Finite-Element Simulations of Glulam Beams with Natural Cracks

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Abstract:
Modeling and simulation of natural cracks and its propagation for glulam beams in numerical method frame work have been studied in this thesis. The aim of this study was to find out the influence of formed cracks on the Glulam beam load-carrying capacity. The simulation has been developed with the finite element calculation software ABAQUS. First the simple simulations were compared with previous available experimental results to achieve calibrated simulation model. Then simulation of long glulam with different natural cracks has been done based on calibration. This project has been focused on fracture mechanic and its effects on shear and bending capacity of the cracked glulam beam used in practical application by extended finite element method.

Keyword:
Glulam beams, Fracture mechanics, XFEM, Natural crack, ABAQUS, VCCT.
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1 Notations

\( A \) Area
\( B \) Width
\( E \) Young’s modulus
\( F \) Force
\( G_i \) Energy release rate \((i=I, II, III)\)
\( G_{ic} \) Critical value of energy release rate \((i=I, II, III)\)
\( G_{ij} \) Shear modulus in the \(i,j\) orientation
\( K \) Stress intensity
\( K_c \) Critical Stress intensity
\( L \) Length
\( M \) Moment
\( P \) Pressure
\( R \) Reaction force
\( V \) Shear force
\( W \) Section modulus
\( a \) Crack length
\( h \) Height
\( t \) Time
\( \tau \) Shear stress
\( f_k \) Characteristic value
\( f_{10k} \) Characteristic Tensile strength parallel to grain
\( f_{90k} \) Characteristic Tensile strength perpendicular to grain
\( f_{vk} \) Characteristic shear strength
\( f_{mk} \) Characteristic bending strength
\( k_{cr} \) Crack factor
\( \nu_{ij} \) Poision’s ratio in the \(i,j\) orientation
\( \sigma \) Stress

\( \sigma_m \) Bending stress

\( \Pi \) Potential energy

**Abbreviations**

LEFM Linear Elastic Fracture Mechanics

FEA Finite Element Analysis

FEM Finite Element Method

XFEM Extended Finite Element Method

MAXPS Maximum Principle Stress Criterion

MAXS Maximum Nominal Stress Criterion

VCCT Virtual Crack Closure Technique

STATUSXFEM Status of the Enriched Elements
2 Introduction

Glued laminated timber beams are load-bearing members for construction systems, e.g. bridges, building, posts, etc. Typically, cracks caused by climatic changes can be formed on glulam beams and can have effects on load bearing capacity of the structures. The aim of this thesis is to be able to model and analyze the effects of these cracks on load capacity of glulam beam.

In 2011, Erhan Saracoglu carried out his master thesis about “Finite-Element simulation of the influence of cracks on the strength of glulam beams”. The main objectives were to understand the mechanical behavior of the glulam beams with particular and certain types of cracks under static load and finding critical (ultimate) load conditions. He carried out a simulation of glulam beams with different type of cracks and location by using the finite-element method. He also performed some experiments to obtain bending strength, shear strength, and crack initiation of these glulam beams and compared with simulation [1].

This thesis project has continued the work of Erhan Saracoglu with modeling and simulation real formed cracks on wooden beams and investigating the effects of those cracks on shear and bending capacity of the glulam beams especially in long beams, which are used in practical applications.

Chapter 3 contains a short description about wood structure and background theory of fracture mechanics.

Chapter 4 presents numerical method for analyze of glulam beam, modeling procedure and assumptions.

Chapter 5 covers calibration of the model of glulam beam.

Chapter 6 includes the simulation of glulam beam in different load conditions and results.

Chapter 7 gives a conclusion and discussion about this work.
3 General Properties of Wood and Glulam Timber

3.1 Wood Structure

Wood is anisotropic material because its properties vary in different direction, to a good approximation, wood can be considered cylindrically orthotropic material [1]; this means that it is assumed to have three principal material directions, the grain direction (L), the radial direction (R) and the tangential direction (T) as shown in Figure 3.1.

![Figure 3.1. Principal axes of wood](image)

As a result, twelve constants (nine are independent) are necessary to express the elastic behavior of wood that are three moduli of elasticity $E$, three moduli of rigidity $G$ (shear module) and six Poisson’s ratios $\nu$ [2].

Due to cellular structure of wood, some properties assisted with L axis are substantially stronger and stiffer than equivalent properties associated with the R and T axes [3].

3.2 Glulam Beam

Glued laminated timber, glulam, is generally built from spruce or pine timber boards (laminates) bonded together with adhesives. Commonly used adhesives in Sweden are phenol- resorcinol (PR) and melamine-urea-formaldehyde (MUF); the grain direction of boards is aligned parallel to the longitudinal axis [3].
Individual laminates are typically 19–50 mm in thickness and 1.5–5 m in length [3]. In Sweden generally 45mm or 33 mm thickness is used. In order to get laminations of arbitrary length the boards are finger jointed then glued together to produce the desired size.

The some of the main advantages of glulam members are as follows [4]:

- High strength/weight ratio, enabling wide spans.
- Glulam can be produced in any size, length and shape.
- Glulam has high resistance to chemical attack and aggressive environments.
- Glulam has high resistance to fire.

And the main disadvantages can be stated as:

- Low strength in tension perpendicular to the grain.
- Highly anisotropic material.
- Shrinkage due to varying moisture content can induce stresses and leads to cracks.

Low tensile strength perpendicular to the grain direction $f_{90k}$ can be 60 times less than tension along the grain $f_{60k}$ [5]; therefore, special attention shall be paid for designing timber structures in order to limit this type of stress, furthermore, crack initiation and propagation caused by tension perpendicular to grain is important issue to be consider.

Glulam structures calculate and design in accordance with the European Community’s Eurocode 5. More information about Glulam beams and design regulations can be found in Saracoglu (2011) [1].

### 3.3 Fracture Mechanics

In this part, some aspect of fracture mechanics is considered. For analyzing of cracks and crack propagation, linear elastic fracture mechanic (LEFM) is considered, which is based on the assumption of an ideally linear elastic behavior of the material and the existence of a crack. In this thesis, wood is assumed to be a linear elastic material.

There are two basic approaches to fracture analyze or crack propagation criteria: The stress intensity approach and the energy approach.
Stress intensity approach emphasizes on distribution of stresses in the vicinity of the tip, based on this approach crack will grow if the stress intensity factor $K$ reaches the critical value $K_c$ (also known as fracture toughness) [25].

The energy approach expresses that crack propagation occurs when the energy available for crack growth is adequate to overcome the strength of the material [25]. The energy release rate $G$ (may also be known as crack extension force or crack driving force) is defined as

$$G = -\frac{d\Pi}{dA}$$  \hspace{1cm} (3.1)

Where $G$ is the rate of changes in potential energy ($\Pi$) with respect to the crack area ($A$). Based on energy release rate failure criterion, fracture may be occurred when the available energy release rate $G$ is equal or larger than a critical value $G_c$

$$G \geq G_c$$  \hspace{1cm} (3.2)

Where $G_c$ is measure of fracture toughness of the material and is considered to be material property and in contrast with $G$, is independent of the geometry of the structure, the geometry of the crack and applied load [6]. There are three possible crack propagations [6]:

- stable, when $G$ decreases with increasing crack length ($a$), and if the value of $G$ falls below the critical energy release rate $G_c$, the crack extension will stop $\frac{dG}{da} < 0$.
- semi-stable, when $G$ is constant within increasing crack length $\frac{dG}{da} = 0$.
- unstable, when $G$ increases with increasing crack length $\frac{dG}{da} > 0$.

In this thesis, the energy approach for analyzing crack propagation is used. A crack can be loaded in three different ways, Mode I represents crack is opened due to pure tensile stress perpendicular to the plane of crack, mode II represents crack is sheared in the z direction due to in-plane shear stresses, and mode III represents crack is sheared in the x direction due to transverse shear stress, see Figure 3.2.
In general, failures or cracks may occur through combination of all three modes, which is known as the mixed mode failure or mixed mode fracture. Depending on which mode of loading is applied, there is three different critical energy release rate, in other words $G_c$ may have three different values for different mode, and subsequently, it is possible to separate the energy release rate $G$ into the three modes and getting $G_{I}, G_{II}$ and $G_{III}$[6]. More study about crack propagation and fracture mechanic in wood see [7], [5].
4 Numerical Method and Assumptions for Analysis of Glulam Beams and Modeling Glulam

Finite element analysis (FEA) is a numerical method that can divide complex domains, and represent them by an assembly of simpler finite sized elements connected by nodes [8]. Nodes represent the points of calculation and the systems equations are solved for unknown parameters at the nodes [9].

