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Fracture behaviour of wood and its composites. A review

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Stefanie E. Stanzl-Tschegg[1,*] and Parviz Navi[2]

[1] Institute of Physics and Materials Science, BOKU-University of Natural Resources and Applied Life Sciences, Vienna, Austria

[2] Bern University of Applied Sciences, Biel, Switzerland

*Corresponding author.
Institute of Physics and Materials Science, BOKU-University of Natural Resources and Applied Life Sciences, Peter Jordan Strasse 82, A-1190 Vienna, Austria
Phone: +43-1-47654 5160
Fax: +43-1-47654 5159
E-mail: stefanie.tschegg@boku.ac.at

Abstract

Fracturing of wood and its composites is a process influenced by many parameters, on the one hand coming from the structure and properties of wood itself, and on the other from influences from outside, such as loading mode, velocity of deformation, moisture, temperature, etc. Both types of parameters may be investigated experimentally at different levels of magnification, which allows a better understanding of the mechanisms of fracturing. Fracture mechanical methods serve to quantify the fracture process of wood and wood composites with different deformation and fracturing features. Since wood machining is mainly dominated by the fracture properties of wood, knowledge of the different relevant mechanisms is essential. Parameters that influence the fracture process, such as wood density, orientation, loading mode, strain rate and moisture are discussed in the light of results obtained during recent years. Based on this, refined modelling of the different processes becomes possible.

Keywords: crack initiation and propagation; fracture energy; fracture surface analysis; loading mode; moisture influence; non-linear fracture mechanics; strain-rate effects; wood fracture; wood microstructure.

Introduction

Fracturing of wood is one of the many processes that essentially determine wood machining. But surprisingly, less scientific work has been performed on understanding fracture and damage of wood than on other materials. The complexity of the wood structure, which is responsible for its many unique mechanical features, hampers the understanding of the underlying mechanisms.

The books by Bodig and Jayne (1982) and Smith et al. (2003) belong to the standard literature on the relationship between mechanical and fracture properties on the one hand, and structural features on the other hand, in which fracture mechanical features and modelling are also considered. Jeronimidis (2004) treated the relevance of structure and fracture properties for wood machining purposes, and Koponen (2004) gave an overview concerning the effect of ultra- and cellular structure of wood on its mechanical properties and failure mechanisms. In the book "Wood Structure and Properties" by Kettunen (2006), the mechanisms are discussed in a large context in terms of fracturing a cell structured material.

One of the most typical features of wood is its hierarchical structure. This implies that specific properties are caused by specific structural features, in fact on all length scales – ranging between macroscopic and nanostructural levels. Stiffness and toughness, e.g., may be understood and modelled on the basis of micro- and nanometer scale properties, such as fibril and elementary fibril angles and molecular arrangements of the chemical constituents. In wood composites, the properties on the micro- and nanolevels are superimposed by individual properties of the components on the macro-level.

Investigation of the fracture features of wood became possible during recent years, especially with the advent of new testing equipments, e.g., new surface imaging techniques (stereo imaging, laser scanning microscopy, interferometry), scanning electron microscopy (SEM), environmental scanning electron microscopy (ESEM) and atomic force microscopy (AFM). Moreover, in situ loading possibilities arose, e.g., the dynamic infra-red spectroscopy. The X-ray and neutron scattering techniques are also very valuable. It is easier now to gain knowledge about the correlation between fracture, structure and various properties of wood on different size levels, i.e., on molecular, cellular, growth ring and macroscopic level. Fracture surface analysis together with new fracture mechanical testing methods brought especially new insights.

In the present paper, different parameters influencing the fracture properties have been revisited and reviewed. The impact of wood species, density, orientation of the grain, modifications of wood, strain rate, loading mode (I, II, III and mixed modes) and humidity are emphasised.

Fracture mechanical characterisation of fracture properties

During wood machining, several physical processes take place, such as deformation (e.g., compression) of the material ahead and below the tool, fracturing in front of it in the opening (mode I) or shear (mode II) modes. Moreover, friction and wear occur (Figure 1). A most important

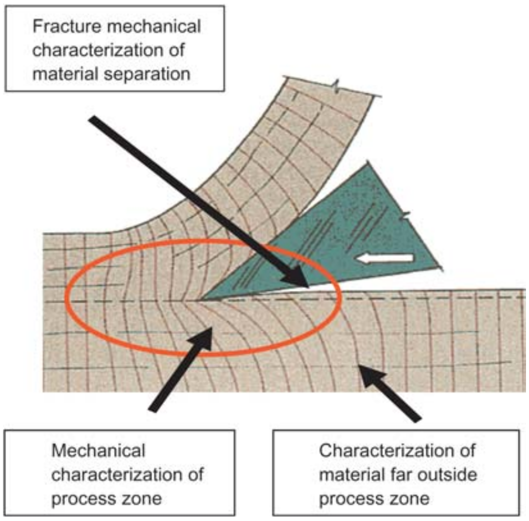

Figure 1 Main processes determining the cutting properties of wood.

role is played in these processes by the tensile or compressive strength, Young's modulus and density. But the tool features and environmental conditions (humidity, temperature) are also crucial.

Fracturing of wood and wood-based materials takes place mainly in two steps: crack initiation and crack propagation in which energy dissipation occurs. During crack initiation, a process zone is formed in front of the crack tip, which contains more or less numerous microcracks. The already existing microcracks join and form a macrocrack. With this, the crack initiation period is finished, the crack propagation period begins, and the main crack propagates into the material. The process zone is continuously translating along with the propagating crack tip. In the weak zone behind the crack tip, bridging effects take place, i.e., unbroken fibres bridge the already existing crack (Figure 2). With increasing crack length, bridging becomes gradually weaker, until complete separation of the fracture surfaces finally takes place. The bridging processes in the weak zone cause energy dissipation and strongly influence the fracture behaviour. The sum of energy consumption during crack initiation and propagation is called fracture energy. Only a small part of the whole fracture energy is needed to create new fracture surfaces in wood and wood composites, and the major part is consumed for the initiation and propagation of microcracks, as well as for "plastic" deformation in the process zone and in the weak zone. This is the main reason why standard fracture-mechanics methods for brittle-elastic materials with traction-free cracks cannot be applied to wood with process zones and fibre bridging on cracks. The analysis of wood requires non-linear approaches or new type linear-elastic fracture mechanic (LEFM) methods, as suggested by Matsumoto and Nairn (2007).

