



FINITE ELEMENT MODELING OF HARDWOOD FRACTURE ENERGY

Azobé Fracture Energy FEM

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1. Introduction

To get a better understanding about fracture energy of hardwood timber, finite element modelling (FEM) is used to model the 3 point-bending beam test proposed by Gustafsson (1990) to obtain the fracture energy of timber. The FEM models are compared to the fracture energy results obtained from the experimental research performed by Boerenveen (2019) on Azobé. The beam test specimen used by Boerenveen (2019) for testing is shown in figure 1. Designing a finite element model that reflects the beam tested by Boerenveen (2019), and also obtain similar results, required several choices to be made in designing the model. This report will explain the choices made to create the finite element model and the results will be discussed in the following chapters.

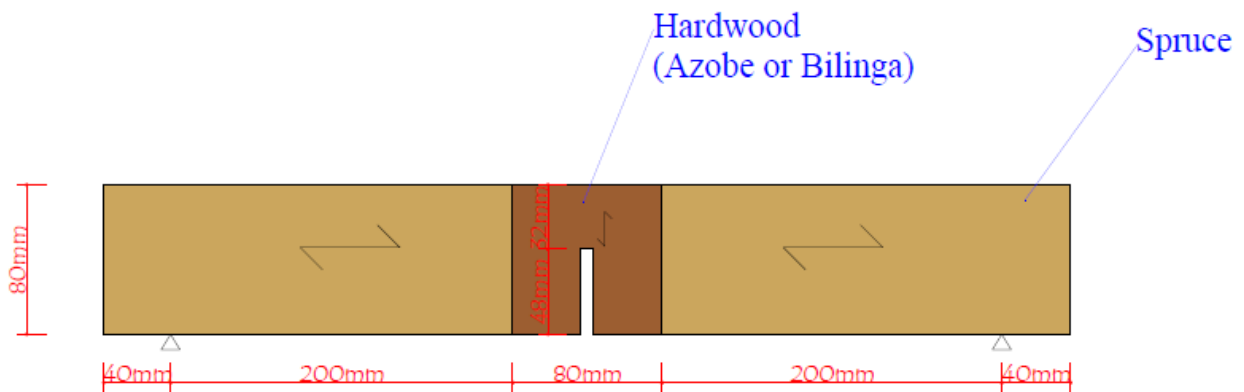


Figure 1: Test specimen used in fracture energy experimental program Boerenveen (2019)

The finite element program that is used is Diana 10.3. Diana is used to model the beam, to determine the load-deflection curve and display the results (Dianafea.com, 2019). The load-deflection results are then exported to Excel 2011 to calculate the total work done by the mid-point force. The mid-point force is located at the top of the beam exactly in the middle of the beam (see figure 2). The deflection of the beam at the location where the force is being applied is considered when plotting the load-deflection curve (figure 3 shows an example of a load-deflection curve). From the obtained load-deflection curve the work done by the mid-point force for the beam to completely crack is calculated by taking the area under the load-deflection curve. Once the work is calculated the fracture energy is calculated by dividing the work by the crack area, see equation 1. The calculated fracture energy is then used to verify the fracture energy of the material.

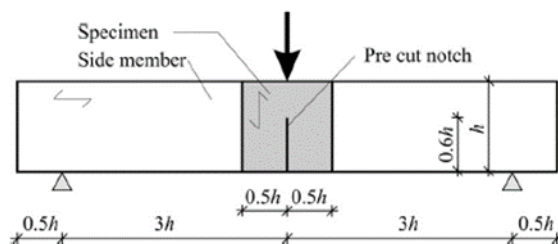


Figure 2: Test specimen dimension (h=80mm)

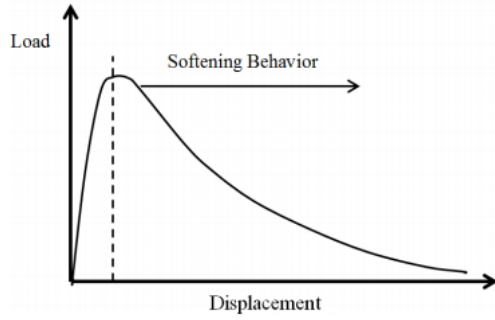


Figure 3: Example load deflection curve

$$G_c = \frac{(W)}{(A)} = \frac{1}{h_c b} \left(\int_0^{\delta_0} F(\delta) \partial \delta \right) \quad (1)$$

Where:

W Work done by the external force. Calculated as the area under the load-displacement curve.

δ_0 The deflection at failure

A Area fracture surface.

In total 3 models were created and analyzed. The following models were created and analyzed:

- Beam without notch made completely out of Azobé (model 1)
- Beam without notch made out of Spruce and Azobé (Similar to Boerenveen (2019) notch test specimen) (model 2)
- Beam with notch made out of Spruce and Azobé (as the test specimens Boerenveen (2019) used to determine the fracture energy) (model 3)

The first two models were created to check if the model was correctly build. By building a beam without a notch made completely out of Azobé, beam theory can be used to verify the linear stiffness of the model is in the range of the calculated linear stiffness.

Once the Azobé model is verified, the Spruce-Azobé model without a notch can be checked by comparing the load deflection curves of the Azobé model with the Spruce-Azobé model. The linear stiffness's will differ but the peak loads will be similar or in the same range due the fact the Azobé section of the beam in the Spruce-Azobé model is the middle part of the beam that will govern the failure load. The physical nonlinear effects was only modeled for the middle Azobé section of the beam models and the rest of the beam sections are modeled linear elastic. The tensile strength of Azobé governs the peak load. From the load deflection curves of the first 2 models the fracture energy can already be calculated and checked. After the second model is checked, the third model is built by adding the notch to model two. Once the notch is added the results analyzed and the fracture energy is once checked. In the next chapter the finite element models will be discussed.

