Optimization of Cross Laminated Timber floors through locally varying the major direction based on the geometry, support and loading conditions

Vincent STAAT*, ir. Arjan HABRAKEN, dr. ir. Faas MOONEN

*University of Technology Eindhoven, Built Environment, Chair of structural design and Engineering
Het Kranenveld 8, 5612 AZ Eindhoven
vincent.staat@gmail.om

[a] University of Technology Eindhoven, Built Environment, Chair of structural design and Engineering
[b] University of Technology Eindhoven, Built Environment, Chair of structural design and Engineering

Abstract

Cross Laminated Timber (CLT) is a viable alternative for concrete floors and walls. CLT allows for good load bearing capacity by having timber run in two different directions with one distinct major direction. While CLT floors show great potential, not every building application lends itself to having this one distinct major direction. In this research, an optimization method is proposed wherein the lay-up of the CLT floor is varied throughout the floor to better follow the flow of forces. An algorithm was set up that optimizes CLT floors based on the stresses and deflections in the floor. By using the algorithm it was found that for particular geometric, loading and support conditions, the optimized CLT floors could be made with 25% less material as compared to non-optimized CLT while still satisfying the implemented stress and deflection checks. The optimization method was set up from scratch and is in an early stage and thus more future research is required. It does however show that there is potential in optimizing CLT floors by locally varying the major direction.

Keywords: Cross Laminated Timber, Optimization, Rhino, Grasshopper, GSA, algorithm, timber, parametric design

1. Introduction

It is widely known that the construction industry is responsible for around 40% of the global CO2 emission [1]. This means that if the construction industry can change its emission numbers, it would have a significant effect on the world. One of the many ways to make these changes is to use carbon neutral and bio-based construction materials like timber. It was shown that constructing a building out of timber as opposed to concrete could reduce the CO2 emission of construction, use and demolition of the building by up to 42% [2].

When looking at timber construction products Cross Laminated Timber (CLT) is a popular choice as it makes it possible to make large scale, multiple story building out of timber [3]. CLT is manufactured by laminated timber in layers where each layer is rotated 90° compared to the previous one. This layered stacking of timber gives CLT panels two load bearing directions. This makes them good alternatives for concrete slabs for example. However, a CLT panel will always have a major and a minor direction. For scenarios where there are a distinct major and minor direction in the flow of forces CLT is highly suitable. However, when there is no clear major direction for the flow of forces throughout the entire floor, like a point supported floor, CLT can show its weakness. The required thickness of the floor can be governed by local stresses and deflections in the minor direction of the floor. The aim of this research is to set up an optimization algorithm that can locally vary the major and minor direction of a floor. This optimization will be achieved by varying the direction of planks in a single layer. The optimization algorithm will have to detect in which parts of the floor the planks should be rotated so the major direction is changed.

There have already been studies on the optimization of CLT floors. Two of these studies looked at removing timber from CLT and essentially creating a hollow core CLT floor leading to around 20% material reduction [4], [5]. Another study looked at CLT floors strengthened with vertical ribs in the bottom layer. In this study it was found that up to 50% material can be saved compared to conventional CLT [6]. Due to the added ribs the total thickness of the floor package is significantly increased. These studies show that CLT has potential for optimization, but all these studies have only looked at optimizing floors in the same way for the whole floor. The optimization methodology in this research is based on a global level for the element and not a local level. This study will mostly focus on the development of the optimization algorithm. Only after this algorithm is set up and optimized floor design can be found, can the structural performance of these floors be studied. This research will form a starting point from which the newly developed optimization technique can be further studied and improved

2. Literature review

Due to the cross-wise stacking of CLT the panels have relatively high in-plane and out -of-plane strength and stiffness giving the panels two-way action capabilities like a reinforced concrete slab [7]. CLT panels are however always made using and odd number of layers to superficially form a homogenous wooden panel [8]. This means that CLT panels always have a major and a minor direction.

The individual planks in CLT are made by finger jointing shorter planks. The planks in a single layer can be glued together which is called edge bonding. Edge bonding allows for transfer of stresses between adjacent planks and creates a more uniform layer which can enhance the physical properties like air tightness, fire resistance and acoustic performance [9]. A disadvantage of edge bonding besides the increased production complexity is that it can cause irregular crack formation in a panel due to shrinkage and swelling [10].

Due to the layered orthotropic nature of CLT the stress distribution in CLT is unique. The large difference in strength between the direction parallel and perpendicular to the grain in timber(11000 MPa against 370 MPa for C24 timber [11]) causes the perpendicular layers to remain relatively unstressed. Calculation methods even propose to set the E-modulus of perpendicular layers (E_{90}) to zero. This is because in addition to the large stiffness difference, normal stresses can almost not be transferred in the cross layers between adjacent planks due to regular gaps and cracks in the boards (Thiel, 2013, p86). These effects cause the bending stress distributions in the two directions of the panel to be as shown in Figure 1.

