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Effects of Loading Speed and Moisture Content on Crack Propagation in the Radial Direction of Wood *1

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木材の半径方向のき裂進展におよぼす負荷速度と含水率の影響*1

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木材の半径方向のき裂進展におよぼす負荷速度と含水率の影響について検討した。

ベイスギの片側き裂試験体（SEN-TR）の曲げ試験（ASTM E399）により，インストロンタイプの試験機を用いて，クロスヘッド速度 100, 10, 1, 0.1, 0.01, 0.005 mm/min, 含水率 6.9%, 208%（平均値）の条件で破壊靱性試験を行った。

高含水率材の破壊靱性値 K_{IC} はクロスヘッド速度の上昇につれて増加したが，限界荷重におけるき裂開口変位 COD_C はほぼ一定値を示した。COD_C 破壊基準を考慮して Zener body による粘弾性モデルから予測した限界荷重は，実験値の傾向とよく一致した。

低含水率材においては，速いクロスヘッド速度の領域では速度の上昇につれて K_{IC} は若干低下し，K_{IC} 概念による破壊基準が有効なことがわかった。また，低速度域では高含水率材と同様な傾向が認められた。

The effects of loading speed and moisture content (MC) on crack propagation in the radial direction of western redcedar were examined according to ASTM Standard E339. The crosshead speeds used were 100, 10, 1, 0.1, 0.01, and 0.005 mm/min, and the MCs were 6.9 and 208% on average.

The stress-intensity factor (K_{IC}) of high MC specimens increased with increasing crosshead speed ; however, the critical crack opening displacement was almost constant. The critical load which was estimated from the rheological model of a Zener body and the critical crack opening displacement (COD) fracture criterion explained very well the experimental trend of the relationship between critical load and crosshead speed.

In low MC specimens, K_{IC} slightly decreased with increasing crosshead speed in high crosshead-speed tests. However, low MC specimens in low crosshead-speed tests showed the same trend as in high MC specimens.

1. INTRODUCTION

Moisture content (MC) and the strain or stress rate are the principal factors affecting the mechanical properties of such hygroscopic and rheological materials as wood.

The application of fracture mechanics to wood is becoming popular, and the MC effect on the fracture toughness of wood under equilibrium MC[1-4] and non-equilibrium MC[5] conditions have been studied. However, only limited studies on the strain-rate effect have been reported other than that by Schniewind[6] and by Bajolet and others.[7]

This work is directed at the effects of loading speed

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and MC on the fracture toughness of the crack opening mode, K_{IC}, and the fracture mechanism of wood specimens of the single edge-notched tangential-radial (SEN-TR) system. The TR crack propagation system was selected because it is one of the most probable cases of wood exhibiting brittle fracture behavior during the usage of wood and wood processing as in surface check propagation during the drying of lumber and in check formation of veneer during veneer peeling.

2. MATERIAL AND METHOD

Western redcedar (*Thuja plicata* D. Don) was used. Its specific gravity in an air-dried condition was 0.313.

Fracture tests were made according to ASTM Standard E339.[8] Bending fracture specimens, 12 mm × 24 mm × 120 mm, were designed as SEN specimens of the TR crack propagation system. A notch was cut initially into each fracture specimen using a thin bandsaw to a 9 mm depth ; then it was extended by a razor blade so that the final notch-length was 12 mm. The crosshead speeds used were 100, 10, 1, 0.1, 0.01, and 0.005 mm/min. The crack opening displacement (COD) was measured by a clip gage which was attached to the small-knife edge glued at the crack mouth.

Air-dried and water-saturated specimens whose MCs were 6.9 and 208% on average, respectively, were used, and the tests were made at 20 °C. The high MC specimens were wrapped with plastic film during tests to avoid the evaporation of moisture.

