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Mixed mode fracture energy of sprucewood

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The characterization of Mixed Mode (Mode I and Mode II) behaviour of wood was concentrated on concepts of linear fracture mechanics in the past. Using an adopted version of the splitting test it was possible to obtain complete load displacement curves under different Mixed Mode loading cases for crack propagation along the grain. Therefore fracture energy concepts (specific fracture energy) could be used to characterize the material behaviour. Additionally strength parameters were used in order to describe crack initation in two crack propagation systems. The values for specific fracture energies as well as the strength values were compared with pure Mode I fracture tests. Moreover, the size effect under Mixed Mode loading was investigated to guarantee size independent material characterizing values for the specific fracture energies.

1. Introduction

It is well known that wood is a highly anisotropic material with variable mechanical properties. In a simplified way wood can be described as an orthotropic material with three main directions, namely the longitudinal (L), radial (R) and tangential (T) directions. This holds at least if a specimen is taken out of a stem with sufficient distance from the pith. As a consequence for fracture mechanical characterization the plane of the crack in relation to the symmetry planes must be specified in addition to the Mode of crack propagation. Consequently, six combinations of material symmetry and crack direction are required for a complete analysis. These crack propagation systems are denoted with two letters characterizing the plane normal to the crack and and the direction of crack propagation. As an example the notation RL indicates that the crack plane is normal to the radial direction and propagates in the longitudinal direction. All six crack propagation systems are shown in Fig 1.

Both in using wood as a construction material as well as in wood machining the material is often subjected to combined loading of opening Mode (Mode I) and forward shear Mode (Mode II). For pure Mode I loading of wood characterization methods exist which use the concepts of linear fracture mechanics (see for example [1, 2] as well as concepts which allow to go beyond linear fracture mechanics and to use more general energy criterions, for example the concept of the specific fracture energy [3] or damage mechanics Models [4]. This is to our knowledge not the case for pure Mode II loading and Mixed Mode loading (Mode I and Mode II) of wood where test methods and specimen geometries have been used which allow a description in terms of linear elastic fracture mechanics only (see for example [5–9]) or maxmium force values have been presented [10, 11]. In the present paper we show the application of a new Mixed Mode test on wood according to Tschegg [12, 13]. In particular we present results for the specific fracture energy for different Mixed Mode cases in the

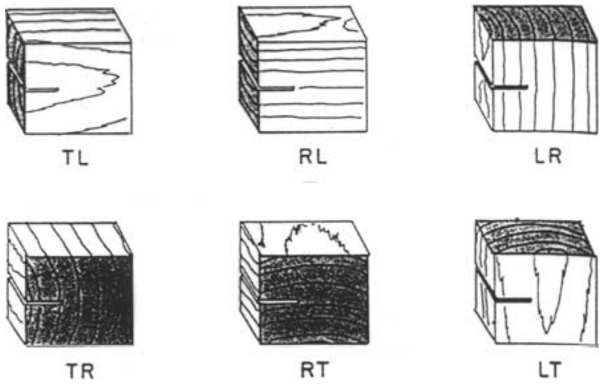


Figure 1 Principal crack propagation systems in wood. The first suscript denotes the plane normal to the crack, the second suscript denotes the direction of crack propagation (from [24]).

RL crack propagation system as well as strength values characterizing crack initiation and results from finite elements simulations for the RL and LR systems. These findings are compared to results for pure Mode I loading. Moreover the size effect for Mixed Mode testing of sprucewood is shown.

2. Material and methods

Mode I experiments were performed using the wedge splitting technique as described more detailed elsewhere [3, 14, 15]. The basic idea is that a notched specimen resting on a linear support is splitted by help of a load transmission equipment which is situated in a groove of the specimen. The principle can be seen in Fig. 2. The horizontal splitting force F_{H} is calculated from the force of the testing machine F_{M} according to

$$F_{\mathrm{H}} = F_{\mathrm{M}}/2\tan(\alpha/2), \tag{1}$$

where α denotes the wedge angle. The displacement δ_{I} was detemined using an optical measurement system as described in [16]. From the whole load displacement curve the specific fracture energy $G_{\mathrm{f,I}}$ was determined according to

$$G_{\mathrm{f,I}} = \frac{1}{A}\int_0^{\delta_{\mathrm{Imax}}} F_{\mathrm{H}}(\delta_{\mathrm{I}})\,\mathrm{d}\delta_{\mathrm{I}}. \tag{2}$$