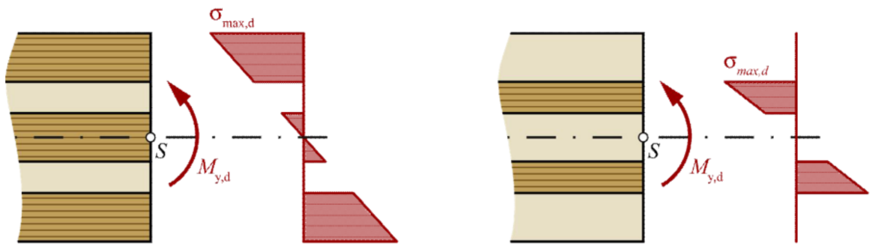

Figure 1: Bending stress distribution in CLT in major (left) and minor (right) direction [12]

When considering shear stresses all the layers are able to transfer stresses, so the stress distribution is not as step-wise as previously shown for bending. However, cross layers of a cross section are subject to rolling shear: the grains in the plank can start rolling over each other. The rolling shear stiffness of timber is significantly lower than the transverse shear stiffness (0.8 MPa against 3.5 MPa [11]. This causes the stresses to minimally increase in cross layers but still be transferred through these layers. The simplified (taking $E_{90} = 0$) shear stress distribution in a CLT panel is illustrated in Figure 2.

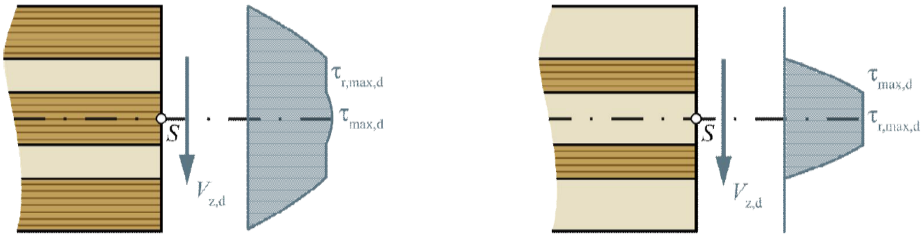

Figure 2: Shear stress distribution in CLT for major (left) and minor (right) direction [12]

The rolling shear strength of timber is significantly lower than the transverse shear strength of timber. This causes rolling shear failure to be one of the governing failure modes of CLT alongside glue line failure (delamination) and tension failure [13].

3. Methodology

3.1 Optimization principle

The aim of the optimization of CLT floors is to reduce the required amount of material (thickness of the floors) to meet the structural and serviceable limits by locally changing the major direction of the floors. A floor is divided into rectangular zones. The optimization will look at the stresses in each zone of the floor and thereby determine if the major direction of each zone will have to be rotated. The size of these zones should ideally be equal to squares the size of the width of the used planks. The size can be taken larger or smaller, but this will create challenges during production as some planks will then have to be made less wide along their length to fit them between other zones.

To change the major direction of a zone the two outer-most layers at the top and bottom of a zone will be rotated. This means that after rotation there are still only two layers running in the old minor direction. However, as these layers are at the outside of the floor package, they are structurally the most effective. This means that after rotating the major direction is still changed while there are still sufficient layers left running in the other direction. The rotation method is shown in Figure 3. For a five ply CLT floor this would mean that the middle layer of the floor is continuous throughout the floor ensuring the floor will still function as a single structural element. For more plies there will be even more continuous layers. The choice to have at least one continuous layer in the floor means that the optimization process will not work for 3-ply CLT floors. If only the outer layers are rotated there will be no plies left in one direction. Additionally, if the outer layers are rotated but the center layer is rotated in the other direction there will be layers running in both directions but there will not be a continuous layer in the floor anymore.

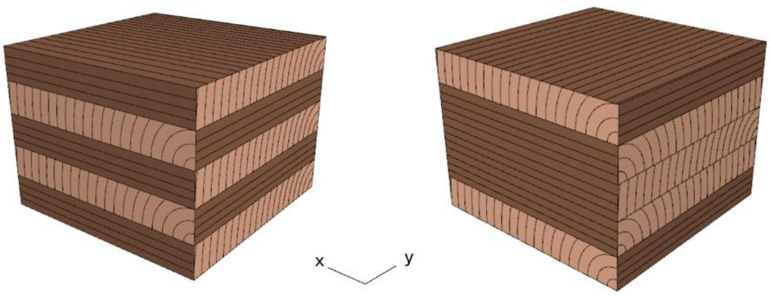

Figure 3: Proposed optimization method where the outer two layers at the top and bottom are rotated

The effect of a rotation strategy like this on the stress distribution in a 5-ply floor has been visualized in Figure 4 to Figure 7 below.

