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A CRITERION FOR THE EFFECTIVE STRENGTH OF WOODEN BOARDS WITH KNOTS DERIVED BY A 3D FINITE-ELEMENT TOOL

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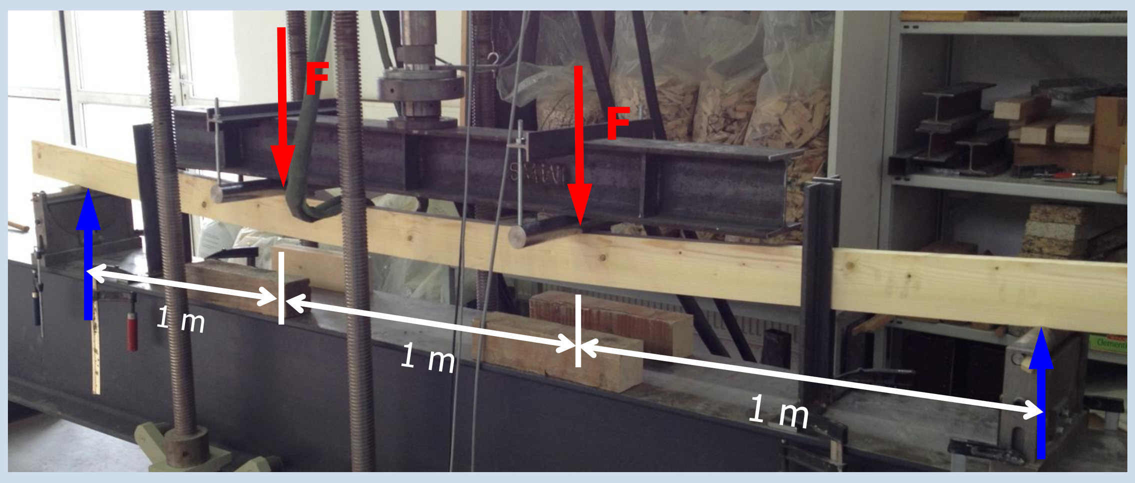
Motivation

Wood grading

Knots and the resulting fiber deviations are the main defects in wooden boards and as such they have a large influence on the effective stiffness and strength behavior. Depending on the arrangement of knots/knot groups, certain effective mechanical properties can remain unaffected or change significantly. For example the ultimate bending strength of a wooden board can differ by a factor of three for the same board dimensions and experimental setup. For this purpose, a Finite-Element simulation tool [1,2] was developed to allow a 3D virtual reconstruction of wooden boards enabling the mechanical testing of such timber elements with knot inclusions.

