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THE EFFECT OF EDGE BONDING TO THE
PROPERTIES OF CROSS LAMINATED TIMBER

SILESERVSEOTISE MÕJU RISTKIHTLIIMPUIDU OMADUSTELE

MASTER THESIS

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AUTHOR'S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material.
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Foreword

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Table of Contents

List of Symbols and Abbreviations	6
List of Figures.....	7
List of Tables	8
Introduction.....	9
1 Literature Review	11
1.1.1 CLT panel product description	11
1.1.2 Brief history.....	12
1.1.3 Crack formation in CLT panels	12
1.1.4 Advantages and disadvantages of edge bonded CLT panels	15
2 Materials and Methods.....	16
2.1 Specimens	16
2.1.1 Design.....	17
2.1.2 Production technology of edge-bonded panels	18
2.2 Conditioning.....	25
2.3 Apparatus for carrying out the test	26
2.3.1 Air permeability.....	26
2.3.2 Crack formation.....	28
2.4 Test procedure	30
2.4.1 Process.....	30
2.4.2 Measuring intervals	30
2.4.3 Recording the results	31
2.5 Test methodology for determining the formation of cracks in CLT panels	32
2.5.1 Test specimens.....	32
3 Results and Discussion.....	34
3.1 Results of air permeability test.....	34
3.1.1 Air Permeability results for panels produced with boards conditioned at RH 70%..	34
3.1.2 Air Permeability results for panels produced with boards conditioned at RH 30%..	37
3.2 Results for determining cracks formation in CLT	39
3.2.1 Results of MC in specimens	39

3.2.2 Results of crack formation for panels produced with boards conditioned at RH 70%	41
3.2.3 Results of crack formation for panels produced with boards conditioned at RH 30%	47
Conclusion	50
References	52
Abstract	54
Kokkuvõte	55
Appendices	56

List of Symbols and Abbreviations

MC – Moisture content in %

NOGE – Specimens without bonded edges

WGE – Specimens with bonded edges

RH – Relative humidity in %

Press. diff. – Pressure difference

List of Figures

Figure 1 Typical configuration of a CLT panel [3]	11
Figure 2 Dimensional shrinking in wood [8].....	13
Figure 3 Gap between lamellae's of CLT panel prepared without bonded edges	14
Figure 4 Cracks and checks in CLT with edge bonded layers (left) and without edge bonding (right) [2].....	14
Figure 5 Cross-section of 3- and 5-layer CLT panels.....	17
Figure 6 Overlapping gaps between lamellas	18
Figure 7 Boards with cross-section of 18x100mm	19
Figure 8 Adhesive line on edge-bonded lamellas	20
Figure 9 Jig with loading straps to add sufficient pressure.....	21
Figure 10 Using corks to remove defects from layers	22
Figure 11 Application of adhesive.....	23
Figure 12 Vacuum pressing in Peetri Puit OÜ.....	24
Figure 13 Hydraulic press in Tallinna Ehituskool	25
Figure 14 Panels with dimensions of 1300x460x40mm inside climate chamber Climacell 707	26
Figure 15 Air permeability test apparatus.....	27
Figure 16 Laminated veneer with sealed edges used for testing the airtightness of system	28
Figure 17 Marked crack between laminations	29
Figure 18 Crack Width Gauge for measuring cracks in CLT panels [13].....	29
Figure 19 EMC corresponding to RH on certain temperature in wood [14]	31
Figure 20 Climate chamber Climacell 707 [16]	33
Figure 21 Average air leaking of specimens.....	36
Figure 22 MC in specimens after conditioning.....	40
Figure 23 Surface of specimen without bonded edges after conditioning.....	42
Figure 24 Average number of cracks.....	43
Figure 25 Surface of specimen with bonded edges after conditioning.....	44
Figure 26 Average crack area for specimens.....	47
Figure 27 Air permeability test box front view	56
Figure 28 Air permeability test box section view	57
Figure 29 Clamping system for fastening the panel	58

List of Tables

Table 1 Different types of specimens	16
Table 2 Properties of Loctite® HB S509 Purbond adhesive [11]	22
Table 3 Specimens used for experiment	32
Table 4 Air permeability test results	35
Table 5 Mean values of air permeability test results	37
Table 6 Air permeability test results (l/min).....	38
Table 7 EMC and average MC of specimens in given conditions.....	40
Table 8 Total number of cracks	45
Table 9 Area of specimens covered with cracks.....	46
Table 10 Number of cracks on the specimens	48

Introduction

Cross-laminated timber (CLT) is an engineered wood panel originally developed in Europe in the mid 1990s [1]. CLT panels are usually produced from three to seven perpendicular layers. The panels are mostly used for prefabricated wall and floor structures.

CLT panels have many advantages, which make it a competitive construction material. The high degree of pre-fabrication decreases the erection time on site compared to, for example, concrete buildings [2]. In addition, CLT has high dimensional stability, which ensures the fitting accuracy with minimum tolerances.

As with any other wood product, one of the issues with CLT is in its behaviour when exposed to moisture. Over time changes in moisture content (MC) can change the properties of CLT or cause damages (for example, cracks forming on the surface of the panel). As there are many ways to construct a panel the changes in moisture affects the properties of a panel in different ways.

Air permeability is one of the factors that influences the whole performance of a building. It is influenced by the number of layers, thickness of layers, edge bonding, moisture content of the lamellas and the overall moisture content of the panel. This thesis is focused on determining the crack formation panel surfaces and studying the air leakages of CLT. Consequently, main objective was set:

- 1) to observe and compare the crack formation and its effect on air permeability properties on CLT panels with and without bonded edges

To achieve this objective, different subtasks were proposed. The first task was to do a theoretical research on the topic. Second task was to study the test standards and develop test methods to carry out scientific experiments and the last task was to obtain the results for analysing and confirming the given objectives.

The aim of the scientific experiments was to confirm the following hypothesis:

- 1) CLT panels produced with bonded edges will have fewer cracks and therefore less air leakages after conditioning than panels produced without glued edges.

Thesis structure consist of three main chapters: 1) Literature review; 2) Materials and methods; 3) Results and discussion. Based on results the conclusions are made.

1 Literature Review

1.1.1 CLT panel product description

Cross-laminated timber (CLT) is an engineered wood product described as a multi-layer wooden panel (in general three, five or seven layers), which is made of uneven number (minimum 3) of layers of timber [1] [3]. The layers are placed perpendicular to each other and joined by using adhesive to form a structural panel. A typical configuration of CLT panel is described in Figure 1.

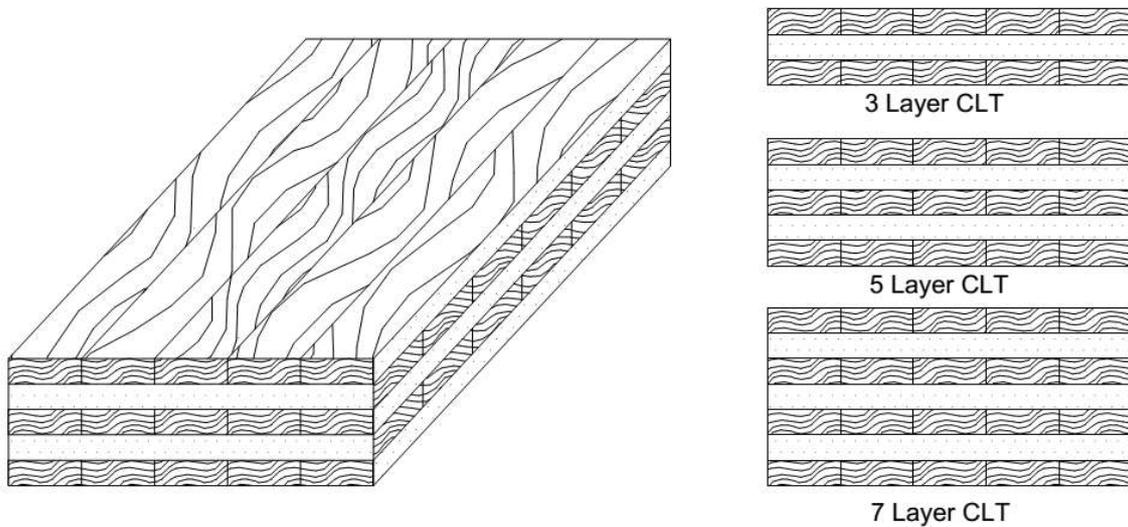


Figure 1 Typical configuration of a CLT panel [3]

The thickness of one layer is determined by European Standard EN 16315 [4] to be at least 6mm and a maximum of 45mm whereas each layer has to be made of laminations of one strength class. The overall thickness of CLT cannot be more than 500mm.

According to EN 16351 standard [4], the laminations can be made of several (mostly softwood) species, such as Norway Spruce (*Picea abies*), Fir (*Abies alba*), Austrian pine (*Pinus nigra Arnold*), Sitka-spruce (*Picea sitchensis*) etc. The adhesives used for bonding the laminations are phenolic and aminoplastic adhesives, moisture curing one-component polyurethane adhesives (most common) and emulsion polymer isocyanate adhesives.

1.1.2 Brief history

The origins of CLT development reach back nearly 3 decades to Austria. In the 1990s an industry-academia research resulted in the development of modern CLT. The development of the product was initially slow, but in the beginning of 2000s the production and construction in CLT escalated. Since then the production volume has increased 15-20% per year. [1]

Until 2012 one of the issues with CLT was the lack of a proper standard. In 2011 December the first standard, which was valid for both U.S and Canada, for CLT panels was published. The ANSI/APA PRG 3420 Standard for Performance-Rated Cross Laminated Timber was developed by American National Standards Institute (ANSI) and The Engineered Wood Association (APA) [5]. In Europe, the first standard for CLT was released in 2015. The standard EN 16351 was developed from EN 14080 “Timber structures – Glued laminated timber and glued solid timber” – Requirements.

Currently the biggest producers of CLT are located in Europe. The production volume for 2016 was set to increase to 1 million m³ with Austria being the leading country. [6] The Largest manufacturers of CLT in Europe are Stora Enso, Binderholz, KLH *Massivholz* and *Mayr-Melnhof Holz*, whose productions are all located in Austria.

1.1.3 Crack formation in CLT panels

As the main input for CLT is dimensional lumber, the formation of cracks in CLT panels is connected to the crack formation in wood.

Moisture movement in wood has a major role in crack formation. Important benchmark for the wood properties affected by moisture is fibre saturation point (FSP). FSP is defined the point where all the free water in the lumen has been removed but the cell wall is still saturated [7]. If the moisture content changes below this point, the properties of wood also change.

