A NEW EXPERIMENTAL TECHNIQUE FOR DETERMINING THE FRACTURE ENERGY OF WOOD UNDER MODE II LOADING CONDITIONS

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ABSTRACT

Wood is a highly optimised natural composite material suitable for a number of different applications. Its orthotropic and inhomogeneous structure and non-linear behaviour during fracture leads to various differences in a fracture mechanical description compared to other materials. This study presents a new experimental technique for recording the complete load-displacement diagram for mode II loading conditions under stable crack-propagation. It allows the determination of various fracture mechanical parameters including stiffness, strength and specific fracture energy as well as an assessment of the fracture behaviour until complete separation of the specimen. The experiment is suitable for any crack propagation system in wood and requires only few raw material for specimen preparation which is advantageous for statistical significance and can be performed on any conventional testing machine. The experimental data of a first test series performed on spruce wood (*Picea abies* [L.] Karst.) in the RL (radial-longitudinal) direction is presented and compared with results in literature. The "size effect" is taken into consideration. Based on the experimental fracture mechanical data and fractographic observations in a light microscope and an Environmental Scanning Electron Microscope (ESEM) some basic principals of mode II fracture in wood are discussed and compared to other loading cases.

KEYWORDS

spruce wood, mode II loading, orthotropy, specific fracture energy, stable crack propagation, damage zone;

INTRODUCTION

Wood is a highly optimised and complex material being a multi-level fibre composite mainly consisting of tubular cells of 3-4 mm length and about 30 μm diameter oriented in the longitudinal direction of the stem. Seasonal differences in vegetation are causing repetitive gradual changes of the fibre-properties which are forming growth rings in the stem. The growth rings are causing a structure of cylindrical orthotropy with three principal directions termed L (longitudinal, along the axis of the stem), R (radial) and T (tangential). In terms of a mechanical and fracture mechanical description anisotropy, hierarchic and cellular structure cause substantial differences compared to metals or artificial composite materials and require the modification of established concepts for describing fracture and crack propagation especially those using LEFM principles [1, 2, 3]. Recording the load and displacement data for a fracture mechanical experiment under conditions of stable crack propagation was found to be a very powerful method to investigate the fracture behaviour of wood. Material parameters like elasticity, fracture toughness or global strength as well as the energy consumed during the fracture process can be derived from the load displacement curves. Especially the determination of energy portions assigned to the different phases of crack propagation provides useful information about the fracture process itself.

To obtain load and displacement data it is necessary to apply experimental techniques which guarantee stable crack propagation until the complete separation of the specimen. For the mode I loading case a experimental technique was developed and applied to obtain fracture mechanical data for several wood species [4]. There is less information about in plane shear fracture of wood and only a few studies dealing with stable crack propagation under mode II loading conditions are available in literature [5, 6, 7]

The aim of this study is to present a new experimental procedure to record load and displacement data of fracture mechanical experiments on spruce wood (*Picea abies* [L.] karst.) under mode II loading conditions until ultimate fracture. The results of a first test series are described and some principal differences between mode I and mode II fracture are discussed.

EXPERIMENTAL TECHNIQUE

Specimen

A new technique has been developed using a notched bending beam (NBB) specimen as shown in Figure 1a. A beam fixed on one side and supported on the other is loaded by a single load close to a necked down cross section close to the support generating a vertical shear stress. After applying a sufficiently high vertical force a crack will start propagating throughout the cross section (ligament) until the pieces are separated. The fixed part is generating an elastic bending moment acting against the applied load which is preventing a too fast transfer of the energy elastically stored in the specimen and therefore supporting slow and stable crack propagation.

The experiments were performed on a conventional material testing machine which was equipped with the devices for fixing the beam at constant cross head displacement rates. Force and displacement are measured with a load cell and linear displacement sensor and recorded on a PC for later evaluation.