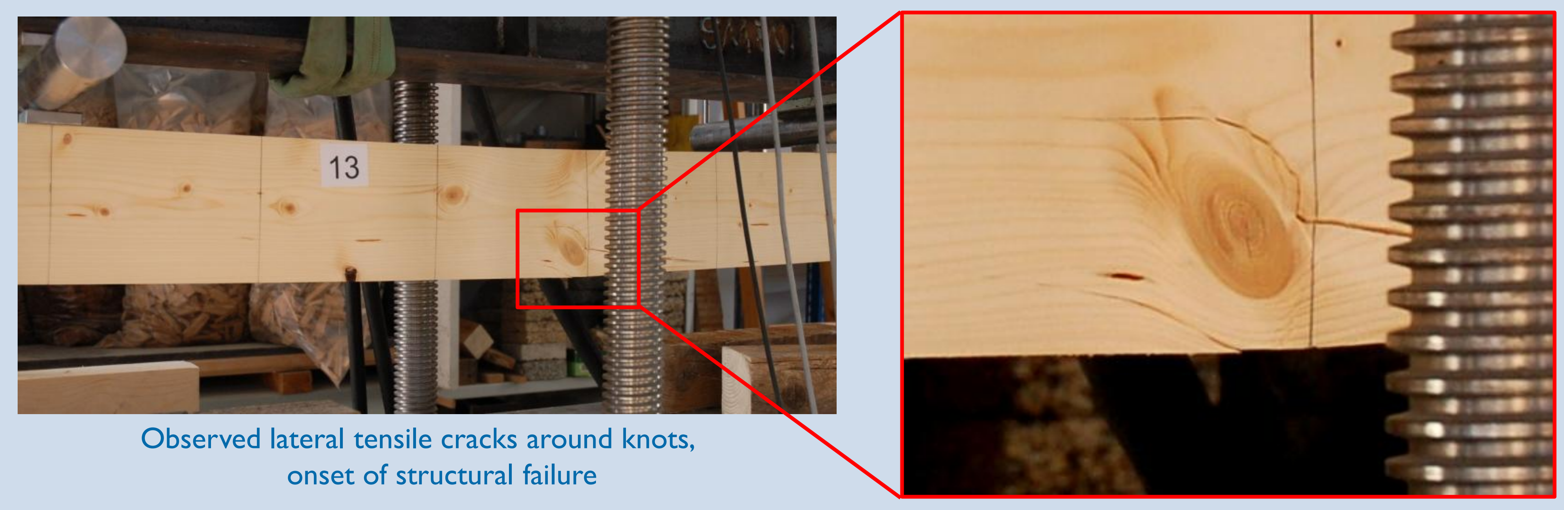
This method delivers insight into internal stress and strain fields without the need of expensive experiments. Knowledge of load transfer mechanisms and the effect on mechanical properties will improve the wood grading process and may become crucial in the production process of wood products, like Glued Laminated Timber (Glulam) and Cross-Laminated Timber (CLT), to remain competitive with respect to other less sustainable building materials.



Wooden board in a four point bending test setup used for model validation

Failure mechanisms

Preliminary test results for wooden boards under four point bending loads indicated that structural failure starts with transverse tensile cracks close to knots. The observed failure mechanisms confirmed the need of a modeling approach, which considers the 3D fiber course in the vicinity of knots, especially for the localization of the onset of global failure.



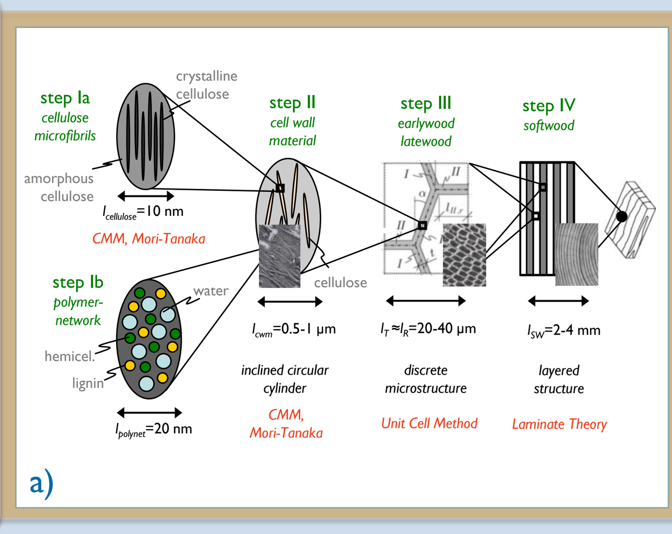
Observed lateral tensile cracks around knots, onset of structural failure

