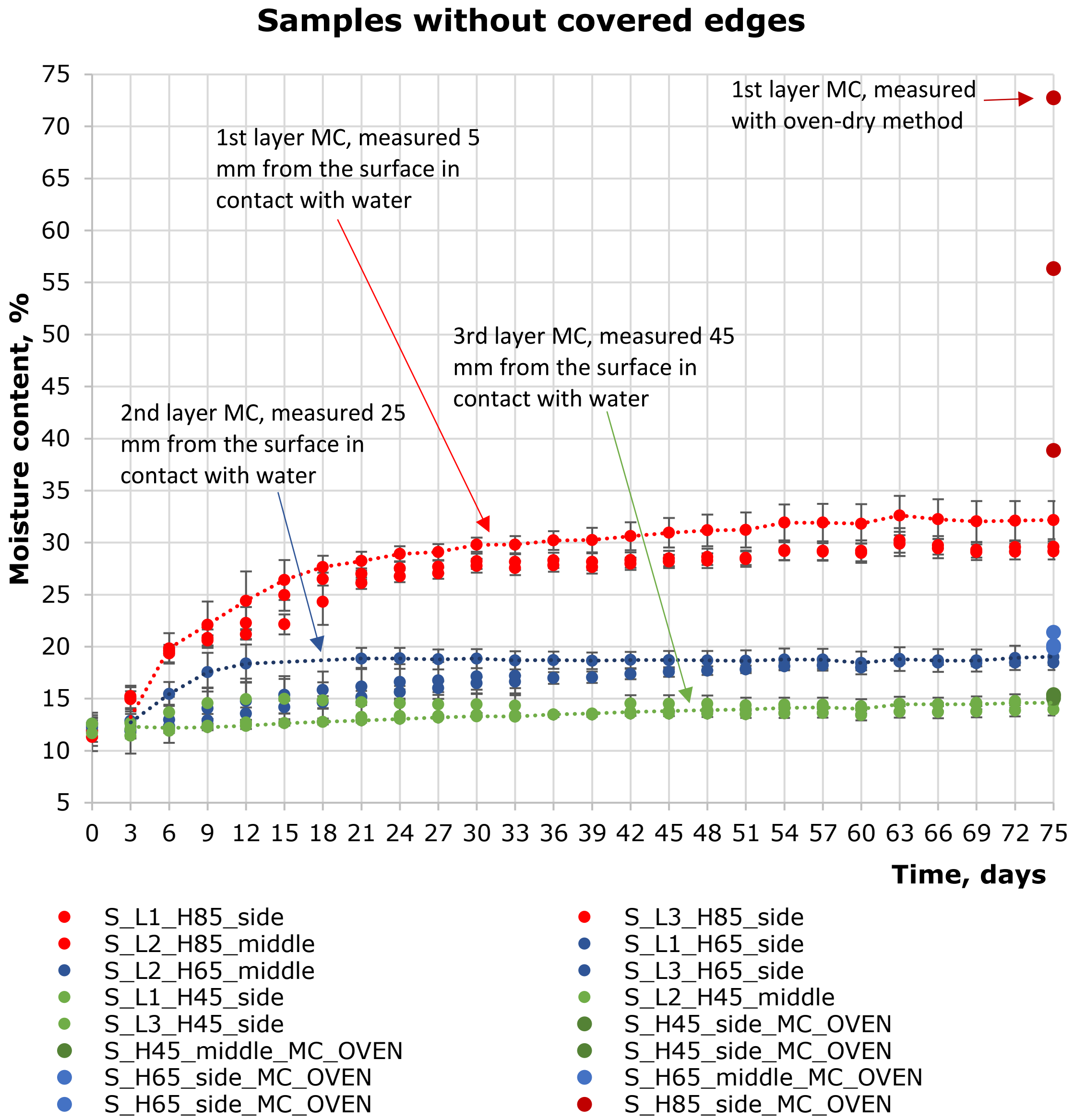

Figure 3.2 Moisture content of samples without covered edges: S – the sample type; L1, L2, L3 – different measuring areas; H85, H65, H45 – different depths of measuring points (H85 being in layer 1 of CLT panel (direct contact with water), H65 in layer 2 and H45 in layer 3); MC_OVEN – moisture content of oven-dry method

Figure 3.2 shows how MC results gathered by the electrical resistance method of three different layers of CLT panel changed over time. The initial measured MC for each measuring point was 12% which increased over time. The MC of the first layer of the CLT panel (with direct contact with water) rose intensively for the first 18 days and then slowed down. By the end of testing, the MC of the first layer had reached an average of 30%. The second and third layer of the CLT panel had an intensive rise of MC in the first 12 days and then slowed down. The second layer reached MC 20% and the third layer 15% by the end of testing.

The average standard deviation for different measuring points in the first layers were 1.50 (S_L1_H85), 0.74(S_L2_H85) and 0.88 (S_L3_H85). For the second layer, the average standard deviation for different measuring points were 3.31 (S_L1_H65), 0.48 (S_L2_H65) and 1.04 (S_L3_H65). The third layer's standard deviation for different measuring points were 0.96 (S_L1_H45), 0.15 (S_L2_H45) and 0.31 (S_L3_H45).

Figure 3.2 also shows the results of the oven-dry method. Oven-dry method results for the first layer were much higher than results collected with electrical resistance method, the result of side measuring area rose almost up to 75%, the middle area over 55% and other side are almost 40%. The second layers oven-dry method result was also a bit higher than the electrical resistance method results, reaching up to 21%. The third layer's results of the oven-dry method were closest to the electrical resistance method results.

Figure 3.3 shows the measured moisture content of two different methods in samples with mastic and tape covered edges. Initial measuring of MC for each measuring point was almost at the same point, around 10% MC. Here the first layer has an extensive range of results which rose quickly to 30% in about 6 to 9 days and kept rising to 35% and over. The second layer's electrical resistance method rose steadily up to 21% and the third layer up to 15%-16%. Oven-dry method results stayed in the same range as electrical resistance method results for the second and third layer. The first layer's oven-dry method results were much higher, rising to 72%, than electrical resistance method results.

The average standard deviation for different measuring points in the first layers were 5.19 (SM_L1_H85), 2.05 (SM_L2_H85) and 9.63 (SM_L3_H85). For the second layer, the average standard deviation for different measuring points were 0.63 (SM_L1_H65), 0.43 (SM_L2_H65) and 1.69 (SM_L3_H65). The third layer's standard deviation for different measuring points were 0.32 (SM_L1_H45), 0.42 (SM_L2_H5) and 0.40 (SM_L3_H45).