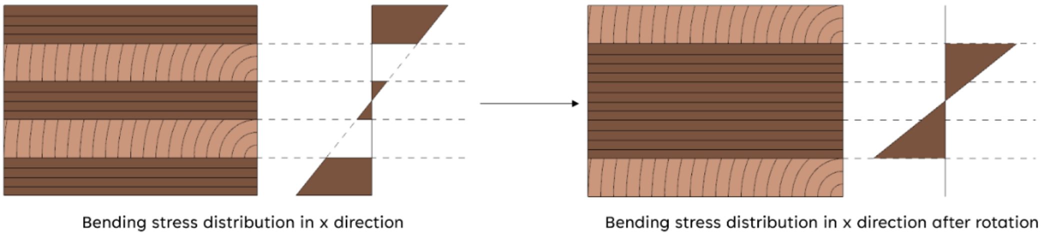

Figure 4: Bending stress redistribution in original major (x) direction

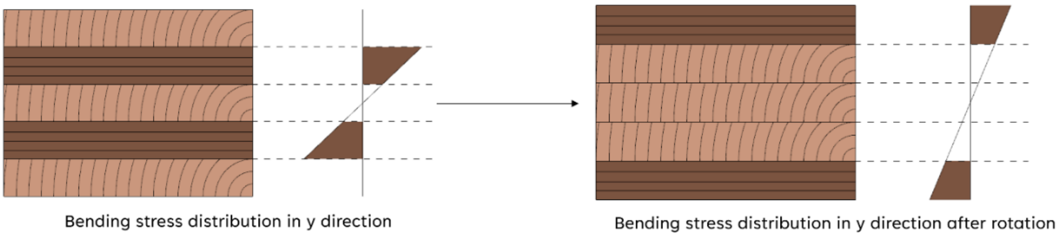

Figure 5: Bending stress redistribution in original minor (y) direction

The bending stresses in the Y-direction will be decreased as the effective layers are moved away from the center of the cross section. For the X-direction the opposite is happening. It is therefore important that during the optimization algorithm it is checked that rotating fixes a stress problem in the y-direction but does not simultaneously create a stress problem in the x-direction.

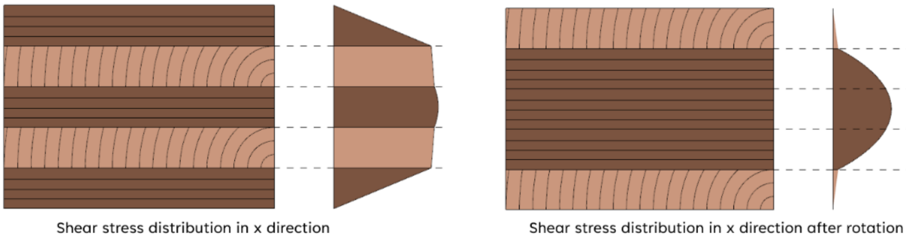

Figure 6: Shear stress redistribution in original major (x) direction

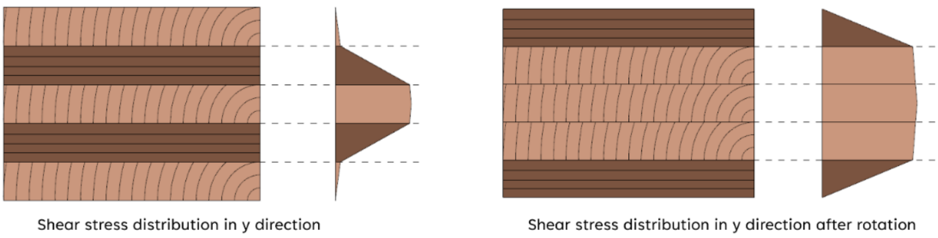

Figure 7: Shear stress redistribution in original minor (y) direction

For the shear stresses a similar phenomenon is happening where the stresses are decreased as the effective material is in the outer most layers. Due to the low stiffness of the timber in its minor direction the stresses will not increase significantly in the middle three layers. The highest stress will however occur in the middle layer which needs to be checked with the rolling shear strength of the used timber. In the X-direction we again see an increase in maximum stress. This maximum stress is located at the center of the cross section where the planks run in the strong direction. This means that the regular shear capacity of the timber must be checked which is significantly higher than the rolling shear strength [11].

3.2 Optimization algorithm

The optimization algorithm was set up using the Rhino Grasshopper software. Native Grasshopper components have been used for the geometry input of the script, the data management throughout the script and the geometric output of the script. For the structural calculations within the script the Osays GSA grasshopper plugin was used. These components transferred the geometric input to a calculatable FEM mesh with material properties, support conditions, loads and load combinations. Natively, GSA does not have a way to define CLT material. To overcome this, the CLT was modelled as a homogenous orthotropic material with an equivalent E-modulus in the strong and the weak direction corresponding to the CLT section. There are various ways to simplify the mechanical attributes of a CLT floor to single, equivalent values for each direction as opposed to values for each individual layer. The method chosen for the algorithm is the composite method presented by Blass and Fellmoser in 2004. Using the composite theory it is possible to take the strength and stiffness contribution of each layer into account in a single value that can be used to describe the performance of the floor [14].

