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Publication date
2018

Document Version
Final published version

Published in
WCTE 2018 - World Conference on Timber Engineering

WCTE 2018
2018 World Conference on Timber Engineering
August 20 - 23, 2018 | Seoul, Republic of Korea

DEVELOPMENT OF AN ANDVANCED FE-NUMERICAL METHOD FOR VIRTUAL GRADING OF TIMBER

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ABSTRACT: Structural heterogeneities in wood are changing the complexity of the numerical modelling of this material. Knots are the main strength governing parameters, which are changing the uniformity of the stress distributions through the boards. These weak locations may result in failure in the material. Comprehensive reconstruction of the boards, based on the knot data on the surfaces of the boards makes it possible to access the virtual model of the element and predict new material behaviors. The aim of the current study is to develop a more technologically advanced numerical method for grading of the wooden boards. Simulations are run using ABAQUS and PYTHON. By programming the structural model of the boards, covering the total quality range, the mechanical behavior is predicted under a uniform tension. Simulations are run for low-medium quality Douglas fir and medium-high quality spruce boards. Based on the extracted numerical parameters, the strength of the boards are predicted virtually. The results of the simulations are benchmarked to the currently available visual and machine grading methods. By getting a promising correlation between the tensile and the predicted strength results, a more advanced numerical method is provided for virtual strength grading of the boards. The method is later applied for the reconstruction of the glulam model based on the information of the single lamellas.

KEYWORDS: Finite element analysis, strength grading, fiber deviation

1 INTRODUCTION

Natural defects, such as knots in wooden lamellas are the main strength governing parameters, which may initiate failure in the material. These are the weak points, leading to fiber deviations in wood that vary from board to board and from species to species. As wood is a naturally grown material, the structure of different species are different. This difference is more obvious, if comparing softwoods to hardwoods. All these non-homogeneities, and anisotropic properties are resulting in some difficulties in creation of a virtual material model of wood. Previous studies tried to develop the numerical models to describe these imperfections in 2D [1, 2, 10] and 3D [3, 4, 5, 6], and analyse the failure procedure of this material. Most of these studies considered the flow-grain analogy [2] as the bases of their studies and tried to develop the numerical model to predict the mechanical behaviour of the material. Regarding hardwood species, new studies are being performed for better strength predictions, with a focus on glulam applications [7]. By having a big database of tested and visually graded hard and softwood boards, the aim of this study is to develop a reliable numerical model which can fully represent the knots for better strength predictions. This can be an important step in the structural applications of the engineered wood composites. Different geometrical configurations and number of the knots are some of the parameters which are considered in this study. Visually graded knots are categorized into 55 different knot configurations and are stored in the database. These configurations are based on the knot geometries and the surfaces of the boards, which are covered by each knot. By finding the geometrical locations of the knots, the CAD model of the boards is virtually reconstructed, which is later used for further numerical analysis. In the recent study PYTHON is used to create an automatic link to the knot data of the database and to reconstruct the geometrical model of the boards, and ABAQUS is used for FE-numerical simulations. By reconstructing the full 3D geometrical model of the timber boards, the structural model of the boards are created, considering the fiber deviations [1, 3]. The numerical analyses are run under uniform tensile loading. Three parameters are extracted from the numerical simulations for the virtual tensile strength predictions. The simulation results are used in the regression analyses and each parameters is compared to the tensile strength values in each case. This is done to validate the prediction capabilities based on both, visual and virtual methods.