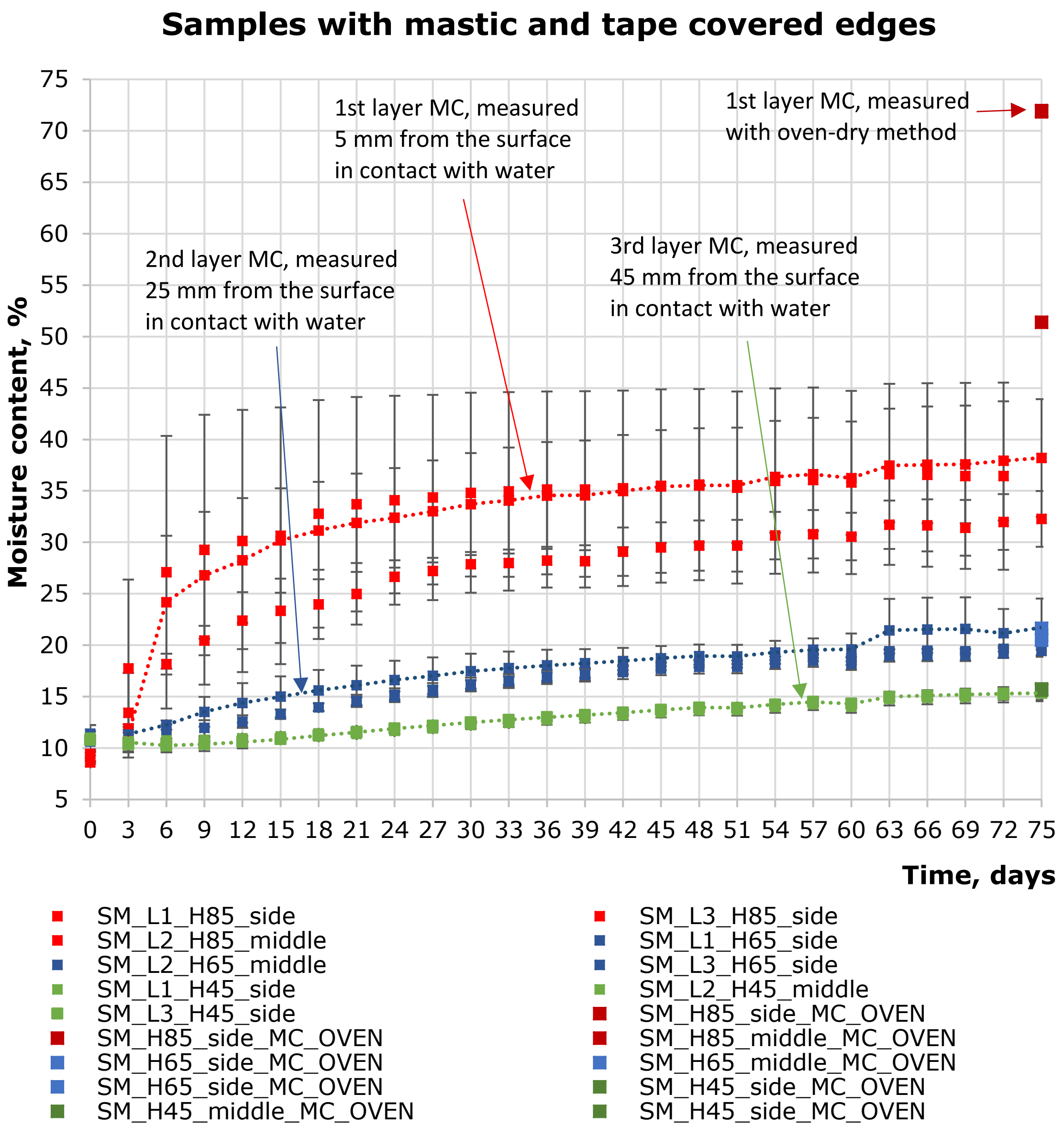

Figure 3.3 Moisture content of samples with mastic and tape covered edges: S – the sample type; L1, L2, L3 – different measuring areas; H85, H65, H45 – different depths of measuring points (H85 being in layer 1 of CLT panel (direct contact with water), H65 in layer 2 and H45 in layer 3); MC_OVEN – moisture content of oven-dry method

Figure 3.4 Figure 3.4 Moisture content of samples with mastic and tape covered edges and incisions on the bottom surface: S – the sample type; L1, L2, L3 – different measuring areas; H85, H65, H45 – different depths of measuring points (H85 being in layer 1 of CLT panel (direct contact with water), H65 in layer 2 and H45 in layer 3); MC_OVEN – moisture content of oven-dry method shows the moisture content of samples with mastic and tape covered edges and incisions on the bottom surface. Here also, the first layer rises the fastest and highest. Initial measured MC of each measuring point of all layers stays in the range of 7% - 11%. The first layer's electrical resistance moisture content rose quickly to 28% in 18 days and then slowly to 30%, while the

oven-dry method results of the same layer were higher (38% - 46%). The second layers electrical resistance moisture content rose steadily to 20%, and the third layers MC to 16%. The oven-dry method results of the second layer mainly were the same as the electrical resistance ones. The third layer oven-dry method results stayed in the same range as the electrical resistance method.
The average standard deviation for different measuring points in the first layers were 0.26 (SML_L1_H85), 0.85 (SML_L2_H85) and 0.42 (SML_L3_H85). For the second layer, the average standard deviation for different measuring points were 0.80 (SML_L1_H65), 0.64 (SML_L2_H65) and 1.53 (SML_L3_H65). Third layer's standard deviation for different measuring points were 0.31 (SML_L1_H45), 0.45 (SML_L2_H45) and 0.36 (SML_L3_H45).

The average standard deviation of the first layer of samples without covered edges was 1.04, second layer 1.55 and third layer 0.46. The standard deviation of the first layer of samples with covered edges was 5.57, the second layer 0.94, and the third 0.34. The standard deviation of the first layer of samples with covered edges and incisions was 0.51, the second layer 0.92 and the third layer 0.38.

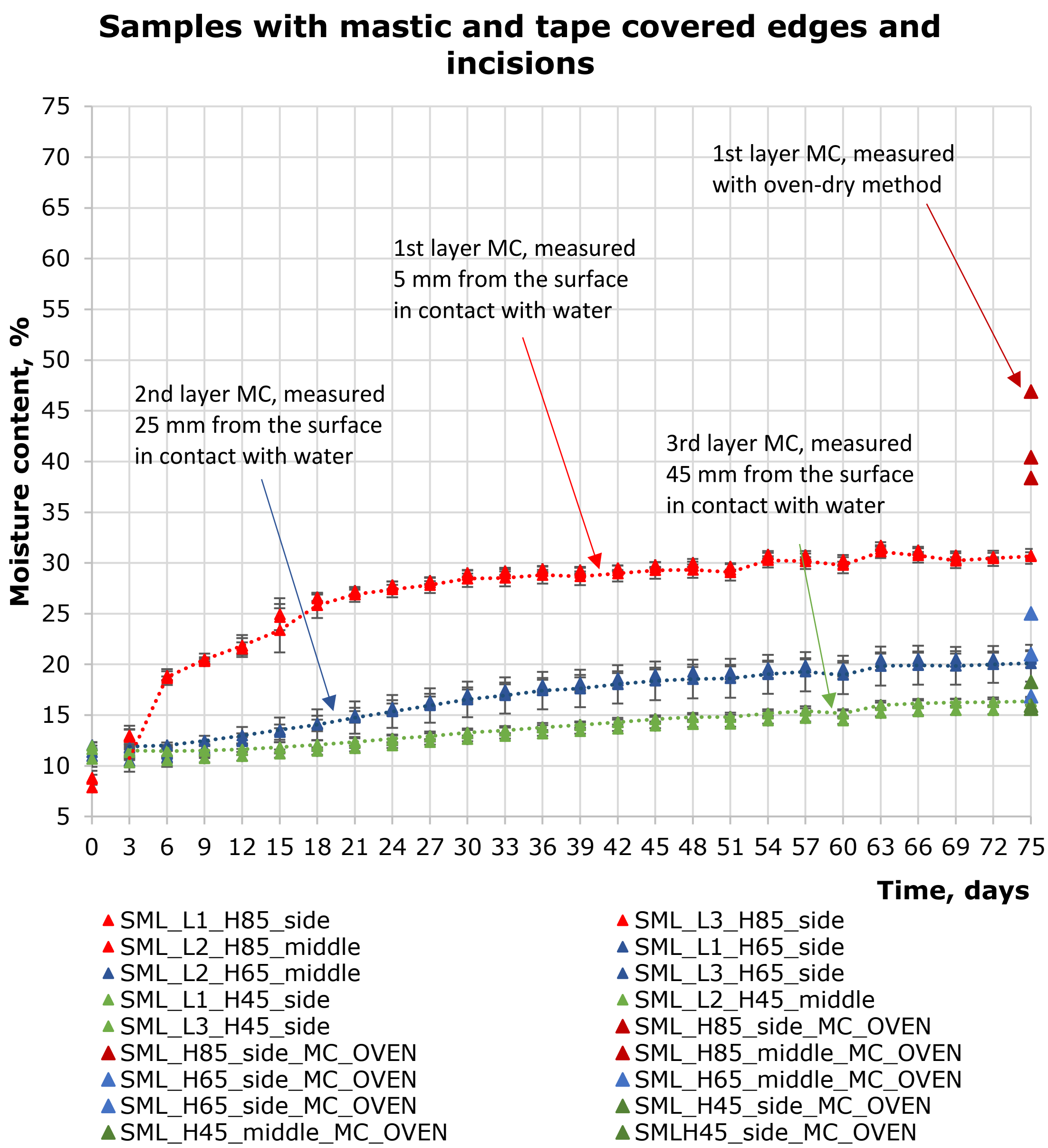

Figure 3.4 Moisture content of samples with mastic and tape covered edges and incisions on the bottom surface: S – the sample type; L1, L2, L3 – different measuring areas; H85, H65, H45 – different depths of measuring points (H85 being in layer 1 of CLT panel (direct contact with water), H65 in layer 2 and H45 in layer 3); MC_OVEN – moisture content of oven-dry method