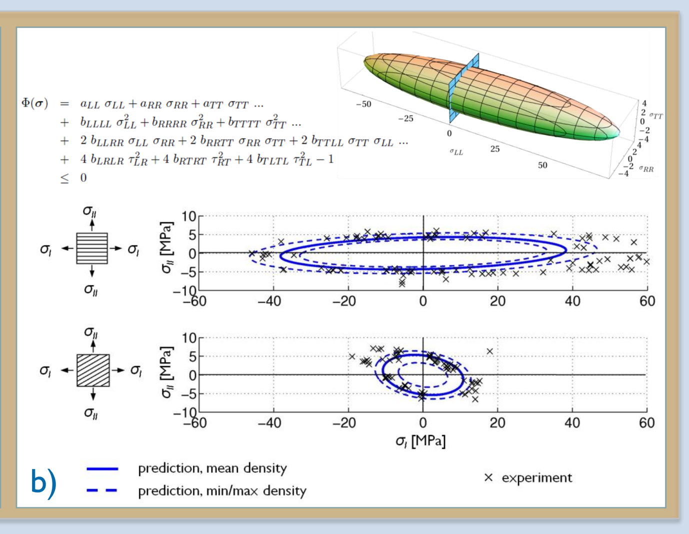
Methods

Finite Element simulation tool

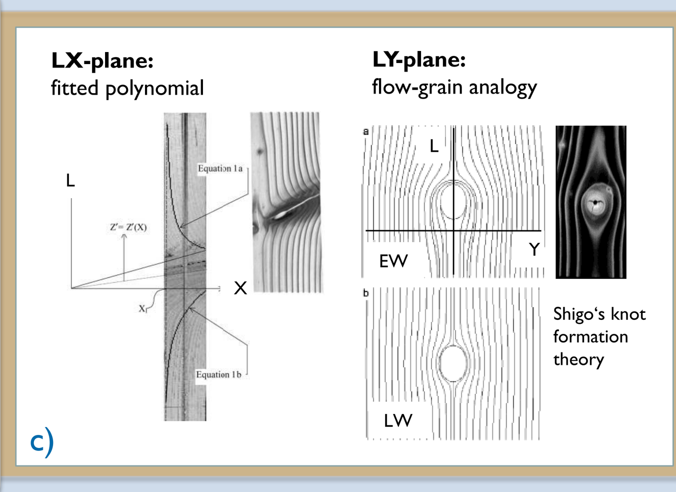
The numerical simulation tool for wood grading enables the virtual reproduction and mechanical testing of wooden boards with knots. The characterization of the clear wood with respect to the principal material directions is done by means of a micromechanical model (a) [3], which allows the calculation of the stiffness tensor based on microstructural characteristics (species, density, moisture content, …). The common failure criterion of Tsai and Wu for orthotropic materials with different strengths in tension and compression is used to define local failure, where the independent tensor components are estimated according to [4] (b). To approximate the 3D fiber course in the vicinity of knots a geometrical model (c) was implemented [5]. Thereby, knots are modeled as rotationally symmetric cones with their apexes lying on a piecewise linear pith (d). The principal material directions are calculated in each integration point of the Finite-Element mesh, based on the 3D fiber course.