2. Finite Element Model

In this chapter an explained will be given of how the models were build, the characteristics of the models, and what material parameters were used.

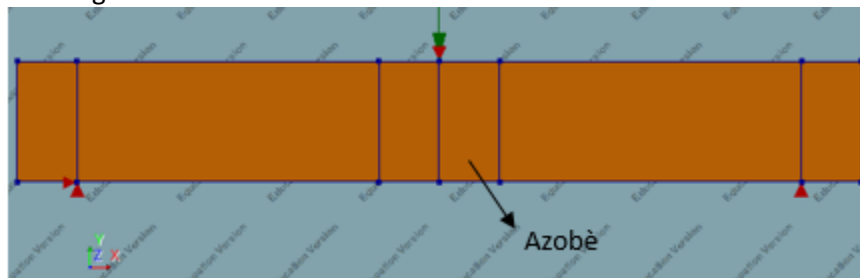
The models used in this thesis have the flowing characteristics:

- Linear elastic orthotropic material in 2 dimensions
- It is considered that deformation occur in a plane stress state, consequently a 2D model is used.
- The material is considered homogeneous.
- The supports of the model are handled by prescribed displacement and rotations.
- The cracking of the beam is modeled by 2D line interface with discrete cracking.
- The beam notch is modeled by 2D line interface model with a very low normal and shear stiffness
- Linear and non-linear finite element analysis are performed

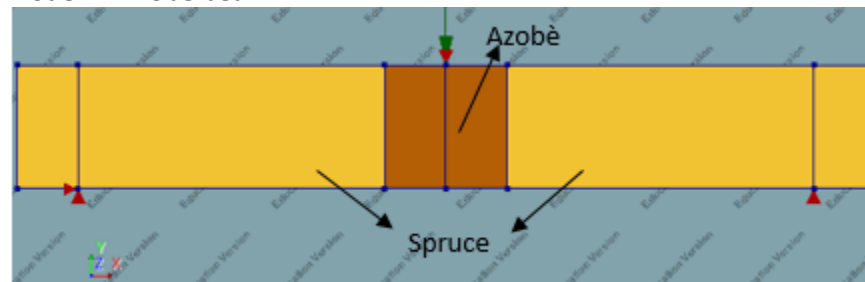
These points will be explained in the next paragraphs.

2.1 Size, boundary conditions and material orientation

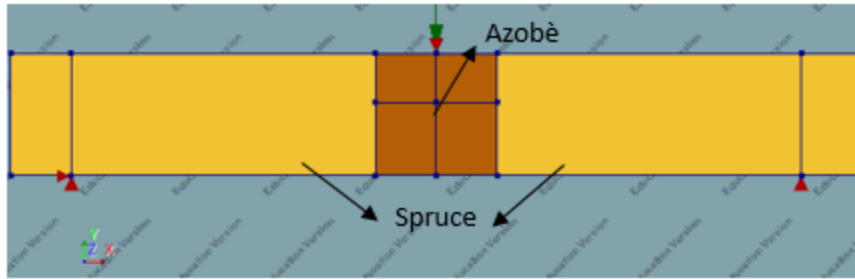
The geometry of the beams in the different models is shown in figure 2. Figure 4 shows the models with a total length of 560mm. Model 1 is consist of a solely Azobé beam, model 2 consist of Spruce and Azobe constructed beam, and model 3 consist out of a Spruce and Azobé beam with a notch at center. The length of the notch is 48mm.



Model 1: Azobe beam



Model 2: Spruce-Azobé beam



Model 3: Spruce-Azobe beam with notch

Figure 4: Beam models

The local and global coordinate systems is displayed in figure 5. For all 3 models the middle Azobè section is rotated 90° to be able simulate mode 1 failure (tension perpendicular to the grain). The beam is simply supported with a constraints in x- and y-direction on the left hand side and only y-direction constraints on the right hand side. The load is applied in displacement control at the center of the beam. Being the displacement known (prescribed) in that node, a constrained in the y-direction is placed. This resulted in knowing what the reaction force is as the beam is deflecting and cracking along the center. For the supports there is assumed that there is no friction, or shear resistance thus only roller supports are used. The supports that are used are a simplification. In reality friction is present at supports.