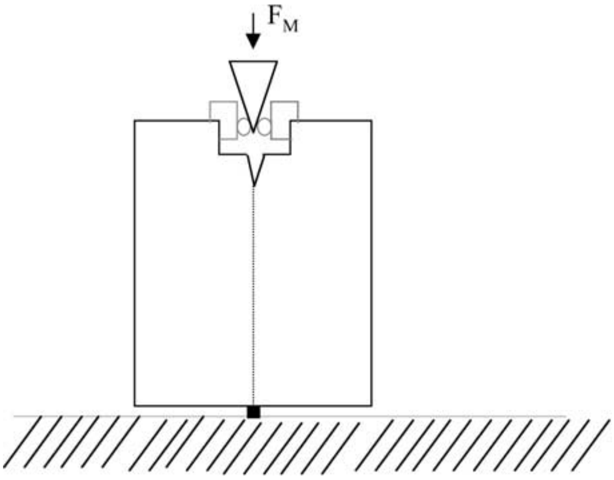


Figure 2 Schematic view of the test arrangement for the splitting test.

where A is the fracture surface. A notch tensile strength (Harmuth *et al.*, 1996) was calculated from the maximum load $F_{\mathrm{H,max}}$:

$$\sigma_{\mathrm{max,I}} = \frac{F_{\mathrm{H,max}}}{A} + \frac{M}{R}, \tag{3}$$

where M is the bending moment of the specimen and R the moment of resistance.

Fracture mechanical investigations for Mixed Mode loading were performed according to a new test technique developed by Tschegg [12]. This method is described in detail in [13] and was submitted to the Austrian Patent Office. In principle it bases on the wedge splitting technique but using some modifications, especially an asymmetric wedge, it was possible to obtain Mixed Mode loading. The Mode I and Mode II parts were changed using different wedges where a larger wedge angle corresponds to a higher Mode II part.

The force acting horizontally F_{H} is determined from the force of the testing machine F_{M} accoring to

$$F_{\mathrm{H}} = F_{\mathrm{M}}/\tan(\alpha), \tag{4}$$

α denoting the angle of the asymmetric wedge, whereas the vertical force F_{V} is equal to the force of the testing machine F_{M},

$$F_{\mathrm{V}} = F_{\mathrm{M}}. \tag{5}$$

The horizontal and vertical displacments δ_{I} and δ_{II} were again determined optically in a contact free manner. The specific fracture energy for Mixed Mode loading $G_{\mathrm{f,M}}$ was then determined as the sum of the two parts $G_{\mathrm{f,I}}$ and $G_{\mathrm{f,II}}$

$$G_{\mathrm{f,M}} = \frac{1}{A}\left(\int_0^{\delta_{\mathrm{Imax}}} F_{\mathrm{H}}(\delta_{\mathrm{I}})\,\mathrm{d}\delta_{\mathrm{I}} + \int_0^{\delta_{\mathrm{IImax}}} F_{\mathrm{V}}(\delta_{\mathrm{II}})\,\mathrm{d}\delta_{\mathrm{II}}\right). \tag{6}$$

In order to study different Mixed Mode cases different wedge angles were used, namely 10°, 25°, 39° and 50° for the RL system and 10°, 25°, 39°, 50° and 70° for the LR system. In order to characterize the maximum stress state from the maximum forces, $F_{\mathrm{H,max}}$ and $F_{\mathrm{V,max}}$ a strength value was defined adding tensile, shear and flexural stresses:

$$\sigma_{\mathrm{max,M}} = \frac{F_{\mathrm{H,\,max}}}{A} + \frac{F_{\mathrm{V,max}}}{A} + \sum_i \frac{Mi}{Ri}. \tag{7}$$

The specimen geometry for Mode I loading is shown in Fig. 3 and the geometry for Mixed Mode loading is similar to it. The Mode I specimens had the following dimensions: the starter notch a was 10 mm in the RL and 50 mm in the LR system, therefore the ligament length L was 90 mm (RL) and 50 mm (LR), the width $W = 120$ mm, the height $K = 120$ mm and the thickness $T = 40$ mm. The specimens for Mixed Mode testing had a starter notch a = 25 mm (RL) and 30 mm (LR),

