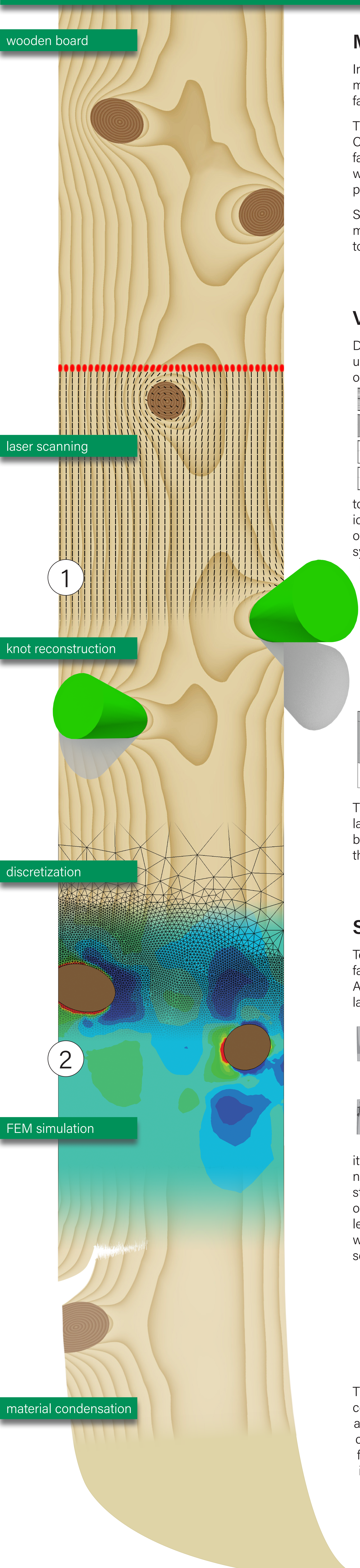
Simulation of failure mechanisms in wooden boards with knots as a basis for timber engineering design concepts

M. Lukacevic, J. Füssl, S. Pech, J. Eberhardsteiner

Institute for Mechanics of Materials and Structures, Vienna University of Technology (TU Wien), Austria

TECHNISCHE UNIVERSITÄT WIEN Vienna | Austria



Motivation and outline

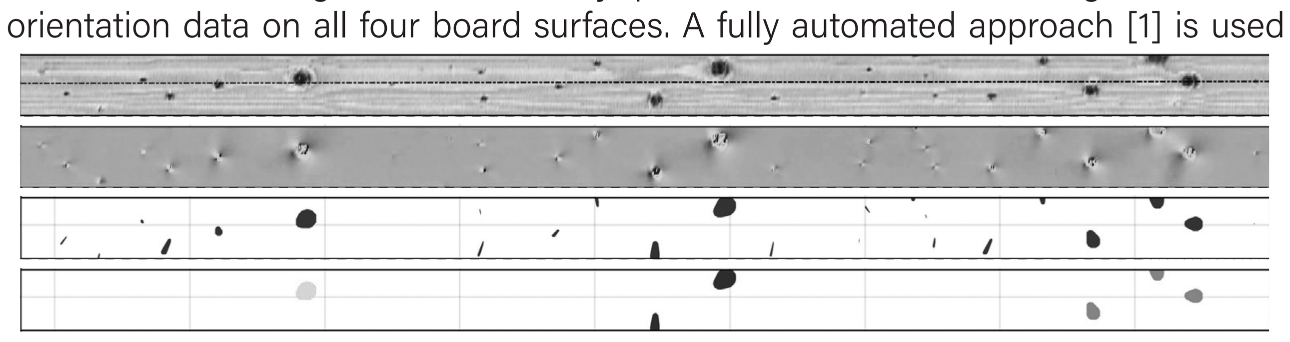
Increased use of wood has led to complex timber constructions and new types of wood-based products. In simulations, however, mainly simplified models are used to describe this material with strongly varying properties. Thus, to exploit the full mechanical potential of wood, a more accurate prediction of the mechanical behavior, especially when it comes to failure, is needed.

Therefore, we developed a multi-surface failure criterion, which is able to describe brittle and ductile failure mechanisms of wood, based on simulations on several length scales. Combined with a geometric reconstruction algorithm for knots, such a tool can be used to determine effective strength properties of knot sections. Due to the highly orthotropic failure behavior of wood and the strong variations of material directions close to knots, this task is very challenging. Widely used methods in fracture mechanics all have drawbacks when applied to such a material. For example, XFEM is limited by frequently occurring geometric incompatibilities, or the use of plasticity models easily encounters numerical problems due to the quasi-brittle nature of wood failure. Here, the emergence of the phase field method in recent years seems to be a promising solution for these problems.