Until the wood moisture content reaches the fibre saturation point, the free water evaporates with the same speed in every direction of fibre. As the FSP is reached, the bound water evaporation can differ up to 25 times in different directions. [7]

If the moisture content of wood changes below the FSP, wood shrinks or swells unequally for different fibre directions (See Figure 2). The tangential change is about 8%, radial change about 4% and longitudinal change is approximately 0,1%.

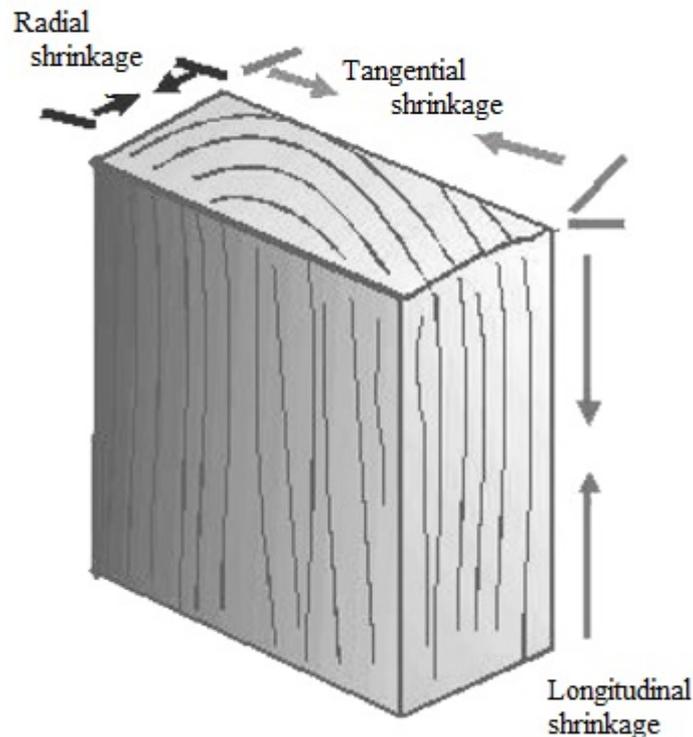


Figure 2 Dimensional shrinking in wood [8]

The unequal shrinking of wood in different directions (MC lowers) causes stresses inside wood [9]. This can result in the formation of checks and cracks. In contrary to shrinking, if the moisture content increases above the FSP, the timber can swell. The main reason for the formation of cracks is uneven moisture losing from wood. The outer surface of wood loses moisture quicker than the core, which shrinks the outer surface whereas the internal core remains the same. These changes cause stress to the wood cell and eventually break it.

Moisture content changes cause shrinking and swelling of the boards and the CLT element itself. The formation of cracks in CLT can be different for panels with or without bonded edges. As the timber loses moisture content the boards will shrink and, in addition to the cracks appearing in timber, gaps appear between edges of the lamellae's (see Figure 3)



Figure 3 Gap between lamellae's of CLT panel prepared without bonded edges

Cracks and gaps can affect the properties (fire resistance, air permeability, acoustic properties) of CLT [2]. To reduce the width of gaps, the edges of boards are bonded to form a single layer, which is later cross-wise bonded to form a CLT panel.

Although the formation of cracks and checks cannot be avoided, the advantage of edge bonding the boards is in the placement of forming cracks (see Figure 4) [2].

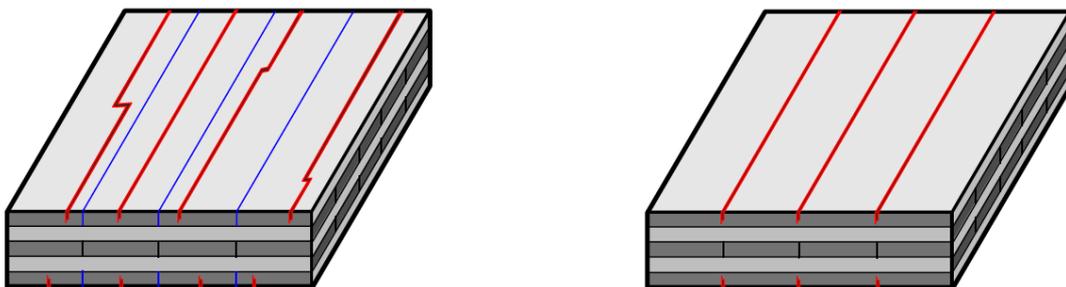


Figure 4 Cracks and checks in CLT with edge bonded layers (left) and without edge bonding (right) [2]

For the panels with bonded edges the cracks appear in an irregular pattern, which reduces the possibility of the formation of overlapping gaps. For comparison, the gaps and cracks on panels without bonded edges appear between the lamellae's. As the width of the lamellas is the same for all the layers, the gaps and cracks appear in a more regular pattern and increases the possibility of the formation of overlapping gaps. [2]

1.1.4 Advantages and disadvantages of edge bonded CLT panels

The edge bonding of boards to form a uniform layer has many advantages. As mentioned in the previous chapter, edge bonding can enhance the physical properties of the panel as it reduces the gap with and lowers the possibility of formation of overlapping gaps.

The surface of a pre-made layer is already smooth and calibrated (equal thickness). Thus the pressure needed for cross-wise surface bonding is reduced [2]. In addition, the handling of single lamellas in automated production is easier (for example, relocating the layers with a vacuum lifting device).

One of the biggest disadvantages regarding the edge bonding of boards is the increase in the cost of the final product. The edge bonding requires an extra step in the production process, which means the production time and cost will rise. In addition, the machinery for edge bonding the boards needs bigger investments to the production line. Additional machinery also needs production area. All in all, increased production time, bigger investments and need for more space increases the price of the end product.

2 Materials and Methods

This chapter describes the procedure of carrying out the tests to achieve the main objective of this thesis, and which methodologies were used for it. The conditions for tests were simulated to imitate the heating period (from autumn to spring in Estonia), during which the interior temperature remains constant but the relative humidity drops.

The methodology for air permeability test and evaluating the formation of cracks in CLT panels are described in detail in the following subchapters.

2.1 Specimens

Twenty-four specimens of rectangle-shaped cross-laminated timber panels with dimensions of 1300x460mm and thickness of 30mm from spruce wood (*Picea abies*) were designed and prepared for the air permeability test and crack evaluation test. The types of samples are described in Table 1. For accurate results three specimens of each type were produced and tested. The test specimens were the same that were used for G.Lucianis' scientific experiment [10].

Table 1 Different types of specimens

With bonded edges	Without bonded edges
Layer thickness 10 mm, 3 layers in panel; initial conditioning environment of lamellas RH 70%	Layer thickness 10 mm, 3 layers in panel; initial conditioning environment of lamellas RH 70%
Layer thickness 10 mm, 3 layers in panel; initial conditioning environment of lamellas RH 30%	Layer thickness 10 mm, 3 layers in panel; initial conditioning environment of lamellas RH 30%
Layer thickness 6 mm, 5 layers in panel; initial conditioning environment of lamellas RH 70%	Layer thickness 6 mm, 5 layers in panel; initial conditioning environment of lamellas RH 70%
Layer thickness 6 mm, 5 layers in panel; initial conditioning environment of lamellas RH 30%	Layer thickness 6 mm, 5 layers in panel; initial conditioning environment of lamellas RH 30%

2.1.1 Design

The panels were produced following the requirements of international standard EVS-EN 16351_2015 [4].

The length and width of the panels designed for the test were 1300x460mm and the thickness of the panels was 30mm. Depending on the thickness of one layer (6mm or 10mm) the panels had 3 or 5 layers accordingly. The layers consisted of spruce lumber with width of 100mm. Subject to the length of the lamella (1300mm or 460mm), 5 or 13 lamellas, respectively, per layer were used. The cross-sections of 3- and 5-layer panels with adhesive-bonded edges is described on Figure 5.

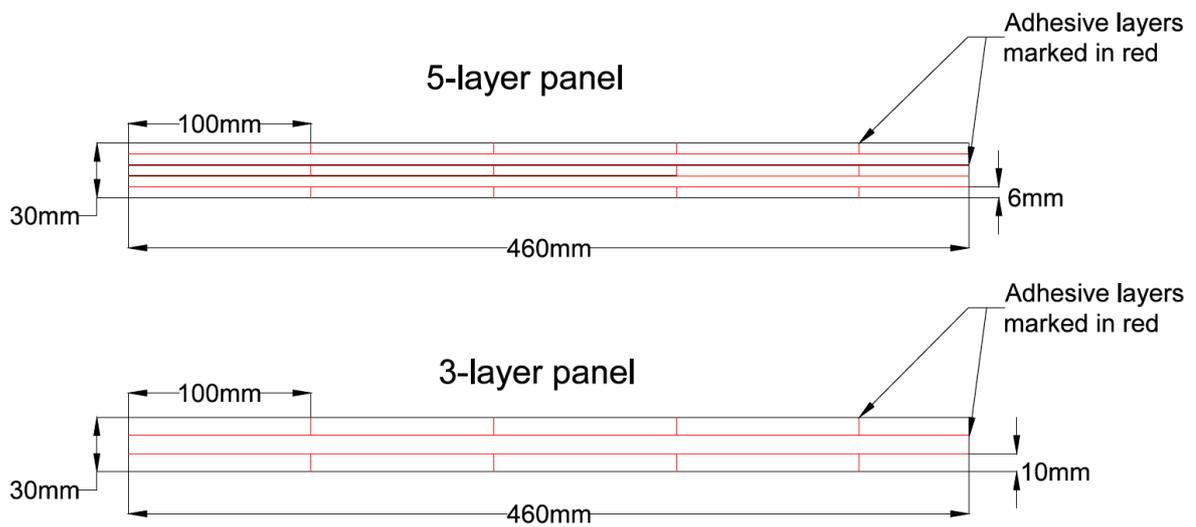


Figure 5 Cross-section of 3- and 5-layer CLT panels

The specimens were designed in a way to carry out the tests in a reasonable time, yet to have as many overlapping gaps between lamellas as possible (formation of overlapping gaps is described in Figure 6).

