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Mixed Mode Fracture of the Crack Inclined to the Grain Direction in Wood*1

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木材의 纖維方向에 傾斜진 균열의 혼합모－드破壞에 관한 연구*1

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1. 적 요

목재의 섬유방향에 경사진 균열의 모－드I과 모－드II의 혼합모－드파괴시의 파괴거동을 조사하기 위하여 라왕(Shorea spp.)의 LA시스템에 있어서 서로 다른 경사각도를 가진 SEN시험편(Single edge notch specimen)에 대하여 휨 시험을 행하였다. 얻어진 결과는 혼합모－드파괴시, 모－드I응력확대계수K_I과 모－드II응력확대계수K_{II}간에 일정한 상호작용이 존재한다는 것을 나타내었다.

또한, 모－드I과 모－드II의 임계응력확대계수(Critical stress intensity factor) K_{IC}와 K_{IIC}를 이용하여 혼합모－드파괴시의 K_I과 K_{II}간의 상호관계를 규정할 수 있었으며, 이미 보고된 여러 실험식과 본 실험결과를 비교하여 가장 적합한 관계로서 아래와 같은 관계를 얻을 수 있었다.

I. INTRODUCTION

The concepts of linear elastic fracture mechanics (LEFM) have been applied to characterize the fracture behaviour in wood. A considerable amount of theoritical and experimental work reported have been concerned with the fracture in opening mode, Mode I, and sliding mode, Mode II, and then the results demonstrated that the the fracutre toughness K_{IC} and K_{IIC} are the geometry independent material properties of wood.[3-8, 9-10, 14-18] However, wood structural members are often subjected to the complex loading condition of Mode I and Mode II that results in mixed mode fracture failure.

Wood is, generally, considered as an orthotropic material. The principal directions can be defined along the longuitiduinal direction L, the radial direction R, the tangential direction T. Due to these directions, it is possible to characterize six principal systems of crack propagation, namely TL, TR, RL, RT, LR, and LT system. In the first four systems, the direction of crack propagation is collinear with the original direction. In the last two systems, however, the direc-

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tion is noncollinear as inhibited by the longuitudinally oriented wood fibers.

Concerning to the collinear crack propagation, Wu[23] investigated in Balsa wood (assumed Ochroma pyranidale) and Mall et al[12] in Red Spruce (Picea rubens) and then they proposed an empirical criterion for the mixed mode fracture of the form:

$$K_I/K_{IC} + (K_{II}/K_{IIC})^2 = 1 \quad \cdots\cdots (1)$$

William and Birch[19] studied in hardwood Utile (Entandrophragma utile) and softwood Scots Pine (Pinus sylvestris). They concluded, however, that a constant K_{IC} fracture criterion was independent of K_{II} value and then proposed the following form:

$$K_I/K_{IC} = 1 \quad \cdots\cdots (2)$$

Woo and Chow[22] studied in two species of hardwood Kapur (Dryobalanops spp.) and Gagil (Hope segal). The results indicated that although there was some interaction between K_I and K_{II}, criterion form as eq. (1) or (2) could not be determined.

Concerning to the noncollinear crack propagation, Leiscester[11] studied in Radiata Pine (Pinus radiata) and proposed the following form:

$$K_I/K_{IC} + K_{II}/K_{IIC} = 1 \quad \cdots\cdots (3)$$

Form these previous works, it seemed a useful exercise to further investigate the mixed mode fracture behaviour of wood. Consequently, this study was conducted to investigate this mixed mode fracture behaviour of the crack inclined to the grain direction, to develop a mixed mode fracture criterion for the noncollinear crack propagation based on experimental results.

2. EXPERIMENTAL METHOD AND ANALYSIS

Clear, straight-grain Lauan (Shorea spp.) with 60cm diameter was used for this study. Single edge notch specimen was chosen by cutting the material. Fig. 1 shows the configuration of specimen. Specimenns were conditioned to 12% nominal moisture content in a humidity room controlled at 20°C temperature and 65% RH for one month. After conditioning, the specimens were machined to final shape. The crack was made by making a sawcut of 9mm in depth which was then extended by means of a razor blade so that the final razor cut could be made to a depth of exactly 10mm. Six sets of specimens having crack inclinations, θ, of 0°, 15°, 30°, 45°, 60°, 75° were prepared. The crack was inclined to the grain direction. The specimen with the crack perpendicular to the edge (θ = 0°) provided the fracture toughness K_{IC} and the inclined crack provided the failure stress intensity factors K_I and K_{II}. The geometry of specimen is shown in Fig. 1 where L = 350mm, W = 20mm, a = 10mm, thickness = 30mm. The crack-length ratio is 0.5.

Experiments were conducted with universal testing machine in the humidity room (20°C, 65%RH). Specimens were tested in bending with a-third points loading over 300mm span at a cross-head speed 1mm/sec. Clip gage was used for measuring crack opening displacement (COD). The load-COD relation was recorded and the critical load was taken as the load at the discontinuity in this load-COD curve. The mechanical properties of no crack specimen in the LR plane were also measured in accordance to ASTM standard[1] and given in Table 1. Ten specimens were tested for each set, both with crack and without crack.