3.2.3 Comparison of oven-dry and electrical resistance method for moisture content measurement

As previously stated, measurements were taken from each sample in three measuring areas and three different layers. Based on the placement of two electrodes and the measuring area of those electrodes, the results collected can be categorised as longitudinal, radial and middle (Figure 3.5). Table 3.3, Table 3.4, Table 3.5 give an overview of moisture content in each layer and area. The difference in the two measurements (ΔMC, %) was calculated by separating the moisture content of the electrical resistance method (MC_EL) from the moisture content of the oven-dry method (MC_OVEN).

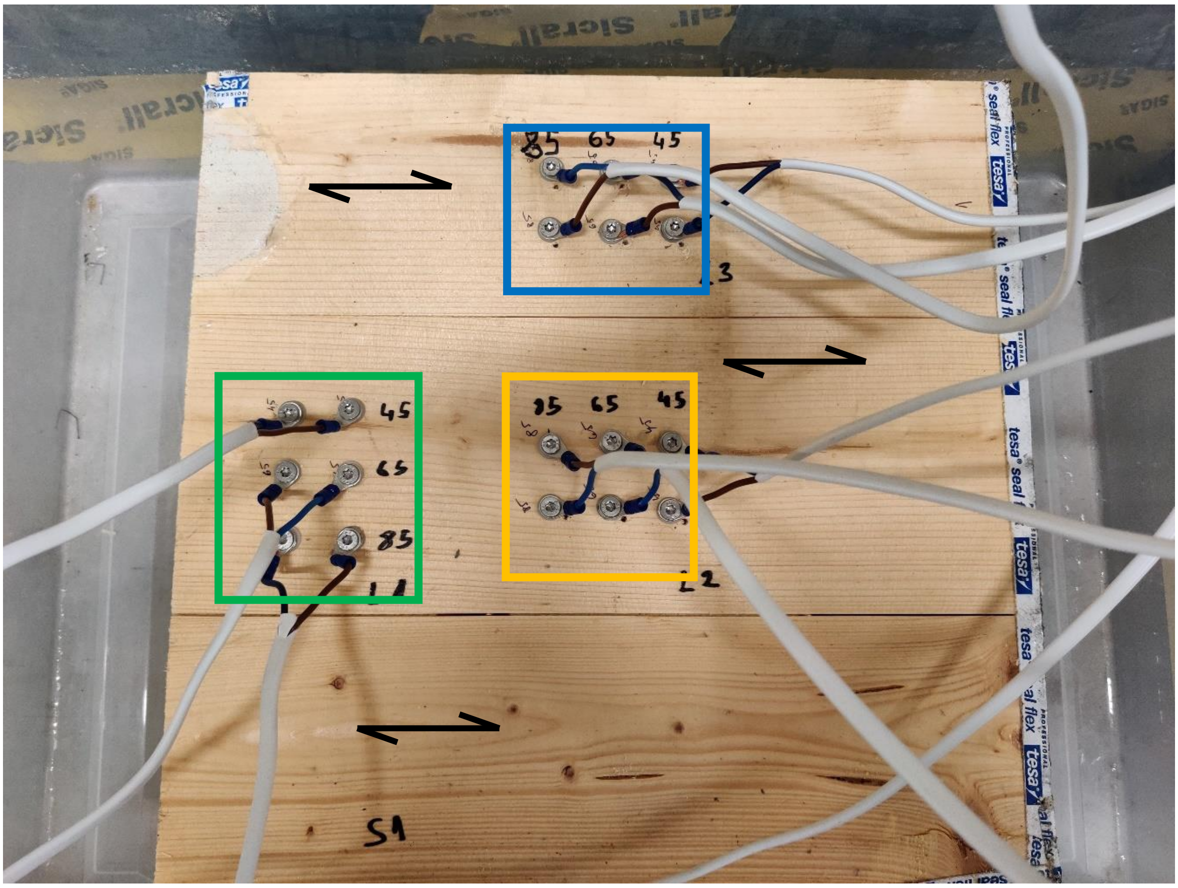

Figure 3.5 Drillings of holes for electrodes: yellow box – middle part of the CLT panel, blue – electrical resistance is measured radial to the wood grain, green - electrical resistance is measured longitudinal to the wood grain

Table 3.3 Comparison of moisture content results gathered with electrical resistance and oven-dry method in the first layer of CLT panel

	S1			S2			S3		
H85	longitudinal	radial	middle	longitudinal	radial	middle	longitudinal	radial	middle
MC_OVEN	88.7	37.1	67.1	67.4	36.1	49.6	62.2	43.4	52.3
MC_EL	32.5	29.9	30.1	34.2	28.1	29.8	29.8	29.5	28.9
ΔMC, %	**56.2**	7.2	37.0	**33.2**	8.0	19.8	**32.4**	14.0	23.4
	SM1			SM2			SM3		
MC_OVEN	52.6	58.1	53.9	35.8	57.3	43.2	127.3	100.5	57.0
MC_EL	7.2	35.0	29.9	31.0	33.5	31.0	49.4	46.3	36.1
ΔMC, %	**45.4**	23.1	24.0	4.8	**23.8**	12.2	**77.9**	54.2	20.9
	SML1			SML2			SML3		
MC_OVEN	39.9	33.7	39.7	36.6	62.5	38.0	44.7	44.4	37.4
MC_EL	31.2	30.8	31.7	30.7	30.7	30.4	30.4	30.8	30.0
ΔMC, %	**8.7**	2.9	8.0	5.9	**31.8**	7.6	**14.3**	13.6	7.4
*S1, S2, S3 - specimens without covered edges, SM1, SM2, SM3 - specimens with covered edges, SML1, SML2, SML3 - specimens with covered edges and incisions									

In the first layer of the CLT panel (layer with direct contact with water), moisture content was mainly highest in the longitudinal direction to the wood grain (Table 3.3). Also, the most significant difference between results measured with two standard methods was in the longitudinal direction. Only two samples, SM2 and SML2, differed, with the highest difference in MC being in a radial direction. Overall, the moisture content results of the oven-dry method were higher than the electrical resistance method.

Sample's S1 and S2 highest moisture content of oven-dry method (MC_OVEN) and the electrical resistance method (MC_EL) were both in the longitudinal direction. S1 highest MC_OVEN was 88.72%, and MC_EL was 32.5%, S2 highest MC_OVEN was 67.38%, and MC_EL 34.2%. Both samples also had the lowest MC's in a radial direction. S1 lowest MC_OVEN was 37.06%, and MC_EL was 29.9%, S2 lowest MC_OVEN was 36.12%, and MC_EL 28.1%. S3 highest MC_OVEN and MC_EL were in the longitudinal direction as well. S3 MC_OVEN was 62.15% and MC_EL 29.8%. The same sample's lowest MC_OVEN was in a radial direction with 43.43%, and the lowest MC_EL was in the middle part of the CLT panel with 28.9%.

