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Department of Materials and Environmental Technology

IMPACT OF MOISTURE CONTENT OF WOOD LAMELLAE TO THE AIR-PERMEABILITY OF CROSS LAMINATED TIMBER

PUITLAMELLIDE ALGNIISKUSE MÕJU RISTKIHTLIIMPUIDU ÕHUPIDAVUSELE

MASTER THESIS

Student Giovanni Luciani

Student code KVEM 156303

Supervisor Prof. Jaan Kers

Tallinn, 2017

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material.
All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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Author: .... (Giovanni Luciani)
/signature /

Thesis is in accordance with terms and requirements

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/signature/

Accepted for defence

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Chairman of theses defence commission: ....

FOREWORD

The author wishes to thank his supervisor Prof. Jaan Kers and co-supervisor engineer Villu Kukk for helping and advising, and fellow students Martin Püssa and Ricardo Lopez Horta, in cooperation with them the scientific experiments were conducted. Special mention for Prof. Targo Kalamees for the important collaboration in this academic work.

MASTER THESIS ASSIGNEMENT

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Aim and tasks of the Master's thesis:

The aims of Master's thesis were to investigate how the air-permeability properties of different cross-laminated panels change with different initial moisture content of lamellae and after different steps of conditioning. The panels were made with different number of layers (but same overall thickness) and with bonded edges or without bonded edges . In different environmental conditions on the wood surface cracks and gaps will change their length and width.

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Introduction

Cross laminated timber (CLT) is a 20 year old building material and it has been studied by huge number of scientists all over the world and is becoming more popular year by year (Collins S., 2016).

CLT panels usually are made of 3, 5, 7 or more layers of timbers, oriented at right angles to one another and then glued to form structural panels with excellent strength, dimensional stability, and rigidity.

Because of their characteristics panels are used as prefabricated building components which can speed up construction. Length is usually limited by transportation restrictions, longer panels can be manufactured. CLT panels are typically installed like plywood in terms of grain orientation. Wall panels are oriented with the grain of the outside layers parallel to the vertical loads of the application. Floor and roof applications have the grain of their exterior layers oriented parallel to the span direction.

Openings within panels can be pre-cut in the factory to any dimension and shape, including openings for doors, windows, stairs, service channels and ducts.

CLT panels have quite good insulation properties, but they need façade coverings and insulation layers. Facades are always exposed to fluctuating of moisture condition and weathering. CLT panels must be protected from moisture (wet, rain, wet ground) even during the building process, because panels can absorb a large quantity of water and can take long time to dry out. Cycles of wetting and drying may damage the panels, like distortions and dimensional changes (Davies & Wood, 2010).

„*The issue of whether CLT panels remain airtight in service has not been determined yet. Gaps between individual boards or layers and checking in board may occur due to dimensional changes during storage, transportation and construction as result of drying or cyclical wetting and drying"*(Karacabeyli, E., Douglas, B. 2013).

Air-permeability is a basic aspect in modern building design, it is connected to many problems as moisture, acoustic, air quality, fire safety, thermal comfort, energy consumption (Axel Berge, 2013).

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

Air leakage in CLT panels, produced with lamellae with lower initial moisture content (MC), will increase less during conditioning in environment with different relative humidity (RH) than panels produced with higher initial MC lamellae.

Thesis structure is formed by three parts:

- Literature review on moisture in wood, drying processes of timber and CLT;
- Materials and methods;
- Results and discussions.

Figures and tables used are numbered and listed.

1. Literature review

In this chapter a short literature review on moisture in wood, on CLT and on state of art of CLT production has been done. Moisture is one of the most important parameters of solid wood and wood engineered products and, for this thesis, 24 CLT panels have been made according to EVS EN 16351.

1.1 Moisture in wood

In Figure 1 (Workshop Companion, 2009) is a simply but clear explanation of the water in the wood cell lumen.

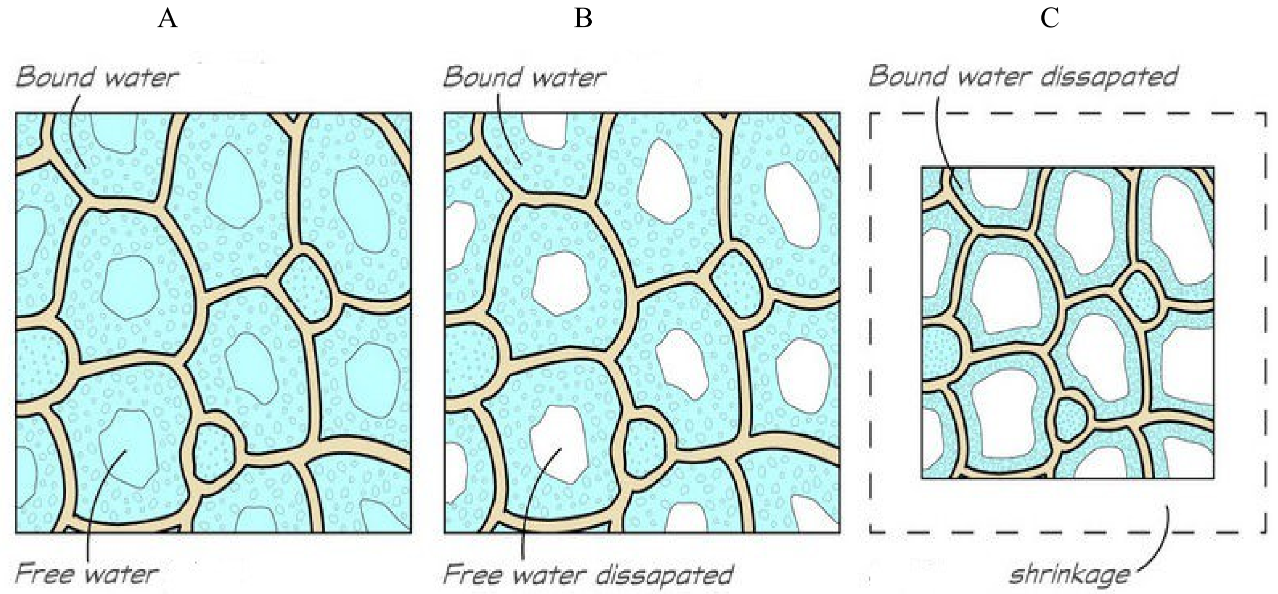


Figure 1.(A-B) water in the cell of green wood; (C) water in the cell of dry wood. Source: (Work Shop Companion. Google. 2009)

In green or freshly harvested trees, water is in the cell wall (the amount is constant during the seasons) and in the cell lumen (the amount is not constant during the seasons and in this water there lot of organic and inorganic food materials). During any manufacture of wood, by drying the water in cell lumen is removed, but not some vapour. The amount of water in cell wall depends also on drying and on environmental conditions. **All wood construction products (when there is not a contact with the ground) are in the condition of Figure 1.B.** The names *free water* (in the cell lumen) and *bound water* (in the cell wall) explain the main difference between these two conditions. Free water because is very easy to remove during drying and bound water is held to wood by strong hydrogen bonds (adsorption forces) water molecules-hydrogen bonding in cellulose, hemicelluloses and lignin.

With the term Fibre Saturation Point (FSP) is described the condition when in the lumen there is not any more water, but the cell wall is still saturated. Wood, as hygroscopic material, exchanges water vapour with the surrounding air until reach the moisture equilibrium. Below the FSP the forces which hold the bound water are great when MC decreases. The relationship relative vapour pressure in the environment and MC in wood is not linear (sorption isotherm-Figure 2) and characterized by 3 curves (desorption, adsorption and cyclic desorption-adsorption). First of all, desorption and adsorption are not reversible; for the same MC, there are two different relative vapour pressure or for the same relative vapour pressure, there are two different MC (one for desorption, one for adsorption). This difference is called hysteresis and it is common for many hygroscopic materials.

Another critical parameter is the equilibrium moisture content (EMC); the value of MC of wood in a constant temperature and humidity environment (Shmulsky R. and Jones P.D. 2011).

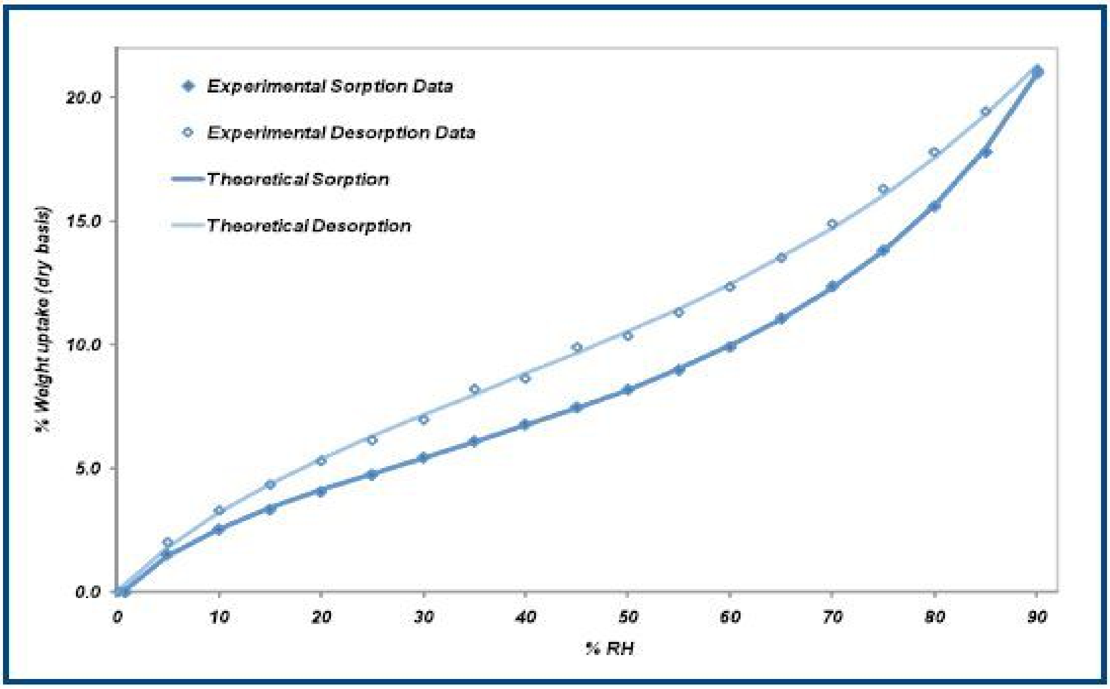


Figure 2.Classical Sorption-Desorption isotherm of of wood. Source: (Azom. Google. 2015)

Table 1. Percent of MC of wood in equilibrium with air temperature and relative humidity conditions. Source: (Shmulsky R. and Jones P.D. 2011).

	Relative humidity (%)							
Dry bulb tempera-ture °C	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
21	4.6	6.3	7.9	9.5	11.3	13.5	16.5	21.0
10	4.6	6.3	7.9	9.5	11.2	13.4	16.4	20.9
21	4.5	6.2	7.7	9.2	11.0	13.1	16.0	20.5
32	4.3	5.9	7.4	8.9	10.5	12.6	15.4	19.8
43	4.0	5.6	7.0	8.4	10.0	12.0	14.7	19.1
54	3.7	5.2	6.6	7.9	9.4	11.3	14.0	18.2
66	3.4	4.8	6.1	7.4	8.8	10.6	13.1	17.2
77	3.0	4.3	5.6	6.8	8.2	9.9	12.3	16.2

According to Table 1, MC of wood at RH from 30% to 70% vary from 6.2% to 13.1%; this is the range which most of wood products are used. Also the temperature effects wood-water relationships, but not with big influence. Wood subjected to temperatures over 100 C for long period has lower hygroscopicity (plywood, fibreboard and particleboard have lower EMC than solid wood).

When wood is dried and it starts to loses bound water (below FSP), shrinking will take place. When water will re-enters in the cell walls, wood will swells (Shmulsky R. and Jones P.D. 2011).

The process is reversible in small samples (stress-free), but it is not completely reversible in products such fibreboard and particleboard. Also in a big piece of solid wood the dimensional changes are not reversible due the internal drying stresses. Shrinkage is proportional to the amount of water removed from cell wall and this is the same with the reverse process of swelling. The S_2 layer is thicker than the others are and in it the molecules chains are oriented along the longitudinal axis of the cell. It is the S_2 layer which influences the shrinking. For all these reasons the length does not change greatly, but when traverse dimensions decrease all the molecules will move together (cell lumen diameter remains constant, cell wall shrinks or swells).

The shrinkage of different samples of same species under same conditions is conditioned from three factors:

- Size and shape of piece;
- Density of the sample (the higher the density the more it will shrink or swell);
- Drying rate (quick drying conditions produce internal stresses, due the different shrinking).

The relationship shrinkage-MC is basically linear (Figure 3) and quite easy to calculate. Also big changes in humidity can have small effects if the new conditions are only for short periods (hours or days) in which wood does not enough time to reach new EMC. The problems will start with over long cycles of humidity and temperature *("keep wood dry; do not let the wood get wet; separation between water and wood"* this is an old elementary motto, but actually this is true!).

The dimensional changes of engineered products such veneer, particleboard and fibreboard is different (and smaller) than the dimensional of a solid wood sample, due:

- Action by one element to the others elements;
- Degree of compression during manufacturing;
- Adhesives effects.

During drying, inside the wood can move as liquid, vapour or as diffusion of molecules.

The diffusion occurs when water moves from higher concentration areas to lower concentration areas. It is necessary a moisture concentration gradient or vapour pressure gradient. The rate of diffusion in one species is expressed with diffusion coefficient. Diffusion is possible only below FSP. In some species, wood structure cannot allow the movement of liquid water but only the diffusion (impermeable wood, due tyloses). The sapwood is generally permeable in all the species (Shmulsky R. and Jones P.D. 2011).

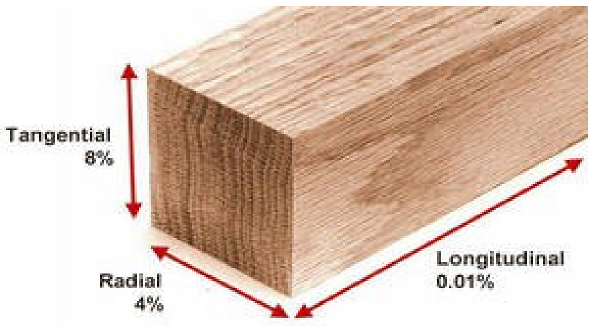


Figure 3.Shrinkage/swelling in wood for radial, tangential and longitudinal directions. Source: (Work Shop Companion. Google. 2009).

1.2 Drying processes of timber

1.2.1 Moisture movement during drying

Movement of water in wood involve liquid phase, vapour phase and diffusion. I the diffusion the water moves from higher concentration to lower concentration through cell walls (moisture concentration gradient or vapour pressure gradient). Diffusion´s rate depends on temperature, the moisture gradient and wood species (diffusion coefficient) and is considerable only below FSP.

Above FSP woos is like series of pipes with the water evaporating from the ends. Drying rate is determined by the rate of water removing from surface and rate of inner liquid and vapour diffusion. At the beginning the rate is related to surface evaporation and this is a big problem during the drying of highly permeable woods. In other species tyloses , aspirated pits, extractives depositions can make timber impermeable or refractory; all the movement of water is done by diffusion (drying is extremely slow). The sapwood is generally permeable in all the species, while heartwood not (Shmulsky R. and Jones P.D. 2011).

1.2.2 Methods of drying

The most common technique is dry kiln in which temperature (up to 100 degrees Celsius) and humidity are controlled and fans make air circulation. Series of scheduled temperature and relativity humidity steps dry carefully the wood at higher moisture content, after free water has been removed the process became more severe. Softwood are dried by a time schedule (cycles) that is the conditions are changed at a specific time. In the dehumidification drying the water removed is condensate in a refrigerated coils (high efficiency, emissions reduced or eliminated as liquid and low energy consumption, but slow process) (Shmulsky R. and Jones P.D. 2011).

There are quite lot of non conventional drying methods studied in recent years such:

1. Wood in heated organic liquid (ex. Fuel oil);
2. Vapour drying;
3. Radio frequency;
4. Radio frequency and vacuum drying;
5. Press drying (in between two heated plates, used with some type of veneer);
6. Solar drying.

1.2.3 Moist air

Most of wood are dried in the circulation air dryer kilns, in which air is heated and flows trough the lumber piles, with electrical fans (Moren T. 2016) . Timber emits vapour in the air. The air circulation involves an high number of theories and topics:

1. Physics: heat transfer and storage, thermodynamic, fluid mechanics, etc..;
2. Chemistry: wood chemistry;
3. Wood physics: wood and moisture, swelling and shrinkage, sorption and desorption, cracks formations, etc..;
4. Kiln technology and construction;
5. Climate control (temperature and moisture).

First of all, for drying application the moist air is a mixture of only two gas (dry air and water vapour). The range from 20 to 100 degrees Celsius is where most of industrial drying is working, moist air is at atmospheric pressure and vapour has lower density than dry air. The higher the temperature, the more vapour can be contained, up to 100 degrees.

All the process involved in the drying, with exchange of energy and changes of state of moist air, can be evaluated with Mollier diagram.

In this diagram different areas are identified:

a) Heating: moist air heated by heating coils and fans;

b) Cooling: moist air cooled by air stream;

c) Water spraying; liquid water injected

Water spraying and streaming in kilns is a way to control the humidity of moist air and avoid board ´s distortions. Usually the drying climate is controlled by measuring dry and wet bulb temperature.

Another way to study the process is by calculations based on three conservation relations: dry mass, mass of water and enthalpy.

1.2.4 Water movement in wood

Liquid water moves due the force of pressure gradient (Darcy´s law liquid state) generated from temperature increase in voids during kiln drying and capillarity forces. Later on, heating cause the evaporation of the inner water; this steam pressure gradient can cracks the wood if the permeability is low (Darcy´s law with liquid and vapour). It is really hard to find a good model for the water flow during drying, cause it depends of many factors. The most important can be wood permeability, driving forces (moisture, pressure and temperature gradients), evaporation at surface and heat transfer. In phases: capillarity regime, transition regime and diffusion regime. If wood has liquid water inside and it starts to dry, evaporation of water on the surface is a driving force with the moisture gradient. When there is not any more liquid water in cells lumen, than the inner vapour can expand with a negative pressure that will suck air into the wood. Also a negative pressure can have liquid water due the small dimension of pit opening (water flow is generated anyway by capillarity forces). In any cases the cell wall can collapses under these different actions. Usually to avoid the collapse, after the liquid water is removed, air must replace it into cells (Moren T. 2016).

An example about softwood; in tangential direction, the free water flows in tracheids due the bordered pits, in radial direction water can flow only in ray tracheids. Bordered pits aspiration will work as a hydraulic valve under pressure (blocking the flow) and in an non reversible way. Usually drying rate is greatest in longitudinal direction, than radial directions and finally tangential direction. To have a good drying the aspiration of pits must to not start before the kiln drying, if not the process would be much longer. The flow of vapour is important in microwave drying and the wood permeability can be a huge limit. The water vapour in cell walls is transported by a pressure or concentration gradient (bound water diffusion) in a slow process and it need extra energy.

1.3 Stress development during drying and conditioning

In a sawn timber (Figures 4-5-6-7-8), when the wood surface reach the fibre saturation point, in the surface will be established tension and compression in the centre (Moren T. 2016), the shrinkage is locked and the risk of surface checking would be high (surface layer shape is a shell). When the wood interior starts drying and shrinking, the surface would be under compression and the inner part under tension. Checks increase where the shrinkage is highest (tangential); in the flat side of the board, where an annual ring touches the surface. Checks develop in radial direction. The difference between thick and thin boards depends on heartwood content and on tensile stress on the surface. A thin boards has mainly sapwood and low surface tensile stress, due the small volume of heartwood which restrains the shrinkage.

