WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

RECENT DEVELOPMENTS ON TAILORED LAMINATED TIMBER

Erik Serrano[1], Kay Ackermann[2], Philipp Dietsch[3], John Haddal Mork [4]

ABSTRACT: The paper gives an overview of the research project InnoTLT and preliminary results. The aim of InnoTLT is to develop cross-laminated timber (CLT) into next generation Tailored Laminated Timber (TLT) by studying concepts to optimise the mechanical performance while, at the same time, assuring compliance with principles of a circular economy. A general objective is to reach a 20% improvement in performance-to-material usage ratio, in relation to standard CLT of today. Walls and floors are the main areas of studies, and the paper presents early results from some of the studies, including an inventory phase gathering the industry's perspectives on future products. An approach for early product design in terms of real-time and combined evaluation of LCA and structural response is also discussed. The results show a great potential for the industry to optimise their products, both in terms of technical performance, and in terms of environmental and climatic impact. The optimisation could be based on alternative geometries for the lay-ups, including voids (gaps), the use of hardwood laminations or the use of low-quality laminations from grading rejects or recycling.

KEYWORDS: cross-laminated timber, structural design, resource efficiency, LCA

1 – INTRODUCTION

1.1 BACKGROUND

Over the past few decades, the growth of the timber construction industry has been closely tied to the development and successful adoption of cross-laminated timber (CLT) as a standard solution. This is largely thanks to the product's versatility and the advancements in prefabrication technology. To remain competitive in the future, CLT must innovate to enhance material efficiency and address its reliance on a limited number of softwood species.

Innovative Tailored Laminated Timber, *InnoTLT*, is a research project under the Bioeconomy in the North program. Its goal is to advance CLT by developing innovative solutions to enhance the future competitiveness of timber construction. This involves creating optimised and customised solutions, known as Tailored Laminated Timber (TLT). The project addresses several challenges, including the technical potential of tailored and innovative products, verifying their environmental and climatic benefits compared to other materials, highlighting their role in a circular construction sector, and proposing new joining techniques. The main hypothesis is that the performance-to-material usage ratio of CLT-like products can be improved by optimising material use, incorporating new species, and customising lay-ups and connections for specific design scenarios.

1.2 PROJECT DESCRIPTION

The project consists of work packages that cover general concept development, and technical work packages in which TLT-floors, walls and joints are investigated. Here, focus will be on the general concept development and on showcasing results from the studies relating to TLT-floors.

Concept development

The concept development involves, as a first step, a concept study covering an inventory phase based on expert interviews and a comprehensive literature review.

In a second step, a concept development tool for estimating the mechanical and the environmental performance of innovative TLT concepts, in real time, is developed.

TLT-Walls

To increase resource efficiency, the influence of large gaps in the layup has been investigated. By introducing large gaps, TLT products can be optimised to a much higher ratio of strength utilisation, leading to reduced material use. The study consists of a series of experimental tests, such as four-point bending, buckling and in-plane shear tests. The methods and results are presented in a separate publication at WCTE2025, see [1].

TLT-Floors

Various lay-ups involving different gap patterns were analysed by means of finite element analysis (FEA). The main aim was to investigate the elastic, static, out-of-plane stiffness, since the serviceability limit state often is of prime concern for floors. The influence of varying gap size and the thickness of the layers was investigated. Finally, different analytical approaches were compared to the finite element analyses, with the aim to find a relevant analytical approach to serve as the backbone for the development tool mentioned above.

[1] Erik Serrano, Division of Structural Mechanics, Lund University, Lund, Sweden, erik.serrano@construction.lth.se, ORCID iD: 0000-0002-5333-0682

[2] Kay Ackermann, KIT Timber Structures and Building Construction, Karlsruhe Institute of Technology, Karlsruhe, Germany, kay.ackermann@kit.edu

[3] Philipp Dietsch, KIT Timber Structures and Building Construction, Karlsruhe Institute of Technology, Karlsruhe, Germany, dietsch@kit.edu, ORCID iD: 0000-0003-3568-8290

[4] John Haddal Mork, OMTRE A/S, Hønefoss, Norway, john@raaas.no

https://doi.org/10.52202/080513-0466

2 – INDUSTRY AND RESEARCH PERSPECTIVE ON TLT

The concept study includes expert interviews and a literature review. The interviews mainly focus on the industry perspective. The methodology for concept development including development scales is described. The literature review shall highlight potential for further development of new tailored laminated timber products.

2.1 INDUSTRY PERSPECTIVE

The interviews realised within the preliminary study covered five topics: resource efficiency, material technology and production, building construction, multi-functionality, and circularity. Resource efficiency emerged as a key concern, focusing on replacing high-quality materials and increasing material yield. Beyond economic benefits, these measures are essential due to declining material quality and availability, particularly affecting spruce (*picea abies*). Fig. 1 shows the most frequently mentioned aspects by industry.

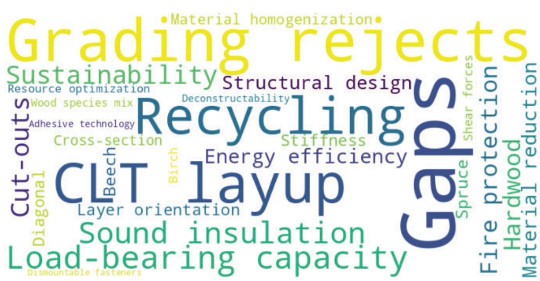

Figure 1. Key-aspects for innovative layups obtained from interviews.

An efficient method to reduce timber volume in a TLT layup is to decrease the number of laminations per layer, creating gaps in the structure. Larger gaps in glued laminated products create structural challenges but also challenges for manufacturing. The trend towards highly automated production technology supported by robotic manufacturing could lead to more economical production of tailored layups. Additional challenges include building physics aspects. Further challenges are discussed in the section *Overview of Innovative Layups* within the *GapLaminations* concept.

The industry is continuously striving for an increase in material yield. One option includes using more grading rejects. Industry projects a potential increase in material yield by 10–20 %. Strength rejects with lower mechanical properties than required are most common. However, the possibilities for substitution of high-quality laminations with grading rejects are limited, due to production and structural requirements depending on the quality of rejects. Highly utilized layers such as outer layers require high quality laminations. Also, visual quality aspects can limit the use of rejects.