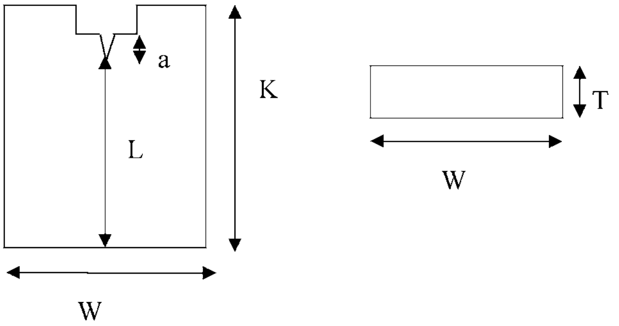


Figure 3 Geometry of the splitting specimens.

the ligament length $L = 60$ mm (RL) and 55 mm (LR), the height $K = 125$ mm, the width $W = 120$ mm and the thickness $T = 40$ mm.

In order to investigate the size effect in Mixed Mode loading experiments using the 35° wedge were performed on specimens with different ligament length L (30, 45, 60, 75 and 90 mm) as well as with different thickness W (10, 40 and 60 mm) in the RL crack propagation system.

All experiments were performed on sprucewood under standard environmental conditions (20° C, 66% relative humidity) with a standard testing machine (QTS 10) using a cross head speed of 1mm/min. The specimens were stored in a climate chamber and were conditioned to 13% moisture content prior to testing. The starter notch was additionally sharpened with a razor blade.

3. Results and discussion

3.1. RL crack propagation system

3.1.1. Mixed mode specific fracture energy

All experiments in the RL system took place under stable crack propagation. A typical load displacement curve for Mode I loading is shown in Fig. 4. The maximum strength value characterizing the resistance against crack initiation was evaluated to be (2,1 ± 0,3) MPa. The specific fracture energy was (202 ± 20) J/m^2. This result agrees well with earlier findings for sprucewood (see for example [3]).

Typical load displacement curves for Mixed Mode loading using the 10° and the 39° wedge are shown in Fig. 5. As can be expected the part belonging to the F_V-δ_{II} curve increased with increasing wedge angle. The maximum vertical force was much higher and the shape of both the Mode I and Mode II part changed.

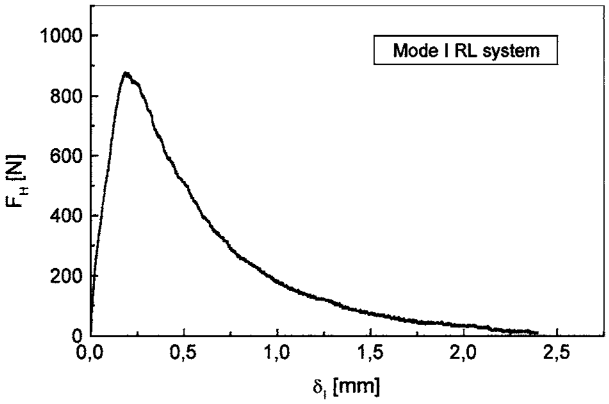
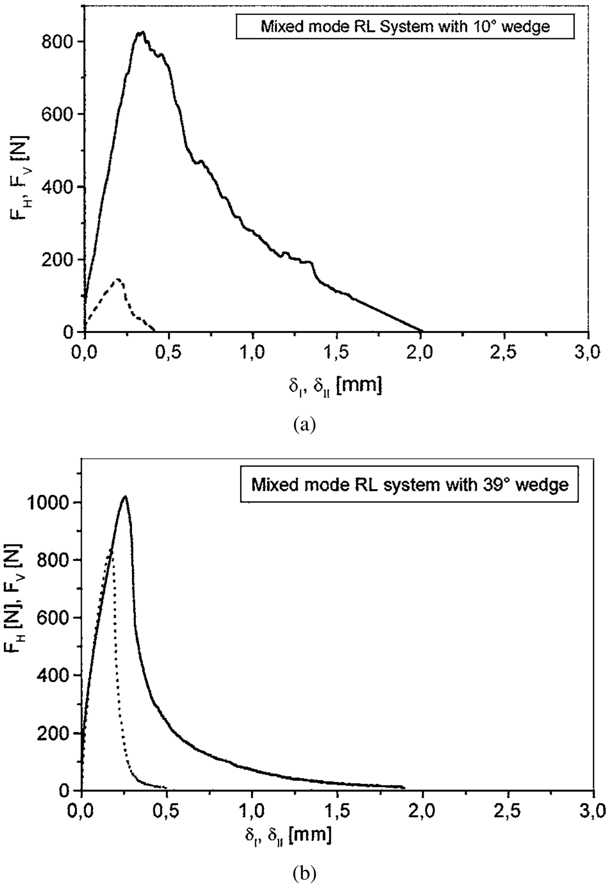