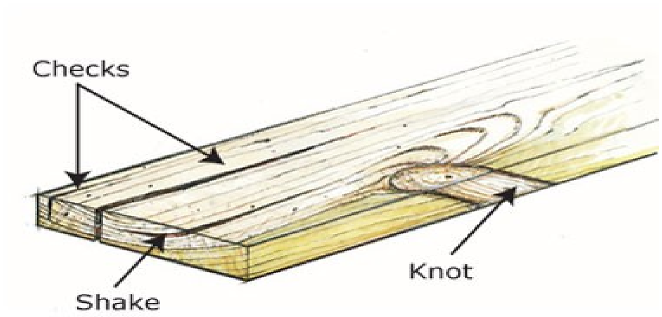


Figure 4.Most common surface checks. Source: (Trade info site. Google. 2016)

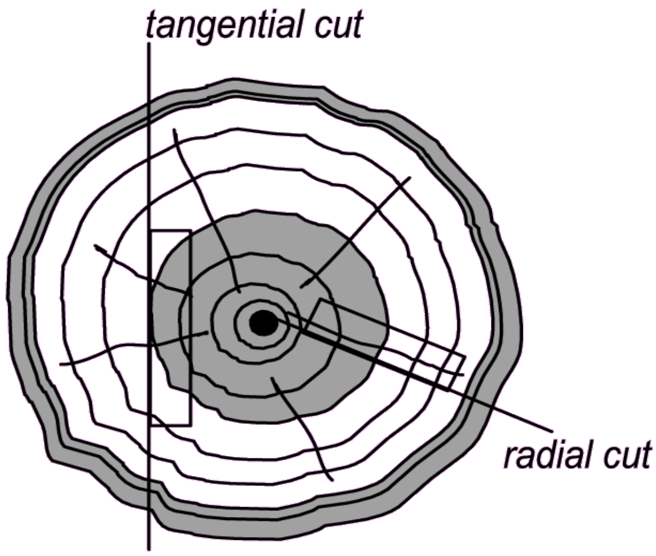


Figure 5.The risk of checking is greatest in timber where the heartwood reaches the surface (on the left). Source: (Geoff`s woodwork. Google. 2016)

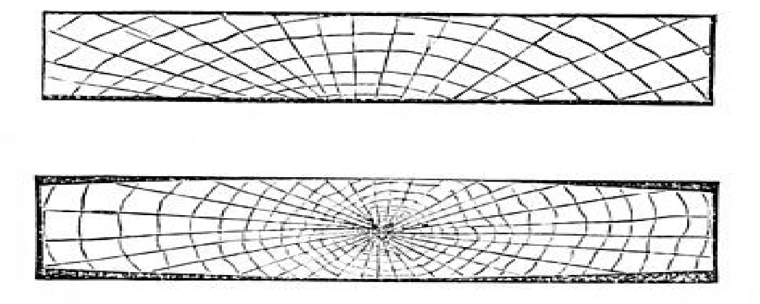


Figure 6.If the pitch is located within the cross section (bottom), most probably checks will occur . Source: (Wikisource. Google. 2016)

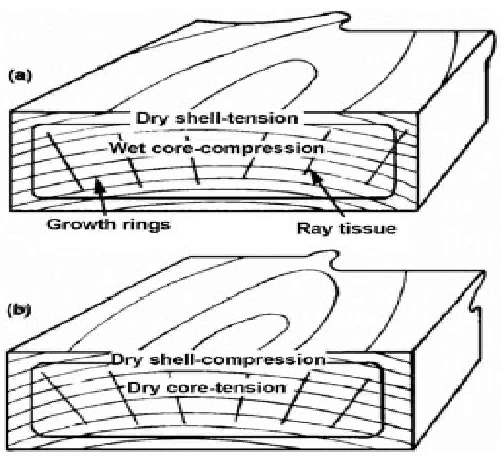


Figure 7. Development of drying stresses a) early b) later. Source: (Wood handbook USA. 2010)

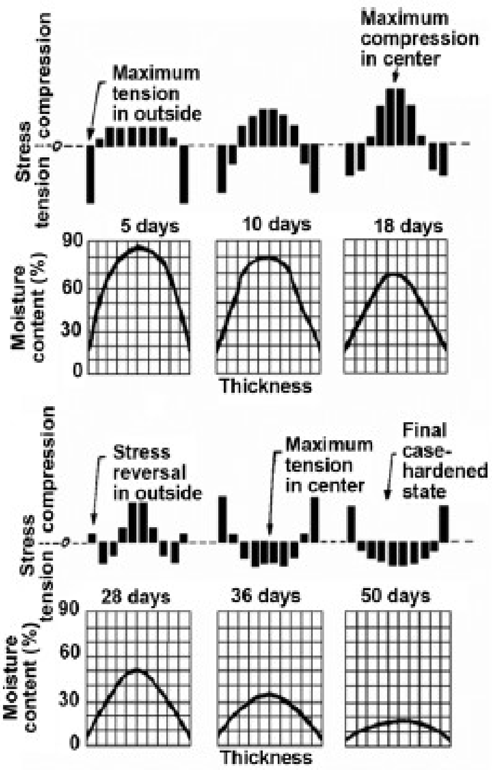


Figure 8.MC-stresses relationship after 6 steps of drying 50 mm read oak. Source: (Wood handbook USA. Google. 2010)

For Gereke T. and Niemz P. (2009) (Moisture induced stresses in spruce cross laminates) the annual ring angle (Figure 9) has a significant influence on the development of moisture inducted stresses. Compressive stresses were lowest with annual ring angle 45º . The largest stiffness and the lowest swelling in radial direction make a panel preferable with vertically oriented annual rings. It is recommended to avoid horizontal annual ring (annual ring angle 0º), for the tangential swelling. In drying tests, compressive pre-stress in outer layers has also huge influence. Compressive pre-stress can be applied mechanically or by changing the initial moisture content of middle and outer layers. In this way it is possible generate fewer stresses when the panels are dried.

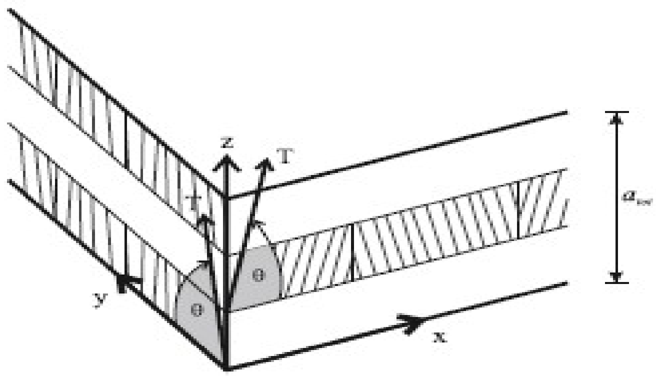


Figure 9.Definition of annual ring angle. Source: (Gereke T. and Niemz P.. 2009)

For Fragiacomo M. *et al.* (2011) (Moisture inducted stresses perpendicular to grain in cross sections of timber members exposed to different climates) the moisture induced stresses perpendicular to grains depend on moisture distribution in the cross section and on the type of exposure and the size of cross section. Northern European climates generate higher moisture gradients than Southern European climates. Variation of relativity humidity may induce stresses exceeding tensile and compressive strength.

1.4 Cross Laminated Timber (C.L.T.)

CLT (cross laminated timber) panels usually are made of 3, 5 and 7 layers of timbers, oriented at right angles to one another and then glued to form structural panels with excellent strength, dimensional stability, and rigidity.
Because of their characteristics panels are used as prefabricated building components which can speed up construction.
Length is usually limited by transportation restrictions, longer panels can be manufactured. CLT panels are typically installed like plywood in terms of grain orientation. Wall panels are oriented with the grain of the outside layers parallel to the vertical loads of the application. Floor and roof applications have the grain of their exterior layers oriented parallel to the span direction.
Openings within panels can be pre-cut in the factory to any dimension and shape, including openings for doors, windows, stairs, service channels and ducts.
CLT panels have quite good insulation properties, but they need façade coverings and insulation layer.
Using external timber cladding, you can have a low environmental impact, and at the end of its life timber can be recycled.

Regarding CLT constructions, when cladding and structure are made from wood, we will have lower problems with differential movements.

In most timber facades we have (Figure 10):

1. cladding: primary rain and wind barrier (closer or open joints);
2. drained cavity (in most of case ventilated): break between façade and structure;
3. moisture barrier (at the back of the cavity, usually formed from a breather membrane): second defence against rain and allows water vapour migrating from inside;
4. air barrier.

Facades are always exposed to fluctuating of moisture condition (excessive moisture can reduce thermal insulation) and, of course, to weather change (weathering).

A ventilated cavity reduces the risk of moisture damage; however, the thermal resistance of ventilated cavity is lower than an unventilated or vented cavity.

Generally, fungal decay and insect attack are not a problem for the Scandinavian Countries (in UK are the main threats).

CLT panels must be protected from moisture (wet, rain, wet ground) even during the building process, because panels can absorb a large quantity of water and can take long time to dry out.

Cycles of wetting and drying may damage the panels (distortion, dimensional change).

Regarding the insulation layer, several types are used:

-fibre board;

-rigid mineral fibre board;

-EPS, XPS (waterproof but with law vapour permeability and a reduction drying capacity of CPT panel);

-semi-rigid fibreboard;

-mineral wool board (vapour-permeable, but require additional framing for cladding attachment and has tendency to absorb water and this reduces the insulation properties) (Davies & Wood, 2010).

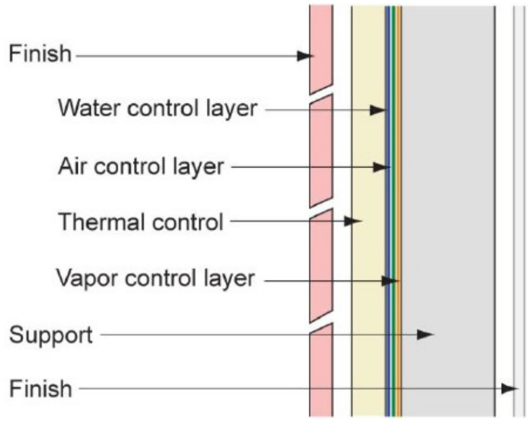


Figure 10.The Perfect Wall. Source: (L. Stiburek, 2008)

1.4.1 Material properties

CLT panels are built by using wood boards. Dimensional lumber is the main input material.
The most common type of wood used is softwoods, although hardwoods may also be used.
The adhesives are sprayed at approximately 0.2 kg/m^2 on the CLT panels (KLH, 2011), polyurethanes are the most commonly used adhesives (FP Innovations, 2011). The former consisting of only the face of the boards having adhesives applied to them, whereas edge glued panels also have the sides of boards coated with adhesive as well. While most CLT panels are attached with adhesives, some use nails or wooden dowels.
After the boards have been glued, the composite is put through a press to firmly bond the plies together. Once the panels are made, they are planed and sanded and then placed in a CNC router, to cut the required holes and openings for windows, doors, and service channels. Some manufacturers will make a cut along the edge of the laminated boards to induce a stress relief joint (Leapage R.T.M., 2012).
The development of the product was mainly controlled by technological aspects and production facilities.
In Table 2 and Table 3 some common properties and characteristics of CLT on the market
Actually, the mechanical potential of the product has not been fully sounded yet, and also the mathematical description of the mechanical behaviour of CLT in terms of efficient calculation tools for engineering purposes is not fully developed yet (Stürzenbecher *et al.*, 2014)

Table 2.Typical properties of CLT. Source: (Sutton, D. Black, P. Walker. CLT: An introduction to low-impact building materials. University of Bath. 2011)

Typical properties of CLT

- Thermal conductivity 0.13 W/mK
- Density 480-500 Kg/m^3 (spruce)
- Bending strength 24 N/mm2 (parallel to grain)
- Elastic modulus (370 N/mm^2 (perpendicular to grain, 12,000 parallel to grain)

Table 3.Data sheet of Stora Enso Wood Production CLT. Source: (clt.info. 2015)

- Width: up to 2.95 m
- Length: up to 16 m
- Thickness: 19 mm, 27.5 mm, 35 mm, 42 mm
- Wood types: Spruce (pine and larch)
- Grading: C24/C16 (DIN 4074)
- MC: 10%/14%
- Adhesive: Formaldehyde free adhesive for edge bonding, finger jointing and surface bonding
- Standard and visible quality
- Surface finish Sanded

1.4.2 Hygrothermal performances and moisture

Sixteen CLT panels (0.6*0.6 ml) with five types of wood, with two type of water resistive barrier and two type of insulation layers were tested in a "*building envelope test facility*", under the Ontario (Canada) climate. The panels were initially wetted (MC at surface over 30%), the MC at various depths was measured and the drying behaviour was analysed. All the measured MC (over one year period) were compared with a commercial hygrothermal software.

The five most important results of the study (Ruth Mc Clung *et al*., 2014) were following:

- *"most of the CLT panels dried to below 26% within one month except for CLT walls with a low-permeance interior membrane" ;*
- *"Low-permeance materials such as polyethylene and non-vapour permeable WRBs caused slower drying of CLTs";*
- *"The low-permeance materials may have a more deleterious effect due to the reduced drying capacity when an incidental moisture source is present";*
- *"The drying behaviour of wetted CLT panels was significantly influenced by the configuration of wall assemblies rather than wood species";*
- *"With adjusted material properties and properly assigned initial conditions, simulation results were generally in good agreements with field measurements at MCs below 26%".*

1.4.3 Air Control

The boards in the CLT element and the element itself should shrink and swell depending on the relative humidity in the surroundings.

To evaluate how the air leakages can influence on a buildings air flow rate a typical wooden house was considered. The building had a base area of 80 m^2. The length of the external walls was 10 m and 8 m. The building had two floors and the floor height is 2.4 m (total building volume of 384 m^3).

The results of the study were:

- Water vapour transport caused by convection may cause moisture problem.
- The measurements made in the study confirm that CLT constructions need to be designed with airtight Joints (rubber moulding or with sheets of airtight material).
- But…*"because of shrinking cracks near the boundary of the CLT elements and movements in the elements caused by shrinking and swelling, local sealing have some uncertainties regarded to how airtight the sealing will stay over time"* (Table 4).
- In the Nordic climate a performance with one water vapour barrier and one wind barrier is a more recommended solution to ensure minor air leakages through the building envelope and avoid moisture problems than a local sealing (Figure 11).

Table 4.The measured air leakages through wall and floor sections. Source: (Air leakages through cross laminated timber CLT constructions. Hans Boye, Skogstad. ScienceDirect. 2011)

Test section	MC kg/kg	Air Leakage Wall m3/h	Air Leakage floor m3/h	Influence on the building air change rate 1/h
Without bonded edges	0.14	210	904	2.90
Without bonded edges	<0.10	2023	934	7.7
Bonded edges	0.14	202	489	1.8
Bonded edges	<0.10	411	658	2.8

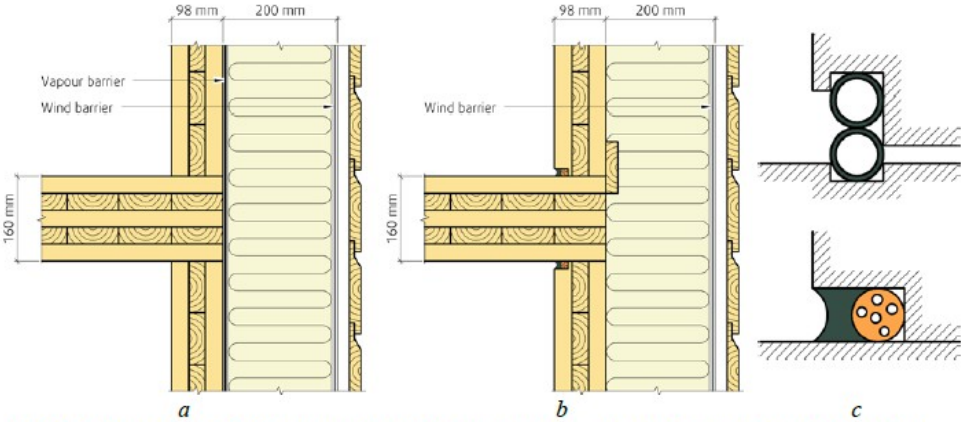


FIG 10. Cross section of CLT construction with separate water vapor barrier and wind barrier (a), and local sealing of joints between floor and wall elements with separate wind barrier under a ventilated wooden cladding (b). Examples of local sealing with rubber molding or sealing compound.

Figure 11.Specific view of link attic-wall. Source: (Air leakages through cross laminated timber CLT constructions. Hans Boye, Skogstad et al. ScienceDirect. 2011)

1.4.4 Air Leakage and CLT

CLT panels must be protected from moisture (wet, rain, wet ground) even during the building process, because panels can absorb a large quantity of water and can take long time to dry out. Cycles of wetting and drying may damage the panels (distortion, dimensional change) (Davies & Wood, 2010). From the U.S. edition of „CLT Handbook: cross laminated timber, chapter 10, paragraph 2.3 „Control of Air Flow: "*The issue of whether CLT panels remain airtight in service has not been determined yet*. *Gaps between individual boards or layers and checking in board may occur due to dimensional changes during storage, transportation and construction as result of drying or cyclical wetting and drying" ."*(Karacabeyli, E., Douglas, B. 2013). *"However, in most cases, it would be prudent not o rely on the CLT panels themselves being the primary air barrier"* (Karacabeyli, E., Douglas, B. 2013). Air-permeability is a basic aspect in modern building design (Figure 12), it is related to lot of problems as moisture, acoustic, air quality, fire safety, thermal comfort, energy consumption. Cross laminated timber is a 20 years old building materials, it has been studied by huge number of scientists all over the world and is becoming more popular year by year (Collins S., 2016).

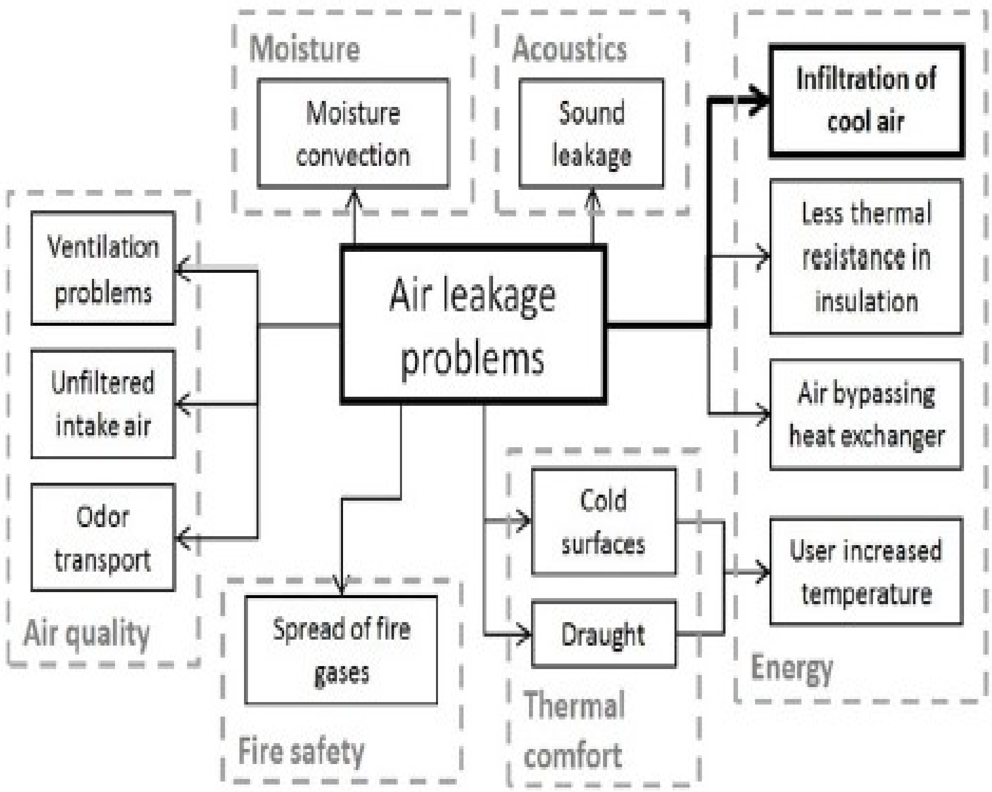
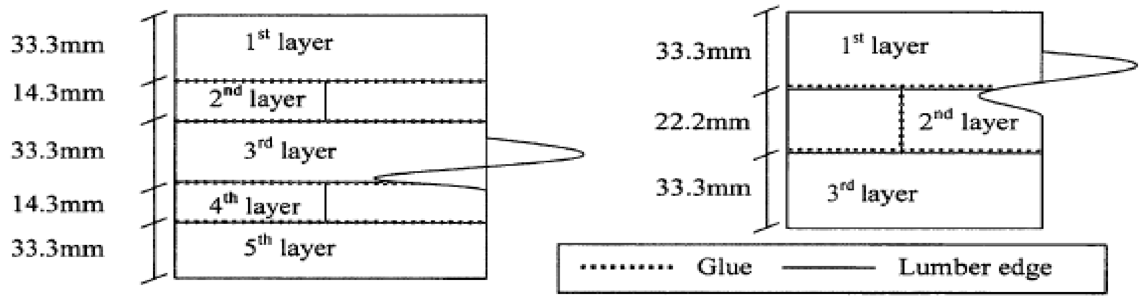


Figure 12.Problems related to air-leakage. Source: (Axel Berge. Google. 2013)

In „Production and Technology of Cross Laminated Timber (CLT)-State of the art Report. COSTFP 1004“ (Brandner R. *et al.* , 2014) is highlighted how with glued edges (also if it is preferable for to avoid air leakage) the cracks would appear on the lamellae surface with irregular shape and with not glued edges cracks most likely would be in the gaps between lamellae. In „Air-permeability test on Stora Enso CLT by Graz University“ (Stora Enso 2013) standards for this experiment were two (EN 1026-Windows and doors and EN 12114-Thermal performances of building). The difference between the standards is in the difference pressure generate and in the intermediate pressure. Test samples were a 2 ml* 2 ml, 3 layers (100 mm thick) Stora Enso CLT panels. The Moisture content were four different values (11.4% -13.6% -8.3% -12%), but very close to the value at the end of the CLT production (12%). With those conditions the CLT panels were completely airtight.