Subsequently, such strength properties of wooden boards are condensed into so-called strength profiles. By applying this approach to a large set of wooden boards, probabilistic material models can be developed and used in simulations of wood-based products. Such a framework for sensitivity analysis and robust design optimization should help engineers to design efficient timber structures.

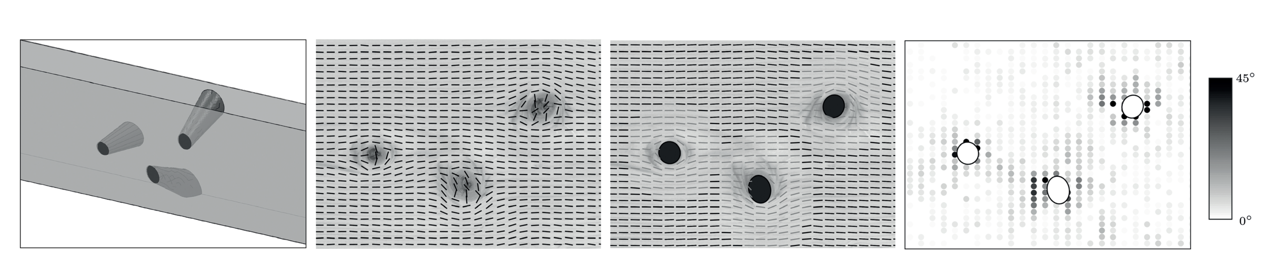
Virtual reconstruction (1)

During the strength grading process of wooden boards in sawmills, nowadays, the use of laser scanning devices is already quite common. This results in grid-like fiber orientation data on all four board surfaces. A fully automated approach [1] is used



to reconstruct the knot morphologies based on this data. This figure shows the identification of knot areas and subsequent division into knot sections after exclusion of insignificant small knots. The knots themselves are then modeled as rotationally symmetric cones. Their axes are found by iteratively connecting knot surfaces and minimizing previously defined knot measures. A simulated-annealing optimization scheme is employed to minimize the reconstruction error.

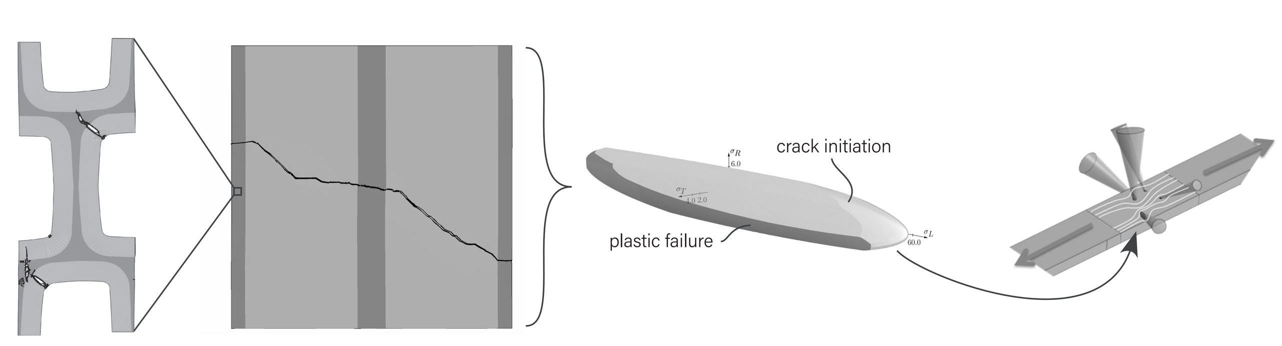
The reconstructed knot morphologies can now be used to calculate the local orthotropic material directions in any point of the board [2]. Following the so-called grain flow analogy, the longitudinal-tangential fiber directions can be determined by mimicking the trajectories of a laminar fluid flowing along the board axis, with knots as elliptical obstacles. The angle in radial-longitudinal direction is obtained from polynomials fitted to photographs of knot sections.