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2 MATERIALS AND METHODS

2.1 GEOMETRICAL REPRESENTATION OF KNOTS

Before performing the physical tests, all boards are visually graded. Visual grading is done based on the visible parameters of the knot geometries [8, 9]. Based on this grading system, the 3D geometrical position of the knots are measured and are registered in the database. These data is accessible at any time and for any board. At the chair of Wood Technology in Technical University of Munich a database is available, containing the information of more than 10000 different softwood and more than 5000 different hardwood boards. The registered data contains the information about the geometrical aspects of the boards, including the length, width and the thickness. Additionally, the database contains the information of the knots, including:

- The number of the knots in the board
- The surfaces which are covered by each knot
- The x, y, and z coordinates for the beginning and ending position of the knot on each surface
- The maximum and the minimum diameters of the knots
- The distance to the center of the knot
- The rotation direction of the knot

An example of a wooden board in presented in figure 1. Numbering of the surfaces of a board, the global coordinate system, and a cylindrical knot which is covering surfaces 1 and 3 in the board is represented schematically in this figure.

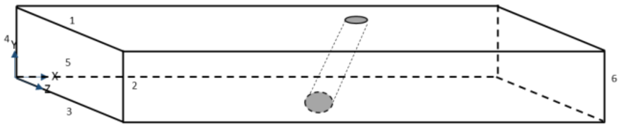

Figure 1: *Geometrical representation of a board with a conical knot*

Figure 2 shows a real board with the diameters and the rotation of the knot. Angle γ, the angle in the xz-plane of the board is also presented in this figure, showing the rotation of the knot on this surface.

Figure 2: *A real board with a knot. Red arrow is the maximum diameter and the yellow arrow is the minimum diameter of the knot*

The visual knot parameters, which are used in this study for the knot assessment, are the TKAR, DEB, and DAB, which consider different criterion for the measurement of the cross sections of the knots [14]. These parameters are used here for the strength predictions based on the visual measurements, and are compared to the predictions based on the parameters, extracted from the simulations.

2.2 NUMERICAL ANALYSIS

2.2.1 GEOMETRICAL RECONSTRUCTION AND NUMERICAL SIMULATIONS

By having the data of the natural defects, registered in the database, the aim of this study is to virtually reconstruct the boards based on computer methods, to be able to perform different numerical analysis and predict the strength of the material. For this reason, an automatic link is created to the database, to reconstruct the full 3D geometrical model of the boards. As exact representation of the board may not be always possible, and some errors could happen during the visual knot registration process, an additional error term of ±2 (mm) is added to the program for the extraction of the coordinate direction and for calculation of the angle of rotation of the knot. Additionally, a separate central axis and plane is defined for each knot, which makes it possible to assign different material properties in different locations of the model. Based on the categorization of the knots in different groups of live and dead knots, different contact properties need to be defined between each knot and its bulk material. In this study knots are modelled as holes, with no contact to their bulk material, in order to be able to make some simplifications and to reduce the calculation costs. To be able to cover the whole quality range in this study, two sets of species are chosen from the database for modelling and validation. The simulations are run for more than 400 softwood and hardwood boards. This study includes 102 medium to high quality spruce boards and 137 low to medium quality Douglas fir boards. Additionally, some beech, ash and maple boards are modelled for some validations [13]. Douglas fir boards have much higher number of knots compared to the spruce and hardwood boards, which are affecting the quality of these boards. The dimensions of the boards are presented in table 1.

Table 1: Dimensions of the boards, used for the simulations

Species	Dimensions (mm)		
	Length	Thickness	Width
Spruce	4200	40	150
Douglas fir	4500	46	146

Figure 3 shows virtual geometrical reconstruction of three boards, based on the data, registered in the database. The model is created in ABAQUS/Standard, using the PYTHON programming language to program the link to the data of the database.

Due to the bad geometrical configuration of some knots, the reconstruction of the full geometrical model can sometimes be difficult. This is especially the case for extremely elongated and curved knots or the ones with extremely steep angles. The geometrical problems can also lead to some problems in the numerical steps. This may be due to the mesh disturbance because of the interactions of the mesh elements in the surrounding of the knots, and the difference in the aspect ratios of the elements around some knots, which have bad shapes and/or are located close together. These are the problems, which cause numerical instabilities and convergence problems during the numerical analysis. In total, 137 Douglas fir boards are modelled out of 150 selected boards in this study, due to the numerical instabilities. This problem was not the case for the spruce boards with fewer knots.
The model is created in three consecutive numerical steps. After geometrical reconstruction of the boards, the structural and the mechanical models of the boards are created and analysed.
For creating the structural model of wood, the theory of flow-grain analogy is implemented [2, 3]. Based on this model, the flow pattern of the wood fibers is predicted around the knots.