Alsayegh et al. (2012) has tested different CLT, European and Canadian, (Figure 13) of different wood species, different, number of layers, different layer thickness, with and without glued edges at room temperature (actually with a MC not well specified) . Although the test standard was Canadian (ASTM C522:2009) and not European, only one sample with visible gaps was not tight and all the others were or perfectly impermeable or with a low air circulation (lower than minimum measurable level with the instrument system). *„CLT is less permeable compared to building* *construction wood….especially that CLT thickness is above 100 mm and is composed of more than one layer of adhesive"* (Alsayegh *et al.,* 2012). The continuity of glue between layers is plays a very important role in air permeability and the moisture in deforming the shape of lamellae (related to wood orientation). Actually, all the European CLT panels have been found impermeable.



	Region	Number of layer	Dimensions (layer 1,3, and 5) (L x W x H) (mm)	Dimensions (layer 2 and 4) (L x W x H) (mm)
Hem-Fir	Canada	5	689 x 137 x 33.3	689 x 137 x 14.3
ESPF	Canada	5	689 x 137 x 33.3	689 x 137 x 14.3
WSPF	Canada	5	689 x 137 x 33.3	689 x 137 x 14.3
Euro	Europe	3	* x 114 x 33.3	* x 114 x 22.2

*Data not available due to finger jointing.

Figure 13.Test specimens Canadian on the left, European on the right. Source: (Alsayegh *et al., Sciencedirect.* 2012)

1.4.5 Thermal Properties

The thermal performance of an element is evaluated by the U-value (thermal transmittance). To calculate this value we must know location, structure and thermal conductivity λ of the material. In the wood, thermal conductivity is related by bulk density and moisture content (12%). The method of calculation of thermal conductivity and of U-value (raw CLT and CLT plus insulation layer) is shown below. Figure 15 and Figure 16 show the variation of U-value through the thickness of raw CLT panel and CLT plus insulation layer (Stora Enso, 2013).

Thermal conductivity λ

$$\lambda = 0{,}000146 * \rho_k + 0{,}035449, \qquad (1.4.5.1)$$

where

bulk density of CLT ρ_k= 512 kg/m^3

Thermal conductivity λ (W/mK) for CLT is 0,110 W/mK, with MC 12%.

This method has been proved also from SP Technical Research Institute of Sweden and Austrian standard ÖNORM B 3012.

U value of raw CLT panel (CLT wall with thickness of 100 mm)

Thermal transmittance U

$$U = 1 / (R_{si} + \Sigma\, d_i/\lambda_i + R_{se}), \qquad (1.4.5.2)$$

where

Heat transmission resistance R_{si} = 0,13 m^2K/W, Rse = 0,04 m^2K/W

Thermal conductivity of CLT λ = 0,11 W/mK

U for CLT 0,927 W/m^2K

U value of insulated CLT panel (CLT wall with thickness of 100 mm and 16 cm thick insulation material thermal conductivity group WLG 040)

Thermal transmittance U

$$U = 1 / (R_{si} + \Sigma\, d_i/\lambda_i + R_{se}), \qquad (1.4.5.3)$$

where

Heat transmission resistance R_{si} = 0,13 m^2K/W, R_{se} = 0,04 m^2K/W

Thermal conductivity of CLT λ = 0,11 W/mK

U for CLT 0,197 W/m^2K

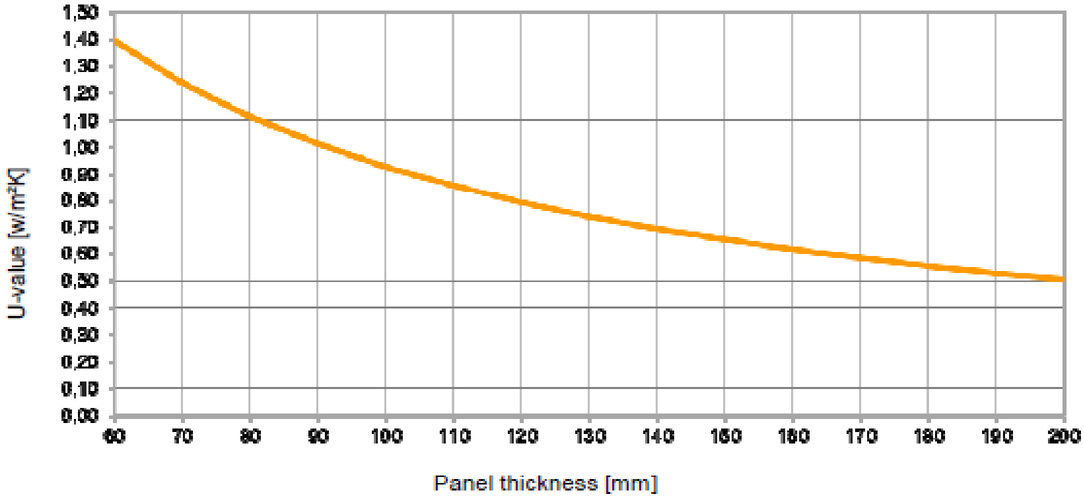


Figure 14.Variation of U-value through the thickness of clt panel. Source: (clt.info. 2015)

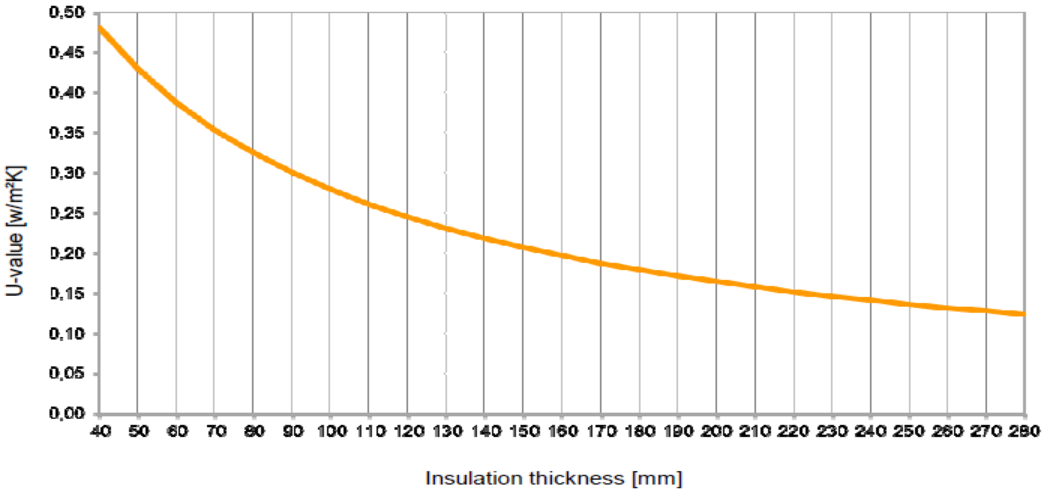


Figure 15.Variation of U-value through the thickness of the insulation (WLG 040 insulation material). Source: (clt.info. 2015)

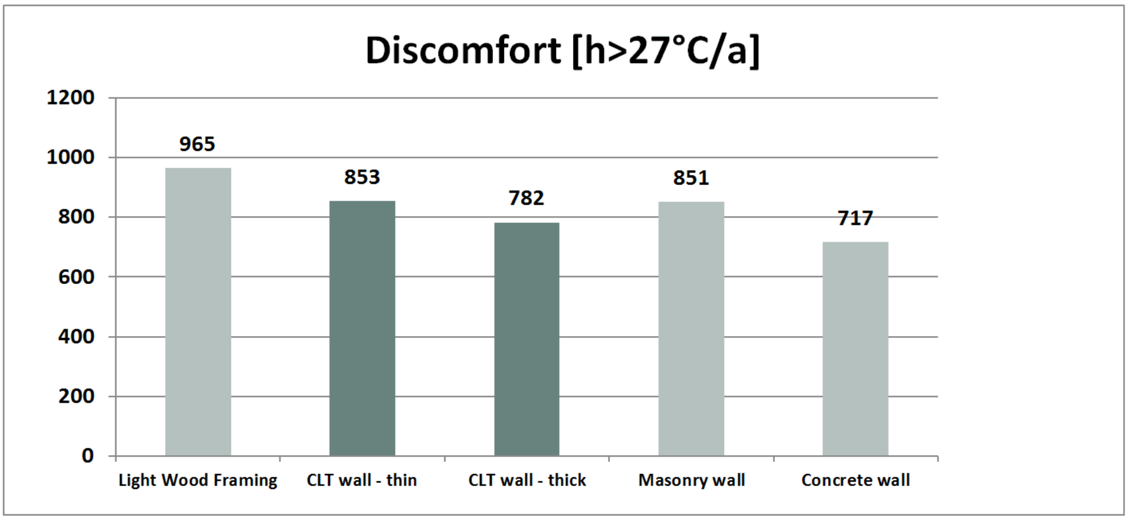


Figure 16. Thermal inertia of CLT in comparison to other building materials such as masonry or concrete. Source: (clt.info. 2015)

The Thermal inertia (Figure 16) describes, when the temperature around a mass is different than the temperature of this mass, its behaviour to adapt to the surrounding temperature.

If the adaptation of mass It's fast, the thermal inertia is low and vice versa. To analyse this effect, the Stora Enso research and development team did a *dynamic thermal analysis* of a building over a year with weather data from the city of Vienna (Austria). There was a reference building. For a comparative analysis, 5 different wall compositions have been analysed:

Light Wood Framing, CLT wall (th.=10 cm CLT), CLT wall (th.=20 cm CLT), Masonry wall (light weight hollow blocks made from burnt clay), Concrete wall.

Each of them had outer thermal insulation and all wall compositions have the same U-value (thermal insulation). This provision makes a comparison possible. All the boundary conditions were kept the same and over a year, the internal operative temperature (mean value of internal surface temperature and internal air temperature) was recorded on an hourly base.

The hours within a year can be counted, where the internal operative temperature was exceeding a certain benchmark temperature (27 °C). The amount of hours, in which the internal operative temperature is exceeding the benchmark temperature for a given system, is exposed in the diagram.

„This study shows that a building with light wooden framing is overheating easily and a building with lot of thermal mass, as in a building with concrete walls, overheating is less of a topic….. A thin CLT wall (10 cm CLT) is performing slightly worse than a masonry block wall, with a difference of 0.2 %. The thick CLT wall (20 cm CLT) is clearly outperforming the masonry wall with a difference of 8.1 %" (Figure 16. Stora Enso, 2013).

1.4.6 Industrial production of CLT

The CLT production is very similar to the glulam production (Figure 17, Brandner R. *et al.* , 2014).

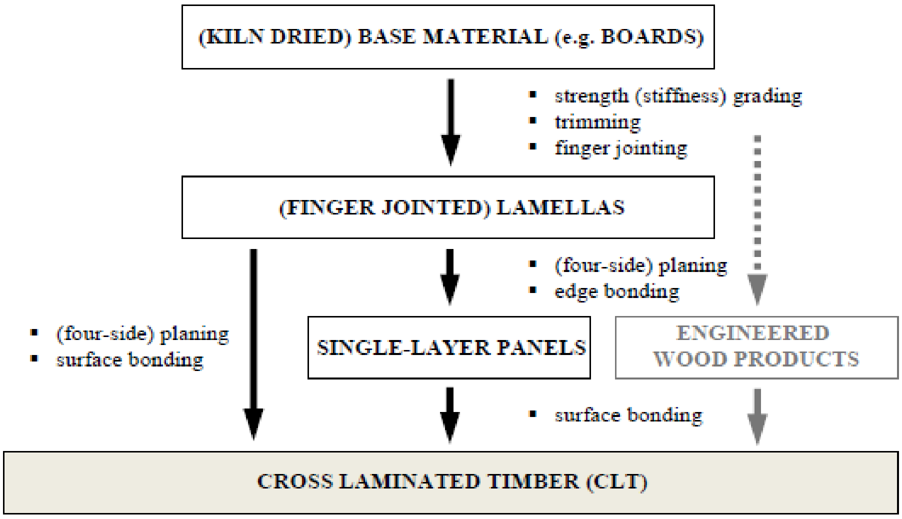


Figure 17.CLT process overview. Source: (Brandner R. *et al., Sciencedirect.* 2014)

The most important steps are:

- Strength grading of dried boards;
- Finger jointing;
- Cutting;
- Planning;
- Edge and surface bonding;
- Curing (Pressing).

Currently the Norway spruce is the specie most used. The raw material is kiln dried and conditioned to a MC of 10-14% (but current technical approvals can be also 6-14%). The strength grading is performed by EN 14081-1 and EN 338 Standards. It is crucial to have in same layer boards with same grade. Strength class usually is C24. The aim of CLT producers is reducing the width of the gaps within the lamellae (fire design, airborne sound, air-tightness) and for this reasons they produce single layer panels. another aspect of this procedure is lower surface bonding pressure. Three are the approaches for the production of a single layer panel:

- single layer panel gained by edge bonding of boards or lamella;

- single layer panels according to EN 13986;
- single layer panels gained by axial splitting of glulam.

Regarding the pressure devices, the following different cases can be possible:

- hydraulic press equipment (0.10-1.00 N/mm^2), a great advantage is the automation of all the process steps before and after pressing;
- vacuum press equipment (0.05-0.10 N/mm^2),

the bonding pressure, the machinable layer thickness and timber species are limited, but pros are the evenness and thickness tolerances usage in a single layer, vacuum pressing is profitable for small/medium CLT production also if the process is semi-mechanical ;

- pressure of screws, brackets or nails (0.01-0.20 N/mm^2), the advantage is given by a smaller investments than with the hydraulic pressing machines and almost the same of vacuum pressing machines.

Briefly surface bonding pressure is function of:

- adhesive system;
- timber species;
- geometry;
- adhesive application system;
- quantity of adhesive.

1.4.7 Biggest CLT producers in Europe

In Table 5 the top 5 Austrian CLT companies (70% of European production) data sheet data sheets comparison. Stora Enso has the biggest capacity (95.000 m^3), panels till 8 layers and thickness (320 mm), Binderholtz the longest length and width (24 m-3.5 m).

Table 5.Top 5 CLT companies in Austria. Source: (Cameron Stauder. CLT. An analysis of the Austrian industry and ideas for fostering its development in America. Fachhochschule Salzburg University of Applied Sciences. 2013)

		Binderholz	**Hasslacher**	**KLH**	**MMH**	**Stora Enso**
Capacity m3		80,000	30,000	90,000	50,000	95,000
Layers		3-5-7	3-5	3-5	3-5-7	3-5-7-8
Wood types		Spruce, pine, fir, larch	Spruce, pine, fir, larch	Spruce, pine	Spruce	Spruce, pine
Adhesive		PUR EN 301, single ply board MUF, emissions class E1	MUF	PUR	Melamine resin based EN 301	PUR
Dimensional capabilities	**Le.**	Up to 24 m	Up to 22 m	Up to 16.5 m	Up to 16.5 m	Up to 16 m
	Wi.	Max 3.5 m	Max 3,15 m	Max 2.95 m	Max 3 m	Max 2.95 m
	Th.	60-280 mm	57-200 mm	57-500 mm	57-278 mm	60-320 mm
	Lam	20-40 mm	19-40 mm	10-40 mm	19-40 mm	20-40 mm

2. Material and methods

The chapter describe how the scientific experiment was performed to achieve the aim of this Thesis and which methodologies were used.

2.1 Test specimens

The lamella for the experiment came from the company Raitwood, timber spruce C24 18 mm*95 mm*4500 mm profile HS40, commercial grading and have been machined in Tallinn Technology University, Woodworking Laboratory, in Tallinn Ehituskool and Peetri Puit (Arcwood) facility in Põlva. The air permeability tests have been performed in Tallinn Technology University, Laboratory of Wood Technology, in laboratories of Department of Mechanical and Industrial Engineering and in Department of Civil Engineering and Architecture.

The test samples have the following characteristics:

- n. 3 samples 1300 mm * 460 mm, 3-layers, 30 mm thickness, 10 mm layer thickness, without bonded edges, conditioned in environment of RH 30%;
- n. 3 samples 1300 mm * 460 mm, 3-layers, 30 mm thickness, 10 mm layer thickness, without bonded edges, conditioned in environment of RH 70%;
- n. 3 samples 1300 mm * 460 mm, 3-layers, 30 mm thickness, 10 mm layer thickness, with bonded edges, conditioned in environment of RH 30%;
- n. 3 samples 1300 mm * 460 mm, 3-layers, 30 mm thickness, 10 mm layer thickness, with bonded edges, conditioned in environment of RH 70%;
- n. 3 samples 1300 mm * 460 mm, 5-layers, 30 mm thickness, 6 mm layer thickness, without bonded edges, conditioned in environment of RH 30%;
- n. 3 samples 1300 mm * 460 mm, 5-layers, 30 mm thickness, 6 mm layer thickness, without bonded edges, conditioned in environment of RH 70%;
- n. 3 samples 1300 mm * 460 mm, 5-layers, 30 mm thickness, 6 mm layer thickness, with bonded edges, conditioned in environment of RH 30%;
- n. 3 samples 1300 mm * 460 mm, 5-layers, 30 mm thickness, 6 mm layer thickness, with bonded edges, conditioned in environment of RH 70%.

The dimensions of the samples depends from the following reasons:

- The weight of one panel is almost 10/12 kg (easy to handle);
- The conditioning time for 30 mm thick panel is 30 days (according to WUFI software simulation made with Prof. Targo Kalamees aid);
- The length and height of the panel is 1400 mm* 460 mm, to avoid air-flow higher through the edges than through the panel itself;
- The length and the height of panel allow to have a huge number of gaps crossing points where most probably the air flow would go through (56 point in each panel);
- 3 and 5 layers are the most common numbers of layers for the walls;
- The majority of the CLT companies makes not edges glued panels, due the higher costs of panels with edges glued.

All the CLT samples were made according to EVS EN 16351 standard and tested on the basic of EVS EN 12114 standard.

For twelve panels made in Tallinn Ehituskool a cold press has been used (see Appendix 8), the other twelve panels were made in Põlva Peetri Puit facility with a vacuum press (see Appendix 9-10). Also the thinning of the lamella, to reach the experiment thickness of 10 mm and 6 mm, has been made in Tallinn Ehituskool and in Põlva Peetri Puit facility (see Appendix 8). To avoid crack formation during the operation in each tesp in the machinery 1 mm per time has been removed.

The adhesive used in the Laboratory of Wood Technology and in the Ehituskool was Loctive HB S509 Purbond (Polyurethane adhesive from Peetri Puit, Appendix 19), with a consumption of 140-180 g/m^2 (one side), a MC exceeding of 8%, an assembling time 50 minutes, curing time 125 minutes, storage time after gluing 10 hours and a press load 0,6-1 N/mm^2. For the panels produced in Peetri Puit factory, the application of adhesive to surface was carried out mechanically (Appendix 9).

The amount of adhesive on the layers was adjusted forward to match the amount used for the panels made in Ehituskool.

In the case of making without bonded edges panels, to avoid glue on the lamella´s edges, a paper tape (5 cm width) has been used during gluing; this tape was removed before placing the upper layer.

In the case of making the layers of bonded edges panels, a simply wooden jig, loading straps and/or bench clamps to apply the pressure have been used (Appendix 7).

After this phase all the single layers were wrapped into a plastic film to maintain the MC.

The metal frame box for the air permeability test has been designed by Prof. Targo Kalamees (Department of Civil Engineering and Architecture) (see Appendix 3-4).

2.2 Initial cracks and MC measuring

All the initial cracks and gaps between the lamella of the specimens have been measured (length and average width) by a crack width gauge (ruler by Avongard); the methodology was developed from Brischke, Humar, Meyer et al. [COST Action FP 1303-Cooperative Performance Test]. For lengths up to 200 mm the average width was calculated with three values, for lengths greater than 200 mm the average width was calculated with five values. Cracks and gaps with length less than 5 mm have not been measured. Also the moisture content has been measured for each panel in different RH conditions with an handheld moisture meter with nails.

