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Coniform-shape tool for splitting of wooden logs

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Abstract

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The article deals with design of a coniform tool with rotary motion for splitting of logs. The tool is proposed using a fracture mechanics theory. The approach of energy balance during crack growth in a split wood log is applied for construction design of the shape of the splitting tool. The proposal of the tool shape is based on the experimental fracture methods. The only used criteria it is the demand of the minimum quantity of the consumed energy.

Keywords: fracture mechanics; wedge splitting test; fracture energy

Splitting of wood is a process when wood is separated along wood fibres through action of a working tool. The tool causes initiation of the crack and its propagation in the wood tissue. The failure mechanism at splitting of the wood is complicated due to anisotropy of wood material, orientation of wood fibres in a log, due to wood heterogeneity of earlywood and latewood, due to different dimensions and shapes of the split log and also due to shape of the splitting tool. All these factors influence the initiation and propagation of cracks in the log, which in the final stage entails splitting of the log. The problems of crack initiation and propagation are basic questions of fracture mechanics. Researchers with various backgrounds investigate fracture mechanics especially for purposes of design and reliability of structures against the failure. Here the fracture mechanics is used to design a splitting tool with rotation motion which is applied for splitting of wooden logs. A portable tool is proposed for splitting of reclining logs, without need to manipulate with them. A driving gear of the splitting tool is an electromotor and the splitting tool is a wedge with a straight circular cone shape. The penetration of the tool in the wooden material is caused through the medium of a thread on the coniform surface of the rotating splitting tool. The basic idea at design of the splitting tool was to attain min. energy consumption.

Pioneering studies regarding fracture mechanics were developed by Griffith (1921) and Irwin (1948). Griffith developed a theory for an infinite plate containing a crack and subjected to uniform stress. Drawing upon the concept of potential energy, Griffith showed that for every level of applied stress, there is a critical value for the crack length. At this value, the system is at a max. of potential energy, meaning that if the stress or the crack length is increased above this condition, the system will reduce its potential energy by increasing the crack length, basically developing a failure. Irwin introduced the concept of stress intensity factor and strain energy release rate. Critical values of stress intensity factor and strain energy release rate are material attributes that characterize the resistance to elastic fracture. The critical strain energy release

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is the amount of energy per unit of area required to create new crack area.

Griffith's energy balance approach and stress intensity factor concept are fundamental theories of linear elastic fracture mechanics. Linear elastic fracture mechanics is strictly applicable to highly brittle materials and other materials at which failure occurs in an elastic range.

The two mentioned concepts are widely used to analyse the correlation among crack growth, material properties, and input test parameters, which include the imposed displacements or loads. In general case, a crack can grow in different directions due to different kinds of loading. In case of the splitting, the load acts perpendicular to the crack plan and this mode of fracture is so called mode I (opening or cleavage mode).

The concept of the strain energy release rate comes from an energetic approach with elastic deformation hypotheses (Orowan 1970). When external loads are applied to a cracked system crack propagates, part of the work given by the loads is stored in the system as elastic energy and part is spent in propagation of the crack. The available energy for crack propagation equals:

$$G\mathrm{d}A = \mathrm{d}W - \mathrm{d}U \qquad (1)$$

where:

G – strain energy release rate (J/m^2)

dA – infinitesimal propagation of crack area (m^2)

dW – work of the external forces (J)

dU – variation of stored elastic energy (J)

A large amount of literature has described fracture in homogenous and isotropic materials. Fracture often occurs with nucleation of a crack that then grows and can lead the material to complete failure. Nucleation may occur at points with stress concentrations or singularities in the material. These points are dependent on material properties, discontinuities, presence of voids, of flaws and of the other irregularities, which also influence the nucleation and propagation phases.