The substitution of high-quality timber can also be achieved by including recycled material from the production process. Manufacturers mention challenges in obtaining the required quality of finger joints between low-grade timber or gluing quality between recycled laminations. Further aspects will be explored in the *ReLaminations* concept.

The addition of hardwood to tailored laminated timber products was also discussed. Especially the combination of hardwood and softwood in TLT elements can have benefits on structural aspects, such as reinforcement of connections. The challenges and benefits of hybrid TLT products are explored in the *HardwoodLaminations* concept.

Diagonal layer orientations were also discussed. Fig. 1 shows that diagonal layer orientations experienced less interest from the industry. Manufacturers explained this with a high effort of production and a decrease in material yield due to a high ratio of cut-offs and waste material. Towards this aim, new or optimised production lines and methods would be required. Further aspects will be discussed in the *DiagonalLaminations* concept.

Advancing TLT for standardised modular building systems is another key aspect. The industry is highly interested in developing concepts that enhance component reuse and enable easy dismantling. According to industry, simple prefabricated elements facilitate connection placement but often pose drawbacks for dismantling and reuse.

The interviews highlighted resource efficiency. Hence, challenges in terms of integration of recycled or waste materials, along with a focus on alternative wood species, should be addressed in the further development of TLT. Multifunctionality and modularity of building systems are secondary objectives. A major challenge from an industry perspective is the lack of flexibility of the current production lines to produce TLT. In most cases, the production lines need to be adapted to handle multiple wood species or to produce layups with gaps or diagonals.

2.2 CONCEPT SCALES

The concept development process can be structured into four main characteristic scales, see Fig. 2. This structure is meant to support the identification of areas where more research is needed to establish innovative TLT. Each scale characterises the level of detail for the literature review, starting with the building component scale. With the focus on concepts for TLT, the layer scale and lamination scale were reviewed. The fourth scale describes the mechanical phase of a layup, meaning specific mechanical properties of layers and laminations.

Building Components

The first scale describes the projected application of TLT as building components. In the long term, TLT should be capable of being adjusted dependent on its structurally intended purpose. For the conceptual study, this meant to review recent research which is related to investigations on the mechanical behaviour of wall and floor elements.

Layers

At the layer scale three different concepts were discussed. Standard, orthogonally oriented CLT marks the reference product to TLT. This is compared to layers with gaps, which significantly reduce material use. Further, diagonal oriented layers were reviewed.

Laminations

The third scale focuses on materials for laminations in layers. Laminations from softwood (e.g. spruce, pine, fir) represent the reference material. Concepts focusing on hardwood, grading rejects or recycled material are categorised at the lamination scale, as those can be combined with concepts from the layer scale.

Mechanical Scale

The fourth scale describes the mechanical functions and properties of the laminations but also the interacting crossing areas between laminations. A wide range of research activities deal with the investigation of specific mechanical behaviour. Three main objectives were considered in this study. Laminations represent the load-bearing component of a TLT element. Fillings represent laminations without a load-bearing function. Those should not be neglected in building physics analysis, as they can contribute to thermal behaviour of TLT. In addition, it is necessary to investigate the mechanical behaviour of the crossing areas.

Some key advantages and disadvantages of large gaps in the layup include:

- \+ significant reduction of redundant material by lowering volume fraction (lightweight structure)
- \+ potential for multi-functional use by filling gaps with materials like wood fibre boards for thermal or sound insulation
- \- need to address potential compromise in terms of fire resistance and air tightness
- \- increased production effort due to required arrangement, potentially offsetting material savings

2.3 INNOVATIVE LAYUPS – STATE-OF-THE-ART

This overview will give an introduction into four conceptual areas of InnoTLT. The state-of-the-art will be illustrated and evaluated to highlight research needs for the further development of TLT.

GapLaminations

In residential buildings, CLT is mostly used in wall and floor components. In both cases, the utilisation of the material over the layup is rather low, especially in the inner layers. Due to this, it is desirable to optimise the structural layup. The concept *GapLaminations* represents the adjustment of the layer scale by spacing adjacent laminations to create gaps. The aim is to minimise material use while ensuring sufficient mechanical properties.

First studies on wall and floor elements with large gaps were performed by Blass et al. in 2001 and 2002. The investigation on elements with disintegrated layers focused on the out-of-plane [2] as well as in-plane properties [3]. Rolling shear was identified as a predominant failure. Large gaps increase global deformation, as cross layers exhibit lower shear stiffness under perpendicular loading. Elements with gaps can only transfer shear forces under in-plane loading adequately, if the crossing areas of adjacent laminations are rigidly connected.

Investigations on shear properties of CLT with **small** gaps, conducted by Kreuzinger et al. [4] have shown that small gaps act as imperfections, redistributing forces into adjacent laminations. Diagonal rolling shear tests confirmed that local cracking at the edges of laminations can occur due to tensile stresses perpendicular-to-grain. This behaviour is strongly influenced by the rolling shear strength of the material in the cross-layer. Further relevant tests were performed by Ehrhart et al [5].