2.3 Specimens conditioning

For the panels with initial conditioning in environment of RH 70%, after the cracks and gaps measuring, the MC measuring and the air permeability test, multiple phases of conditioning in a climate chamber in Mechanical Department (Climacell 707) and ‘ Department Civil Engineering Department (see Appendix 11) began. The longer conditioning cycle consists of initial step in environment of RH 70% and three steps in climate chamber (RH 50%-RH30%-RH10%). More in detail about the steps in climate chamber:

- 12 Panels for 30 days with constant RH 50% and 23 ºC;
- 12 Panels for 30 days with constant RH 30% and 23ºC;
- 12 Panels for 20 days with RH 10%-15% and 23ºC.

Similar procedure for lamellae of the panels with initial environmental conditioning in RH 30%. The short cycle is constituted by one step in environment of RH 30% and one step in climate chamber at RH 10%. More in detail about the single step in climate chamber:

- 12 Panels for 20 days with RH 10%-15% and 23ºC.

At the end of each conditioning step, the cracks and gaps measuring, the moisture content measuring and the air permeability test have been repeated.

The conditioning steps simulate the weathering (from autumn to spring in Estonia), during which the indoor temperature remains constant and the RH can drop (from RH 75%) up to 25%; RH 10% represents an extreme condition.

The reason of 30 days in climate chamber is justified by the simulation with the German software WUFI in which a wooden sample (30 mm thick needs 30 days to have same value of MC in all the points of it cross-section, in other words to condition the wooden specimen in an environment with same RH and temperature. WUFI software can simulate (two dimensional model) the heat and moisture transportation in a wall of a building made of different materials, this software has been validated with several tests in laboratory and in field (WUFI.de).

RH 70% corresponded in the wood at the Moisture content of the saw timber in pack delivered by Raitwood (from 10 to 15%). Relativity humidity 30%, MC around 6%, was reached after storing the saw timber for four weeks in Furniture Laboratory in TTÜ wood-building (RH 30% and temperature 22 degrees); in a real situation after or after a period of time in a warehouse (after wrapping film around) or after kiln drying.

Last step is only 20 days for "practical reasons" and with RH between 10 and 15% cause this is the lowest value for the climate chamber in Civil Engineering Department with the aid of 3 electric radiators and one fan. In real conditions RH cannot be lower than 25% , as RH 10% is an extreme value, in 20 days it is possible to reach a plausible value.

2.4 Air-permeability test

The metal frame box for the air permeability test has been designed by Prof. Targo Kalamees (Department of Civil Engineering and Architecture) (see Appendix 3-4-5)
The test machinery consists of the following parts (Appendix 6):

- Air compressor (from 50 Pa till 550 Pa);
- Air flow regulator;
- Digital measuring the air flow (l/min) SMC_PFM 710 (Flow rate range 0.2-10 l/min; minimum unit setting 0.01 l/min; repeatability +/-1%) with integrated flow adjustment valve;
- Digital manometer Huba Control 699 (Pressure range 0-1600 Pa; tolerance 0.7%);
- Air filter with mechanical air pressure difference regulator;
- Wires;
- Flow pipes;
- Metal frame box, to avoid distortions (see Appendix 6), sealant made of neoprene closed cells and mechanical clamping system.

At the bottom of the box, there is a plywood panel (15 mm thick).

In the test was used only with positive pressure and (Air Permeability test for CLT panels made by Graz Technical University 2013) the maximum pressure difference Δp_{max} was 550 Pa and minimum Δp_{min} 50 Pa.

According to the EVS EN 12144, the pressure should be applied to the specimens in two following stages according to the EN 12114:

- I stage- three pulses of pressure were applied to the specimens. Each pulse maintained about one minute. Each pulse produced about 550 Pa of pressure difference;
- II stage- seven steps of pressure difference (between and including maximum and minimum pressure differences) were applied to the specimens. In Table 9, it is shown values for each pressure step. Each pressure step maintained about 5 seconds.

Values for each pressure step pressure difference in second stage of pressure application were calculated by following equation (2.5.1):

$$\Delta p_i = 10^{i\frac{\log\Delta p_{max} - \log\Delta p_{min}}{N} + \log\Delta p_{min}}, \qquad (2.5.1)$$

where

N- total number of pressure steps,

i- number of pressure step.

Table 6. Pressure differences

Number of pressure steps, i	Pressure steps values, Δp_i (Pa)
0	50
1	73
2	108
3	158
4	232
5	341
6	500

Due the mechanical characteristics (mechanical air flow valve and digital manometer and flow meter) of the test apparatus and box (see paragraph 2.5.4 and 2.5.5), the pressure was applied in the following procedure:

-One big step, in which the air flow valve was opened till the maximum pressure of 550 Pa; not a pulse, but gradually after intermediate steps (not from (2.5.1) equation).

When the maximum pressure cannot be reached (due gaps of cracks in the samples), the air valve is opened till the flow meter limit of 5 litres per minute.

2.5 Problems during manufacturing process

The production phase was the longest operation of this academic project and any time the project team has figured out how to do a certain procedure due the lack of experience and the absence of specific machineries.

2.5.1 Making glued edges panels

Using a wooden jig, stripes and a mechanical clamping is an easy and practical procedure, but everything is conditioned by the initial quality of lamella. The greater are cupping and twisting the harder is to glue the edges together.

2.5.2 Hydraulic pressing in Ehituskool

The hydraulic press with six pistons (Orma Macchine) is not a specific machinery for the CLT production; it is not possible to apply an horizontal force to confine the panel and one panel has one layer rotated over the other (angle greater than 90 degrees). In the first attempts with this some layers were laminated , due the applied force not constant over the press´s plate (the force is bigger right under the cylinders).

2.5.3 Planning in Ehituskool

Some lamella have knots and during the planning in Ehituskool the knots were expelled due the vibrations. In this case, the lamella were patched with a wooden patch of the same species and with the same glue. With the planning also twisted or cupped layers were machinated with an acceptable final result.

2.5.4 Air flow closing valve in test apparatus and pressure steps

In the apparatus the manometer and the flow-meter are digital, but the closing valve is a mechanical device (rotation clockwise, air flow closed, rotation counter-clockwise, air flow is open). When the flow is open the pressure starts to increase, when the system is in equilibrium to reach an higher pressure, it is necessary open again the flow. The maximum pressure was 550 Pa and with such devise is practically and manually hard to reach (and keep it constant) the exact value of pressure. The EVS 12144 provides three steps at the maximum pressure and six intermediate steps till the top value; same comment made above is for the second part of the air permeability test, due also the quite big dimensions of the box and the ability to stop the flow quickly). One thing to add, if a panel is air-tight, it will be certainly air-tight in the first part and quite lot of panels not air-tight, after the conditioning, did not allow to apply the same pressure but a lower one.

2.5.5 Metal box in test apparatus

The box has been tested at the beginning of the experiment with a plywood panel, using the same clamping system used in all the tests. The result was a perfectly air-tight box. During the CLT, test before all the conditioning , due the design of the box, some panel with defects (knots, resin ducts, shorter lamella) on the edges were impossible to test (with zero Pascal of pressure and a huge air leakage). To avoid this problem, all the sample were testes in both faces. For the panels without bonded edges, after the conditioning cycles, the gaps between the lamella were very important (also more than 1 mm). This occurrence makes the sample completely not air-tight or better, with the used box is not possible to determine if the air flow go through also the central part of it.

2.5.6 Sealing the edges

Sealing the edges with air thigh tape is one possible solution for further studies to avoid the leakage of air from the wider gaps of not bonded edges panels. Panel P3 face A 3 layers no bonded edges showed at RH 10% 5 litre/min air leakage with a pressure of 0 Pa, after wrapping the shorter edges with air thigh tape the leakage is also 5 litre/min but with 260 Pa of pressure. Panel C5 5 layers no bonded edges (Face A) showed 0.36 litre/min at 550 Pa, after applying the tape (Face A) leakage was 0.20 litre/min at 550 Pa. For Face B, from 3.71 litre/min (282 Pa) to 2.34 litre/min (550 Pa). In other hands, up to 40% of leakage from the gaps.

3. Results and Discussion

In this chapter all the data of the research have been showed (Appendix 2-12-13) with tables and charts. After each data paragraph a discussion paragraph will take place. At the end, some comments about all the work done.

3.1 Moisture content in the samples after conditioning

The longer cycle is formed from four steps (RH 70%, RH 50%, RH 30%, RH 10%, only last three in climate chamber), the shorter cycle is formed from two steps (RH 30% and RH 10%, only last one in climate chamber).

The initial MC for the first 12 panels at RH 70% (Figure 19) was in a range from 9,10% to 15,10%. The average MC is 12.02%, at the end of first cycle at RH 50% the MC for the same panels was in a range from 8.30% to 9.70%, the average MC is 9,10% very close to 9.50% (Table 1 in literature review). For the second cycle at RH 30% average MC 6.12% and values between 5.80% and 7.20%. In the last step at RH 10% the range is from 2% to 3.80% and average is 3.08%. For the second half of the samples (with initial conditioning RH 30%) (Figure 20) MC was in the range 4.70%-6.90%, with average 6.00%., also close to the value of 6.30% in Table 1. In the last step at RH 10% the values were from 2% to 4.20% and average was 3.44% .

In the longer cycle (from RH 70%) the higher values of MC was found in the 3-layers not bonded edges panels, with a similar shape of the bar chart for second (RH 50%) and third (RH 30%) cycles. In RH 10% cycle this trend is inverted. In the shorter cycle (from RH 30%) the initials MC values were closer to the value of 6% and also after the first step of conditioning most of the values were homogeneous (up to 3.00%).

In Figures 18 and 19 specimens are from P1 to P3, from A3 to C3 and from A5 to C5. WBE means with bonded edges, NBE means not bonded edges. 3 and 5 are the number of layers for a sample.

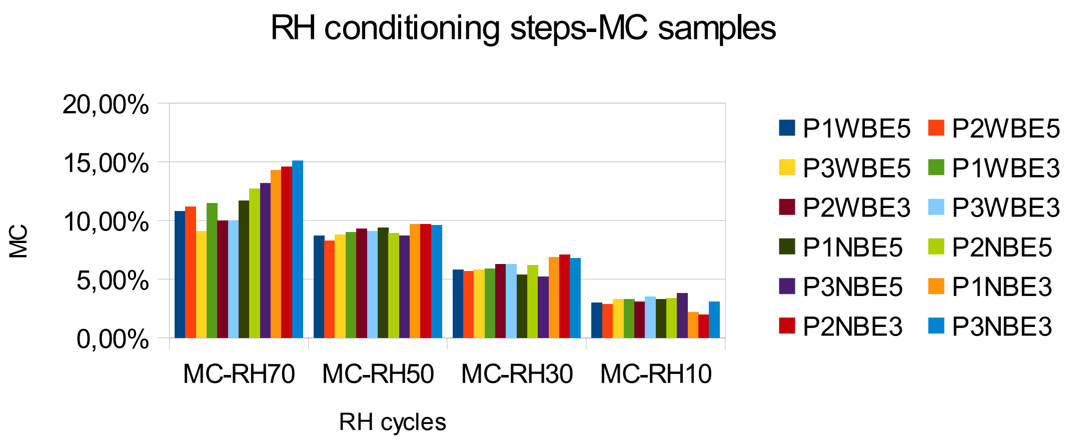


Figure 18.Chart of variation of MC for longer cycle (from RH 70% to RH 10%)

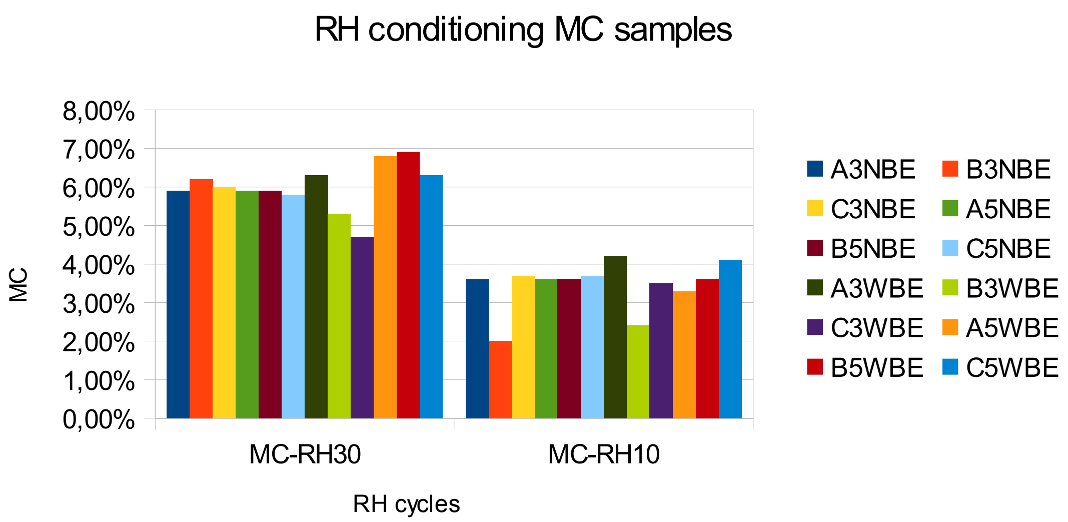


Figure 19.Chart of variation of MC for shorter cycle (from RH 30% to RH 10%)

3.1.1 Moisture content according EVS EN 16351

According to EVS EN 16351 standard during the manufacturing process the lamellae shall have from 6% up to 15% MC (unless the adhesive MC range, in this work higher than 8%), between two lamellae bonded the MC difference shall not be greater than 5%. The CLT as finally product in factory generally has from 10% to 14% MC (Brandner R. *et al.* , 2014). For COST E53 a timber in joinery for internal use and heated buildings need 6-10% MC, for external use 12-19%, Machined softwood without groove for internal use 10-14%, for external use 15-19%.

3.1.2 Variation in moisture content in specimens

For the longer conditioning cycle (RH 70%), the initial average value of MC for the samples was up to 12.02% in the classical range of and a machined softwood for internal, or, in other hands, a finished CLT panel in factory. With the second cycle (RH 50%) the value 9.10% is comparable to the value for the lamellae in the EVS EN 16351 (6-15%) or to a timber product for internal use in journey (6-10%). In the third step the average value of 6.09% actually is lower than the value of MC recommended for the glue (8%) and on the border line according the CLT standard and the COST E53. Last cycle (RH 10%) represent an extreme value, actually some samples had 2.00% of Moisture Contain. To underline how the differences in MC of all the samples, after each cycle, became smaller and smaller. Logically this means that during the conditioning cycle in Climate chambers some panel has lost more moisture than another, only checking the average in each cycle almost 3% of water in samples is evaporated.

3.2 Cracks and gaps

In Figure 20 and Table 7 the average width and length of cracks and gaps measured during the tests.

Table 7.Values of chart in Figure 20.

	% Width RH70-RH50	% Length RH70-RH50	% Width RH50-RH30	% Length RH50-RH30	% Width RH30-RH10	% Length RH30-RH10
RH 70%						
3L NBE	79.72%	74.00%	41.37%	23.07%	53.94%	37.93%
3L WBE	24.41%	19.02%	55.52%	47.7%	57,15%	56.25%
5L NBE	63.00%	66.82%	39.19%	28.12%	51,32%	43.78%
5L WBE	23.84%	20.19%	24.52%	16.76%	53.76%	50.79%
RH 30%						
3L NBE	-	-	-	-	35.74%	32.11%
3L WBE	-	-	-	-	29.32%	26.15%
5L NBE	-	-	-	-	51.46%	37.14%
5L WBE	-	-	-	-	65.39%	53.47%

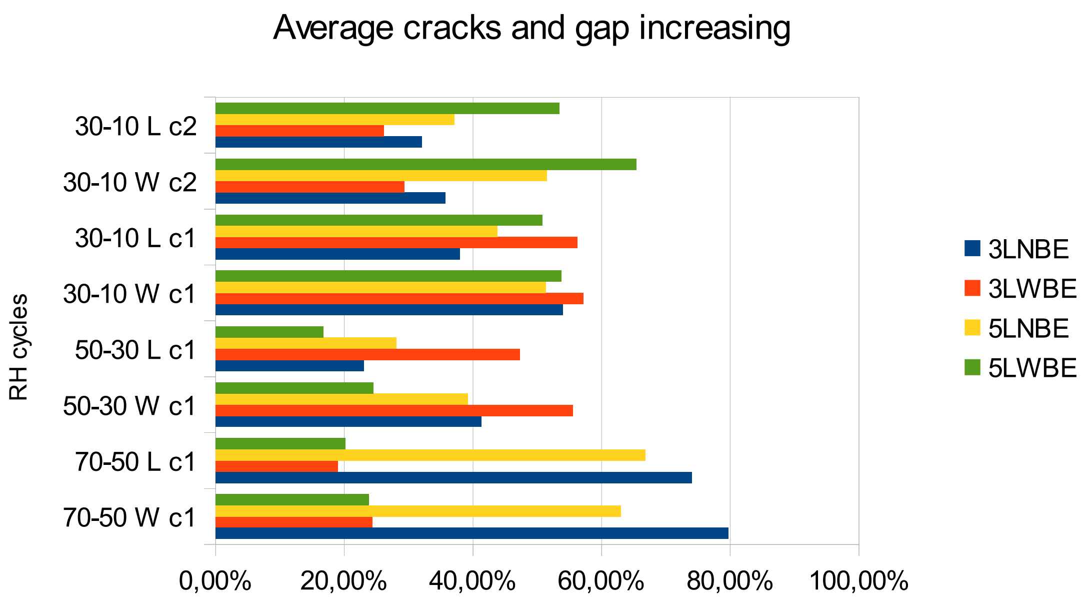


Figure 20.Chart of average increasing percentage of cracks and gaps increasing for all the panels, from RH 70% to RH 50% , from RH 50% to RH 30% (c1) and from RH 30% to RH 10% (c2), (W width, L length)

3.2.1 Cracks Developing

For the panels without bonded edges, and with longer cycle, almost all the gaps and cracks appeared in the first half of the cycles, in the second part the increasing was in a range between 20% up to 50%. For the bonded edges panels, generally the increasing is much lower than the no bonded edges (up to 20%); the exception is for 3 layers specimens, cycle RH 50%-30%, where the values are comparable with the not bonded edges samples in same conditions. To remark the homogeneous behaviour of the 5 layers bonded edges panel in all the conditions. Also in the not bonded edges panels after cycles is possible to find cracks in the lamellae and not only gaps.

For the shorter cycle (RH 30-10%), generally the values are lower than the same in the other cycle (RH 70-10%) with one exception; 5-layers with bonded edges panels. In this case, bonding the edges and the thickness of the layers (6 mm) may be a plausible reason to the cracks developing.

Overall shrinkage of all the specimens were in the range of 0.00% to 0.22%. Naturally the samples with lower initial moisture content had lower shrinkage.

3.3 Air-leakage

In Figures 21 and Table 8 the average maximum air leakage (both sides A and B) for panels with and without bonded edges at RH 50% (12 panels) and at RH 30% (12 panels). In Figure 22 and Table 8 the average maximum air flow for all 24 panels at RH 30%. 3L and 5L mean three and five layers, WBE means with bonded edges, NBE means not bonded edges.