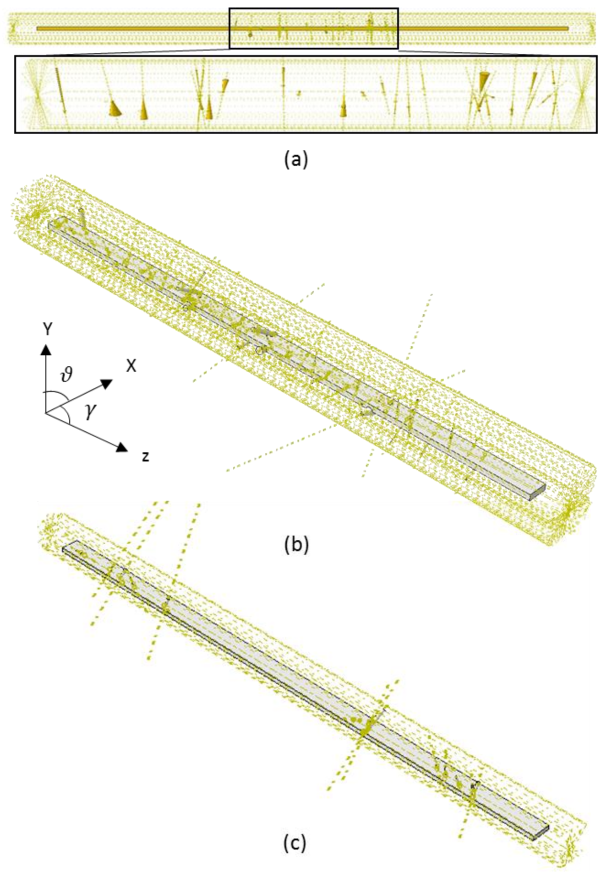

Figure 3: *Virtual geometrical reconstruction of the boards. a) example of a spruce board, b) example of a Douglas fir board, c) example of a maple board*

In contrast to the softwoods, the prediction of the fiber patterns for hardwoods are more complicated. Softwoods have relatively uniform fiber patterns, although having complex geometrical models due to the existence of more number of the knots. To be able to validate the structural model, the results of the simulations are compared to the CT-scan images of the boards. Figure 4 shows an example of an ash board and the verification of its structural model with its CT-scan image.

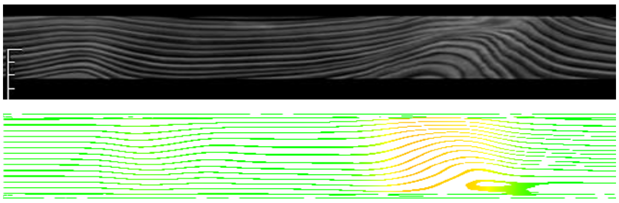

Figure 4: *Numerical simulation of the structure of ash wood and comparison to CT-scan image [13]*

Wood is defined as an orthotropic material for the simulations. In such a material the material properties are changing in the three coordinate direction of radial, longitudinal, and tangential directions. The average material properties of each sample set is used as the input parameters for the simulations. The compliance matrix for such an orthotropic material is presented in equation 1 [11, 12].