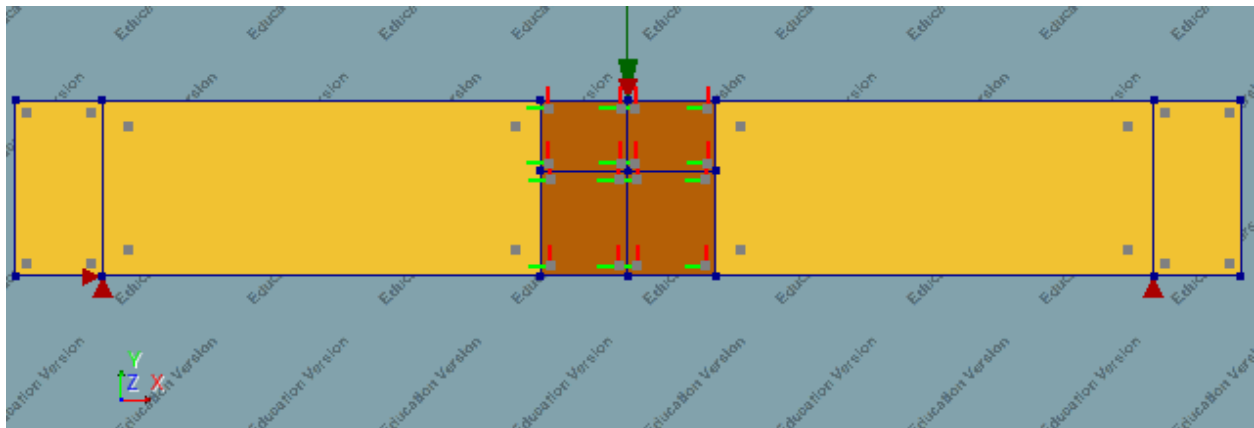


Figure 5: Local and global axis beam.

The middle section of the beam has a different local axis compared to the rest of the beam. This can also be seen in figure 5. The material orientation of the two outer sections of the beam match with the global coordinate system. These 2 outer sections use the material orientation where the fiber is parallel to the length of the beam. The middle section of the beam where the notch is located the fiber is perpendicular to the length of the beam. This is done by rotating local axis 90° clockwise around the y axis of the global coordinate system. The material orientation is simply used to identify what material properties need to be used for the model

2.2 Material properties for the model

For the model the following material properties were selected:

- Moduli of elasticity $E_{//}$ (Young's moduli parallel to the grain) and Moduli of elasticity $E_{\perp}$ (Young's moduli perpendicular to the grain) [N/mm^2]. The Young's modulus describes the relationship between the stress and the strain in a linear elastic material.
- Moduli of rigidity or shear $G_{//}$ [N/mm^2] this describe the relation between the shear stress and the shear strain. Is calculated by the following equation:

$$G_{//} = \frac{E_{//}}{16} \quad (2)$$

- Poisson's ratio. The Poisson ratio describes the perpendicular distortion of the material due to the elongation or shrinking, parallel from a force.
- Tensile strength perpendicular to grain for Azobè. The tensile strength used was calculated from the fracture energy experimental results obtained by Boerenveen (2019). From the test result it was concluded that the tensile strength perpendicular to the grain was higher than the tensile strength perpendicular to grain of $0.6 N/mm^2$ found in literature for Azobè. The average peak load obtained from the tests is 550N. This load is used to calculate the tensile strength perpendicular to grain for Azobè.

$$\begin{aligned} f_{t,90,k} &= \frac{M_{cr}}{W} \\ M_{cr} &= \frac{F}{2} * \frac{l}{2} = \frac{550 * 480}{4} = 66000 \text{ Nmm} \\ W &= \frac{1}{6} * b * h^2 = \frac{1}{6} * 40 * 32^2 = 6826.67 \text{ mm}^3 \\ f_{t,90,k} &= \frac{66000}{6826.67} = 9.67 \text{ N/mm}^2 \end{aligned}$$

- Fracture Energy due to tension perpendicular to the grain
- Normal Stiffness (k_n) and shear stiffness (k_t) modulus. To ensure that in the initial elastic phase, in which cracking is not observed, the beam behaves as a homogeneous material, high stiffness values are adopted for the interfaces. Equation 3 provide an indication of what the value for these parameters are. Since the notch is also modeled as an interface element with very low stiffness, the stiffness parameters obtained by equation 3 is divided by 10^{12} and used as the notch stiffness properties

$$k_n = 1000 \frac{E}{l}, k_t = 1000 \frac{G}{l} \quad (3)$$

Wood is an organic material with a large variation of its material properties. The variation of its material properties depends on the condition of the wood at the time the properties are determined. Due to this large variation, strength grades are used to categorize the wood in different timber strength classes. The strength grading is done according to NEN-EN 384 (2016) and NEN-EN 14081 (2016). According to NEN-EN 338 (2016) Azobè falls in the strength class D70 and Spruce C24. Even though Azobè falls in the strength class D70 strength, the Young's moduli and Shear moduli used come from material properties measured by Boerenveen (2019) during his fracture energy experimental research. In table 1 the material properties used for these models are displayed.

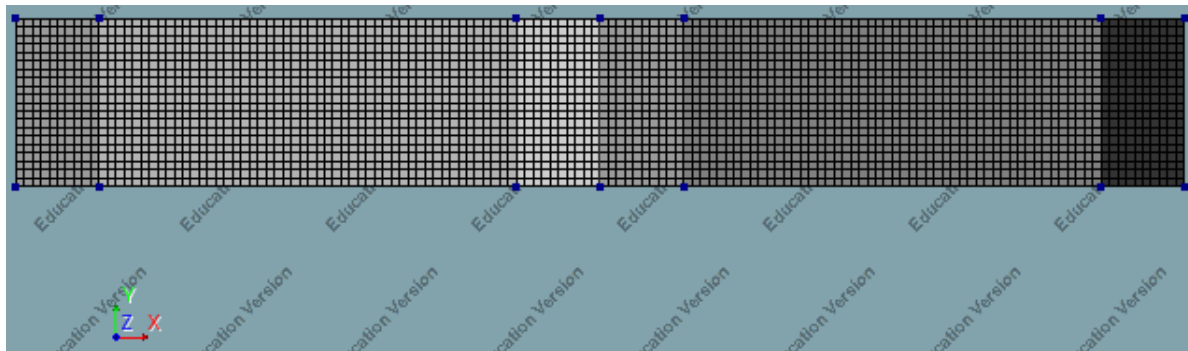
Table 1: Material properties used in model

