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Modelling of mechanical properties of wood and wood-based materials

PER JOHAN GUSTAFSSON

Keywords: Wood; fibre; material structure; modelling; simulation; finite element. FDK 81 : UDK 519.876.5

1. The concept of modelling

In a scientific context modelling requires a mathematical or theoretical description in order to reproduce or simulate certain physical properties, performances or a course of events. Given the wide range of disciplines involved there is a risk of misunderstandings between disparate areas of research, e.g. engineering and biology. The concept of the modelling of mechanical properties as used by forest scientists, timber engineers, wood scientists and technologists can have several meanings. The most widely used are probably the following:

- Statistical regression analysis: the development of a best-fit equation by means of empirical data. Such an equation shows how a parameter, e.g. the stiffness of clear wood, is affected by one or more other parameters, e.g. the density of the wood.
- Continuum mechanics' constitutive equations for the performance of a material. «Hook's law» is a simple example of such an equation. The material is assumed to be a continuous homogenous medium, which performs in a linear elastic manner with respect to deformation, i.e. showing proportionality between stress and strain, the constant(s) of proportionality being different for different materials and determined by experimental testing.
- Idealized and simplified mathematical definitions of quantities such as geometry, load and support of a structure.
- Equations and formulas derived from well-defined basic assumptions. Such equations are primary rational rather than empirical, although commonly including one or more parameters that must be determined by tests. An example is the explicit formula for calculating the stress in a beam, assuming validity of beam theory and linear elastic properties of the material. A further example is the ordinary differential equation for 1D moisture flow derived at the assumption of proportionality between moisture gradient and flow.
- Numerical simulations of the performance of a structure or a body. Such simulations are often carried out using the finite element method, which is a numerical method for solving differential equations. In turn, these differential equations represent a model (the so-called governing equations) of the structural performance and, consequently, are usually based on natural laws (the equations of equilibrium being very important in mechanics) and continuum mechanics equations (models) for the performance of a material and models for the geometry and the loading of the structure. The simulations may refer to mechanical quantities – stress, deformation or strain in the structure – or other physical quantities, such as moisture or temperature. The structure or body analysed may range from a large building to the micro-structure in a material.

The present examples of modelling are numerical simulations by means of the finite element method. They deal with material properties at various levels of scale. *Figure 1* shows the size hierarchy of wood as a structural material and as the raw material for wood fibre based materials. For the past decade, research done at the Division of Structural Mechanics at Lund University has included model development research studies of some materials and products in the two legs of the forest product industry indicated in the figure.

2. Micromechanical modelling of wood and fibre properties

Starting from the properties of the chemical constituents of a microfibril, PERSSON (2000) developed models for theoretical predictions of the stiffness and hygro-expansion coefficients of the cell wall layers. Then, starting from the cell wall properties, predictions were made of the properties of clear wood, made up of a large number of cells forming an annual ring. Such a chain of models makes it possible to identify the micro-

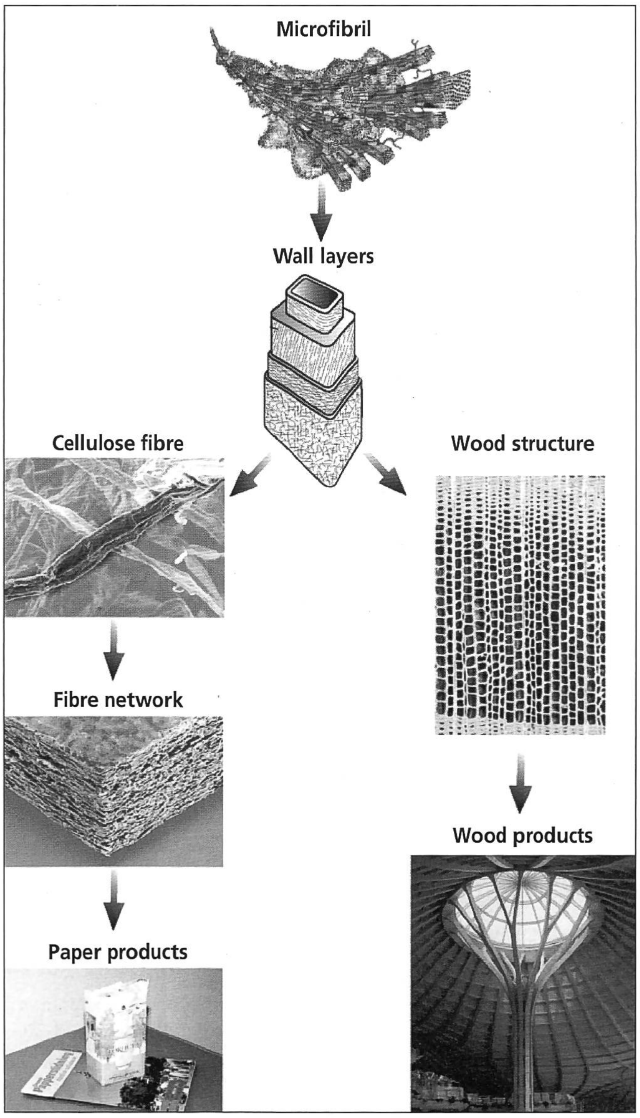

Figure 1: **Wood at different scale as the raw material for structural elements and fibre based products.**