$$\begin{bmatrix} \varepsilon_{LL} \\ \varepsilon_{RR} \\ \varepsilon_{TT} \\ \gamma_{LR} \\ \gamma_{LT} \\ \gamma_{RT} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_L} & \frac{-\nu_{RL}}{E_R} & \frac{-\nu_{TL}}{E_T} & 0 & 0 & 0 \\ \frac{-\nu_{LR}}{E_L} & \frac{1}{E_R} & \frac{-\nu_{TR}}{E_T} & 0 & 0 & 0 \\ \frac{-\nu_{LT}}{E_L} & \frac{-\nu_{RT}}{E_R} & \frac{1}{E_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{LR}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{LT}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{RT}} \end{bmatrix} \cdot \begin{bmatrix} \sigma_{LL} \\ \sigma_{RR} \\ \sigma_{TT} \\ \sigma_{LR} \\ \sigma_{LT} \\ \sigma_{RT} \end{bmatrix} \quad (1)$$

Where *R*, *T*, and *L* represent the radial, tangential, and longitudinal directions respectively. E_{ij} is the moduli of elasticity, G_{ij} is the shear moduli, and ν_{ij} is the Poisson's ratio.
The compliance matrix should be symmetric which results in equations 2 to 4.

$$\nu_{RT} = \nu_{LR} \frac{E_R}{E_L} \quad (2)$$

$$\nu_{TL} = \nu_{LT} \frac{E_T}{E_L} \quad (3)$$

$$\nu_{TR} = \nu_{RT} \frac{E_T}{E_R} \quad (4)$$

C3D10 quadratic tetrahedral elements are used for the numerical simulations.
To be able to perform the virtual strength prediction of the boards, three different parameters are extracted from the FE numerical simulations in this study. These parameters represent the geometrical aspects of the knots as well as the material behaviour under the loading conditions. The simulations are performed by applying uniform tension load to the boards. The applied boundary conditions are shown in figure 5.

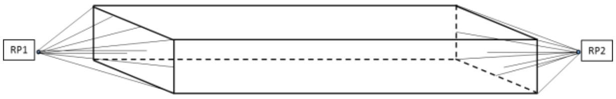

Figure 5: *Boundary conditions of the model. RPs represent the rigid points for boundary conditions*

Figure 6 shows an example of the numerical simulations, including the structural and the mechanical models, for a spruce board. The board in this figure contains nine knots, which are well distanced through the board.
The softwood boards, modelled in this study, contain minimum of one to up to 89 knots, where the fiber patterns around one knot may be influenced by the other knots in the vicinity.

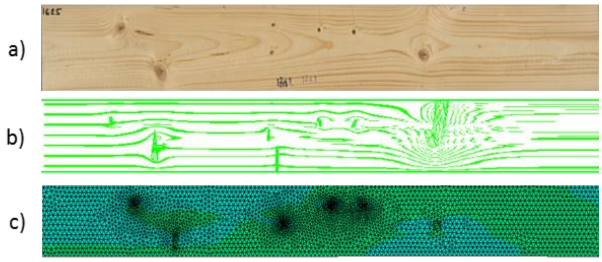

Figure 6: *a) Real spruce board (1241), with all measured knot parameters and tested in tension. b) structural model of the board, c) mechanical model of the board for prediction of the numerical parameters*

As shown in figure 6, the uniform stress distribution pattern is disturbed in the location of the knots. This disturbance is due to the geometrical configurations of these natural defects, which may determine the load carrying capacity of the board.

2.2.2 NUMERICAL PARAMETERS FOR STRENGTH PREDICTIONS

FE models are not only giving the opportunity to reconstruct the reasonable geometrical model of the boards, but different parameters, extracted from these models can be used in regression analysis to predict the tensile strength of the material.
By looking at the stress distribution patterns in the boards with different numbers of knots, the uniformity of these patterns are disturbed by the geometrical configuration of these defects. To be able to use the geometrical non-uniformities as parameters, affecting the strength properties of the material, three mathematical methods are provided to calculate the knot effects. These parameters are mainly calculated by considering the cross-sectional areas of the knots separately and/or in a group, to analyse the effects of the knot clusters on the stress flow. Moreover, these analyses are based on the calculation of the stresses in the vicinity of each knot and/or the knot clusters in a board. The knot parameters are calculated, considering the following cross-sections:

- Parameter 1 is measured based on the sum of the length of all the edges of the surfaces, where knot is appearing, in the real knot configuration. This is similar to the measurement of the DEB in visual knot assessment method [14].
- Parameter 2 is measured by considering windows of 150 mm over the board and summing up the edges of the projected areas of the knots, existing in the window. Therefore, $\sum a_i$ is not anymore for single knot, but it is considering all the knots which are existing in the limit of 150 mm window. This is similar to the measurement of DAB in visual assessment [14].
- Parameter 3 is measured similar to Parameter 1 but instead considering the projected cross-section of the knot with maximum stresses.

These surfaces are shown in figure 7.

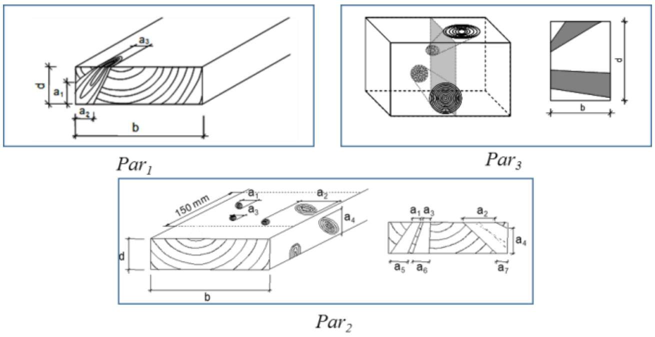

Figure 7: Knot surfaces, used for the calculation of the numerical parameters [14]

2.2.3 Glulam modelling

Having more than 400 lamellas modelled, and based on the information about single lamellas, the glulam model is created, considering knots in different layers.
Due to the geometrical non-uniformities of each lamella, a complicated mesh structure can be observed for the glulam beams.
To connect the glulam layers on top of each other, a surface-to-surface contact is defined, representing the behaviours of the tangential and normal movement of the lamellas with respect to each other. By defining a thin adhesive layer in the model, the calculation costs

increases. This is due to the definition of an additional contact layer between wood and adhesive bond and the difference of the aspect ratios of the elements of both materials. In order to solve the problems of the variation of the aspect ratio of the elements of both materials in the contact region, much finer mesh needs to be defined for wood as well, which increase the calculation time. To overcome these problems, and to be able to balance the calculation costs for the initial models, the effects of the adhesive properties are not considered in this study. Instead, hard contact behaviour is defined for these models, which is a stiff contact, connecting the lamellas to each other.

The stress distributions in the glulam are not only affected by the knots and geometrical complications of a single lamella, but they are also affected by the contact layer, which is defined in-between the lamellas.

Figure 8 shows a sample of a 3-layer and 4-layer spruce glulam beams, including these defects.

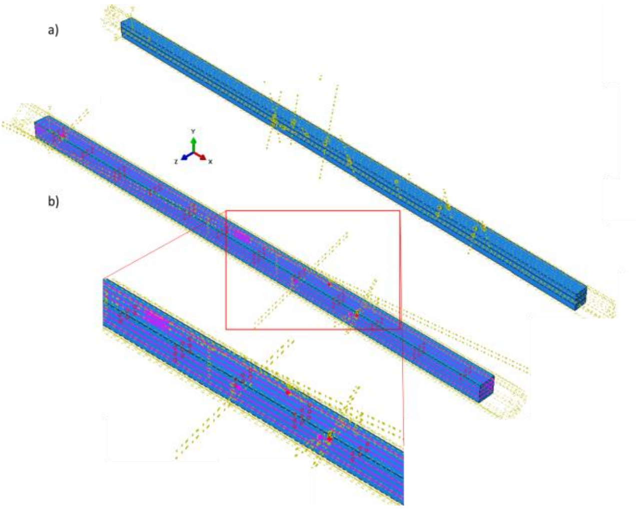

Figure 8: *Glulam model based on imperfections in the lamellas. a) 3-layer spruce glulam, and b) 4-layer glulam model. The pink surfaces in figure 8.b show the contact surface between lamellas*

Figure 9 shows the results of the numerical simulations and the stress distribution patterns in the 3-layer spruce glulam.