	Material Property	Wood species	Value	Units
	Young's Moduli //	Spruce	11000	N/mm ²
	Young's Moduli $\perp$		370	N/mm ²
	Young's Moduli //	Azobè	17800	N/mm ²
	Young's Moduli $\perp$		1330	N/mm ²
	Shear Moduli	Azobè	1112	N/mm ²
	Poisson's ratio		0.3	
	Tensile strength	Azobè	9.67	N/mm ²
Crack Interface	Normal Stiffness		4.45E+06	N/mm ³
	Shear Stiffness		2.78E+05	N/mm ³
Notch interface	Normal Stiffness		4.50E-06	N/mm ³
	Shear Stiffness		2.78E-07	N/mm ³
	Fracture Energy	Azobè	0.931	N/mm

The cracking of the beam is modelled by 2D line interface element with the material model type being discrete cracking. The notch interface has no discrete cracking. The interface properties for the notch and crack are shown in table 1. The shear and normal stiffness parameters for the crack interface are calculated by equation 2 for all 3 models with l being equal to the mesh size length. The reason for this is that each individual beam element is connected with each other, and as the crack propagates each individual element connection breaks. The beam element size is determined by the mesh size. Therefore the stiffness parameters are calculated for each individual element size.

2.3 The mesh

The mesh that is used is displayed in figure 6 for all model. An element size of 4mm is selected. The smaller the mesh the better the results. The selected mesh element size provides only straight lines, which makes it more suitable to make Excel graphs and identify specific location on the graph.

**Figure 6: Beam generated mesh**

2.4 Applied Load

The load that is applied at the middle of the beam has prescribed deformation. An average maximum deflection of 15 mm was found in the experimental fracture energy research performed by Boerenveen

(2019) for the beam to the completely fracture. For all 3 models a deflection of 15 mm was used for the prescribed deformation of the load. The deformation was applied in step sizes of 0.075 mm.

2.5 Calculation method

At first a linear static analyses is run, and after the linear analysis checks out the following structural non-linear analyses is run. The nonlinear analysis is performed by using Newton- Raphson method, with a maximum of 10 iteration. For the converge norm the displacement convergence norm need to be satisfied. The convergence tolerance for the norm is set at 0.01. Also the analyses continues if the norm does not converge.

3. Results Finite Element Models

In this chapter the results of the finite element models will be discussed. The check of the first two models will be discussed and the fracture energy will also be calculated from the obtained load-deflection curves of these models. The notched beam (model 3) will be analyzed and the calculated fracture energy of this model will be compared to the calculated fracture energy of the first two models.

Model 1 and 2 the other section were modelled as linear elastic isotropic material and the middle Azobè section was modelled as orthotropic material. This reason for this was due to the high tensile strength no convergence was in displacement equilibrium norm. This required to reduce the load step size to such an extent, that the non-linear analyses of the models would take very long. Model 3 was modelled as full orthotropic beam.

For model 1 and 2 the fracture energy will be calculated from their obtained load-deflection curves. The calculated fracture energy will be compared to the average Azobè fracture energy obtained from Boerenveen (2019) experimental program. Model 3 results will be discussed and the fracture energy results will be compared to the fracture energy calculated in model 1 and 2, and the fracture energy obtained by Boerenveen (2019). Using Excel to calculate the work done by the midpoint force, the fracture energy will be calculated as the crack propagates to see what the fracture energy is as the crack propagates. The interface elements are checked in the linear stage for all models. In model 3 the interface of notch needs be completely open in the first load step, but the interface element of the crack in the linear stage needs to be completely closed. The traction of the crack interface needs to less than the tensile strength perpendicular to the grain.

3.1 Results Azobè Beam (Model 1) and Spruce – Azobè Beam (Model 2)

The prescribed load deformation for model 1 and 2 was set to 15mm, but the obtained load deflection curve show that the full failure of the beam is reach 12mm. At 12mm the load is equal to zero. The results obtained for model 1 cannot be accepted, because convergence is not med in several load steps, which provide strange load-deflection curve see figure 7. Model 2 analyses on the other hand is acceptable. The peak load obtained for model 2 is extremely high, due to the high tensile strength perpendicular to the grain of Azobè. The exact a peak load obtained for model 2 is 5310 N. The load deflection curves for model 2 is shown figure 8. From the obtained load- deflection curves the fracture energy is calculated. The fracture energy is calculated by equation 1. Due to unacceptable load-deflection curve obtained for model 1 the fracture energy is not calculated. The Fracture Energy calculated for model 2 is 0.92 N/mm which is close the average fracture energy of 0.931 N/mm obtained by Boerenveen (2019).