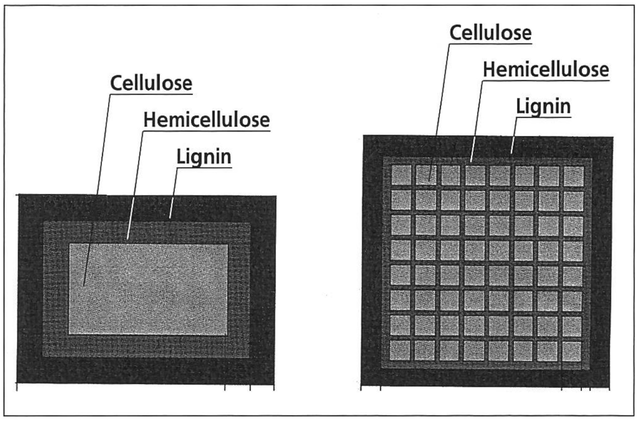

Figure 2: **Two models of the structure of the cross-section of a micro-fibril.**

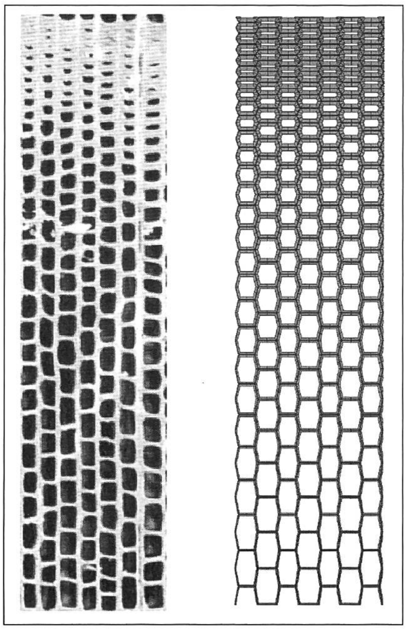

Figure 3: **A micrograph and a finite element model of fibers forming a growth ring.**

scale parameters that influence the material performance at the macro-scale, where wood is regarded as a homogeneous material.

Figure 2 shows two different geometry models of the cross-section of a microfibril, assumed to be built of three constituents, each having known properties in terms of orthotropic linear elastic properties, defined by the nine elasticity parameters and the three hygro-expansion parameters of such materials. The properties of a cell wall layer, regarded as a homogeneous continuum, were obtained by analysing the stiffness properties of an assembly of microfibrils using the finite element method and a homogenization method for periodic three-dimensional structures. The properties of a cell wall layer will be effected by the volume fraction of the constituents and the orientation of the microfibrils in the cell wall layer.

Knowing the properties of the cell walls, each fibre was assumed to be built of three layers: the thin, inner S3 layer, which may have a significant slope of the microfibrils, the thick S2 layer and a third layer representing the S1 layer, the primary wall and the middle lamella. The thickness of the cell wall layers, as well as the total cell wall thickness and the shape of the cross section of a cell, were assumed to vary within an annual ring according to microscope observations. In the modelling of the geometry of the cells we analysed both uniform geometries and geometries with irregularities. *Figure 3* shows a picture of an annual ring of softwood, together with the geometry of a finite element model. The finite element model is a three-dimensional model, where each cell is represented by a number of solid elements.

Knowing the variation in wood density from pith to bark of and the microfibril angle in the fibres, it is possible to analyse how the stiffness and hygro-expansion properties vary within a tree with micro-to-macro modelling. The right-hand side of *Figure 4* shows computational results of the hygro-expansion coefficient in the radial, tangential and longitudinal direction of clear wood. Corresponding experimental results are shown on the left-hand side. The results are valid for Norway spruce with moisture content of approx. 12%. The experimental results relate to samples from 11 trees and three different