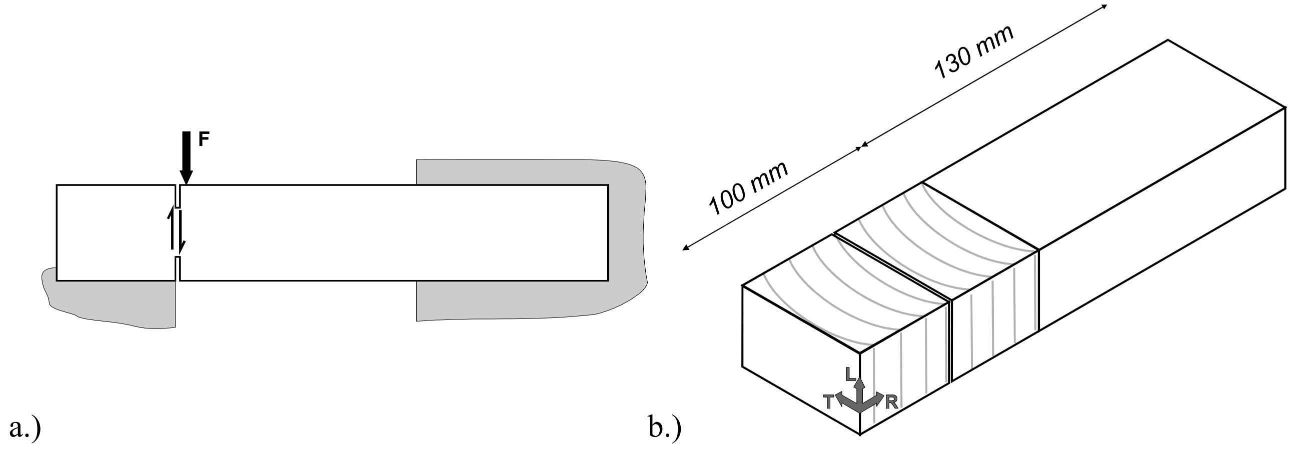


Figure 1: (a) Principle of the notched beam specimen; (b) geometry of the notched beam specimen consisting of a bending part and a notched specimen part

The NBB specimen is made of two parts of clear spruce wood and has a total length of 230 mm and a cross section of 60 × 40 mm. The actual specimen part is 100 mm long and shows a RL crack propagation system where the first letter (R) indicates the direction of the crack plane normal and the second one (L) indicates the direction of crack propagation. The 130 mm long bending part is glued to the specimen part as shown in figure 1b. The rectangular ligament was cut with a band saw shortly before performing the experiment.
All pieces were obtained from a conventional board with an average density of 440 kg/m³ and stored until testing in an environment of 22°C and 60% relative humidity.
Tests with four different rectangular ligament areas between 400 and 720 mm² were performed.. Additional test series were carried out with a trapezoid ligament of 1.300 mm² to investigate the influence of ligament shape on the characteristic parameters. To obtain significant results when experimenting with wood an adequate number of experiments is required. Therefore the comparably low amount of raw material needed for these test series is advantageous. The number of replications for these tests was chosen to be eight for each of the five tested ligament geometries.

RESULTS

Load-displacement diagrams

Figure 2 shows an example for a typical load-displacement diagram. The upper curve represents the measured data for a sample of 720 mm². It includes also the load which is carried partly by the bending beam and doesn't influence the fracture process itself but need to be considered before analysis. To obtain the net load-displacement curve the elastic load-displacement behaviour of the beam was measured separately after the experiment and subtracted from the original data. The negative values for load and displacement are indicating compressive loads during the experiment.
At the beginning of the experiment the notched beam bending specimen shows a linear elastic behaviour followed by a short phase of non-elastic behaviour indicated by some deviation from the straight line before reaching the maximum load. After passing the maximum load some further energy consumption appears which is accompanied by a steep decrease of load and finally the complete fracture of the specimen as soon as the load reaches a plateau value. This plateau is caused by friction between the fractured surfaces which is still transmitting load between the two already separated specimen parts.

