# FRACTURE TOUGHNESS AND DURATION OF LOAD FACTOR I. SIX PRINCIPAL SYSTEMS OF CRACK PROPAGATION AND THE DURATION FACTOR FOR CRACKS PROPAGATING PARALLEL TO GRAIN[1,2]

*Arno P. Schniewind* and *Julio César Centeno*
Forest Products Laboratory, University of California, Richmond, CA 94804

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ABSTRACT

Critical stress intensity factors for air-dry Douglas fir were found to be 2200, 2450, 281, 373, 323, and 323 psi $\sqrt{\text{inch}}$ for the LT, LR, TL, RL, TR, and RT systems, respectively, where the first letter indicates the direction normal to the crack plane and the second the direction of crack propagation. Long-term load tests with notched beams showed that for the TL system the load duration factor was similar to that applying to modulus of rupture. Moisture changes significantly reduced the mean time to failure of notched beams under dead loads as compared to tests under constant moisture conditions.

*Additional keywords: Pseudotsuga menziessii,* static testing, stress intensity factor, notches, notched beams, moisture changes.

## INTRODUCTION

The concepts of fracture mechanics, which were developed originally to deal with brittle fracture problems of metals having high yield strength, also show promise of helping solve certain problems of design of wood structural elements. Fracture mechanics can be used to treat the effect of butt joints on the strength of glued laminated timbers (Leicester and Bunker 1969; Leicester 1972; Walsh 1973), and problems involving end notches in timber beams can be dealt with similarly (Leicester 1969). Direct application of concepts of fracture mechanics makes it possible to assess tensile strength perpendicular to grain of structural timber containing checks or glued laminated timber with partially open glue lines (Schniewind and Lyon 1973). Undoubtedly, other applications of these same concepts will be found.

The intensity of the stress field in the vicinity of a crack in a body under load is given by the stress intensity factor, $K$. Depending on the mode of crack surface displacement, stress intensity factors are denoted as $K_I$ for the opening mode (loading normal to the crack surface), $K_{II}$ for the forward shear mode (crack loading by in-plane shear), or $K_{III}$ for the transverse shear mode (crack loading by out-of-plane shear). The discussion in this paper will be confined to the opening mode and hence $K_I$.

The stress intensity factor is used to formulate a failure criterion by stating that for unstable crack propagation, catastrophic failure will occur when the stress intensity factor reaches a critical value, $K_I \rightarrow K_{Ic}$. The critical stress intensity factor, $K_{Ic}$, is the parameter characterizing the fracture toughness of an isotropic material for opening mode loading. For orthotropic materials such as wood, six principal systems of crack propagation are recognized (Schniewind

[1] This paper was presented at Technical Session 6, 27th Annual Meeting of the Forest Products Research Society at Anaheim, California, 25 June 1973.

[2] The senior author first started working on this project while a guest at the former Division of Forest Products, CSIRO, Melbourne, Australia, during the academic year 1969/70. Experimental difficulties delayed successful experimentation until after his return to California. The senior author would like to express his gratitude to the staff of the Division of Forest Products for many discussions, particularly with R. H. Leicester about fracture mechanics and Nell Ditchburne about statistical approaches, and for the opportunity to gain experience by carrying out many unsuccessful experiments.