FEA and other numerical analysis techniques can only approximate a solution and then cannot be a certain substitute for experimental results and data. For confirming simulations, it is important to compare obtained results with existence experimental results to reach reliable FE simulation.

The finite-element program Abaqus is chosen for the numerical analysis and FE simulation in this thesis.

There are several damage criteria that have been proposed to predict the initiation of crack and fracture in Abaqus.

In this thesis Maximum principal stress (MAXPS) is used as a damage initiation criterion in the XFEM enriched region for the bottom lamella to determine bending failure, and Maximum nominal stress (MAXS) is used to find damage initiation due to shear stress in the middle lamellas.

MAXPS criterion can be stated as;

\[ f = \left\{ \frac{\sigma_{\text{max}}}{\sigma_{\text{max}}} \right\} \] (4.1)

Where \( \sigma_{\text{max}} \) is the maximum allowable principal stress and symbol \( \left\{ \right\} \) is Macaulay bracket that normally states as;

\[ \left\{ \sigma_{\text{max}} \right\} = \begin{cases} 0, & \sigma_{\text{max}} < 0 \\ \sigma_{\text{max}}, & \sigma_{\text{max}} \geq 0 \end{cases} \] (4.2)

And the Macaulay brackets mean that a purely compressive stress state does not initiate damage. In this criterion damage is assumed to initiate once the maximum principle stress ratio reaches a value of one [10].
MAXS is the second criterion to find damage initiation and can be represented as:

\[ f = \max \left\{ \left( \frac{t_n}{t_n^0}, \frac{t_s}{t_s^0}, \frac{t_t}{t_t^0} \right) \right\} \]  \hspace{1cm} (4.3)

Where \( t_n \), is the component normal to the crack surface, \( t_s \) is the first shear direction and \( t_t \) is the second shear direction on the crack surface and depending on what we chose. \( t_n^0 \), \( t_s^0 \) and \( t_t^0 \) are the peak value of the nominal stress and as it is mentioned symbol \( \langle \rangle \) is Macaulay bracket to avoid damage initiation by purely compressive state. It is assumed damage initiates when the maximum nominal stress ratio reaches a value one [10].

Modeling and simulating crack propagation and fracture by using traditional finite-element methods is problematic and complex because the shape and topology of the crack domain changes continuously to match the geometry of the discontinuity as the crack grows.

The Extended Finite Element Method (XFEM) has solved this problem very effectively to model cracks. XFEM allows us to investigate crack growth along an arbitrary, solution-dependent path and without requiring to re-mesh domain [10]. The (XFEM) were developed by Belytschko and Black (1999) and improved by Moes et all [11].

In this method crack geometry can be modeled independently from the mesh and additional functions referred to as enrichment functions can be added to the classical finite element polynomial approximation based on the concept of partition of unity described by Melenk and Babuska (1996). In order to model a crack discontinuity, the crack interior is defined by a discontinuous function, while the interaction around the crack-tip is modeled by crack-tip enrichment functions [12].

Abaqus as a finite-element analysis (FEA) software can support XFEM to simulate of crack initiation and propagation. Modeling stationary cracks in Abaqus/Standard can be modeled by two alternative approaches:

1. Modeling moving cracks with the cohesive segments method and phantom nodes.
2. Modeling moving cracks based on the principles of linear elastic fracture mechanics (LEFM) and phantom nodes.
The second approach is more appropriate for modeling brittle materials and crack propagation and is used in this thesis. Based on this approach, the strain energy release rate is calculated by modified virtual crack closure technique (VCCT).

To model based on this approach, it is necessary to define an enriched feature and its properties; furthermore, because of XFEM-based LEFM approach is based on the principles of linear elastic fracture mechanics, it requires initial cracks in the model. The initial cracks can be existence, or it can come into existence during the analysis. XFEM-based LEFM approach is not activated until a crack nucleates, and if one or multiple pre-existence cracks are available, these cracks should be linked with an enriched feature and also specifies crack direction [10].

The Virtual Crack Closure Technique (VCCT) criterion computes energy release rate and then compares to corresponding critical values [13]. For more study [14] and [15].

In the other hand, it is assumed that in the VCCT, the amount of energy released rate when a crack propagates is equal to the energy required to close the crack [10].

Generally, fracture criterion for mode I, II and III can be defined as;

\[ f = \frac{G_{\text{equiv}}}{G_{\text{equivc}}} \geq 1.0 \quad (4.4) \]

Where \( G_{\text{equiv}} \) is the equivalent strain energy release rate at a node and \( G_{\text{equivc}} \) is the critical equivalent strain energy release rate calculated based on mode-mix criterion and fracture will occur when, \( f \), reaches the value 1.0.

There are three mode-mix formulas in Abaqus to calculate \( G_{\text{equivc}} \), which are BK law, the power law, and the Reeder law models, selecting the suitable model may be found experimentally [10]. In this master thesis, the power law is chosen that is based on the relationship between energy release rates in I, II and III and corresponding critical values [1], [10].

The power law model is defined by the following formula:

\[ \frac{G_{\text{equiv}}}{G_{\text{equivc}}} = \left( \frac{G_I}{G_{\text{equivc}}} \right)^{a_m} + \left( \frac{G_{II}}{G_{\text{equivc}}} \right)^{a_n} + \left( \frac{G_{III}}{G_{\text{equivc}}} \right)^{a_0} \quad (4.5) \]
Where $G_{IC}$, $G_{IIIC}$ and $G_{IIIIC}$ are the critical values corresponding to mode I, mode II and mode III respectively, and are assumed to be constant during crack growth and also the exponent of $a_m$, $a_n$ and $a_0$ are taken 1 [13], [14].

After considering the method for crack growth it is necessary to state the assumption in simulation, describe the geometry and model, type of the loading, mesh and, etc.

There are many difficulties in modeling wood due to it is an anisotropic material which includes many defects, knots, angel grains and, etc. For modeling wood, It is considered that wood is orthotropic (transversely isotropic) material, which has constant and similar properties in three local coordinates that are radial-R, longitudinal-L and tangential-T [1].

The assumptions in this thesis are the same as [1], it means, the moisture and temperature of each lamella are constant and have no influence on beam simulation in addition the elastic properties of each lamella are same. The pith location is centered in width direction and adhesives between each lamella is not considered and assumed that the adhesive is a part of the lamellas.

To create a 3D model of timber structure with cracks the following steps are applied [1], [16];

- In order to avoid problems with discontinuities in the simulation, first in the part field create a whole beam in the required dimensions then divide it into several lamellas.
- Create the necessary 3D cracks in the required dimensions with shell as base feature and extrusion as type.
- Create partition cells by using datum planes then create a local cylindrical coordinate system for each lamella.
- Enter the section assignment field and attribute each lamella of the glulam to the corresponding section then enter orientations field to attribute material orientations for each lamella of glulam beam, using the local cylindrical coordinate system.
- Enter the property field. Identify density and using “Engineering Constant” to define elastic properties for each lamella.
- Define damage criterions to identify damage initiation, depending on which damage criterion is desired in each lamella, choose “Damage for Traction Separation Laws” and then decide on “MAXPS Damage” or “MAXS Damage”.
- In the assembly field, instance the parts; select all parts and cracks, then chose “Independent”.