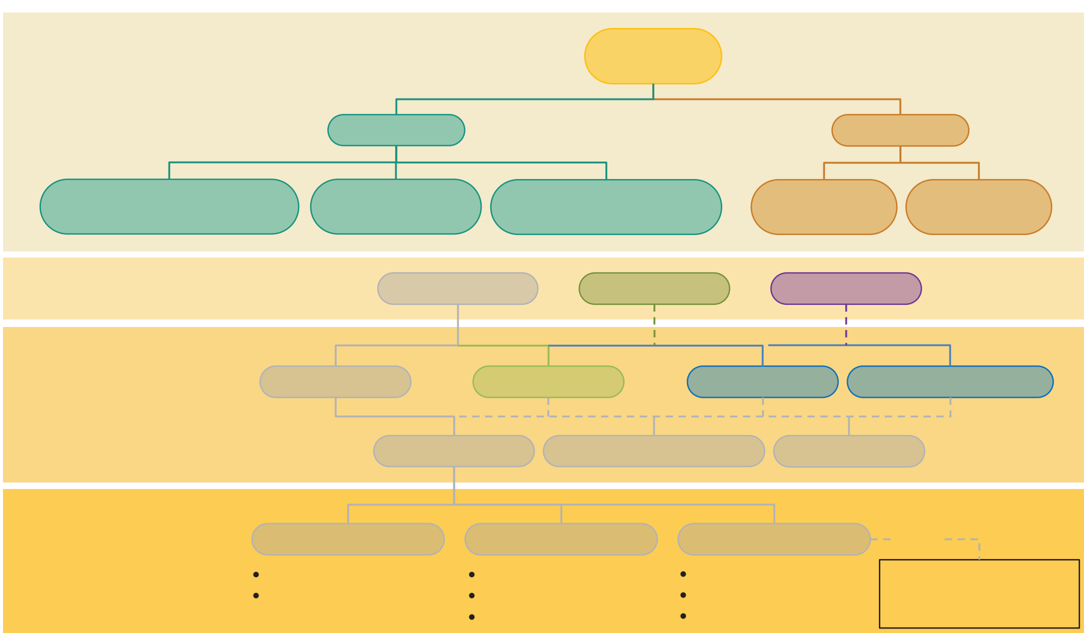

Figure 2. Schematic overview of characteristic phases of TLT used for concept development.

https://doi.org/10.52202/080513-0466

Smaller width-to-thickness *w*/*t*-ratios increase normal and shear stresses due to a reduced effective area for stress redistribution (Fig. 3). Investigations by Brandner & Dietsch et al. [6] on the in-plane shear stiffness, show a notable 35% reduction for 5 mm gaps.

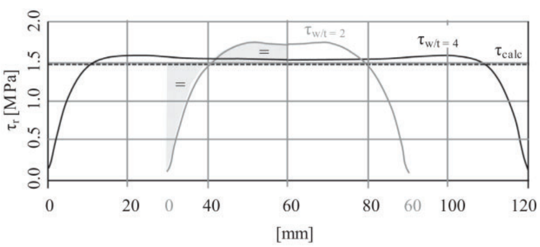

Figure 3. Rolling shear stress distribution of different w/t-ratios (Ehrhart 2018).

It can be concluded that in the presence of small gaps, which can't be excluded due to production tolerances, higher *w*/*t*-ratios improve shear stiffness. Small gaps have minimal impact on bending properties, with the *w*/*t*-ratio being a more relevant factor.

Considering **large** gaps, the significant reduction of the timber volume fraction in the layup has an influence on bending and shear properties, Franzoni et al. [7]. In [7] it was shown that, considering a reduced volume fraction in the analytical approach, the reduction of bending stiffness could be predicted with high accuracy, whereas the reduction of shear stiffness does not agree with the volume fraction, and shear behaviour is overestimated. By focusing on strength properties Feichter [8] observed an increase of bending stresses in the longitudinal outer layers, potentially due to shear stress redistribution at gaps. This was confirmed by Gardner et al. [9], where larger gap-ratios in cross-layers lead to greater shear strength reduction.

Research studies on the in-plane behaviour of wall elements from CLT with gaps were performed by Glaso & Nore [10] and Arnold et al. [11]. Neither study is fully representative. Glaso & Nore observed failure due to local crushing at the area of load introduction. Arnold et al. investigated the load-bearing behaviour of wall elements with excentric gaps. Due to the high stiffness of the remaining layers without gaps, no significant changes between the layups with gaps and common CLT could be found.

This review shows that recent research focused primarily on the evaluation of out-of-plane properties and the influence of large gaps on deformations. Hence, additional research on in-plane properties is required. This should include analysis of local failure mechanisms. Furthermore, TLT layups with filled gaps need to be further investigated in terms of building physics aspects.

HardwoodLaminations

The concept *HardwoodLaminations* aims to reduce material input, by adding laminations from hardwood with increased material properties. Depending on the functional use of the structural element, it can be favourable to add hardwood to the outer or inner layers. The volume fraction of hardwood in a layer or overall layup has a direct impact on the strength and stiffness properties. For floors it can be favourable to use hardwood laminations in the outer layers to improve the bending properties. Hardwood in cross layers can reinforce shear properties thanks to higher rolling shear strength. Some of the benefits and challenges of hardwood in a TLT or hybrid layup are:

+ improvement of mechanical properties and local reinforcement in areas of high utilisation, e.g. connections, concentrated loads or openings
+ increase slenderness by reducing material in inner layers while ensuring similar strength and stiffness
+ higher fire resistance when used in outer layers
- difference in density and swelling behaviour may cause issues in manufacturing and structural integrity
- adaption of production lines with more durable tools for cutting, milling, planing and formatting

Recent research focused on the investigation of CLT with integrated laminations from beech. Franke et al. [12] report mechanical properties of beech CLT, with 100 % beech in all layers. Most strength parameters increase by up to 300 % when compared to CLT from spruce. Delamination testing showed negative results, as delamination exceeded normative limits in 80 % of all specimens. The high moisture sensitivity of beech makes it less favourable for use in outer layers.

Testing on the rolling shear strength of various hardwoods was performed by Ehrhart et al. [5]. The aspect ratio *w*/*t* and sawing pattern were identified as main influencing parameters on rolling shear properties, stating that an aspect ratio $w/t \geq 4$ has no further beneficial effect on the rolling shear strength, whereas a decreasing angle of annual rings results in decreasing rolling shear stiffness.

Bienert et el. [13] investigated the load-bearing behaviour of hybrid CLT plates with disintegrated inner layers from European beech. The outer layers were from spruce. Via bending tests, it was shown that the use of beech laminations could improve the mechanical properties compared to CLT made solely from spruce. However, the use of beech could not fully compensate the reduction in mechanical properties due to the gaps.

Further studies on hybrid CLT with beech were conducted by Aicher et al. [14]. In most tests, longitudinal shear failure inside of the spruce layers occurred as a result of the high rolling shear strength of beech laminations.

An alternative hardwood species for CLT products is European birch. Jeitler et al. [15] investigated the material properties of birch laminations and its application in GLT and CLT products. The mechanical properties of birch show significantly elevated values compared to Norway spruce. Positive aspects of birch include the fact that in a hybrid layup with softwood, the lamination as well as the swelling behaviour are far better compared to beech hybrid layups. Processing of birch can be done on the same production lines as spruce.