As shown in figure 9, a non-uniform mesh is used for each of the layers, due to the effects of the knots. Moreover, it is shown that the contact layer between lamellas influences the stress transfer through the lamellas. Figure 9.c shows the stress distribution around the knots and its transfer through the contact layer to the neighbouring lamella, without considering the adhesive properties in the model.

Therefore, the same approach as the single lamellas is used for the prediction of the stress distribution patterns in glulam.

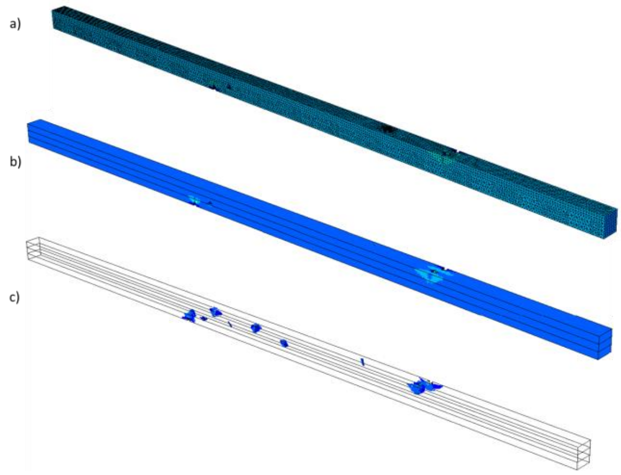

Figure 9: *Stress distribution in glulam. a) mesh in 3-layer spruce glulam, b) stress distribution in glulam, and c) detailed look on the stress distribution around the knots, the stress transfer to the neighbouring layer, and the effect of the contact layer.*

3 RESULTS AND DISCUSSION

To be able to validate the results of the numerical simulations, three extracted parameters of the finite element analysis are benchmarked to the visual knot assessment parameters, including TKAR, DEB and DAB.

Figure 10 shows the non-linear correlation of predicted strength based on each of the numerical parameters, and the tensile strength. For the 3D anisotropic and heterogeneous wooden boards with different geometrical features and imperfections, different conditions need to be considered for calculation of the numerical parameters, including the cross-sectional areas and the total stress distribution patterns. Moreover, the interacting effects of the knots in the 3D space may disturb the uniformity of the stress distribution patterns, as shown in figure 6.

These numerical parameters are used in a regression analysis to check the correlation with the tensile strength. The regression results of figures 10 and 11 are presented in tables 2 and 3 respectively.

As shown in table 2, parameter 1 has the highest correlation to the tensile strength of the softwood species. This parameter is playing the most important role in the tensile strength prediction of the good quality spruce boards. For the lower quality Douglas fir boards, more uniform results are visible between the three numerical parameters and the tensile strength.

Figure 11 shows the results of the multiple regression analysis, and comparisons between the strength predictions based on the numerical results, the visual knot assessments, and the visual and machine grading methods.

The results are categorized and shown in three groups in figure 11. These results are as follows:

- Simulation parameters, including Par1, Par2, Par3 from numerical modelling
- Knot parameters, including TKAR, DEB, and DAB, from visual knot assessments methods
- Tested parameters, including the dynamic modulus of elasticity, TKAR, DEB, DAB, and density, from knot and machine grading methods