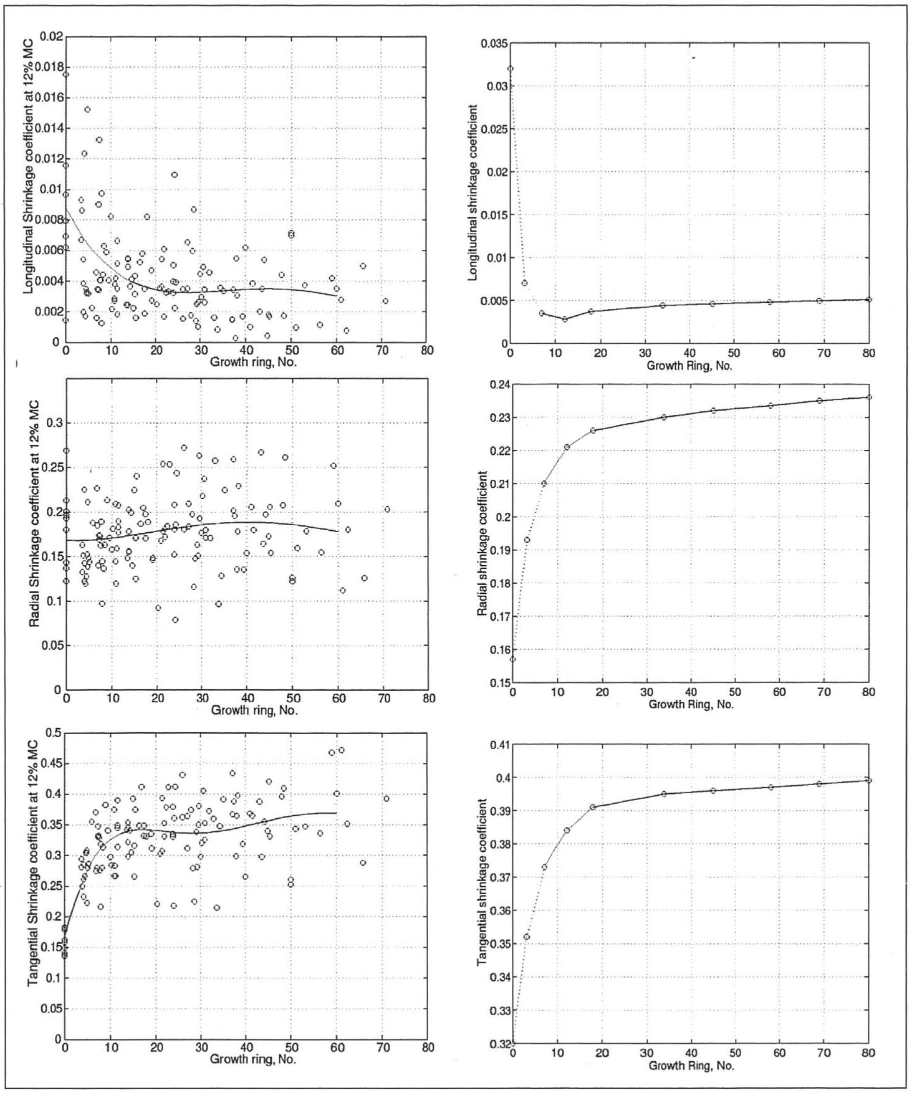

Figure 4: **Experimental (left) and calculated (right) hygro-expansion coefficient in longitudinal, radial and tangential direction versus number of growth rings.**

Figure 5: **Free deformation of fibers during drying.**

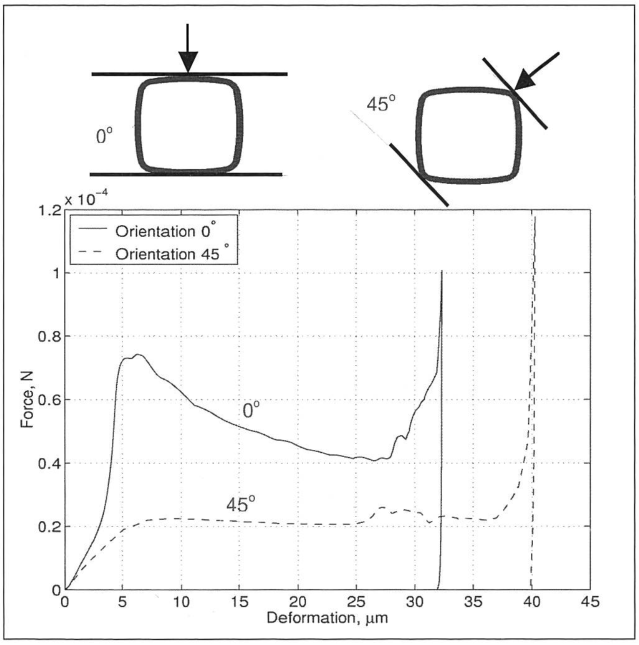

Figure 6: **Force versus deformation during squeezing of fibers.**

heights of each tree. The curves in the diagrams on the left are best-fit-curves drawn according to the experimental results.