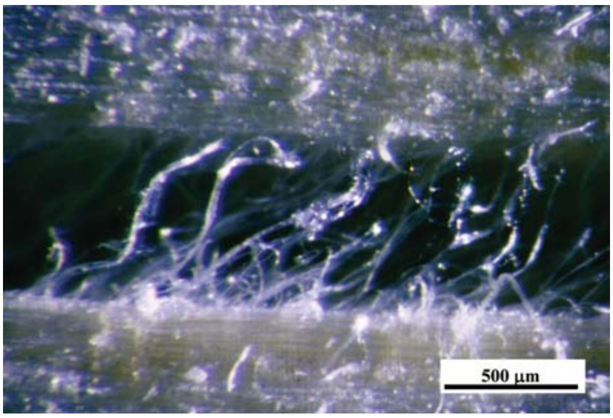

Figure 2 Fibre bridging in spruce during tensile loading in RL orientation causing energy dissipation and thus retarded crack propagation.

For a quantitative characterisation of the fracture properties, the principles of fracture mechanics have shown to be a useful tool. After attempting to introduce fracture mechanical methods, the question arose whether linear-elastic (LEFM) or non-linear principles should be applied. It could be demonstrated that in some cases, which are essentially determined by the direction of loading, wood behaves mainly like a brittle material, so that LEFM principles based on the fracture toughness parameter K_{IC} are able to characterise the fracture process adequately. Linearity and non-linearity also depend on the specimen geometry, and the size-effect reflects non-linear elastic fracture behaviour. In many cases, it is nowadays commonly accepted that wood may be treated as a quasi-brittle material, characterised by the development of a fracture process zone (FPZ) and may be efficiently described by "cohesive crack" models, which include the process of crack propagation. Measurement of load-displacement diagrams is needed, from which the corresponding fracture resistance curves (R-curves) may be derived.

A comprehensive overview on application of linear and non-linear elastic methods and a discussion of some test methods is given by Serrano and Gustafsson (2006). The critical stress intensity factor K_{IC} and the critical energy release rate G_C are used for characterising LEFM quantities, and the Weibull weakest link theory is adequate for modelling, because stress- and strain-based methods are not useful in situations where large stress or strain concentrations arise, e.g., at flaws, cracks or sharp corners. Measurement of compliance and assumption of a small FPZ are applied for sharp notches, and general approaches with a mean stress (Tsai-Hill or Norris criterion) along a predefined area (relevant for high density fibre boards) are performed. In time-dependent processes, the fictitious crack model introduced by Hillerborg et al. (1976) – and further developments based on this – is used in most non-linear elastic studies, against the background that wood is a "strain softening" material (in the cases of tension perpendicular to grain and in shear along grain). Here, strength, stiffness and fracture energy G_f are the basic material parameters. The main assumption of the fictitious or cohesive crack model is that the FPZ can be described by a fictitious ("equivalent") crack, which transmits the (normal) stress (in mode I loading). For modelling purposes, different softening behaviour, i.e., bilinear (b) or obtained from a polynomial function (c) is applied (Figure 3) (Coureau et al. 2006).

Several testing and analysing methods with different specimen shapes have been developed to measure frac-

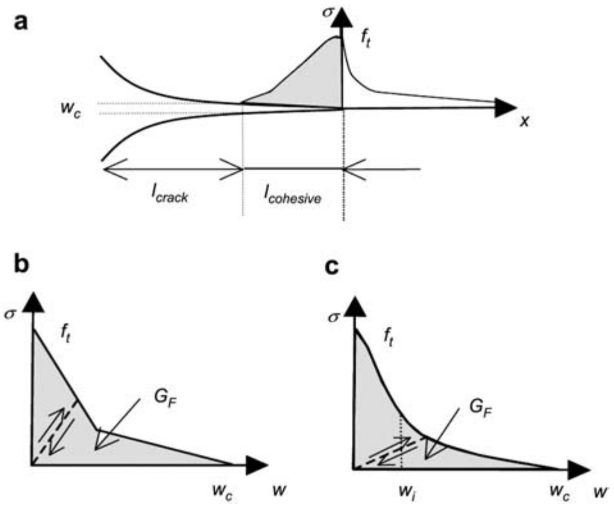

Figure 3 Cohesive (or fictitious) crack model with stress distribution (a). Bilinear softening (b) and polynomial softening (c) characterising crack propagation (Coureau et al. 2006).

ture mechanics quantities, such as the fracture toughness K_{IC}. Quite often, double cantilever beams for mode I and end-notched flexure (ENF) for mode II testing are used, as discussed by Yoshihara and Kawamura (2006), together with different methods of analysis, based on elementary beam theory, compliance calibration methods, etc. Dourado et al. (2006) performed three point-bending fracture measurements on pine and spruce. The authors estimated the corresponding crack resistance curves (R-curves: energy release rates vs. crack length) by measuring the specimen compliance of the propagating crack. An initially rising R-curve was found, which is typical for toughening materials. After a specific equivalent crack length, a plateau of the R-curve is observed, which characterises the "critical" resistance or fracture energy G_{RC}, where the resistance to crack growth becomes independent of the equivalent crack length. Also, Lespine et al. (2006) point out that the G_{RC} value is not an intrinsic material property but appears to depend on the specimen geometry. The specific fracture energy G_f values can be calculated by means of a bilinear softening function. The results are associated with the processes of microcracking and fibre bridging (Stanzl-Tschegg et al. 1995; Sinn et al. 2001).