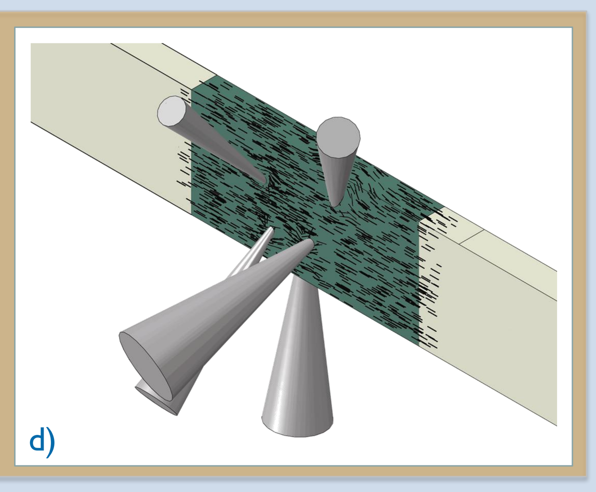
Mechanical model



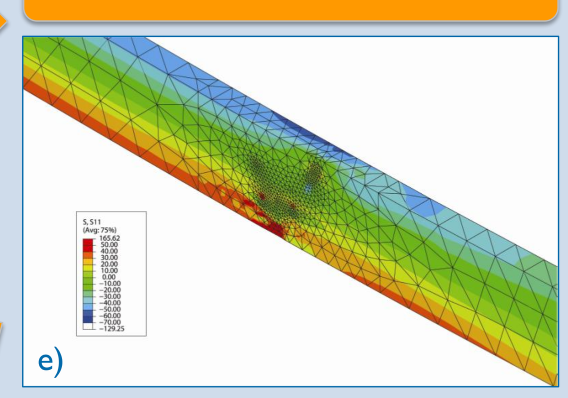


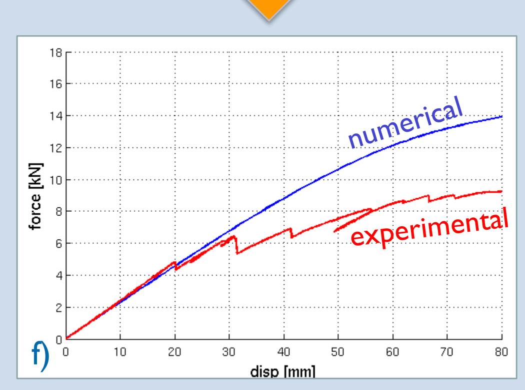
Geometric model



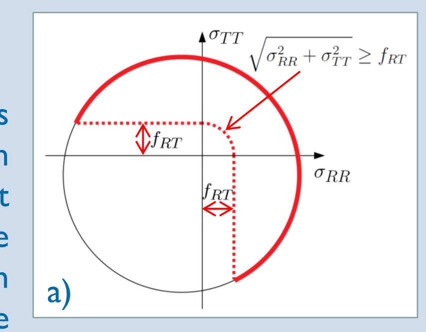


Finite element model

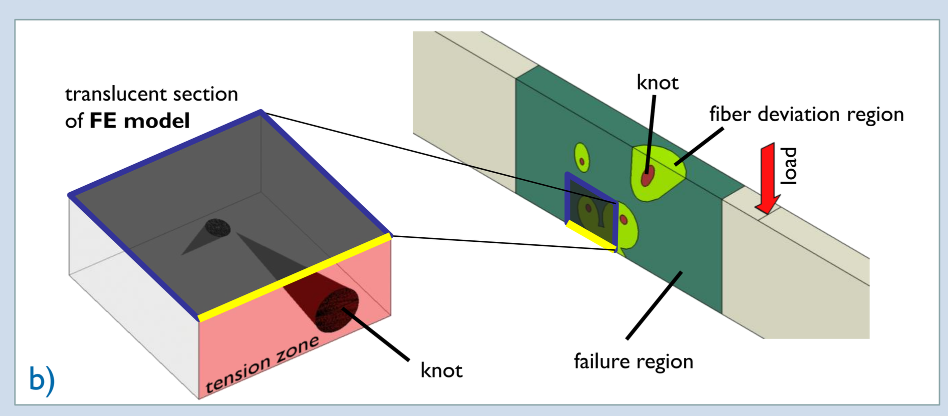


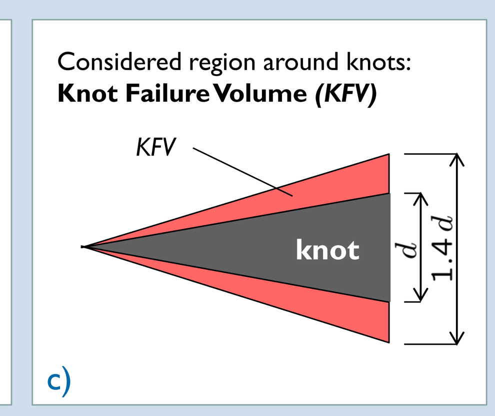


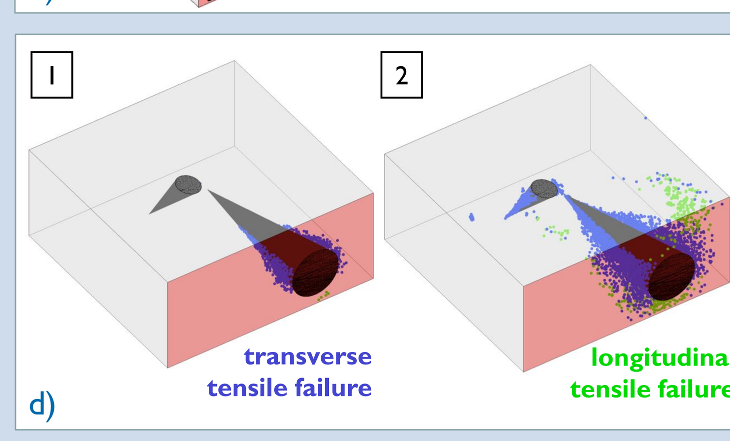
Effective strength criterion

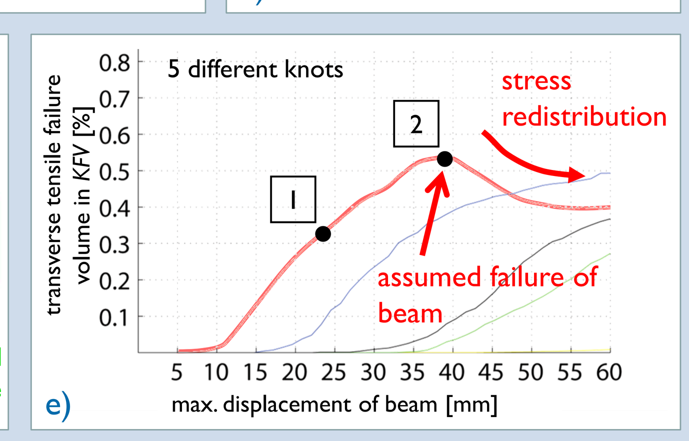


Because of the used ideal plasticity model stress transfer mechanisms induced by cracks cannot be taken into account, leading to an overestimation of the effective strength. In (d) it can be seen that failure starts at the interface zone around the knots. Subsequently, the whole zone fails due to lateral tension and stress redistribution from the lateral to the longitudinal direction starts, indicating the development of global failure modes. This formation of failure zones is used to identify the effective strength of the wooden board. For each cone a so-called failure cone is defined (c). If an integration point in the failure cone reaches the failure criterion and its transverse tensile stress components reach a threshold f_{RT} (a), its volume is added to the failure volume of this cone (e). The first flattening of the resulting curve corresponds to the point of the first stress redistribution, which in reality is caused by the formation of cracks. Thus, the first peak of any curve is used to evaluate the point of failure, which can be used to back-calculate the effective strength.