Analytical and experimental analysis of fracture mechanics properties in orthotropic materials was performed by Sih at al. (1965) and Wu (1967) who independently found that, comparing orthotropic with isotropic materials, the stress distributions at the crack tip have singularities of same order and also the stress intensity factors are similar. A review of fracture propagation in orthotropic materials, such as wood, is presented by Boone et al. (1987). Porter (1964) focused on the critical strain energy release rate and concluded that in white pine the critical value of G along the tangential direction is higher than in the radial direction. Danielsson and Gustafsson (2011) presented and applied a probabilistic fracture mechanics method, which is based on combination of Weibull weakest link theory and a mean stress method. Within the frame of the linear elastic fracture mechanics van der Put (2007, 2011) proposed a new fracture mechanics theory of wood. This theory is based on using of a new orthotropic – isotropic transformation of the Airy stress function, Wu-mixed mode I–II fracture criterion and of the failure criterion of a flat elliptic crack.

In elastic-plastic fracture mechanics the local stress field around the crack tip is expressed by J-integral. Hence, for the case of I fracture mode, the energy release rate G generally can be computed by J-integral, as is given in Rice (1968).

In conjunction with Eq. (1) it is necessary to distinguish between fracture process with steady state crack propagation and with unsteady state motion of the crack. The steady state crack propagation is required for finding of the material attributes as critical stress intensity factor or specific fracture energy.

The fracture energy for pure mode I crack extension in wood is equal to the elastic energy change caused by this crack extension. As a result of the low strength, strong elastic anisotropy and high brittleness of wood when subjected to tension load perpendicular to the grain, the predominant direction of crack propagation is along the grain, in the radial-longitudinal (RL) and tangential-longitudinal (TL) crack propagation system (R and T, respectively, indicating the direction of the crack plane normal and L the direction of crack propagation).

MATERIAL AND METHODS

It was shown that application of linear elastic fracture mechanics is a useful tool to characterize crack initiation and propagation in wood. The fracture toughness K_{IC} characterizes the max load which is endured by the material before a crack starts. Slope of the load-displacement diagram characterizes the deformation behaviour before crack initiation. All

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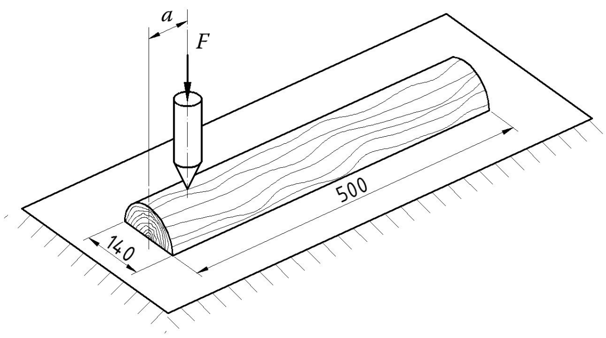

Fig. 1. Sketch of splitting test with the coniform tool

needed information about crack propagation in the crack opening mode (mode I) can be derived with using of the wedge-splitting technique from the recorded load-displacement diagram; it does not only allow determining the specific fracture energy G_f (fracture toughness) but also the total fracture energy which is needed to split a specimen completely. The specific fracture energy is obtained from the integral area under the load-displacement curve divided by the fracture area. The specific fracture energy, as well as the total fracture energy, characterizes the whole fracture process until the wooden log is split into two parts, but this one, in contrast to the total fracture energy, does not depend on size and shape of the split specimen.

In order to obtain the fracture energy, the whole load-displacement curve had to be recorded. The fracture energy was calculated from the area integral below the recorded load-displacement curve. The testing at the wedge splitting technique consisted of pressing of the coniform wedge against wood specimen in a standard material-testing machine (Fig. 1). The testing machine (Testometric M500-100CT; Testometric Co. Ltd., Lancashire, UK) measured and recorded the acting loading force F and displacement Δl of the wedge in the line of the load force action. Taking into account that the results of the testing are used for construction design of the shape of the splitting tool, the effect of the friction at realization of the test was not minimized. It is one of reasons, why the crack propagations in our tests were unstable.

