Examination the Failure Behavior of Agathis Wood by MOde I Single Edge-Notched Bending Test

by Cicilia Susanti

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Kehutanan Tropika
Jalan Gunung Salju, Amban
Phone: 0986 211065
Fax: 0986 211 065
E-mail: kehutanan.tropika@gmail.com

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Isu-isu terkini kehutanan di daerah timur Indonesia tentunya selain berkisar diantara ekplorasi biodiversitas juga setrahap demi setahap meluas ke bidang lainnya terutama dalam bidang pemanfaatan hasil hutan, interaksi antara hasil hutan dengan lingkungan dan bagaimana manusia mempunyai kearifan tersendiri dalam mengelola hutannya.

Isu-isu tersebut diangkat dalam volume tahun ini, dengan harapan bahwa tulisan-tulisanyang hadir di hadapan saudara pembaca dapat menjadi pengisi di antara kekosongan dan gap informasi mengenai isu kekeinian kehutanan di tanah Papua. Selain itu, diharapkan dengan hadirnya jurnal ini, bisa menjadi jembatan antara praktisi pendidikan dan penelitian dengan praktisi kebijakan dalam hal ini pemerintah yang sedang menjalankan tughasnya dalam rangka membangun tanah Papua menuju ke kehidupan yang lebih baik.

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Telp/fax (0986) 211065, 211364
Email: kehutanan.tropika@unipa.ac.id

EXAMINATION THE FAILURE BEHAVIOUR OF AGATHIS WOOD BY MODE I SINGLE EDGE-NOTCHED BENDING TEST[1]

Cicilia Maria Erna Susanti[2], **Tetsuya Nakao**[3] and **Hiroshi Yoshihara**[3]
[2]Forestry Faculty of the State University of Papua
[3]Faculty of Science and Engineering, Shimane University

[1] Part of this report was presented at the 60th Annual Meeting of Japan Wood Research Society, Miyazaki, March 17-19, 2010

ABSTRAK

Berbagai penelitian sifat fraktur kayu berdasarkan konsep mekanika perpatahan telah dibahas dalam beberapa ulasan terakhir, oleh karena itu fraktur properti di kayu masih dianggap sangat penting untuk dilakukan penelitan. Tunggal tepi berlekuk-lentur (Senb) adalah salah satu model dalam mode I dalam pengujian mekanika. Dalam tulisan ini, dibahas mengenai fenomena fraktur agathis kayu (Agathis sp.) pada arah (RL) sistem tangensial-radial (TR) dan radial-longitudinal dengan menggunakan pengujian tunggal tepi-berlekuk. Dari penelitian didapatkan bahwa sifat fraktur kayu dapat diperoleh dengan menggunakan konsep mekanika fraktur, meskipin patahan yang terjadi sangat singkat. Kekuatan σnc nilai lentur dan faktor KIC modus I stres intesity kritis spesimen kayu agathis dipengaruhi oleh panjang retak. Jika tidak, intensitas tegangan konstan kritis faktor nilai KIC dapat diprediksi dengan menggunakan celah panjang Δ tambahan yang diperoleh dengan rata-rata semua data termasuk panjang retak a = 0, dan dengan menggunakan panjang retak Δ tambahan, kita dapat *memprediksi nilai kekuatan lentur σn serta intensitas* tegangan KIC faktor penting berdasarkan nilai mekanika patahan

ABSTRACT

The various studies of the fracture properties of wood based on the fracture mechanics concepts have been discussed in several recent reviews, therefore fracture properties in wood is still a great need for investigation. Single edge-notched bending (SENB) is one of the uncomplicated models in mode I fracture mechanics testing which easy to conduct even with a short crack. In this paper, the fracture phenomenon of agathis wood (**Agathis** sp.) in the tangential-radial (TR) and radial-longitudinal (RL) systems were conducted by the single-edge-notched testing. The research found that the fracture properties of wood can be obtained by using fracture mechanics concept, even when the crack is short. Bending strength value σ_{nc} and the mode I critical stress intesity factor K_{IC} of agathis wood specimens were affected by the length of the crack. Otherwise, constant critical stress intensity factor value K_{IC} can be predicted by using the additional crack length Δ which is obtained by averaging all data including crack length $a = 0$, and by using additional crack length Δ, we can be predict the bending strength σn value as well as the critical stress intensity factor K_{IC} based on fracture mechanics value.