The critical stress intensity factor, (K_{IC}), was calculated by the isotropic solution of Tada,[9]

$$K_{IC} = \frac{3SP_Q}{2BW^2}\sqrt{\pi a}\, F(a/W), \qquad (1)$$

where P_Q is the critical load, S the span, B the thickness of a specimen, W the height of a specimen, a the notch depth, and $F(a/W)$ a form factor.

The P_Q used for the determination of K_{IC} was computed according to the procedure of ASTM Standard E339. However, it was not proper to adapt it for high MC specimens because of the nonlinear behavior in load-COD diagrams. Therefore, the point at which an abrupt change in slope on the load-COD diagram occurred, was chosen for high MC specimens.

3. RESULTS AND DISCUSSION

Load-COD diagrams give fundamental information about the fracture mechanism of specimens with cracks as in the sress-strain diagrams of clear-wood specimens.

Figure 1 shows typical load-COD diagrams. Low MC specimens showed almost linear load-COD diagrams up to the failure load. High MC specimens however, showed nonlinear behavior from low stress levels.

The initial slope of the load-COD diagrams of both low MC and high MC specimens decreased with decreasing crosshead speed. Its interpretation from the concept of linear elastic fracture mechanics (LEFM) is that the apparent Young's modulus of wood decreases with decreasing crosshead speed. This trend usually is shown in Young's modulus of clear-wood specimens.

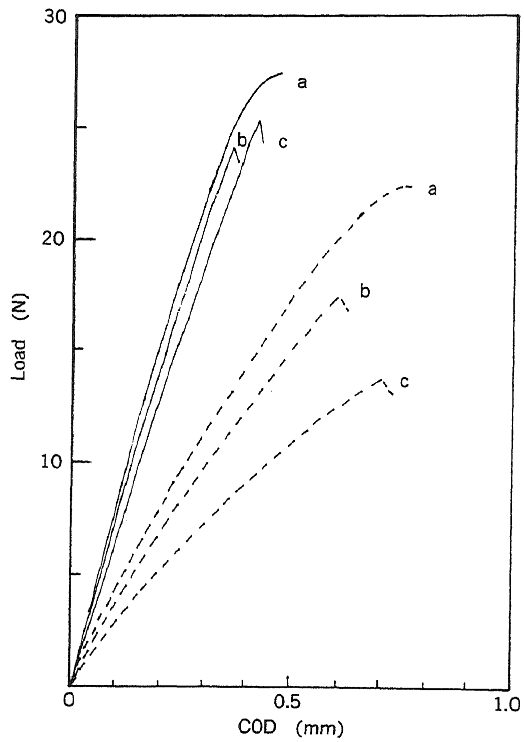

Fig. 1. Effects of loading speed and moisture content on load-COD diagrams.
Note: a, b, and c correspond to crosshead speeds 100, 1, and 0.005 mm/min, respectively.
Legend : ------, High MC specimen ; ——, Low MC specimen.

Figure 2 shows the relationship between K_{IC} and the logarithm of crosshead speed. Although low MC specimens had considerable dispersion of data, K_{IC} exhibited a maximum at about 1 mm/min in crosshead speed. The diminution of K_{IC} above this point can be interpreted from the LEFM concept as the effect of the stress concentration near the crack tip which was caused by the increase of the elasticity of specimens as seen in the initial slope change of the load-COD diagrams. According to the LEFM theory, the Young's modulus is proportional to the slope of the load-COD diagrams.

Schniewind[6] also reported a decrease in strength with decreasing time to failure in ramp loading in the LT (longitudinal-tangential) system: namely, that a failure load decreased with an increase of crosshead speed. The cause was explained to be the redistribution of stress, which is time-dependent, near the crack tip.

