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Effect of Drying Stress on the Fracture Toughness of Wood [*1]

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木材の破壊靱性におよぼす乾燥応力の影響[*1]

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乾燥中における木材の破壊靱性 K_{IC} を SEN 引張試験 (TR-System) によって求めた。乾燥の進行につれて K_{IC} は低下し，その低下には乾燥速度の影響が大きいことがわかった。K_{IC} の低下の原因は，乾燥中に試験体表層付近に発生する乾燥応力がクラック近傍の応力集中を高めるためと考えられる。また，荷重—クラック開口変位曲線は破壊荷重付近で非線形となった。

The critical stress intensity factor (K_{IC}) in the TR system was investigated in relation to residual stress during drying. The K_{IC} value decreased very much with the decrease of mean moisture content and also was sensitive to the drying rate. These results suggested that the diminution of K_{IC} resulted from the residual drying stresses. It also was observed that the load-COD (crack-opening displacement) curve showed non-linearity near the failure load.

1. INTRODUCTION

Fracture mechanics is concerned with the failure of materials by catastrophic crack propagation, and it has been proved that the concept of linear elastic fracture mechanics (LEFM) is useful for describing the failure of wood and wood-based materials.[1)-6)]

However, all of these applications have been concerned with failure under equilibrium moisture content conditions, that is, the moisture content of a sample is conditioned to be constant at a given relative humidity. The failure of wood under non-equilibrium moisture content conditions also is very important, for example, in the checking of wood during drying. In this case, it may be necessary to apply the generalized theory of fracture mechanics of non-elastic materials, but it forces us to endure much complexity and difficulty. Therefore, the concept of LEFM was applied to explain the problem of crack propagation during drying.

The object of this work was to investigate the effect of the development of internal stress during drying on the fracture toughness of openimg mode I in the TR system (the first letter refers to the direction normal to the crack plane and the second to the propagation direction) under non-equilibrium moisture content conditions, and the results also are compared with those under equilibrium moisture content conditions at different moisture contents.

2. MATERIALS AND METHODS

European beech (*Fagus sylvatica* L.) 40 years of age and 30 cm in diameter was used. The specific gravity in the air-dried condition was 0.72, and the average ring width was 3.2 mm.

Fracture specimens were designed as the single edge-notch (SEN) in the TR system. The configuration of the SEN tension specimen used is shown in Fig. 1. Initially a notch 3 mm deep was cut by a thin

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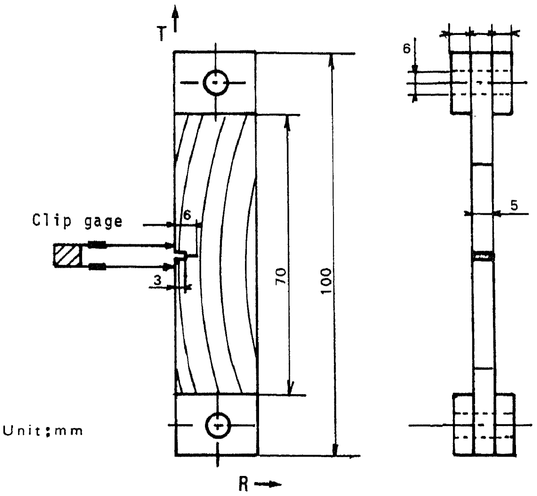

Fig. 1. Configuration of specimen.

band-saw; then it was extended by a razor blade with a special guide so that the final notch-length was exactly 6 mm. Specimens were held by a pin-loading system in order to avoid the restriction of rotation at the ends during loading.

For the preparation of the specimens for non-equilibrium moisture content conditions, two groups of fifteen green specimens each were placed in a chamber in which the nominal air circulation was 2 m/sec and the air conditions were controlled at 20 °C, R. H. 55% for one group and 20 °C, R. H. 17% for the other. Specimens of each group were taken out at the same time interval from the chamber and immediately were subjected to the fracture tests.

The conditioned specimens with different moisture contents were prepared as follows: the green specimens were left at room conditions of 20 °C, R. H. 50%. Then groups of three specimens were wrapped together in plastic film at some time interval for equalization of the moisture distribution in the specimens until the fracture tests. The moisture content of specimens was measured just after the fracture tests by an automatic balance.

The fracture tests were made at 20 °C. The cross-head speed used was 0.5 mm/min. The crack opening displacement (COD) was measured by a specially designed clip gage (Fig. 1), and the load *versus* COD curves were recorded on an X-Y recorder. At the same time, the load *versus* time curves also were recorded.

The critical stress intensity factor (K_{Ic}) was calculated by the isotropic solution, Equation 1, from Tada[7] namely

$$K_{Ic} = \sigma\sqrt{\pi a}\, Y(a/w) \qquad (1)$$

where σ: gross section-stress at failure,
a: notch depth,
w: specimen width, and

$$Y(a/w) = 1.12 - 0.231\,(a/w) + 10.55\,(a/w)^2 - 21.72\,(a/w)^3 + 30.39\,(a/w)^4.$$

There has been little discussion about the critical load in the case of the TR system[3]. Generally, the maximum load at failure has been regarded as the critical load. In this work, the maximum load is used also as the critical load.