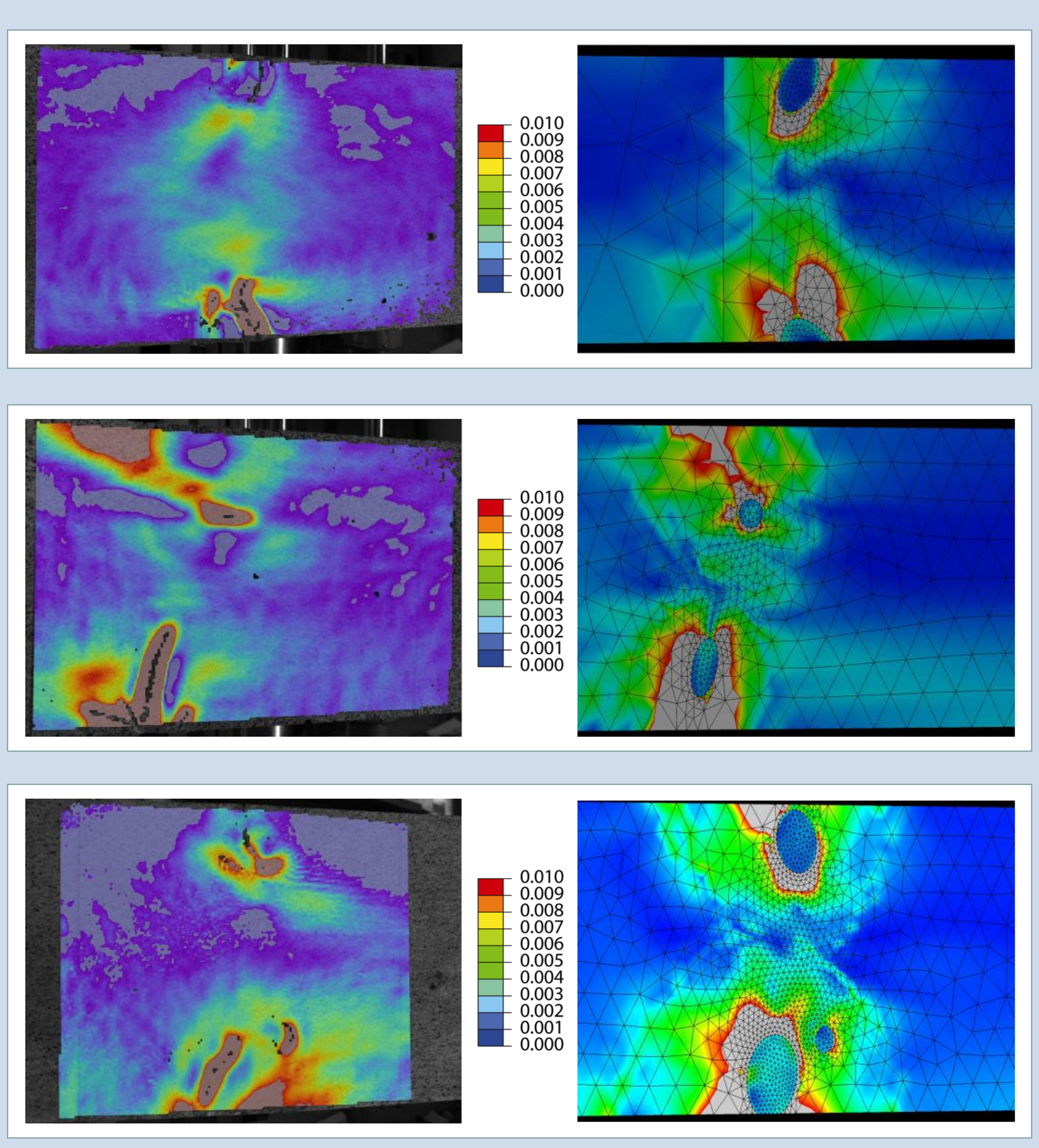






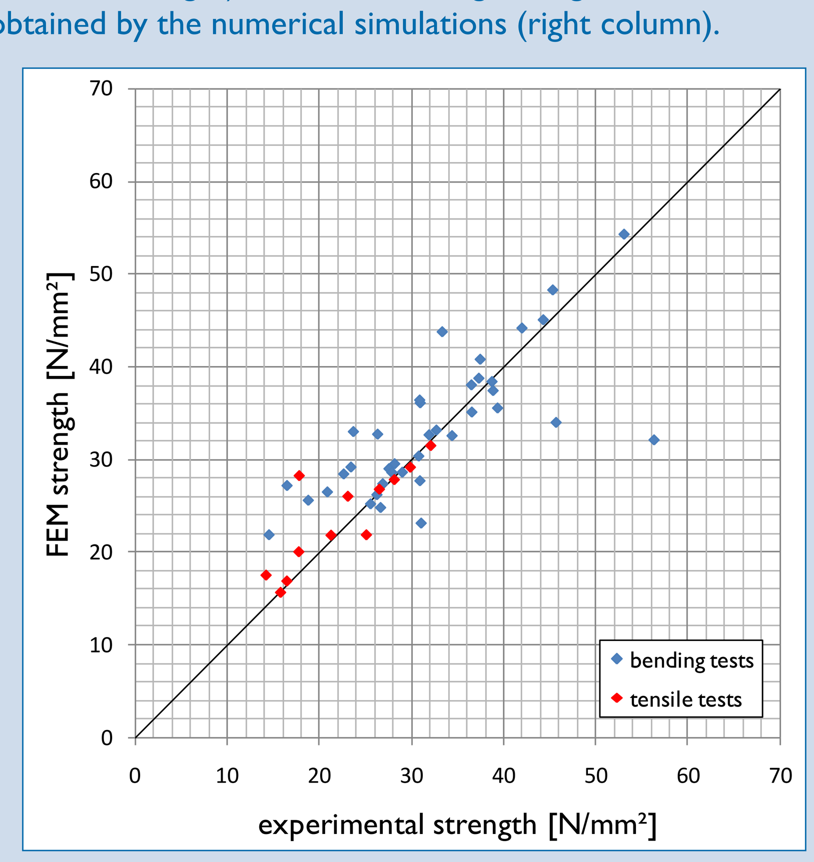


Results – Validation



Comparison of experimentally (left) and numerically (right) obtained strain fields