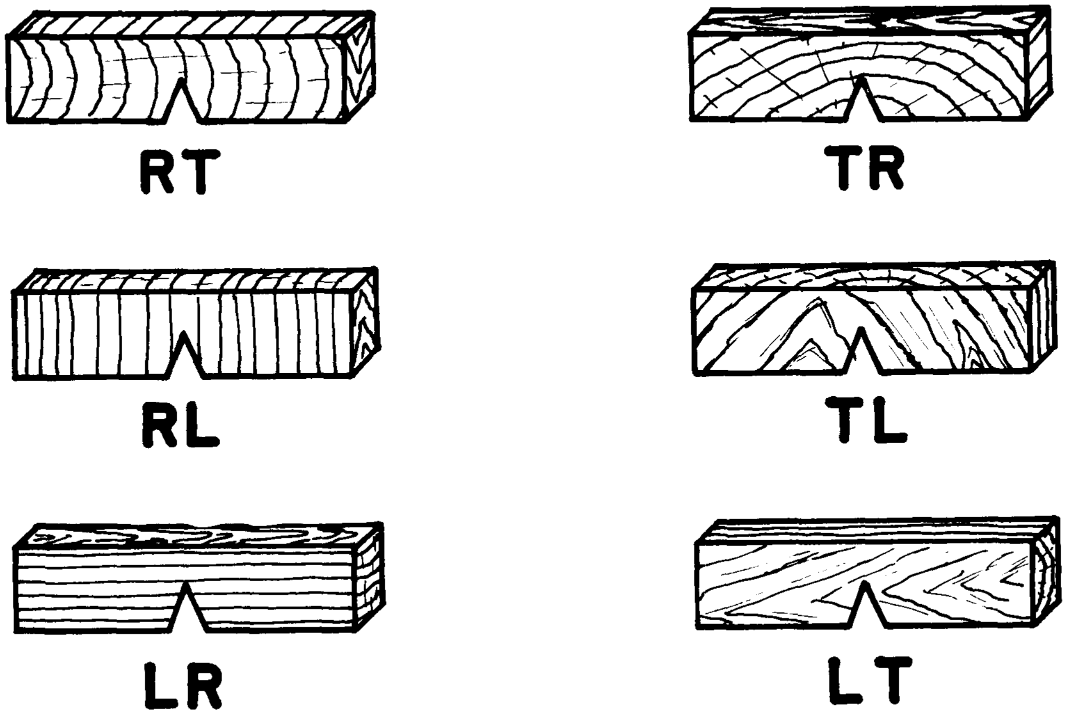


FIG. 1. Specimens illustrating the six principal systems of crack propagation. The strips may be tested either in tension or by bending with the notch on the tension side.

and Pozniak 1971). These arise because a crack may lie in one of three principal planes and may, within each plane, propagate in either one of two principal directions. Thus as many as six parameters might be required to characterize the fracture toughness of an orthotropic material.

The six systems of crack propagation may be denoted by two indices, the first referring to the normal to the crack plane, and the second to the direction of crack propagation. Figure 1 illustrates the six systems. Schniewind and Pozniak (1971) showed that the critical stress intensity factor was lower for the TL than for the TR system, i.e., the fracture toughness of a specimen with a crack in the T (radial-longitudinal) plane is less if the crack propagates along the grain as compared to propagation perpendicular to grain. A complete comparative study of all six systems has apparently never been made.

If the critical stress intensity factor is to be useful as a parameter in the design of wood structural elements, the question arises if it is subject to the same kind of duration of load factor known to apply to other wood properties. For the TL system, the time dependence of $K_{Ic}$ appears to be about the same or even somewhat more severe than for modulus of rupture (Walsh 1971). Experiments with notched beams reported by Madsen (1972), although not evaluated in terms of fracture mechanics, suggest that for the LR system (or the LT system or both) the time dependence is significantly reduced, possibly through blunting at the crack tip.

This paper reports on the first part of a study intended to develop comparative data on the six systems of crack propagation of one wood species, and to determine the duration of load factor for critical stress intensity factors of these systems. The specific objective of the work discussed here was to obtain static test data for all six systems and to investigate the duration of load factor of the TL system.

## MATERIAL AND METHODS

### *Static tests*

Air-dry Douglas-fir was used for this study. Six 3- × 6-inch cants were used for the static tests in the six systems. Three of the cants were flatsawn and three were quartersawn. For some of the specimen configurations, material had to be glued up. Glue lines were positioned so that they would not interfere with specimen performance. None of the systems depended entirely on glued-up specimens.

Single edge-notch (SEN) specimens were chosen as the most suitable for investigation. Figure 2 shows specimen dimensions and location of the glue line for specimens where it was required. LT and LR specimens were never glued. Notches were cut on a milling machine with a fly-cutter.

Specimens were conditioned to 12% nominal moisture content. They were tested in bending with center loading over a 4-inch span. Testing speed was 0.02 inches per minute of the movable cross head, and this usually led to failure in 1 to 2 minutes.

TL, RL, TR, and RT systems were tested on a table model Instron testing machine and maximum load was recorded. Visible crack initiation usually occurred at maximum load; short cracks (0.04 inch or less) sometimes developed at lower loads but remained arrested until maximum load. The critical load was always regarded as the maximum load. Crack length was measured microscopically before test, and no adjustments for slow crack growth were made.