The review shows that many studies investigated the material properties of hardwoods focusing on rolling shear properties and the benefits on hybrid CLT products on the shear strength and stiffness of elements in out-of-plane loading. Further research should focus on the in-plane load-bearing behaviour of hybrid elements. Topics of interest include material reduction and structural integrity when exposed to moisture changes.

ReLaminations

The concept *ReLaminations* focuses on the use of a wide variety of materials made from low quality timber, such as recycling, waste or grading rejects. Depending on material composition and quality, these types of laminations can substitute high-quality laminations in the less utilized inner layers. This can lead to:

- \+ high potential to compensate limited availability of high-quality spruce material
- \+ increased material exploitation of logged timber by use of grading rejects for structural purposes
- \+ low-grade laminations from waste, recycling or fast-growing wood species in less utilised layers
- \- adaption of manufacturing process
- \- availability of material for recycling must be secured to prevent downtime in production and supply of products.

The application of recycling material or grading rejects is highly relevant for a more holistic use of raw timber as the current material yield of a tree for structural purposes is about 30 % [16]. This could partly be achieved by incorporating grading rejects. Cherry et al. [17] summarise crucial challenges of out-of-grade timber from pine in CLT. Furthermore, about 20 % of the produced CLT ends up as waste material due to cutting out element openings. These cut-outs could be further processed to new laminations.

Reclaimed timber from dismantled buildings has potential for use in new structural TLT elements. Rose et al. [18] investigated the influence of reused secondary timber on the bending properties of a hybrid CLT. It was experimentally shown that secondary timber had a larger impact on bending than on compression properties.

To reduce wood waste and increase material yield of logged wood, a possible alternative is to produce wood-based panels. Panels or laminations from recycling material can be used in TLT as substitution for high-quality material in the cross-layers. Wang et al. [19] and Davis et al. [20] investigated the material behaviour of hybrid CLT with laminated strand lumber (LSL). Both came to the result that despite some gluing challenges the substitution of SPF (Spruce-Pine-Fir) in the cross-layer increases the out-of-plane shear strength, while the bending stiffness could not be improved.

Technically, laminations from recycling material or grading rejects can be integrated to any TLT layup. Effects on TLT strength and stiffness need to be further investigated.

DiagonalLaminations

Within the concept *DiagonalLaminations* the adaption of layer orientation at angles different from an orthogonal arrangement should be further investigated. Diagonal layer orientations can be applied to wall or floor elements. This can lead to:

- \+ increased element stiffness such as in-plane shear of wall elements or shear and torsional stiffness of floors
- \+ material reduction by reducing element / layer thickness compared to reference CLT elements with orthogonal layer orientation
- \+ improvement of vibration damping
- \- challenges in production leading to increase of waste from cut-offs and labour-intensive assembly of layers
- \- challenges in the design of joints for sufficient load transfer or disrupted load transfer due to openings in the element

Bosl [21] investigated the influence of diagonal laminations on wall elements by numerical calculations and experimental testing of in-plane shear properties of CLT. It was shown that the shear stresses are redistributed inside the element, resulting in lower stress concentrations.

Further research on the in-plane load bearing behaviour was conducted by Tavoussi et al. [22]. In this study, the capacity of wall elements and connections under cyclic loading was tested. Results show lower decrease in element stiffness compared to CLT elements. Turesson et al. [23] performed diagonal compression tests with elements containing diagonal laminations of 30° and 45° angles in the middle layers. The shear modulus was increased by a factor of 1.8 and 2.9 respectively, confirming the existence of a bracing effect.

Focussing on floor elements, diagonal layers can also have positive benefits on the out-of-plane properties of TLT. Buck et al. [24] investigated the influence of a ±45° orientation of the cross-layers on uniaxial bending and shear properties. The global bending stiffness could be increased by 15.5 % and shear stiffness by 35 %

In terms of plates under bi-axial bending such as point supported floors, diagonal layers can cause a more direct load transfer to the supports. Arnold et al. [25] performed experimental tests with cross-layer orientations of ±30° and ±45° on torsional stiffness. Compared to CLT, the DLT elements had a 28.4 % and 21.9 % higher torsional stiffness.

The diagonal orientation of layers in a CLT layup has a long history but has not yet reached full acceptance by the industry. This is mainly due to manufacturing challenges of the diagonal layup in rectangular elements. With a diagonal orientation of layers, internal forces can be redistributed, leading to more homogenised stresses. Most mechanical models, developed for CLT can also be applied to DLT, such as shear failure mechanisms of laminations. Further development should focus on in-plane shear for wall elements, investigating failure mechanisms and stiffness parameters with a wider variation of angles in the layup.

 https://doi.org/10.52202/080513-0466

3 – CASE STUDY: TLT FLOORS

3.1 NUMERICAL AND ANALYTICAL

A series of parameter studies were performed to investigate the influence on the static bending stiffness of introducing large gaps in TLT. The studies included the use of finite element analyses and compared the results from those with results from analytical approaches.

Limitations and assumptions

The models used here include the following limitations:

- 5-layer symmetric CLT.
- Load cases include three-point bending and uniformly distributed load.
- One-dimensional bending (i.e. bending as a beam) in the main direction of the CLT.
- Evaluation is based on maximum deflection.

FE-models use boundary conditions which minimise the influence of local stress irregularities at the supports and load introduction points.

FE-models

All models are linear elastic. The wood is modelled as an orthotropic material in a rectangular, Cartesian coordinate system. As examples, some configurations of the FE-models are shown in Fig. 4. The model is three-dimensional, although acting primarily in uniaxial bending, similar to a 2D plane stress model. Only one board is modelled in the width direction. Symmetry conditions are assumed and thus only half the length needs to be modelled.