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• Enter the step field; create as many steps as required for the load case. Then define the time period, the maximum number of increments, and the initial, minimum and maximum number of increments. It is notable that since displacement control is used in this study; enter small value in time period.
• Create a field output, and cross the desired option in the output such as “PHILSIM”, “STATUSXFEM”, and “RF” etc. Moreover, cross “ALLEN” option in history output.
• Enter interaction properties field. Select “Contact”, then define the “Fracture Criterion” option, this option is based on XFEM and using VCCT method. Enter direction of crack growth, mixed mode behavior and critical energy release rate value for each mode, furthermore, select its exponents. In the top main menu, enter “Special” menu then select “Crack” and “Create”. Select the “XFEM” option and then chose each lamella, which include cracks as a crack region, which is called enrichment area. Active “Allow crack growth” check box. Cross the “Crack location” and chose crack in the corresponding crack region. At the end cross “Specify contact property” and select the contact property as defined previously.
• In the module of load, select boundary condition and because of using displacement-control, select the point that is desired to apply load and enter the needed value in the correct direction. Create appropriate boundary condition based on simulation.
• Enter the mesh field; seed the part instance, assign element type, select “3D Stress”, use C3D8 element type for enrichment areas and C3D8R element type for other parts. Apply hourglass control, and then mesh the part instance.
• Finally enter the jobs field and create a job and then submit the model.

In general, case a structure can be subjected to two loading cases;

1- Loading control
2- Displacement control

Loading control; when a structure is subjected to prescribed load P, which can be any type of loading such as concentrated load, distributed load, or moment. Another type is when a structure is subjected to prescribed displacement that is called displacement control.

In this study, displacement control (Deflection-controlled bending) is chosen and after applying specified displacement (loading) we can plot the load-displacement diagram.
In this method a static small displacement analysis is undertaken, whereby a series of displacement–controlled increments are applied at the loading plate during which convergence is obtained. The deflection and the reaction force are recorded for every increment. In this simulation, the time period for the whole procedure is set equal to 0.1, the displacement loading value is set to -1 m in Y-direction, the maximum displacement will set at the end 0.1 m in the monotonic loading case.
Wood fracture and failure models need several experimental calibrations, which can present and clarify ambiguity into numerical predictions because at present there is a large quantity of irregularity in test methods. In this chapter, the calibration of the simulated beam with the experimental result is presented and includes three main sections, first is a brief definition of the tested beam and experimental set up, Second the general creation of the model is explained and the material properties used in the model are introduced, and at the last section calibration and some aspects of calibration are stated. The main purposes of this part are obtaining the value of critical energy release rate, bending and shear criterion. Following algorithm illustrates the whole calibration procedure graphically.

![Figure 5.1. Calibration algorithm](image)

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**Figure 5.1. Calibration algorithm**
5.1 Tested Beam and Experimental Set up

Anna Pousette et al (2011) [17] wrote a report about shear strength of the glulam beams and they tested six groups of glulam beams and each group had five test specimens. In this report, the influence of cracks and its parameters (length, depth, and location) on shear strength of glulam beam were studied. Timber structures are designed according to Eurocode 5 [27]. Eurocode 5 [28] has considered a crack factor $k_{cr}$ to decrease shear strength of glulam beam where the influence of the cracks has to be taken into account. This factor for glued laminated timber member 0.67 is recommended [28].

In this report, CE L40 c class of the Swedish glulam beam was tested according to the three-point tested method because this method is close to the real-life circumstances, despite that a risk of bending failure instead of shear failure exists [1].

The Experimental set up based on Anderson, Odén [18] as following figure:

![Figure 5.2. Test set up Anderson, Odén [18]](image)

The cylinder of the bending machine was adjusted to 6mm/min and rubbers were attached to the support to keep rigidity of them [1].

In this master thesis, two groups of the glulam beams are studied; the first group is considered as a reference group, it means there is no crack on these types of glulam beams, and the second group is the beams which had been affected by moistening and drying to create and provoke “natural” cracks on them. In the following tables, the properties of these types of beams are presented it is considerable that the glulam beams were made of Spruce;
Table 5.1. Group one (beams without crack)

<table>
<thead>
<tr>
<th>No</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>Density (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1</td>
<td>2600</td>
<td>313</td>
<td>112</td>
<td>465.63</td>
</tr>
<tr>
<td>1:2</td>
<td>2600</td>
<td>313</td>
<td>113</td>
<td>457.59</td>
</tr>
<tr>
<td>1:3</td>
<td>2600</td>
<td>313</td>
<td>113</td>
<td>451.94</td>
</tr>
<tr>
<td>1:4</td>
<td>2600</td>
<td>313</td>
<td>113</td>
<td>459.33</td>
</tr>
<tr>
<td>1:5</td>
<td>2600</td>
<td>313</td>
<td>112</td>
<td>465.41</td>
</tr>
</tbody>
</table>

Table 5.2. Group two (beams with cracks)

<table>
<thead>
<tr>
<th>No</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>Density (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:1</td>
<td>2600</td>
<td>312</td>
<td>114</td>
<td>469.74</td>
</tr>
<tr>
<td>2:2</td>
<td>2558</td>
<td>313</td>
<td>114</td>
<td>468.48</td>
</tr>
<tr>
<td>2:3</td>
<td>2558</td>
<td>312</td>
<td>114</td>
<td>469.54</td>
</tr>
<tr>
<td>2:4</td>
<td>2600</td>
<td>313</td>
<td>115</td>
<td>428.48</td>
</tr>
<tr>
<td>2:5</td>
<td>2600</td>
<td>313</td>
<td>114</td>
<td>449.70</td>
</tr>
</tbody>
</table>

In this thesis, for calibration of the cracked beam, beam number 2:2 of the cracked beam (row no: 2 of table 5.2) is chosen, the reason is, shear failure in this beam occurred due to the existing crack on the second lamella, and this issue helps to find unknown parameters for calibration accurately.

In addition, cracks on this beam were more significant than crack on the other beams in this group.

The table below presents its cracks characteristics. Both cracks are assumed horizontal along the fiber.
Table 5.3. Crack coordinates of beam number 2:2

<table>
<thead>
<tr>
<th>Crack No</th>
<th>Start point</th>
<th>End point</th>
<th>Length (mm)</th>
<th>X-angle (°)</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Z1 Y1</td>
<td>Z2 Y2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-356 223.5</td>
<td>-400 223.5</td>
<td>44</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>-1025 137.5</td>
<td>-1195 137.5</td>
<td>170</td>
<td>-</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 5.3. Cracks on glulam beam

For calibrating modeled beam without crack versus experimental beam, two failures are studied, shear and bending failure.

5.2 Creation of Model

The model that has been used in Abaqus, is a rectangular cross-section beam with seven lamellas, the temperature and moisture content are
constant, the local cylindrical coordinate systems of the lamellas are aligned to each lamella, and pith is centered in width direction; furthermore, each lamella has the same elastic properties and density.

To make similar with reality, elastic foundation has been applied to the supports that behave like rubber. One of the supports is fixed at one point in the Z and X direction as boundary condition and another support is only fixed in the X-direction at one point, also the upper edge is needed to be constrained that prevented strains in X-direction. For loading point, a stiff plate has been modeled in order to avoid stress concentrations at these locations and displacement control loading is applied $U_2 = -1$.

Total number of elements is 10842, and 8-node linear brick elements (C3D8) with full integration points are used. C3D8 element type for enrichment area and C3D8R element type for other parts are used. The model is shown in *Figure 5.4.*

![Figure 5.4. Boundary condition and crack location in Abaqus](image)

The initiation damage criterion for shear failure in the wood is defined as “damage for traction separation laws” with “MAXS” refers to *maximum nominal stress*, and “MAXPS” refers to *maximum principal stress* as the damage criterion for bending failure. *Table 5.4* shows the material properties used in simulation.
Table 5.4. Material properties according in simulation

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_r = E_1$</td>
<td>240 MPa</td>
</tr>
<tr>
<td>$E_t = E_2$</td>
<td>240 MPa</td>
</tr>
<tr>
<td>$E_i = E_3$</td>
<td>12000 MPa</td>
</tr>
<tr>
<td>$G_{rt(12)}$</td>
<td>72 MPa</td>
</tr>
<tr>
<td>$G_{rl(13)}$</td>
<td>720 MPa</td>
</tr>
<tr>
<td>$G_{tl(23)}$</td>
<td>720 MPa</td>
</tr>
<tr>
<td>Poisson’s Ratio*</td>
<td>$\nu_{rt(12)} = \nu_{rl(13)} = \nu_{tl(23)} = 0 $</td>
</tr>
</tbody>
</table>

*Poisson ratio may be taken as zero [24].