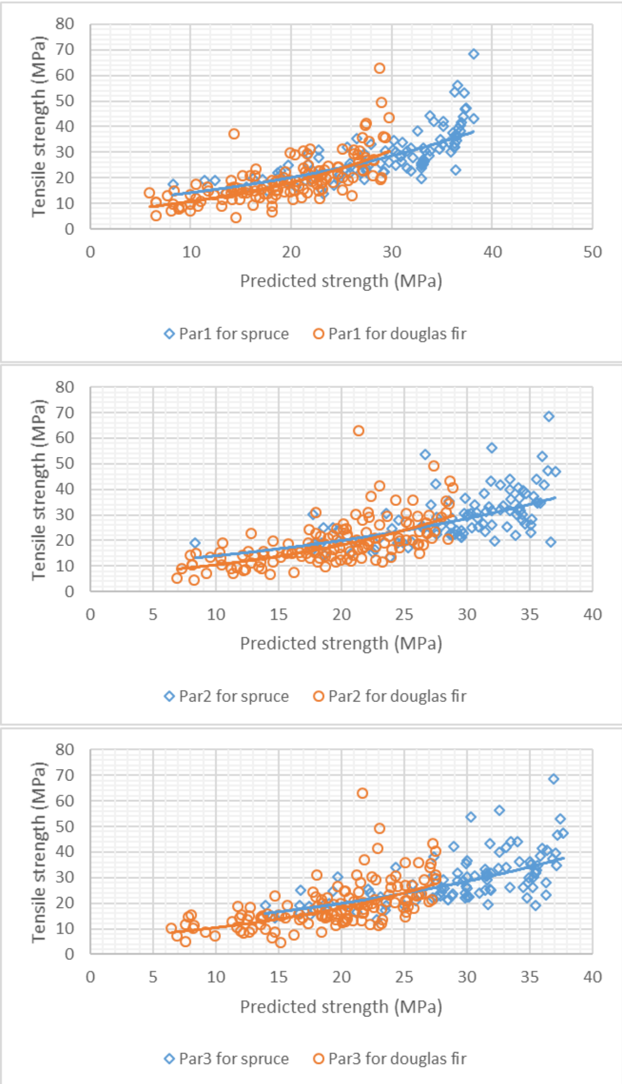

***Figure 10**:* Relation between numerical parameters and tensile strength for spruce and Douglas fir boards. This figure shows the linear correlation between the numerical parameters and the tensile strength

Table 2: R^2 values of three numerical parameters vs. tensile strength for both wood species, presented in figure 10

	Par1	**Par2**	**Par3**
Spruce	0. 5057	0.3304	0.3915
Douglas fir	0.4707	0.3883	0.3578

Figure 11 shows non-linear correlations between the each set of the parameters and the tensile strength for each sample.

Table 3 shows the regression results of the multiple correlation analysis. As shown in table 3, the simulation parameters for both samples have much higher R^2 values compared to the visual knot assessment parameters. This shows the strength of the numerical predictions in comparison to the visual grading. The R^2 values of the numerical parameters are also equally good compared to the tested parameters, which are the parameters of the visual and machine grading methods.

Based on figure 11 and table 3, the parameters of the FE-model are highly improving the quality of the strength predictions compared to the currently available visual plus machine grading methods.