SM1 and SM2 had the highest MC's in a radial direction, SM3 had the highest MC's in the longitudinal direction. The highest MC_OVEN results were 58.12% in SM1, 57.3% in SM2 and 127.28% in SM3. The highest MC_EL results were 35 % in SM1, 33.5% in SM2 and 49.4% in SM3. SM1 and SM2 had both MC_OVEN and MC_EL lowest results in the longitudinal direction. SM1 lowest MC_OVEN was 52.55%, and MC_EL 7.1%, SM2 lowest MC_OVEN was 35.77% and MC_EL 31%. SM3 had the lowest MC_OWEN (57.03%) and MC_EL (36.1%) in the middle part of the CLT panel.

SML1 had the lowest MC_OVEN and MC_EL in a radial direction with the results of 33.74% and 30.8%, respectively. The same sample's highest MC_OVEN was 39.92% in the longitudinal direction, and the highest MC_EL was 31.7% in the middle part of the panel. Results of MC_OVEN of sample SML2 were highest in a radial direction (62.53%) and lowest in the longitudinal direction (36.59%). SML2 results of MC_EL were highest in both radial and longitudinal direction (30.7%) and lowest in the middle part of the panel (30.4%). SML3 had the highest MC_OVEN in the longitudinal direction (44.7%) and highest MC_EL in the radial direction (30.8%). The same sample's lowest MC_OVEN and MC_E were in the middle part of the panel (37.39% and 30%).

Table 3.4 Comparison of moisture content results gathered with electrical resistance and oven-dry method in the second layer of CLT panel

	S1			S2			S3		
H65	longitudinal	radial	middle	longitudinal	radial	middle	longitudinal	radial	middle
MC_OVEN	21.5	26.0	20.0	20.6	19.7	19.5	18.2	18.5	20.1
MC_EL	8.4	20.5	18.1	20.5	19.2	18.7	17.9	17.4	18.6
ΔMC, %	**13.1**	5.5	1.9	0.2	0.5	**0.8**	0.3	1.1	**1.5**
	SM1			SM2			SM3		
MC_OVEN	19.8	21.0	19.3	19.3	20.5	20.4	25.8	21.4	21.7
MC_EL	19.9	20.0	19.6	19.6	19.0	20.2	25.7	19.4	19.9
ΔMC, %	-0.1	**1.0**	-0.3	-0.4	**1.5**	0.2	0.1	**2.0**	1.8
	SML1			SML2			SML3		
MC_OVEN	20.8	20.7	20.0	20.7	20.8	21.0	33.7	21.6	9.6
MC_EL	20.0	20.6	19.4	18.0	21.6	21.0	22.5	19.9	21.2
ΔMC, %	**0.8**	0.1	0.6	**2.7**	-0.8	0.0	**11.2**	1.7	-11.6

*S1, S2, S3 - specimens without covered edges, SM1, SM2, SM3 - specimens with covered edges, SML1, SML2, SML3 - specimens with covered edges and incisions

In Table 3.4 moisture content of the CLT panel's second layer is shown. Two of the samples without covered edges (S2, S3) had the biggest difference of moisture content gathered with two methods in the middle part of the sample, respectively 0.78% and 1.54%. Sample S1 had the biggest difference in the longitudinal direction, 13.08%. All samples with covered edges (SM1, SM2, SM3) had the biggest difference in MC in a radial direction (1.04%, 1.45% and 2.02%), and samples with covered edges and incisions (SML1, SML2, SML3) had it in the longitudinal direction with 0.77%, 2.69%, 11.20%.

Sample's S1 highest MC with oven-dry method (MC_OVEN) was 26.01% in a radial direction, and MC with electrical resistance method (MC_EL) was 20.5%, also in a radial direction. The highest MC_OVEN and MV_EL of sample S2 were 20.6% and 20.45% in longitudinal direction and sample S3 20.14% and 18.6% in the middle part of the CLT panel. The lowest MC_OVEN and MV_EL of sample S2 were 19.48% and 18.7% in the middle part of the CLT panel, sample S3 18.19% in the longitudinal direction, and 17.4% radial direction.

Sample's SM1 highest MC_OVEN and MC_EL were radial, with results 21.04% and 20% respectively and lowest moisture contents in the middle part of the CLT, 19.34% and 19.60%. SM2 had the highest MC of the oven-dry method in a radial direction (20.45%) and the lowest in the longitudinal direction (19.25%). The highest MC of the electrical resistance method for the same sample was 20.2% in the middle part of the CLT panel and lowest in a radial direction, 19%. SM3 had the highest moisture content of both methods in the longitudinal direction (25.81% and 25.70%) and the lowest in the radial direction (21.42% and 19.40%).

SML1 lowest MC's were 19.99% and 19.40% in the middle part of the CLT panel, the highest MC_OVEN was 20.77% in the longitudinal direction, and the highest MC_EL was 20.60% in a radial direction. SML2 had the lowest moisture content of both methods in the longitudinal direction with 20.69% MC_OVEN and 18% of MC_EL. The same sample's highest MC_OVEN was 20.96% in the middle part of the CLT panel, and MC_EL was 21.6% in a radial direction. SML3 highest MC's were in the longitudinal direction, with MC_OVEN being 33.65% and MC_EL being 22.45%. The same samples lowest MC's were 9.61% (MC_OVEN) in the middle part of the panel and 19.9% (MC_EL) in a radial direction.

Table 3.5 Comparison of moisture content results gathered with electrical resistance and oven-dry method in the third layer of CLT panel

	S1			S2			S3		
H45	longitudinal	radial	middle	longitudinal	radial	middle	longitudinal	radial	middle
MC_OVEN	16.1	15.6	15.6	14.1	14.3	15.5	16.0	15.2	14.8
MC_EL	15.1	14.5	14.9	13.9	-	14.4	15.5	13.4	-
ΔMC, %	1.0	**1.1**	0.7	0.1	**14.3**	1.1	0.5	1.8	**14.8**
	SM1			SM2			SM3		
MC_OVEN	15.2	16.0	15.2	15.1	15.2	15.7	16.5	16.0	16.1
MC_EL	14.6	15.4	14.3	15.3	14.9	15.5	16.2	16.3	16.2
ΔMC, %	0.6	0.6	**0.9**	-0.2	**0.3**	0.2	**0.3**	-0.3	-0.1
	SML1			SML2			SML3		
MC_OVEN	15.2	15.8	16.4	15.2	16.3	16.0	16.4	22.8	15.4
MC_EL	16.3	15.1	17.0	16.0	15.5	16.3	16.8	16.1	16.0
ΔMC, %	-1.1	**0.7**	-0.6	-0.8	**0.8**	-0.3	-0.4	**6.7**	-0.6
*S1, S2, S3 - specimens without covered edges, SM1, SM2, SM3 - specimens with covered edges, SML1, SML2, SML3 - specimens with covered edges and incisions									

Table 3.5 shows the comparison of moisture content collected with two different methods in the third layer of the CLT panel. Here most of the highest differences are in a radial direction, where the samples S1 and S2 have a difference of 1.07% and 14.34%. Sample SM2 has a 0.34% difference in two measurements, and samples with covered edges and incisions (SML1, SML2, SML3) have 0.66%, 0.77% and 6.65% difference in measurements.