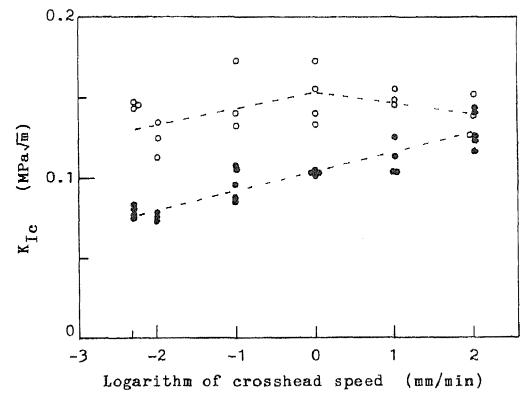

Fig. 2. Relationship between K_{IC} and crosshead speed.
Legend: ●, High MC specimen; ○, Low MC specimen.

However, the diminution of K_{IC} at low crosshead speed can not be explained from the LEFM concept in such low strain-rate regions where the rheological behavior near the crack tip probably would hold the key of the critical condition of failure.

On the other hand, high MC specimens noticeably exhibited positive slopes in the K_{IC} *vs* logarithm of crosshead-speed plot. The same phenomenon was found initially by Bajolet and others[7] in the SEN-TR tension specimens of green European beech (*Fagus sylvatica* L.). However, the explanation of this trend from the LEFM concept also is difficult. The K_{IC} probably does not have the physical meaning as does the stress intensity factor in the case of when load-COD diagrams exhibit highly nonlinear behavior.

The K_{IC} concept is a fracture criterion based on the stress condition near the crack tip. The COD concept is another concept based on the deformation of the material near the crack tip: namely, a fracture of material with a crack occurs when a crack opening reaches a critical value. This concept was introduced for describing the critical condition of crack propagation in ductile materials and nonlinear elastic materials.

The opening of a crack at its tip is distinguished from the COD, in other words, clip gage displacement, and is denoted as crack tip opening displacement (CTOD). However, the clip gage displacement usually is used instead of CTOD because of the facility of experiments.

The relationship between the critical COD (COD_C) and the logarithm of the crosshead speed is shown in Figure 3 for both low MC and high MC

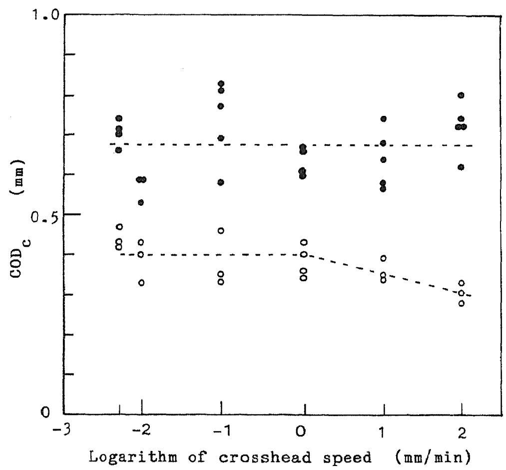

Fig. 3. Relationship between COD at critical load (COD_C) and crosshead speed.
Legend: ●, High MC specimen; ○, Low MC specimen.

specimens. The COD_C of high MC specimens was almost constant against crosshead speed. This fact means that the fracture criterion of high MC specimens can be given by the COD concept. This fact can be interpreted also as proof of the validity of the generalized St. Venant assumption that there is a critical strain that determines the rupture of a material.

Then, a rheological model using the Zener body[10] (three-element model) shown in Figure 4 was

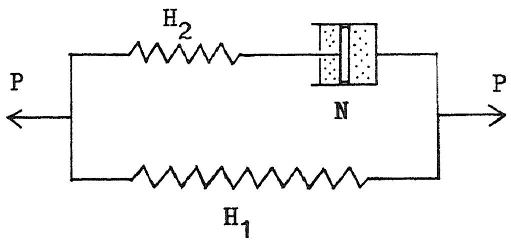

Fig. 4. Rheological model of the Zener body.
Note: H_1 and H_2 represent Hookian elements, and N represents a Newtonian element.

examined to represent the trend of the K_{IC} *vs* logarithm of crosshead-speed plot of high MC specimens. This application is based on the assumptions that the fracture process of specimens fundamentally belongs to that of a rheological one and that the specimens have one critical COD value that determines the rupture. Here, the critical load was used instead of K_{IC} because the K_{IC} probably has no physical meaning as the critical stress-intensity factor under such conditions when the rheological law governs the physical properties of wood.