Depending on the number of layers and the E-modulus of the layers it is possible to define the effective E-modulus of the floor in two directions. This method was chosen as it makes it possible to calculate an effective E-modulus regardless of the moment of inertia of the floor. This makes it a suitable method as the custom material in GSA only has an E-modulus input because the moment of inertia is dependent on the geometry of the cross-section. Using equations 1 and 2 the factors k1 and k2 can be determined in which a_m is the thickness of each layer as illustrated in Figure 8 where *m* is the number of layers. By multiplying the E-modulus of the used timber parallel to the grain by the factors k1 and k2 the E-modulus in the major and minor direction of the floor can be determined. For example, a 5-layer CLT floor with layers of 30 mm made up of C24 timber is considered. The E modulus C24 parallel to the grain (E_0) is 11000 MPa and perpendicular to the grain (E_{90}) 370 MPa. Using the composite theory, it can be determined that k1 is 0.79 and k2 is 0.24. This means that the effective E-modulus of the floor in the major direction is E_0 * k1 = 11000 * 0.79 = 8704 MPa and in the minor direction E_0 * k2 = 11000 * 0.24 = 2666 MPa. The effective E-modulus in the major direction is lower than that of sawn timber in its major direction (parallel to the grain). This is logical as in CLT not all the wood is running in the major direction so not all the stiffness is “running” in this direction. On the other hand, the other direction of the floor is significantly stiffer than sawn timber is perpendicular to the grain.

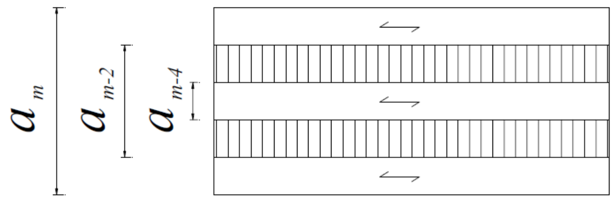

Figure 8: Example of am for m = 5 [15]

$$k_1 = 1 - \left(1 - \frac{E_{90}}{E_0}\right) * \frac{a_{m-2}^3 - a_{m-4}^3 + \cdots \pm a_1^3}{a_m^3} \quad (1)[15]$$

$$k_2 = \frac{E_{90}}{E_0} + \left(1 - \frac{E_{90}}{E_0}\right) * \frac{a_{m-2}^3 - a_{m-4}^3 + \cdots \pm a_1^3}{a_m^3} \quad (2)[15]$$

Using the composite theory the equivalent mechanical properties of various CLT sections were defined in a separate GSA file. The thinnest section defined was 5 layers of 20mm thick and the thickest section defined was 11 layers of 40mm thick. For sections with 5, 7, 9 and 11 layers multiple sections were defined with increasing layer thicknesses. The predefined sections are read by the Grasshopper file so that the script can cycle through these sections when running the algorithm. The deflection results of the GSA calculation can directly be used to determine if the relevant optimisation criteria are satisfied. The stress results are however not usable as GSA does not "know" the material is actually layered. It cannot present the correct stress distribution throughout the layers. It can however calculate the moments and shear forces throughout the floor. These moments and shear forces can be used to calculate the stress distribution throughout the section using various formulas and equations.

The formulas used in the algorithm are the same formulas used in CLT designer presented by [12]. The equations presented by Thiel [12]. can be used to calculate the bending and shear stresses given the bending moments and shear forces. The formulas are adjusted slightly to make distinctions between the stresses in de x and the y direction. This distinction is not made by Thiel [12] as the formulas presented are as they are used in CLT designer which is a one-dimensional calculation tool representing a CLT floor as a beam. Both the bending and the shear stresses are calculated using an effective stiffness factor K_{CLT} that is first calculated. In contrast to the composite method, this K_{CLT} factor incorporates the moment of inertia, area, and eccentricity of each layer. It does not give a single effective E-modulus which means it cannot be used to define an orthotropic material in GSA. The factors $K_{CLT,x}$ and $K_{CLT,Y}$ are determined using equations 3 and 4 below.

$$K_{CLT,x} = \sum\left(E_{i,x} * I_{i,x}\right) + \sum(E_{i,x} * A_{i,x} * e_{i,x}^2) \quad \text{(3) adjusted from [12]}$$

$$K_{CLT,y} = \sum\left(E_{i,y} * I_{i,y}\right) + \sum(E_{i,y} * A_{i,y} * e_{i,y}^2) \quad \text{(4) adjusted from [12]}$$