To determine non-linear elastic properties, the wedge-splitting technique according to Tschegg (1986) proved to be a useful technique. This was developed for inhomogeneous materials, such as concrete, to account for non-linear fracture processes, such as plastic deformation and friction. It was found to be an effective experimental testing technique in several studies to determine the specific fracture energy G_f, besides the fracture toughness K_{IC}. While K_{IC} characterises the onset of fracturing, G_f quantifies the whole energy that is needed for fracturing, i.e., also the period of crack propagation. In standard K_{IC} experiments, unstable crack propagation takes place after the onset of crack formation at the maximum load in brittle materials. This measured maximum notch strength, however, may be identical for a brittle and ductile material so that the measured K_{IC} value does not permit distinction to be made between brittle and ductile behaviour. In contrast, the wedge-splitting method makes measurement of the crack propagation phase and recording of the load-displacement curves after crack initiation possible by using appropriate specimen shapes and a stiff loading machine. With this, differentiating between brittle and ductile fracture is possible. An average of the specific fracture energy G_f as quantifying material parameter, being consumed by different physical mechanisms, such as microcracking and fibre bridging (Stanzl-Tschegg et al. 1995; Ehart et al. 1996), may be derived from the area integral below the load-displacement curve (Figure 4).

Influence of density and loading direction

It is well known that the fracture toughness of wood is strongly dependent on density. The fracture toughness generally increases with increasing density, and modelling by Gibson and Ashby (1997) is based on the assumption that elastic deformation in the radial direction is controlled by cell wall bending. A 3/2 power law dependence, normal as well as parallel to the grain, was suggested whereby $K_{IC} \approx (\rho/\rho_s)^{3/2}$. For their model, a honeycomb-like network of cells, with cell wall layers of different density, and a middle lamella in between, was assumed. Modén (2006) reanalysed this model and also assumes cell wall stretching as a significant mechanism and predicts a linear relationship between radial modulus and density. Also, measured data show a strong linear correlation over a wide density range. The radial Young's modulus was measured by digital speckle photography at several places of each year ring, and the dependence on density was found to vary more than expected, between 600 and 3000 MPa. In addition to a one-phase honeycomb model including both bending and stretching of the cell walls, Modén suggests a two-phase model to characterise the annual ring structure of wood and finds a higher average cell wall modulus than expected. Because bending is considered more important for the tangential modulus at all densities than for the radial modulus, this model would explain the transverse isotropy.

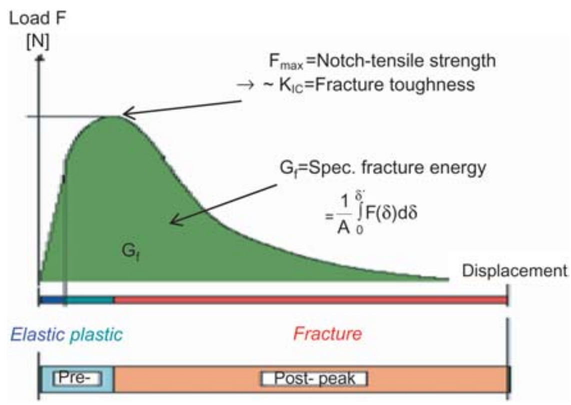

Figure 4 Determination of specific fracture energy G_f from area below load-displacement diagram of wedge splitting test (Tschegg 1986). K_{IC} can be approximated from the maximum notch-strength F_{max}.

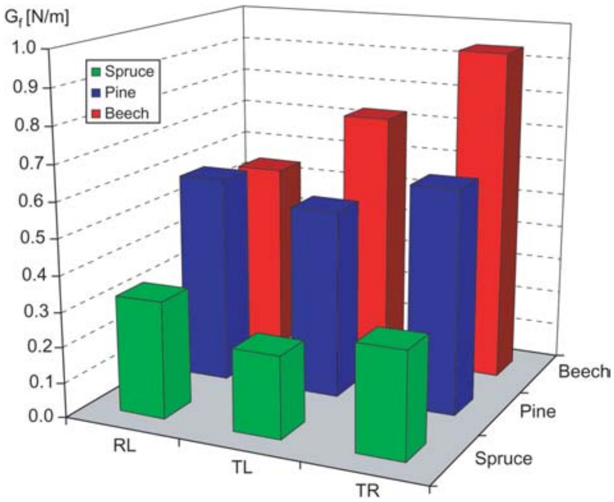

Figure 5 Mode I specific fracture energies of different wood species. Influence of orientation (Frühmann et al. 2003a).

Studies of the influence of loading direction on fracture toughness and specific fracture energy were performed on different wood species. Testing in different orientations showed higher G_f values of hardwood and higher values perpendicular to the grain (TR) than parallel (TL) (Figure 5) (Frühmann et al. 2003c). In addition, Becker and Döhrer (2003) performed a finite element analysis and applied the J-integral method for determining the stress intensity. They report notably higher fracture toughness values for hardwoods and a pronounced dependence on the density, especially for the radial-longitudinal (RL) system.

Also, details of microstructural influences, such as the role of rays, have been studied. In beech and oak, e.g., with more numerous and stronger rays than in larch or other species, a stronger "bridging effect" by fibre reinforcement occurs in the RL rather than in the TL orientation (Frühmann et al. 2002a), and thus higher fracture resistance can be observed. In the TL orientation, however, rays facilitate crack growth, as the crack is propagating in the direction of the fibres and needs rather less energy for this. In the TR orientation, ray cells may also act as planes of weakness (Ashby et al. 1985). Smooth fracture surfaces are created by cell breaking of the vessels in beech and oak, and crack propagation becomes easier (Frühmann et al. 2003a).