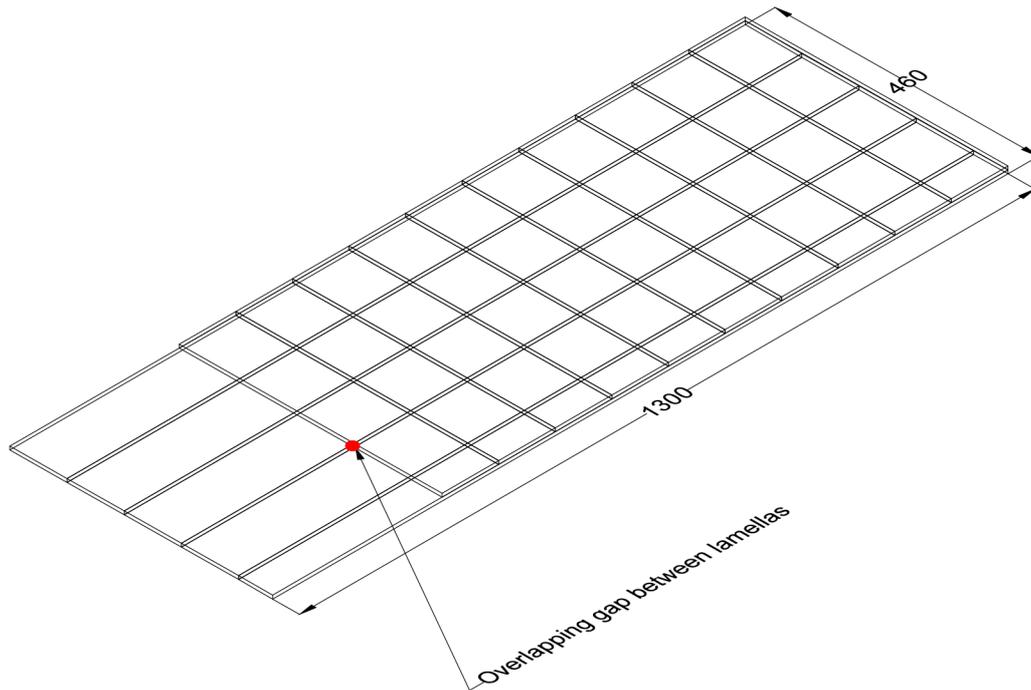


Figure 6 Overlapping gaps between lamellas

The total number of possible overlapping gaps for 3- and 5-layer panels were 128.

2.1.2 Production technology of edge-bonded panels

In total, 24 panels were produced. Twelve of them were with bonded edges and the rest, for comparison, without bonded edges. Six panels with bonded edges were produced in Peetri Puit OÜ factory using technology and equipment which is used in everyday production, whereas six panels were produced in Tallinna Ehituskool. All the specimens made for this study were brought to Tallinn University of Technology for testing.

From company Raitwood four sides planed spruce (*Picea Abies*) boards with dimensions of 95x18x4500mm and with initial moisture content of 12% were purchased (see Figure 7).

The preparation process for making the test specimens began with cutting the boards with cross-section of 95x18mm to the right length (1300mm for longer layers and 460mm for shorter layers).



Figure 7 Boards with cross-section of 18x100mm

For the production of panels with bonded edges, single layers (with adhesive-bonded edges), which are further cross-wise surface bonded to CLT, needed to be made first.

For the preparation of edge bonded panels the lamellas were bonded by edges using single component polyurethane adhesive (Loctite HB S509 Purbond). On Figure 8 the adhesive lines on edge-bonded lamellas are shown.

The adhesive was applied to one edge of the wood lamella by using a paint roller.

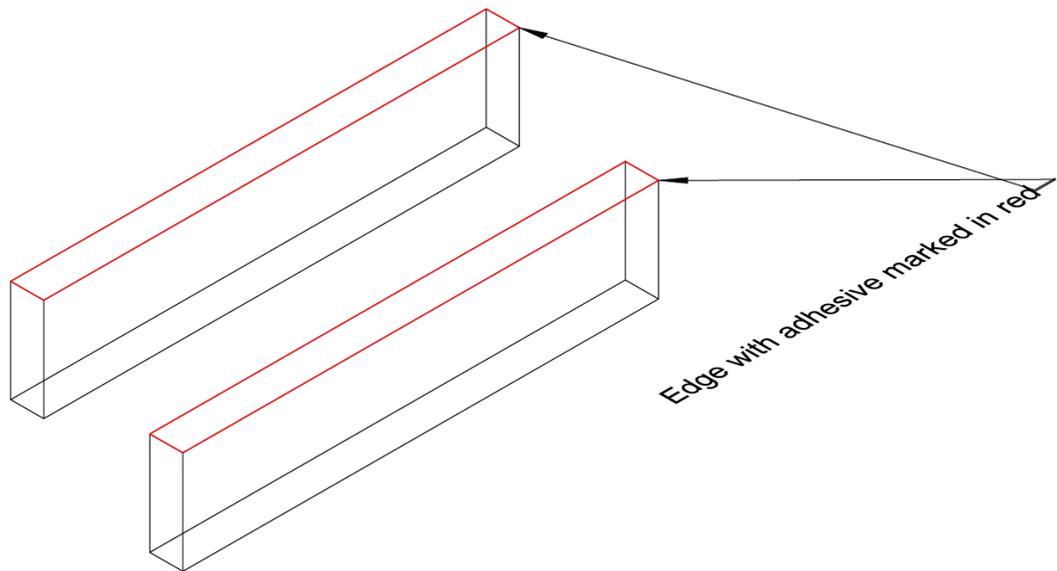


Figure 8 Adhesive line on edge-bonded lamellas

To achieve better bonding quality, the surface, where the adhesive layer will be applied, is recommended to be planed and cleaned from residue.

Stability of the lamellas during the curing period of 125 minutes was achieved by using a previously designed jig. To add sufficient pressure to the glue lines, the lamellas were tightened by using loading straps or bench clamps (Figure 9).



Figure 9 Jig with loading straps to add sufficient pressure

After the curing of the layer, thickener Projecta Robland was used to obtain equal thickness of 6 mm (for 5-layer panels) and 10mm (for 3-layer panels) for the lamellas. To avoid defects and formation of cracks the process was done by 1mm steps.

To achieve more accurate results, the defects (loose knots, wholes) were removed by using corking method. The defected area was removed and replaced with a cork, which was glued to the layer using the same adhesive (Figure 10).

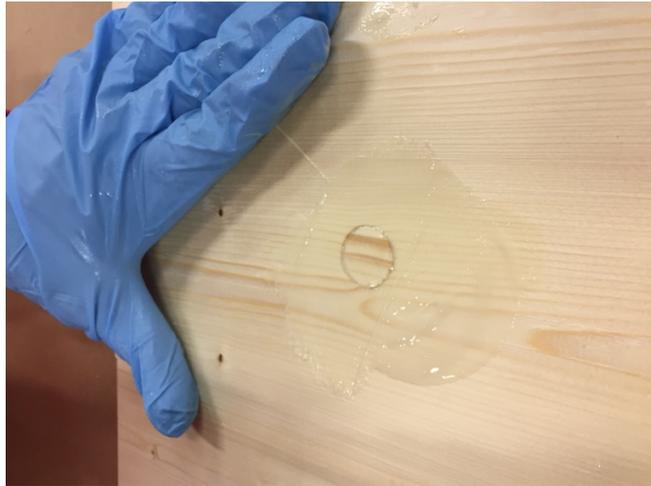


Figure 10 Using corks to remove defects from layers

As the adhesive was added, it expanded during curing time and the defects did not affect the results for air permeability test.

The Loctite® HB S509 Purbond adhesive [11] used for producing of the panels from CLT large-scale production company Peetri Puit OÜ.

Loctite® HB S509 Purbond is a single-component liquid polyurethane adhesive, which cures under the action of air humidity and moisture in wood. It forms a strong non-brittle film. The properties of the adhesive are described below in Table 2.

Table 2 Properties of Loctite® HB S509 Purbond adhesive [11]

Basis	Isocyanate prepolymer
Assembly time	50 min
Curing time	125 min
Brookfield viscosity	Approx. 24 000 mPa.s (Sp.6 / 20 rpm / 20°C, measurement between 16 to 36 hours after production)
Density	1 160 kg/m ³

For the panels that were produced in Tallinna Ehituskool the amount of adhesive was calculated from the suggested rate of 120-160 g/m² (calculations for the amount of adhesive used for one layer can be found below, Equation 1). The adhesive was applied to one side of the layer using paint roller.

$$X = y \times a \quad (1)$$

where

x - amount of adhesive for one layer (g)

y - surface area of specimen (m²)

a – suggested rate of adhesive

For the panels manufactured in Peetri Puit OÜ factory, the application of adhesive to surface bonding was carried out by automated spray-jet system (Figure 11). The amount of adhesive per square meter was adjusted beforehand to match the amount used for panels produced in Tallinna Ehituskool.



Figure 11 Application of adhesive

Masking tape was applied to the junctures of lamellas to reduce the risk of adhesive filling the gaps between lamellas for panels to be prepared for testing without glued edges.

Depending on the pressure device used for manufacturing CLT panels the following differences can be brought out:

- 1) Surface bonding by using hydraulic press (pressure of 0.10 – 1.00 N/mm²), shown on Figure 13
- 2) Surface bonding by using vacuum press (pressure of 0.05 – 0.10 N/mm²), shown on Figure 12.

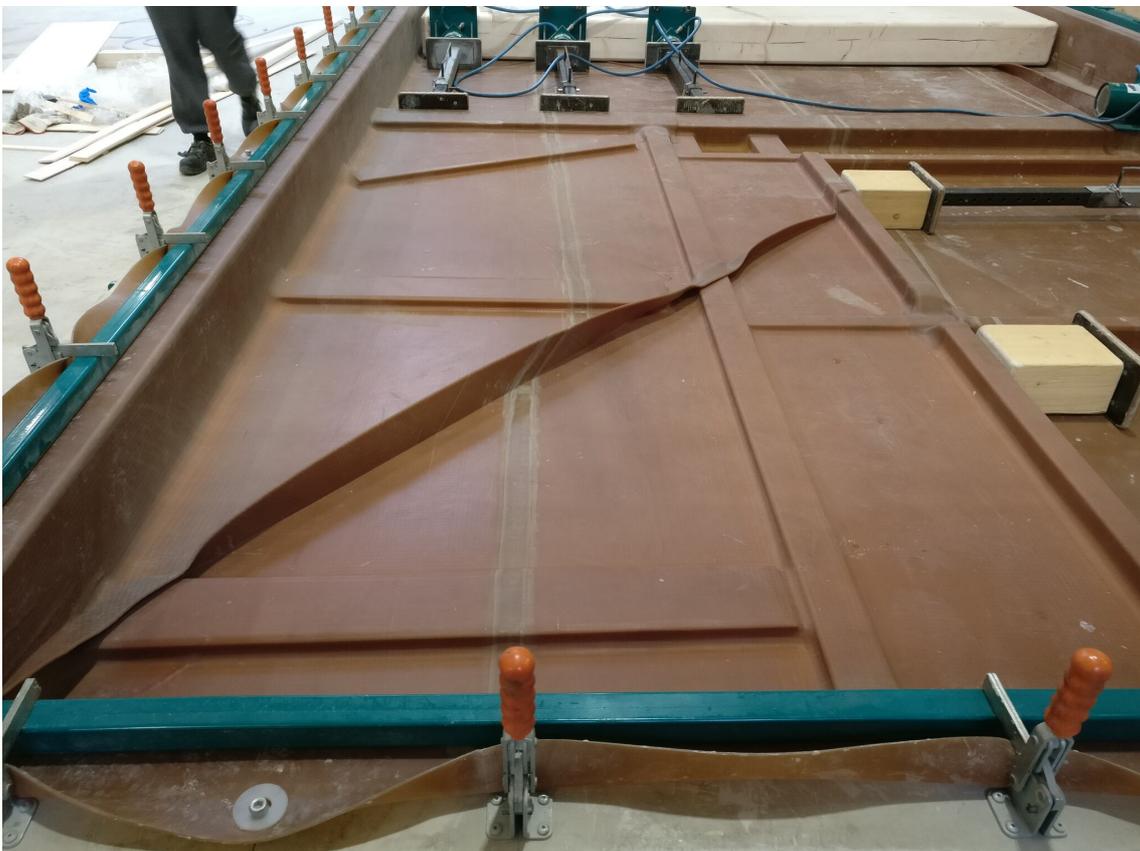


Figure 12 Vacuum pressing in Peetri Puit OÜ

The minimum bonding pressure depends mainly on the type of adhesive and the adhesive application system used. The requirement is to ensure a complete wetting and sufficient bond line thickness on a layer. For polyurethane adhesives the minimum bonding pressure required is 0.01 – 0.10 N/mm² [2].