The characteristic shape of the obtained load-displacement curves of realized experiments is depicted in Fig. 2. In order to distinguish between crack initiation and propagation as to their energy consumption, the recorded area bellow the load-displacement curve may be subdivided into two parts (Ehart at al. 1996; Majano-Majano at al. 2012). The first part is the crack initiation energy, G_{init}, which is dissipated in the crack initiation phase. There are two theories to interpret the nonlinear behaviour of the load-displacement curve (sections O-A and B-C). The first theory is a theory of plastic deformations and the second theory of forming microcracks, which leads to the generation of a macrocrack (Ehart at al. 1996). Here the so called "plastic model" is used, in which the crack initiation energy is considered as energy consumed on creation of plastic deformations. In this case, the crack initiation energy is proportional to the area under the line destined from origin of the curve to the point of the max. load and a parallel line from maximum load to linear part of the line (section A-B) on the curve (Ehart at al. 1996) (area O-A-B-C-D-O). Characteristic feature of load-displacement diagram for splitting with coniform surface splitting tool is a nonlinear part of the load-displacement curve from origin O of the curve to point A. Therefore the slope of the linear part of the curve is defined through the medium of coordinates of points A and B in the load-displacement diagram. Points A and B designate the beginning and ending of the linear part of the curve, respectively, point C is the point with the max. measured load.

The second part of the overall consumed energy is the energy needed for crack propagation, G_{prop}. It can be obtained by subtraction of the crack initiation energy G_{init} (area O-C-D-O) from the total fracture energy (area O-C-M-O). The energy in-

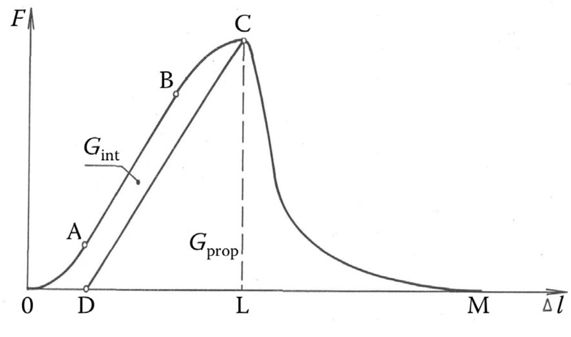

Fig. 2. Total fracture energy and its parts (Ehart et al. 1996) F – loading force; A – beginning of linear part of the line; B – ending of linear part of the line; C – max. measured load; D – permanent displacement; M – total displacement of the wedge; L – displacement responsive to max. load; G_{init} – crack initiation energy; G_{prop} – crack propagation energy; Δl – displacement of the wedge

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flicting the crack propagation consists of the elastic energy (area D-C-L-D) and remaining energy (area C-L-M-C) (Ehart at al. 1996). The elastic energy is dissipated during crack propagation.

In this manner the supplied work *W* (area O-C-M-O) by the coniform wedge was consumed on crack initiation and crack propagation. It can be said that splitting of logs in our tests was convoyed by energy dissipation in both parts of crack formation – in the crack initiation phase as well as in the crack propagation phase.

The experimental tests were carried out on samples made of beech (*Fagus sylvatica*) wood. All performed experiments were carried out with specimen of moisture content above fibre saturation point. The testing specimens were dimidiate logs of a diameter 140 mm and of a length 500 mm. The used splitting tool was the steel coniform wedge of a straight circular cone shape with apex angle of 40, 60, and 80°. Fig. 1 shows a simplified description of the wedge splitting test. The acting loading force *F* and displacement Δl in the line of action of the loading force were measured and recorded by the testing machine Testometric M500-100 CT. Within the framework of one measurement over six thousands couples of measured values of forces and displacements were recorded. A distance *a* of the wedge axis from the boundary of the log in presented experiments was 50 mm.