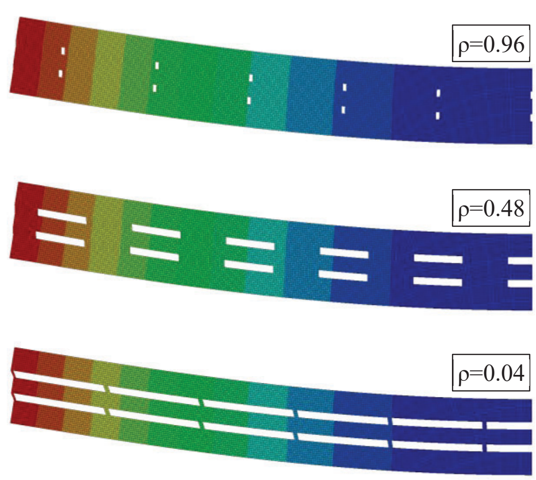

Figure 4. Configurations of gap CLT (60-20-40-20-60) with varying material densities, ρ, of the transverse layers. See study no. 4 of Tab. 1.

Second order, 3D brick elements with 20 nodes per element are used in all analyses (named C3D20 in ABAQUS, the software used). Element size was determined based on a convergence study, indicating an element size of 5 mm being adequate and resulting in a good balance between accuracy and calculation time.

All model variants were analysed for two load cases: three-point (3P) bending and bending due to a uniformly distributed load.

The 3P loading was introduced by applying a surface shear traction over the symmetry section at mid span. Uniform load was applied as a surface pressure on the upper and lower faces of the beam. These loading conditions were used to minimise the influence of local stress irregularities at load introduction and supports, thus also minimising local bending of the laminations, which can occur for large gap widths.

The support boundary conditions were introduced using multi point constraints, corresponding to plane cross sections remaining plane *for each lamination.* Thus, the stiffening effect of beam theory assumptions, applied across the whole cross-section, was avoided.

Layups and parametric studies

The reference configuration is a five-layer CLT, made from 40 mm thick laminations (i.e. 200 *mm* total thickness), 160 *mm* wide. The reference configuration was complemented with different parametric studies to investigate the influence of lay-ups in terms of layer thicknesses, material properties in terms of rolling shear modulus, and most importantly, different gap configurations. All models consisted of eleven cross laminations.

Two approaches to introduce the gaps were investigated. The first approach used a constant lamination width (160 *mm*) and varying gap widths (10–240 *mm*). Thus the length of the CLT varied, from 11 × (160+10) = 1870 *mm* to 11 × (160+240) = 4400 *mm*. Since in all cases the CLT total thickness was 200 *mm,* the length-to-thickness ratio also varied in the range of 9.35<L/H<22. In the second approach, gaps of length 10–240 *mm* in combination with lamination widths of 240–10 *mm* were employed, such that the length of gap+lamination width was always 250 *mm*. This means that the CLT length was constant (L=11×250=2750 *mm*) for all analyses using this approach. Consequently, the length-to-thickness ratio of the CLT was L/H=13.75.

In total 144 different models were analysed, and as each model was analysed for two load cases, a total of 288 analyses were used for the verification of the analytical approaches, see Table 1.

Table 1. Summary of the different models analysed. Six different studies were performed, with each study comprising 24 individual analyses, each including two load cases.

Study no.	Lay-up	Gap sizes (mm)	Lamination widths (mm)	Material density range (cross layers)	Rolling shear modulus (MPa)
1	40-40-40-40-40	10–240	160	0.40–0.94	69.0
2	40-40-40- 40-40	10–240	**240–10**	0.04–0.96	69.0
3	**60-20-**40-**20-60**	10–240	160	0.40–0.94	69.0
4	**60-20-**40-**20-60**	10–240	**240–10**	0.04–0.96	69.0
5	40-40-40-40-40	10–240	160	0.40–0.94	**138.0**
6	40-40-40-40-40	10–240	**240–10**	0.04–0.96	**34.5**

https://doi.org/10.52202/080513-0466

The material parameters used in the analyses are summarised in Table 2, where indices L and T refer to the longitudinal and transverse directions of the material, respectively.

Table 2. Elastic stiffness parameters used.

Notation	Description	Value (MPa)
E_L	Longitudinal MOE	11 000
E_T	Transverse MOE	370
G_L	Longitudinal shear modulus	690
G_T	Rolling shear modulus	69
ν,	Poisson's ratio (three identical)	0.45

Analytical approach

The results from the FE-analyses were compared to the prediction from various analytical approaches. Beam theory predictions used Bernoulli-Euler and Timoshenko theory.

A simplified shear layer approach, similar to the one of Kreuzinger and Scholz in [26], is also used as one option for analytical evaluation. Thus, the shear stiffness is estimated by a summation of the compliances of the layers, each such layer with thickness t_i, shear modulus G_i and with a material density of ρ_i. The equivalent shear stiffness of a cross section of width B, with longitudinal layers, i=1, 3, 5, …, n and cross-layers, i=2, 4, 6, …, $(n-1)$ is:

$$(GA) = \frac{BH_{eff}^2}{\left(\frac{0.5t_1}{\rho_1 G_1} + \frac{t_2}{\rho_2 G_2} + \cdots + \frac{t_{n-1}}{\rho_{n-1} G_{n-1}} + \frac{0.5\, t_n}{\rho_n G_n}\right)} \quad (1)$$

where $H_{eff} = (H - \frac{t_1}{2} - \frac{t_n}{2})$ is the effective depth of the cross section (assuming that outer layers are longitudinal). Note that the shear compliant cross layers normally contribute much more than the longitudinal layers. The contribution of the longitudinal layers to the total compliance could even be neglected (at least if the wood ratios of longitudinal layers are high). Eq. (1) is applicable for bending in the main direction of the CLT.

After calculating the equivalent shear stiffness (GA), we can estimate the maximum displacement, u, due to bending and shear deformation using beam theory. As an example:

$$u_q = u_{q,\text{bending}} + u_{q,\text{shear}} = \frac{5qL^4}{384\, EI} + \frac{qL^2}{8\,(GA)} \quad (2)$$

for a uniformly distributed loading, q. In (2) (EI) is the bending stiffness of the cross section, which is calculated considering the composition of the cross section, including the layers' material density. Thus, for a five-layer *symmetric* CLT we obtain:

$$\begin{aligned} EI = \frac{B}{12}\ &[\rho_1 E_1 (H^3 - (t_2 + t_3 + t_4)^3)\ + \\ &+\ \rho_2 E_2 ((t_2 + t_3 + t_4)^3 - t_3^3)\ + \\ &+\ \rho_3 E_3 t_3^3] \end{aligned} \quad (3)$$

where E_1, E_2 and E_3 are the moduli of elasticity of the different layers. Commonly, the transverse layers are assigned a zero modulus, thus not contributing to the bending stiffness. Here, only symmetric cases are considered and $\rho_1=\rho_3=1.0$, $E_1=E_3=E_L$, $E_2=E_T$ and B=160 *mm.*

3.2 CONCEPT DEVELOPMENT TOOL

A multi-purpose parametric tool has been developed using visual scripting in Grasshopper/Rhinoceros.