Figure 5 and *6* show results from two other finite element simulations of the performance of fibres, both from PERSSON 2000. *Figure 5* shows the free deformation (twist) of fibres when dried from 30% to 0% moisture content. The right-hand side fibre is a collapsed fibre of the type found in paper. The colours or darker/lighter areas illustrate the magnitude of the stresses that develop within the fibre during the drying process. The diagram in *Figure 6* shows calculated load versus deformation during compression and collapse (squeezing) of fibres when loaded perpendicular to its length axis. Such deformation of fibres is a part of the pulp and papermaking process. Different amounts of energy are needed for the deformation, depending on the direction of the load.

3. Modelling of drying distortion of boards

Timber structural elements show moisture induced shape instability. A certain proportion of sawn boards delivered to a building site are usually distorted during the timber drying process, sometimes to such an extent as to render them useless for the foreseen purpose. The magnitude of the distortion varies greatly for different boards. To study the development and magnitude of distortion induced by the drying process, ORMARSSON (1999) developed a finite element simulation model. Material property parameters effecting the distortion were surveyed and experimental verification carried out of the theoretical simulation. The work was part of a European research project, partly reported by DAHLBLOM *et al.* (2001).

In the simulation the wood was regarded as a continuous orthotropic material with varying material orientation and properties within the board. The material orientation at any given point was measured according to the spiral grain angle and growth ring orientation, which were determined by distance to the pith and the location and orientation of the board in relation to the pith of the log. The material properties in terms of elastic stiffness parameters and shrinkage coefficients were determined by distance to the pith of the log. The material performance model assumed the strain at any point to be the sum of elastic strain, shrinkage strain and mechano-sorptive strain.

In addition to the material and geometrical data, the simulation input (cf. *Figure 7)* includes the moisture distribution during the drying process. This distribution was obtained by separate moisture flow finite element analysis. The simulation method was verified by means of test results from almost 700 boards originating from 274 spruce trees in 29 stands in Finland, Sweden, Germany, France and England. *Figure 8* shows two examples of calculated drying induced distortion of boards.

The actual simulation model has also been used to calculate the drying distortion of green-glued structural elements (ORMARSSON 1999). *Figure 9* shows beams made up of four parts of a log, glued together to form a beam with a centre hole. It is clear that the twist distortion can be significantly reduced by appropriate orientation of the glued parts.