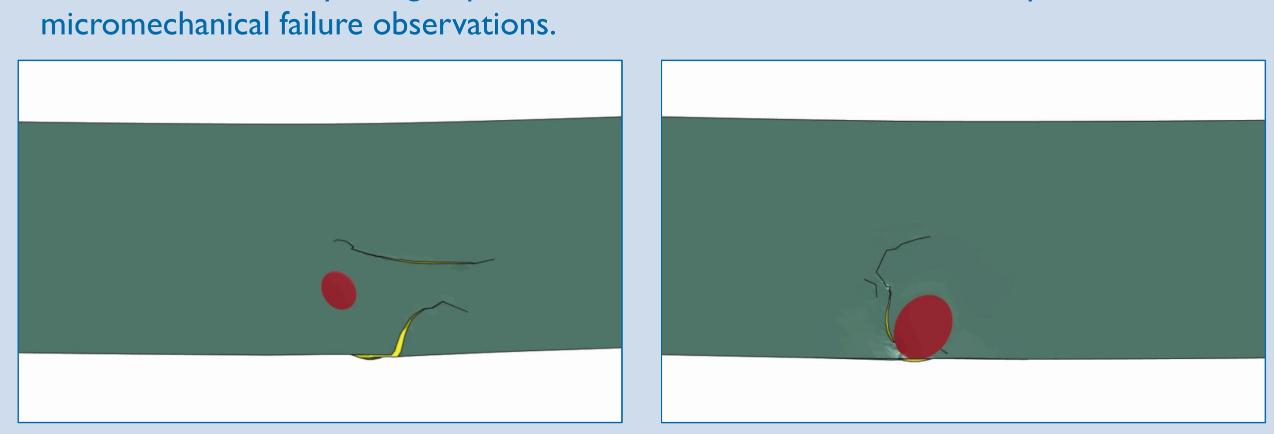
The global strength criterion was validated based on three different test series, with four different cross sectional dimensions. The boards were loaded up to failure in bending for the first two validation series and up to tensile failure for the third validation series. All boards were manually reconstructed for the numerical analyses. Compared to the experimental results, this criterion was found to be appropriate for the prediction of the effective strength of wooden boards. Furthermore, some experiments were accompanied by digital image correlation measurements (left column of images), which showed good agreement with the strain fields obtained by the numerical simulations (right column).



Summary & Outlook

A new model for the estimation of the effective strength of wooden boards was proposed and implemented into an existing numerical simulation tool for wood grading. The model is based on the formation of plastic zones in the vicinity of knots, whereas the plastic volume with predominant stress components in radial and/or tangential direction in such zones is assumed to climax at the point of failure.

In a next step a damage initiation criterion for orthotropic materials was adapted for wood and used in the framework of the extended finite element method (XFEM) to capture the main failure mechanisms up to the onset of global failure: the formation of cracks in the vicinity of knots due to tensile failure in radial and/or tangential direction and shear failure, respectively. First preliminary simulations show that reasonable results could be obtained by using sophisticated models for the crack development based on micromechanical failure observations.



Development of a crack (yellow) in the vicinity of a knot for a wooden board under bending load

References:
[1] Hackspiel (2010), Doctoral Thesis, Vienna UT
[2] Hackspiel et al. (2013), *Wood Sci Technol*, to be published
[3] Hofstetter et al. (2005), *Eur J Mech A/Solids* 24:1030-1053
[4] Foley (2003), Doctoral Thesis, Lund University
[5] Eberhardsteiner (2002), Springer Wien, New York

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