5.3 Setting and Calibration

Shear and bending failures are the most typical failures in straight glulam beams [19]; therefore, shear strength and bending strength should be determined.

Shear force and bending moment for rectangular cross-section can be calculated as below:

Shear force:

$$ V = \frac{Af_{vk}}{1.5} $$  \hspace{1cm} (5.1)

Where;

$V$ = shear force

$A$ = cross-section area

$f_{vk}$ = shear strength

Bending moment:

$$ M = f_{mk} \times W $$  \hspace{1cm} (5.2)

Where;

$W = \frac{bh^2}{6}$, section modulus  \hspace{1cm} (5.3)
\[ f_{mk} = \text{bending strength} \]

The required force for bending and shear failure can be estimated as follows:

Shear strength was taken 4 MPa so ultimate load for shear failure can be estimated

\[ f_{vk} = 4 \text{MPa} \]

\[ V_A = \frac{115 \times 315 \times 4}{1.5} = 96.6 \text{ kN} \] (5.4)

\[ F = \frac{V_A \times L}{l_2} \] (5.5)

\[ F = \frac{96.6 \times (0.7875 + 1.4875)}{1.4875} = 147.7 \text{ kN} \] (5.6)

And if the bending strength was assumed 33 MPa, ultimate load for bending failure is:

\[ M = 33 \times \frac{115 \times 315^2}{6} = 62759812.5 \text{ Nmm} = 62.7 \text{ kNm} \] (5.7)

\[ F = \frac{M \times L}{l_1 \times l_2} \] (5.8)

\[ F = \frac{62.7 \times (0.7875 + 1.4875)}{0.7875 \times 1.4875} = 121.8 \text{ kN} \] (5.9)

These values (5.6 and 5.9) can be known as Analytical value.

In order to calibrate modeled beam in Abaqus with the experimental result the test results should be considered:
### Table 5.5. Test result of the first group (without crack)

<table>
<thead>
<tr>
<th>No</th>
<th>Failure type</th>
<th>Ultimate Load(kN)</th>
<th>Shear force V (kN)</th>
<th>Shear stress (\tau) (MPa)</th>
<th>Bending stress (\sigma_m) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1</td>
<td>Bending</td>
<td>163.659</td>
<td>107.01</td>
<td>4.58</td>
<td>44.3</td>
</tr>
<tr>
<td>1:2</td>
<td>Bending</td>
<td>159.74</td>
<td>104.45</td>
<td>4.43</td>
<td>43.3</td>
</tr>
<tr>
<td>1:3</td>
<td>Bending+Shear</td>
<td>166.55</td>
<td>108.9</td>
<td>4.462</td>
<td>45.1</td>
</tr>
<tr>
<td>1:4</td>
<td>Bending</td>
<td>168.76</td>
<td>110.34</td>
<td>4.68</td>
<td>45.7</td>
</tr>
<tr>
<td>1:5</td>
<td>Shear</td>
<td>176.800</td>
<td>115.60</td>
<td>4.95</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 5.6. Test result of the second group (with crack)

<table>
<thead>
<tr>
<th>No</th>
<th>Failure type</th>
<th>Ultimate Load(kN)</th>
<th>Shear force V (kN)</th>
<th>Shear stress (\tau) (MPa)</th>
<th>Bending stress (\sigma_m) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:1</td>
<td>Shear</td>
<td>167.19</td>
<td>109.32</td>
<td>4.61</td>
<td>-</td>
</tr>
<tr>
<td>2:2</td>
<td>Shear</td>
<td>192.57</td>
<td>125.91</td>
<td>5.29</td>
<td>-</td>
</tr>
<tr>
<td>2:3</td>
<td>Shear</td>
<td>173.96</td>
<td>113.74</td>
<td>4.78</td>
<td>-</td>
</tr>
<tr>
<td>2:4</td>
<td>Bending</td>
<td>185.04</td>
<td>120.99</td>
<td>5.04</td>
<td>50.1</td>
</tr>
<tr>
<td>2:5</td>
<td>Shear</td>
<td>151.50</td>
<td>99.06</td>
<td>4.16</td>
<td>-</td>
</tr>
</tbody>
</table>

### 5.4 Shear Strength of Glulam Beam without Crack

In this section, the calibration of the glulam beam for obtaining shear strength is explained.

As following figure illustrates, shear stress distributes parabolically over a rectangular cross-section;
As it is apparent from Figure 5.5 the shear force intensity varies from zero at the top and bottom, to a maximum value in the middle of the cross-section at the neutral axis. This issue should be considered to obtain the accurate result when define enrichment area (the area that used as crack and failure initiation area in Abaqus), so this is led to define just three middle lamella to obtain the accurate result.

As it is mentioned before, MAXS (maximum nominal stress) is used for damage initiation criterion for finding shear failure initiation. The initial guess values used for simulation in the first attempt are shown in Table 5.7.

<table>
<thead>
<tr>
<th>Criterion for shear</th>
<th>Data</th>
<th>Value (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nominal Stress (MAXS)</strong></td>
<td>Normal-only mode</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>First direction</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Second direction</td>
<td>3.5</td>
</tr>
</tbody>
</table>

The result from the numerical simulation in the first attempt is shown in the following figure:
The above graph shows a combination of load-deflection and damage dissipated energy (ALLDMD, blue line) of the glulam beam without any crack by applying the maximum nominal stress criterion (MAXS) that was used for shear failure. The blue line shows energy dissipated in whole model by damage and can denote the initiation of crack. The Table 5.8 shows the result of the first attempt based on Table 5.7. Initial criterion value.

**Table 5.8. Ultimate load by Abaqus without crack MAXS=3.5MPa**

<table>
<thead>
<tr>
<th>Shear Failure</th>
<th>Ultimate Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaqus MAXS=3.5 MPa</td>
<td>149.67</td>
</tr>
</tbody>
</table>

Now it is desirable to compare the obtained value by Abaqus with the experimental result to calibrate the ultimate load of the glulam beam.
In order to calibrate shear strength, a mean value of experimental shear strength is needed and in these experimental results, only the last beam failed due to shear failure, and since in the experimental result 3 beams failed due to bending stress, it can be said that the shear strength at these beams were higher than bending strength or at least were equal to the bending strength. In this instance, the mean value of beams 1:3 and 1:5 for the failure is considered because in these cases shear failure was occurred thus ultimate load is 171.6 kN.

With the aim of matching Abaqus result and experimental result, the initial value of nominal stress for MAXS criterion was changed from 3.5 MPa to 4 MPa and the new result is given (see Figure 5.7 and Table 5.9.)

Figure 5.7. Load-Deflection (Shear Failure) MAXS=4MPa
### 5.5 Bending Strength of Glulam Beam without Crack

Bending failure is another typical failure of beams, which is caused by tension failure in the tension side of the beam. Now it is required to calibrate bending strength of glulam beam. It is very similar to shear strength calibration but the difference is, in this case the 2 bottom lamella should be defined as enrichment or crack initiation area. The table below shows the initial guess value used for *maximum principle stress criterion* (MAXPS) for finding bending failure in the beam.

#### Table 5.10. Initial criterion value MAXPS

<table>
<thead>
<tr>
<th>Criterion for bending</th>
<th>Data</th>
<th>Value (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAXPS</td>
<td>Maximum principal stress</td>
<td>33</td>
</tr>
</tbody>
</table>

Following figure shows the result of the first attempt.
Figure 5.8. Load-Deflection (Bending Failure) MAXPS=33MPa

The above graph represents a combination of load-deflection and *Energy dissipated by damage in whole model*. (Blue line) of the glulam beam without crack; from the figure, we can determine the initiation of bending failure, where there is a jump in *Energy dissipated by damage*. The table below shows the result of the first attempt based on *Table 5.10 Initial criterion value*.