Keywords: failure behaviour, agathis, Mode.I, SENB

INTRODUCTION

Previously, Porter (1964) explore the mechanics in wood based on fracture mechanics theory. Then, the various studies of the fracture properties of wood based on the concepts have been conducted, and many of these studies are discussed in several recent reviews (Patton-Mallory and Cramer, 1987; Le-Ngoc and McCallion, 1997; Dourado *et al.*, 2008), therefore fracture properties in wood is still a great need for investigation.

Wood is a complex and highly anisotropic materials, hence the wood has inherent natural crack itself, examples the shape of wood cell, pores, knots etc. In actual case of timber engineering and wood drying, the crack length in wood are often short. Otherwise, it is difficult to find any examples of studies that examine the fracture properties of specimens with short crack lengths, perhaps because it is assumed that the theory of fracture mechanics is not applied to material with a short crack. From the previous research, the strength of wood with a crack, even when a small crack, has significant different with un-cracked wood specimen (Susanti *et al.*, 2010^{a,b}; Susanti *et al.*, 2011; and Nakao, *et al.*, 2011).

Mode I is a simple method in fracture mechanics testing to obtain the rupture behaviour of materials. From many model can be used to investigate the opening behaviour of materials include wood, single edge-notched bending (SENB) is one of the uncomplicated models which easy to conduct even with a short crack. Many researcher suggested that SENB is a model for determining the value of K_{IC} based on finite element analysis (FEA) (Walsh, 1972 Valentin and Adjanaohoun, 1992). Beside, Susanti *et al.* (2010^{b}) suggested that the fracturing mechanics theory can be described the failure behaviour of wood with a very short crack. Therefore, in this paper, for examining the fracture phenomenon of agathis wood (*Agathis* sp.) in the tangential-radial (TR) and radial-longitudinal (RL) systems, the single-edge-notched model specimen was used.

Three-point single-edge-notched bending test

The schematic diagram of the three-point single-edge-notched bending (SENB) test showed in Fig. 1. The specimen had a crack at its center with the configuration of the specimen shows in Table 1. It was supported with a span of S, and the load was applied at the mid-span. The crack length is defined as *a*. in this loading condition. The nominal bending stress σ_n is derived from elementary beam theory as follows:

$$\sigma_{\mathrm{n}} = \frac{3SP}{2BW^2} \tag{1}$$

where *P* is the applied load, *B* and *W* are the beam width and depth, respectively. This notation is applicable to the crack-free specimen. When the crack-free specimen is bent, the failure-by-bending moment is induced when σ_n reaches its critical value σ_{nc}, which is usually defined as the "bending strength" of the material.

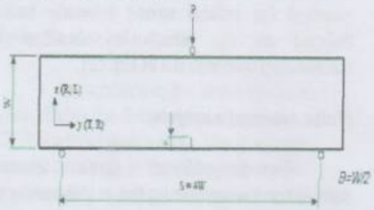

Fig. 1. The schematic diagram of the threepoint single-edge-notched bending (SENB) test.

Irwin *et al.* (1958) explained that σ_{nc} has been thought to be constant in the range of short crack. When the crack length is large, however, the value of σ_{nc} decreases with increasing crack length. Therefore, the fracture behavior of a material with a long crack should be analyzed using the mode I stress intensity factor K_I or the energy release rate G_I, each of which is derived based on fracture mechanics theory. The value of G_I can be determined based on energy considerations of material and is mathematically well defined, while K_I is regarded as a localize parameter which is influenced by micro-structural local anisotropy (Morel *et al.*, 2005). The measurement of G_I, which requires the load-deformation relation corresponding to the crack length, is preferable to that of K_I. If G_I is measured by the SENB test, compliance calibration method in which the loading-line compliance, crack length relation is required, is usually adopted. In the SENB test of the specimens with a short crack, however, it is difficult to obtain this relation appropriately because the loading-line compliance does not vary with varying the crack length so the loading-line compliance/crack length relation is not appropriately determined. In contrast, K_I, for which the load-deflection relation is not required, is more easily measured using an approximating equation than is G_I in spite of the less mathematical rigorousness.