Mixed mode loading

During separation processes of wood or wood composites in sawing, cutting, milling, etc., deformation and fracturing take place not only in the crack opening mode (mode I), but also in sliding modes (mode II: in-plane shear and mode III: antiplane shear). Therefore, these loading conditions and mixed-mode loading in all directions – radial, tangential and longitudinal – have been investigated. Mode II measurements by Frühmann et al. (2003a) revealed larger K_{IC} and G_f values than in mode I. Torsional fracturing has been accomplished by use of compact tension (CT) type specimens and a tension-torsion machine (Ehart et al. 1998). The resulting K_{IC} and G_f values in both weak orientations (RL and TL) were approximately three times higher and could be explained mainly by fracture surface roughness-induced friction processes. In experiments on larch and beech under mode III loading, the crack mouth opening displacement (CMOD) and crack mouth sliding displacement (CMSD) induced by fracture surface roughness were measured (Tschegg et al. 2001) for two fibre orientations. They reach rather high values, depending on the fracture surface roughness (and with this on the orientation), and thus govern the transition of crack propagation in mode III to mode I growth by crack surface interference. Correlating fractographic observations with load-displacement diagrams of beech and spruce (Frühmann et al. 2002a) showed that mode I loading results in a rather ductile behaviour and a comparably small damage zone, whereas for mode II and mode III the damaged volume is essentially larger and the FPZ more complex.

Different superimposed loading conditions (mode I+mode II) could be realised (Tschegg et al. 2001) by means of an asymmetric wedge. Higher wedge angles lead to an increasing portion of mode II loading, and experiments on spruce and beech showed that the specific energies G_f are smaller for higher mode II portions. Most interesting, a minimum of G_f at a wedge angle of 25° resulted, which indicates a non-linear coupling of the mode I and mode II components (mode coupling) under mixed mode loading. This has been predicted by Holmberg et al. (1999) using the fictitious crack model of Hillerborg et al. (1976). A coupling between the modes indicates that the tensile and the shear stress components of the fictitious crack zone are functions of both the opening and shear displacements, and will lead to a minimum in the specific fracture energy for mixed mode cases.

Moura et al. (2006) applied the ENF, tapered ENF, and four-point ENF configurations for a numerical study of mode II loaded specimens and incorporated the equivalent crack concept in a compliance-based beam method, in order to avoid difficulties in monitoring crack propagation. The equivalent crack is related to the fracture process zone, and a cohesive linear softening damage model is used to simulate crack propagation. Good agreement between the predicted critical strain energy release rates G_{IIc} and those obtained from the experimental P-δ curves is obtained. Yoshihara (2005) measured mode II fracture initiation toughness in three-point bend-notched flexure (3-ENF) tests. In the quoted paper, loading-line and load-longitudinal strain compliances and critical load for crack propagation studies were combined. The author analysed the experimental results with those of different conventional methods, such as beam theory methods, compliance methods and the shear crack displacement measurement method.

Fracturing under torsion as well as under combined tension-torsion loading has also been studied in the strong directions and compared with results in the weak orientations (Loidl et al. 2008). It was shown that LEFM principles may be applied successfully to determine the fracture toughness under combined tension and superimposed torsion, as well as for pure torsion loading in the radial orientation. Thus, failure envelopes for com-

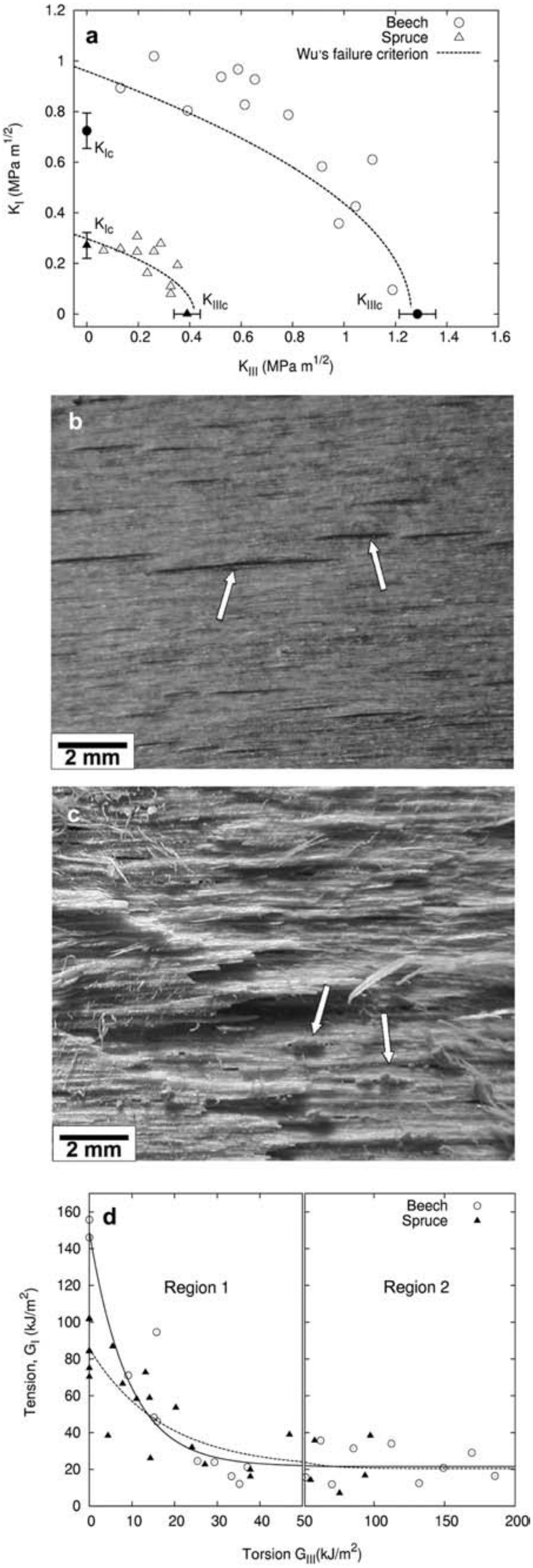

Figure 6 Tension-torsion loading of beech and spruce in radial orientation. Failure envelopes for combined loading (a). Fracture surfaces of beech after mode I (b) and mode III (c) loading. Arrows denote sticking out rays. Specific fracture energies under mode III versus mode I, solid (beech) and dashed (spruce) lines are drawn as visual guides (d). (Loidl et al. 2008).