In addition to minimum requirements, maximum allowable bonding pressure is defined. Too high pressure can damage the adherents' surface by harming the cell structure of adhesive or drive out the adhesive from the bond line. This may therefore reduce the shear and penetration resistance of the panel. To maintain the quality of bond line the upper limit of bonding pressure is estimated with 1.10 N/mm² [2].



Figure 13 Hydraulic press in Tallinna Ehituskool

The pressing of the CLT panels made in Tallinna Ehituskool was performed with 6-cylinder Orma hydraulic press and, for the panels produced in Peetri Puit OÜ, with custom built vacuum press. The assembly time and curing period was determined by the requirements from the adhesive manufacturer, 50 min and 125 min, respectively.

The completed panels were wrapped in film to prevent the changes in MC.

2.2 Conditioning

The conditions of RH 70-30% were simulated in Climacell 707 (Figure 14), which was continuously ventilated with built-in ventilators, so that the conditions would remain as stable as possible. The conditions were chosen to simulate the summer period, where RH is high and winter heating period, where RH drops lower.



Figure 14 Panels with dimensions of 1300x460x40mm inside climate chamber Climacell 707

The conditioning in relative humidity of 15% was performed in custom-made climate chamber in Faculty of Civil Engineering. After every conditioning step the moisture content of wood lamellas in CLT were measured.

2.3 Apparatus for carrying out the test

2.3.1 Air permeability

The apparatus (see Figure 15) for carrying out the air permeability test consisted of following equipment:

- 1) airtight closable test rig made from stainless steel and reinforced with veneer to avoid changes in the volume of test box (see APPENDICES 1-3)
- 2) air hoses connecting different parts of apparatus
- 3) manometer for measuring the air pressure difference, Huba Control 699 (pressure range 0-1600 Pa; tolerance of 0.7 %)
- 4) air flow meter SMC PFM710-S-F01-B-M

- 5) air pressure difference regulator
- 6) air compressor.

The air compressor was connected to the apparatus, providing sufficient air flow. The air flow meter was connected to the test box showed the amount of air going in. If the panel was airtight then the amount going in was 0 l/min and the pressure inside the test box increased. The exiting air hose was connected to the manometer to see the pressure inside.

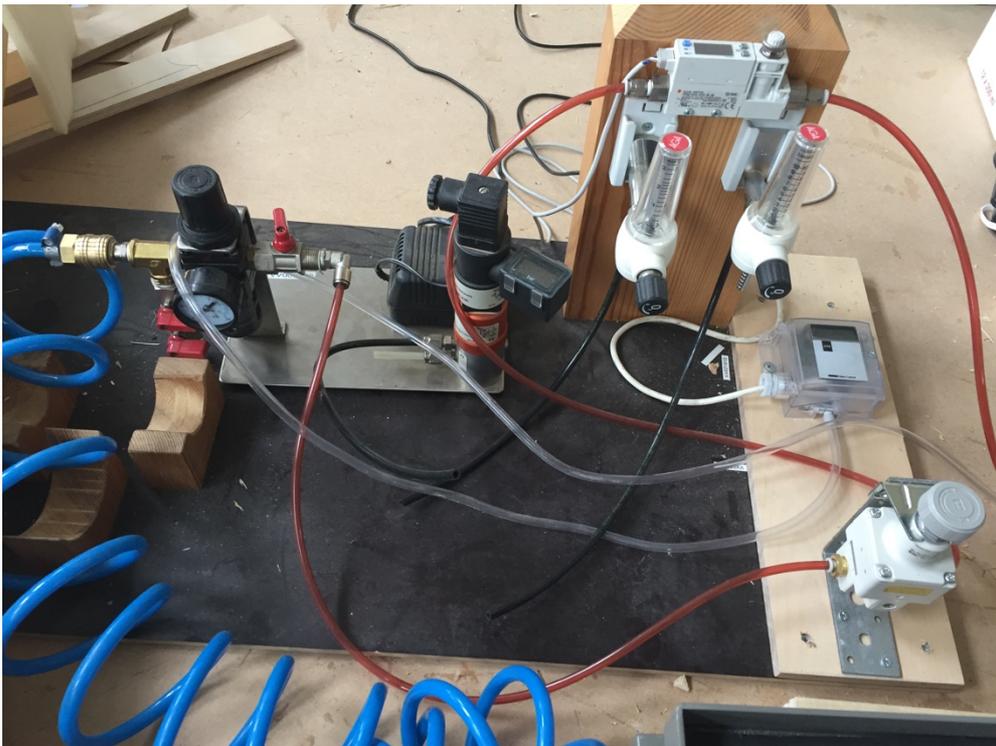


Figure 15 Air permeability test apparatus

The air permeability test rig was designed to fit the panels with length and width of 1300x460mm made for the test. To ensure air tightness of the rig, the edges of it were covered with airtight, one-piece, closed cell neoprene sealant. The air permeability of the system was tested with 12mm thick and 2 sides laminated plywood sample (Figure 16).

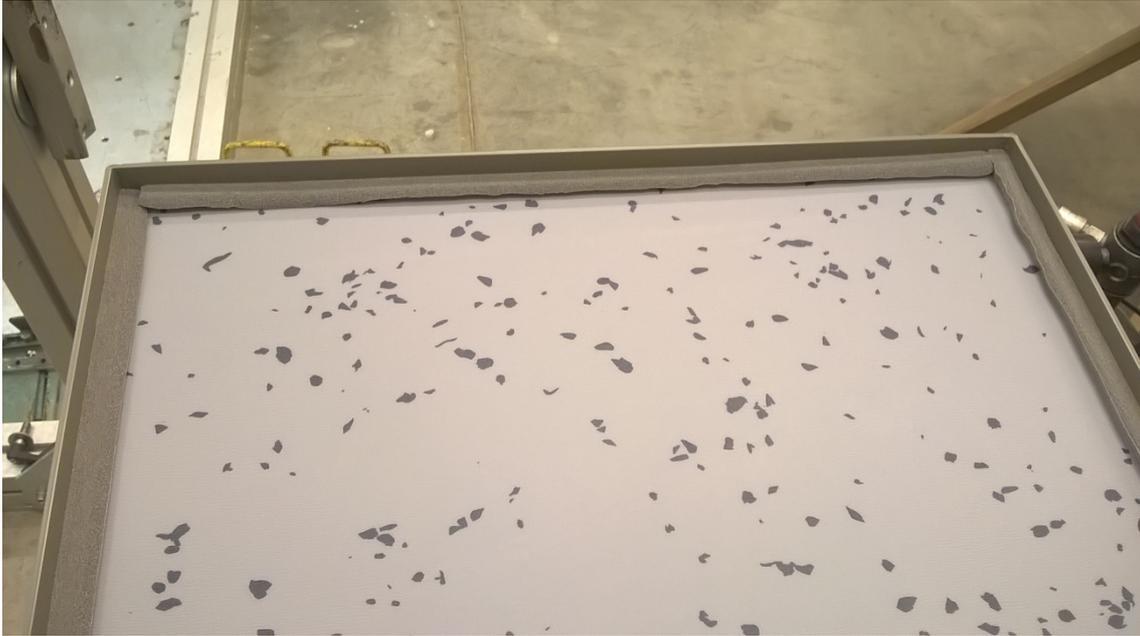


Figure 16 Laminated veneer with sealed edges used for testing the airtightness of system

The edges of the test piece were sealed with self-expanding tape to ensure the absence of leakages. The system was completely airtight at pressure difference of 1100 Pa.

2.3.2 Crack formation

As reported in the guidelines for crack evaluation worked out by Brischke, Humar, Meyer *et al.* [12] the following measurements were recorded from panels with dimensions 1300x460x30mm:

- 1) total length of crack (crack length of more than 5 mm)
- 2) number of cracks (with length of more than 5 mm)
- 3) mean value of maximum crack width (3-5 measurements per crack, depending on the length of the crack)

The cracks (between and on laminations) were measured and marked with pencil, to identify the changes with the next conditioning cycle (Figure 17).



Figure 17 Marked crack between laminations

The width of a cracks was determined in accordance with the guidelines provided by Brischke, Humar, Meyer *et al.* [12] The specific ruler for it was named Crack Width Gauge by Avongard® (Figure 18). The ruler had lines with certain thickness to match the crack width.

The length of a crack was measured using the same gauge, or, for cracks with longer lengths, with a regular ruler.



Figure 18 Crack Width Gauge for measuring cracks in CLT panels [13]

2.4 Test procedure

The air permeability tests were carried out by using the methods developed by author. The methodology adapted for this thesis for evaluating the formation of cracks in CLT panels was developed by Brischke, Humar, Meyer et al. [12].

2.4.1 Process

The air permeability test and evaluation of cracks was carried out in 5 steps:

1. Preparation of specimens: calibrating and cutting of lamellas; conditioning. Gluing and pressing of lamellas (cold press).
2. Measuring of initial cracks and air permeability.
3. Conditioning of panels in different stages
 - a. Panels initially conditioned in RH 70%:
 - i. RH 50% ↓
 - ii. RH 30% ↓
 - iii. RH 15% ↓
 - b. Panels initially conditioned in RH 30%:
 - i. RH 10% ↓
4. Measuring of air permeability and cracks in every step
5. Analysis of results (described in Chapter 3)

The air permeability measuring was carried out with only positive pressure following the guidelines from EN 12114 standard.