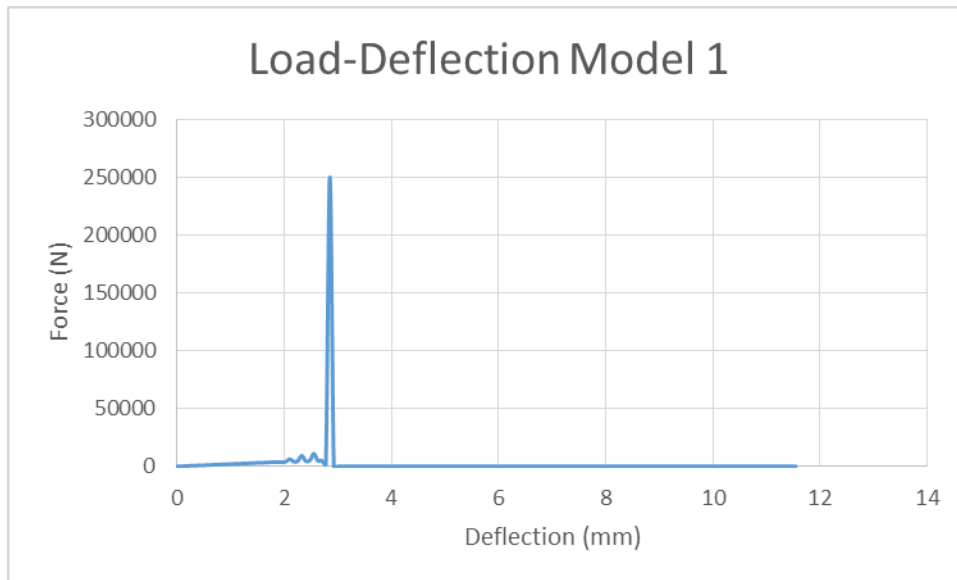


Figure 7: Model 1 Load-Deflection curve

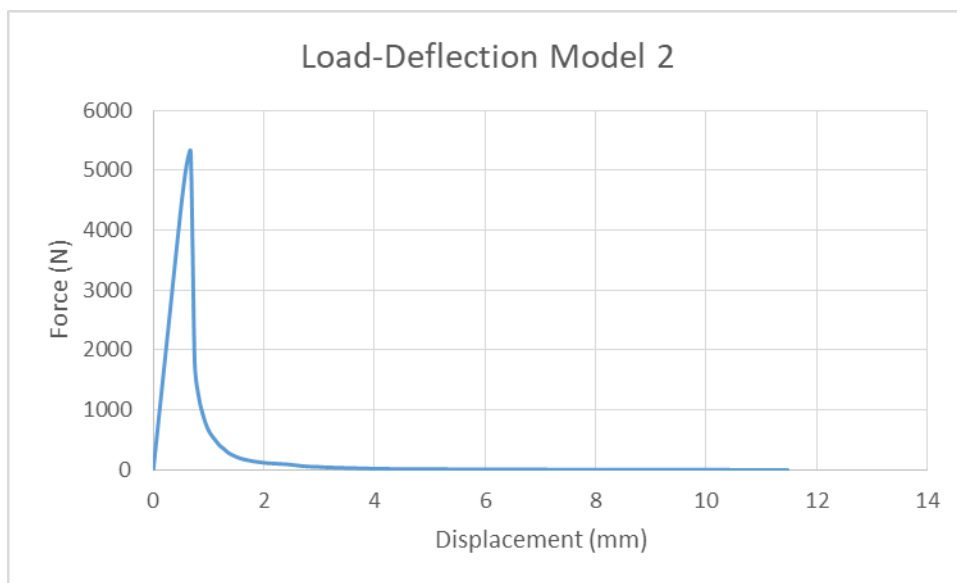


Figure 8: Model 2 Load-Deflection curve

3.2 Results Azobè Notch Beam (Model 3)

3.2.1 Model Check

With the notch being modelled as an interface element, it needs to open completely when performing a linear analyses and in the nonlinear analyses when the beam is in its linear stage before it starts to crack. The interface properties are shown in table 1. In figure 9 the traction (STNy) and the relative displacement (DUNy) of the interface element are shown of the nonlinear analyses when the beam is in its linear stage. To know if the beam is in its linear stage during the nonlinear analyses the traction (STNy) needs to be less than the material tensile strength ($f_{t,90}$) (Azobè tensile strength $f_{t,90} = 9.67 \text{ N/mm}^2$)

and the relative displacement (DUNy) needs to be less than $\frac{f_{t,90}}{k_n}$. The figure shows that the notch interface stiffness has zero effect on the beam stiffness, because as the notch opened completely the traction of the notch interface is close to zero if not zero, and for the interface element to have effect on the beam the traction would equal to the material tensile strength as soon as it starts to open up (starts to crack).