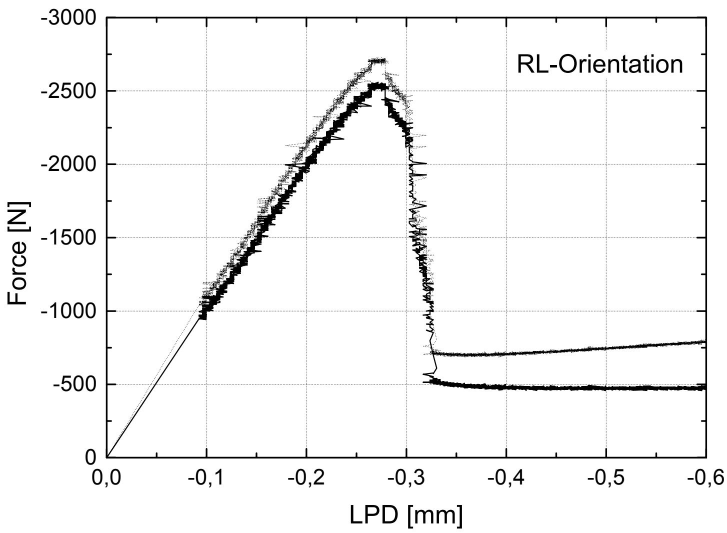


Figure 2: Typical load/displacement diagram showing original (upper curve) and net data (lower curve)

Fracture mechanical parameters
Analysing the load displacement curves several mechanical and fracture mechanical parameters can be derived. Among these the specific fracture energy is the most important one. It represents the total energy consumption during the fracture process related to the created fracture area and is determined according to Eqn. 1

$$G_f^{II} = \frac{1}{A_{lig}} \int_0^{LPD_{end}} F(LPD)dLPD\,. \tag{1}$$

Where A_{lig} is the ligament area and *F(LPD)* indicates the load versus load-point displacement. Although this characteristic parameter is related to the ligament area there are significant differences for the tested series showing an increase with growing fracture areas and a decrease for the biggest but trapezoid-shaped ligament (Figure 3).

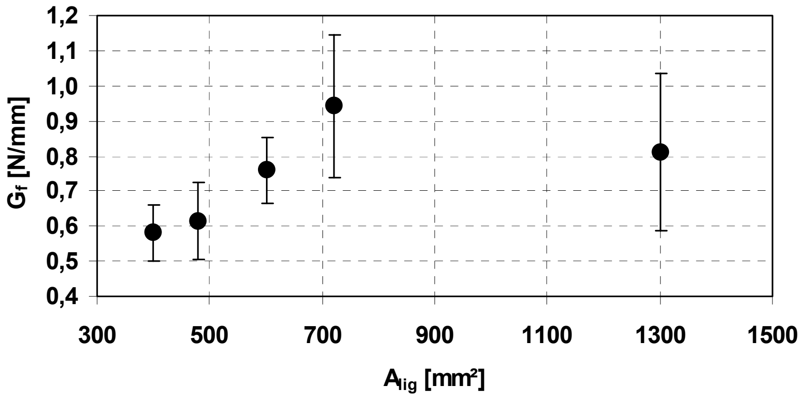


Figure 3: Specific fracture energy (G_f^{II}) versus Ligament area (A_{lig}).

DISCUSSION

Comments on testing method, Relevance of results
The results of this study demonstrate that the NBB specimen is appropriate to determine the characteristic parameters for mode II fracture mechanical experiments. The experiment is advantageous especially in comparison with other systems proposed in literature [4,5] because of its low consumption of raw material and its applicability for all six crack propagation systems in wood using the same geometry.

The decrease of load after passing the maximum load is sufficiently slow to collect enough data in this phase and to call crack propagation sufficiently stable and the specific fracture energy together with other fracture mechanical parameters can be calculated. Figure 3a shows the mean value of the specific fracture energy for all test series performed in this study compared to some results for spruce wood reported in the literature. (The results reported from Aicher *et al.* [7] vary depending on the evaluation method chosen for the experiment.)