Figure 4 Typical load displacement curve obtained from Mode I testing in the RL crack propagation system.



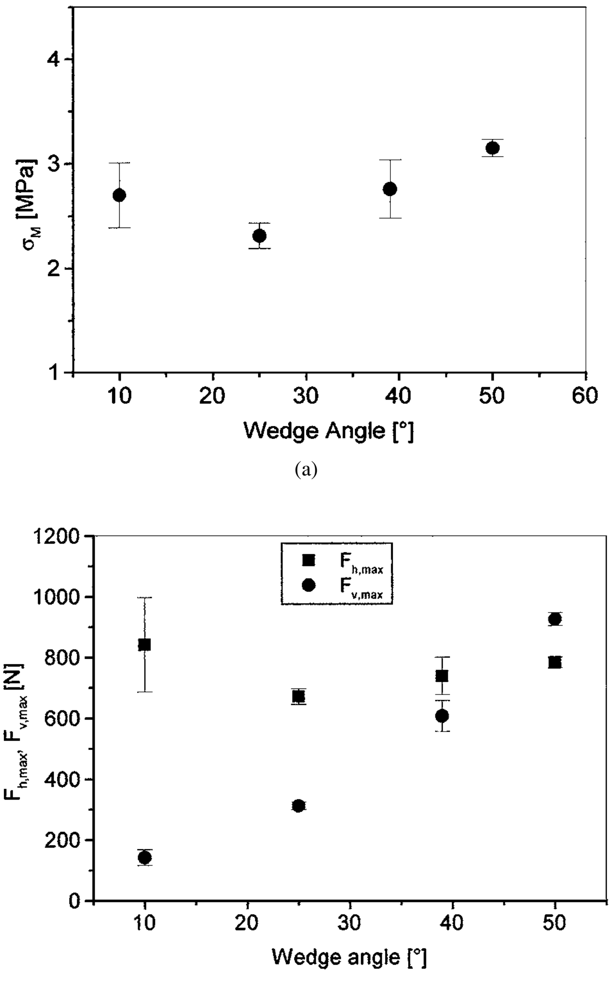
(a)

(b)

Figure 5 Typical load displacement curves for the Mode I (solid lines) and Mode II parts (dashed lines) obtained from Mixed Mode testing in the RL crack propagation system with a wedge angle of 10° (a) and 39° (b).

In order to characterize crack initation the strength values according to Equation 7 were determined from the maximum forces. These strength values and the maximum horizontal and vertical forces are shown in Fig. 6. Considering the relative high scatter of the data the differences were rather small. Nevertheless, a trend of increasing strength values with increasing wedge angle was observed. This increase was due to the fact that the vertical maximum forces increased with increasing wedge angle (Fig. 6b) whereas the maximum horizontal forces stayed approximately constant except for a wedge angle of 25° where the lowest horizontal force and maximum strength was observed. Compared to the strength value for pure Mode I loading the strength values for Mixed Mode loading were slightly higher except for the above mentioned minimum. However, the differences were small.

The total specific fracture energy for different wedge angles is depicted in Fig. 7. As can be seen a minimum of the specific fracture energy at a wedge angle of 25° appeared. This is quite remarkable as this result points to a mutual influence of Mode I and Mode II components (mode coupling). Compared with the specific fracture energy for pure Mode I loading these



(a)

(b)

Figure 6 Strength values (a) and maxmimum horizontal and vertical forces (b) for Mixed Mode tests with different wedge angles in the RL system.