bined tension-torsion fracturing can be constructed, which show that beech is approximately three times stronger than spruce (Figure 6a). The higher ratios of K_{IIIc}/K_{Ic} of 1.8 for beech in comparison to 1.4 for spruce may be explained by the influence of the rays in beech. They lead to a reinforcement effect under torsional loading, and in addition to a higher fracture surface roughness (Figure 6b and c), which induces crack closure and thus leads to a higher fracture resistance. Split rays indicate that they were pulled out during fracturing. Mixed mode loading of specimens in the longitudinal orientation requires the application of non-elastic concepts. Therefore, the specific fracture energies G_f (area under the load-displacement curve, divided by the projected fracture area) were determined. They show that rather small torsion loads (G_{III} values) produce a significant decrease of G_f (Figure 6d). The fracture surfaces reflect this behaviour, showing less rough fracture surfaces under superimposed loading (smaller damage zone) than a pure mode I fracture surface.

Fracture at cellular level

Application of the wedge-splitting technique to submicroscopic studies has been promoted, especially by Frühmann et al. (2003a,b) with a deformation gage

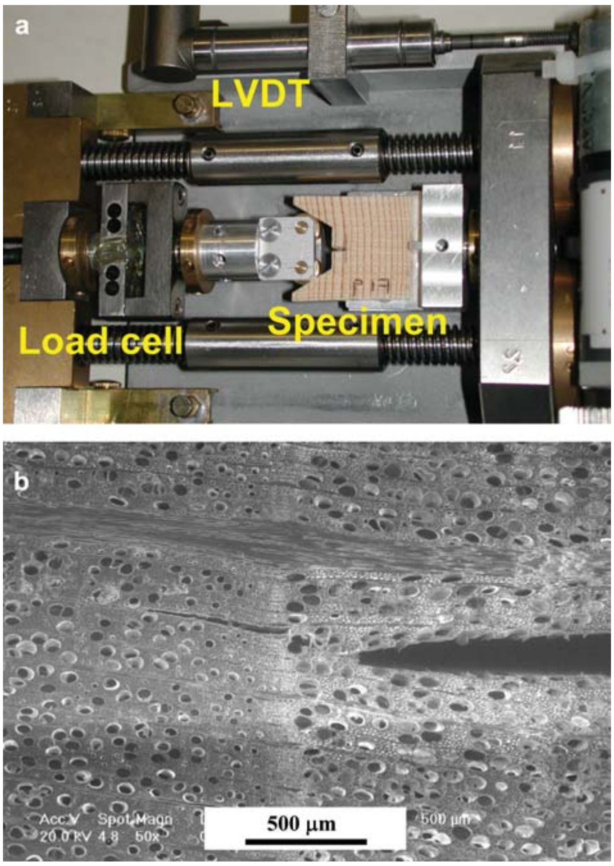

Figure 7 ESEM in situ micro-splitting test. Wedge splitting device with load frame and loading head, notched specimen 30×25 mm, load cell and electronic displacement detector (LVDT) (a). Beech fracturing in TR+ orientation with crack arrest in earlywood and pre-cracking in latewood (b) (Frühmann et al. 2003a).

designed for in situ tests in an environmental scanning electron microscope (Figure 7a). With this and a cooling device, studies of wood in a condition of controlled moisture are possible. Simultaneous detection of load-displacement curves and observation of the propagating crack allow an improved analysing of the fracture process. Thus, the influence of features at cell-size level on the deformation and fracture response of wood has become possible. It can be demonstrated, e.g., that a crack approaching the year ring border, stops in the earlywood, while pre-cracking takes place in the latewood across the year ring border (Figure 7b). Both processes may be considered as reasons for an increase of the crack propagation resistance and thus higher specific fracture energy G_f. In addition, it was observed that fracture in spruce earlywood goes through the thin cell walls, as described by Gibson and Ashby (1997) for $\rho/\rho_s < 0.2$ with ρ/ρ_s being the mean density related to the cell wall density, whereas interlamellar fracturing (in the middle lamella) was observed in latewood. Similar results are reported by Sedighi-Gilani et al. (2007).

Likewise, the fracture properties of yew wood were investigated in micro-wedge splitting tests by Keunecke et al. (2007), after Keunecke et al. (2006) had found that the stiffness of yew wood is rather low (~9000–10 000 MPa) and that its axial fracture strain is high, even though the density is high (~0.62–0.72 g cm^{-3}). The resulting specific fracture energies in the radial-longitudinal (RT) orientation are similar to those of spruce. This is interpreted as the result of two "opposing" properties, namely the higher strength of yew and its lower elasticity compared with spruce. The observed high fracture toughness may be explained as a consequence of strongly pronounced fibre bridging. This together with the narrow growth rings of yew prevents unstable crack propagation and causes stepwise crack advance.

Sedighi-Gilani et al. (2007) investigated softwood fracturing at the fibre level both experimentally and numerically. Mode I fracture experiments were performed on small softwood samples in the RT orientation, and initiation and propagation of cracks was observed by confocal laser scanning microscopy. A three-dimensional (3D) mixed lattice-continuum fracture model, based on lattice fracture models of Van Mier (1996) for concrete and sandstone and Landis et al. (2002), considers the porosity of wood and heterogeneities at the fibre level. Numerical and experimental results are compared, and the stress-displacement curves and crack opening displacements show good agreement. The location and development of microcracks, as well as of a main crack, may be determined substituting different beam elements of the lattice (Sedighi-Gilani et al. 2006) to represent earlywood or latewood fibres, ray cells and the bonding medium between the fibres. Microscopic observations show initial damage to be localised mostly around a few cells.