Samples S1 and S3 both had the highest moisture content of both methods in the longitudinal direction with results of MC_OVEN 16.14% (S1), 16.01% (S3) and MC_EL 15.10% (S1), 15.49% (S3). S2 had the highest results of both MC_OVEN and MC_EL in the middle part of the CLT panel, with 15.50% and 14.40%, respectively. S2 lowest results were in the longitudinal direction, with MC_OVEN being 14.05% and MC_EL 13.93%. The lowest MC_OVEN in S1 was 15.56%, and in S3 14.81%; the lowest MC_EL in S1 was 14.50% and in S3 13.4%.
SM1 had the highest MC's in a radial direction with a result of 16.02% (MC_OVEN) and 15.40% (MC_EL). The same sample had the lowest MC_OVEN in the longitudinal direction (15.16%) and the lowest MC_EL in the middle part of the CLT panel (14.30%). SM2 had the highest MC_OVEN and MC_EL in the middle part of the CLT panel, 15.69% and 15.50%, respectively. SM3 highest MC_OVEN was in the longitudinal direction (16.53%) and lowest in the radial direction (15.96%). The same sample's highest MC_EL was in a radial direction (16.30%) and lowest in both longitudinal direction and the middle part of the panel (16.20%)

The highest MC_OVEN of sample SML1 was 16.38% in the middle part of the panel, and the lowest was 15.22% in the longitudinal direction. The same sample's highest MC_EL was also in the middle part of the panel (17%), and the lowest MC_EL was in a radial direction (15.1%). SML2 highest MC_OVEN was in a radial direction (16.27%) and lowest in the longitudinal direction (15.24%). The same sample's highest MC_EL was in the middle part of the panel (16.3%) and lowest in a radial direction (15.5%). SML3 lowest MC_OVEN and MC_EL were in the middle part of the panel with results of 15.41% and 16%, respectively. The same sample's highest MC_OVEN was 22.76% in a radial direction, and the highest MC_EL was 16.8% in the longitudinal direction.

3.2.4 Visual evaluation

A visual evaluation was done on the samples. The red dye was added to the water, which was used during the test to see how far the water had absorbed. Samples without covered edges had dyed water absorbed from the cut edges as shown in (Figure 3.6, Figure 3.7). Layers one and three had much more water absorbed than the second layer because those layers had wood grain in the longitudinal direction. That means that the water distribution in layers was inconsistent, which was also seen on other samples.

Figure 3.6 Samples without covered edges

Figure 3.7 Oven-dry method sample piece shows how far the water has gotten into the first layer.

Samples with tape and mastic covered edges mostly had no water absorbed from the cut edges because the mastics and tape did not allow it. However, in some parts, the water did have access to the edge (Figure 3.8). Water also got between two pieces of wood. There was a small hole in the surface in one of the samples, which made it easier for water to get absorbed (Figure 3.9).

Figure 3.8 Pieces cut from a sample with mastic and tape covered edges. The left one shows the first layer in the longitudinal direction, with no water leakage from the edge and the right one in the radial direction, where some water has gotten through the tape and mastic and between two pieces of wood.

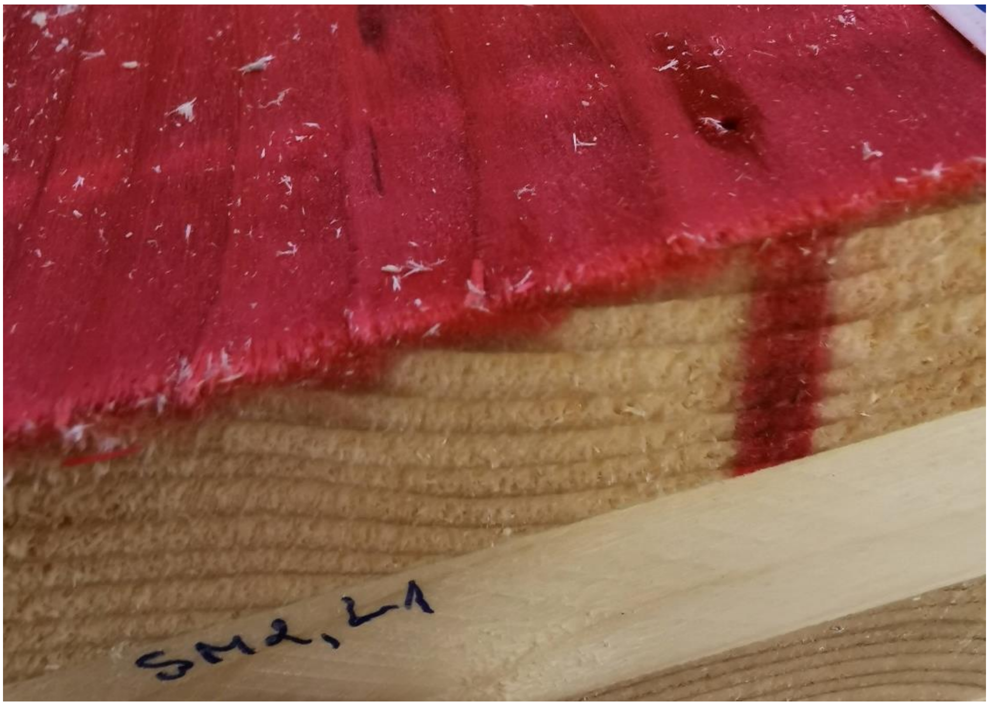

Figure 3.9 Small hole in the surface made it easier to absorb the water

Samples with tape and mastic covered edges and incisions on the surface also had some parts where water had absorbed into the wood from the cut edges, but mostly the mastics and tape did not allow it (Figure 3.10). Incisions were made to the surface of the panel to see if it will affect water absorption. It can be seen that water has absorbed from the incisions; however, it was less than expected (Figure 3.11).

Figure 3.10 Sample with mastics and tape covered edges and incisions. Some of the water has gotten through the tape in the left, and in the right, tape and mastics have done a great job of keeping the water away from the wood.

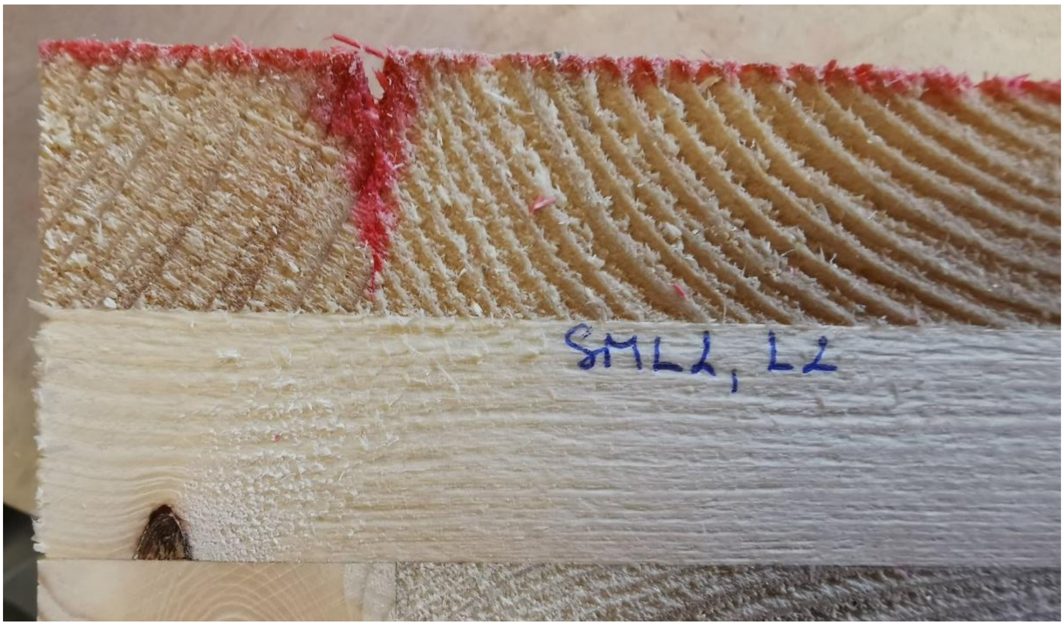

Figure 3.11 Sample with mastics and tape covered edges and incisions. Here is shown the incision and how much water has absorbed through it.