2.4.2 Measuring intervals

Moisture movement in wood is dependent on the surrounding environment (temperature, air humidity) [9]. If wood is placed in a stable environment, in time, it reaches its equilibrium moisture content (EMC). This means, that there is no vapour pressure difference between the wood and the air surrounding it, so the moisture content stays constant (as long as the environment conditions do not change). The equilibrium moisture content corresponding to relative humidity in certain temperatures is described in Figure 19.

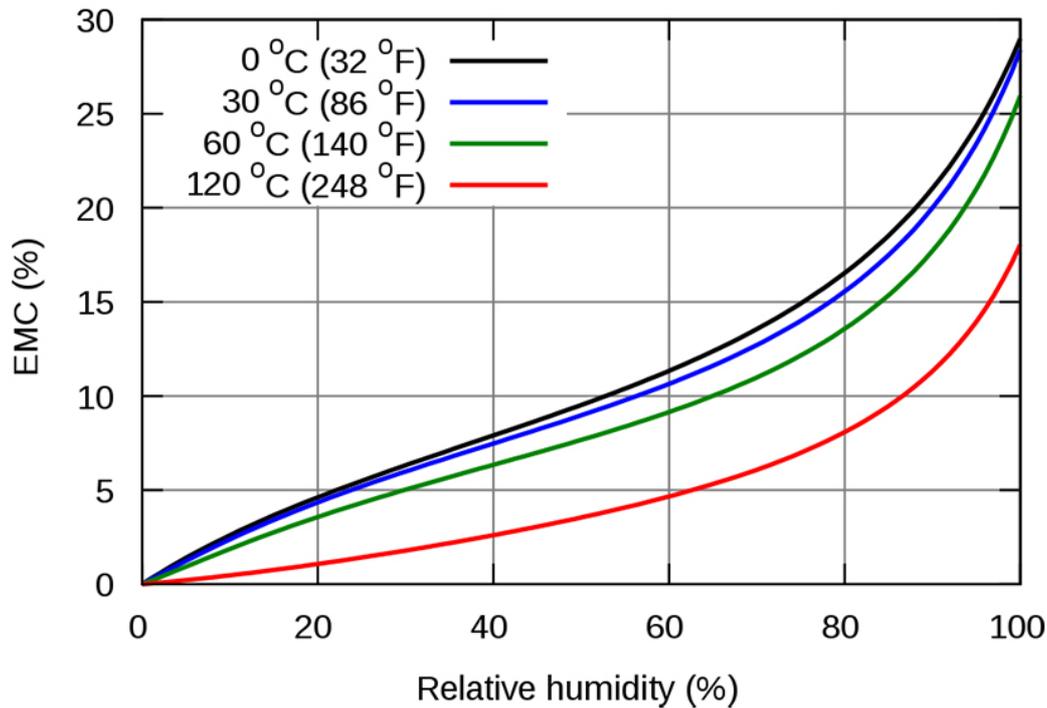


Figure 19 EMC corresponding to RH on certain temperature in wood [14]

The climate chamber cycle for the panels to reach certain MC in given RH was found by making a simulation using WUFI® software [15]. The software is used for determining the hygrothermal performance of building components under different environmental conditions [15]. It performs one-dimensional hygrothermal calculations on building component cross-section, whereas taking into account a number of variables (e.g. built-in moisture) [15].

The results from the simulation indicated that the cycle for a panel to reach EMC is four weeks.

2.4.3 Recording the results

The moisture content of panels was recorded in a table at the beginning of the test and, subsequently, after every conditioning interval. For the air permeability test, the air leakages (l/min) in accordance with the pressure differences on different panels (both sides of the panel) were stated in after every conditioning interval.

For the evaluation of cracks, the total number, length and width (in mm) of cracks on one side on the panel were recorded. All the results named in this subchapter were recorded by using Microsoft Excel software.

2.5 Test methodology for determining the formation of cracks in CLT panels

2.5.1 Test specimens

To determine the formation of cracks in CLT panels 24 test specimens with dimensions of 1300x460x30mm were used to.

The test panels used were the same that were adopted for the air permeability test to see the effect of crack formation to CLT panel air permeability properties. The specimens are described in Table 3.

Table 3 Specimens used for experiment

Initial conditioning environment	70%		30%			
	Specimen number	Bonded edges	Number of layers	Specimen number	Bonded edges	Number of layers
	A1	No	5	C1	No	3
	A2	No	5	C2	No	3
	A3	No	5	C3	No	3
	A4	No	3	C4	No	5
	A5	No	3	C5	No	5
	A6	No	3	C6	No	5
	B1	Yes	3	D1	Yes	3
	B2	Yes	3	D2	Yes	3
	B3	Yes	3	D3	Yes	3
	B4	Yes	5	D4	Yes	5
	B5	Yes	5	D5	Yes	5
	B6	Yes	5	D6	Yes	5

The panels were divided into two groups:

- 1) Twelve panels with initial conditioning environment 70% RH (MC 13,1%); conditioning in temperature of 20 °C and 50% RH, 30% RH and 10% RH (possible relative humidity which may occur during heating period in internal environment)
- 2) Twelve panels with initial conditioning environment 30% RH (MC 6,2%); conditioning in temperature of 20 °C and 10% RH (possible minimum relative humidity, which may occur during heating period in internal environment).

The panels were conditioned in climate chamber Climacell 707 (Figure 20), which was continuously ventilated with built-in ventilators, so that the temperature and relative humidity would remain as stable as possible.



Figure 20 Climate chamber Climacell 707 [16]

The formation of cracks was evaluated on both sides of test specimens, from the surface of external layer.

In each step of conditioning, the MC of the CLT panels was measured to evaluate the correlation between moisture content and the formation of cracks.

3 Results and Discussion

In this chapter the results of carried out scientific experiments are described and analysed. Based on these results the conclusions are made. Results of each experiment are given in separate subchapters.

3.1 Results of air permeability test

3.1.1 Air Permeability results for panels produced with boards conditioned at RH 70%

The air permeability of both faces of the panels with dimensions of 1300x460x30mm was tested. The air leakages (l/min) at certain pressure difference were measured. Air leakages were measured at maximum pressure difference of 550 Pa. If it was not possible to reach, the air leakages at the maximum reachable pressure difference were marked. It must be noted that for the first air permeability test for six panels results from only one side were gathered. Later the test method was improved and results were collected for both sides of the panels, with the exception of two specimens (B5 and B6) where the results were collected throughout the test from only one side.

In addition, as the permeability test was performed in two different buildings, the incoming air pressure to measuring device was different. This means that the maximum possible air leakages were different, depending on the testing place. For comparable results, the values for maximum air leakages were altered in a way that the extremal values were to be the same (if it was clear, that actual air leakage was higher than the result, the value was increased to match the maximum flow).

The air permeability of test panels was tested right after production and subsequently at after every conditioning phase. Initially the air leakages were minimal for both the panels with glued edges and without glued edges. The results for air permeability are described in Table 4.

Table 4 Air permeability test results

Air permeability test results								
RH	70%		50%		30%		10%	
	Without bonded edges							
Specimen nr.	Press. diff. (Pa)	Air leaks (l/min)	Press. diff. (Pa)	Air leaks (l/min)	Press. diff. (Pa)	Air leaks (l/min)	Press. diff. (Pa)	Press. diff. (Pa)
A1	550	0,00	447	1.90	337	2.39	304	4.08
A2	550	0.86	373	1.74	310	2.07	283	3.84
A3	550	1.73	355	2.04	305	2.28	283	4.36
A4	550	0.22	53	3.32	25	5.00	6	5.00
A5	550	0.00	144	3.36	33	5.00	8	5.00
A6	550	0.00	100	3.53	16	5.00	3	5.00
	With bonded edges							
B1	550	0,10	-	-	550	1.71	333	3.17
B2	325	0.94	391	3.00	304	4.35	10	5.00
B3	550	1.16	550	2.20	550	3.05	93	5.00
B4	340	2.12	475	3.09	439	3.52	125	5.00
B5	550	0.20	550	0.20	550	0.26	550	3.36
B6	550	0.00	550	0,00	550	0.00	550	0.50

The results showed that the air leakages increase with every conditioning cycle, whereas the pressure difference decreases.

It can be seen from the results presented in the Table 4 that after the production the air permeability properties were better for panels manufactured without bonded edges. The average air leakages for panels A1-A6 was 0.47 l/min at 550 Pa. whereas for panels B1-B6 it was 0.75 l/min at 478 Pa. The possible reason for the difference in test results can be found in uniform and higher production quality for panels made in Arcwood OÜ.

As the air permeability of test panels was measured at the end of every conditioning step, the results showed that air leaks increased while the pressure difference decreased (550 Pa was not reachable for most of the panels anymore). Only panel B6 remained completely airtight after conditioning at RH 50%. The mean value of air leaks increased to 2.65 l/min for panel without bonded edges and to 1.70 l/min for panels that were produced from single layers (bonded edges). Figure 21 illustrates the mean values of air leakages through the panel after conditioning cycles.

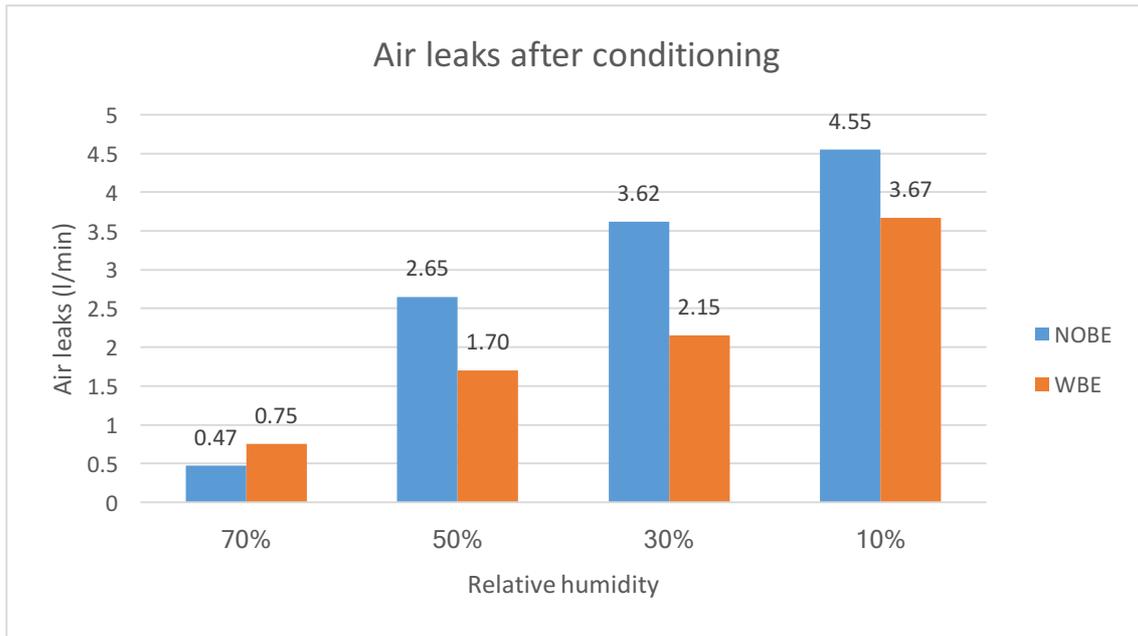


Figure 21 Average air leaking of specimens

The test results show that at the end of this experiment the average air leaks for panels without bonded edges were 24% higher than for the panels without bonded edges. The only specimen which remain almost airtight after conditioning at RH 10% was specimen B6 (with bonded edges). It must be noted that pressure difference decreased as the air leakages increased. For four panels (A4, A5, A6 and B2) the pressure difference achieved was maximum 10 Pa. All of these panels had maximum air leakages at the end of experiment. The analyse reveals that even though the panels with bonded edges had more air leakages after production, the increase of leakages with the drying of specimens was bigger for panels without bonded edges.