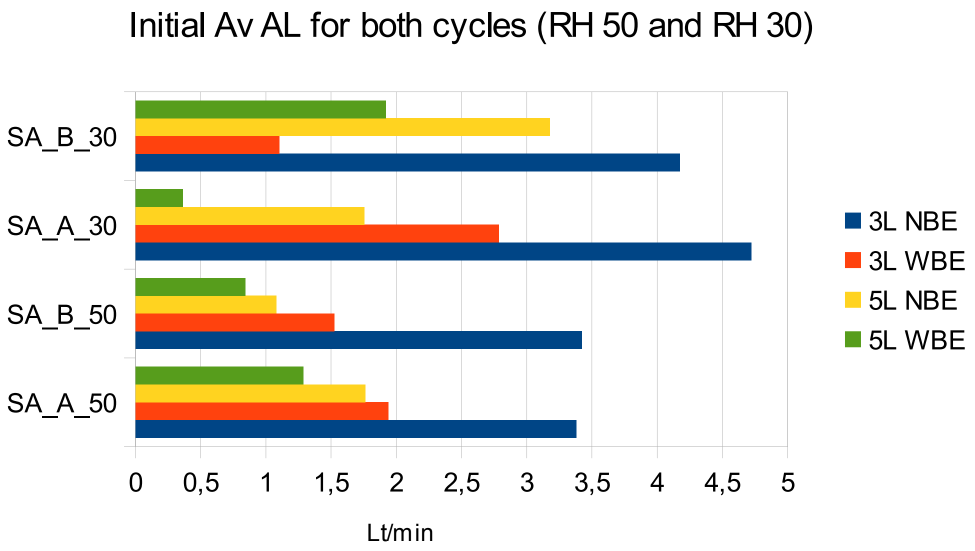


Figure 21.Chart RH-average maximum initial Air Flow (Lt/min) for panels (12 panels) at RH 50% (cycle RH 70-10%) and panels (12 panels) at RH 30% (cycle RH 30-10%)

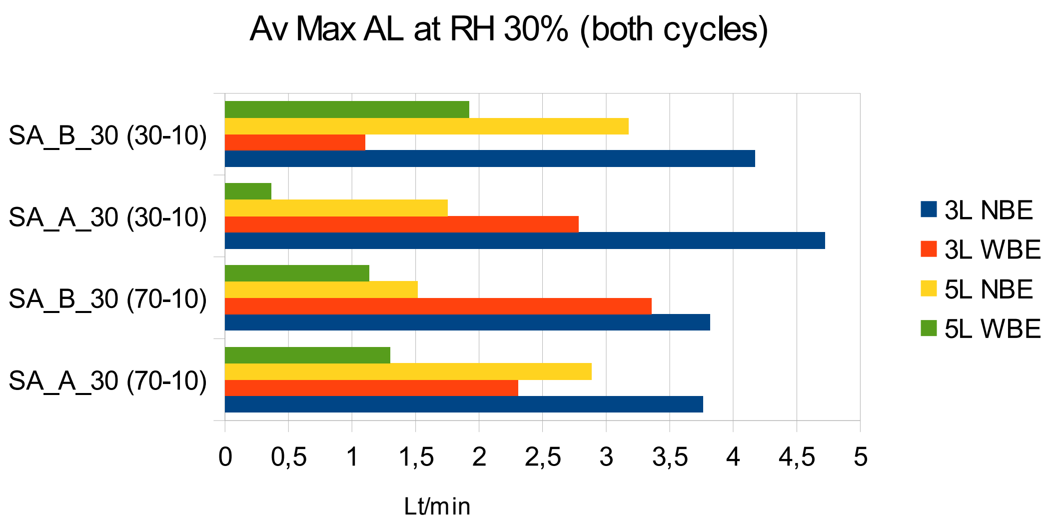


Figure 22.Chart RH-average maximum Air Flow for panels (24 panels) at RH 30% (cycle RH 70-10% and cycle RH 30-10%)

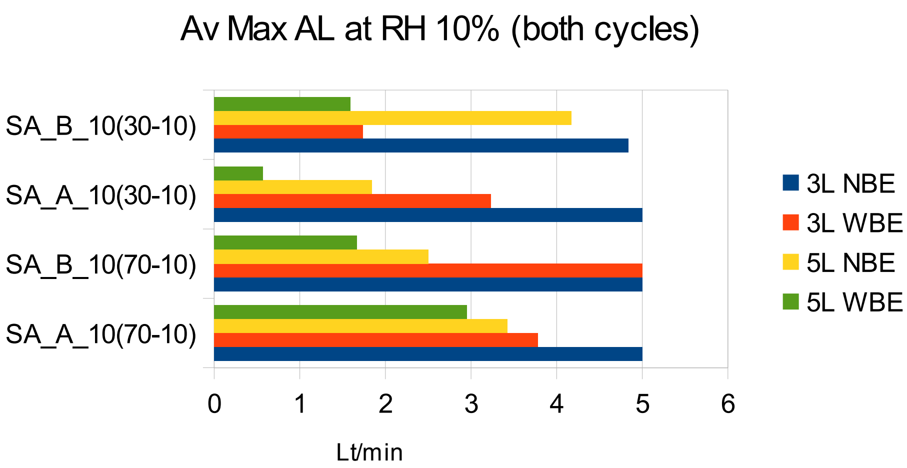


Figure 23.Chart RH-average maximum Air Flow for panels (24 panels) at RH 10% (cycle RH 70-10% and cycle 30-10%)

In Figures 23 and Table 8 the average maximum values of air leakage of all the type of samples at RH 10% .

Table 8.Values of chart in Figures 23-24-25. Average maximum values of air leakage.

	RH 50 (RH 70/RH 10)		**RH 30 (RH 70/ RH 10)**		**RH 30 (RH 30/ RH 10)**		**RH 10 (RH 70/RH 10)**		**RH 10 (RH 30/RH 10)**	
	Face A	**Face B**	**Face A**	**Face B**	**Face A**	**Face B**	**Face A**	**Face B**	**Face A**	**Face B**
3L NBE	3.38	3.42	3.76	3.82	4.72	4.17	5	5	5	4.84
3L WBE	1.94	1.53	2.31	3.36	2.78	1.10	3.78	5	3.23	1,74
5L NBE	1.76	1.08	2.89	1.52	1.75	3.18	3.43	2.50	1.84	4,17
5L WBE	1.28	0.84	1.30	1.13	0.36	1.92	2.95	1.67	0.57	1,59

The calculation of air permeability coefficient has been used (Kuraman N.K. 2006) to interpret the values of the air leakage with the following formula.

$$k_a = J_a \cdot l/(A \cdot \Delta p), \qquad (3.3.1)$$

where

J_a is air flow rate (m^3/sec) across an area A (m^2),

l is the thickness of the specimen.

The area A is equal to 1,38 m * 0,38 m, l is equal to 0,03 m, 1 lt/min of air at temperature 21 degrees is equal to 0,0000167 m^3/sec.

Δp is the difference in air pressure across the specimen surfaces (Pa). Basically dimensions and thickness of samples are the same, but air flow and pressure different are different in the different steps and for each specimen. In Table 9, Figure 24 the initial average values of k_a, in Table 10, and Figure 25 the final average values of k_a.

Table 9.Values of initial air permeability coefficients at RH 50% and RH 30%

	RH 50% (cycle RH 70-10)		**RH 30% (cycle RH 30-10)**	
	Face A	**Face B**	**Face A**	**Face B**
3L NBE	-	2.88E-008	1.06E-007	5.12E-008
3L WBE	9.09E-009	3.98E-009	5.25E-009	3.62E-009
5L NBE	7.77E-009	4.59E-009	3.05E-009	7.61E-009
5L WBE	3.02E-009	1.46E-009	6.31E-010	8.17E-009

Table 10.Values of air permeability coefficients at RH 10%

	RH 10% (RH 70-10)		**RH 10% (RH 30-10)**	
	Face A	**Face B**	**Face A**	**Face B**
3L NBE	2.99E-007	5.97E-007	8.20E-007	8.08E-008
3L WBE	1.53E-007	3.52E-008	8.53E-009	5.36E-009
5L NBE	4.44E-008	1.02E-007	3.65E-008	6,25E-008
5L WBE	5.53E-008	2.17E008	9.84E-010	2.76E-009

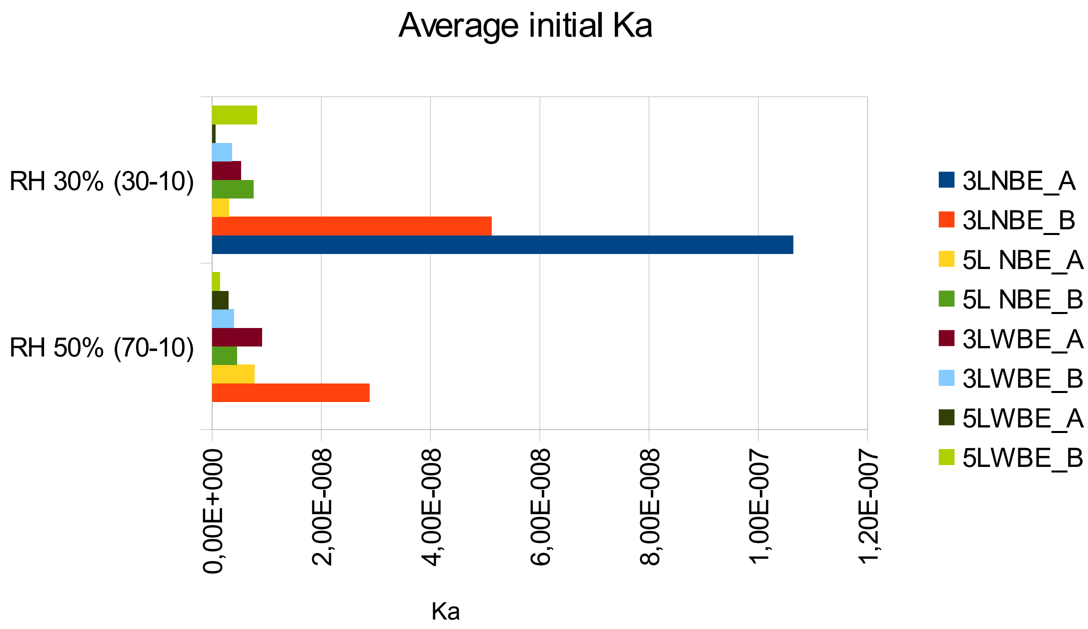


Figure 24.Chart Air Permeability coefficients k_a for all the panels in the initial conditions at RH 50% (cycle RH 70-10%) and RH 30%. (cycle RH 30-10%)

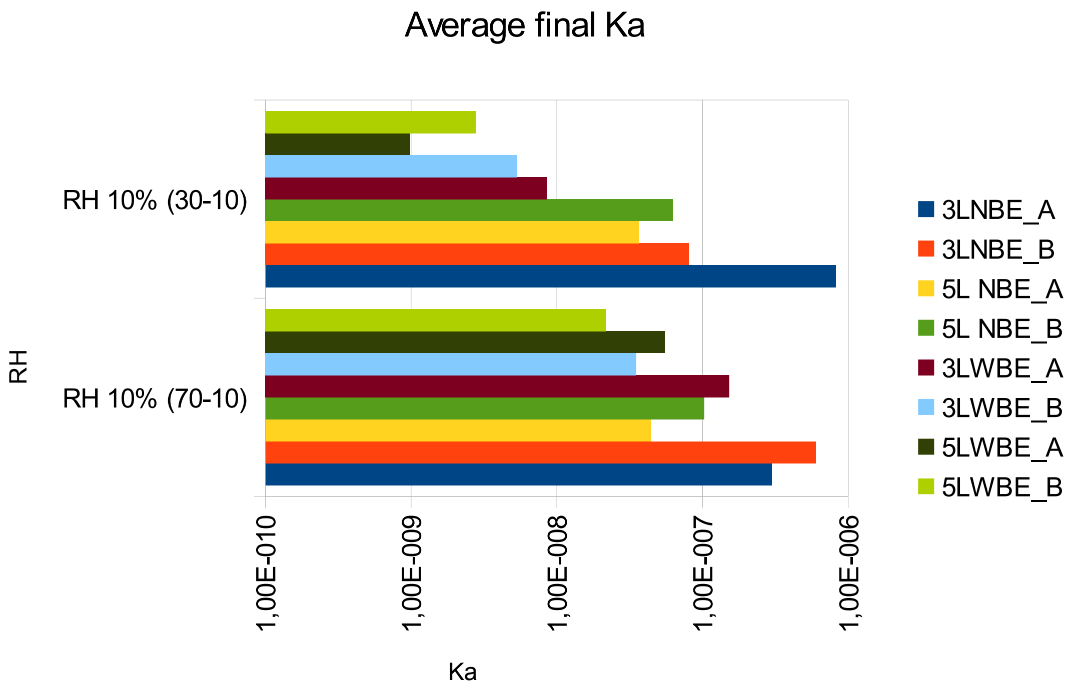


Figure 25.Chart Air Permeability coefficients k_a for all the panels in the final conditions at RH 10% (cycle RH 70-10 and cycle RH 30-10).

3.3.1 Air leakage developing and relationship with MC

It was possible to apply the maximum pressure of 550 Pa, for 8 samples (out of 12 samples) after the conditioning from RH 70% to RH 30%. At RH 30%, with one cycle almost completed and the second one just started, air leakage decreases if the number of layers increase and if the edges are bonded. The difference in air leakage between the faces is lower for not bonded edges samples than bonded edges samples. It seems that for bonded edges air-tightness is related to some defect on the edges of the specimens. Finally on the initial moisture contain, the lower value of leakage between the faces in RH 30% cycle is lower than the related value of the longer cycle (RH 70%). Exception is the case of three layers not bonded edges, generally with deep and wider gaps between lamellae (due our device, it was not possible to keep them airtight in order to investigate the core of the panels) and a lower quality (due the using of the hydraulic press).

At RH 10%, in most cases the air leakage is lower in the samples with the shorter conditioning steps (RH 30-10%); there is only one dissimilarity, actually like in the specimens with longer conditioning steps (RH 70-10%), the panels with three layers and no bonded edges. It must be said as the tests on this type of panels is heavily conditioned by the flow though the gaps and the edges.

To remark how from a cycle to another, in the panel with lower air-permeability the applicable pressure decrease.

To summarize (Tables 12-15), marching the initial (RH 50% and RH 30%) and final (RH 10%) conditions of both cycles;

- Initially only the 3 layers no bonded edges panels of short cycle had an higher air leakage than the corresponding panels of long cycle (increased 21.93% face A increased 39.64% face B);

- Initially in 3 layers bonded edges (decreased 28.10%), 5 layers bonded edges (decreased 71.88%) and not bonded edges (decreased 0.57%) of short cycle had, at least one face, air leakage lower than the corresponding panels of long cycle;

- To underline the difference between 5 layers not bonded edges (decreased 0.57%) and 3 layers bonded edges (decreased 28.10%), even with less layers but bonded air leakage was lower;

- Initially the best typology of panels was 5 layers with bonded edges (decreased 71.88%);

- At the end of both cycles, all the panels of shorter cycle had lower air leakage of the panels in longer cycle;
- At the end of experiment also 3 layers not bonded edges of shorter cycle had same or lower (0.00%/ decreased 3.20%) air leakage than corresponding panels of longer cycle;
- At the end the best typology of panels was 5 layers with bonded edges (decreased 80.68%);
- At the end, as in the initial stage, 3 layers panels with bonded edges had lower air leakage (decreased 65.20%) of 5 layers not bonded edges (decreased 46.36%);
- to remark the different percentages between the shorter cycle and longer cycle in the initial and final stage;

About relationship air leakage and cracks/gaps developing:

- At the end of both cycles the 3 layers panels in shorter cycle had a predictable behaviour with a lower cracks/gaps increasing (3 layers no bonded edges decreased 18.20%/5.82%, 3 layers with bonded edges decreased 27.83%/30.12%);
- At the end of both cycles the 5 layers panels in shorter cycle had particular behaviour related to air leakage: no bonded edges panels had increased 0.14% in width and decreased 6.64% in length, compared to the longer cycle, bonded edges even increased 11.63% in width and increased 2.68%;

The data on 5-layers panels supposedly due to the glue (Increasing of inner stress between lamellae) and the thickness (6 mm) of lamellae itself. In other hands, the decreasing of air leakage, in 5-layers with bonded edges, is strongly related to the 4 glue layers. A remark that can be made is that only the cracks in the outer layers are been studied; in this study is not possible to say what happens in the inner layers.

The calculation of air permeability coefficient (Kuraman N.K. 2006) was necessary to match the data of air flow in case it was not possible to apply the same pressure differences on the specimens. At the beginning of the cycles, according to air leakage measurements, the values for the three layers not bonded edges panels are completely out of the range of the rest of the specimens, due wider gaps. In other types, the shorter conditioning cycle (RH 30-10%) has lower permeability than the longer cycle (RH 70-10%). At the end of the tests (RH 10%) all the data are more homogeneous than the beginning of the experiment, the three layers no bonded edges still have higher values than all the other types, but clearly the shorter cycle shown lower permeability coefficients.

"Wu (2007) reported air permeance of spruce to be (7.2 ±1) x 10^{-9} kg/(m Pa *s) using pressure differences ranging from 50 to 350 Pa. Moreover, Raji et al. (2009) tested specimens with and without laminate, and found that specimens with laminate had low air permeability. It was concluded that the difference in air permeability will have minimal influence due to the very low permeability of wood at large thicknesses"* (Alsayegh et al. , 2012).

The pressure tests difference was from 50 to 550 Pa and the initial k_a values were lower than the value of (7.2 ±1) x 10^{-9} kg/(m* Pa *s) for all the types and with both conditioning cycles, except the not bonded edges panels. At the end of tests only bonded edges panels with a shorter conditioning cycle (RH 30-10%) had a k_a higher that the value of the solid spruce. Summarizing (Tables 11);

- At the beginning of both cycles only 3 layers panels no bonded edges and shorter conditioning cycle had Air permeability higher than the corresponding panels of longer cycle (increased 77.78%);
- At the beginning all the rest of panels in shorter cycle had lower air permeability than the corresponding panels in longer cycle (decreased 9.05%/ 79.11%);
- At the final of both cycles all the panels in the shorter cycle had a considerably lower air permeability (decreased 17.79%/ 100%).

Table 11.Increasing/decreasing percentages Initial and final of sample for Cracks and Gaps, Air Leakage and Air Permeability

<table>
<tr><td colspan="5">Crack and Gaps Developing</td></tr>
<tr><td></td><td colspan="4">RH 30-10 (Cycle 70-10/ Cycle 30-10)</td></tr>
<tr><td></td><td colspan="2">Av ΔW</td><td colspan="2">Av ΔL</td></tr>
<tr><td>3L NBE</td><td colspan="2">-18.20%</td><td colspan="2">-5.82%</td></tr>
<tr><td>3L WBE</td><td colspan="2">-27.83%</td><td colspan="2">-30.12%</td></tr>
<tr><td>5L NBE</td><td colspan="2">0.14%</td><td colspan="2">-6.64%</td></tr>
<tr><td>5L WBE</td><td colspan="2">11.63%</td><td colspan="2">2.68%</td></tr>
<tr><td colspan="5">Air Leakage</td></tr>
<tr><td></td><td colspan="2">RH 50 (Cycle 70-10) / RH 30 (Cycle 30-10)</td><td colspan="2">RH 10
Cycle 70-10/ Cycle 30-10</td></tr>
<tr><td></td><td>Face A</td><td>Face B</td><td>Face A</td><td>Face B</td></tr>
<tr><td>3L NBE</td><td>39.64%</td><td>21.93%</td><td>0.00%</td><td>-3.20%</td></tr>
<tr><td>3L WBE</td><td>43.30%</td><td>-28.10%</td><td>-14.55%</td><td>-65.20%</td></tr>
<tr><td>5L NBE</td><td>-0.57%</td><td>194.44%</td><td>-46.36%</td><td>66.80%</td></tr>
<tr><td>5L WBE</td><td>-71.88%</td><td>128.57%</td><td>-8.68%</td><td>-4.79%</td></tr>
<tr><td colspan="5">Air Permeability</td></tr>
<tr><td></td><td colspan="4">RH 50 (Cycle 70-10) / RH 30 (Cycle 30-10)</td></tr>
<tr><td></td><td colspan="2">Face A</td><td colspan="2">Face B</td></tr>
<tr><td>3L NBE</td><td colspan="2">-</td><td colspan="2">77.78%</td></tr>
<tr><td>3L WBE</td><td colspan="2">-42.24%</td><td colspan="2">-9.05%</td></tr>
<tr><td>5L NBE</td><td colspan="2">-60.75%</td><td colspan="2">65.80%</td></tr>
<tr><td>5L WBE</td><td colspan="2">-79.11%</td><td colspan="2">459.59%</td></tr>
<tr><td></td><td colspan="4">RH 10 (Cycle 70-10) / RH 30 (Cycle 30-10)</td></tr>
<tr><td></td><td colspan="2">Face A</td><td colspan="2">Face B</td></tr>
<tr><td>3L NBE</td><td colspan="2">174.25%</td><td colspan="2">-86.47%</td></tr>
<tr><td>3L WBE</td><td colspan="2">-94.42%</td><td colspan="2">-84.77%</td></tr>
<tr><td>5L NBE</td><td colspan="2">-17.79%</td><td colspan="2">-38.73%</td></tr>
<tr><td>5L WBE</td><td colspan="2">-98.22%</td><td colspan="2">-100%</td></tr>
<tr><td colspan="5">3-5 L: number of layers
NBE: no bonded edges
WBE: with bonded edges
Av ΔW average increasing of the width of crack/gap
Av ΔL average increasing of the length of crack/gap
Cycle 70-10: RH70-RH50-RH30-RH10
Cycle 30-10: RH30-RH10</td></tr>
</table>

3.3.2 Aspects of working with dried lamellae

The drier lamellae (RH30-RH10% smaller cycle of conditioning) showed a more a lower air leakage than the lamellae conditioned with a longer cycle and from RH 70%. at RH 30% the MC was 6.00%, actually lower than the lower limit for the gluing (PUR). It is possible to find in the market CLT in the range of 8 to 12 % ±2% (Brandner R. *et al.* , 2014). If the MC of CLT panel is in the range 6-22% then the in plane shrinkage and swelling in both direction is 0.02% per each percent of MC change (0.24% out of the plane) (Brandner R. *et al.* , 2014).