LR and LT systems were tested on a Baldwin universal testing machine under the same conditions. In these systems special methods are required to determine the critical load, because the crack propagating from the notch tip is almost immediately arrested and the crack tip is blunted by splitting along the grain. Some authors have, therefore, considered the LT and LR systems unsuitable for a fracture mechanics treatment (Schniewind and Pozniak 1971; Tomin 1972). Leicester and Bunker (1969) have shown that even if the crack is arrested or diverted, the onset of rapid crack propagation can be discovered by measuring crack opening displacement (COD) as a function of load. In their tests, critical load was indicated by a discontinuity in the curve. In the present study, an extensometer was placed across the notch to record COD vs. load. The critical load was taken as the load at proportional limit in the COD vs. load curve, since discontinuities did not become evident. This load coincides with visible crack initiation. More detailed justification for this approach will be reported in a subsequent paper.

### *Long-term load tests*

The six systems of crack propagation can be divided into three groups according to the relation of the crack plane and the direction of propagation to the grain (tracheid or fiber direction). In the TR and RT systems, the crack surface lies in a plane parallel to the grain and the crack propagates perpendicular to the grain. In the TL and RL systems, the crack is also parallel to the grain and also propagates parallel to the grain. Finally, in the LT and LR systems the crack is perpendicular to the grain and propagates (at the initial instant) perpendicular to the grain. It was therefore decided to investigate the long-term loading factor using one system in each of these three groups. In this paper, the TL system was studied.

A set of 17 flatsawn boards of Douglas-fir was tested. SEN beam specimens similar to those in Fig. 2 were used, with notch depth, total depth, and span scaled up by a factor of 2 but with the same beam width (specimen thickness) of ½-inch. All material was conditioned to a nominal moisture content of 12%.

Four series of tests were made. The first series were static bending tests at a speed of 0.02 inch per minute using 24 specimens ranging in notch size from 0.2 to 1.2 inches. This series was included to verify the applicability of fracture mechanics methods

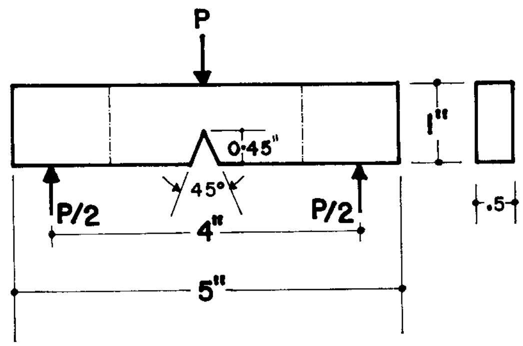


FIG. 2. Small-edge notch (SEN) specimen used for comparative study of the six principal systems of crack propagation. Dotted lines show location of glue lines where applicable.

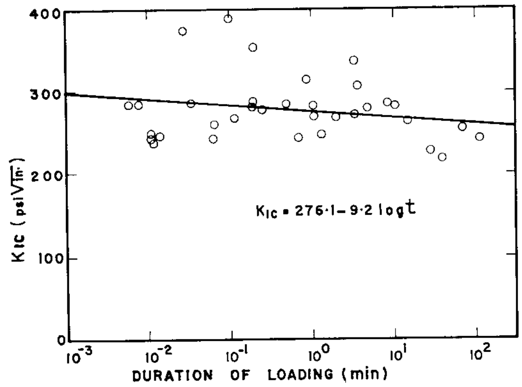


FIG. 4. Critical stress intensity factor as a function of time to failure for ramp loading in the TL system.

and to help establish a base for long-term tests. One specimen was taken from each of the 17 boards plus an additional specimen from seven of the boards selected at random.

The second series included 34 specimens, two from each board, and all having the standard notch size of 0.9 inch. They were loaded at varying rates to obtain a range of times to failure from 0.006 to 113 min. For failure times less than 10 min, loading was continuous ramp loading. For times to failure greater than 10 min, ramp loading was approximated by intermittent cross-head movement at the slowest available machine speed. The number of steps always exceeded 100, thus allowing a close approximation to continuous ramp loading.