The average specific fracture energy of 0,74 N/mm obtained in this study seems to be reasonable in comparison to other experiments especially regarding the comparably low ligament areas which have been considered for the mean value of the test series. In spite of the partly substantially bigger ligament areas of some of the experiments, the G_f^{II}–values of 0,94 N/mm and 0,81 N/mm for the biggest tested ligaments in this study are clearly in the range of the reported values which supports the assumption that the specific fracture energy is size independent for ligaments greater than 1.000 mm. However, a detailed investigation of this phenomenon has still to be done.

Compared to the other loading cases spruce wood fractured under mode II loads shows an about three times bigger specific fracture energy than under mode I loads whereas it is about 60% of G_f under mode III loading conditions (Figure 3b). The higher specific fracture energy indicates a less efficient fracture process for mode II cases compared to mode I fracture which can be seen also from the ESEM photographs of a mode II fracture surfaces. extruded fibres and parts of the longitudinal tracheids cover the surface and indicate substantial intracellular structural damage whereas mode I fracture surfaces were found to be smooth and less hairy [5]. The possible differences are discussed in the next paragraph.

Mode II fracture behaviour of wood

The fracture process of wood under mode II conditions is different to mode I loading conditions. In the later case the applied load generates a zone around the crack tip where the local material strength is exceeded and damage occurs. In this damage zone several micro cracks are formed and weaken the material until some of those micro-cracks join and form a macroscopic crack which is propagating. The damage zone has a finite extend and therefore a distinct crack tip within this volume cannot be determined exactly in wood which makes the application of conventional fracture mechanic concept very difficult. The formation of micro-cracks is an energy dissipating process and the amount of generated micro-cracks as well as the dissipated energy is proportional to the extension of the damage zone. Increasing loads cause macro-crack propagation and therefore a permanent shift of the damage zone into zones of lower stresses and intact material forming a band of weakened and damaged material beside the macroscopic crack path.

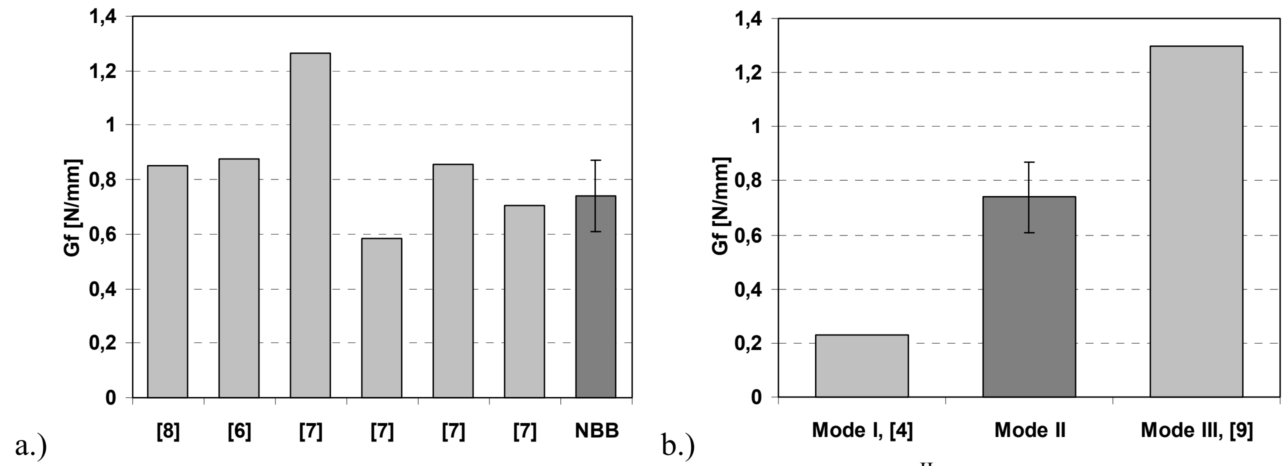
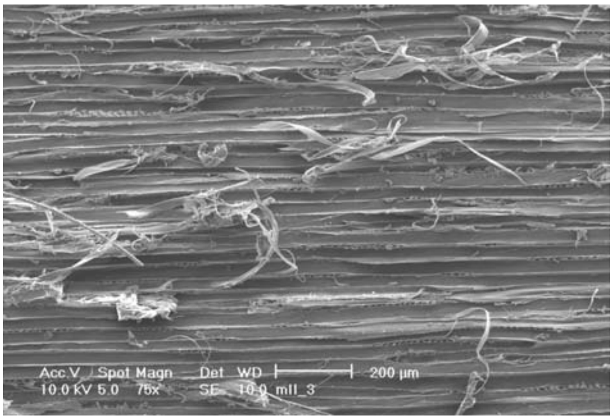