3.1.2 Air Permeability results for panels produced with boards conditioned at RH 30%

The experiment methods for panels with boards initially dried at RH 30% were the same as for those conditioned at 70%. In Table 5 an overview of the test results is given.

Table 5 Mean values of air permeability test results

Air permeability test results				
RH	30%		10%	
	Without bonded edges			
Specimen number	Pressure difference (Pa)	Air leaks (l/min)	Pressure difference (Pa)	Air leaks (l/min)
C1	50	5.00	39	5.00
C2	131	3.77	182	5.00
C3	105	5.00	67	5.00
C4	545	2.50	297	2.50
C5	550	2.86	297	3.76
C6	416	2.04	307	2.77
	With bonded edges			
D1	376	3.64	289	5.00
D2	550	1.75	550	1.90
D3	550	0.45	550	0.56
D4	550	0.34	550	0.59
D5	378	2.50	550	2.19
D6	550	0.59	550	0.46

The test results indicate that at the beginning of the experiment both types of specimens had noticeable air leaks. At the beginning of the experiment, the mean value of air leaks for panels without bonded edges was 3.53 l/min at 300 Pa and the same value for single

layer panels was 1.54 l/min at 492 Pa. The average pressure difference of 300 Pa at the start of the experiment confirms that the leaks were substantial. It must be noted that specimen D5 had a knot on the edge of the panel, which altered the results. It is the reason for the panel to have less leaks after the conditioning at RH 10%.

Following the conditioning phase, the air permeability for both types of specimens decreased. Four panels (C1, C2, C3 and D1) reached the maximum value of air leakages (5 l/min) measurable with this kind of apparatus. Three of the specimens with bonded edges (D3, D4 and D6) had minimal air leakages and it can be said that they were almost airtight at the end of this experiment. On average, panels without bonded edges had air leakages of 4.01 l/min. For comparison, the specimens that were produced with bonded edges had the initial value of 1.78 l/min. Consequently, it can be stated that panels with bonded edges have less air leakages.

To conclude, it can be said that bonding the edges of boards to form single layers can reduce the air leakages in CLT. This is confirmed by the results of air permeability test for this thesis. Table 6 shows the results more comprehensively.

Table 6 Air permeability test results (l/min)

3 layer panels					Increase of air leakage (%) for RH 70%	Increase of air leakage (%) for RH 30%
Parameters	Bonded edges		Without bonded edges			
Steps of conditioning RH (%)	RH 70%	RH 30%	RH 70%	RH 30%		
50	2.60	N/A	3.40	N/A	31	N/A
30	3.70	N/A	5.00	N/A	35	N/A
10	5.00	1.94	5.00	4.59	-*	137
5 layer panels					Increase of air leakage (%)	Increase of air leakage (%)
Parameters	Bonded edges		Without bonded edges			
Steps of conditioning RH (%)	RH 70%	RH 30%	RH 70%	RH 30%		
50	1.10	N/A	1.89	N/A	72	N/A
30	1.26	N/A	2.25	N/A	79	N/A
10	2.95	1.14	4.09	2.47	37	117

*maximum measurable value was reached, no difference can be shown

It can be seen from the test results in Table 6 that air leaks have significantly increased if to compare different panel settings with and without bonded edges. The worst case for the air leakages reached maximum measured value for panels with bonded edges (RH 70%) is for 3-layer panels at RH 10%. For the rest of the specimens' (RH 70%) air leakages increased by at least 30%. For specimens produced at RH 10% the worst difference between panels with and without bonded edges was for 3-layer panel. The difference reached 137%. For 5-layer panels the increase was 117%. Due to that it can be said that part of the hypothesis: "CLT panels produced with bonded edges will have fewer cracks and therefore less air leakages after conditioning than panels produced without glued edges." was confirmed. As stated in previous research by Bradner [2], this is most likely due to the cracks on CLT panels with bonded edges appearing in the middle of laminations. During the experiment it was observed by the author that a majority of cracks on panels with bonded edges did appear in the middle of the lamellae's surface.

It must be noted that during the experiment it was observed that most of the air leakages are caused by cracks on the edges of the panel. For future experiments the author recommends to improve the test methods by sealing the edges of panels with, for example, airtight sealant.

3.2 Results for determining cracks formation in CLT

3.2.1 Results of MC in specimens

Figure 22 illustrates the average MC in specimens after each the conditioning phase. The results show that after each conditioning phase the specimens nearly reached the equilibrium moisture content (EMC).

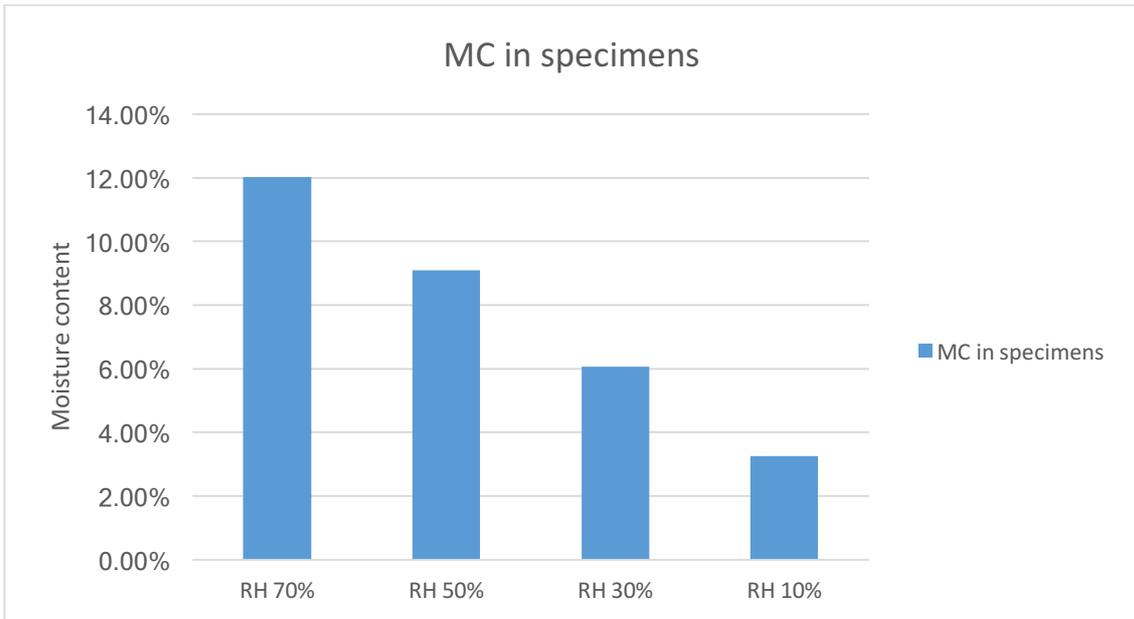


Figure 22 MC in specimens after conditioning

The mean value of moisture content of different kind (with bonded edges and without bonded edges) of specimens and equilibrium moisture content of solid spruce wood in given conditions are described in Table 7. The average moisture content of all conditioned specimens was 12.02% (RH 70%), 9.10% (RH 50%), 6.06% (RH 30%) and 3.26% (RH 10%).

Table 7 EMC and average MC of specimens in given conditions

Conditioning temperature 20 °C			
Relative humidity	Equilibrium moisture content	Average moisture content in panels with bonded edges	Average moisture content in panels without bonded edges
70%	13.10%	10.43%	13.60%
50%	9.30%	8.87%	9.33%
30%	6.20%	6.00%	6.11%
10%	2.50%	3.40%	3.17%

From the comparison of the test results of panels with bonded edges and panels without bonded edges it can be seen that the only significant difference is for specimens after the production (boards conditioned in RH 70%). The initial moisture content for panels with bonded edges was 10.43% whereas for the panels without bonded edges it was 13.60%. The difference in moisture contents was 3.17%. This may have been caused by the longer length of production process of panels with bonded edges and, therefore exposure to lower relative humidity. For the following conditioning phases the results for panels with bonded edges and without bonded edges were similar.

Considering the results of moisture content after each conditioning phase it can be concluded that the only significant difference in moisture contents of panels with bonded edges and without bonded edges was in the first step of conditioning the lamellas in RH 70%. All in all, it can be said that after each phase the moisture content of panels was close to the theoretical equilibrium moisture content.

3.2.2 Results of crack formation for panels produced with boards conditioned at RH 70%

Before the specimens were placed into the climate chamber, the initial existing cracks on top surfaces on both sides of panels were counted and measured. For this thesis, the gaps between laminations are defined as cracks and resin ducts are not included.

The number of cracks on specimens for each phase is described in Table 8. Specimen A4 initially had two cracks and specimen A5 had three cracks. The rest of the specimens without bonded edges initially did not initially have any cracks on external surfaces. The reason for that is most likely the high production quality in Arcwood OÜ manufacturing. After being placed to climate chamber for conditioning cycles, the number of cracks for the specimens was measured after every conditioning cycle. By the end of the experiment, the number of cracks increased for all the specimens. The maximum number of cracks occurred on specimen A4, which had 24 cracks on external surfaces at the end of conditioning in RH 10%. Minimum number of cracks formed on panel A1, which had 11 cracks at the end of experiment. The biggest increase was for panels A4 and A6, both having 22 more cracks than in the beginning of experiment. Panel A4 after experiment is shown on Figure 23.