In current research in the final conditioning cycle the highest change in dimensions was up to 0.22% for 10 percent of MC change (from 12% to 2%). Average price for kiln drying cycle of 80-100 m^3 of timber in Estonia is around 2.000 euro (20-25 euro/m^3) plus taxes. For mass production the lowest MC limit for kiln drying is around 8-10%, in relation to use. To dry at a lower level, other techniques are necessary with a price certainly higher than kiln drying prices.

Conclusion

The aims of current Master’s thesis were to investigate how the air-permeability properties of different cross-laminated panels change with different initial relativity humidity conditions and after different steps of conditioning cycle. The panels were made with different number of layers (but same overall thickness) and with bonded edges or without bonded edges. In different environmental conditions on the wood surface cracks and gaps will change their length and width. After performing the tests, it was possible to draw conclusion and give suggestions for further studies.

1. Improving the apparatus and box design to be able to test also panels with bigger dimensions. The weakness of the apparatus was the functionality of the air valve and the clamping system. To perform Air permeability tests according to EVS EN 12114 standard (with different pressures to apply) the air control should be automatic or done by a software. Clamping and/or additional metal frame system should avoid the air flow from the edges of the panels (in case of not bonded edges specimens).

2. In the CLT manufacturing the initial grading of timber boards is one of the most important phase of this process. The raw material for lamellae for this scientific experiment came from a commercially available timber product, which was not intended to use for the CLT manufacturing. This means the wood defects like knots, cupping, twisting, resin ducts etc. affected the quality of the CLT panel. In the industrial production of CLT there is a phase of grading and finger jointing to improve the quality of final product.

3. The panels with lamellae at lower initial MC had lower air leakage and higher air permeability than the panels with lamellae at higher MC, due to lower shrinkage. In both cycles, the best panels had 5-layers with bonded edges (Table 15). The higher is the MC the bigger is change in the dimensions lamellae on surface layer of CLT panel. Consequently, air leakage would be higher in that case. The 5-layer panels with bonded edges showed particular behaviour in short conditioning cycle with increasing or decreasing of the cracks/gaps. In the short cycle they had faster crack growth than the 5-layer panels tested with longer conditioning cycle. 5-layer panels without bonded edges, which were tested with shorter cycle, had a similar growth of cracks and gaps than those ones tested in longer cycle. Supposedly due to the bigger number of glued layers in 5-layer panels compared to 3-layer panels.

4. The manufacturing process of CLT panels with bonded edges needs to be improved. A wooden jig and stripes do not provide in all cases the right lateral pressure to the lamellae. This step is also strongly influenced by the timber quality (cupping, twisting etc). A good solution for future tests could be a metal frame with lateral screws.

5. The air leakage from the panel edges during the pressure tests was a problem. Sealing the CLT panel edges with air thigh tape is one possible solution for further studies to avoid the leakage of air from the wider gaps of not bonded edges panels.

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Summary

The main objective of this research project was to study how the air-permeability properties of different cross-laminated timber panels change in environmental conditions with different initial relativity humidity and after different conditioning steps.

For manufacturing the CLT panels the initial C24 strength class spruce boards 4,5m in length and with cross-section 95*18mm came from company Raitwood. Panels were made in Laboratory of Wood Technology in TTÜ, Ehituskool Tallinn and Peetri Puit OÜ facility in Põlva. Twenty four panels (1300*460 mm) were made with different number of layers (same overall thickness of 30 mm) and with bonded edges or without bonded edges.

It was assumed that in different environmental conditions cracks and gaps on the wood surface will change their dimensions (length and width). Twelve panels were in a longer conditioning cycle, in a climate chamber, from RH 70%, 50%, 30% to RH 10%, (MC of the panels changed from 10% to 3%). Twelve panels were conditioned in a shorter cycle from RH 30% to RH 10%. In different conditioning cycles the same type of panels were used: 3-layer panels with and without bonded edges, 5-layers with and without bonded edges.

One cycle of conditioning lasted 30 days, at the end of each cycle MC measurements, cracks and gaps measurements were taken and Air Permeability test was performed. After each conditioning cycle panels became less air-tight than compared to the previous one.

The 5.layer CLT panels with lower initial MC had smaller cracks and consequently more airtightness. Based on air-tightness test results the worst kind of panels were the 3-layer CLT panels without bonded edges and the best kind ones were the 5-layers with bonded edges.

It was remarked that 5-layer CLT panels prepared from lamellae with lower initial moisture content had after short conditioning cycle similar or slightly higher growth of cracks and gaps than 5-layer panels with higher initial moisture content and longer conditioning cycle.

Kokkuvõte

Magistritöö eesmärgiks oli uurida, kuidas erineva algniiskusega lamellidest valmistatud ristkihtliimpuidust paneelide õhupidavus muutub konditsioneerides neid erinevate suhtelise õhuniiskusega keskkondade juures. Ristkihtliimpuidust paneelide valmistamiseks kasutati C24 tugevusklassiga kuusepuidust neljast küljest hööveldatud ja 4,5m piikusi laudu ristlõikega 95*18mm, mis osteti ettevõttest Raitwood.

Ristkihtliimpuidust paneelid valmistati Tallinna Tehnikaülikooli puidutehnoloogia laboris, Tallinna Ehituskoolis ja Põlvas asuvas ettevõttes Peetri Puit OÜ. Kooku valmistati 24 erinevate kihtide arvuga ning nii liimitud kui liimimata servadega ristkihtliimpuidust paneeli (mõõtudega 1300x460 mm, paksusega 30 mm).

Enne katsete läbiviimist eeldati, et erinevates keskkonnatingimustes erineva algniiskusega lamellidest valmistatud paneelide pinnakihis praod ja lõhed muudavad oma pikkust ja laiust, vastavalt puidu niiskussisalduse muutusest põhjustatud puidu kuivamiskahanemisele või pundumisele.

Kaksteist paneeli olid kliimakambris pikemas konditsioneerimistsüklis, mille suhteline õhuniiskuse etapid olid 70%, 50%, 30% ja lõpetuseks kuni 10% (algniiskus alates 10% kuni 3%-ni). Teised kaksteist paneeli olid lühemas kliimatestimise tsüklis, kus suhteline õhuniiskus muutus vaid 30%-st kuni 10%-ni. Mõlemas kliimatsüklis olid testimisel sama tüüpi 3-kihilised paneelid: nii liimitud kui liimimata servadega ja 5-kihilised liimitud ja liimimata servadega paneelid. Üks konditsioneerimise tsükkel kestis 30 päeva. Peale igat tsüklit muutusid paneelid järjest vähem õhukindlamaks. Iga tsükli lõpus toimus niiskusesisalduse ja pragude ning lõhede mõõtmine seejärel viidi läbi õhupidavuse test.

Madalama esialgse niiskusesisaldusega paneelidel olid väiksemad praod ja sellest tulenevalt parem õhutihedus. Peale kliimateste olid kõige halvemas seisukorras kolmekihilised paneelid liimimata servadega ning kõige paremas seisukorras viiekihilised paneelid liimitud servadega. Madalama algniiskusega viiekihilistel paneelidel, mida testiti lühikese konditsioneerimistsükliga, olid samasugused või veidi sügavamad praod ja lõhed kui 5-kihilistel paneelidel, mis valmistati algselt kõrgema esialgse niiskusesisaldusega puitlamellidest.

Appendix 1

List, type and dimensions of the samples

Panel	Layers	Technology	Width (cm)	Length (cm)	W (cm) RH 10%	L (cm) RH 10%
P1	3	WBE	46,3	130	46,3	130
P2	3	WBE	46,6	129	46,6	129
P3	3	WBE	46,4	129,7	46,3	129,7
P1	5	WBE	46,9	129,9	46,9	129,8
P2	5	WBE	46,3	130	46,3	129,8
P3	5	WBE	46,5	130	46,5	129,9
P1	5	NBE	47,5	130	47,4	129,8
P2	5	NBE	47,5	130	47	129,8
P3	5	NBE	47,5	130	47,4	129,8
P1	3	NBE	47,5	130	47,5	129,8
P2	3	NBE	47,5	130	47,4	129,9
P3	3	NBE	47,5	130	47,4	129,8
A3	3	NBE	47,6	130	47,6	130
B3	3	NBE	47,7	130	47,6	130
C3	3	NBE	47,5	130	47,5	130
A5	5	NBE	47,8	130	47,7	130,0
B5	5	NBE	47,7	130	47,6	130,0
C5	5	NBE	47,5	130	47,5	130,0
A3	3	WBE	46,1	130	46,1	130,0
B3	3	WBE	46,4	130	46,3	130,0
C3	3	WBE	46	130	46	130
A5	5	WBE	46,3	130	46,3	130,0
B5	5	WBE	46,4	130	46,4	130,0
C5	5	WBE	46,6	130	46,5	130,0

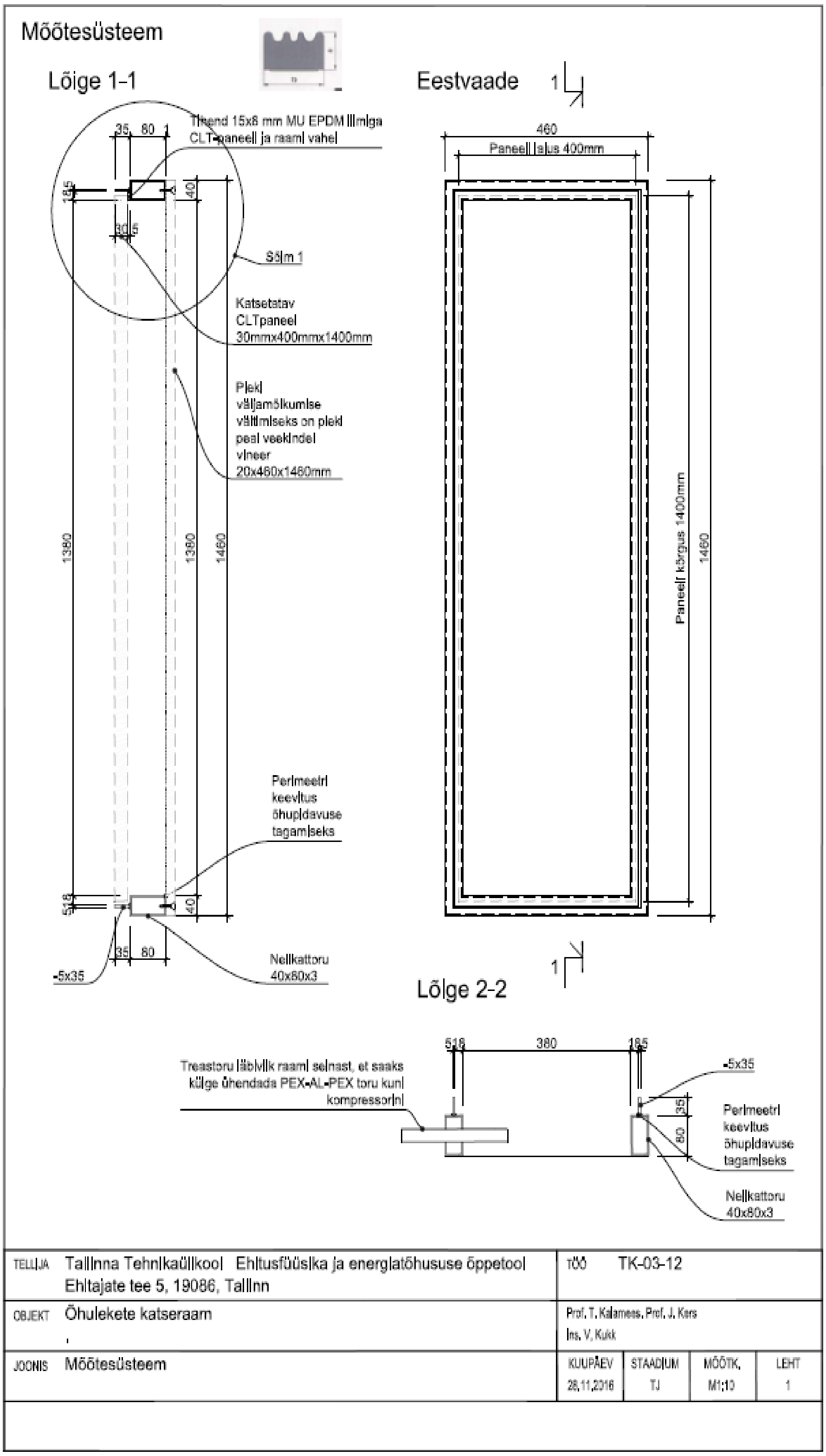
Appendix 2

Moisture content of the samples

TTÜ/Ehituskool							
Panel	**Layers**	**Tec.**	**Made**	**MC RH 70**	**MC RH 50**	**MC RH 30**	**MC RH 10**
P1	3	WBE	1.2.17	11,50%	9,00%	5,90%	3,30%
P2	3	WBE	1.2.17	10,00%	9,30%	6,30%	3,10%
P3	3	WBE	1.2.17	10,00%	9,10%	6,30%	3,50%
P1	3	WGE	1.2.17	11,50%	9,00%	5,90%	3,30%
P2	3	WGE	1.2.17	10,00%	9,30%	6,30%	3,10%
P3	3	WGE	1.2.17	10,00%	9,10%	6,30%	3,50%
Arcwood							
P1	5	NBE	7.4.17	11,70%	9,40%	5,40%	3,30%
P2	5	NBE	7.4.17	12,70%	8,90%	6,20%	3,40%
P3	5	NBE	7.4.17	13,20%	8,70%	5,20%	3,80%
P1	3	NBE	7.4.17	14,30%	9,70%	6,90%	2,20%
P2	3	NBE	7.4.17	14,60%	9,70%	7,10%	2,00%
P3	3	NBE	7.4.17	15,10%	9,60%	6,80%	3,10%
A3	3	NBE	7.4.17	-	-	5,90%	3,60%
B3	3	NBE	7.4.17	-	-	6,20%	2,00%
C3	3	NBE	7.4.17	-	-	6,00%	3,70%
A5	5	NBE	7.4.17	-	-	5,90%	3,60%
B5	5	NBE	7.4.17	-	-	5,90%	3,60%
C5	5	NBE	7.4.17	-	-	5,80%	3,70%
A3	3	WBE	7.4.17	-	-	6,30%	4,20%
B3	3	WBE	7.4.17	-	-	5,30%	2,40%
C3	3	WBE	7.4.17	-	-	4,70%	3,50%
A5	5	WBE	7.4.17	-	-	6,80%	3,30%
B5	5	WBE	7.4.17	-	-	6,90%	3,60%
C5	5	WBE	7.4.17	-	-	6,30%	4,10%

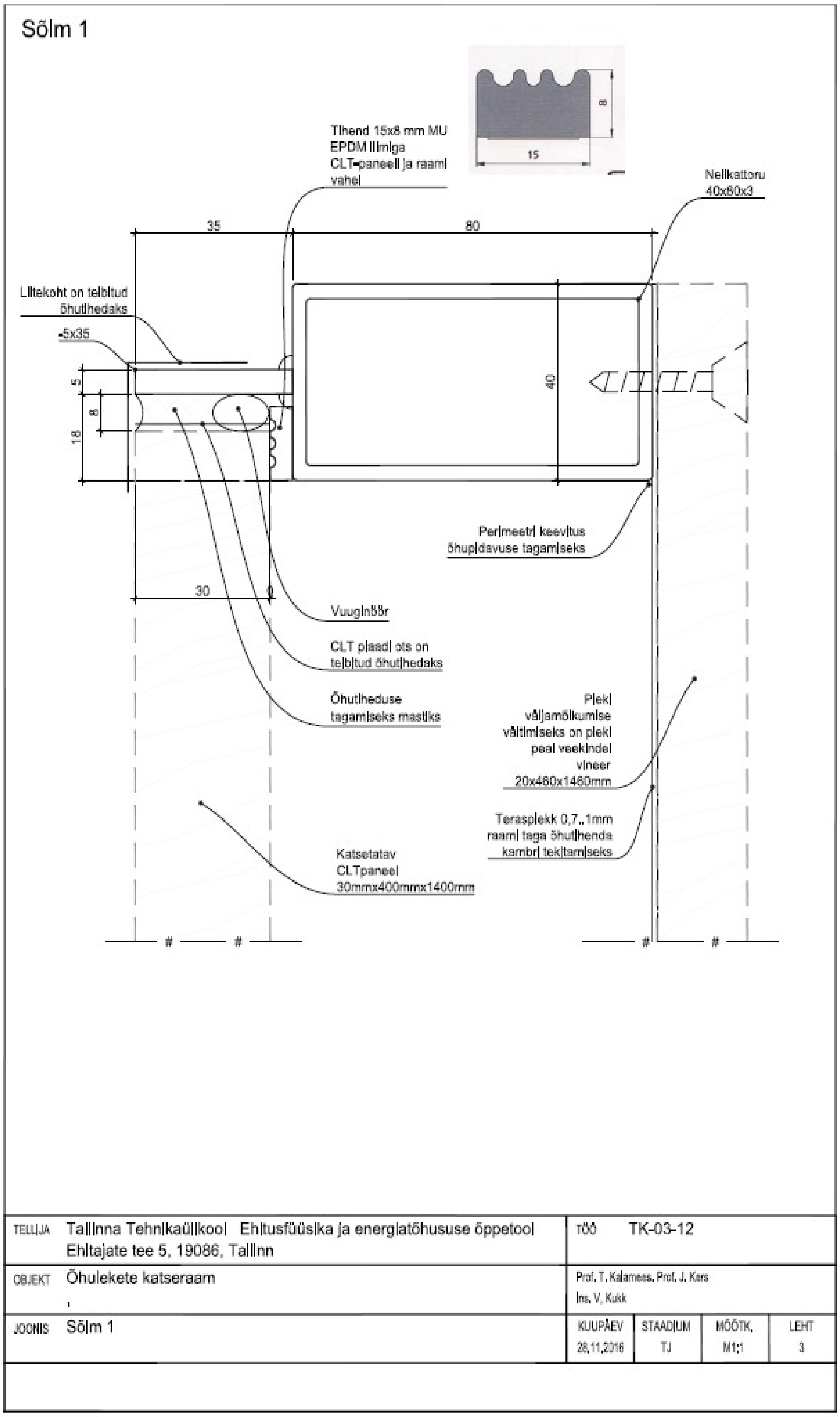
Appendix 3

Sheet of metal box : plan view and longitudinal section



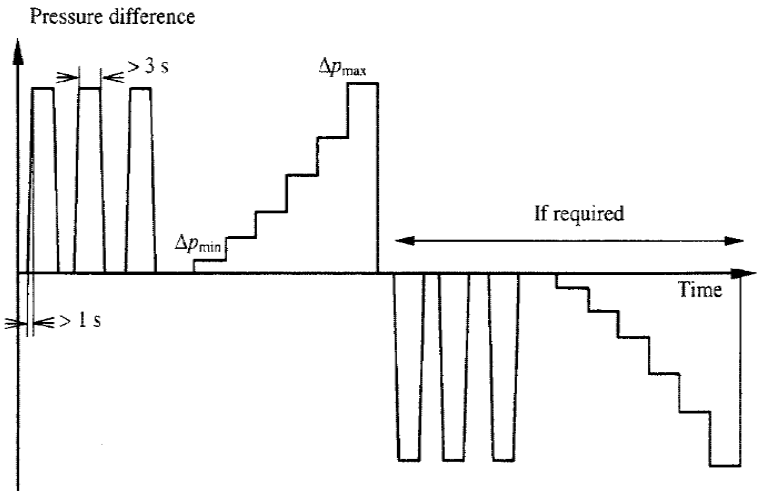
Appendix 4

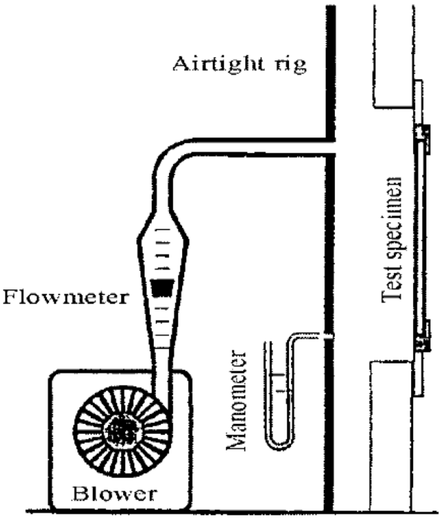
Sheet of metal box : detail of sealing



Appendix 5

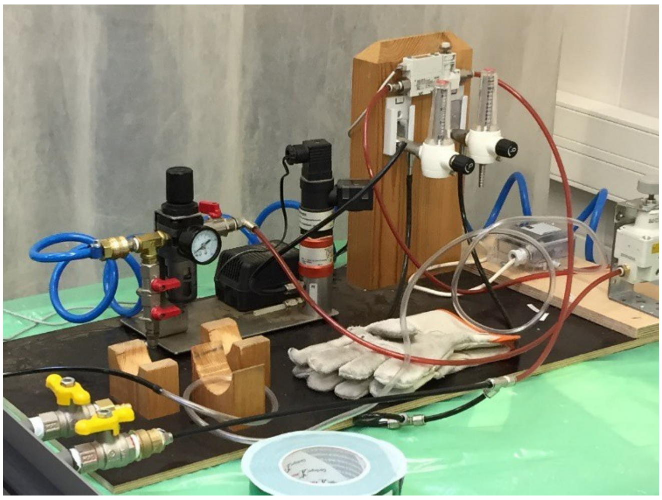
EVS EN 12144 Pressure steps (top) , apparatus (bottom)