Figure 4: (a) Comparison of overall mean specific fracture energies (G_f^{II}) obtained by NBB specimens with values for spruce wood reported from literature [numbers]. (b) Mode II specific fracture energy (G_f^{II}) related to mode I and mode III loading conditions

In the mode II loading case the shear stresses along the complete ligament plane and not only in a small zone in front of the crack tip occur. The local material strength is exceeded in a much bigger volume ahead of the crack tip and micro-cracks are forming simultaneously in a much bigger damage zone now. It is also possible that additional macro-cracks are formed at different positions by those micro-cracks and growing independently of the actual macro-crack like shown in Figure 4b. Stanzl-Tschegg *et al.* [10] performed FEM analyses on mode II specimens for orthotropic materials and found the distribution of Mises equivalent stresses concentrated along the ligament which supports the assumption that the damage zone is elongated around the ligament plane.

The assumption of sudden and simultaneous wide spread damage in wood under mode II loads explains the steep load decrease after passing the maximum load in the load–displacement diagram. Once several micro-cracks exist the resistance for crack propagation is lowered drastically and the specimen can be separated easily contrary to the mode I loading case where a remarkable amount of energy is consumed during this last phase of crack propagation. Beginning with the deviation from the linear elastic behaviour a complex fracture process is initiated where the various occurring effects do not appear necessarily in a sequential manner but happen simultaneously and de-localised.

a.) 

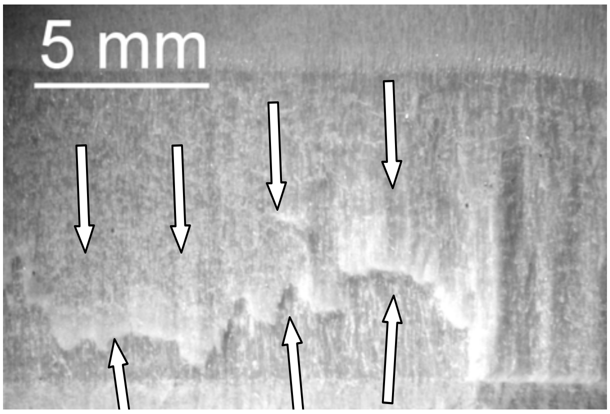
b.) 

Figure 4: (a) ESEM image of mode II fracture surface of spruce wood; (b) Light microscopical image of mode II fracture surface. The arrows mark contrary crack propagation directions in different fracture planes.

CONCLUSIONS

A new testing method to study the fracture behaviour of wood under shear loads was developed and applied for a first test series on spruce wood in RL orientation.

Characteristic fracture mechanical parameters can be determined from the load-displacement diagrams recorded under sufficiently stable crack propagation. The specific fracture energy (G_f^{II}) can be calculated and shows results of 0,74 N/mm which is in reasonable accordance with values reported in the literature.

The mode II fracture process consumes more energy than the mode I case. The damage zone under mode II conditions is much bigger and extended along the ligament especially in an orthotropic material like wood. The mode II fracture process needs to be considered more as a cumulative event than a sequential procedure. A high stress along the entire ligament generates micro-cracks simultaneously and favours the formation of more than one macro-crack possibly with different propagation directions.

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