RESULTS AND DISCUSSION

One of the essential factors at designing of the tools is attainment of min. energy consumption needed for its working activity. The predesign of

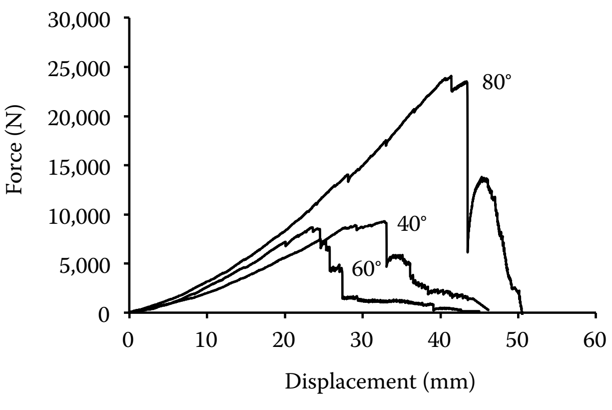

Fig. 3. Load-displacement curves of the splitting test for different apex angles of the tool

the shape of the coniform splitting tool for splitting of the wooden logs is carried out here using the knowledge of the fracture mechanics. The total work of the external force is calculated with using of the energy balance approach from the measured values of the acting force on the wedge and its displacements. The work of the acting external force caused plastic deformations of the split wood, produced microcracks and formalized the notch as a contact patch after splitting tool, and the remaining part was accumulated in split log as the stored elastic energy. When the stored elastic energy achieved the energy which is necessary to propagate the crack, the elastically stored energy was dissipated during crack propagation. The load-displacement curves determined for wedge apex angle of 40, 60, and 80° are depicted in Fig. 3. Given manner of splitting is combination of transverse TR and TL crack propagation systems. While the load-displacement curves of the hardwoods in RL crack propagation system are the same as for linear elastic brittle materials (Stanzl-Tschegg 2006), these load-displacement curves indicate on elastic-plastic behaviour of the beech wood. The unsteady crack motions are visible in load-displacement curves by abrupt slump of the loading force. At carrying out of the experiments it was beheld that the first crack propagation was mainly along radial line and subsequent propagation of crack was along of wood fibre. This phenomenon is well visible on curve for $\alpha = 80°$, when after the first rupture (mostly in radial direction) the loading force was able once again to increase on high level. The abrupt decrease of the loading forces that is visible in Fig. 3 means reduction of the accumulated elastic energy, propagation of the crack and rupture of the wooden log. The large drops of the acting forces are coupled with rupture in longitudinal direction. The total work *W* of the external forces, crack initiation energy G_{init}, elastic part of the crack propagation energy $G_{prop-el}$ as well as the remaining part of the crack propagation energy $G_{prop-rem}$ are calculated from the recorded data for the load-displacement curve at all judged apex angles of the coniform splitting tool. Average values of the given energies and their percentage are given in Table 1. The tool with apex angle 80° is the worst from the point of the consumed energy as it is evident form calculated energies; it consumed multiple more energy than the other apex angles. The best tool from the same point of view is the tool with apex angle 60°. Consumed energy at splitting with

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Table 1. Energy contribution during the fracture process

Apex angle (α)	W		G_{init}		$G_{prop-el}$		$G_{prop-rem}$	
	(J)	(%)	(J)	(%)	(J)	(%)	(J)	(%)
40°	151.0	100	22.1	14.63	91.2	60.42	37.7	24.95
60°	124.7	100	11.1	8.93	69.5	55.76	44.0	35.31
80°	678.7	100	103.7	15.29	480.0	70.68	95.2	14.03

W – work of external forces; G_{init} – crack initiation energy; $G_{prop-el}$ – elastic crack propagation energy; $G_{prop-rem}$ – remaining crack propagation energy

this tool was the least, though the difference in total energy of this tool and the tool with 40° angle is not large. As we can see, the most part of energy (more than 50%) was dissipated as elastic energy needed for crack propagation at all considered cases. The least differences are between the remaining crack propagation energy. Main reasons for differences in particular energy components are unsteady state of crack motion in given fracture process, combination of radial and transverse crack propagation systems that cause the crack propagation along grain and varied magnitudes of acting forces (caused with a change of angle α) that realize the mode I crack extension in wood.