Table 1. Mechanical properties of experimental species.

Species	Sp. Gr.*	MOR ($x10^3 kg/cm^2$) E_L	MOR ($x10^3 kg/cm^2$) E_R	νLR
Lauan	0.47	101.2	7.8	0.4

* Based on oven-dry weight and volume.

The failing stress intensity factors for single edge notch specimen were computed from:

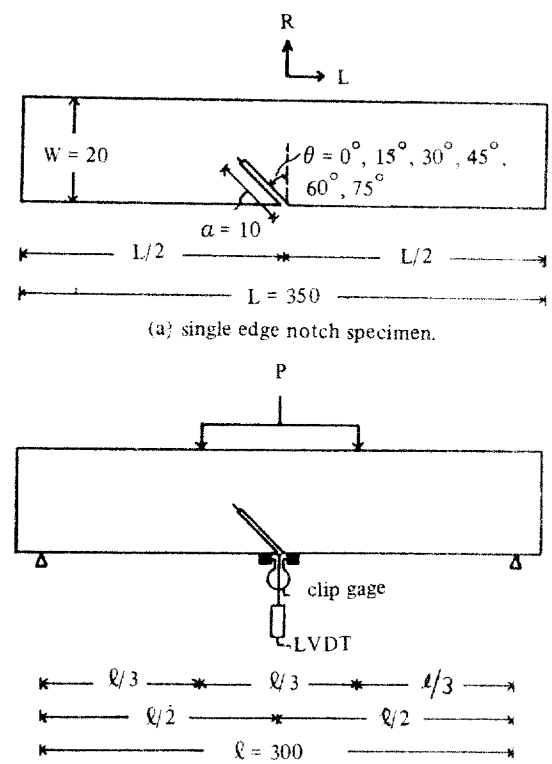

Fig. 1. Geometry for single edge notch specimen and bending test method.

$$K_I = \sigma\sqrt{\pi a}\cos\theta^2 Y_1 \quad (4)$$

$$K_{II} = \sigma\sqrt{\pi a}\cos\theta\sin\theta Y_2 \quad (5)$$

where σ is nominal stress, and Y_1 and Y_2 are the geometric correction factors of Mode I and Mode II, respectively. The cirtical Mode I stress intensity factor K_{IC} could be determined from eq. (4) of $\theta = 0°$. The critical Mode II stress intensity factor K_{IIC} was, however, deduced from the relationship between K_I and K_{II}, suggested by Sih et al[19], such that

$$K_{IIC} = (E_L/E_R)^{1/4} x K_{IC} \quad (6)$$

The finite element method was used to evaluate the geometric correction factor for this investigation. A typical finite element grid is shown in Fig. 2. The finite element formulation utilized primarily eight-node quadrilateral isoparametric elements and six-node triangular elements surrounding the crack tip. The eight-triangular elements were modified to incorporate

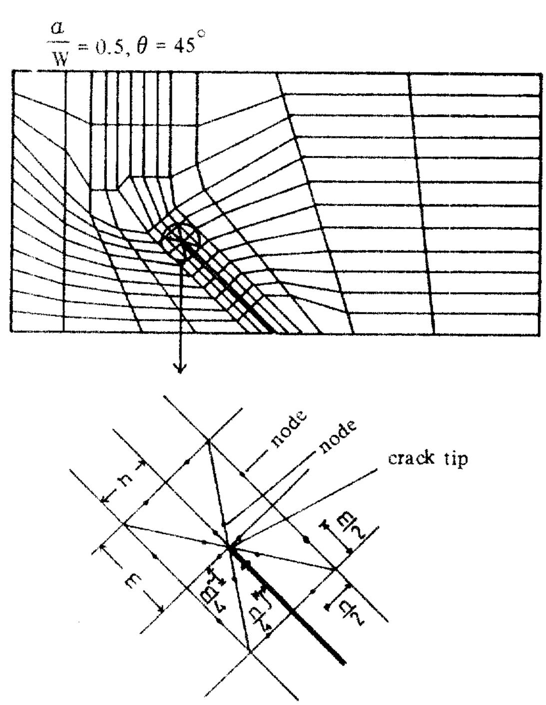

Fig. 2. Typical finite element grid.

the required inverse square root singularity characteristics of LEFM. This singularity was achieved by placing the mid side node of the side connected to the crack tip at the quarter position adjacent to the crack tip as shown in Fig. 2. The stress intensity factors K_I and K_{II} were computed with the displacement method. Within the range of crack geometies investigated here, it was reported by other investigators that the geometric correction factors are very similar for isotropic and orthotropic cases. [2, 8, 13, 20] Thus, the geometric correction factors investigated here were computed by using the isotropic case and the computed results are plotted as shown in Fig. 3. The values of Y_1 and Y_2 computed here are in agreement with other investigation. [21]