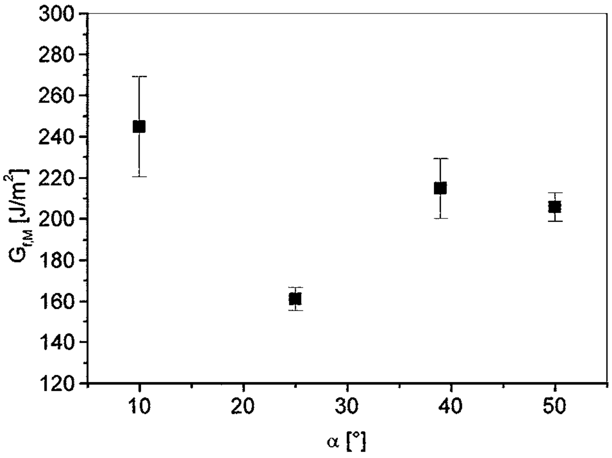


Figure 7 Specific fracture energies for the Mixed Mode tests with different wedge angles in the RL system.

values were in the same range except the minimum at 25° which was even below the Mode I case.

Recently, Holmberg and co-authors presented a fracture Model for Mixed Mode loading where they used softening-relative displacement relations [17], approximated by bilinear curves, corresponding to a fictitious crack model (for basics of the ficticous crack model see for example [18]). They showed in their simulations that a coupling between the modes, meaning that the tensile and shear stress components of the ficticous crack zone are both functions of the opening and the shear displacements, could lead to a minimum in the specific fracture energy for Mixed Mode cases with high Mode I components [19]. Our experimental results point to such a coupling for Mixed Mode loading of sprucewood. In view of such a ficticous crack model the specific fracture energy for Mixed Mode loading can be generally written as

$$G_{\mathrm{f,M}} = \int_{\Gamma} [\sigma_n(\delta_n, \delta_s, m)\,\mathrm{d}\delta_n + \sigma_s(\delta_n, \delta_s, n)\,\mathrm{d}\delta_s], \quad (8)$$

where σ_n and σ_s are the tensile and shear stresses in the ficticous crack zone, δ_n and δ_s are the displacements normal to the crack surface and the shear displacement and Γ is the deformation path resulting in complete separation of the material. The parameters m and n are Mixed Mode coupling parameters. For $m = n = 0$ there would be no coupling between the tensile and shear behaviour. Hence, the use of this new method offers the possibility to determine these coupling parameters using the experimental results as input data for numerical simulations.

The change of the shape of the whole load displacement curve is not only determined by the specific fracture energy but also by the maximum forces and the initial slope of the load displacement curve which is proportional to the stiffness of the material under the current load. These three quantities are often used to characterize whether the material behaviour is more brittle or ductile. Usually these quantities are used to calculate the characteristic length or a brittleness quantity [15, 20, 21]. As all Mixed Mode specimens in our study had the same dimensions we used a brittleness parameter which was calculated from the load displacement curves using the forces F_{M} and crosshead displacements δ of the testing machine according to

$$B = \frac{1}{L} \frac{F_{\mathrm{M,max}}^2}{\frac{dF_{\mathrm{M,max}}}{\mathrm{d}\delta_{\mathrm{M}}} G_{\mathrm{f,M}}}, \quad (9)$$

where $F_{\mathrm{M,max}}$ is the maximum force of the testing machine, L the ligament length and $d\,F_{\mathrm{M,max}}/\mathrm{d}\delta$ the initial slope of the load displacement curve. This parameter with the dimension of a length indicates whether the material is more brittle (higher values) or more ductile (lower values). The brittleness parameter B for the Mixed Mode experiments is shown in Fig. 8. As can be seen B increased with the wedge angle indicating a more brittle behavior as the Mode II part increased. The exception was the result for a wedge angle of 25° due to the minimum in specific fracture energy.