Figure 23 Surface of specimen without bonded edges after conditioning

During the test cracks were found on every specimen. The average number of cracks after conditioning in RH 50% was 9.7 cracks per specimen. The conditioning of panels in RH 30% and RH 10% increased the average number of cracks to 12.2 and 18.2 respectively. Figure 24 illustrates the rise of number of average cracks for specimens, whereas panels without bonded edges are marked as NOBE and specimens with bonded edges are marked as WBE.

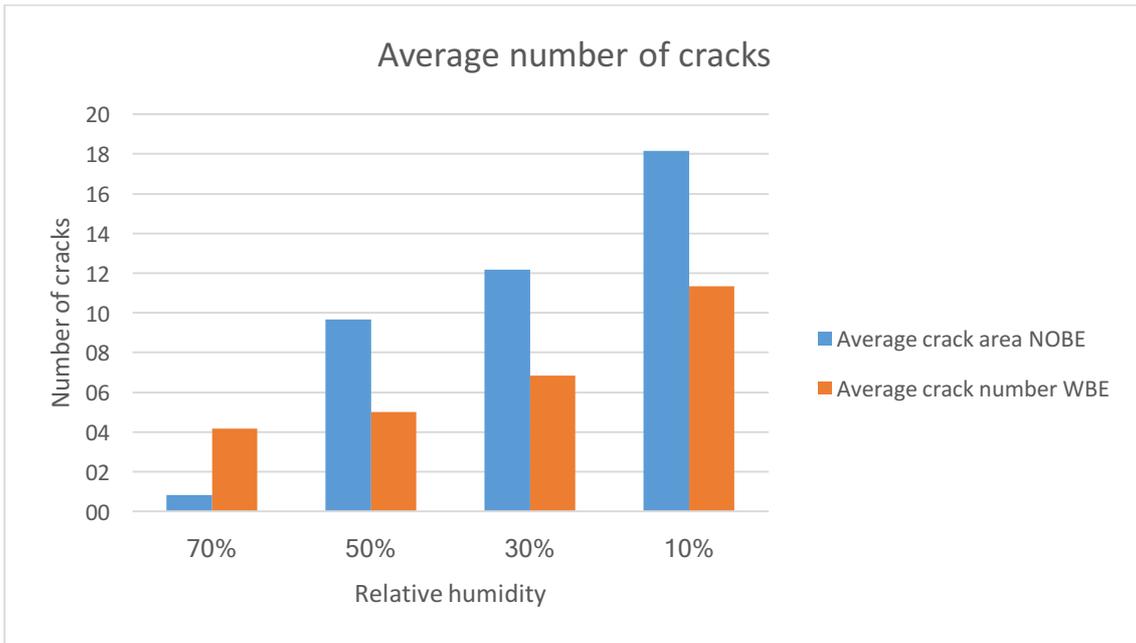


Figure 24 Average number of cracks

Panels with bonded edges had more cracks before the test than the panels without bonded edges. The only specimen without initial cracks was B1. The rest of the specimens had at least two cracks at the beginning of the experiment. After the final conditioning step in RH 10% the number of cracks increased for all the panels. The maximum number of cracks appeared on panel B2, which had 17 cracks on both surfaces. That is almost 30% less than for the panels with bonded edges (specimen A4 with 24 cracks). Minimum number of cracks formed on panel B1 (see Figure 25), having only three cracks at the end of scientific experiment. The biggest increase was for panels B2 and B3, with both having 11 more cracks than at the beginning of conditioning. In comparison, panels A4 and A6 (without glued edges) had an increase of 22 cracks.

For the panels with bonded edges the initial number of cracks was higher than for the panels without glued edges, averaging at 4.2 cracks per specimen. The only panel that did not have any cracks was B1, whereas the others had at least two cracks. The average number of cracks increased with conditioning in RH 50% to 5.0 cracks per specimen. The same mean value for conditioning in RH 30% and RH 10% was 6.8 and 11.3 respectively.



Figure 25 Surface of specimen with bonded edges after conditioning

For conclusion, it can be said that the values indicate that more cracks form on the exterior surface of panels without bonded edges. On average for this scientific experiment, the increase of formation of cracks was 1.61 times lower for panels with bonded edges. In addition, the panel with most cracks after conditioning was without bonded edge, whereas the panel with the least number of cracks was with bonded edges. This is mostly due to the cracks appearing between laminations, as the boards shrink with drying, causing the large crack growth.

Table 8 Total number of cracks

Number of cracks on both sides of test specimens at each conditioning phase				
RH	70%	50%	30%	10%
Specimen number	Specimens without bonded edges			
A1	0	7	11	11
A2	0	10	12	18
A3	0	7	8	16
A4	2	11	11	24
A5	3	12	13	18
A6	0	11	18	22
Specimen number	Specimens with bonded edges			
B1	0	0	1	3
B2	6	7	13	17
B3	5	6	7	16
B4	9	12	12	16
B5	3	3	5	9
B6	2	2	3	7

As seen from the test results in Table 9, the initial crack area for the panels was relatively small. For panels with bonded edges the mean value of crack area for one panel (area of cracks on both surfaces) was 157.6mm² whereas for the panels without bonded edges it was 41.66mm². The value of crack area for panels with bonded edges is most likely higher due to the different production technologies, as the end quality was better for panels produced in Arcwood OÜ. With conditioning, the crack area increased significantly. For panels without bonded edges the minimum area covered with cracks was for specimen A3, reaching 4831.3mm². the maximum area covered with cracks was for specimen A5. For that panel the cracks extended on 16163.1mm² on the panel. The highest increase for

the area of cracks was also for panel A5 (16097,3mm²), whereas the minimum increase was for panel A3 (4831,3mm²).

Table 9 Area of specimens covered with cracks

Crack area for specimens at each conditioning phase (mm²)				
RH	70%	50%	30%	10%
Specimen number	Specimens without bonded edges			
A1	0	1664.2	2850.1	5701.5
A2	0	2109.9	3149.0	5433.4
A3	0	281.0	3250.5	4831.3
A4	142.5	5393.4	8335.5	15436.2
A5	65.8	4769.0	9563.2	16163.1
A6	0	6224.7	929,3	14649.6
Specimen number	Specimens with bonded edges			
B1	0	0	819.0	1423,8
B2	273.8	348.2	1016.6	2828,0
B3	284.8	390.0	746.1	4668,4
B4	298.9	1662.3	2740.1	4563,4
B5	59.1	64.5	418.0	2156,9
B6	29.0	54.6	59.8	1153,1

For panels with bonded edges the increase of surface covered with cracks was lower. The lowest area was for specimen B1 (1423.8mm²) and the maximum was for panel B3 (4668.4mm²). The difference for maximum surface covered with cracks between panels with bonded edges and panels without bonded edges was 11494.7mm². Figure 26 illustrates the rise of average crack area for specimens with conditioning.

For this scientific experiment, on average, for specimens without bonded edges the cracks occurred on 0.16mm² per 1.00mm² of panel surface after final conditioning phase. The same value for panels with bonded edges was 0.01mm² per 1.00mm² of surface.

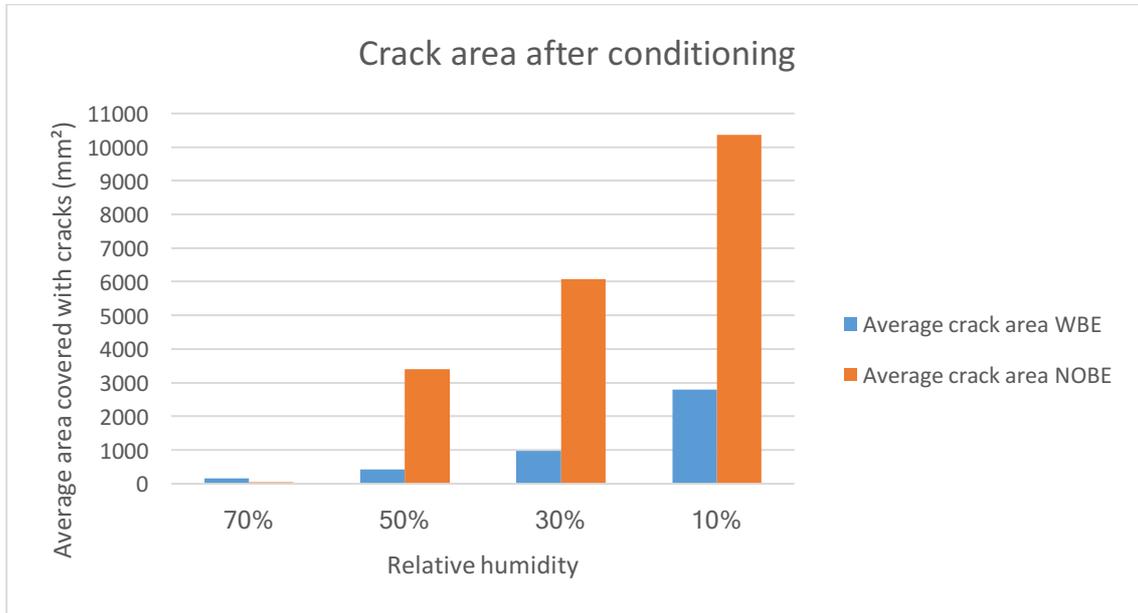


Figure 26 Average crack area for specimens

For conclusion, during this scientific experiment specimen without bonded edges showed a significantly higher increase in both the number of cracks forming and the area covered with cracks after the conditioning of test panels. Due to that it can be said that the hypothesis: “CLT panels produced with bonded edges will have fewer cracks and therefore less air leakages after conditioning than panels produced without glued edges” was confirmed.

3.2.3 Results of crack formation for panels produced with boards conditioned at RH 30%

The crack formation on specimens with and without bonded edges was also determined on panels produced with boards initially conditioned at RH 30%. Table 10 is used to describe the number of cracks on both sides of the specimens at the beginning of the experiment and, for comparison, at the end of the experiment.

Table 10 Number of cracks on the specimens

Number of cracks on specimens at each conditioning phase		
RH	30%	10%
Specimen number	Without bonded edges	
C1	11	11
C2	8	8
C3	10	15
C4	5	8
C5	5	14
C6	8	8
	With bonded edges	
D1	4	6
D2	5	6
D3	0	0
D4	4	5
D5	0	1
D6	0	1

The results show that the panel with lowest number of cracks was D3 (single layer panel), which did not have any cracks at the beginning nor the end of the experiment. The specimen with the highest number of cracks was C3, which had 15 cracks at the end of conditioning. The panels without bonded edges had, on average, 7.8 cracks after production. The number increased to 10.7 with the conditioning. Specimens with bonded edges had a mean value of number of cracks 1.7 at RH 30% and the conditioning added, on average, one crack for every specimen, meaning that after the cycle the panels with bonded edges had, on average, 2.7 cracks per specimen.