Correlation of the fracture characteristics with the R-curve behaviour is useful, besides characterisation of fracture and fracture surface features by means of different methods, such as SEM, X-ray spectroscopy, laser 3D roughness measurements, etc. Quantifying the morphology of fracture surfaces and correlation with the anisotropy of crack propagation in longitudinal and transverse directions shows the following: a crack starting from a straight notch exhibits an initial region of the fracture surface, where the roughness increases as a function of the distance of the notch. In the following region, the roughness becomes constant at a value, which depends only on the specimen size (Morel et al. 2002). Relating the morphology of the first region to the R-curve behaviour results in a material-dependent scaling law relative to the critical energy release rate, and experiments verified this result. The saturation region of roughness is characterised by crack propagation with a constant fracture resistance.

The new numerical material point method (MPM) has been proposed by Nairn (2007) to simulate transverse fracture of wood on the scale of growth rings. The MPM discretises a body into material points based on digital images of wood and describes cracks without using a mesh. Simulating cracks in the radial and tangential directions, as well as at two angles to the radial direction, gives good agreement with the observed crack growth directions in different experiments.

Strain rate effects and moisture influence

The influence of strain rate on the fracture toughness is an interesting topic, especially when considered in relation to other biological or polymeric materials. Subcritical crack growth can take place at low strain rates (Conrad et al. 2003), whereas at higher strain rates due to the shorter times being available higher fracture toughness values result. Vasic et al. (2008), who determined experimental fracture resistance curves at deformation speeds between 0.05 and 200 mm min^{-1}, make inertial effects responsible for a doubling of the fracture resistance of softwood at a deformation rate of 200 mm min^{-1} compared with quasi-static resistance at 0.05 mm min^{-1}. These twice-as-high fracture resistances verify the existence of a critical (threshold) deformation rate, above which the viscoelastic response of wood is suppressed, characterising a ductile-brittle transition limit.

The influence of moisture on fracture toughness has been treated and attributed to increased viscoelastic behaviour of wood in the past by Mindess (1977), explaining that more energy is absorbed and a higher toughness results by viscous deformation. More recently, Sinn et al. (2001) took measurements of the non-linear fracture properties of spruce at different moisture contents (MCs) between 7% and above the saturation point at 55% MC. Finite element (FE) simulations were used to obtain the bilinear softening curves. The results show that the specific fracture energy increases with increasing MC and that this is mainly caused by an increased fibre bridging effect.

To model strain rate effects on the fracture properties in wood, Nielsen (1991) developed the damage viscoelastic material (DVM) model to predict the strength of wood under static and variable loads. It is based on the mechanics of crack propagation in wood behaving as a viscoelastic material with a Dugdale-like crack tip. Prior to crack growth, crack tip opening by non-elastic deformation of the material takes place, and it is assumed that crack extension starts at a critical value of the crack opening displacement. In addition, viscoelasticity is considered by assuming power-law creep (Nielsen 2007). A "short time strength" is defined, which is higher than the fatigue strength obtained during longer testing times, and which in practice is obtained by testing within 5 min. With this, the influence of wood quality, loading rate and moisture influence are modelled and predicted. The increase of the influence of testing rate on strength with increasing MC (Nielsen 2007) may be readily explained.

Chaplain and Valentin (2004) treated crack initiation and propagation in laminated veneer lumber (LVL) timber beams under various relative humidity (RH) conditions. The viscoelastic crack propagation model (VCM) and the DVM model by Nielsen (1985) are coupled with a damage initiation model, in order to obtain the total time to failure. It is found that the initiation times are smaller for dry conditions and also when the notched beams were dried before testing. In contrast, the propagation time is smaller for higher MC. For pine wood, increased crack propagation rates are detected in both cases, i.e., if the RH is increased or lowered quickly, whereby air-drying gives a higher increase than air-wetting (Chaplain et al. 2008). In modelling by fracture mechanics, it is assumed that only the process zone is sensitive to fast variations of air humidity.

Moisture plays a very important role in the deformation and fracture properties of wood. As a consequence, changes of moisture have to be considered for indoor as well as outdoor applications, such as for timber beams of roofs, for parquet floors or wood sculptures in heated rooms, especially when both temperature and humidity are changing.

Serrano et al. (2008) studied moisture-induced stresses, deformation and fracture in parquet flooring, considering deformations, delamination of surface layers and development of cracks owing to indoor climatic changes. A strong influence of material and geometry is detected on the deformation and thus delamination and distorsional effects by FE modelling of stresses in the glue line and gap opening of the surface layer, if growth ring orientation, species of the upper wood layer, and the long-term behaviour of the glue line is taken into consideration. Investigations were performed under mode I, II and mixed mode loading (Desjarlais et al. 2006) in order to make estimates of allowable delamination sizes. The background for this is that fibre reinforced polymer glued-laminated (glulam) timber beams might experience some delamination between wood and the reinforcement after long-term exposure to moisture and freeze-thaw cycles. It is demonstrated that the glulam beams can accommodate a significant level of delamination before crack lengths become critical.

Vasic and Stanzl-Tschegg (2007) performed in situ loadings in humid environment by ESEM (Figure 8). Load-displacement curves were recorded of different wood species at different MCs. An increase of MC from 7% to 30% led to a decrease of the fracture toughness of pine and beech and to a strong decrease between 7% and 12% MC in oak and beech in the RL direction. The total fracture energy, however, increased with increased