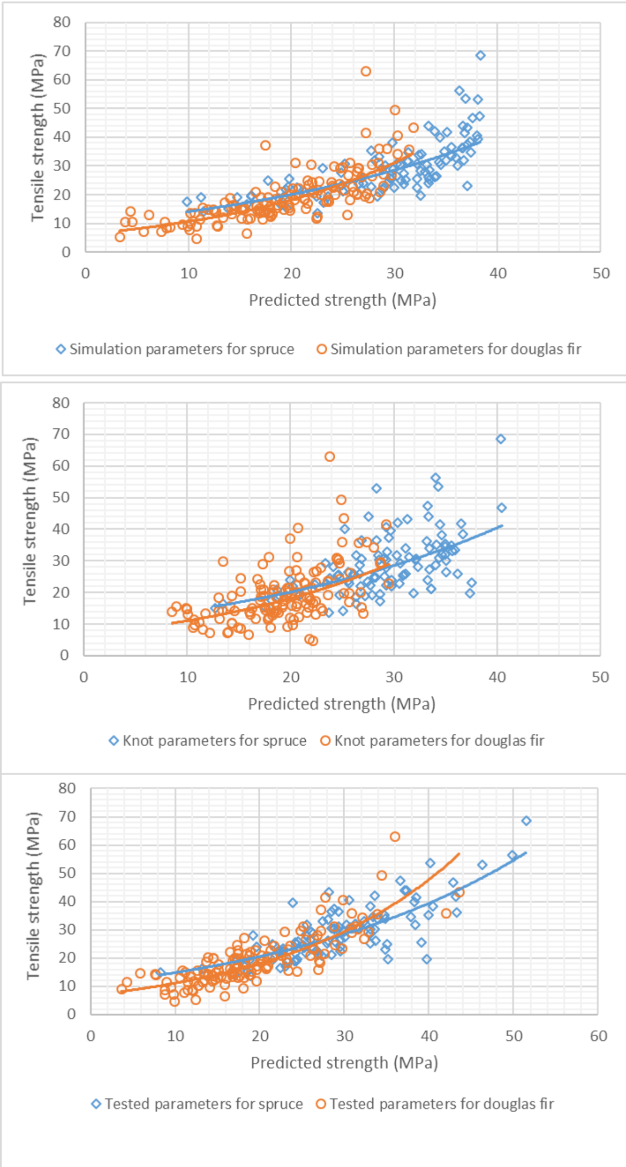

***Figure 11**:* Multiple regression analysis for spruce and Douglas fir boards, including Simulation parameters, knot parameters, and tested parameters.

Table 3: R^2 values of the non-linear multiple regression analysis for three sets of parameters and for both wood species, presented in figure 11

	Simulation Parameters	Knot Parameters	Tested Parameters
Spruce	0.6159	0.3524	0.6036
Douglas fir	0.6491	0.2711	0.6445

Table 4 shows the single and multiple regression results of the numerical and measured parameters with the tensile strength for both samples.

Table 4: Regression results of different correlation parameters for spruce and Douglas fir

	Par 1	Par 2	Par 3	ρ	TKAR	DEB	DAB	MOE	R^2 Linear	R^2 Non-linear
$f_{pred.}$ spruce	x								0.51	0.59
		x							0.33	0.40
			x						0.39	0.48
				x					0.25	
					x				0.22	
						x			0.17	
							x		0.23	
								x	0.58	
	x	x							0.51	0.59
					x	x	x		0.31	0.35
				x	x	x	x	x	0.60	0.60
	x	x	x						0.52	0.62
$f_{pred.}$ Douglas fir	x								0.47	0.54
		x							0.39	0.49
			x						0.36	0.45
				x					0.11	
					x				0.19	
						x			0.13	
							x		0.22	
								x	0.50	
	x	x							0.55	0.65
					x	x	x		0.27	0.28
				x	x	x	x	x	0.67	0.65
	x	x	x						0.54	0.65

4 CONCLUSIONS

Natural defects, such as knots in timber lamellas are the main strength governing parameters, which may lead to disturbance in the uniform stress distribution patterns, and cause failure in the material. Due to the importance of these weak points, the full 3D-geometrical model is reconstructed in this study, based on the visual knot information on the surface of the boards. Numerical analysis are run in three consecutive steps, through which the structural and mechanical models of the boards are generated. Three parameters are extracted from the FE-models to perform the virtual grading. By applying the full computer methods for the strength predictions, the number of the calculation errors are reduced in the presented method compared to the visual grading methods. Numerical simulations are done, covering the total quality range of the timber boards, including low to medium quality Douglas fir and medium-high quality spruce boards. A direct comparison of the predictive quality of the visual grading approach and the FEM approach shows that the strength prediction is better using the 3D FEM modelling approach. Comparisons show also equally good virtual strength predictions as visual and machine grading methods, currently available.

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