3.1.2. Size effect

When testing inhomogeneous and nonlinear materials "size effects" are well known. For example the

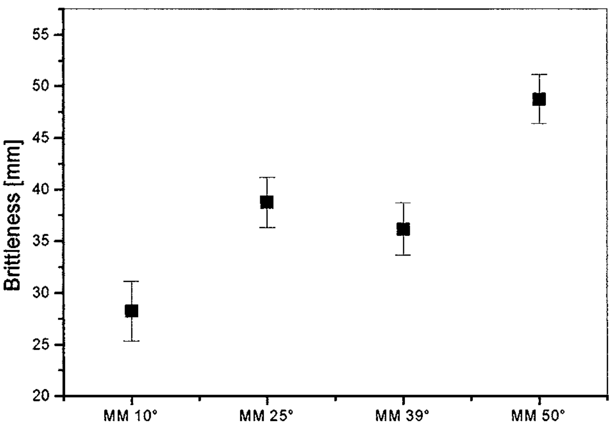
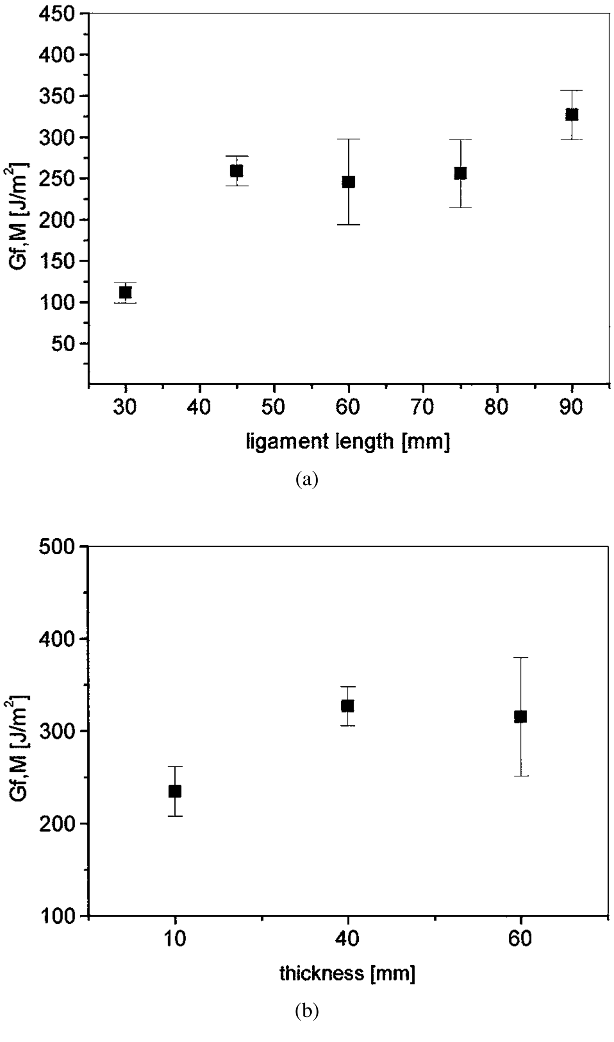


Figure 8 Brittleness number for the different Mixed Mode tests in the RL system.



(a)

(b)