In addition to the number of cracks, the area of cracks also increased for both set on specimens. For the panels without bonded edges the average crack area increased from

1783.2 mm² to 3347.3 mm² and for the panels with bonded edges the increase was from 699.7 mm² to 863.4 mm². This shows that for this thesis the mean increase of surface covered with cracks was 9.55 times higher for the panels without bonded edges. Due to that it can be concluded that the hypothesis: “CLT panels produced with bonded edges will have fewer cracks and therefore less air leakages after conditioning than panels produced without glued edges” was again confirmed.

Conclusion

In current research the impact of moisture content change to the crack formation and air permeability properties for CLT with and without bonded edges was examined. The scientific experiment was carried out in a form of climate chamber test by using test methods developed by author. During this experiment the initiation and development of cracks was evaluated and air permeability values were measured in each conditioning step.

The air permeability of panels was tested after production and subsequently at after every conditioning phase. Initially the growth of air leakages was relatively slow for both types of panels. With the increasing number of conditioning cycles the value of air leaks increased as well. The results showed that air leakages increased most in panels without bonded edges. On average, the panels without bonded edges had close to 65% more air leaks than the panels without bonded edges.

The test results showed that at the end of this experiment the average air leakage at maximum pressure difference of 550Pa for panels produced from boards conditioned at RH 70% without bonded edges was 4.55 l/min and for the panels with bonded edges it was 0.88 l/min lower. On average, the air leakage was 24% higher for panels without bonded edges. This is most likely due to the cracks on CLT panels with bonded edges appearing in the middle of laminations, which decreases the possible number of overlapping gaps. During the experiment it was noted by the author that the number of cracks between the lamellae's was lower for panels with bonded edges. The only specimen which remain almost airtight after conditioning at RH 10% was specimen B6 (with bonded edges). For future experiments, it must be noted that the main sources for air leakages are the edges of the panel. Author would like to recommend to seal the edges with airtight tape.

For more comprehensive conclusion, the effect of edge bonding to the air permeability properties of the CLT panels was compared. Different types of CLT panels (number of layers, initial panel moisture content) were tested. The test results showed that despite of the construction of the panel, specimens with bonded edges had better air permeability properties. Biggest increase in air leaks was for panels with lower initial moisture content, with the difference for panels with and without bonded edges being 136.6%. The analyse

indicates that for this experiment, the edge bonding of the panels can reduce air leakages significantly for both 3-layer and 5-layer panels.

From the experimental test results it was found that the CLT panels without bonded edges will develop less cracks during the drying process caused by decreasing the relative humidity. The specimens without bonded edges developed a bigger number of cracks during the conditioning. At the end of the experiment, the difference was more than 1,5 times.

In addition to number of cracks, the area of cracks was also measured. The test results indicated that panels without bonded edges had a significant increase of crack area with drying, whereas the increase for panels with bonded edges was not that big. On average, for specimens without bonded edges the cracks occurred on 0.16mm² per 1.00mm² of panel surface after final conditioning phase. The same value for panels with bonded edges was 0.01mm² per 1.00mm² of surface. Due to that it can be said that CLT panels produced with bonded edges will have a less cracks and a lower crack area, the difference between the areas of cracks for panels with and without bonded edges was significant.

Considering the results from this scientific experiment, it can be said that panels with bonded edges will have better performance in terms of crack development and air permeability. Due to that it can be said that the hypothesis: “CLT panels produced with bonded edges will have fewer cracks and therefore less air leakages after conditioning than panels produced without glued edges” was confirmed.

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Abstract

Cross laminated timber (CLT) is an engineered wood panel originally developed in Europe in the mid 1990s. CLT is usually produced from three to seven perpendicular layers. The panels are mostly used for prefabricated wall and floor structures. The thesis is focused on the determination of crack formation due to changes in moisture content and its effect on air permeability. Due to that the objective to observe and compare the crack formation and its effect on air permeability properties on CLT panels with and without bonded edges was set.

The scientific experiment was carried out in a form of climate chamber test by using test methods developed by author. The aim of this was to evaluate the crack formation by comparing the number of cracks and crack area in different types of specimens (with and without edge bonding). In addition, the air permeability of CLT was measured during the experiment. The test results showed that the panels which were produced with bonded edges had less cracks than the panels produced without bonded edges. In addition to the overall number of cracks, the crack area at the end of the experiment was significantly larger for panels without bonded edges.

Alongside with the evaluation of crack formation, the air permeability was also measured for the test panels. It was found that similarly to crack formation, the air permeability properties were also better for panels produced with bonded edges, as the panels without bonded edges had better air permeability values at the defined maximum pressure difference. The results showed that with the conditioning of the specimens in the climate chamber, the air leakages increased more rapidly for panels without bonded edges. The results apply to specimens produced from boards conditioned at RH 70% and RH 30%.

Kokkuvõte

Ristkihtliimpuit (CLT – lühend tuleneb ingliskeelsest väljendist *Cross Laminated Timber*) on tehnoloogiline puitpaneel, mille arendamine sai alguse 1990date alguses Euroopas. Ristkihtliimpuitu toodetakse tavaliselt kolmest kuni seitsmest üksteisega risti asuvast kihist. Paneele kasutatakse enamjaolt eelvalmistatud põranda- ning seinakonstruktsioonidena. Antud magistritöös uuritakse niiskuse mõjul tekkivate pragude mõju paneeli õhupidavusele.

Sellest tulenevalt oli töö eesmärgiks vaadelda ning võrrelda pragude teket ning hinnata nende mõju sileservseotisega ning ilma selleta valmistatud ristkihtliimpuidu paneeli õhupidavusomadustele.

Katse teostamiseks töötati autori poolt välja meetodika ning viidi läbi kliimakatsed, mille käigus hinnati pragude teket erinevatel katsekehadel. Selleks võrreldi tekkinud pragude arvu ning arutati nende pindala sileservseotisega ning ilma selleta valmistatud paneelidel.

Samaaegselt pragude tekke uurimisega uuriti ka paneelide õhupidavusomadusi. Katsetulemustest võis järeldada, et sarnaselt pragude tekke ja edasiarengu mõõtmise tulemustele võib öelda, et õhupidavusomadused olid paremad nendel paneelidel mis valmistati sileservseotisega. Tulemused näitasid, et õhulekked suurenesid kiiremini paneelidel, mille tootmisel ei olnud laudad omavahel sileservseotisega ühendatud. Paneelide õhupidavus suurenes katsekehade kuivamisel märkimisväärselt konditsioneerimiskeskonna õhuniiskuse vähenemisel kuni 30%-ni. Katsetulemused olid samad nii paneelidele mis olid valmistatud algselt 70% õhuniiskuse juures konditsioneeritud laudadest kui ka 30% õhuniiskuse juures konditsioneeritud laudadest. Kokkuvõttena võib öelda, et töö eesmärk sai täidetud.

Appendices

Appendix 1

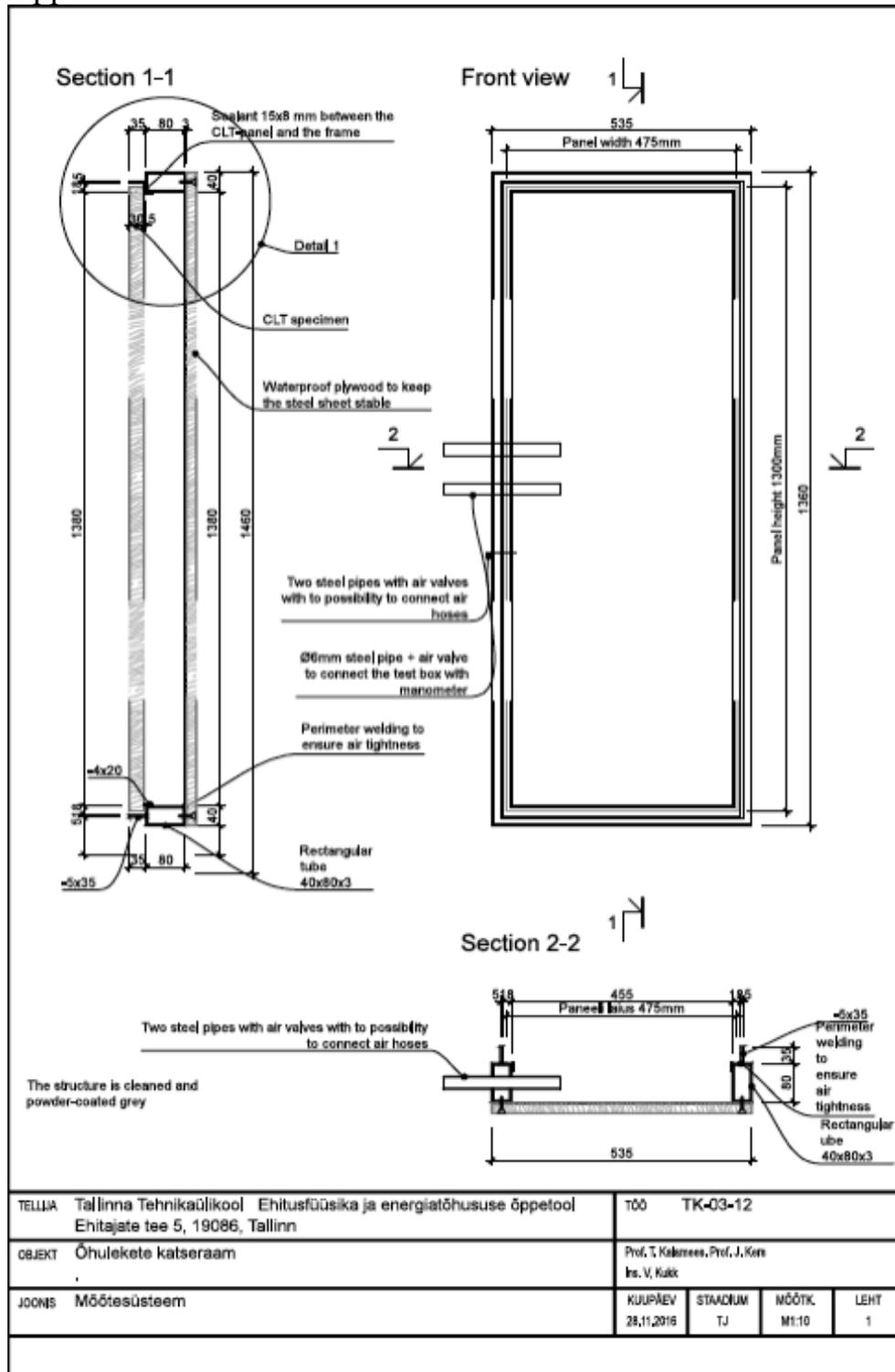


Figure 27 Air permeability test box front view

Appendix 3



Figure 29 Clamping system for fastening the panel