**Table 5.11. Ultimate load by Abaqus without crack MAXPS=33MPA**

<table>
<thead>
<tr>
<th>Bending Failure</th>
<th>Ultimate Load P(kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaqus MAXPS=33 MPa</td>
<td>162.2</td>
</tr>
</tbody>
</table>

To calibrate obtained bending strength by Abaqus, the experimental results are needed. At the first group of the experiment, 3 of beams failed due to purely bending failure and one of them failed because of both bending and
shear, the mean value of bending strength for the first 4 specimens was 164.6 kN, so the value of MAXPS=33 MPa was proper for this group of specimens.

Table 5.12. Ultimate load by Abaqus, Experiment and Analytical calculation without crack for bending failure

<table>
<thead>
<tr>
<th>Bending Failure</th>
<th>Ultimate Load P(kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaqus MAXPS=33 MPa</td>
<td>162.2</td>
</tr>
<tr>
<td>Mean value of experimental result</td>
<td>164.6</td>
</tr>
<tr>
<td>Analytical Calculation $\sigma_m=33$ MPa</td>
<td>121.8</td>
</tr>
</tbody>
</table>

As it is apparent from the Table 5.12 the specified value for MAXPS=33 MPa is matched with mean value in this group of specimens, but it will be increased later because the second group of specimens are stiffer than this group, and this calibration for MAXPS will be changed.

5.6 Shear Strength of Cracked Glulam Beam

The main objective of calibration section is to calibrate shear strength of the real cracked glulam beam with the modeled glulam beam by Abaqus. To calibrate the modeled cracked beam with experimental results, the beam number 2 of the second group of the experimental results (that is highlighted in the Table 5.6) is considered, which failed due to shear failure.
It is obvious from the Figure 5.9; shear failure occurred at the second lamella where there was a pre-existent crack (Figure 5.3 and Figure 5.9) on this lamella, it could be concluded that this beam was failed due to crack propagation in L direction because of shear stress in the second lamella.

As stated earlier, in this simulation, VCCT (Virtual Crack Closure Technique) criterion for XFEM-based crack propagation is applied. To use VCCT, critical energy release rate at each mode should be defined.

In this test set up, Mode III (tearing) of loading could be disregarded, or could be allocated a high value of critical energy release rate for mode III ($G_{IIIc}$) for instant $G_{IIIc} = 10000$ N/m to avoid crack propagation in this...
mode in the simulation. Furthermore, the value of critical energy release rate for mode I and II is also needed.

M.A.L. Silva et al (2006) [20], studied experimentally and numerically on mode II wood fracture characterization. Their experiments were performed on 19 specimens of Pinus pinaster wood and they obtained $G_{IIc} = 939 \text{ N/m}$ for average value of critical energy release rate for mode II [20]. Tan et al (1995) [21], also carried out experiments on spruce to find mode I and mode II characterization.

Saracoglu [1] used 179 N/m for $G_{Ic}$ and 70N/m for $G_{IIc}$ but based on Haller and putzger experiments [22], for $G_{Ic}$ and $G_{IIc}$, respectively the values 179 N/m and 734 N/m were chosen that these values were compatible with our experimental result.

Additionally, the following figure shows the simulation of the crack propagation in the second lamella, and it can be said this propagation, in direction of crack, crack growth location and the strength of the cracked beam are completely matched with the experimental result, and consequently this calibration for this beam is performed well.

![Figure 5.11. Cracks area (a), crack propagation in the second lamella (b)](image)

The table below presents the result of the calibration.
Table 5.13. Ultimate load by Abaqus and Experimental result in cracked beam for shear failure

<table>
<thead>
<tr>
<th>Methods</th>
<th>Ultimate Load P(kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Abaqus (VCCT)</strong></td>
<td>192.35</td>
</tr>
<tr>
<td>$G_{ic} = 179 \text{ N/m}$</td>
<td></td>
</tr>
<tr>
<td>$G_{ic} = 734 \text{ N/m}$</td>
<td></td>
</tr>
<tr>
<td>$G_{Hic} = 10000 \text{ N/m}$</td>
<td></td>
</tr>
<tr>
<td><strong>Experimental result</strong></td>
<td>192.5</td>
</tr>
<tr>
<td>(beam no 2:2)</td>
<td></td>
</tr>
<tr>
<td><strong>Analytical value</strong></td>
<td>122.04</td>
</tr>
<tr>
<td>$\tau = 4 \text{ MPa}$</td>
<td></td>
</tr>
</tbody>
</table>

*This value is obtained by using net width (original width-crack depth)

## 5.7 Bending Strength of Cracked Glulam Beam

Bending strength and bending criteria of group 1 of glulam beams, previously explained and MAXPS= 33 MPa was chosen. But for the second group of the beams, as it is apparent from the experimental result (Table 5.6), except a beam (no 2:4) all other beams were failed due to shear failure, and this caused difficulties to calibrate bending strength of the cracked beam. So it could be said that bending strength at this group of beams might be higher than the shear strength, this means that if MAXPS=33 MPa (which was determined for beam without crack) is used, this beams was failed due to bending earlier than shear failure. *Figure 5.12*, presents bending failure initiation in the bottom lamella before crack propagation in second lamella.

![Figure 5.12. Cracks area (a), bending failure with MAXPS=33 MPa (b)](image_url)
The above figure shows bending failure with MAXPS=33 MPa. Bending failure has been occurred before the crack in the second lamella starts to grow, thus it is necessary to increase the value of MAXPS, in order to obtain crack propagation in the second lamella earlier than bending failure. After examined three different values, MAXPS=35 MPa, MAXPS=38 MPa and MAXPS=42 MPa, finally the last one (MAXPS=42 MPa) is chosen. Figure below shows crack propagation in the second lamella without any bending failure while bending criterion is present.

Figure 5.13. Cracks area (a), crack propagation in the second lamella MAXPS=42MPa (b)

It is noticeable that contrary to our expectations, despite pre-existence cracks in the second group, shear strength and bending strength of this group are higher than the first group (without crack), and this issue is led to increase MAXPS from 33 MPa to 42 MPa to match with experiment and get shear failure.
5.8 Summary of Calibration

The table below presents a summary of the calibration part such as failure criterion, shear and bending strength and, etc.

*Table 5.13. Summary of calibration*

<table>
<thead>
<tr>
<th>Groups</th>
<th>Method</th>
<th>Ultimate force (kN)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Shear failure</td>
<td>Bending failure</td>
</tr>
<tr>
<td>Without Crack Beam (Group 1)</td>
<td>Numerically (Abaqus)</td>
<td>166.75</td>
<td>162.2</td>
</tr>
<tr>
<td></td>
<td>Experimental Result</td>
<td>171.1</td>
<td>164.6</td>
</tr>
<tr>
<td></td>
<td>Analytical Value</td>
<td>147.7</td>
<td>121.8</td>
</tr>
<tr>
<td>Cracked Beam (Group 2)</td>
<td>Numerically (Abaqus)</td>
<td>192.35</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Experimental Result</td>
<td>192.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Analytical Value</td>
<td>122.04</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 5.14. Summary of criterion*

<table>
<thead>
<tr>
<th>Failure</th>
<th>Cracked</th>
<th>Criterion</th>
<th>value</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear</td>
<td>No</td>
<td>MAXS</td>
<td>4 MPa</td>
<td></td>
</tr>
<tr>
<td>Shear</td>
<td>Yes</td>
<td>MAXS (initiation)</td>
<td>4 MPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>VCCT (evaluation)</td>
<td>$G_{ic} = 179 N/m$</td>
<td></td>
</tr>
<tr>
<td>Bending</td>
<td>No</td>
<td>MAXPS</td>
<td>33 MPa</td>
<td></td>
</tr>
<tr>
<td>Bending</td>
<td>yes</td>
<td>MAXPS</td>
<td>42 MPa</td>
<td></td>
</tr>
</tbody>
</table>

*This value has been increased to 42 MPa in the simulation part*
Since the benchmark for calibrating the simulations in Abaqus is experimental results, when simulation of the wood is desired, more experimental results and practical quantities are necessary to calibrate precisely. For instance, in these experiments, the second group of the beams despite some pre-existence cracks on them, are stiffer than the first group (glulam beams without crack), these unpredictable and inaccurate results can be eliminated as much as possible by using mean value of several experimental results.
6 Simulation

This part focuses on a Finite Element model to simulate a real long glulam beam. In this chapter, cracks propagation along the beam, influences of the cracks on strength of the beam, predictions of the load-deflection behavior of the glulam beam are presented.