During the preparation of the oven-dry method, smaller test pieces of bigger samples were made. One test piece, shown in Figure 3.12, had a knot placed precisely between two electrodes. That might have affected the results gathered from this measuring point.

Figure 3.12 Oven-dry test piece with the knot placed between two electrodes

4. DISCUSSION

A suitable method for measuring wood moisture content was determined for this study by testing two different types of electrodes (isolated screws and isolated wires) and comparing Scanntronik and Omnisense devices for measuring systems. There were many criteriums to consider when deciding on the electrodes and measuring system. Reliability and ease of use were considered on both matters. In the case of electrodes, the contact with wood, which would determine their reliability, was vital. The decisive factor in selecting the measuring system was its ease of use. Thus, for electrodes, the isolated screws were picked because the thread of the screw creates mechanical force with the wood. An Omnisense measuring system was chosen because devices can be partially installed wirelessly, and results can be monitored and collected online.

Brischke et al. [21] used Scanntronik measuring devices for long-term (2 years) measurement of moisture content in building cladding and a wooden bridge with glued electrodes. Devices used from Scanntronik were Materialfox Mini data logger to record moisture content and Mygrofox mini data logger to collect relative humidity and air temperature. The study found that the measuring system was suitable for long-term measurement, and in combination with an alarm device, an irregular moisture accumulation can be detected at an early stage.

In Kalbe et al. [2] study, moisture content was measured using wood moisture meter Gann Hydromette LG 3, which consists of a measuring device and a ram-in electrode pair (Teflon insulated pins). This moisture meter is most commonly used to get the readings during the measurements and is not suitable for continuous long-term measurements

Fredriksson [3] listed different types of electrodes in her study, used for measuring the moisture content of wood with the electrical resistance method. She brought out that Teflon rod with stainless steel rings in different depths have been used to measure moisture content in the same point but different depths. Another type of electrodes to use would be PVC insulated hypodermic needles. Similar to the isolated wires used in this study, there was an example of using insulated cables, which were glued to the bottom of predrilled holes with electrically conductive adhesive. The adhesive would keep the electrical contact between the wood and the electrodes even if the wood shrinks or expands.

One of the aims of this study was to find a suitable measurement method for measuring the moisture content of CLT panels under both laboratory and outdoor conditions (a building under construction). Measuring the moisture content of a building's structure during construction requires the smallest possible size and number of measuring devices to not interfere with construction activities and would not attract much attention. The measuring electrodes must also be chosen so that they can withstand minor mechanical "shocks". For example, the builder might accidentally trip or touch the equipment and disturb the ongoing moisture content measuring. Therefore, screw electrodes were chosen because they remain significantly stiffer and stronger in wood than, for example, wire electrodes. Omnisense wireless transmitters reduce the number of devices needed, and their small size allows them to be "hidden" and covered from possible mechanical damage during the construction.

The highest average water uptake coefficient, 0.0104 kg/($m^2 \cdot s^{0,5}$), in the perpendicular direction to wood grain calculated in this study, was in the samples without any coverage on the edges. The lowest coefficient, 0.0019 kg/($m^2 \cdot s^{0,5}$), was in the samples with covered edges and incisions on the surface. Samples with just covered edges had a water uptake coefficient of 0.0026 kg/($m^2 \cdot s^{0,5}$). The difference in coefficient between two types of samples with covered edges was 0.0007 kg/($m^2 \cdot s^{0,5}$). The standard deviation of samples with incisions was significantly smaller (0.00009) than the standard deviation of covered samples without incisions (0.0007). Samples without coverage had water uptake coefficient from 0.0070 kg/($m^2 \cdot s^{0,5}$) to 0.0122 kg/($m^2 \cdot s^{0,5}$), samples with covered edges had coefficients from 0.0019 kg/($m^2 \cdot s^{0,5}$) to 0.0036 kg/($m^2 \cdot s^{0,5}$), and samples with covered edges and incisions had coefficients from 0.0018 kg/($m^2 \cdot s^{0,5}$) to 0.0020 kg/($m^2 \cdot s^{0,5}$). It shows that if any of the samples in different types of samples have any defect, for example, a small hole (Figure 3.9), it could considerably affect the water absorption results. Furthermore, the water uptake coefficient showed a significantly higher absorbance on the samples with uncovered edges than with covered edges.

A study by Kordziel et al. [6] did a similar partial immersion test with five-layered CLT panels where all four sides were coated with an impermeable liquid-applied membrane, and water uptake was measured perpendicular to the wood grain. Specimens of Spruce-Pine-Fir (SPF) had a measured water uptake coefficient of 0.0025 and 0.0028 kg/($m^2 \cdot s^{0,5}$). Another study, done by AlSayegh [24], measured water uptake in the tangential and radial direction of CLT panel with covered edges and obtained a water uptake coefficient of 0.0019 kg/($m^2 \cdot s^{0,5}$) for Spruce-Pine-Fir panels. In Byttebier thesis [4], the water uptake coefficient was measured on CLT panels made of spruce with edges sealed with vapour tight sealant (rubber and plastic tape, silicone sealant, and acrylic resin sealant) so that the absorption would only be perpendicular to the grain. The obtained results showed the water uptake coefficient to be approximately 0.0025 kg/($m^2 \cdot s^{0,5}$) perpendicular to the grain and 0.105 kg/($m^2 \cdot s^{0,5}$) in the longitudinal direction.

The measured water uptake coefficient of the CLT surface perpendicular to the wood grain in all previously referenced studies were similar to this study's average water uptake coefficient of samples with covered edges. The difference between this study's results and mentioned studies results stayed in the range of 0.0002 kg/($m^2 \cdot s^{0,5}$). to 0,0007 kg/($m^2 \cdot s^{0,5}$). That indicates the reliability of this study's results on the surface water absorption of the studied CLT specimens. This study's samples without covered edges and specimens previously mentioned in Byttebier thesis [4], where water uptake was measured in the longitudinal direction, had almost the same coefficient. That implies that water was absorbed into specimens from cut edges towards the longitudinal direction of the wood, resulting in a higher coefficient than in samples with edges covered. Taking into account the large difference between the cut surfaces and the surface area in contact with water, the ratio being 1:40 (cut edge area $0.005 \cdot 0.4 \cdot 2 = 0.004\ m^2$; surface area $0.4 \cdot 0.4 = 0.16\ m^2$), it can be stated that the water absorption from the cut edges of the CLT panel dominates the water absorption of the entire panel. From the point of view of the moisture safety construction of CLT buildings, it can be concluded that, regardless of the surface of the exposed cut edges, its coating is essential to prevent the panel from getting wet during construction. Incisions made to the surface of the samples with covered edges did not have an expected impact of greater water absorption compared to samples with only covered edges. The reason for this is that the incisions were made in the longitudinal direction of the wood grain, as the same direction in which cracks develop in wood, and the cut itself was in a radial direction. Therefore, it can be said that the cracks do not affect the water absorption properties of the CLT surface and thus do not pose a risk of greater wetting of the panel.

Moisture content gathered in long-term measurements with the electrical resistance method in this study showed that in the first layer (surface layer) of the CLT panel that is in direct contact with the water reached and remained at 30% moisture content, which is in a range of fibre saturation point, the second layer 20% and the third layer 15%. The moisture content of each layer increased from their initial moisture content by trying to achieve equilibrium MC, and the MC distribution in each layer was similar in all specimens. The uncovered (exposed) edges did not affect the moisture content distribution in the CLT panel, as was largely the case for water absorption properties. The incisions (cracks) also had no effect.