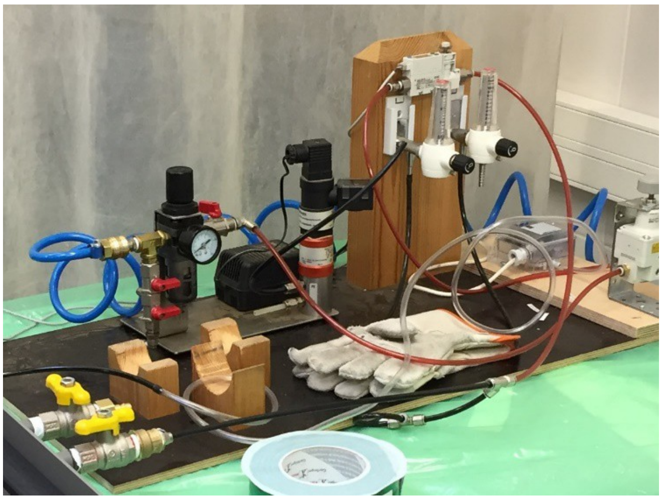


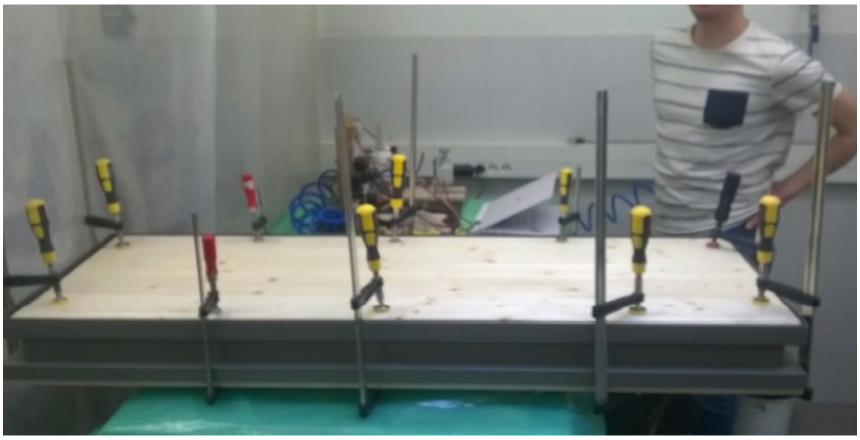


Appendix 6

Test Apparatus and box during test





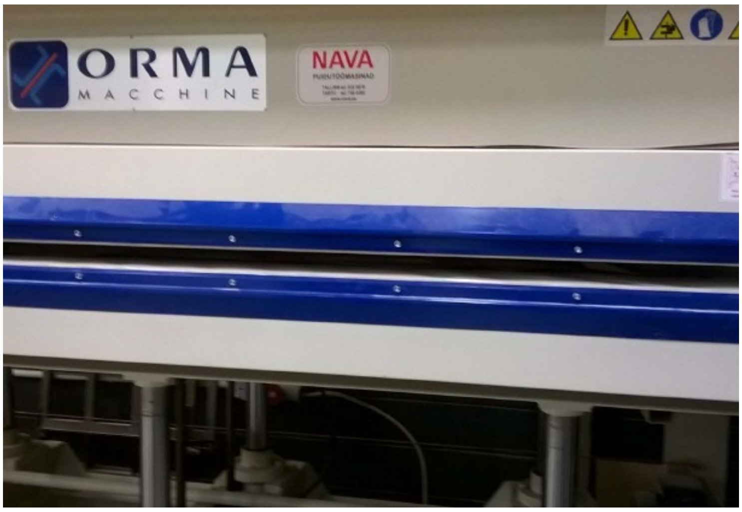


Appendix 7

Pictures of making process in Woodworking Laboratory. Top wooden jig, down wrapping

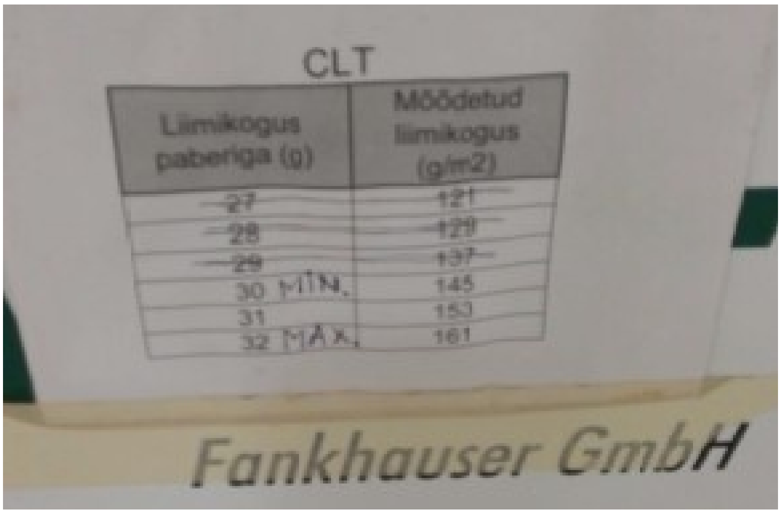
Appendix 8

Pictures of making process in Ehituskool Laboratory. Top planner, down hydraulic press



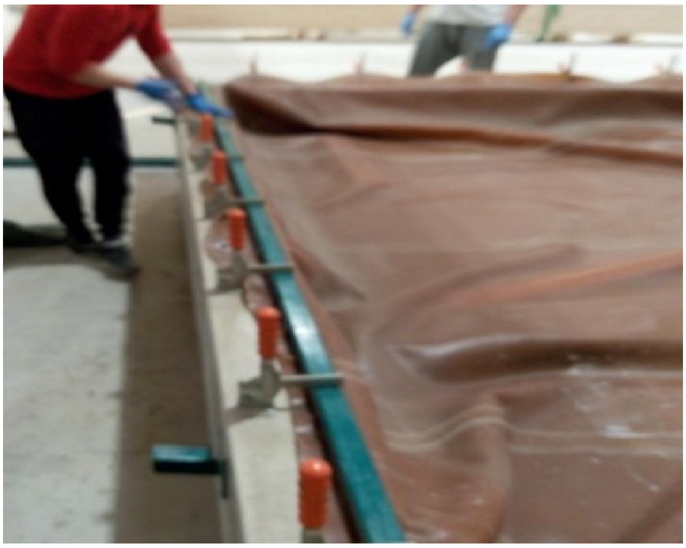
Appendix 9

Pictures of making process in Arc Wood (Peetri Puit) facility. Top gluing values table, centre application of paper tape on the edges of lamella, down gluing in vacuum press



Appendix 10

Pictures of making process in Arc Wood (Peetri Puit) facility. Top vacuum press ready for pressing time, down details of vacuum press fabric clamping system



Appendix 11

Climate chambers. Top Mechanical Department Laboratory, down Civil Engineer Department Laboratory

Appendix 12

Cracks and gaps measurements

Panel	Face	Craks Gaps	Date:06.02 W*L (mm)		Date:14.03 RH 50% W*L (mm)		Date:12.04 RH 30% W*L (mm)		Date: 23.05 RH 10% W*L (mm)	
P1 3LWBE	A									
	B	Gap1					0,63	1300	0,73	1300
		Crack 2							0,36	1040
		Gap 3							0,27	372
P2 3LWBE	A	Gap1	0,25	98	0,28	108	0,6	108	0,68	385
		Crack 2	0,1	44	0,1	44	0,1	68	0,1	68
		Gap 3	0,2	121	0,23	189	0,5	189	0,61	403
		Gap 4					0,46	551	0,5	680
		Crack 5					0,45	39	0,93	52
		Crack 6					0,33	399	0,81	442
		Crack 7					0,25	205	0,53	256
		Crack 8					0,13	112	0,44	622
		Crack 9					0,3	43	0,4	43
		Crack 10							0,25	370
	B	Gap1	0,8	181	0,82	181	0,82	181	1,12	181
		Gap2	0,5	49	0,5	49	0,65	112	0,8	531
		Gap3	0,2	367	0,2	367	0,28	367		
		Gap4			0,22	108	0,37	122	0,47	122
		Gap 5							0,37	122
		Crack 6							0,32	610
		Crack 7							0,25	242
		Crack 8							0,23	210
P3 3LWBE	A	Gap1	0,2	444	0,28	444	0,37	444	0,43	444
		Crack 2	0,6	5,8	0,7	5,8	1,35	56	0,9	56
		Crack 3	0,2	36	0,2	36	0,275	36	0,25	36
		Gap 4					0,53	328	1,1	380
		Crack 5							0,62	1300
		Crack 6							0,64	1300
		Crack 7							0,47	450

		Gap 8							0,6	241
		Crack 9							0,7	830
		Crack 10							0,6	204
		Crack 11							0,6	214
	B	Gap1	0,35	278	0,4	278	0,55	278	0,48	584
		Gap 2	0,2	440	0,2	440	0,33	440	0,53	440
		Gap 3			0,23	240	0,23	240	0,47	240
		Crack 4							0,62	834
		Crack 5							0,23	134
P1 5LWBE	A	Gap 1	0,4	10	0,9	10	0,9	10	0,9	10
		Crack 2	0,1	68	0,38	74	0,52	94	1,1	333
		Gap 3	0,3	73	0,43	73	0,8	73		
		Res dut 4	1,5	37	1,5	37	1,5	37	1,5	37
		Gap 5	0,2	158	0,27	182	0,43	182	0,6	281
		Res dut 6	1,15	21	1,15	21	1,15	21	1,15	21
		Gap 7	0,1	141	0,17	141	0,2	339	0,33	339
		Res dut 8	1,5	38	1,5	38	1,5	38	1,5	38
		Crack 9			0,2	20	0,25	33	0,25	33
		Crack 10			0,175	60	0,18	60	0,5	372
		Crack 11			0,3	205	0,3	205		
		Crack 12							0,56	1135
		Crack 13							0,6	1300
		Crack 14							0,33	380
		Gap 15							0,23	346
	B	Gap 1	0,63	1299	0,63	1299	0,63	1299	0,66	1299
		Gap 2	0,47	106	0,4	1224	1,2	1224	0,53	1224
		Gap 3	0,25	230	0,3	335	0,3	335	0,3	335
		Gap 4	0,28	118	0,3	164	0,38	164	0,55	164
		Crack 5							0,33	742
		Crack 6							0,28	540
P2 5LWBE	A	Gap 1	0,25	51	0,2	78	0,28	78	0,28	78

		Gap 2	0,25	21	0,3	26	0,33	26	0,33	26
		Crack 3					0,28	1009	0,66	1300
		Crack 4					0,22	384	0,5	1300
	B	Crack 1	0,3	137	0,2	137	0,15	137	0,25	137
		Crack 2							0,35	734
		Crack 3							0,27	365
		Crack 4							0,3	520
		Crack 5							0,28	260
P3 5LWBE	A	Res dut 1	1,5	31	1,5	31	1,5	31	1,5	31
		Crack 2	0,1	225	0,15	270	0,15	270	0,27	312
		Crack 3	0,1	65	0,17	83	0,17	270	0,4	124
		Crack 4					0,1	52	0,3	1215
		Crack 5							0,23	245
		Crack 6							0,23	353
		Crack 7							0,3	164
	B	Crack 1							0,36	1300
P1 5LNBE	A	Crack 1			0,15	156	0,2	245	0,33	965
		Crack 2			0,15	135	0,22	224		
		Gap 3			0,25	1300	0,43	1300	0,68	1300
		Gap 4			0,24	1300	0,42	1300	0,66	1300
		Gap 5			0,38	1300	0,44	1300	0,62	1300
		Gap 6			0,31	1300	0,48	1300	0,66	1300
		Gap 7			0,37	234	0,37	234	0,3	1300
		Crack 8					0,17	373	0,44	1300
		Crack 9					0,15	244		
	B	Gap 1					0,28	814	0,4	815
		Gap 2					0,23	158	0,4	1040
		Crack 3							0,2	1300
		Crack 4							0,2	65
P2 5LNBE	A	Gap 1			0,31	1300	0,52	1300	0,54	1300
		Gap 2			0,3	1300	0,36	1300	0.54	1300
		Gap 3			0,28	1300	0,38	1300	0,68	1300
		Gap 4			0,36	1300	0,51	1300	0,74	1300
		Gap 5			0,19	1300	0,33	1300	0,52	1300
		Crack 6			0,25	81	0,2	192	0,3	192
		Crack 7			0,1	64	0,15	64	0,3	64

		Crack 8					0,3	419	0,4	810
		Crack 9					0,2	70	0,43	510
	B	Gap 1			0,2	433	0,2	433	0,3	433
		Gap 2			0,1	442	0,1	442	0,2	442
		Gap 3			0,2	402	0,25	402	0,4	402
		Crack 4							0,3	760
		Gap 5							0,3	444
		Gap 6							0,3	490
P3 5LNBE	A	Res dut 1	2,5	40	2,5	40	2,5	40	2,5	40
		Res dut 2	1,5	30	1,5	30	1,5	30	1,5	30
		Res dut 3	1,5	38	1,5	38	1,5	38	1,5	38
		Gap 4			0,22	530	0,27	530	0,4	530
		Gap 5			0,28	587	0,4	587	0,5	587
		Gap 6					0,23	147	0,4	147
		Crack 7					0,2	177	0,5	912
		Crack 8					0,27	119		
		Crack 9					0,23	100		
		Crack 10					0,3	119		
		Gap 11					0,23	320	0,3	320
		Crack 12							0,36	1300
		Crack 13							0,2	143
		Crack 14							0,2	95
	B	Gap 1			0,33	1300	0,46	1300	0,4	1300
		Gap 2			0,15	1300	0,24	1300	0,28	1300
		Gap 3			0,3	1300	0,46	1300	0,52	1300
		Gap 4			0,26	1300	0,44	1300	0,54	1300
		Gap 5			0,26	1300	0,43	1300	0,64	1300
		Crack 6							0,2	230
		Crack 7							0,4	90
		Crack 8							0,2	117
P1 3LNBE	A	Gap 1	0,1	1300	0,88	1300	1,28	1300	1,9	1300
		Crack 2	0,1	125	0,3	298	0,27	298	0,43	300

		Gap 3			0,5	1300	0,96	1300	1,9	1300
		Gap 4			0,4	1300	0,66	1300	1,08	1300
		Gap 5			0,45	1300	0,57	1300	1,02	1300
		Gap 6			0,28	1300	0,54	1300	1,1	1300
		Crack 7							0,53	425
		Crack 8							0,55	194
	B	Gap 1			0,39	1300	0,63	1300	0,71	1300
		Gap 2			0,26	1300	0,39	1300	0,73	1300
		Gap 3			0,37	1300	0,63	1300	1,01	1300
		Gap 4			0,15	1300	0,28	1300	0,53	1300
		Gap 5			0,4	1300	0,41	1300	0,65	1300
		Crack 6							0,45	205
		Crack 7							0,37	206
		Crack 8							0,35	197
		Crack 9							0,37	297
		Crack 10							0,42	361
		Crack 11							0,37	297
		Crack 12							0,42	361
		Crack 13							0,37	156
		Crack 14							0,47	315
		Crack 15							0,53	408
		Crack 16							0,43	213
P2 3LNBE	A	Gap 1	0,1	128	0,9	1300	1,2	1300	2,13	1300
		Crack 2	0,3	108	0,55	120	0,55	120	0,55	120
		Gap 3	0,1	206	1,4	1300	1,7	1300	2,3	1300
		Gap 4			0,2	1300	0,47	1300	0,74	1300
		Gap 5			0,25	1300	0,53	1300	0,98	1300
		Gap 6			0,73	1300	1,05	1300	1,9	1300
		Crack 7							0,23	108
		Crack 8							0,5	438
		Crack 9							0,41	83
	B	Crack 1			0,25	124	0,22	199	0,46	1066

		Gap 2			0,37	1300	0,55	1300	0,68	1300
		Gap 3			0,18	1300	0,37	1300	0,68	1300
		Gap 4			0,1	1300	0,29	1300	0,46	1300
		Gap 5			0,43	1300	0,7	1300	1,1	1300
		Gap 6			0,28	1300	0,4	1300	0,71	1300
		Crack 7					0,2	77	0,53	100
		Crack 8							0,55	74
		Crack 9							0,33	155
P3 3LNBE	A									
		Crack 1			0,1	107	0,45	557	0,77	578
		Gap 2			0,34	1300	0,45	1300	0,7	1300
		Gap 3			0,59	1300	0,85	1300	1,2	1300
		Gap 4			0,44	1300	0,54	1300	0,58	1300
		Gap 5			0,84	1300	1,06	1300	1,38	1300
		Gap 6			0,89	1300	1,1	1300	1,5	1300
		Crack 7					0,3	29	0,55	60
		Gap 8					0,5	138	0,77	152
		Gap 9					0,47	322	0,57	350
		Crack 10					0,47	285	0,77	295
		Crack 11					0,38	336	0,72	387
		Crack 12					0,35	304	0,26	410
	B	Gap 1			0,44	1300	0,68	1300	1,1	1300
		Gap 2			0,29	1300	0,58	1300	0,89	1300
		Gap 3			0,33	1300	0,42	1300	0,75	1300
		Gap 4			0,32	1300	0,42	1300	0,63	1300
		Gap 5			0,3	1300	0,38	1300	0,54	1300
		Crack 6					0,4	54	0,47	61
		Crack 7							0,25	584
		Crack 8							0,37	481
		Crack 9							0,61	1300
		Crack 10							0,2	230
A3 3LNBE	A	Gap 1					0,25	442	0,28	989
		Gap 2					0,23	726	0,32	1014
		Gap 3					0,17	430	0,2	430

									0,36	955
									0,25	524
	B	Gap 1					0,4	218	0,4	218
		Gap 2					0,45	100	0,45	100
		Gap 3							0,55	58
B3 3LNBE	A	Gap 1					0,23	1300	0,46	1300
		Gap 2					0,22	470	0,54	1300
		Gap 3					0,38	623		
		Gap 4					0,33	490	0,5	1300
		Gap 5					0,45	580		
		Gap 6							0,28	1300
		Gap 7							0,32	1300
	B	Gap 1					1,2	1300	1,2	1300
		Gap 2					0,75	192	0,8	192
		Gap 3					0,55	121	0,55	121
		Gap 4					0,33	171	0,35	171
		Gap 5					0,5	206	0,6	206
		Gap 6					0,5	182	0,6	182
C3 3LNBE	A	Gap 1					0,3	75	0,5	75
		Gap 2					0,45	72	0,5	72
		Gap 3					0,4	60	0,5	60
		Gap 4					0,45	36	0,5	36
	B	Gap 1					0,23	700	0,39	1207
		Gap 2					0,17	432	0,38	1300
		Gap 3					0,23	670	0,28	1300
		Gap 4					0,3	1074	0,42	1074
A5 5LNBE	A	Gap 1					0,3	150	0,4	150
		Gap 2					0,25	102	0,4	102
		Crack 3							0,2	739
	B	Gap 1					0,5	1300	0,68	1300
		Gap 2					0,19	1300	0,52	1300
		Gap 3					0,2	401	0,34	1300
		Gap 4							0,36	1300
		Crack 5							0,15	312
B5 5LNBE	A	Gap 1					0,35	1300	0,6	1300
		Gap 2					0,27	224	0,42	1300