Mode I stress intensity factor K_I is derived using the following equation:

$$K_{\mathrm{I}} = \sigma_{\mathrm{n}} \sqrt{\pi a}\, f\left(\frac{a}{W}\right) \tag{2}$$

where *f(a/W)* is the crack geometry factor, which is usually determined by finite element calculations. The fracture is initiated when K_I reaches the critical stress intensity factor, defined as K_{Ic}, which is obtained by substituting σnc into σn in Eq. (2).

Finite element analysis

Two-dimensional finite element calculations were conducted to determine the crack geometry factor *f(a/W)*. The finite element analysis was conducted with the configuration are shows in Table 1. Fig. 2. shows the finite element mesh of the SENB specimen. The depth of the models, *W*, had values of 15, 30, and 60 mm corresponding to models with spans *S* of 60, 120, and 240 mm, respectively. The mesh was refined so as to be finer closer to the crack tip, as shown in Fig. 2.(b) and Fig. 2.(c). The elastic properties used in the calculations were according to experiments which determined by the vibration and compression tests based on the elastic properties of agathis wood based on (Susanti *et al*., 2010[b]).

Table 1. Specimen configurations used for the SENB tests *and* finite element analyses.

Specimen type	Span *S* (mm)	Depth *W* (mm)	Width *B* (mm)	Crack length *a* (mm)	
				TR	RL
A	60	15	7.5	0, 0.5, 1, 2, 4, 5	0, 0.5, 1, 2, 4
B	120	30	15	0, 0.5, 1, 2, 4, 6, 9, 12	0, 0.5, 1, 2, 4
C	240	60	30	0, 0.5, 1, 2, 4, 8	0, 0.5, 1, 2, 4

The models were supported in the vertical direction at $y = 3$, 6, and 12 mm and $y = 63$, 126, and 252 mm for the models with depths of 15, 30, and 60 mm, respectively, and a vertical displacement u_X of 1 mm was applied at the node located at the top of the mid-span.

Mode I and mode II strain energy release rate components were calculated using the two-dimensional virtual crack closure technique (VCCT) as follows (Rikards *et al*., 1998):

$$\begin{cases} G_I = \dfrac{F_y^j \delta_y^j}{2B\Delta a} \\ G_{II} = \dfrac{F_x^j \delta_x^j}{2B\Delta a} \end{cases}$$

where F_X^j and F_y^j are the nodal forces at the crack tip node *j* in the *x*- and *y*-direction, respectively. Besides, δ_X^j and δ_y^j are the relative displacements between nodes *i* and *i'*, which are located at a distance Δa (= 0.0125 mm) behind the crack tip in the *x*- and *y*-directions. In the calculations, the mode II strain energy release rate component was equal to zero, so the fracture mechanics behaviors could be regarded as the pure mode I condition.

The value of G_I obtained by the VCCT was transformed into the mode I energy release rate K_I by the following equations (Morel *et al*., 2005):

$$K_I = \sqrt{\frac{E_x G_I}{c_1}}$$

where E_X is Young's modulus in the *x*-direction, and

$$c_1 = \frac{1}{\sqrt{2}}\sqrt{\frac{E_x}{E_y}}\sqrt{\sqrt{\frac{E_x}{E_y}} + \frac{1}{2}\left(\frac{E_x}{G_{xy}} - 2v_{xy}\right)}$$

where E_y is Young's modulus in the *y*-direction and G_{xy} and υ_{xy} are the shear (3) modulus and Poisson's ratio in the *xy*-plane, respectively. The crack geometry factor *f(a/W)* is derived from Eqs. (1), (2), and (4), as follows:

$$f\left(\frac{a}{W}\right) = \frac{2BW^2}{3SP\sqrt{\pi a}}\sqrt{\frac{E_x G_I}{c_1}}$$

By substituting the total load applied to the finite element model *P* and G_I as calculated by the VCCT into this equation, the value of *f(a/W)* corresponding to the equivalent crack length *a/W* was obtained.