The main aim was to have a tool that can feedback, in real time, the performance of the proposed design to the user. The performance means here a combination of mechanical performance and climatic footprint. To have a simple and yet reasonably accurate evaluation of CLT floor plates, the floor panels' mechanical behaviour is evaluated using analytical approaches.

A secondary aim is to develop a functionality such that at least parts of the modelling needed for FE-analyses, can be performed in Rhino. The model can then be exported to advanced analysis software (in this case ABAQUS).

To achieve a generic model applicable for optimisation, structural analysis, visualisation and possibly manufacturing, the parametric model is built up in sequences, from schematic to detailed geometry, see Fig. 5. The initial steps are as follows:

1) Global shape and layer-buildup are described with numerical inputs. Material source, width, height, gap, lamella-direction, E-modulus and shear modulus are the inputs that describe the layer-buildup. The global shape is described by width, length and the sum of the lamination thicknesses.
2) An attributed global shape is generated (boundary representation).
3) The global shape and its metadata are used to generate attributed layer geometries (surfaces).
4) Each layer gets divided into individual lamellas, described as attributed centrelines

The result is a multi-scalar model that can be applied for various outputs. Currently, the following outputs have been developed:

1) An analytical calculation that predicts static stiffness performance.
2) A solid, detailed model for visualisation.
3) Numerical outputs for LCA analysis. Further research will implement LCA-data in the algorithm, but volume reduction is a strong indicator.
4) A plugin that writes an *.inp*-file that can be used in ABAQUS for further examination.

Further, the parametric tool, is set up with a multi-objective optimisation tool, applying a genetic algorithm named NSGA-III. An optional selection of parameters in the layer build-up is used as optimisation variables and point load performance ratio, uniform load performance ratio and volume performance ratio is used as optimisation goals. The output is a *.csv* file that can be analysed using TT-design explorer.

https://doi.org/10.52202/080513-0466

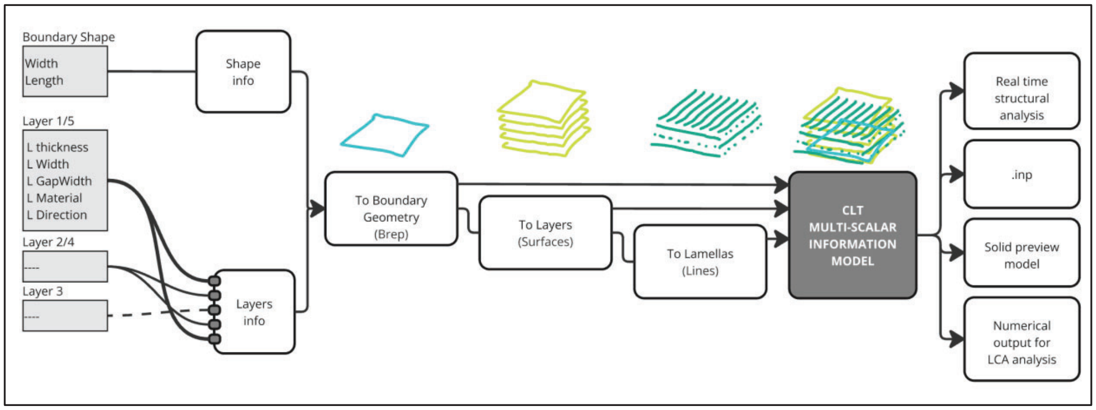

Figure 5. Schematic of parametric model (top) and the multi-objective optimisation tool.

3.3 RESULTS

Numerical and analytical studies

Fig. 6 shows the results from studies no. 1 and 3 (top) and studies no. 2 and 4 (bottom), see also Tab. 1. The approach used for studies no. 1 and 3 gives material densities ranging from 0.40 to 0.94. That approach also results in a variation in specimen length, for different wood ratios. This, in turn, influences the ratio L/H, markedly affecting the amount of shear deformation.

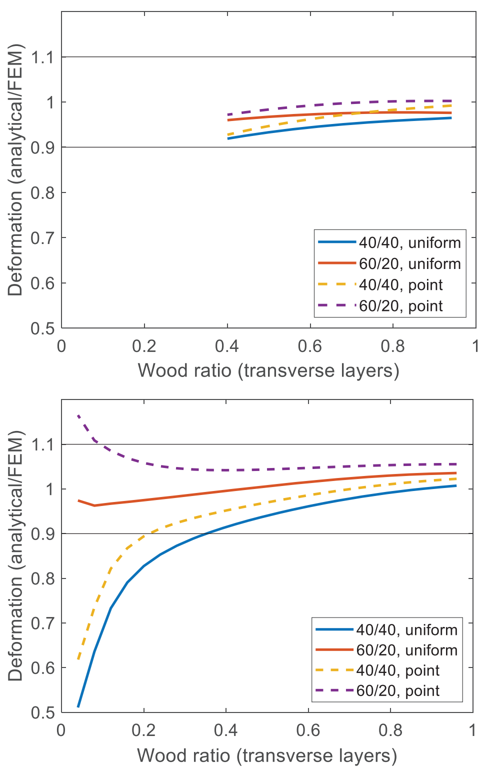

Figure 6. Comparison of shear layer approach, Eq(1)–Eq.(3) to FE-results. Deflection at 1D-bending for 3-point loading and uniformly distributed loading. Cases 1 and 3 (top), and cases 2 and 4 (bottom). The horizontal lines represent ±10% deviation from the FE-results.