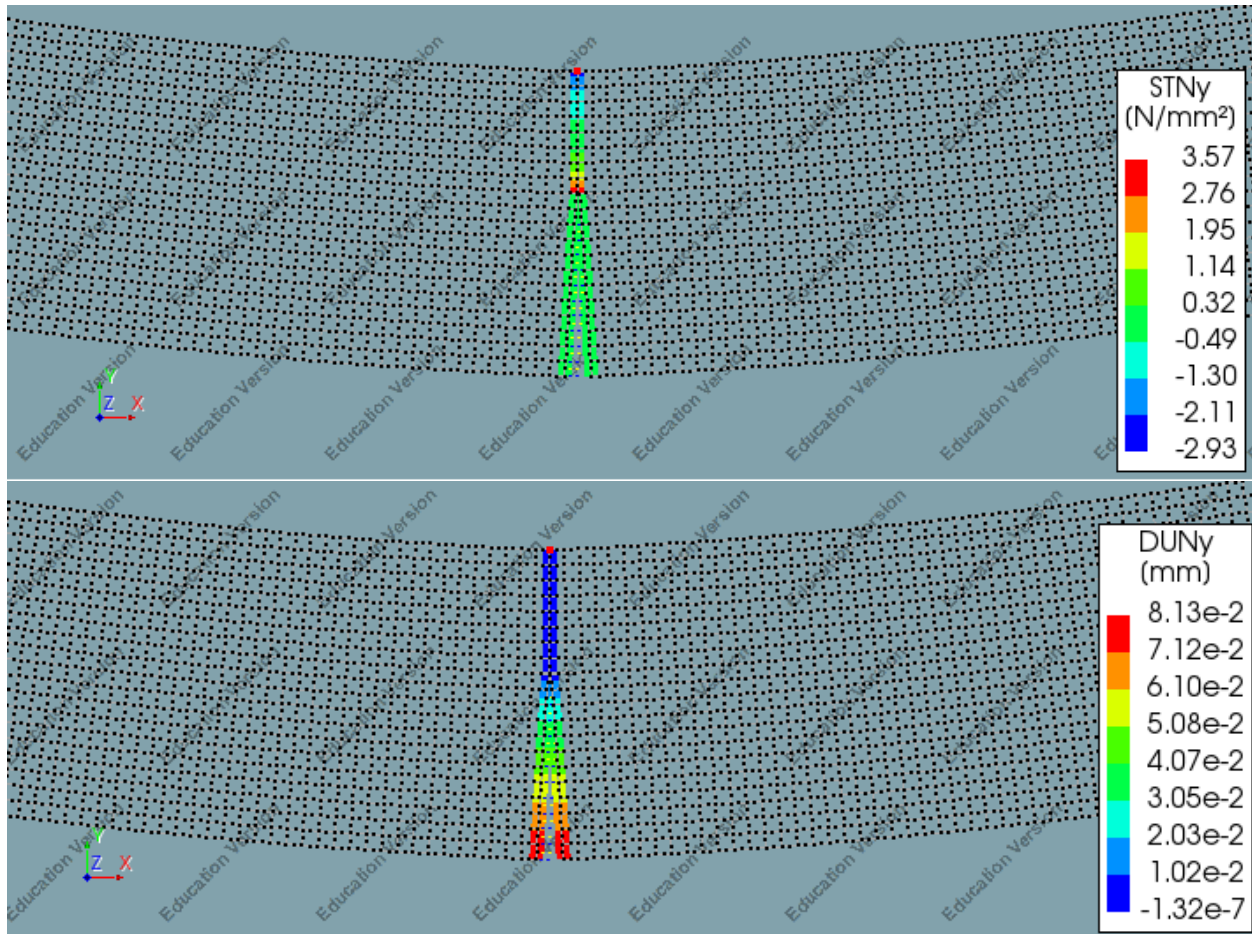


Figure 9: Displacement Linear analyses model 3 Diana

3.2.2 Fracture Energy

The load deflection curve for the non-linear analyses of this model is shown in figure 10 together with tested average load-deflection curve. From the load deflection curve the fracture energy is calculated. The peak load obtained in this model is 554 N, but the crack is initiated at 356 N which is much lower than expected. It was expected that due to the tensile strength being an input parameter the crack initiation load would be closer to the peak load. Noticing the big difference in crack load and peak load, the propagation of the crack along the beam was modelled separately to see if the load-deflection curve has a similar shape as the tested load-deflection curve (see figure 11). The crack was modelled by increasing the length of the notch by 4 mm at a time and decreasing the crack area by 4mm at the same time up to the beam being fully cracked. The load at which the model is cracked during each analyses is recorded as the crack load for the different crack length (see table 3). With knowing the crack length at its crack load, the crack load vs crack length is also plotted (see figure 12).