In the Zener body, because the strain rates in the Hookian element H_1 and in the branch of Hookian element H_2 and the Newtonian element N are the same, we have

$$\frac{d\delta}{dt} = \frac{1}{C_1}\frac{dP_1}{dt} = \frac{1}{C_2}\frac{dP_2}{dt} + \frac{P_2}{\lambda}, \tag{2}$$

$$P = P_1 + P_2, \tag{3}$$

where Ps are forces given to each element, δ is COD, Cs are stiffness of each element, λ is a viscous constant, and t is time.

For the constant-rate condition of COD, the following solution is given:

$$P = C_1\delta + k\lambda v(1 - \exp(-\frac{C_2\delta}{k\lambda v})), \tag{4}$$

where $d\delta/dt = kv$ (v; crosshead speed, k; a constant).

Then, substituting the fracture condition that the critical COD is constant, that is, $\delta = COD_C$, the critical load P_C is given as

$$P_C = C_1 \, COD_C + k\lambda v(1 - \exp(-\frac{C_2 COD_C}{k\lambda v})). \tag{5}$$

Equation 5 represents the relationship between a critical load and crosshead speed.

The results of the curve fitting made by the least squares method is shown in Figure 5 where the

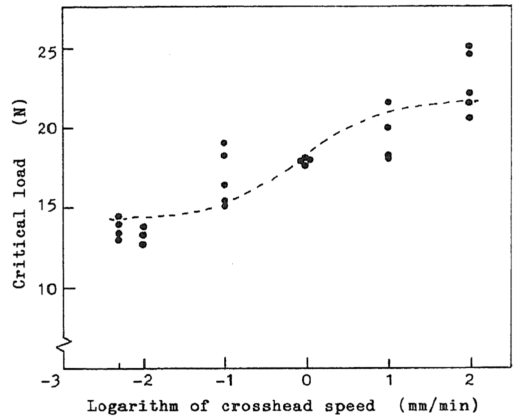

Fig. 5. Prediction curve of the critical load of high MC specimen computed from the rheological model of the Zener body.

constants $C_1 = 22.4$ (N/mm), $C_2 = 10.8$ (N/mm), and $k\lambda = 4.55$ (N/(mm/min)) were obtained. The curve obtained represents very well the trend of the experimental results. This fact proves that the fracture of high MC specimens fundamentally follows the fracture process of rheological bodies. The linear regression of Figure 2 seems to result in a better curve fitting than Figure 5. The degree of fitness of the prediction curve depends on the number of elements of the model used. However, the simle Zener-body model can explain the essential effect of the viscoelasticity of wood.

The COD_C of low MC specimens seems to be almost constant below about 1 mm/min of crosshead speed and to gradually decrease with increasing crosshead speed. This turning point coincides with that in the K_{IC} *vs* crosshead-speed plot. This means that the fracture process at below 1 mm/min in crosshead speed follows a rheological fracture whose mechanism is same as that of high MC specimens, and that at above the point follows a brittle fracture which can be explained by the LEFM concept.

4. CONCLUSION

A fracture mechanics' approach for understanding the loading speed and MC effects on the fracture criterions of wood specimens with a crack was examined.

In conclusion, the fracture mechanism of wood in the TR crack propagation system depends on crosshead speed and MC. The low MC specimens in low crosshead-speed tests and the high MC specimens exhibit rheological fracture behaviors which can be explained by the COD_C concept. The low MC specimens in high crosshead-speed tests exhibit a brittle fracture behavior to which the K_{IC} concept can be applied.

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