3. RESULTS AND DISCUSSION

3.1 "K_{Ic}" in non-equilibrium moisture content condition

Fig. 2 shows a comparison between the apparent critical stress intensity factor (K'_{Ic}) calculated by Equation 1 in the non-equilibrium moisture content condition and K_{Ic} in the equilibrium moisture content condition.

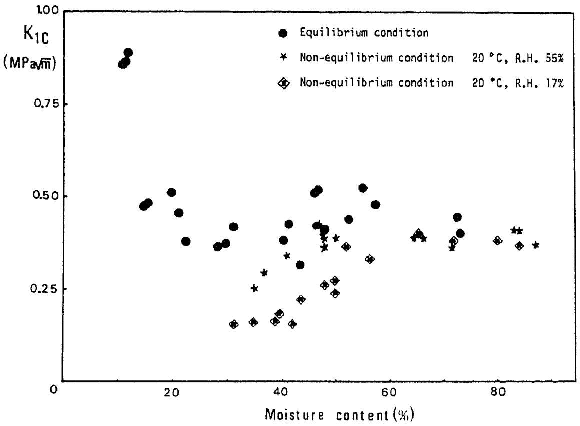

Fig. 2. Comparison of K_{Ic} between non-equilibrium moisture content condition and equilibrium moisture content condition.

In the latter case, K_{Ic} increases with a decrease of moisture content below the fiber saturation point (FSP), about 30%, and it is almost constant above the FSP. This phenomenon is similar to moisture effects on other mechanical properties of wood, for example, Young's modulus and some strengths of wood.

On the other hand, K'_{Ic} under non-equilibrium moisture content conditions begins to decrease with a decrease of the mean moisture content from a higher moisture content above the FSP. Fig. 2 also shows the effect of drying conditions on the curve K'_{Ic} *versus* mean moisture content, and Fig. 3 shows the plots of mean moisture content *versus* drying time and of K'_{Ic} *versus* drying time under two drying conditions. They show that K'_{Ic} decreases more rapidly if the rate of drying increases, and it suggests that the decrease of K'_{Ic} is related to the residual drying stress in the specimens.

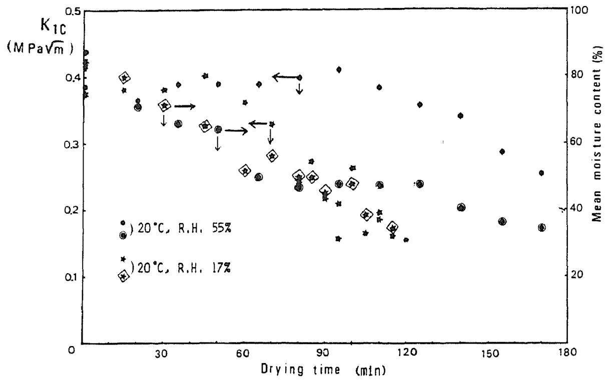

Fig. 3. Relationships between K_{Ic} and drying time and between mean moisture content and drying time.

The drying of the specimens begins at the surface, and as the drying proceeds the plane where the moisture content coincides with the FSP advances in the direction of the center. Fig. 4 shows a simple model of moisture distribution for calculating the average value of K_{Ic} during drying. If we suppose that there is no drying stress in the specimen, the value of K'_{Ic} may be computed roughly from the following equation[5]:

$$K'_{\mathrm{Ic}} = (2\,B_1/B)\;K_{\mathrm{Ic1}} + (B_2/B)\;K_{\mathrm{Ic2}} \qquad (2)$$

where B_1 and B_2 are the thickness of the parts where the moisture content is below and above the FSP, respectively, and K_{Ic1} and K_{Ic2} are mean values of K_{Ic} in parts B_1 and B_2, respectively, as shown in Fig. 4.

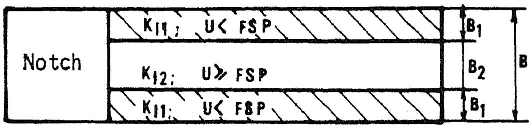

Fig. 4. Three-layer model of moisture content distribution.

In the case of an equilibrium moisture content condition, as shown in Fig. 2, the value of K_{Ic} below the FSP is greater than that above it, that is, $K_{\mathrm{Ic1}} > K_{\mathrm{Ic2}}$. The result of the calculation by Eq. 2 for the model gives

$$K'_{\mathrm{Ic}} = (2\,B_1/B)(K_{\mathrm{Ic2}} + \triangle\,K_{\mathrm{Ic1}}) + (B_2/B)\;K_{\mathrm{Ic2}} \qquad (3)$$

where $\triangle\,K_{\mathrm{Ic1}}$ is the increment of K_{Ic1} from K_{Ic2} (constant) below the FSP.