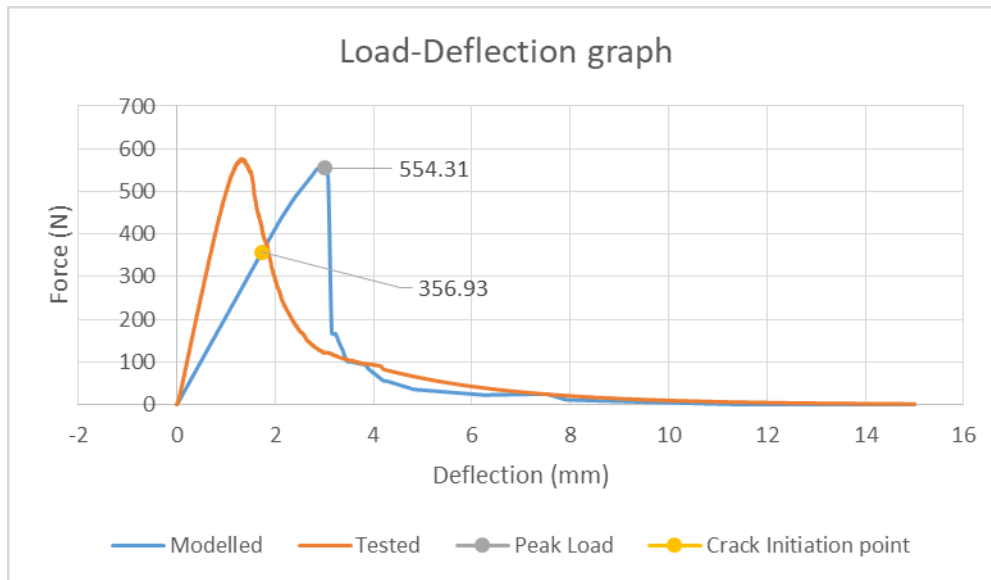


Figure 10: Load-Deflection curve Model 3 and tested average

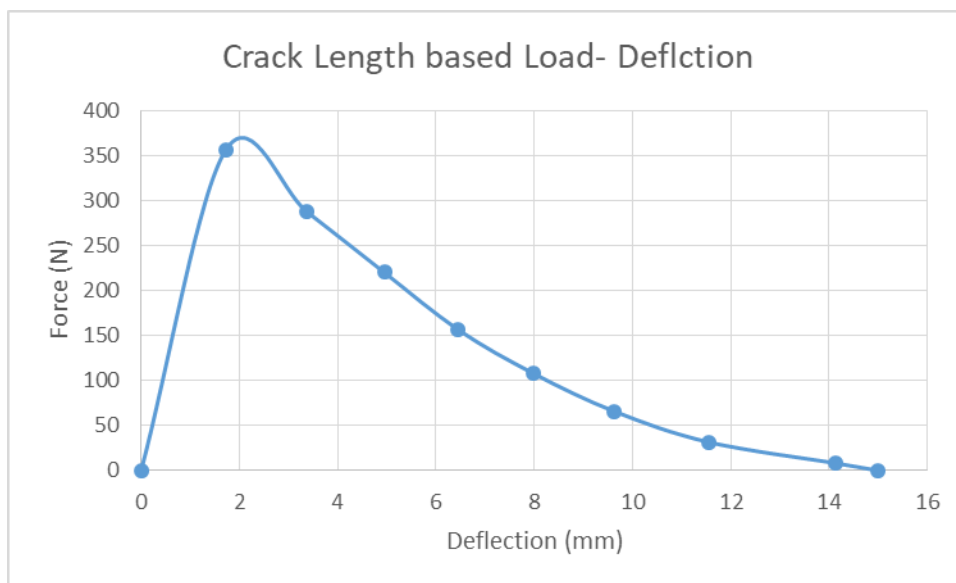


Figure 11: Load-deflection curve based on crack propagation.

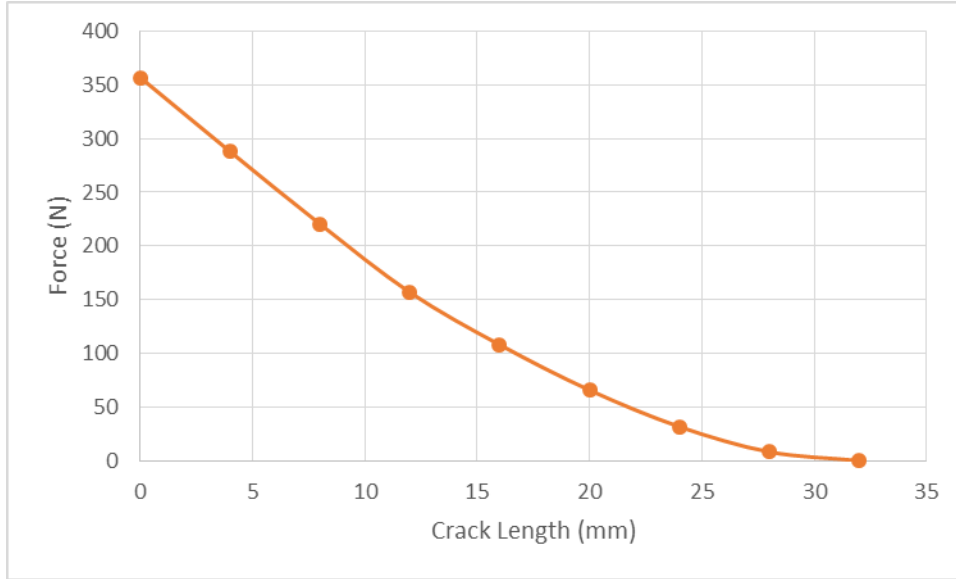


Figure 12: Load vs crack length

The load-deflection (figure 10) curve obtained from the non-linear analyses closely resembles the average load-deflection curve obtained from fracture energy experimental research performed by Boerenveen (2019). The calculated fracture energy from this curves is 0.948 N/mm. This calculated fracture energy from the obtained load-deflection curve for model 3 is practically the same as the average fracture energy obtained from test for Azobè 0.931 N/mm. A Fracture energy of model 3 over average tested fracture energy ratio of 1.02 was found, which indicates that model closely resembles the test performed by Boerenveen (2019)

$$\frac{G_{f,model\ 3}}{G_{f,test\ average}} = \frac{0.948}{0.931} = 1.02 \quad (4)$$

The load-deflection curve obtained from modeling the crack length, has no resembles in its shape when comparing it the tested results. This leads to an inaccurate calculation of the fracture energy. The fracture energy calculated from this graph is equal to 1.576 N/mm. This result indicates that the assumption made for timber, that once the material tensile strength is reached or surpassed and the material is cracked the post peak behavior of the load-deflection curve needs to start, is not correct.

Literature (double cantilever beam (DCB) fracture energy testing) states that the fracture energy can be calculated as potential energy released during crack propagation divided by the beam width multiplied by change in crack length. According to this definition the work needs to be equal for the change in crack length. Based on the load-deflection curve obtained from the crack length modeling this definition does not hold for the 3point bending single edge notch beam fracture energy testing. In table 2 the work per change in crack length is calculated, and it noticeable that the work done by the external force is not constant per change in crack length.