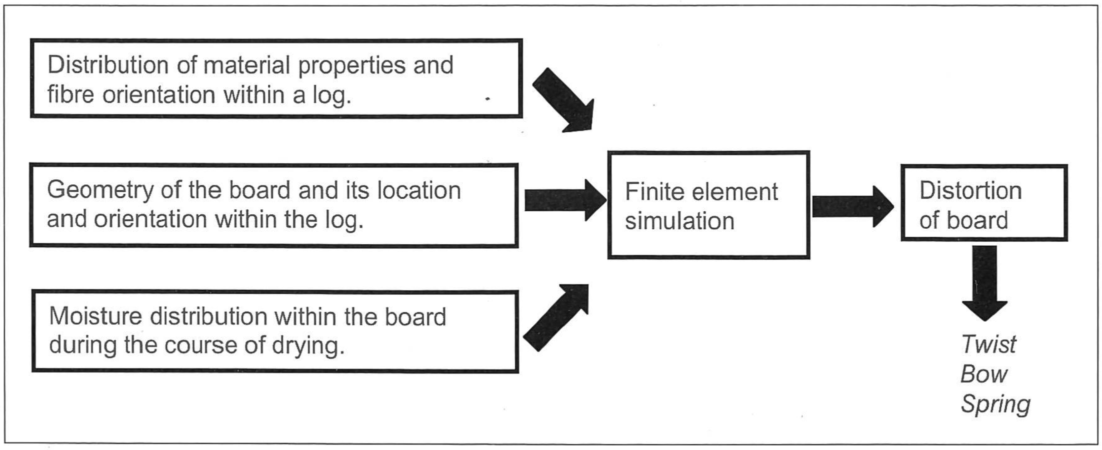

Figure 7: **Finite element simulation of drying distortion of boards.**

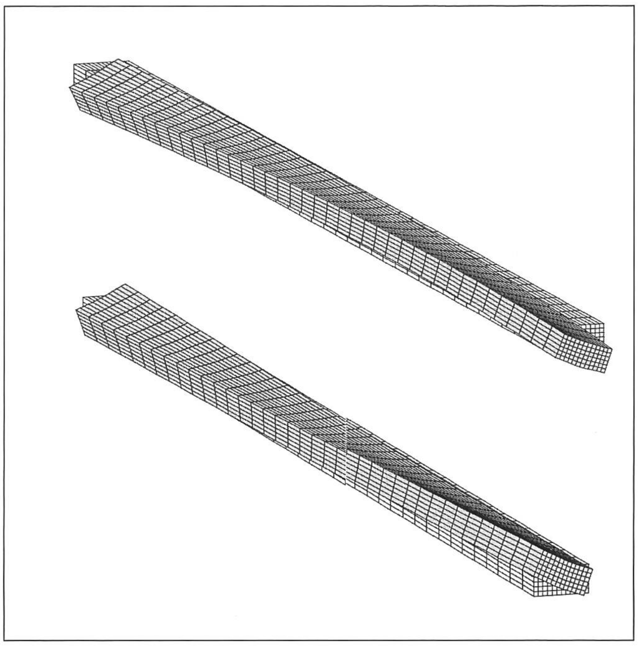

Figure 8: **Drying distorted boards.**

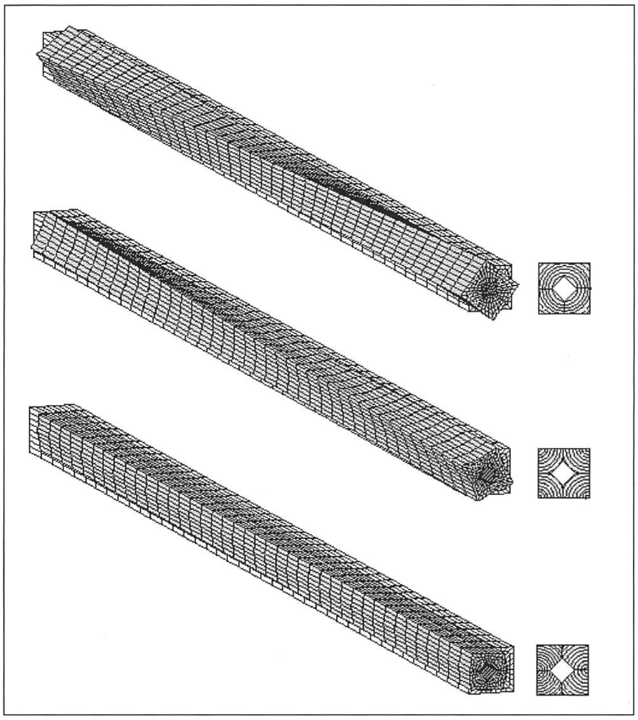

Figure 9: **Drying distorted green-glued structural elements.**