		Gap 3							0,32	1300
		Gap 4							0,4	1300
	B	Gap 1					0,43	924	0,5	492
		Gap 2					0,27	208	0,4	208
		Gap 3					0,27	188	0,3	188
		Gap 4							0,3	540
		Gap 5							0,3	451
C5 5LNBE	A	Gap 1					0,2	60	0,3	60
		Gap 2					0,17	432	0,3	432
		Gap 3					0,23	235	0,3	235
	B	Gap 1					0,33	1050	0,48	1300
		Gap 2					0,33	1068	0,44	1300
		Gap 3					0,67	1300	0,74	1300
		Gap 4					0,1	480	0,25	1300
		Gap 5					0,2	466	0,3	1300
A3 3LWBE	A	Gap 1					0,94	1300	0,94	1300
		Gap 2					0,74	1070	0,74	1070
		Gap 3							0,29	978
		Gap 4							0,24	1028
	B	Gap 1					0,6	153	0,6	153
		Gap 2					0,35	250	0,35	250
B3 3LWGE	A	Gap 1					0,33	1120	0,32	1300
		Gap 2					0,92	1300	0,94	1300
		Gap 3					0,53	68	0,7	68
		Gap 4							0,47	222
	B	Gap 1					0,3	190	0,42	190
		Gap 2					0,43	110	0,43	110
C3 3LWBE	A									
	B									
A5 5LWBE	A	Gap 1					0,3	40	0,4	40
		Gap 2					0,5	206	0,55	206
	B	Crack 1					0,17	109	0,43	123
		Crack 2					0,2	828	0,28	990
		Crack 3							0,1	391
B5 5LWBE	A									

	B	Gap 1							0,65	37
C5 5LWBE	A									
	B	Crack 1							0,1	169
		Crack 2							0,1	395

Appendix 13

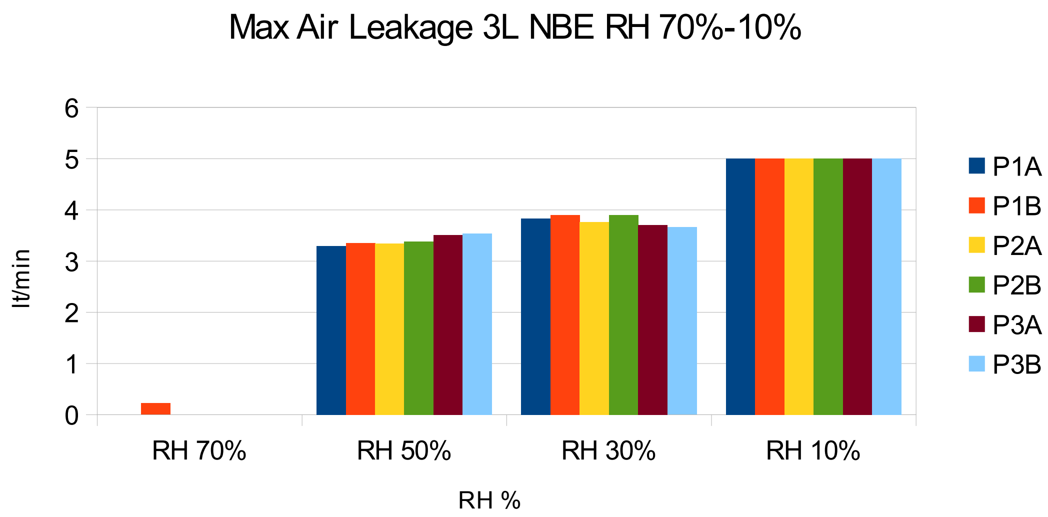
Air permeability test results

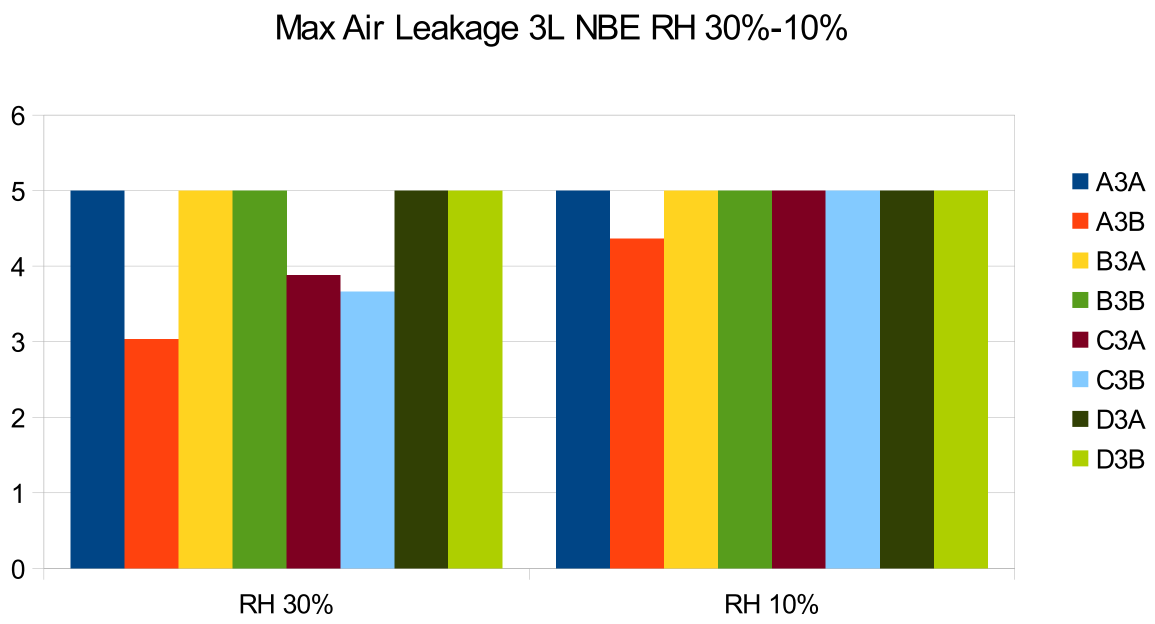
		RH 70%		RH 50%		RH 30%		RH 10%	
Panel	**Face**	**P (Pa)**	**A L (l/min)**	**P (Pa)**	**A L (l/min)**	**P (Pa)**	**A L (l/min)**	**P (Pa)**	**A L (l/min)**
3L NBE									
P1	A			0	3,29	0	3,83	0	5
	B	550	0,22	106	3,35	50	3,90	12	5
P2	A			0	3,34	0	3,76	16	5
	B	550	0	144	3,38	66	3,90	0	5
P3	A			0	3,51	0	3,7	0	5
	B	550	0	100	3,54	32	3,66	6	5
5L NBE									
P1	A					0	3,94	0	5
	B	550	0			550	0,20	550	1,85
P2	A	550	0	344	3,43	124	3,68	58	5
	B	550	0	550	0,37	550	1,09	550	3,15
P3	A	550	0	550	0	550	0,22		
	B	550	1,72	196	3,47	70	3,92		
P4	A	550	0	160	3,61	60	3,7	550	3,71
	B			550	0,47	550	0,85	16	5
3L WBE									
P1	A	550	2,84			550	0	550	1,33
	B	550	0			550	3,42	116	5
P2	A	550	1,32	232	3,40	82	3,77	20	5
	B	100	0,56	550	2,60	526	3,7	0	5
P3	A	550	1,16	550	2,41	550	3,15	22	5
	B			550	1,98	550	2,95	164	5
5L WBE									
P1	A	550	3,23	400	3,65	328	3,64	30	5,00
	B	130	1	550	2,53	550	3,4	220	5,00
P2	A	550	0,2	550	0,2	550	0,26	550	3,36
	B								
P3	A	550	0	550	0	550	0	550	0,5
	B								
5L NBE									
A5	A					550	0	550	0
	B					540	5	44	5
B5	A					550	4,9	44	5

	B					550	0,82	550	2,52
C5	A					550	0,36	550	0,53
	B					282	3,71	64	5,00
3L WBE									
A3	A					470	4,17	274	5,00
	B					282	3,1	304	5,00
B3	A					550	3,28	550	3,58
	B					550	0,21	550	0,21
C3	A					550	0,9	550	1,12
	B					550	0	550	0
3L NBE									
A3	A					178	5	84	5,00
	B					550	3,03	552	4,36
B3	A					26	5	2	5,00
	B					74	5	76	5,00
C3	A					230	3,88	342	5
	B					32	3,66	22	5
D3	A					24	5	0	5
	B					186	5	134	5
5L WBE									
A5	A					550	0,36	550	0,8
	B					550	0,32	550	0,38
B5	A					550	0	550	0,23
	B					206	5	550	4,14
C5	A					550	0,73	550	0,67
	B					550	0,44	550	0,25

Appendix 14

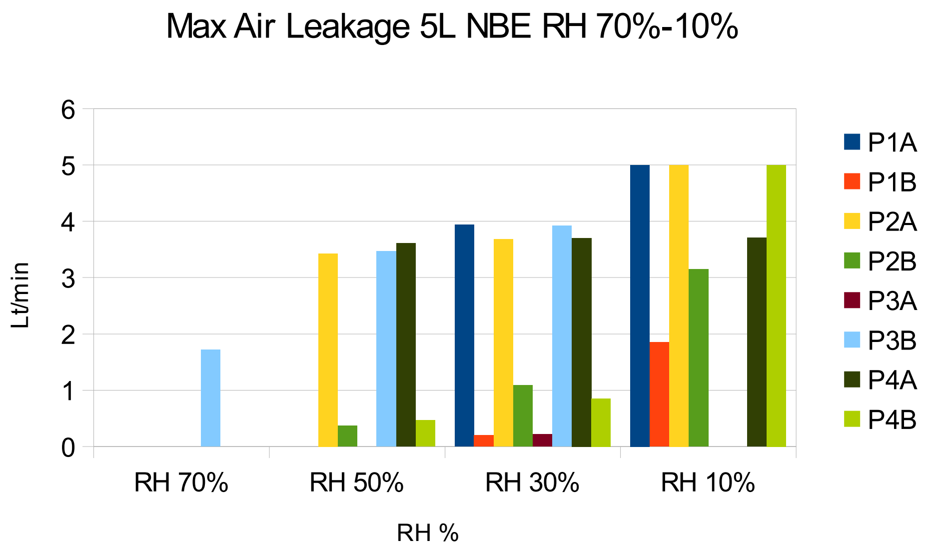
3 Layers panels no bonded edges maximum air leakage for both cycles

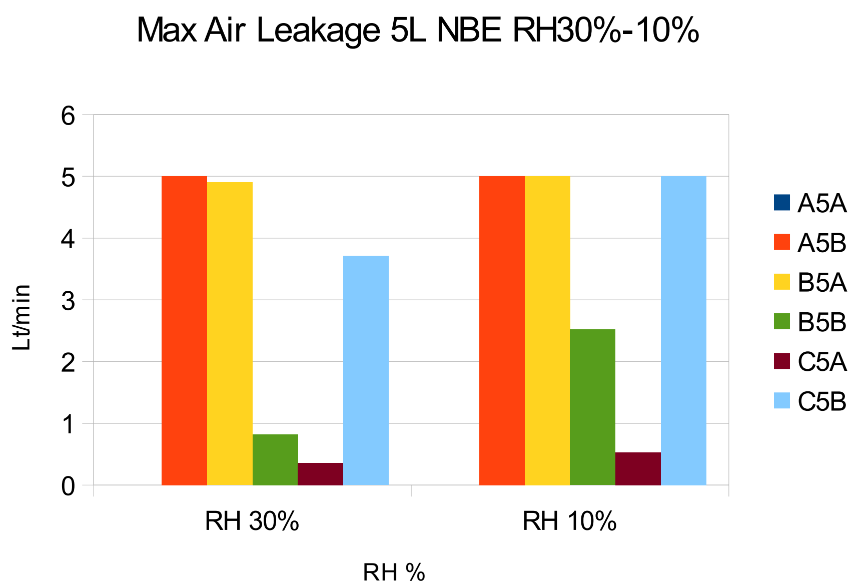




Appendix 15

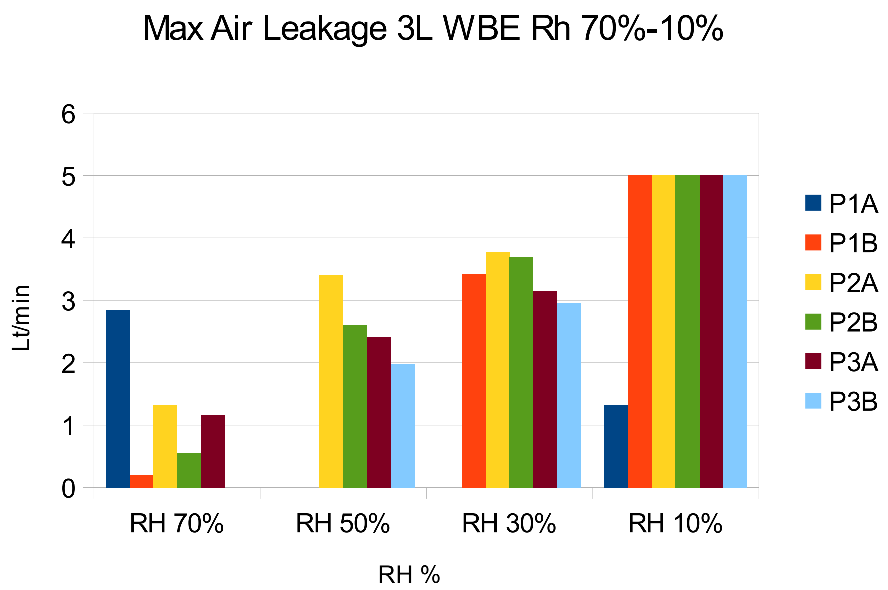
5 Layers panels no bonded edges maximum air leakage for both cycles

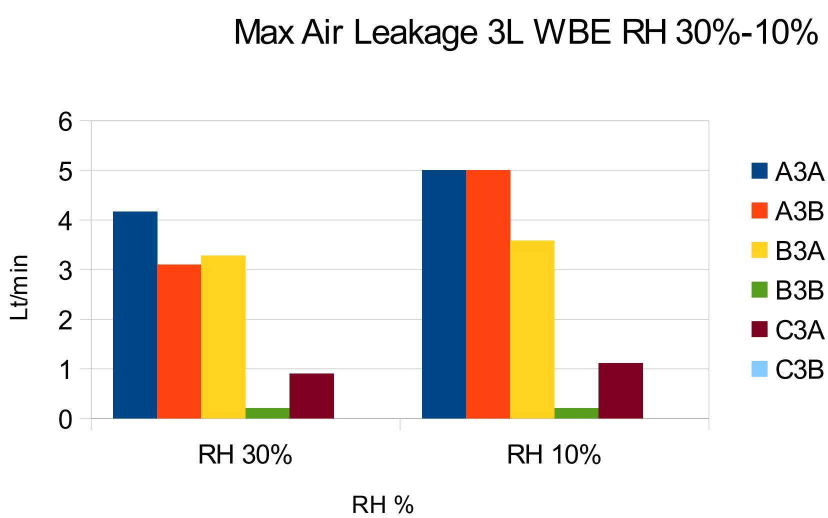




Appendix 16

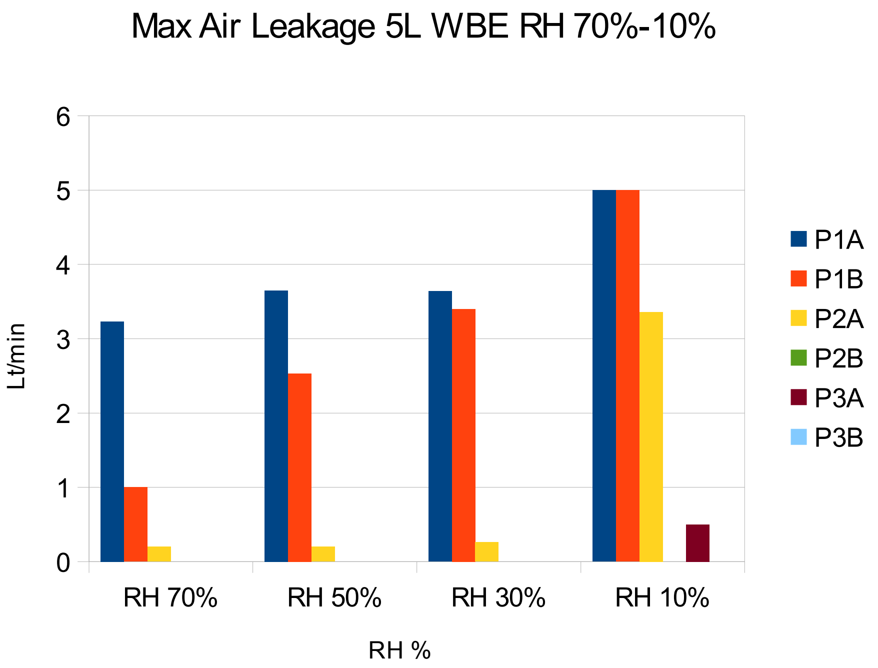
3 Layers panels with bonded edges maximum air leakage for both cycles

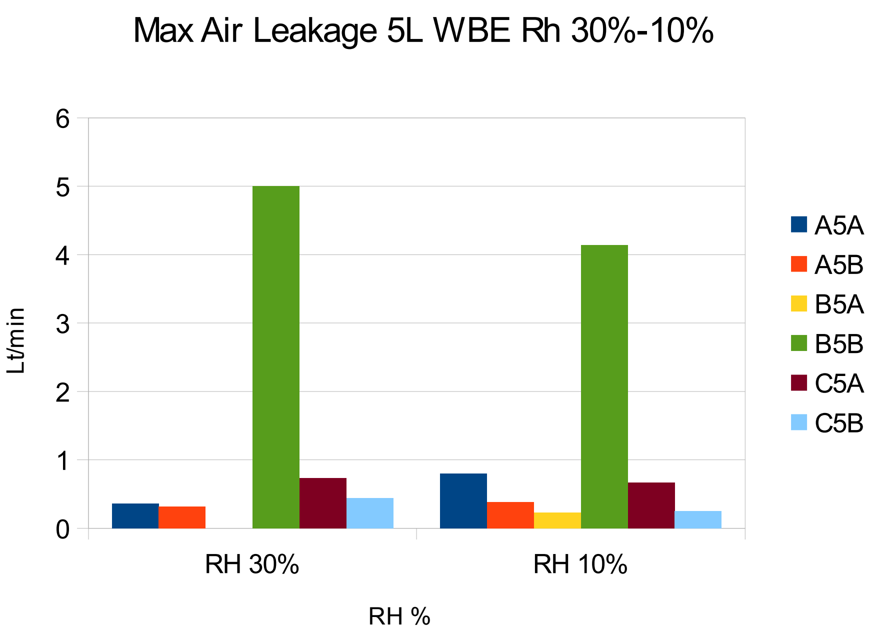




Appendix 17

5 Layers panels with bonded edges maximum air leakage for both cycles





Appendix 18

Ruler and MC device

Appendix 19

Glue date sheet

LOCTITE

LOCTITE® HB S509 PURBOND

Adhesive systems for engineered wood

Single-component polyurethane adhesive for the manufacture of engineered wood products

LOCTITE HB S509 PURBOND_E
Purbond Technik / 04-2015

Properties

LOCTITE HB S509 PURBOND is a liquid single-component polyurethane adhesive. The adhesive cures under the action of air humidity and moisture in the wood to yield a strong non-brittle film. Slight foaming of the adhesive during hardening is caused by the chemical reaction and is normal. PURBOND HB S509 is manufactured without the addition of solvents or formaldehyde.

LOCTITE HB S509 PURBOND is classified as a Type I adhesive and is approved and registered according to Page 4 of this data sheet (Section headed Certifications and Registrations).

This technical data sheet was co-ordinated with Stuttgart University MPA, an independent material testing laboratory.

Product data

Basis	Isocyanate prepolymer
Consistency	Good flow properties
Assembly time[1]	**50 minutes**
Press time / curing time[1]	**125 minutes**
Brookfield viscosity	Approx. 24,000 mPa.s (Sp.6 / 20 rpm / 20°C, measurement between 16 to 36 hours after production)
Colour shade	Beige
Density	1,160 kg/m³
Solids content	100% and free from fibres and abrasive fillers
Fire hazard	Flame resistant
Resistance	To weak alkalis, acids and solvents
Declaration	The Safety Data Sheet (MSDS) for LOCTITE HB S509 PURBOND must be observed and is available at www.purbond.com.