Table 2: Work calculated based on change in crack length

a	Δa	δ	F_y	Work
0		1.725	356.9304	531.9879
4	4	3.375	287.9035	400.278
8	4	4.95	220.386	282.8685
12	4	6.45	156.772	203.4867
16	4	7.9875	107.9262	143.2405
20	4	9.6375	65.69866	93.06461
24	4	11.55	31.62381	51.50973
28	4	14.1375	8.190474	3.532142
32	4	15	0	

Conclusion

The goal of this research was to use finite element modeling to model three point bending beam fracture to determine the fracture energy of Azobè. In total 3 model are created and analyzed. The first model consist of Azobè beam, the second of a combined beam consisting of Spruce and Azobè, and the third model is notch Spruce-Azobè beam. The beam setup, location where the load is applied and beam dimensions are shown in figure 13. For all three models the obtained load-deflection curves for the beam to reach failure are used to calculate the fracture energy for Azobè by using equation 5.

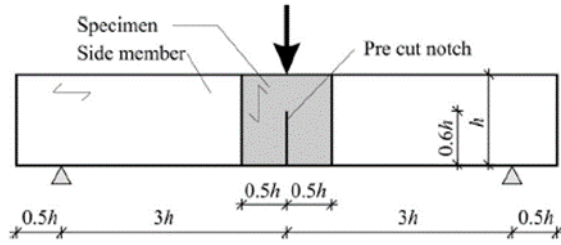


Figure 13: Test specimen dimension (h=80mm)

$$G_c = \frac{(W)}{(A)} = \frac{1}{h_c b} \left(\int_0^{\delta_0} F(\delta) d\delta \right) \quad (5)$$

Where:

- W Work done by the external force. Calculated as the area under the load-displacement curve.
- δ_0 The deflection at failure
- A Area fracture surface.

The Azobè fracture energy results obtained from the finite element models 2 and 3 are similar to the obtained Azobè fracture energy by Boerenveen (2019). Model 1 did not provide acceptable results because there was no convergence in the displacement equilibrium norm in several load steps. This issue may have been solved by increasing the load steps number (smaller load step sizes) for the analyses to be able reach convergence in the equilibrium norm.

For model 2 and 3 a calculated fracture energy over tested average fracture energy ratio of 0.99 and 1.02 was found, which is a very good result.

The notch beam finite element model (model 3) did deliver the expected results, the calculated fracture energy was 0.028 N/mm higher than the fracture energy calculated for model 2 and 0.017 N/mm higher than the tested average. It was expected that the peak load would be in the same range as the average peak load obtained during Boerenveen (2019) tests of Spruce - Azobè notched beams, the only difference in that the peak load is reached at a higher beam deflection for the model compared to the test. This caused the model to have a lower linear stiffness than the tested beam by Boerenveen (2019), and also a faster post peak behavior of the beam.

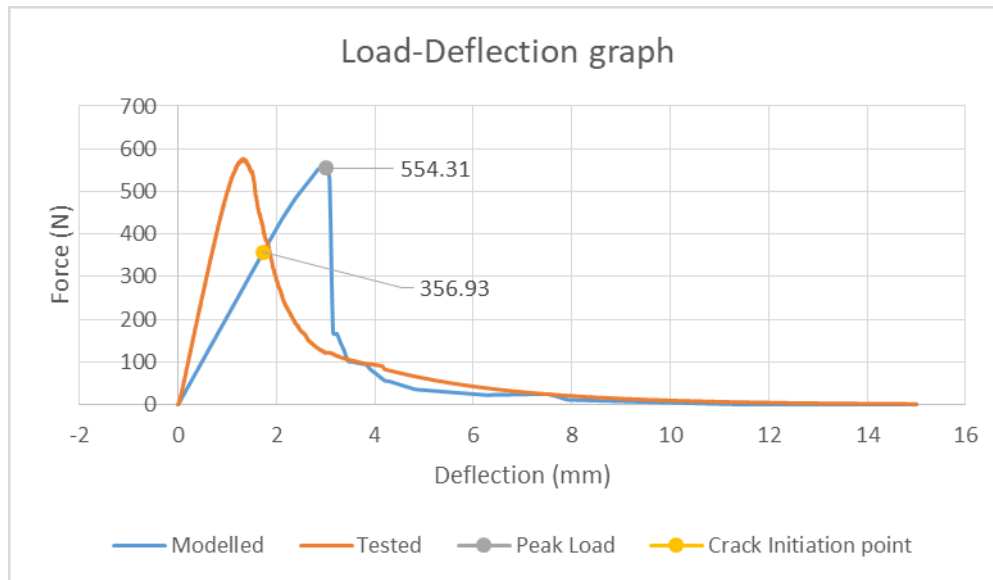


Figure 14: Load-Deflection curve Model 3 and tested average

A noticeable thing also is that in model 3 the crack load is about 200N lower than the peak load. This result was not in line with expectations. It is expected that crack load and peak load need to be closer to each because the crack load is based on the material tensile strength perpendicular to the grain. Once the material tensile strength is reached it is expected that material cracks and the peak load is almost reached. This is not the case in for this model. A good explanation for this phenomenon could not be made. Therefor it is import to take a deeper look at this issue in future research

Recommendations

After doing this research a couple of recommendations are made regarding additional research on finite element modeling (FEM) of the fracture energy hardwood. The recommendations are:

- A notch beam FEM model that better describes the notch, which may provide results that closer resemble the test results obtained by Boerenveen (2019).
- A more realistic material model where the fracture energy is not an input parameter, but it can be calculated from the obtained load-deflection curve. By doing so a better comparison can be drawn with experimental results.
- A study on the behavior of the material once the material tensile strength is reached. This provide more inside how timber behaves between the crack load and peak load.
- Parametric research can be used to study the influence of different parameters, on how they influence the material fracture energy