As indicated in Fig. 6, the analytical approach gives predictions within 10% from the FE-results, for wood ratios 0.40–0.94. For cases 2 and 4, the analytical approach, cf. Eqs. (1)-(3), gives prediction within 10% from the FE-results, for wood ratios as low as 0.21–0.35, depending on load case. As a comparison, for a Timoshenko approach the same accuracy was found in the range of 0.32–0.44.

Material optimisation

If the total thickness of the CLT is to be kept unchanged, while reducing material usage, the ratios of the layer thicknesses must change. For a substantial reduction in material use, gaps are needed also in the mid layer.

With the above FE-models, lay-ups with considerable material savings and with only minor stiffness changes were found. Examples are given in Tab. 3 for lay-ups involving a beam of length 2750 mm and 125 mm wide laminations. A lay-up resulting in a 10% reduction of material can be achieved by setting ρ=0.5 in the transverse layers, and using the lay-up 60-20-40-20-60. A 20% reduction of material use can be achieved by introducing gaps also in the central (longitudinal) layer, see Tab. 3 and Fig. 7.

Table 3. Lay-ups analysed for optimised material use.

Study	Lay-up	Gap / lamination width (mm)	Material density (cross layers / mid layer)	Relative material usage	Rel. max deflection (uniform/ point)
Ref	40-40-40-40-40	0 / 125	1.0 / 1.0	1.0	1.00 / 1.00
7	60-20-40-20-60	125 / 125	0.5 / 1.0	0.90	0.970 / 0.969
8	60-20-40-20-60	125 / 125	0.5 / 0.5	0.80	1.045/ 1.042

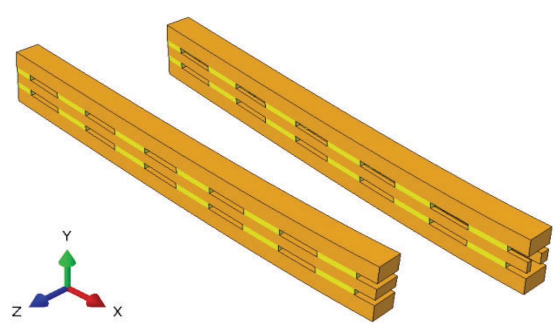

Figure 7. Optimised CLT-lay-ups, according to Tab. 3, study 7 (left) and study 8 (right). Symmetric half of 2750 mm long beam.

Concept development tool

A multi-objective optimisation was conducted to explore various concepts. The tool was configured to both reduce volume and enhance uniform load performance. Both objectives were expressed as a ratio relative to a benchmark geometry: 5-layer CLT, measuring 3800×250×200 mm, with all layers having a thickness of 40 mm, a lamella width of 140 mm, and no gaps.

The optimisation variables were as follows:

- Layers 1 and 5 thickness: 20–80 mm, in 10 mm increments.
- Layers 2 and 4 thickness: 20–80 mm, but trimmed if the total thickness exceeded 200 mm.
- Layer 3 thickness: Determined as the remaining value.
- Lamella width: Minimum = lamella thickness, maximum 200 mm, in 10 mm steps
- Individual gap size in layers 1/5, 2/4, and 3: Range of 0–240 mm, in 10 mm increments.
- The following parameters were fixed: total width, height, length, material properties, and lamella direction.

A uniform unit distributed load was applied, and the optimisation tool evaluated 3 000 samples. The Pareto-optimal solutions predominantly exhibit a structural form resembling a beam, which is a result of the limited optimisation goals at this stage. However, when filtering out the most extreme solutions, several interesting configurations emerge.

Fig. 8 depicts a solution with a structural performance ratio of 1.2 and a volume ratio of 0.9. The solution in Fig. 9 is optimised more towards more volume reduction, while also performing structurally better than the benchmark solution.

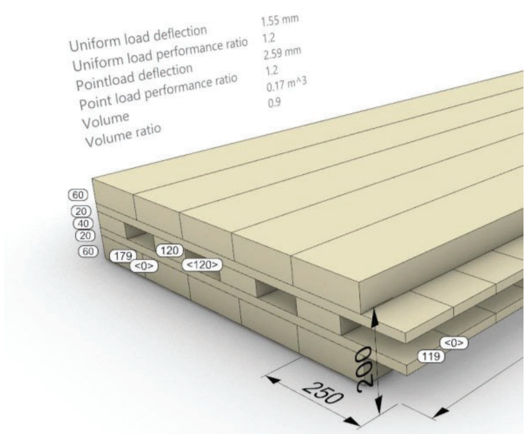

Figure 8. A balance between structural and volume optimisation.

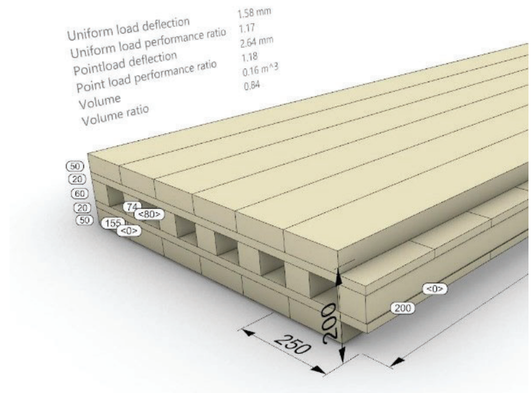

Figure 9. A CLT more optimised on volume reduction.

4 – CONCLUSIONS AND FUTURE WORK

The overall conclusion from this work is that there is a considerable potential in optimising and tailoring CLT to find more material-efficient solutions, although more needs to be done. More specifically:

- Real-time evaluation tools (LCA and structural) are valuable in initial stages of product design.
- GapLaminations to optimise the bending stiffness of floors, could be an efficient approach.
- A 20% reduction of material use, without reducing static out-of-plane stiffness, is possible.
- Further studies on several topics are needed:
    - performance of TLT with gaps
    - joints for TLT with gaps
    - strength grading and production technology for ReLaminations

5 – ACKNOWLEDGEMENTS

The InnoTLT project is part of the European “Bioeconomy in the North” programme and the project has received national funding from several sources. The financial support from Sweden’s Innovation Agency (Vinnova), Federal Ministry of Education and Research (BMBF), Germany, The Research Council of Norway, and the ÅForsk foundation, is gratefully acknowledged.