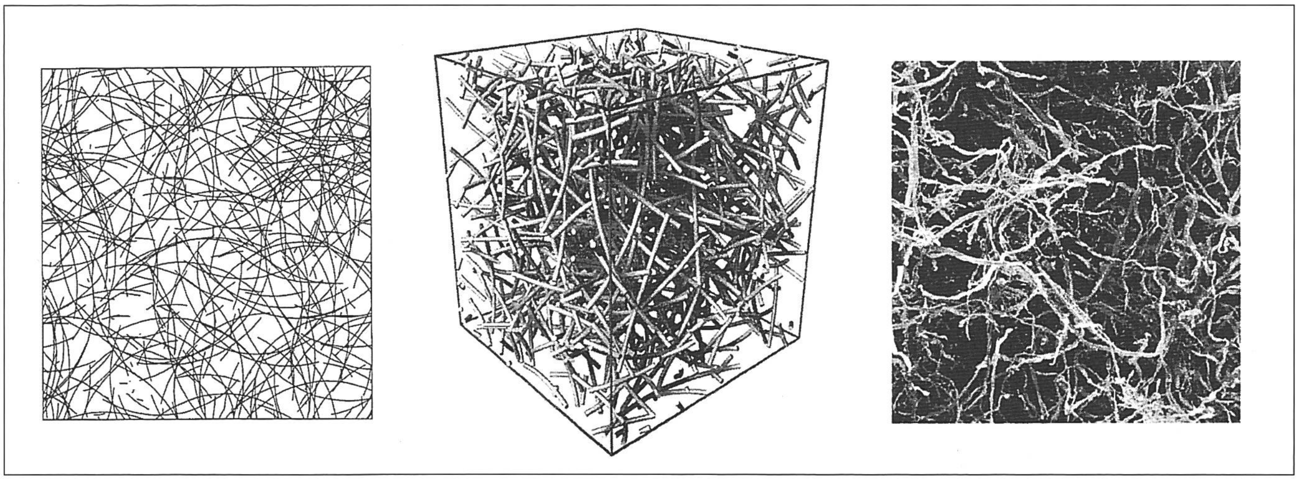

Figure 10: **A 2D model, a 3D Model and a micrograph of a fluffy material.**

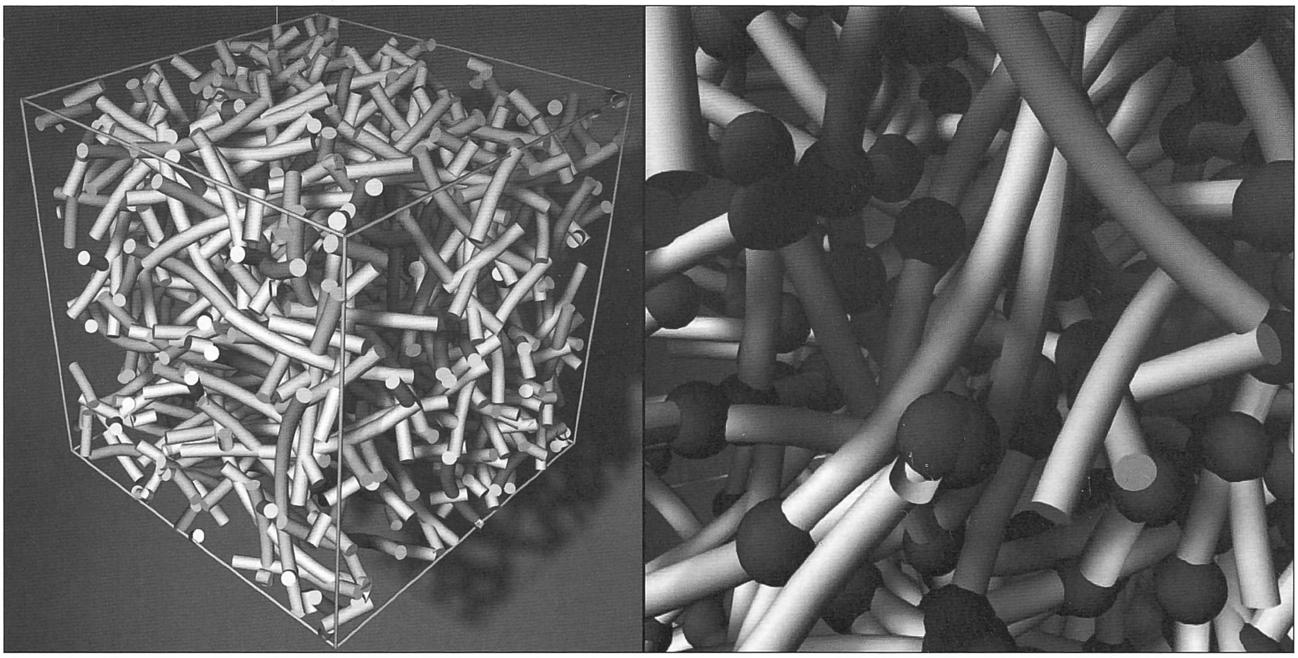

Figure 11: A material structure cell (left) and enlargement showing the fibre-to-fibre linkage elements.