In the third series, specimens with 0.9-inch notches were subjected to dead loads representing 90, 85, 80, and 70% of the load causing rapid crack propagation in static tests. At each load level, 19 specimens were tested. Tests were made under constant equilibrium conditions of 12% in a humidity chamber. Loads were applied through a lever system. Time to failure was determined with time meters to 0.1 min.

The fourth series of tests was similar to the third, except that tests were made only at load levels of 70 and 50% and equilibrium moisture content conditions were varied cyclicly. Temperature was held constant,

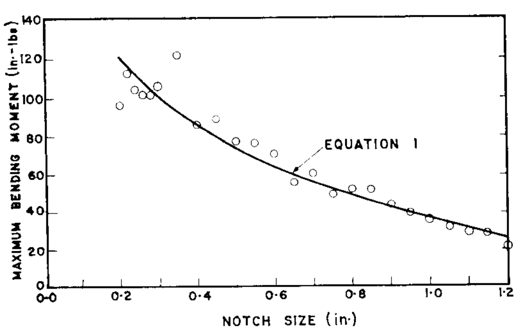


FIG. 3. Maximum bending moment as a function of notch size for the TL system.

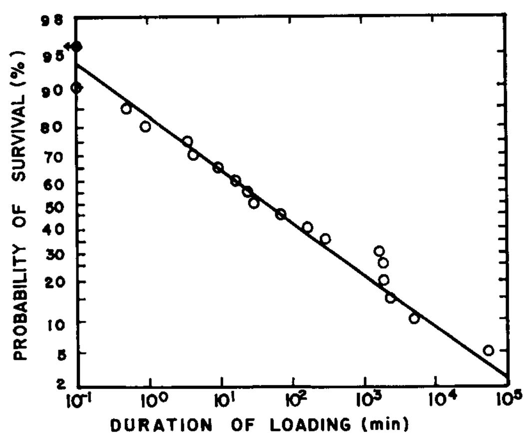


FIG. 5. Survival probability as a function of load duration at 90% load level in the TL system under constant conditions.

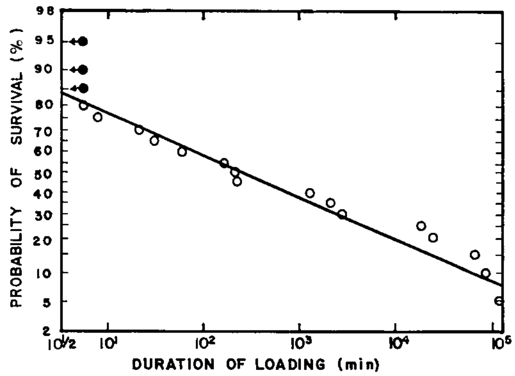


FIG. 6. Survival probability as a function of load duration at 85% load level in the TL system under constant conditions.

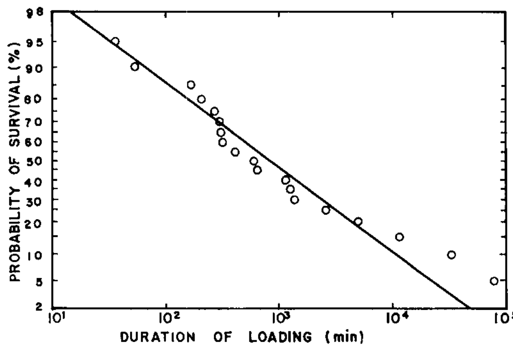


FIG. 7. Survival probability as a function of load duration at 80% load level in the TL system under constant conditions.

and relative humidity was alternately held at 35 and 87% for 12 hr each, i.e., a square wave function with a period of 24 hr. Specimens were conditioned to 12% moisture content and then loaded at the beginning of the low humidity portion of the cycle. Nineteen specimens were tested at each load level.

Stress intensity factors were calculated according to the following equation (Brown and Srawley 1966):

$$K_{Ic} = Y \frac{6M_c a^{1/2}}{BW^2} \quad (1)$$

where $W$ = specimen width (beam depth), $B$ = specimen thickness (beam width), $a$ = crack depth, $M_c$ = critical moment, and:

$$Y = 1.93 - 3.07\left(\frac{a}{w}\right) + 14.53\left(\frac{a}{w}\right)^2 - 25.11\left(\frac{a}{w}\right)^3 + 25.80\left(\frac{a}{w}\right)^4 \quad (2)$$

Equation 1 applies to center-loading and a span-depth ratio of 4, and will give $K_{Ic}$ within 0.2% for all values of $a/W$ up to 0.6.