6 – REFERENCES

[1] Kay Ackermann, S. Christl, P. Dietsch, “Cross-Laminated Timber with Gaps for Wall Elements” World Conference on Timber Engineering (WCTE): Brisbane, Australia, 2025.

[2] H. J. Blaß and R. Görlacher, “Zum Trag- und Verformungsverhalten von LIGNOTREND Decken und Wandsystemen aus Nadelschnittholz” *Bauen mit Holz*, 103(4), pp. 37-40, no. 5, pp. 68-71, 2001.

[3] H. J. Blaß and R. Görlacher, “Zum Trag- und Verformungsverhalten von LIGNOTREND Elementen bei Beanspruchung in Plattenebene” *Bauen mit Holz*, 104(11), pp. 34–41, no.12, pp. 30-34, 2002.

https://doi.org/10.52202/080513-0466

[4] H. Kreuzinger and A. Scholz, *Schubtragverhalten von Brettsperrholz*. Research report, München: Technical University of Munich, 2001.

[5] T. Ehrhart and R. Brandner, “Rolling shear: Test configurations and properties of some European soft- and hardwood species” *Engineering Structures*, vol. 172, pp. 554–572, Oct. 2018.

[6] R. Brandner, P. Dietsch, J. Dröscher, M. Schulte-Wrede, H. Kreuzinger, and M. Sieder, “Cross laminated timber (CLT) diaphragms under shear: Test configuration, properties and design” *Constr Build Mater*, vol. 147, pp. 312–327, 2017.

[7] L. Franzoni, A. Lebée, L. Florent, and G. Foret, “Bending behaviour of regularly spaced CLT panels,” *14th World Conference on Timber Engineering (WCTE): Vienna, Austria*, 2016.

[8] I. Feichter, “Spannungs- und Traglastberechnungen an ausgewählten Problemen der Holz-Massivbauweise in CLT”. Master Thesis, Technische Universität Graz, Graz, Austria, 2013.

[9] C. Gardner *et al.*, “The effect of edge gaps on shear strength and rolling shear modulus of cross laminated timber panels,” *Constr Build Mater*, vol. 259, 2020.

[10] G. Glaso and K. Nore, “Shear Strength of CLT with integrated acoustic properties,” *12th World Conference on Timber Engineering (WCTE): Auckland, New Zealand*, 2012.

[11] M. Arnold, P. Dietsch, and S. Winter, “Mechanical Properties of Innovative Multifunctional Cross-Laminated Timber,” *16th World Conference on Timber Engineering WCTE: Santiago, Chile,* 2020/21.

[12] S. Franke, M. Vogel, M. Lehmann, and F. Sauser, *Mechanische Eigenschaften von Buchen-Brettsperrholz*. Research report, Bern, Schweiz: Berner Fachhochschule, 2014.

[13] L. Bienert, N. Schumacher, S. Winter, and K. Richter, “Development of Disintegrated Hybrid Cross Laminated Timber,” ICEM 2023, pp.943-954, Porto, Portugal, 2023.

[14] S. Aicher, M. Hirsch, and Z. Christian, *Schlussbericht - ERA-WoodWisdom: European hardwoods for the building sector (EU Hardwoods)*, Final report. Stuttgart: Universität Stuttgart, 2018.

[15] G. Jeitler, M. Augustin, and G. Schickhofer, “Mechanical properties of glulam and CLT produced with the wood species birch,” *14th World Conference on Timber Engineering (WCTE): Vienna, Austria*, 2016.

[16] U. Mantau, *Holzrohstoffbilanzierung - Kreislaufwirtschaft und Kaskadennutzung: 20 Jahre Rohstoffmonitoring Holz*. Schriftenreihe nachwachsende Rohstoffe, no. 40. Gülzow-Prüzen: Fachagentur Nachwachsende Rohstoffe e.V. (FNR), 2023.

[17] R. Cherry, A. Manalo, W. Karunasena, and G. Stringer, “Out-of-grade sawn pine: A state-of-the-art review on challenges and new opportunities in cross laminated timber (CLT),” *Constr Build Mater*, vol. 211, pp. 858–868, 2019.

[18] C. Rose *et al.*, “Cross-Laminated Secondary Timber: Experimental Testing and Modelling the Effect of Defects and Reduced Feedstock Properties” *Sustainability*, 10(11), 2018.

[19] Z. Wang, M. Gong, and Y.-H. Chui, “Mechanical properties of laminated strand lumber and hybrid cross-laminated timber,” *Constr Build Mater*, vol. 101, pp. 622–627, 2015.

[20] W. G. Davids *et al.*, “Structural performance of hybrid SPFs-LSL cross-laminated timber panels,” *Constr Build Mater*, vol. 149, pp. 156–163, 2017.

[21] R. Bosl, “Zum Nachweis des Trag- und Verformungsverhaltens von Wandscheiben aus Brettlagenholz,” Dissertation, Universität der Bundeswehr München, München, 2002.

[22] K. Tavoussi, W. Winter, and T. Pixner. “Das erdbebensichere Holzhaus - Forschungsbericht” *Bauingenieur*, 85(3), pp. 129–135, 2010.

[23] J. Turesson, Z. Sharifi, S. Berg, M. Ekevad, and Mats Ekevad, “Influence of laminate direction and glue area on in-plane shear modulus of cross-laminated timber” *SN Applied Sciences*, 2(12), pp. 1–11, 2020.

[24] D. Buck, O. Hagman, A. Wang, and A. Gustafsson, “Further Development of Cross-Laminated Timber (CLT) : Mechanical Tests on 45° Alternating Layers” Vienna University of Technology, Austria, 2016.

[25] M. Arnold, R. Maderebner, P. Dietsch, and S. Winter, “Diagonallagenholz (DLH) – Ressourceneffizienz durch diagonale Orientierung einzelner Lagen: Bestimmung der Steifigkeitsparameter und Verformungsanalysen,” *Bautechnik*, 100, (8), pp. 444–462, 2023.

[26] H. Kreuzinger and A. Scholz, *Wirtschaftliche Ausführungs- und Bemessungsmethode von ebenen Holzelementen (Brücken, Decken, Wände)*. Research report, München: Technical University of Munich, 1999.