$E_{i,x}$ and $E_{i,y}$	Young's modulus of layer i in x and y direction respectively in MPa
$I_{i,x}$ and $I_{i,y}$	Moment of inertia of layer i in x and y direction respectively in mm4
$A_{i,x}$ and $A_{i,y}$	Area of cross section of layer i in x and y direction respectively in mm2
$e_{i,x}$ and $e_{i,y}$	Distance between center of gravity of layer i and center of gravity of CLT element in x and y direction respectively in mm

The maximum bending stresses in each layer are subsequently calculated as follows:

$$\sigma_x(z) = \frac{M_x}{K_{CLT,x}} * z * E_x(z) \quad \text{(5) adjusted from [12]}$$

$$\sigma_y(z) = \frac{M_y}{K_{CLT,y}} * z * E_y(z) \quad \text{(6) adjusted from [12]}$$

E_x and E_y	Young's modulus in x and y direction respectively in MPa
M_x and M_y	Moment in x and y direction respectively as calculated by GSA in Nmm
$K_{CLT,x}$ and $K_{CLT,y}$	K_{CLT} as calculated using equations 3 and 4
z	Height at which the stress is determined in mm

Similarly, the maximum shear stresses in each layer are calculated using:

$$\tau_x(z) = \frac{V_x * \int_{A_{0,x}} E_x(z) * dA_x}{K_{CLT,x} * b(z)} \quad \text{(7) adjusted from [12]}$$

$$\tau_y(z) = \frac{V_y * \int_{A_{0,y}} E_y(z) * dA_y}{K_{CLT,y} * b(z)} \quad \text{(8) adjusted from [12]}$$

E_x and E_y	Young's modulus in x and y direction respectively in MPa
V_x and V_y	Shear force in x and y direction respectively as calculated by GSA in N
A_x and A_y	Area of cross section in mm^2
$K_{CLT,x}$ and $K_{CLT,y}$	K_{CLT} as calculated using equations 3 and 4
z	Height at which the stress is determined in mm
b	Width of cross section in mm

Now that all the results required for the optimization are available, the optimization criteria can be set in the algorithm. For the deflections the algorithm finds the points of largest deflection. The deflection of these points is then compared to the closest relevant span direction (e.g. along the long or the short edge of the floor or along the diagonal over the floor). For the stresses it is checked whether the present stresses exceed the strength of the CLT.

Every iteration can be divided into two parts: the first part where the zones that should be rotated are found and the second part where all the stress and deflection checks are performed. The top part of Figure Figure *9* shows the steps in this part of the iteration. If a zone should be rotated or not is based on the largest bending stress direction and if there are any zones where the shear stress in the y direction exceeds the strength limit.

After the zones that should be rotated are determined a new GSA calculation is performed where the rotated zones are incorporated in the meshed floor. After this, the stresses and deflections are checked as described earlier. This logic is shown in the bottom part of Figure 9.

The first part of the iteration is mostly relevant during the first iteration where the initial rotation zones are determined using an isotropic floor. After that the first part of the iteration will not change anything to the floors until layers are added to the floor. Adding layers affects the ratio between stiffness in the x and y direction and therefore could lead to more zones needing to be rotated or zones needing to be rotated back to the initial configuration.

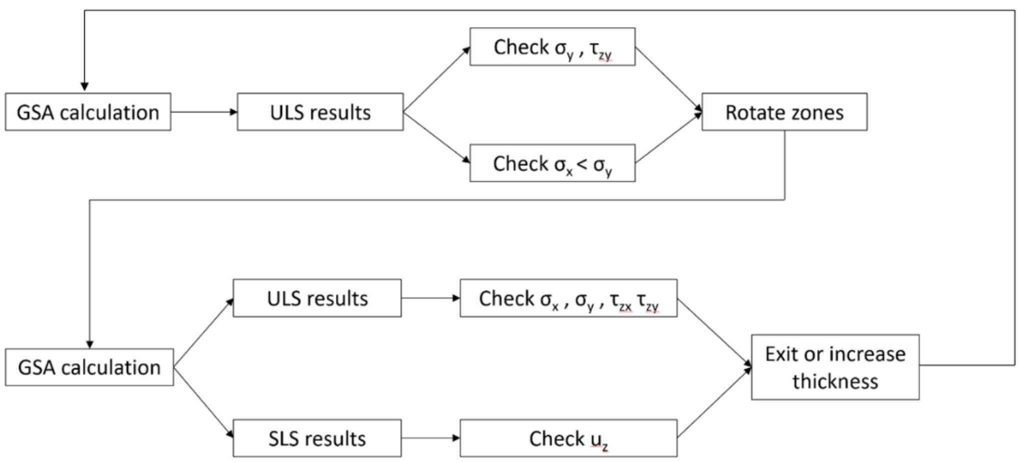

Figure 9: Steps in a single full iteration

The iterative loop is run until the loop exit conditions are met. These conditions are that all stresses and deflection checks must be satisfied. If any of these checks is not satisfied the loop is ran again with two types of data being changed for the next iteration. The first data type is the zones that should be rotated. The loop starts with no rotated zones and a fictional isotropic material for the floor. If a CLT floor is used in the first iteration the location of the largest stresses and deflections is already influenced by the orthotropic nature of the floor. By starting with an isotropic material, the zones that need to be rotated are based on a more realistic and natural flow of forces. After running the first iteration with the isotropic material the zones are found. These zones are then rotated in the following iteration. The second type of data is which property the floor should get in the next iteration. At the end of each loop the next layup is selected from the list of all properties and assigned mesh of the floor in the next iteration.