In general long glulam beams can be used in roofs, floors, truss system and other structural systems. Normally cracks form in these beams after some time, therefore, knowing the strength of these glulam beams in different type of loading is important and will be considered in this chapter. The algorithm of simulation has been shown as below;

![Simulation Algorithm Diagram]

*Figure 6.1. Simulation Algorithm*
Considered beam is pine CE L40 c and its dimensions are 140x450x9000 mm. Figure below shows beam, supports and load place dimensions.

**Figure 6.2. Glulam Beam dimensions**

The real beam in this study is part of a big field test of glulam beams and columns. The beam has been exposed to outdoor climate during five years. Cracks have been measured every year and photo of the surface have been taken.

In this simulation, a beam with 101 cracks on its surface is chosen; simulating this amount of cracks in Abaqus is problematic to some extent and it arises some difficulties, in addition takes a lot of time for calculating in Abaqus; furthermore, some of those cracks have no effect on the strength of the beam. Hence using a criterion for selecting deep and long cracks is vital and based on that criterion can eliminate short and shallow cracks. A photo of the real beam is shown in **Figure 6.3**.

**Figure 6.3. Photo of real cracked glulam beam**

This criterion chooses cracks with depth 15 percent of the beam width regardless of crack location within one side of the glulam beam [23]. Thus, the width of the beam is 140 mm so their depth limit is 0.15x140=21mm. With this criterion, there are 12 significant cracks on the beam as they are shown in **Figure 6.4** and **Table 6.1**.
Table 6.1. Significant cracks location and dimensions.

<table>
<thead>
<tr>
<th>No</th>
<th>Lamella No</th>
<th>No in the real beam*</th>
<th>Start point</th>
<th>End point</th>
<th>Length (mm)</th>
<th>X-angle (°)**</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Z1  Y1</td>
<td>Z2  Y2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>2</td>
<td>0  350</td>
<td>-8043</td>
<td>8043</td>
<td>0,2</td>
<td>44</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>15</td>
<td>0  290</td>
<td>-994</td>
<td>994</td>
<td>-1,2</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>16</td>
<td>0  255</td>
<td>-5328</td>
<td>5328</td>
<td>0,1</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>22</td>
<td>-3826  316</td>
<td>-8997</td>
<td>5171</td>
<td>0,0</td>
<td>34</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>26</td>
<td>0  210</td>
<td>-1630</td>
<td>1630</td>
<td>-0,4</td>
<td>26</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>28</td>
<td>-1683  200</td>
<td>-3385</td>
<td>1702</td>
<td>0,0</td>
<td>22</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>31</td>
<td>-3519  160</td>
<td>-3830</td>
<td>311</td>
<td>2,8</td>
<td>24</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>36</td>
<td>-7587  199</td>
<td>-8997</td>
<td>1410</td>
<td>1,3</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>11</td>
<td>37</td>
<td>0  127</td>
<td>-5586</td>
<td>5586</td>
<td>0,0</td>
<td>35</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>41</td>
<td>-7062  158</td>
<td>-8997</td>
<td>1935</td>
<td>0,1</td>
<td>26</td>
</tr>
<tr>
<td>11</td>
<td>13</td>
<td>43</td>
<td>0  60</td>
<td>-2125</td>
<td>2125</td>
<td>0,1</td>
<td>23</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>46</td>
<td>-617  80</td>
<td>-798</td>
<td>181</td>
<td>0,9</td>
<td>32</td>
</tr>
</tbody>
</table>

*location and dimensions of the cracks are taken from measurement of the real cracks in the glulam beam B4-H16 during summer 2010.

** cracks are assumed horizontal along the fiber.
The model that has been used in Abaqus, has the same conditions as the calibrated model except in the supports (bearings). In the calibrated model elastic foundation was applied to the supports but in this simulation, stiff steel plates are modeled in the support and loading point (above figure). One of the supports is defined as a fixed support and is constrained at one line in the X, Y and Z direction and another one is fixed in the X and Y direction like a roller. Similar to the calibration part a displacement control loading is applied to the loading point in different situations. The number of elements in the mesh of the entire model is 60600. The model and its boundary conditions are shown in Figure 6.5.
6.1 Applying Load to the Middle of the Beam

The first simulation has been done with load applied to the middle of the beam and is calculated in two parts, glulam beam without crack and cracked glulam beam.

6.2.1 Without Crack

The required force for bending and shear failure can be estimated with the aid of following formulae;

The shear capacity was taken as \( f_{vk} = 4 \text{MPa} \) based on equation (5.1):

\[
V_A = \frac{140 \times 450 \times 4}{1.5} = 168 \text{ kN} \quad (6.1)
\]

When applying the load to the middle of the beam, ultimate load for shear failure can be obtained;

\[
F = V_A \times 2 \quad (6.2)
\]

\[
F = 168 \times 2 = 336 \text{ kN} \quad (6.3)
\]

And bending strength was chosen as \( f_{mk} = 33 \text{MPa} \) and based on equation (5.2);
And ultimate load for bending failure can be calculated;

\[ W = \frac{140 \times 450^2}{6} = 47.25 \times 10^6 \text{ mm}^3 \]  \hspace{1cm} (6.4)

\[ M = 33 \times 47.25 = 155.92 \text{ kNm} \]  \hspace{1cm} (6.5)

\[ F = \frac{ML}{L_1^2} \]  \hspace{1cm} (6.6)

\[ F = \frac{155.92 \times (9-0.155)}{4.4225^2} = 70.51 \text{ kN} \]  \hspace{1cm} (6.7)

The ultimate load for shear and bending failure can be obtained by Load-Deflection graph by Abaqus as below; it is noticeable that Load-Deflection graph for shear failure is reached by eliminating bending criterion just for comparing with the analytical value.
Figure 6.7. Load-Deflection –Ultimate shear force in the absence of bending criterion (a) and Ultimate bending force (b) -when load applied to a middle of the glulam beam.
Table 6.2. Abaqus and Analytical result for ultimate load

<table>
<thead>
<tr>
<th>Method</th>
<th>Ultimate load Shear failure (kN)</th>
<th>Ultimate load Bending failure (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaqus</td>
<td>361.35</td>
<td>99.63</td>
</tr>
<tr>
<td>Analytical value</td>
<td>336</td>
<td>70.51</td>
</tr>
</tbody>
</table>

The value of ultimate shear failure (361.35 kN) does not make sense because in this condition bending failure will occur.

6.2.2 With Crack

The aim of this part is to make a simulation of the glulam beam model to investigate on how pre-existence cracks will propagate in the glulam beam after applying a load to the middle of the beam and the effect of the cracks on shear and bending strength.

In this case due to load applied to the middle of the beam, the failure usually initiates by tension failure at the bottom and bending failure will occur.

To calculate the ultimate load by Abaqus due to bending failure, based on calibration section, the ultimate load is obtained 93.7 kN from the following load-deflection graph when MAXPS=42 MPa according to chapter 5.

Figure 6.8. Load-Deflection cracked beam- bending failure (bending criterion)
It can be possible to see crack propagation within the beam, by assuming that no bending criterion exists.

![Graph showing Load-Deflection and Damage dissipation energy in cracked beam](image)

**Figure 6.9. Combination of Load-Deflection and Energy Dissipated by Damage in each lamella without bending criterion.**

The above graph shows the ultimate load for this beam, which is 96.3 kN when the load is applied to the middle of the beam. According to Figure 6.9, can be noticed that failure is occurred in lamella number 10 because after load reaching to the value 96.3 kN, a discontinuous jump in damage dissipated energy is appeared and by monitoring cracks, can be seen cracks number 7 start to propagate in lamella number 10 as below:

![Crack location in the 10th lamella](image)

**Figure 6.10. Crack location in the 10th lamella**
Figure 6.11. Contour plots of STATUSXFEM from simulation, crack propagation in the 10th lamella. Before crack propagation (a), beginning of crack propagation (b), and failure (c).