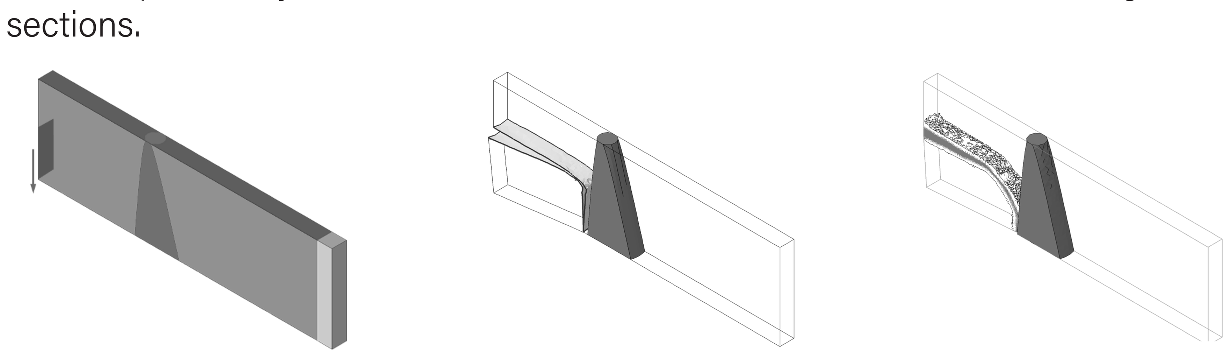
This figure shows a knot section, fiber deviations on the front surface, obtained by laser scanning and computed ones, respectively, and the comparison of both versions by plotting the absolute difference in fiber angles at the same locations illustrating the good agreement [3].

Simulation of wooden boards (2)

To simulate not only the elastic material behavior of knot sections but also their failure, a multisurface failure criterion for clear-wood was previously developed [4]. As the figure shows, this criterion is based on simulations of unit cells, representing late- and earlywood cells, respectively, up to the point of failure. This information



itself was then condensed into failure criteria, which were used in simulations on the next higher length scale, the annual year ring level. By determining the failure stress states for 1000 different loading conditions, a clear-wood failure criterion could be obtained, which consists of failure surfaces leading to crack initiation and others leading to plastic failure mechanisms. This criterion can now be used in combination with the previously mentioned fiber deviation model to simulate the strength of knot sections.

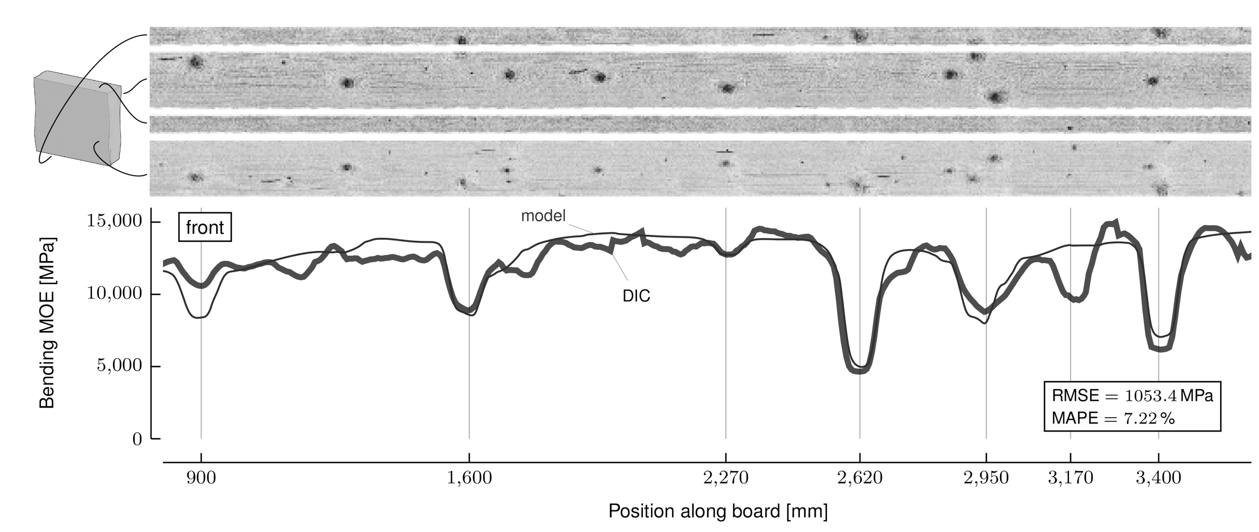


This figure shows such a simulation of a board section with a single knot. In the center image the XFEM is used to determine the fracture behavior in the vicinity of a knot, starting with perpendicular-to-grain failure close to the applied boundary condition, following the fiber course and ending parallel to the knot surface. But for more complex fracture surfaces, this method frequently encounters geometric incompatibilities and similar problems. Thus, we currently develop an orthotropic phase field method-based fracture model. The last image shows the promising results of this implementation for complex 3D failure surfaces.