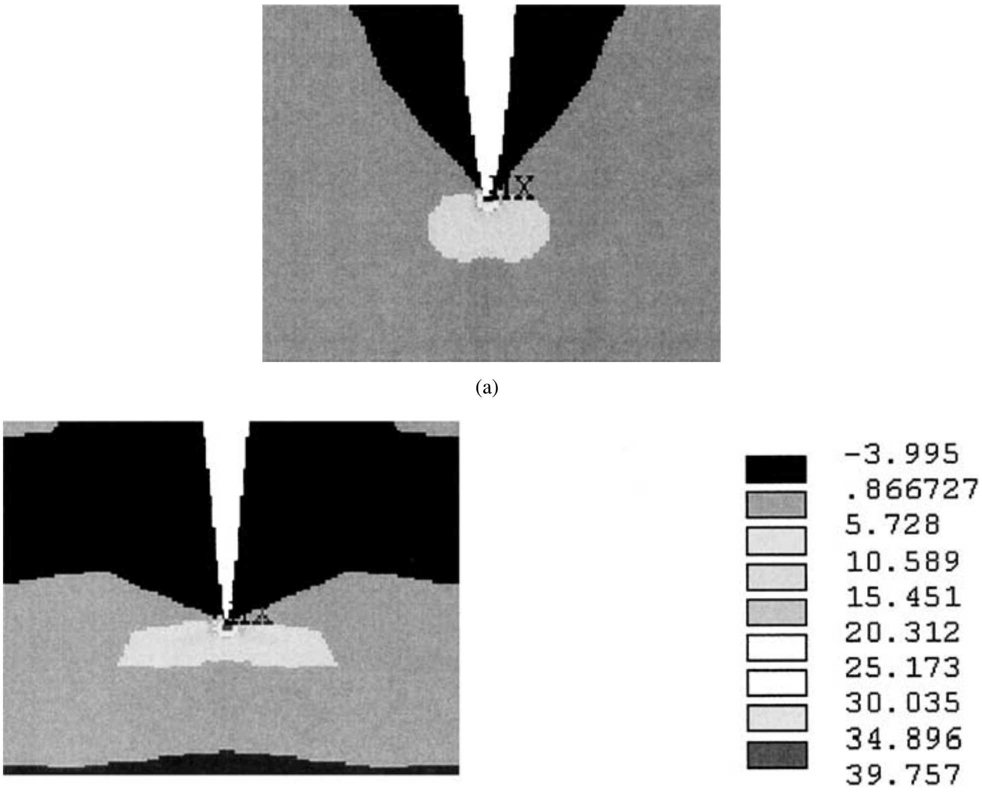
Figure 9 Size effect for Mixed Mode loading using the 39° wedge: influence of ligament length (a) and specimen thickness (b).

influence of ligament length and specimen thickness on the specific fracture energy for Mode I loading of sprucewood was investigated by [3]. We performed experiments with the 39° wedge on specimens with different ligament lengths (30, 45, 60, 75 and 90 mm) and specimen thicknesses (10, 40 and 60 mm) to make sure that our results are independent of the specimen size. The results pertaining the influence of the ligament length on the specific fracture energy for Mixed Mode loading are presented in Fig. 9a. The specific fracture energy increased from approximately 120 J/m^2 at a ligament length of 30 mm to approximately 260 J/m^2 at a ligament length of 45 mm and remained essentially constant for further increases of the ligament length (the value for a ligament length of 90 mm is statistically not significantly different). In Fig. 9b the dependence of the specific fracture energy on specimen thickness is shown. For specimen thicknesses beyond 40 mm no increase of the specific fracture energy was recognized. Therefore it may be concluded that the used dimensions for ligament length and thickness are appropiate for the evaluation of material characterizing data.

3.2. LR crack propagation system

The fracture tests against the macroscopic fiber direction took place under unstable crack propagation. Due to the great difference of the properties of wood parallel and perpendicular to the grain the crack changed direction immedately after initiation and propagated in an unstable manner parallel to the grain. This behaviour was observed for Mode I loading as well for all wedge angles under Mixed Mode loading. The stress distribution obtained from a linear elastic finite element simulation using the programm code ANSYS© is shown in Fig. 10. For the modelation of the crack tip quarter point elements as suggested in [22, 23] were used. The normal stresses under the same load are shown for the RL (Fig. 10a) and the LR (Fig. 10b) crack propagation system under a pure Mode I loading case. As can be seen these normal stresses perpendicular to the direction of crack initation vary considerably due to the orthotropic behaviour of wood. Therefore, it is not surprising that crack propagation always occured parallel to grain for both systems immedately after crack initation.

In order to characterize crack initation the maximum stress level was calculated according to Equation 3 for Mode I and to Equation 7 for Mixed Mode loading. Under pure Mode I loading a strength of (6,4 ± 0,6) MPa was found. The strength value for Mixed Mode loading showed less variation with wedge angles between 10° and 50°. Only for the wedge angle of 70° a clear increase was found (see Fig. 11a). The reason was the increase of the maximum vertical force while the maximum horizontal force stayed more or less constant. The maximum forces are shown in Fig. 10b. Compared with the Mode I tests these values were slightly lower exept for 70° were the highest strength value was found. The strength values for the notched specimens under Mixed Mode loading are higher in the LR crack propagation system than in the RL system. The ratio of these stress levels parallel and perpendicular to the grain are approximately 1 : 2. For Mode I loading the ratio between the RL and LR system was approximately 1 : 3. However, compared to classical strength values of unnotched wood samples parallel and perpendicular to the grain like for example tensile or shear strength [24], the difference between RL and LR system for all load cases was much smaller.