This means that the mean value of K_{Ic} is greater than its value in a green condition if the wood begins to dry. But, the result of the calculation ($K'_{\mathrm{Ic}} > K_{\mathrm{Ic2}}$) contradicts the experimental result ($K'_{\mathrm{Ic}} < K_{\mathrm{Ic2}}$). This contradiction suggests that the residual stress during drying plays an important role in the decrease of K'_{Ic} under non-equilibrium moisture content conditions.

Tensile stress appears on the surface, and compressive stress appears in the inner part during drying, and the gradient and the level of residual stresses become greater if the rate of drying becomes more rapid. The tensile stress makes the local concentration of stress near the crack tip greater. Therefore, it is possible that the tensile stress diminishes the global external stress which is necessary for catastrophic propagation of a crack.

3.2 Load-COD curves

A load-COD curve gives useful information about the stress condition near a crack tip. Fig. 5 shows three typical curves at different mean moisture contents during drying. A load-COD curve is almost linear in the first stage of loading, but it shows gradual non-linearity when the load approaches the failure load. Fig. 5 exhibits two important characteristics: 1) the maximum load decreases with the decrease of mean moisture content, and 2) the load-COD curve trails behind its load after the maximum load point when the mean moisture content decreases. The first point was discussed in § 3.1. The second point gives interesting information about crack propagation. When the moisture distribution in specimens is uniform, the load decreases suddenly at the maximum load point, that is, the crack propagation is catastrophic. However, the trailing of the load suggests that the crack propagation is rather subcritical.

Fig. 6 shows the plots of COD at failure δ_t *versus*

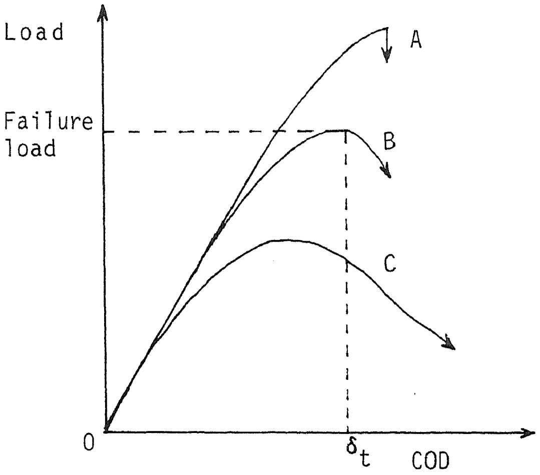

Fig. 5. Typical curves of load *vs* COD at different stages of drying.
Notes: A ; Initial state of drying (uniform distribution of moisture content), B ; Middle mean moisture content state, C ; Low mean moisture content state, δ_t ; COD at failure load.

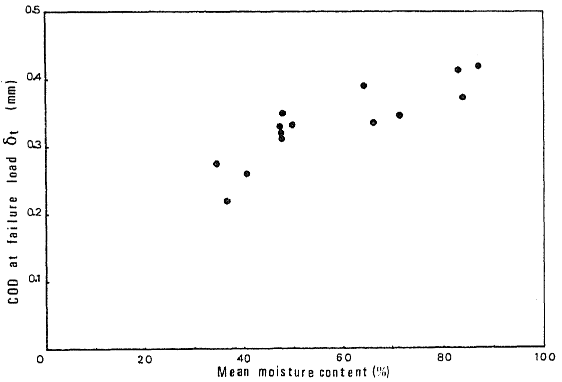

Fig. 6. Relationship between COD at failure load and mean moisture content in non-equilibrium moisture content conditions.

mean moisture content. The δ_t decreases with a decrease of mean moisture content. This means that the specimen becomes fragile, and it coincides seemingly with the decrease of critical load. However, it contradicts the tendency of the trailing of the load after the maximum load point shown in Fig. 5.

It is difficult to interpret the above findings from only the viewpoint of LEFM. This is because there is a high stress concentration near the crack tip, and the theory of LEFM requires that materials have elasticity at infinite stress. Wood is a viscoelastic material, and it is unreasonable to suppose elasticity at high stress levels near a crack tip. For these materials, the path independent *J*-integral proposed by RICE[8] may be useful.

4. CONCLUSION

It was proved that the critical stress intensity factor, K_{Ic}, was reduced by the residual drying stress. On the other hand, K_{Ic} under equilibrium moisture content conditions was almost constant above the FSP, and it increased below the FSP.

The implications of these results for the propagation of a crack during drying are that the critical condition of crack propagation is affected very much by residual drying stress, and it occurs under smaller global stress than those which are estimated from the results for equilibrium moisture content conditions.

It also was proved that the load-COD curve showed non-linearity, and it might be necessary to consider the viscoelastic property of wood.

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