Effective material profiles (3)

The detailed simulation of entire timber structures including all their local defects, like knots, up to the point of failure is most likely not feasible. But, by being able to compute the failure mechanisms of arbitrary sections of wooden boards, it is possible to consider the spatial variability and uncertainty of mechanical properties, in particular stiffness and strength, of single boards with effective material profiles.

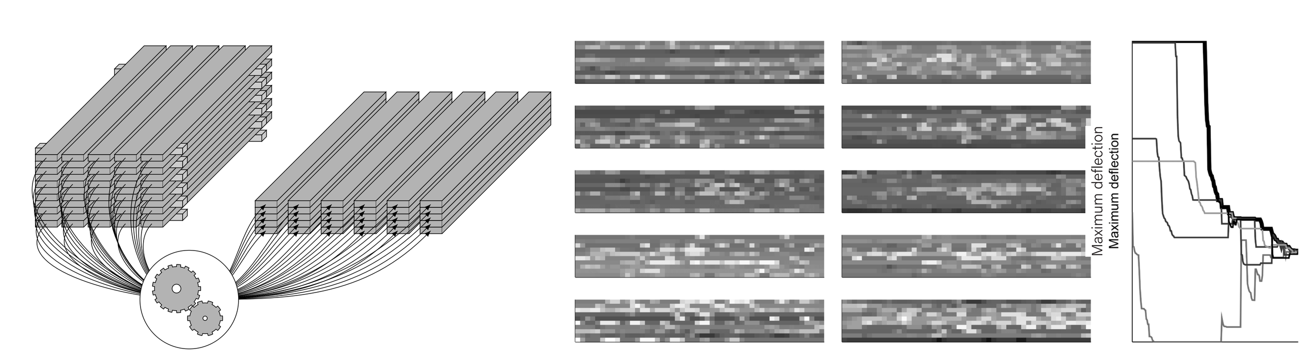
An example of such a condensed effective material profile is shown in the following image [3]. Here, bending stiffness profiles are compared for a board subjected to four-point bending. For the experimental profile, a strain field on the board surface was



computed by using digital image correlation measurements and by estimating the local cross sectional bending stiffness of the board with linear fits into the strain fields. For the numerical model results, the virtually reconstructed board with computed fiber deviations was subjected to the same boundary conditions in an elastic FEM simulation. This comparison shows the capabilities of our well-validated numerical simulation tool to capture even local effects accurately.

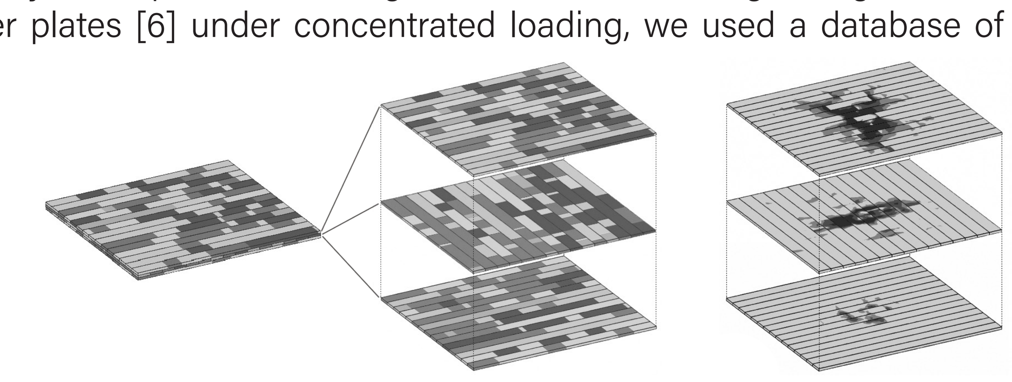
Application to wood products (4)

By running simulations of knot sections we are able to obtain effective material properties for them. One possible result of such calculations are piecewise constant profiles of the longitudinal stiffness of wooden boards. An application [5] of such profiles is pictured next. Here, the goal was to optimize the assembly of five glued laminated timber beams out of a stack of 50 wooden boards for which stiffness data



is available. The objective is to minimize the maximum deflection of all four-point loaded beams, which is achieved by using an iterative local search algorithm. The first column of beams shows the original assembly, with darker sections being of higher stiffness, and the second one the final optimized configuration with the minimized deflection.

To study the impact of inhomogeneities on the bending strength of cross-laminated timber plates [6] under concentrated loading, we used a database of longitudinal



strength profiles within numerical limit analysis simulations. The comparison of the calculated bending strengths of 50 arbitrarily assembled CLT plates to experiments showed the great potential of such an approach, which can easily be extended to stochastic timber engineering design concepts [7].

References

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