CONCLUSION

Proposal of the apex angle of the coniform-shape tool for splitting of wooden logs is made using the fracture mechanics. Three apex angles in combination with two propagation systems, RL and TL, on mode I fracture behaviour of beech were evaluated using the splitting test. The load-displacement diagrams were used to determine the energy contribution during fracture process. Calculated energies from data of the experiments carried out allocate the best apex angle of the coniform splitting tool from the point of consumed total energy. The best apex angle of the splitting tool, out the considered cases, is 60°. The next observations can be oriented on search of the optimal point of action of the tool.

In most cases the experimental fracture methods are used for study of fracture properties of different materials. Merhar and Bučar (2012), Orlowski at al. (2013) use the fracture mechanics for estimation of energetic effects of wood sawing. Here the use of the fracture mechanics and the experiments as a background for design of a working tool are shown. Knowledge on the fracture mechanics can be used also for non-traditional purposes. It is needed, however, to look for the possibility of their advantageous application.

References

Boone T.J., Wawrzynek P.A., Ingraffea A.R. (1987): Finite element modelling of fracture propagation in orthotropic materials. Engineering Fracture Mechanics, 26: 185–201.

Danielson H., Gustafsson P.J. (2011): A probabilistic fracture mechanics method and strength analysis of glulam beams with holes. European Journal of Wood and Wood Products, 69: 407–419.

Ehart R.J. A., Stanzl-Tschegg S.E., Tschegg E.K. (1996): Characterization of crack propagation in particleboard. Wood Science and Technology, 30: 307–321.

Griffith A.A. (1921): The phenomena of rupture and flow in solids. Philosophical Transactions of the Royal Society of London, Series A, 221: 163–198.

Irwin G.R. (1948): Fracture dynamics. Fracturing of metals. In: Proceedings of the ASM Symposium on Fracturing of Metals, Cleveland, 40 A: 147–166.

Majano-Majano A., Hughes M., Fernandez-Cabo J.L. (2012): The fracture toughness and properties of thermally modified beech and ash at different moisture contents. Wood Science and Technology, 46: 5–21.

Merhar M., Bučar B. (2012): Cutting force variability as a consequence of exchangeable cleavage fracture and compressive breakdown of wood tissue. Wood Science and Technology, 46: 965–977.

Orlowski K.A., Ochrymiuk T., Atkins A., Chuchala D. (2013): Application of fracture mechanics for energetic effects predictions while wood sawing. Wood Science and Technology, 47: 949–963.

Orowan E. (1970): The physical basis of adhesion. Journal of the Franklin Institute, 290: 493–512.

Porter A.W. (1964): On the mechanics of fracture in wood. Forest Products Journal, 14: 325–331.

doi: 10.17221/47/2013-RAE

Rice J.R. (1968): A path independent integral and the approximate analysis of strain concentration by notches and cracks. Journal of Applied Mechanic, 35: 379–386.

Sih G.C., Paris P.C., Irwin G.R. (1965): On cracks in rectilinearly anisotropic bodies. International Journal of Fracture, 1: 189–203.

Stanzl-Tschegg S.E. (2006): Microstructure and fracture mechanical response of wood. International Journal of Fracture, 139: 495–508.

van der Put T.A.C.M. (2007): A new fracture mechanics theory for orthotropic materials like wood. Engineering Fracture Mechanics, 74: 771–781.

van der Put T.A.C.M. (2011): A New Fracture Mechanics Theory of Wood. New York, Nova Science Publishers, Inc.

Wu E.M. (1967): Application of fracture mechanics to anisotropic plates. Journal Applied Mechanics, 34: 967–974.

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