The 30% moisture content measured in the first layer is also a limit value when using an electrical resistance measurement method, above which the measurement accuracy is significantly reduced. However, the results obtained by the oven-dry method were significantly higher in the first layer than when measured by electrical resistance. The average MC gathered with the oven-dry method of the second and the third layer was again similar to the MC gotten with the electrical resistance method (20% and 15%, respectively). When the samples were cut open, it was seen that the water mixed with dye had only absorbed 1-3 mm perpendicular to the wood grain in the first layer and 10-30 mm longitudinal to the grain from the cut edges. That suggests that free water was only absorbed by the wood top surface of the panel, and this also explains the large difference between the electrical resistance and the results obtained by the oven-dry method. The result found by the oven-dry method took into account both the free water on the top surface and the high equilibrium humidity in the middle of the first layer. The results found by the electrical resistance method were measured only in the middle of the layer, where the free water did not reach- did not reach the electrodes. In the top surface of the first layer, moisture absorbs capillary as free water and saturates the wood. From there, the moisture travels along the cell walls as both liquid and water vapour by trying to achieve equilibrium. Water vapour in wood moves from an environment with a higher water vapour pressure to an environment with a lower water vapour pressure. In this experiment, the temperature was constant, and the evaporation of free water on the surface resulted in a higher water vapour pressure and moved towards a lower water vapour pressure environment in dry wood and achieving equilibrium moisture content. The equilibrium moisture content achieved is described by our results at the end of the experiment.

Since the water vapour in the microcapillary system condenses capillary already at 60% of relative humidity, in addition to the diffusion of water vapour, the moisture moves in the cell walls as a liquid. The liquid in the cell walls of the wood moves from an environment with higher capillary pressure to an environment with lower capillary pressure. Since the capillary pressure is directly related to the relative humidity, the liquid also moves from a higher relative humidity environment to a lower relative humidity environment. All this explains why the long-term measurements showed different results in the first layer than the oven-dry method, as well as a difference in finding the water uptake coefficient. In conclusion, it can be said that the CLT in contact with water (standing water, rain, snow), only the surface saturates, and the cell voids (lumens, vessels) are entirely filled with water, but in the panel layers, the wood reaches the equilibrium moisture content, and in the first layer it reaches the fibre saturation point.

Wang et al. [7] measured the moisture content of the CLT panels in laboratory conditions and an outdoor environment. CLT panels used were 3-ply of Spruce-Pine-Fir with polyurethane adhesive. In the laboratory, the panels were sprayed hourly for 5 seconds for 18 days (delivering approx. 35 L of water per specimen). In the natural weather, the panels were kept for two-month period in Vancouver, British Columbia, Canada. The findings for outdoor and laboratory test were similar – laboratory test showed average moisture content of 24% and an outdoor test of 22%. The gap between the laboratory and the outdoor test was small, only 2 %. From that, it can be concluded that the results of CLT panels with constant contact with water and ones in an outdoor environment have a very small difference.

Kalbe et al. [2] measured moisture content on-site of exterior wall CLT panels in different construction phases. The testing took place in Estonia during the period when the precipitation was the highest (14.08.2019 to 31.01.2020). Results were measured at the height of 30 mm from the lower edge of the CLT wall panels at a depth of 30 mm. The first measuring showed an average of 21% MC, which rose to 29.5% during first floors concrete pouring, which is a very moisture-intensive task. After that, the MC decreased, and by the end of the test, CLT panels had an average MC of 16.5%.

Additionally, the measurement from the intermediate ceiling and wall connections were gathered. The first results of moisture content were between 11% and 14%, and the last results stayed below 13%. The study found that the most critical places where the CLT panels got most of the wetting were the junctions of the exterior wall to the foundation. There the panels were not covered and absorbed water longitudinally to the grain. The moisture content of intermediate ceiling and wall connections, which was weather protected, stayed below 17% throughout the testing period. It leads to the conclusion that edges of CLT elements should be covered, and the proper moisture safety management should be implemented during construction.

In a case study by Kuus et al. [1], moisture content of horizontal elements and horizontal-vertical joints made of CLT were measured on-site in the most critical positions for moisture in two depths 10 mm (short pins, external MC) and 80 mm (long pins, internal MC). Similar to the previous study, the construction was done during the highest precipitation. Horizontal elements showed higher moisture content throughout the test period than horizontal-vertical joints. However, there were more irregularities in the latter. MC of horizontal element stayed in the range of 13% to 16% and horizontal-vertical joint in the range of 7.5% to 11%.

Additionally, testing of three constant situations was done near the construction site (elements unsealed and exposed to all weather conditions, elements unsealed but under protective cover, and elements sealed in the factory and kept unopened). Uncovered and exposed horizontal CLT elements reached a moisture content of over 25%, and covered CLT elements had MC under the safe limit of 17%. Vertical elements showed similar results, but moisture content was approximately 10% lower. The tests showed that it is crucial to cover the CLT elements from environmental factors because the prolonged direct contact with water can lead to high moisture content, which will be hard to dry out.

Only a few of the previous studies show that CLT panels that are open to the outside climate for an extended period reach the moisture content of 30%. Those panels that are open to outside climate for a short time reach 20% of moisture content. From that can be concluded that the first layer of the CLT panel can reach the fibre saturation point (30%) in few months if not protected from the precipitation. From a moisture safety point of view, it is dangerous and beneficial to biological damage to wood, such as mould and rot, if the CLT dry-out capacity is not sufficient in the assembly of the building envelope during the time of use.

Limitations occurred in this study. Firstly, only two measurement methods were compared, but there are several methods in use and studied, and in the future, it will be possible to improve the method used in this study. The two methods were chosen because they were available existing laboratory measurement systems. Secondly, the accuracy of the results above 30% obtained by the electrical resistance method was indeterminate, which in turn added uncertainty to the determination of the moisture content distribution in the first layer of CLT. Additionally, when measuring the MC with electrodes, the locations of electrodes in some places were longitudinal to the wood grain, which may also have had a small effect on the results. The probability of possible defects is higher when weighing large samples instead of smaller ones, and results showed that there were some defects. Using smaller samples would have given more accurate results. The oven-dry method was done throughout the thickness of the first layer. More accurate results of moisture distribution in the first layer could have been obtained if the first layer had also been separated into layers and smaller test pieces. The moisture distribution of the first layer could have been determined more precisely.

Given the limitations in this study, future research should focus on the distribution of the moisture content of the first layer of the CLT panel on both the surface and the cutting surface. In this study, only the wetting of the CLT panel was investigated, but for future works, the drying of different layers of the CLT panel should be studied.

CONCLUSION

The main objective of this study was to investigate the impact of waterproofing of cut edges and cracks on the water absorption properties of the CLT surface and moisture content distribution in the cross-section of the CLT panel. In addition, it was important to find a suitable measurement method for measuring the moisture content of CLT under both laboratory and outdoor conditions (construction site). Based on the results of this work, the following conclusions were drawn:

- This study found that when deciding on the electrodes and measuring system, the reliability and ease of use should be considered. Both insulated screws and Omnisense measuring system performed positively regards these criteriums. Insulated screws give good contact with wood and can withstand mechanical "shocks" on the construction site. The Omnisense measuring devices are small, and data transfer is wireless, thus making them easy to hide and cover for possible mechanical damage during the construction.

- The water absorption from the CLT cut edges without waterproofing dominates the water absorption of the entire panel. Therefore, from the point of view of the moisture safety construction of CLT buildings, it can be concluded that, regardless of the surface of the exposed cut edges, its coating is essential to prevent the panel from getting wet during construction. The cracks do not affect the water absorption properties of the CLT surface and thus do not pose a risk of greater wetting of the panel.

- The CLT in contact with water (standing water, rain, snow) only the surface saturates with water, filling the cell voids, and moisture inside the panel is distributed by liquid conductivity and water vapour diffusion along the cell walls, achieving equilibrium moisture content. In this study, the first layer of CLT achieved ≈30% moisture content (FSP), the second layer ≈20%, and the third layer ≈15%. Such distribution was present in all studied panels. The uncovered (exposed) edges and the incisions (cracks) did not affect the moisture content distribution in the cross-section of the CLT panel.