However, with a simple comparing it is clear that this beam will fail due to bending failure, because the ultimate load for bending failure in the beam without crack in the presence of bending criterion is 99.63 and for cracked beam is $F=93.7$ kN.
The table below shows the obtained results:

*Table 6.3. Abaqus result for ultimate load of cracked beam and without crack*

<table>
<thead>
<tr>
<th>Methods</th>
<th>Ultimate Load without crack P(kN)</th>
<th>Ultimate Load cracked beam due to shear P(kN)</th>
<th>Ultimate Load cracked beam due to bending P(kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Abaqus (VCCT)</strong></td>
<td>99.63</td>
<td>-</td>
<td>93.7</td>
</tr>
<tr>
<td>(G_{lc} = 179 \text{ N/m} )</td>
<td>(G_{lfc} = 734 \text{ N/m} )</td>
<td>(G_{tllc} = 10000 \text{ N/m} )</td>
<td></td>
</tr>
</tbody>
</table>

6.2 Applying Load in the One Quarter of the Beam

![Figure 6.12. Simulation set up](image)

Now considering load applied to the one quarter of the beam. Similar to previous chapter glulam beam is studied in two circumstances, the glulam beam without crack and glulam beam with crack.

6.3.1 Without Crack

If the shear strength is chosen as \( f_{vk} = 4 \text{MPa} \), with the aim of the equation (5.1) and (5.2) we have;

\[
V_A = \frac{140 \times 450 \times 4}{1.5} = 168 \text{ kN}
\]  

(6.8)

When applying the load to the one quarter of the beam, ultimate load for shear failure can be obtained;
Moreover, bending strength was assumed $f_{mk} = 33 \text{ MPa}$ and based on equation (5.2);

\[ F = \frac{168 \times 8845}{6633.75} = 224 \text{ kN} \quad (6.9) \]

\[ W = \frac{140 \times 450^2}{6} = 47.25 \times 10^6 \text{ mm}^3 \quad (6.10) \]

\[ M = 33 \times 47.25 = 155.92 \text{ kNm} \quad (6.11) \]

And Ultimate load for bending failure can be calculated;

\[ F = \frac{155.92 \times (9 - 0.155)}{2.21125 \times 6.63375} = 94.01 \text{ kN} \quad (6.12) \]

The ultimate load for shear and bending failure by Abaqus is shown in the following figure. Bending criterion for finding shear failure is eliminated similar to previous simulation.
Figure 6.13. Load-Deflection –Ultimate Shear force (a) and bending force (b) - load applied to a quart of the Glulam Beam.

Table 6.4 presents the obtained result of the ultimate load by mean of Abaqus and analytical formulation.
### Table 6.4. Abaqus and Analytical result for ultimate load

<table>
<thead>
<tr>
<th>Method</th>
<th>Ultimate load Shear failure (kN)</th>
<th>Ultimate load Bending failure (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaqus</td>
<td>295.8</td>
<td>140.1</td>
</tr>
<tr>
<td>Analytical value</td>
<td>224</td>
<td>94.01</td>
</tr>
</tbody>
</table>

#### 6.3.2 With Crack

To study about cracks growth and the influence of cracks on the load-carrying capacity of the beam, load applied to one quarter of the beam and by using load-deflection graph, ultimate load can be calculated.

Following graph shows the ultimate load of the cracked beam because of the bending failure.

![Graph showing ultimate load of cracked beam](image)

**Figure 6.14. Load-Deflection cracked beam- bending failure (bending criterion)**

Thus according to simulation this beam at load 123.7 kN will fail due to bending when the load apply to the one quarter of the beam.

Now in the absence of bending criterion we can study how crack propagates in the beam if no bending failure occurred in the beam.
According to the above figure, it can be stated that when (displacement) load applied to the one quarter of the cracked beam, from the damage dissipation energy curve, inconsiderable crack growths have been started to propagate after nearly 14 kN load in lamellas number 4, 7 and lamella number 10 it is obvious from changing dissipation energy level. Moreover, after load is reached to the 134.5 kN, a considerable jump comes into view in lamella number 8, 10, 11 and 12 that means damage is occurred in these lamellas at this particular load.

Similar to pervious simulation crack propagation in lamella number 10 (which include crack number 7) is significant and is shown in the following figure.

**Figure 6.15. Combination of Load-Deflection and Energy Dissipated by Damage in each lamella without bending criterion.**

**Figure 6.16. Crack location in the 10th lamella**
In this beam alike to the previous simulation, bending failure is occurred at $F=123.7$ kN before shear failure.
Table 6.5. Abaqus result for ultimate load cracked and without crack beam

<table>
<thead>
<tr>
<th>Methods</th>
<th>Ultimate Load beam without crack P(kN)</th>
<th>Ultimate Load cracked beam due to shear P(kN)</th>
<th>Ultimate Load cracked beam due to bending P(kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaqus (VCCT)</td>
<td>140.1</td>
<td>-</td>
<td>123.7</td>
</tr>
<tr>
<td>$G_{fc} = 179 \text{ N/m}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G_{sc} = 734 \text{ N/m}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G_{sc} = 10000 \text{ N/m}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.3 Applying Load to One Eighth of the Beam

So far, two simulations have been studied which involved

1-Aplying load to the middle of the beam
2-Aplying load to one quarter of the beam

As it was discussed before, both of them in the presence of any bending criterion were failed due to bending caused by load location. Another desired simulation is, studying load-carrying capacity when the load applied to one eighth of the beam length.

6.4.1 Without Crack

When shear strength is taken as $f_{vk} = 4\text{ MPa}$ by using the equation (5.1) and (5.2) we have;

$$V_A = \frac{140 \times 450 \times 4}{1.5} = 168 \text{ kN}$$  (6.13)
Applying load to one eight of the beam length, ultimate load for shear failure can be obtained;

\[ F = \frac{168 \times 8845}{7739.375} = 192 \text{ kN} \quad (6.14) \]

And bending strength \( f_{mk} = 33 \text{ MPa} \);

\[ W = \frac{140 \times 450^2}{6} = 47.25 \times 10^6 \text{ mm}^3 \quad (6.15) \]

\[ M = 33 \times 47.25 = 155.92 \text{ kN} \quad (6.16) \]

And ultimate load for bending failure can be calculated;

\[ F = \frac{155.92 \times (9 - 0.155)}{1.105625 \times 7.739375} = 161.17 \text{ kN} \quad (6.17) \]

The ultimate load for shear and bending failure by Abaqus is shown in the following figure. Bending criterion is not considered to gain ultimate load for shear failure.
Figure 6.19. Load-Deflection – Ultimate shear force (a) and bending force (b) - load applied to one eighth of the glulam beam length.
Table below presents the obtained result of the ultimate load by mean of Abaqus and analytical formulation.

<table>
<thead>
<tr>
<th>Method</th>
<th>Ultimate load Shear failure (kN)</th>
<th>Ultimate load Bending failure (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaqus</td>
<td>257.9</td>
<td>228.2</td>
</tr>
<tr>
<td>Analytical value</td>
<td>192</td>
<td>161</td>
</tr>
</tbody>
</table>

6.4.2 With Crack

Knowing the load-carrying capacity of the cracked beam is the main purpose of this study. To estimate the ultimate load capacity of the cracked beam for bending failure, it is necessary to define a bending criterion, similar to the previous sections. In this loading case, there is a noticeable point, some cracks are situated in shear critical zone that effects on shear capacity of the beam; this effect is intensified due to load applied in this area.

In general, shear critical zone is the high shear stress area that is normally defined as the areas at both ends of a simply supported beam which is shown in the following figure [23].

![Critical shear zone](image)

Accordingly, in this simulation after applying load at one eighth of the beam no bending failure is occurred and based on this simulation this beam may be failed due to purely shear failure.

The following diagram shows a combination of load-deflection of the beam with energy dissipated by damage. Changing and discontinuity in dissipated energy at each cracked lamella states a crack propagation. Based on the simulation, insignificant crack propagation can be recognized in the lamella
4,7,10 after 13.8 kN load magnitude. But there is a huge jump in damage dissipated energy in the lamella number 5 (crack no 2) when the load is reached to 158.6 kN and then damage in lamella number 12 (crack no 12) is occurred, when the magnitude of the load 168 kN significant crack propagation is occurred, and beam is failed.