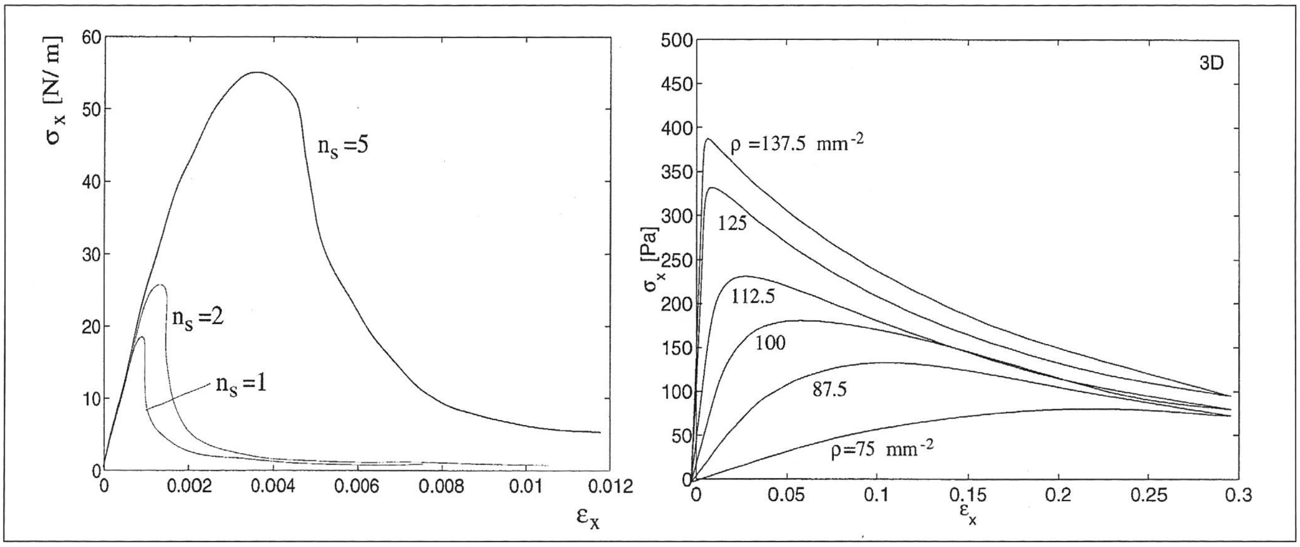

Figure 12: **Calculated global stress versus strain curves for fluffy material with various fibre-to-fibre ductility (left) and various fibre network density.**

4. Modelling of fluffy materials

Dry-shaped cellulose fibre based materials are used in the production of hygiene products, such as diapers, or for insulation. The mechanical performance, in particular the strain instability and localisation during fatigue, damage and fracture is important when used in diapers. To enable studies of the mechanical performance, finite element simulation models of the material structure were developed (HEYDEN 2000).

Figure 10 shows a micrograph of a fluffy material (right). To the left, there is a two-dimensional model and in the middle, a three-dimensional model. The fibres are represented by curved beam elements in the finite element simulations. The fibre-to-fibre interaction where fibres are in touch is represented by linkage elements with friction stick-slip deformation properties. The geometry of the simulated material structure is randomly generated, taking any prescribed fibre orientation distribution, fibre length distribution, fibre curl and network density into account. Since the structure is stochastic, several nominally equal structures are generated and analysed, making it possible to evaluate average and scatter in the mechanical property to be studied. Studied properties include the elastic stiffness matrix, strength, fracture energy, course of fracture and the global non-linear stress versus strain performance. These properties were determined by calculating the structural response to external load or prescribed normal and/or sheer deformation in one or more directions.

The area or volume of the cell of material under observation is very small, the side length of the cell typically being only one or a few times the length of a fibre. However, the structure's loading response is due to use of periodic geometry and cyclic loading conditions valid for a piece of material of an infinitely larger size. The periodic geometry means that a cell exactly fits all neighbouring cells in an infinitely large structure, all cells having the same geometry. The cyclic boundary conditions mean that there is equilibrium and geometrical fit at every point of the cell boundaries, even when structure is loaded.

Figure 11 shows a 3-D representation of a material cell with an enlargement on the right-hand side showing the linkage fibre-to-fibre finite elements. Examples of computational results are indicated in *Figure 12.* The curves show global stress versus strain of simulated material structures. They were obtained from the reaction force in the x-direction acting on the structure when subjected to incremental increase of elongation in the x-direction. The diagram on the left shows the influence of the fibre-to-fibre linkage properties when the strength of the connection is kept constant but the ductility varied. The diagram on the right shows the effect of the fibre network density, defined as total length of the fibres per volume of material. We found that a fairly small increase of the density can significantly increase the strength of a more brittle failure performance, indicated by a steeper slope of the curve during the damage process when the stress is decreased.

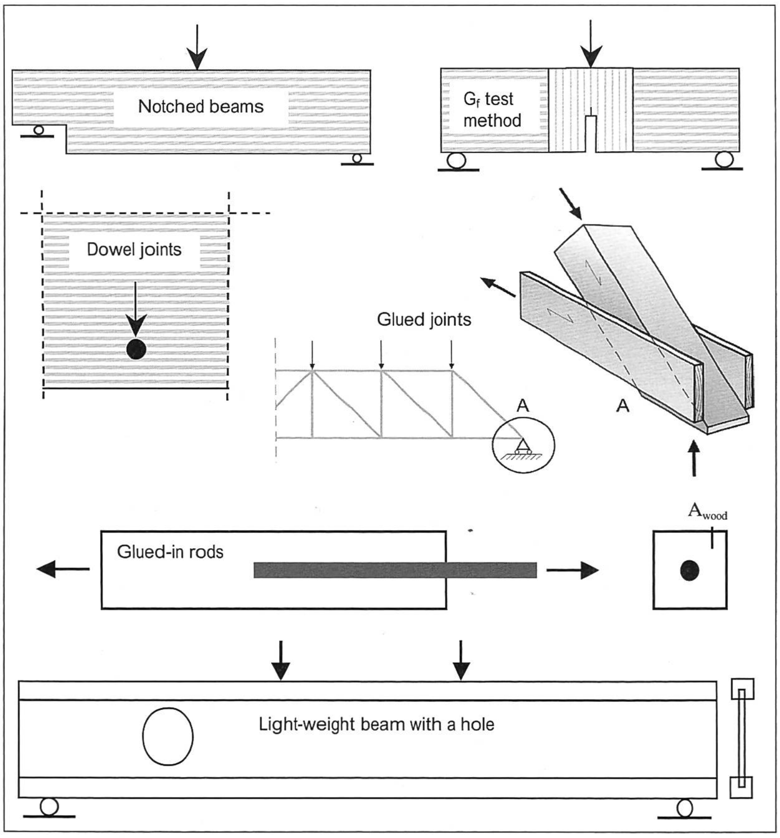

Figure 13: **Structural elements and a test specimen analysed by fracture mechanics modelling.**