- Future research should focus on the distribution of the moisture content of the first layer of the CLT panel on both the surface and the cutting surface.

SUMMARY

The use of cross-laminated timber (CLT) in construction is constantly growing, due to its advantages over competing materials such as steel and reinforced concrete. The advantages are its weight, mechanical properties and its use is significantly more environmentally friendly. On the other hand, wood is significantly more susceptible to moisture and it is therefore important to ensure proper moisture safety during construction to avoid possible moisture damage to CLT elements.

Previous studies [1]–[7] have found that the moisture content of CLT panels exposed to the outside environment for a long-term period (more than two months) can reach the fibre saturation point, which is 30%. In a short-term period (less than two months), the moisture content can reach 20%. However, previous results have not determined exactly how moisture is distributed across the cross-section and surface of the CLT panel. This master's thesis focuses on the solution of this problem.

The main objective of this study was to investigate the impact of waterproofing of cut edges and cracks in the surface on the capillary water absorption properties of the CLT surface (perpendicular to wood grain) and moisture content distribution in the cross-section of the CLT panel. In addition, it was important to find a suitable measurement method for measuring the moisture content of CLT in both laboratory and outdoor conditions (construction site).

Following tasks were done to fulfil the objective. Moisture content in the first three layers of the CLT panel was measured with the electrical resistance method based on EN 13183-2 standard and oven-dry method based on EN 13183-1 standard. The water uptake coefficient of the CLT panel was determined with a partial immersion test based on ISO standard 15148:2002. Visual evaluation of capillary water absorption in the cross-section of a CLT panel was carried out using red dye in water. Three types of specimens were used: CLT panels without treated cut edges, CLT panels with waterproof (mastics and vapour tight sealing tape) cut edges, and CLT panels with incisions (imitated cracks) on the surface of the panel and waterproof cut edges.

This study found that the choice of electrodes and measuring system should take into account reliability and ease of use. Both the insulated screws and Omnisense wireless measuring system performed positively regards these criteriums and were selected as measuring equipment.

Laboratory studies showed that water is most rapidly absorbed capillary into the CLT panels from cut edges, and CLT panels with uncovered cut edges had the highest water uptake coefficient. Therefore, when constructing CLT buildings, it is strongly recommended to make the cut edges waterproof already during production. Cracks (surface incisions) did not have a significant effect on the water absorption properties of the CLT surface and thus do not increase the risk of wetting the panel.

When the CLT is in constant contact with water (standing water, rainwater, melting snow) only the surface (1-3 mm perpendicular to wood grain) is capillary saturated with water. The moisture inside the panel is distributed along the cell walls by liquid conductivity and water vapour diffusion, reaching equilibrium moisture content. In this study, the first layer of CLT reached ≈30% equilibrium moisture content (fibre saturation point), the second layer ≈20%, and the third layer ≈15%. Such distribution was present in all studied panels. The uncovered cut edges and the incisions (cracks) in the surface did not affect the moisture content distribution in the cross-section of the CLT panel.

Given the limitations in this study, future research should focus on a more accurate distribution of the moisture content of the first layer of the CLT panel on both the surface and the cut surface. The drying of different layers of the CLT panel should also be studied.

KOKKUVÕTE

Ristkihtliimpuidu (CLT) kasutus ehituses on pidevalt kasvav, ja seda tema eeliste tõttu konkureerivate materjalide ees nagu teras ja raudbetoon. Eelisteks on selle kaal, mehaanilised omadused ja selle kasutamine on oluliselt keskkonnasõbralikum. Teistpidi on puit oluliselt vastuvõtlikum niiskusele ja seetõttu on oluline tagada nõuetekohane niiskusturvalisus ehitustegevuse käigus, et vältida võimalikke niiskuskahjustusi CLT elementides. Varasemad uuringud [1]–[7] on leidnud, et väliskeskkonnale pikaajaliselt (üle kahe kuu) avatud CLT paneelide niiskussisaldus võib jõuda ligilähedale puidu rakuseina küllastuspunktini, mis on 30%. Lühema perioodi (alla kahe kuu) jooksul võib niiskussisaldus ulatuda 20%-ni. Varasemad tulemused ei ole siiski määranud kuidas täpselt niiskus jaotub CLT paneeli ristlõikes ja pealispinnas. Selle probleemi lahendusele keskendub antud magistritöö.

Käesoleva uuringu peamiseks eesmärgiks oli välja selgitada CLT paneeli lõikeservade veekindlalt katmise ja pealispinnas olevate pragude mõju CLT pealispinna (ristikiudu) kapillaarse veeimavuse omadustele ja niiskusesisalduse jaotumisele CLT paneeli ristlõikes. Lisaks oli oluline leida sobiv meetod CLT niiskussisalduse mõõtmiseks nii labori- kui ka välistingimustes (ehitusplatsil). Eesmärgi saavutamiseks teostati järgmised ülesanded. CLT paneeli esimese kolme kihi niiskusesisalduse mõõtmine EN 13183-2 standardil põhineva elektritakistuse meetodil ja kuivatusmeetodil, mis põhineb EN 13183-1 standardil. CLT paneeli kapillaarse veeimavuse koefitsiendi määramine ISO standardi 15148:2002 järgi laboratoorse katsega. Vee kapillaarse imavuse visuaalne hindamine CLT paneeli ristlõikes kasutades punast värvainet leotusvees. Laboratoorsetes katsetes kasutati kolme tüüpi katsekehi: katmata, veekindlalt kaetud lõikeservadega CLT paneelid (veekindel mastiks ja aurutõkke teip) ning pealispinnas sisselõigetega (imiteeritud praod) CLT paneelid, millel samuti veekindlalt kaetud lõikeservad.

Selles uuringus leiti, et elektroodide ja mõõtesüsteemi valikul tuleks arvesse võtta töökindlust ja kasutusmugavust. Nii isoleeritud kruvi kui ka juhtmevaba Omnisense mõõtesüsteem toimisid nende kriteeriumide osas positiivselt ja osutusid valitud mõõteseadmeteks.

Laboratoorsed uuringud näitasid, et kõige kiiremini imendub vesi kapillaarselt CLT paneelidesse lõikeservadest ja katmata lõikeservadega CLT paneelidel oli kõige suurem veeimavuse koefitsient. Seepärast on tungivalt soovitatav CLT hoonete ehitamisel niiskusturvalisuse seisukohalt katta veekindlalt lõikeservad juba tootmise käigus.

Pragudel (pealispinna sisselõigetel) ei esinenud suurt mõju CLT pinna veeimavusomadustele ja seega ei suurenda paneeli märgumise ohtu.

CLT pideval kokkupuutel veega (seisev vesi, vihmavesi, sulalumi) küllastub kapillaarselt veega ainult pealispind (1-3 mm ristikiudu puidus). Paneeli sees olev niiskus jaotub vedelikujuhtivuse ja veeaurudifusiooni kaudu mööda rakuseinasid, saavutades tasakaaluniiskuse. Selles uuringus saavutas CLT esimene kiht ≈30% tasakaaluniiskuse (rakuseina küllastumispunkt), teine kiht ≈20% ja kolmas kiht ≈15%. Selline jaotus esines kõigis uuritud paneelides. Katmata lõikeservad ja sisselõiked pealispinnas (praod) ei mõjutanud niiskusesisalduse jaotumist CLT paneeli ristlõikes.

Arvestades selle uuringu piiranguid, peaksid tulevased uuringud keskenduma CLT paneeli esimese kihi täpsema niiskusesisalduse jaotumisele nii pealispinnal kui ka lõikepinnal. Samuti tuleks uurida CLT paneeli erinevate kihtide kuivamist.

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