(a)

(b)

Figure 10 Normal stress around the notch tip in horizontal direction in a pseudogray scale obtained by finite element simulations under Mode I loading for the RL (a) and LR (b) system. The values corresponding to the gray levels are given in MPa.

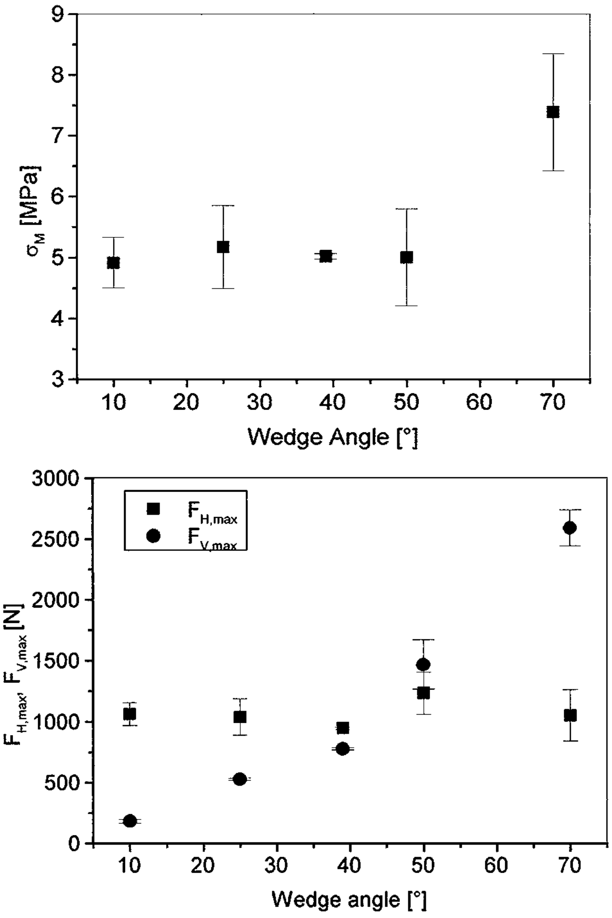


Figure 11 Strength values (a) and maxmimum horizontal and vertical forces (b) for Mixed Mode tests with different wedge angles in the LR system.

4. Conclusions

In this paper the fracture mechanical material properties of sprucewood under Mixed Mode loading (Mode I and Mode II) have been determined. The main results obtained may be summarized as follows:

1. Fracture mechanical tests in the RL crack propagation system could be performed under stable crack propagation. Therefore it was possible to determine complete load displacement curves and as a consequence specific fracture energies for different Mixed Mode loading cases and compare these values with the specific fracture energy for pure Mode I loading.
2. The specific fracture energy shows a minimum for Mixed Mode loading if a wedge angle of 25° is used. This minimum is even lower than the specific fracture energy for pure Mode I loading. This behaviour indicates a non linear coupling of Mode I and Mode II components under Mixed Mode loading as suggested recently by Holmberg and co-authors [19] by a ficticous crack model.
3. The shape of the load displacement curves was characterized using a brittleness parameter combining initial slope, maximum force and specific fracture energy. This value indicates that the material behaviour becomes more brittle with increasing wedge angle, that means increasing Mode II component.
4. In order to obtain material characterizing values the size effect was investigated using specimens with different ligament length and width. It could be shown that the used dimensions were sufficient for obtaining size independent values.

5. Crack propagation occured in an unstable manner in the LR crack propagation system and the crack propagated parallel to the macroscopic fiber direction. A strength value was defined in order to characterize crack initation. The strength values increased with increasing wedge angle (= increasing Mode II component) for both crack propagation systems. This was due to increasing vertical forces as the horizontal forces stayed approximately constant. The ratio of the strength values between LR and RL crack propagation system was in the order of 2 : 1. This relative difference is much smaller than differences in conventional strength values like for example tensile or compressive strength of unnotched specimen.

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