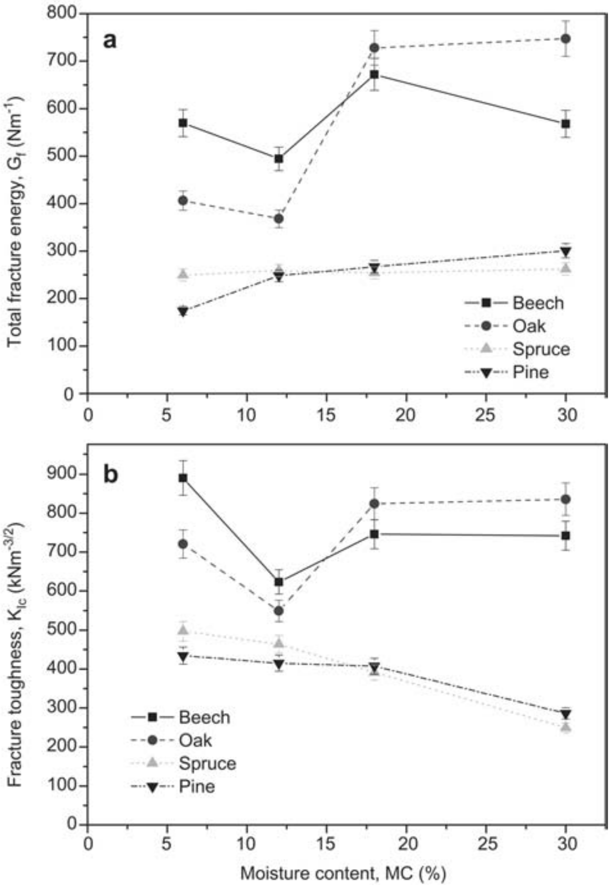

Figure 8 Influence of moisture content (MC) on hard- and softwood in RL direction. Fracture toughness (a) and total specific fracture energy (b) (Vasic and Stanzl-Tschegg 2007).

MC in pine and spruce and decreased only slightly in oak and beech between 7% and 12% MC. The increase of the total fracture energy with increasing MC obviously reflects the moisture-induced higher "ductility" (extensibility) of wood and thus demonstrates the underlying deformation mechanism better than the fracture toughness. Based on the in situ ESEM observation that water droplets from cell lumens move away from the FPZ during loading prior to extension of the crack, it is assumed that stress gradients at the crack tip might have a significant effect on the local moisture distribution by free water flow and vapour diffusion in the vicinity of the crack. Supposedly, the crack propagation resistance in green wood is not influenced by fluid pressure around the crack tip. Distributed damage in the most stressed regions is demonstrated by means of the lattice fracture model, which presumes linear elastic brittle failure of elements perpendicular to the grain.

Fracture studies with in situ ESEM experiments were performed (Vasic and Stanzl-Tschegg 2005) on freshly-cut green wood of spruce, pine, beech and oak at high MC, in which the cell walls are completely saturated with water and where water is also in the cell lumens, in the RL and TR orientations. These and also earlier studies (Frühmann et al. 2003c) showed that the process zones are confined to one or only a few cell rows alongside the crack. A similar result is reported by Sedighi-Gilani and Navi (2007). Tukiainen (2006) measured load-displacement curves with small birch CT specimens and found that specimens with a MC of 14% at 60°C had highest fracture energies in comparison with green wood (MC 60%–68%) and modelled this with the cohesive zone method and with the program FRANC2D in the RT orientation.

Recently, ESEM in situ experiments with the wedge-splitting technique were performed at 95% RH on oak and spruce to correlate fracture resistances (R-curves) with fracture morphology (Vasic and Stanzl-Tschegg 2008). For modelling, the lattice fracture model is applied, which belongs to discrete finite element models and which is capable of introducing material in homogeneities and simulating crack propagation. Mesh, deformed shape, fracture progression and the damage evolution are shown. The lattice indicates distributed damage in the most-stressed regions between the area where a concentrated force is applied and the notch plane where the fracture is initiated.

Modified wood

Fracture mechanical methods have also been applied to characterise artificially modified wood by thermal, chemical and genetic treatments. Heat treatments of spruce wood may lead to a reduction of fracture mechanical properties by approximately 50%–80% (Reiterer and Sinn 2002), whereas the reduction by acetylation is in the range of only 20%. Thermal modifications are performed to obtain higher dimensional stability, mainly reduced swelling and shrinking, and higher durability against environmental changes and against fungus, owing to a reduced water absorption capability induced by a decomposition of hemicelluloses. The elastic modulus is reduced in thermally treated wood (Loidl et al. 2007), and fracture tests (Beikircher 2007) on beech in the RL and TL orientations showed reduced values of fracture toughness K_{IC} and especially fracture energy G_f (Figure 9). Changes of the molecular bonds leading to a decomposition of cellulose, and formation of bonds between cellulose, xylan and lignin in the secondary cell wall structure, as reflected by dynamic Fourier transform infrared spectroscopic investigations (Salmén et al. 2008), are made responsible for the changed load carrying capacity of thermally treated wood.

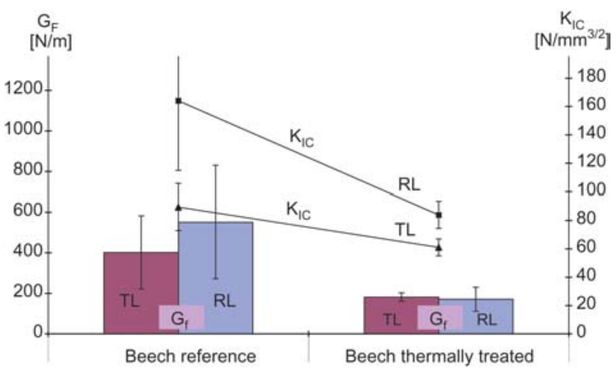

Figure 9 Change of specific fracture energy G_f and fracture toughness K_{IC} by thermal treatment of beech (columns: G_f; dots: K_{IC} with error bars of maximum deviation). Values on the left panel: untreated material, and on the right panel: thermal treatment: 180°C for 4 h (Beikircher 2007).