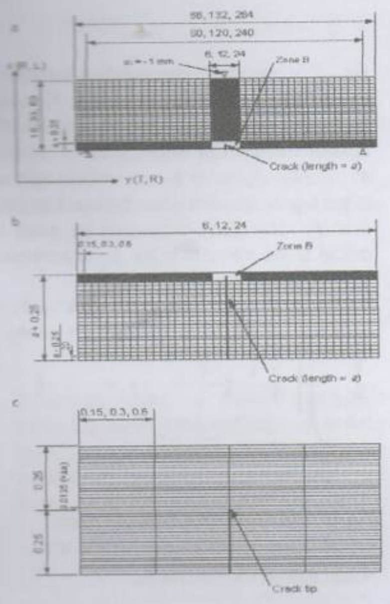

Fig. 2. The finite element model used for the SENB test analysis. (a) Overall mesh, (b) detail of zone A in (a), and (c) detail of zone B in (b). The crack length *a* is shown in Table 1.

METHODOLOGY

Agathis (*Agathis* sp.) is one of tropical wood species which has unclear annual rings, therefore it was used in this experiment. I this experiment, agathis lumber with average density 530 kg/cm^3 was used. The lumber has no defect and the specimens cut from it were being regarded as small and clear specimens. It was stored for several months in a room temperature (around 20^{o}C) before cutting into small specimens. Then, it was confirmed to be in the air-dried condition which was maintained to the testing condition.

The configuration of specimen dimension shows in Fig. 1. Besides, the dimension of specimens was used in this experiment shown in Table 1. Four to ten specimens were used for each condition. In the single edge-notched bending testing, the load was applied with crosshead speed 1 mm/min for the test with span lengths of 60 and 120 mm, and 2 mm for the test with the span length of 240 mm. The test was conducted until the load markedly decreased. The critical load P_c was determined as the maximum load.

Finite Element Analysis

For obtaining the crack geometry factor, *f(a/w)* the finite element analysis VCCT method was used. The the finite element analysis in the TR system was found that the crack geometry factor, *f(a/w)* shows in Fig. 3.

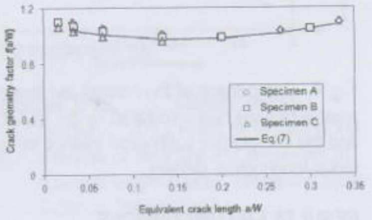

Fig. 3. Relationships between the crack geometry factor *f(a/W)* and the equivalent crack length *a/W* obtained by the VCCT method in the tangential-radial system and Eq. (7) proposed by Gross and Srawley (1965).

There was a concern that the orthotropy of the wood might influence the crack geometry factor. However, Fig. 3 shows that the relationship between the crack geometry factor, *f(a/W)* and the equivalent crack length a/W obtained by the VCCT which is so insignificant with the Eq. (7). Hereafter, for this paper the crack geometrical factor *f(a/W)* in Eq. (2) for tangential-radial and radial-longitudinal systems was used the equation proposed by Gross and Srawley (1965).

$$f\left(\frac{a}{W}\right)=1.09-1.735\left(\frac{a}{W}\right)+8.20\left(\frac{a}{W}\right)^2-14.18\left(\frac{a}{W}\right)^3+14.57\left(\frac{a}{W}\right)^4 \qquad (7)$$

Thus, K_I is derived as follows:

$$K_I=\frac{3SP}{2BW^2}\sqrt{\pi a}\left[1.09-1.735\left(a/_W\right)+8.20\left(a/_W\right)^2-14.18\left(a/_W\right)^3+14.57\left(a/_W\right)^4\right] \qquad (8)$$

Fig. 4. compares of the normalized strain energy release rate G_I/P^2 calculated by the VCCT and G_{Total}/P^2 calculated by the

compliance calibration method of agathis wood in radial-longitudinal system. Note that the value of G_I/P^2 and G_{Total}/P^2 are similar and the value of G_{Total} can be regards as G_I and indicated that the fracture toughness G_I can be measured by the compliance calibration method.

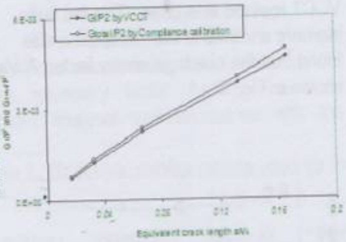

Fig. 4. Comparison of the normalized strain energy release rate calculated by the VCCT and the compliance calibration method in radial-longitudinal system.