![Graph of Load-Deflection and Energy Dissipation](image)

**Figure 6.21. Combination of Load-Deflection and Energy Dissipated by Damage in each lamella**

The following figures show crack propagation in lamella number 5 and no 12.

![Crack location in the 5th and 12th lamellas](image)

**Figure 6.22. Crack location in the 5th and 12th lamellas**
Figure 6.23. Contour plots of statusxfem from simulation, crack propagation in the 10th lamella. Before crack propagation (a), beginning of crack propagation (b), and failure (c).

According to simulation in this set up, beam without crack is failed due to bending failure at 228.2 kN, and beam with crack is failed due to shear failure at 168 kN see table 6.7.
6.5 Applying Distributed Load (Abaqus)

Distributed load is studied in this part, as following figure shows, a pressure with the value $P=1 \times 10^6$ Pa is applied to the whole upper area of the top lamella. In contrast with previous sections in this case Load-Control loading is used.

![Figure 6.24. Pressure applied to the glulam beam](image)

When a bending criterion is considered it can be found the ultimate load for bending failure by means of following formula;

$$F_{\text{ultimate}} = \frac{P \times t_{\text{failure}} \times A_p}{t_{\text{all}}}$$  \hspace{1cm} (6.18)

Where
\( F_{\text{ultimate}} \) is the ultimate load
\( P \) is the pressure
\( t_{\text{failure}} \) is the time for damage
\( A_p \) is the area at which the pressure is applied
\( t_{\text{all}} \) is the time period (time of the whole procedure)

According to the damage dissipation energy graph we have

6.5.1 Without Crack (Shear)

![Image](damage_dissipation_energy.png)

**Figure 6.25. Damage Dissipation Energy beam without crack versus Time in the absence of bending criterion**

The ultimate load for shear failure in glulam beam without crack is obtained as below:

\[
F_{\text{ultimate}} = \frac{1 \times 10^6 \times 0.253 \times 0.14 \times 9}{1} = 318780N = 318.78 \text{ kN} \quad (6.19)
\]
6.5.2 Without Crack (Bending)

Figure 6.26. Damage Dissipation Energy beam without crack versus Time with the presence of bending criterion

By using bending criterion, MAXPS that has been found in calibration part (chapter 5) the ultimate load for bending failure while a distributed load applies to the beam can be calculated from the Figure 6.26;

\[ F_{\text{ultimate}} = \frac{1 \times 6 \times 0.15 \times 0.14 \times 9}{1} = 189000N = 189 kN \]  (6.20)
6.5.3 With Crack (Shear)

Figure 6.27. Damage Dissipation Energy versus Time for whole beam with crack in the absence of bending failure

From the above figure, the ultimate load for shear failure when this distributed load applied to the cracked beam can be calculated;

$$\text{\( F_{\text{ultimate}} = \frac{166 \times 0.1710 \times 0.14 \times 9}{1} = 215460 \text{ N} = 215.46 \text{ kN} \quad (6.21) \)}}$$
6.5.4 With Crack (Bending)

In the presence of bending criterion in cracked glulam beam, ultimate load for bending failure can be determined by following formula;

\[
F_{\text{ultimate}} = \frac{166 \times 0.1460 \times 0.14 \times 9}{1} = 183960N = 183.96 \text{ kN}
\]  

(6.22)

Therefore, this beam will be field by bending at 183.96 kN.

**Table 6.8. Abaqus result for ultimate load cracked and without crack beam**

<table>
<thead>
<tr>
<th>Methods</th>
<th>Ultimate Load beam without cracks P(kN)</th>
<th>Ultimate Load cracked beam due to shear P(kN)</th>
<th>Ultimate Load cracked beam due to bending P(kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Abaqus (VCCT)</strong></td>
<td>189</td>
<td>-</td>
<td>183.96</td>
</tr>
<tr>
<td>(G_{IC} = 179 \text{ N/m})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(G_{IIc} = 734 \text{ N/m})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(G_{IIIc} = 10000 \text{ N/m})</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7 Conclusion and Future Work

The purpose of the thesis was, to make models of the glulam beams in order to simulate and study about the effects of cracks and fractures on strength of the glulam beams by means of the finite-element program ABQUS. A long glulam beam with several pre-existing natural cracks under four various loading conditions was studied. The simulation model was calibrated and modified based on experimental results for another glulam beam.

The applied material properties of the wood were based on Eurocode 5 [24], but because of complex and unpredictable structure of wood may vary noticeably between lamellas and glulam beams in addition lead to difficulties to model and simulate wood structure.

In order to model the crack growth, the extended finite-element method (XFEM) and VCCT (Virtual Crack Closure Technique) criterion as the crack propagation criterion was used.

For accurate simulation, more experimental results are needed to calibrate criteria and finding unknown parameters in the modeling. For example, in the calibration part, one considerable fact to note was the second group of the glulam beams regardless of some pre-existence cracks on them, exhibited better mechanical properties and were more resistant than the reference group of glulam beams (beams without cracks). These unexpected results may cause some difficulties to model of glulam beams. Additionally, modeling crack propagation with “Cohesive segments approach” in ABAQUS and compare the results with “Linear Elastic Fracture Mechanics (LEFM) approach” can give better perspective of simulation.

Finding correct critical energy release rate value for each fracture mode to match with available experimental results and material properties was one of the main parts of calibration but despite insufficiency of literature and material data $G_{Ic}$ and $G_{IIc}$ were obtained, but it is noticeable, these values are correct for this case with this dimensions and test set up. In other words, based on size effect law, there are differences between the energy release rates of small and large structures, namely critical energy release rates are functions of the structural size [26].

The simulations were investigated on two common failures in glulam beams, bending failure and shear failure, thus two criteria, one for bending and another for shear failure were used, but due to importance of shear
failure in this study, each simulation was performed in the absence of bending criterion.

It is noticeable that in the simulation, the influences of mode I and mode II of fracture were considered, and it is not possible to say that shear failure occurred only through stress in “S23” direction; consequently, a mix mode failure happened in the simulation, and it is extremely similar to what is occurred to the reality.

The most important limitation in this thesis was lack of experiments on natural long cracked beam to compare the simulation results with experiment.

Comparing cracked glulam beam with glulam beam without cracks in the end of each simulation can give us a scheme view of simulation. The table below shows ultimate load and failure mode for each load conditions.

*Table 7.1. Comparison between cracked beam and without crack beam obtained from simulation.*

<table>
<thead>
<tr>
<th>Applied Load Conditions (Point load)</th>
<th>Ultimate Load Without crack beam (kN)</th>
<th>Failure Mode For Without Crack beam</th>
<th>Ultimate Load Cracked beam (kN)</th>
<th>Failure Mode For Cracked beam</th>
<th>Strength reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle</td>
<td>99.6</td>
<td>Bending</td>
<td>93.7</td>
<td>Bending</td>
<td>5.9</td>
</tr>
<tr>
<td>One quarter</td>
<td>140.1</td>
<td>Bending</td>
<td>123.7</td>
<td>Bending</td>
<td>11.7</td>
</tr>
<tr>
<td>One eighth</td>
<td>228.2</td>
<td>Bending</td>
<td>168.0</td>
<td>Shear</td>
<td>26.0</td>
</tr>
<tr>
<td>Distribution</td>
<td>189.0</td>
<td>Bending</td>
<td>183.9</td>
<td>Bending</td>
<td>2.6</td>
</tr>
</tbody>
</table>

As it is apparent from the above table, while a load applied to the one eighth of the cracked glulam beam, this beam failed due to shear failure and in the absence of cracks, failing is caused by bending; in other words, when a load applied to the on eighth of the cracked beam, the strength of the beam is 26% less than this glulam beam without crack, whereas in other cases, cracks have not significant effects on strength reduction of the glulam beam.
8 References


Engng., 46: 131–150. DOI: 10.1002/(SICI)1097-0207(19990910)46:1<131::AID-NME726>3.0.CO;2-J


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