Wood composites

Extensive studies on the fracture behaviour of different wood composites – such as particleboard, medium density fibreboard (MDF), Parallam PSL and Intrallam LSL with varying particle size – have been carried out under mode I and mode III loading by Ehart et al. (1996, 1998, 1999). Crack resistance curves and from this specific fracture energy (G_f), values were determined with the wedge-splitting technique. The specimen shapes were similar for mode III as for mode I loading, and the crack plane was either perpendicular or parallel to the panel plane. It was demonstrated that a strong mode I contribution arises from fracture surface roughness interactions (Figure 10). The experimental background for this statement: mode I crack opening induced by fracture surface asperities during mode III loading, together with finite element (FE) simulations of the resulting deformation patterns. Figure 10a illustrates the very rough fracture profile of a Parallam specimen, which was broken in a tensile (mode I) test, and Figure 10b the CMODs (dotted curve) in Intrallam LSL induced by this roughness during mode I and mode III superimposed loading, reaching values as high as 17 mm. Typical for all tested materials (also for MDF and particleboard) are linearly

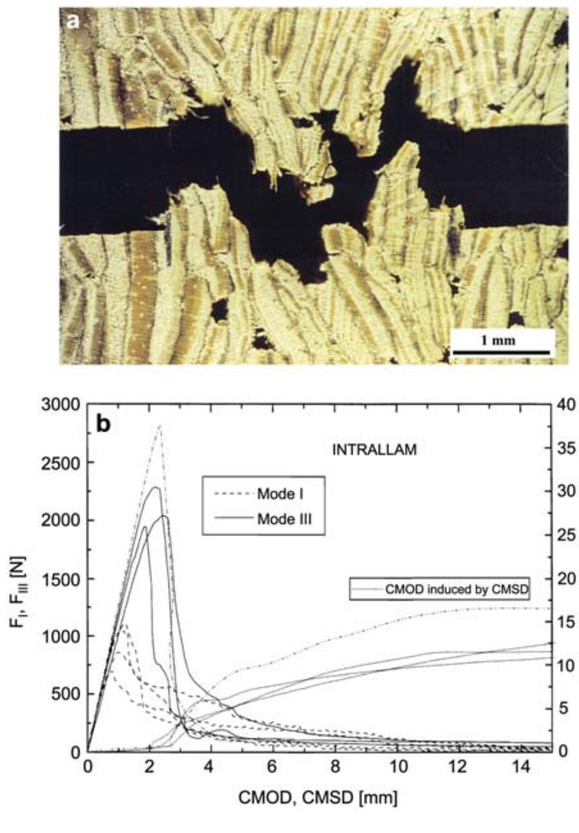

Figure 10 Fracture surface roughness and induced CMODs. Fracture surface profile of Parallam (a). Mode III load displacements (crack mouth sliding, CMSDs, dotted) and induced mode I opening displacements (CMODs, solid) during superimposed (mode I+mode III) loading of Intrallam LSL (b) (Ehart et al. 1998).

increasing values until the maximum mode III load is obtained. This is caused by interlocking of the bridging particles. Once they start to debond, much higher CMODs are observed together with a steep decrease of load as a consequence of the increased mode I component. The crack then propagates in mixed mode or even dominated mode I.

To quantify the effect of mode I opening during mode III loading, the area A_{open} was introduced (Frühmann et al. 2002b). It is the integral of the induced CMOD induced by fracture surface interference along the mode III CMSD and provides information about the roughness of the fracture surface and the induced opening effect. The CMODs reflect quite well the relationship of fibre orientation in LVL and loading direction during loading. All relevant fracture mechanical values could be determined, such as stiffness/compliance, microstructural damage, crack initiation energy, specific fracture energy, etc. (Frühmann et al. 2002b). It is demonstrated that under mode III loading, crack initiation occurs in mode III, whereas crack propagation takes place under mode I owing to crack surface interference.

More recently, Matsumoto and Nairn (2007) performed fracture mechanics experiments, including crack growth measurements on MDF and applied several analysis tools. With this they could show that standard LEFM equations do not work and can be replaced by energy methods.

When characterising the fracture behaviour of wood and wood composites during machining, fracturing alone cannot be considered independently of other processes taking place before and at the same time, such as friction, compressive forces, etc. Therefore, the work of fracture of particleboard was determined in a microtome cutting experiment and compared with the specific fracture energy obtained with wedge-splitting tests (Beer et al. 2005). In addition, density profiles across the thickness of the boards were determined. The results indicate that most of the energy is consumed by creation of chips and increases strongly with their thickness, and only a smaller part of energy is used for the work of fracture. The shapes of the chips, their arrangement in the board and the type of glue influence the energy of cutting more than the density profile of the boards. Moreover, the fracture work during microtome cutting consists not only of the fracture energy (as determined during splitting) but also of friction and compression properties of the cut material.

Analysis of glued joints (1K-PUR) with different adhesives under tensile and shear loading with a video extensometer (Niemz et al. 2007) showed that the ultimate strain of 1K-PUR increases and the shear strength decreases with growing joint thickness. Finite element analysis with commercial software, considering the shear stress components in wood-adhesive bonds, is reported by Serrano and Gustafson (2006). Comparison of the results with experimental findings of pull-out tests on bonded-in rods showed good correlation for all adhesives besides epoxy.

Damage processes in wood-fibre plastic composites have been investigated with microtomography by Watanabe and Landis (2007). They detected by means of 3D imaging processing techniques changes in void and crack structure due to mechanical compressive loading of wet and dry specimens. For wet specimens, a significant increase of larger voids (sizes above 10^5–10^6 μm^3) could be found, which is interpreted as an effect of pore pressure induced when the specimen is under pressure loading. In dry specimens, the majority of damages was in the form of larger cracks, leading to more brittle deformation behaviour.

Outlook

Additional new results, knowledge and understanding of the processes of wood fracturing may be expected during the coming years, as commercial equipment with new testing techniques becomes increasingly available. Techniques are required that enable access to the nanometer level, such as AFM or synchrotron facilities. In situ deformation possibilities may offer additional information and permit direct correlations between morphological features and mechanical behaviour. Further developments in spectroscopic techniques may also provide more insight into chemical structure and chemical changes connected with fracture and damage processes. With new input of experimental results, new modelling possibilities will also arise that will be assisted by further development of computer technology.

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