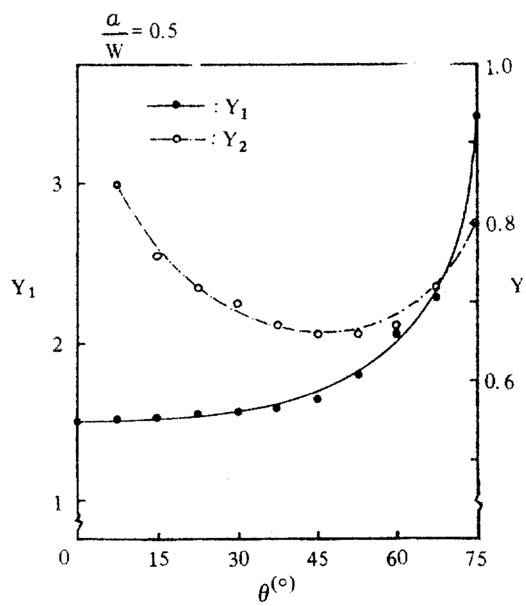

Fig. 3. Geometric correction factors Y_1 and Y_2 for single edge notch specinen where is applied to pure bending roment.

3. RESULTS AND DISCUSSION

The failure stress intensity factors K_I and K_{II} obtained from these tests are shown in Table 2. The critical Mode I stress intensity factor K_{IC} in the LR system of crack propagation was $240 kg/cm^2 . \sqrt{cm}$. With this K_{IC} value, the ciritical Mode II stress intensity factor K_{IIC} was calculated by eq. (6) and the value was $456 kg/cm^2 . \sqrt{cm}$. From the data in Table 2, it can be observed that as the crack inclination θ increases, the K_I value decreases and the K_{II} value increases. This demonstrates that there exists any interaction between failure K_I and K_{II}. To define the functional relationship between K_I and K_{II}, an F-test was performed on the data assuming four different failure models. The results are indicated in Table 3. As can be seen from table 3, the failure model proposed by Leicester[11], which is concerned with the non-collinear crack propogation with the original direction, shows the highest F-value. However, the failure model proposed by Wu[23] and Mall et al[12] indicates very high F-value and have significant relation. These relations are replotted in Fig. 4 using the average values. Seeing Fig. 4, it seems, however, that the Leicester's model is fitter for the empirical data the than the Wu's model. Consequently, the criterion obtained here could be defined as $K_I/K_{IC} + K_I/K_{IC} = 1$.

Table 2. Failure stress intensity factors K_I and K_{II}.

Crack angle	K_I $(kg/cm^2 . \sqrt{cm})$	K_{II} $(kg/cm^2 . \sqrt{cm})$	$\frac{K_I}{K_{IC}}$	$\frac{K_{II}}{K_{IIC}}$
0°	240	0	1.00	0.00
15°	231	30	0.95	0.06
30°	225	60	0.93	0.13
45°	214	87	0.87	0.19
60°	186	105	0.78	0.23
75°	165	137	0.70	0.30

Table 3. F-values for various failure criteria.

Failure criterion	F-value	Signif. F-value
$K_I/K_{IC} + K_{II}/K_{IIC} = 1$	842.8	0.000
$K_I/K_{IC} + (K_{II}/K_{IIC})^2 = 1$	100.2	0.002
$(K_I/K_{IC})^2 + K_I/K_{IC} = 1$	75.6	0.003
$(K_I/K_{IC})^2 + (K_{II}/K_{IIC}) = 1$	20.6	0.027

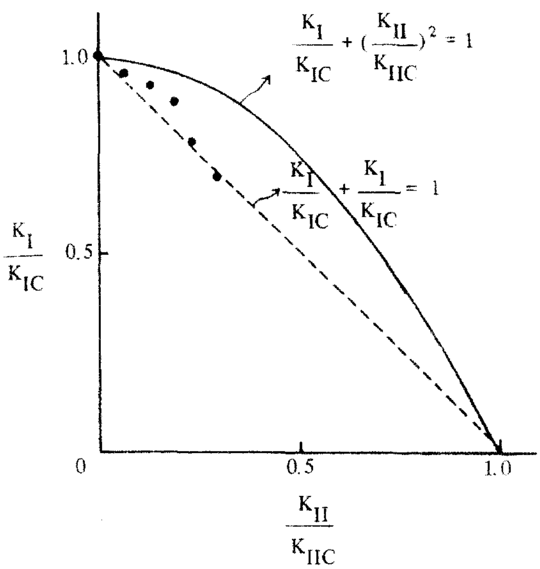

Fig. 4. Relations between K_I/K_{IC} and K_{II}/K_{IC}.

There are several considerable things to determine the criterion for the mixed mode: (1) The crack propagation is collinear or noncollinear with the original direction; (2) How to evaluate K_{IIC} value, measuring directly or calculating; (3) How to measure K_{IIC} value, if required. The K_{IIC} value may be, especially, effective to determine the criterion.

4. CONCLUSION

To determine the criterion for the mixed mode fracture on crack inclined to the grain direction, this investigation was conducted. It was found that the criterion could be expressed in the following form:

$$\frac{K_I}{K_{IC}} + \frac{K_{II}}{K_{IIC}} = 1$$

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