RESULTS AND DISCUSSIONS

Fig. 5 shows the nominal bending strength, σ_{nc} of the agathis wood measured by mode I SENB in tangential dan radial and radial-longitudinal systems according to Eq. (1). There was show the differences of the strength of wood specimens between un-cracked and cracked specimens, even when a short crack. The bending strength values of the un-cracked specimens have differences with the cracked specimens for all type. The cracked specimens up to 4 mm show the constant line of the bending strength value. Fig. 5 shows that the specimens at tangential-radial system are highest bending strength value than radial-longitudinal system. Although, the propagation in the tangential-radial and radial-longitudinal are through cell fracture (Conrad *et al.*, 2003).

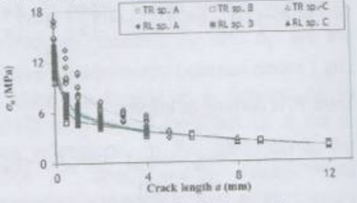

Fig. 5. The relationship between the nominal bending strength, σ_n and crack length *a* obtained from eq. (1)

Fig. 6 shows the corresponding between mode I critical stress intensity factor, K_{IC} and the crack length *a* for TR and RL systems of agathis wood. The dependence of critical stress intensity factor K_{IC} on crack length *a* is still significant even when the crack length is short. The graph shows that the mode I critical stress intensity factor K_{IC} is increase with increasing the length of crack.

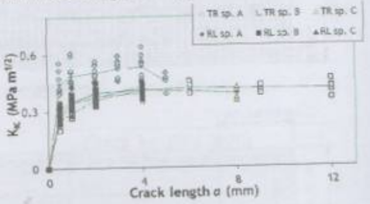

Fig. 6. The relationship between mode I critical stress intensity factor K_{IC} and crack length *a* obtained from Eq. 8.

When the critical stress intensity factor K_{IC} was calculating from true crack length, the un-cracked specimens were equal with zero. By giving a slight crack, the critical stress intensity factor K_{IC} become increasing. By adding crack length *a* with some additional crack length Δ the critical stress intensity value become a constant line. Actually, by adding a small value of crack length as non-experimentally, we can be determining the inherent properties from the materials. Wood is a natural material with heterogeneous properties that affected by wood cell and chemical component of wood. As natural, wood has the inherent crack and artificial crack affected by wood processing. The method which used to determine the additional crack length was proposed by Susanti *et al.* (2010). Therefore, the additional crack length *Δ of* agathis wood shows in Table. 2.

Table 2. The additonal crack Δ of agathis wood by using SENB in TR and RL systems.

	TR System	RL system
Specimen A	0.38 mm	0.25 mm
Specimen B	0.31 mm	0.33 mm
Specimen C	0.44 mm	0.33 mm

The mode I critical crack length with additional crack length Δ can be obtained by following equation:

$$K_{IC} = \sigma_n \sqrt{\pi(a+\Delta)} f\left(\frac{a+\Delta}{W}\right) = \sigma_n \sqrt{\pi a'} f\left(\frac{a'}{W}\right) \tag{9}$$

Otherwise, based on fracture mechanics value, the bending strength value σ_{nc} and the mode I critical stress intensity factor K_{IC} can be obtained directly by using additional crack length Δa as shows in Fig. 7.

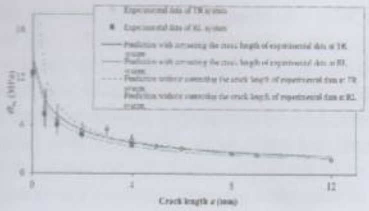

Fig. 7. The relationships between the nominal bending strength σ_{nc} and the crack length a obtained from Eq. (1) and (9).

CONCLUSIONS

1. The fracture properties of wood can be obtained by using fracture mechanics concept, even when the crack is short.
2. The bending strength value σ_{nc} and the mode I critical stress intensity factor K_{IC} of agathis wood specimens were affected by the length of the crack
3. Constant critical stress intensity factor value K_{IC} can be predicted by using the additional crack length Δ which is obtained by averaging all data including crack length $a = 0$
4. By using additional crack length Δ, we can be predict the bending strength σ_n value as well as the critical stress intensity factor K_{IC} based on fracture mechanics value.

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