The loop will stop when all the checks are satisfied and remain in the last calculated state. This last calculated state is the minimal thickness with rotated zones for which the floor will satisfy all the stress and deflection checks. In the algorithm the load combinations for the ULS and SLS have been set-up according to the Eurocodes.

4. Results

The results of the optimization algorithm are shown using two case studies. In these case studies two floors with different geometric and support conditions have been optimized using the algorithm.

4.1 Case study 1

The first floor that is analyzed is the floor that has been used as an example case throughout this report. The floor is 3 by 6 meters and supported at 6 points and has no openings. The floor design is showed in Figure 10 where the support conditions for each support point are shown as well. The floor is loaded with a permanent load of 3 kN/m^2 and a variable load of 3.5 kN/m^2. The floor is located in a commercial store and in climate class 1.

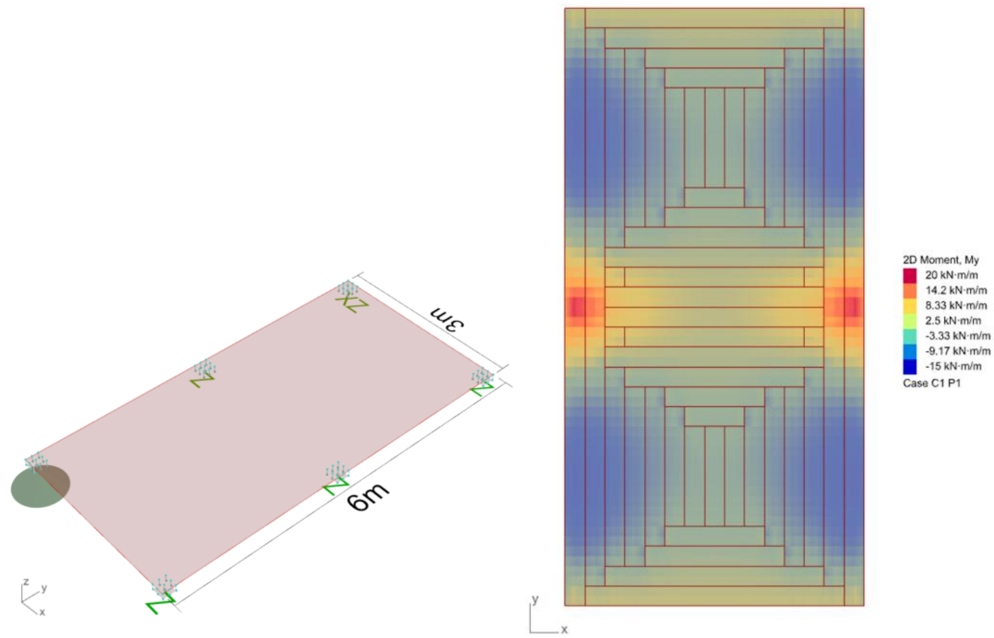

Figure 10: Geometry and support conditions for floor 1(left), optimization result of floor 1(right).

Running the optimization algorithm leads to the plank layout shown in Figure 10 where it is overlayed over the moment in the y-direction to illustrate the relation between force distribution and plank direction. The optimization results in a floor consisting of 5 layers of 30 mm thick totaling to a thickness of 150 mm. The governing check was the deflection which determined the total thickness of the floor. If the optimization is run without rotating zones the thickness at which all checks are satisfied is 5 layers of 40 mm thick totaling to 200 mm. For this case the shear stress in y direction was governing. By rotating the zones, the floor can satisfy all stress and deflection checks with 25% less timber. To create a good insight in what the rotation has done for the floor the values of a rotated 150mm thick and a non-rotated 150mm thick floor have been compared in Table 1. Because of the rotation in one of the floors the maximum stresses do not always occur in the same places for both floors. The values in Table 1 should thus be interpreted to show how the maximum stress value for the entire floor is changed not at a specific location. From this table it can be seen that the maximum stresses in the x-direction increase as this is made the minor direction in the rotated zones. The stresses in the y-direction do however decrease because in these zones the major direction is changed to be in the y-direction. The deflection also significantly decreases due to the rotations.