5. Concluding remarks

The above examples of modelling represent numerical simulations by means of the finite element method. In line with a seemingly unlimited increase in computing power, it has become possible to develop more advanced modelling. A powerful computer, however, does not guarantee good simulations. Access to accurate constitutive material models to mathematically define mechanical properties and performance at a specific «point» or in a small volume of the material are vital in producing good simulations. In addition it is necessary to have good descriptions of the actions in terms of loading and climatic conditions, as well as the build and geometry of the structure to be analysed, be it a material structure, the structure of some product or a building structure. This means that there is demand for experimental tests and observations to provide both input data and data for verification. It is to be expected that the purpose, demands and methods of experimental research will be significantly affected by the ongoing development of methods for rational theoretical modelling.

The modelling examples described above focused on the deformation analysis of materials. To complete the picture to a certain extent, *Figure 13* shows examples relating to the strength and the fracture analysis of structural elements. The elements shown were analysed using fracture mechanics, employing either finite elements or various kinds of beam theory as tools for the calculations. By using rational fracture mechanics modelling based on energy balance equations instead of relying only on compilations of experimental strength data, the available experimental data can be used much more generally. In addition attention is drawn to certain phenomena, which is not always the case when using only empirical data. One such phenomenon is the size effect in load capacity when structural geometry leads to stress concentration instead of uniform stress distribution. Another similar phenomenon is the dualism between material strength and material fracture toughness as decisive for the load bearing capacity of a structural element. The examples in *Figure 13* are taken from MORRIS *et al.* (1995), SERRANO (2000), GUSTAFSSON & LARSEN (2001), GUSTAFSSON *et al.* (2001) and GUSTAFSSON (2003).

Summary

Modelling is a wide concept. This paper describes various meanings of modelling in relation to mechanical properties of wood and wood-based materials. Three examples of modelling by means of the finite element method, presented in recent years in PhD theses, are used as reference points. They relate to modelling of the micro-structure of wood and its mechanical properties, modelling of drying-induced distortion of boards and modelling of the micro-structure and properties of dry-shaped cellulose fibre materials. The paper concludes with remarks on some studies relating to fracture simulations, strength modelling and glued joints.

Zusammenfassung

Modellierung mechanischer Eigenschaften von Holz und Holzwerkstoffen

Das Konzept der Modellierung ist breit gefächert. In diesem Aufsatz werden zuerst verschiedene Bedeutungen von Modellierung bezüglich mechanischer Eigenschaften von Holz und Holzwerkstoffen aufgeführt. Danach werden drei Beispiele von Modellierung anhand der Finiten-Element-Methode genannt, die in kürzlich erschienenen Doktorarbeiten präsentiert wurden. Diese Beispiele beziehen sich auf die Modellierung der Mikrostrukturen von Holz und deren mechanischen Eigenschaften, die Modellierung von durch Trocknung hervorgerufenen Verformungen von Brettern und die Modellierung von Mikrostrukturen und Eigenschaften von trocken geformtem Zellulose-Fasermaterial. Einige Studien bezüglich Bruchsimulationen, Modellierung von Dauerhaftigkeit und verleimten Verbindungsstücken werden in einer abschliessenden Bemerkung erwähnt.

Résumé

Modélisation de propriétés mécaniques du bois et de matériaux dérivés du bois

Le concept de modélisation est vaste. Cet article traite tout d'abord de divers sens qui sont donnés au concept de modélisation en relation avec les propriétés mécaniques du bois et de matériaux dérivés du bois. Trois exemples de modélisation par la méthode de l'élément fini, tirés de thèses de doctorat récentes, sont ensuite abordés. Ces exemples se rapportent à la modélisation de la structure microscopique du bois et de ses propriétés mécaniques, à la modélisation de la déformation de planches due au séchage, enfin à la modélisation de la structure microscopique et des propriétés de fibres de cellulose travaillées à sec. D'autres études se rapportant à la simulation de ruptures, à la modélisation de la résistance et aux joints collés sont mentionnées en conclusion.

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