Table 1: Optimization results of floor 1 compared to conventional floor of equal thickness

Value	Rotated 150 mm floor	Non-rotated 150 mm floor	% difference
Bending x [MPa]	6.84	6.13	+11.58
Bending y [MPa]	5.75	10.33	-55.66
Shear x [MPa]	1.07	0.63	+69.84
Shear y [MPa]	0.58	1.03	-56.31
Deflection [mm]	8.47	12.13	-69.83

4.2 Case study 2

The next floor that was analyzed is a 3 by 4-meter floor supported along its edge on one side and at its two corners at the opposing side. The floor is visualized in Figure 11. The floor is loaded with a permanent load of 2 kN/m^2 and a variable load of 3 kN/m^2. The floor is situated in an office building in climate class 1.

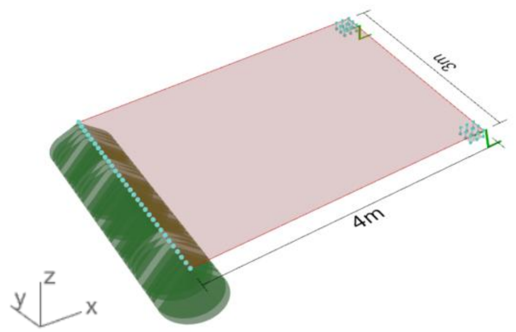

Figure 11: Geometry and support conditions for floor 2

When the optimization is performed a layup of 5 layers of 35 mm thick totaling to 175 mm is found with its plank layout shown in Figure 12. When the optimization is run without rotating it was found that all checks were only satisfied when 7 layers of 30 mm thick were used totaling to 210 mm. This means that rotating zones in the floor saves almost 17% timber. Additionally, rotating the zones means the floor can be made with only 5 layers instead of 7. The 17% material saving might be lower than the previously observed 25% but having two less layers in the floor makes the floor faster and cheaper to produce. Less glue and fewer individual planks are required meaning that the 17 % material savings does not paint the whole picture of what is saved in terms of cost and efficiency. For both the rotated and non-rotated floors the governing check was once again the deflection.

This floor clearly illustrates how changing the properties of the floor locally makes the floor behave differently. This is visualized in Figure 12 and Figure 13. Figure 12 shows the rotated floor with 5 layers of 35mm overlayed over the deflection with the 4 largest deflection points indicated with red crosses. The maximum deflection occurs to the right of the center of the floor. This deflection is compared to the main diagonal of the floor where it satisfies the slenderness ratio of 400. When looking at the non-rotated floor of 5 layers of 35 mm in Figure 13 the different major direction of the floor results in the largest deflection being located at the short unsupported edge of the floor. This deflection is thus compared to the 3m span of this free short edge. Given that this span is shorter than the main diagonal of the floor, the slenderness ratio of 400 allows for smaller deflections at this location than in the middle of the floor. This causes the floor to fail the deflection requirement. Only when the thickness is increased and there are 7 layers of 30 mm each it becomes evident that the maximum deflection shifts towards the center of the floor. Figure 13 shows the 7 layers of 30 mm unrotated floor that now satisfies the deflection checks. This floor is a clear example of how rotating the zones might not directly reduce the maximum deflection, but it changes the location where the maximum deflection occurs, leading to the deflection checks being satisfied earlier.

Table 2*Table 1* below compares the values for a rotated floor with 5 layers of 35 mm and a non-rotated floor with 5 layers of 35 mm. These values show that rotating the zones increases all but one of the checked values. This shows that the optimization is working well as it is finding an optimized solution which is not likely when only looking at maximum values.

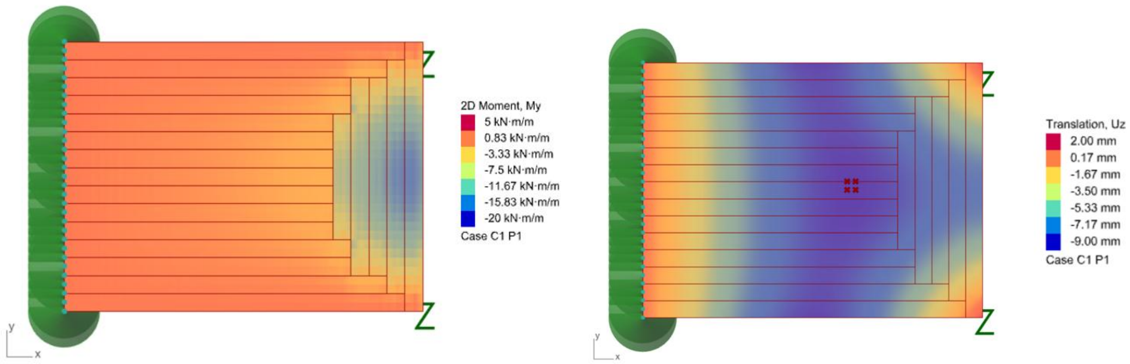

Figure 12: Optimization result of floor 3 (left), Maximum deflection of optimized floor 3 (right)

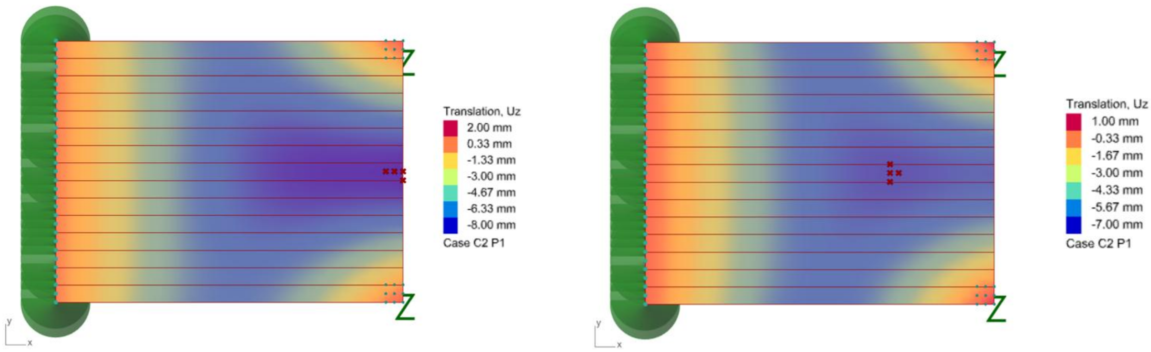

Figure 13: Maximum deflection of non-optimized floor 3 with equal thickness (5 layers of 35mm) (left), Maximum deflection of non-optimized floor 3 with required thickness (7 layers of 30mm) (right).

Table 2: Optimization results of floor 3 compared to conventional floor of equal thickness

Value	Rotated 175 mm floor	Non-rotated 175 mm floor	% difference
Bending x [MPa]	4.58	3.78	+21.16
Bending y [MPa]	3.63	2.06	+76.21
Shear x [MPa]	0.58	0.50	+16
Shear y [MPa]	0.36	0.53	-32,1
Deflection [mm]	8.45 close to floor middle	7.61 at free short edge	+11,03

The three floor case studies above clearly show the capacity of the optimization algorithm. The first case study shows that up to 25% of the used timber can be saved when rotating zones in the floor. The second case study shows that not all floors can be optimized using the algorithm as they can already be optimal when they are in their initial non-rotated CLT configuration. The third case study shows that the algorithm can find significant material savings that can be very hard to do so by hand. The third case study shows the algorithm not only looks at maximum values but analyzes the floor behavior as a whole, leading to surprising amounts of material savings.

5. Discussion

The proposed optimization algorithm can lead to theoretical material savings of up to 25%. The case studies have already highlighted that the optimization technique does not lead to significant material savings for all types of floors. Because the optimization system and algorithm have been set up from scratch, there are still many points of discussion that can influence the practical results of the proposed optimization technique.

The optimization technique is based on theoretical stress distribution and a 100% interacting connection between layers and optimization zones. Using FEM calculations it was found that the proposed optimization technique could lead to large stresses perpendicular to the grain around intersections between optimized and non-optimized zones. This calculation is however based on a full connection between all layers and planks. Further FEM calculations and preferably laboratory tests are needed to determine of the proposed optimization technique is viable or not.

It is expected that it can be found that the continuous layers in the optimized CLT floor will be stressed significantly when no edge bonding is used as these can become the only layers that can transfer the stresses throughout the entire floor. Especially for 5-ply floors this could become problematic as there is only a single continuous layer. The optimization technique is already not possible for 3-ply CLT but upon further research it could be concluded that it is also not possible in its current state for 5 ply floors as the optimization can be governed by the stresses in the continuous layers.

Additionally, the optimization now works with an equal thickness for all layers. This somewhat limits the results of the optimization. A stress problem could for example be solved by only increasing the thickness of the outer layers instead of the thickness of all layers. If a varying thickness of layers is implemented, it is expected that the optimization results could be further improved. It must then be studied of it is required to have a constant thickness for each layer throughout the floor or if this thickness can also be varied locally.

Recommendations for further research include FEM and laboratory tests of the proposed optimization technique. Additionally, the productional viability of the proposed floors needs to be researched in collaboration with CLT producers. Lastly, the optimization algorithm is in a first, experimental state and should be elaborated and improved by implementing additional features and stress checks like compression stress perpendicular to the ground at the supports.

6. Conclusions

A parametric optimization tool for locally optimizing CLT floors has been presented. The optimization method can lead to theoretical materials savings of 25%. The tool can be used for various types of floors with different geometries, loading conditions and supports. This means that the goal of the research has been achieved. Material savings like these will lead to various effects like lower production costs, faster and easier construction because the elements are lighter, more efficient transport because more elements can be transported at a time and lighter foundations as the weight of the building is reduced

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