## RESULTS AND DISCUSSION

Table 1 shows the results of tests of the six principal systems of crack propagation. The six systems have been arranged in three groups; the table shows that there are no major differences between $K_{Ic}$ values within groups, but that values for the LT and LR systems are nearly one order of magnitude greater than all others. A comparison of values of the LT and LR systems by means of a *t*-test showed a statistically significant difference at the 1% level.

Data of the remaining four systems were subjected to an analysis of variance, which showed a statistically significant difference due to the system of crack propagation at the 1% level. Values for the TR and RT systems are equal, but there is a larger difference between the TL and RL systems than expected. This could be attributed to the rays acting as crack arrestors in the RL system, while in the TL system the crack can run along the rays. Scheffe's test (Li 1964) was made comparing $K_{Ic}$ values of the TL and RL systems individually to the combined values of the TR and RT systems. For both comparisons the difference was

TABLE 1. *Critical stress intensity factors for the six principal systems of crack propagation in Douglas-fir*

| Crack propagation system | Critical stress intensity factor psi $\sqrt{\text{inch}}$ | Standard deviation psi $\sqrt{\text{inch}}$ |
|---|---|---|
| LT | 2200 | 305 |
| LR | 2450 | 398 |
| TL | 281 | 23.8 |
| RL | 373 | 33.8 |
| TR | 323 | 54.4 |
| RT | 323 | 45.6 |

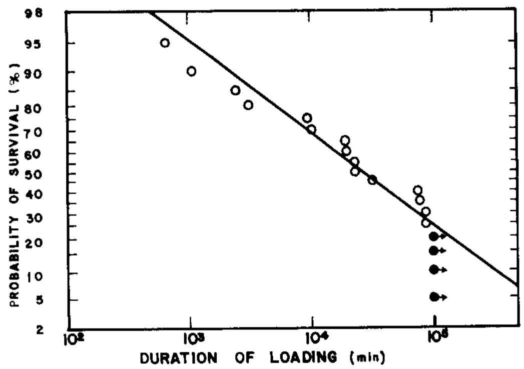


FIG. 8. Survival probability as a function of load duration at 70% load level in the TL system under constant conditions.

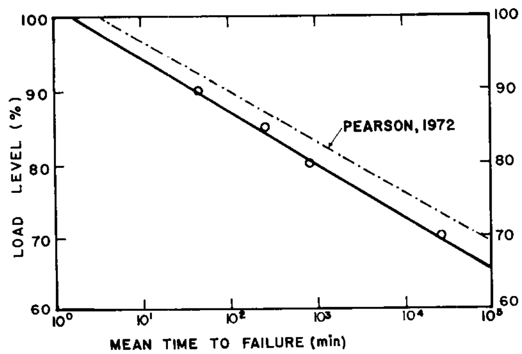


FIG. 9. Load level in relation to time to failure in the TL system under constant conditions.

significant at the 1% level. It follows that all of the remaining systems of crack progagation are significantly different from each other except for the TR and RT systems.

There are few data in the literature to which present results can be compared. $K_{Ic}$ values in the TR system are similar to others obtained for Douglas-fir with tension specimens (Schniewind and Pozniak 1971; Schniewind and Lyon 1973). Schniewind and Pozniak (1971) found a similar difference between TL and TR systems (crack surface in the same plane but crack propagating in different directions) in specimens from a single board, as was found in this study.

Figure 3 shows the results of tests of TL specimens with notch sizes ranging from 0.2 to 1.2 inches. The maximum bending moment was plotted against notch size. $K_{Ic}$ values were calculated for each specimen, and the mean of all values was used to calculate points for the theoretical curve shown in Fig. 3 according to Eq. 1. As may be seen in the figure, there is close agreement between the shape of the theoretical curve and the data points, indicating that Fig. 3 gives the proper relationship of strength to notch size.

Figure 4 shows the results of TL tests made at standard notch size of 0.9 inch at varying testing speeds. There is considerable scatter of data, and the slope of the computed regression line shown in Fig. 4 is not significantly different from zero at the 5% level. The regression line does show a negative slope comparable to what might be expected for other wood properties obtained at different testing speeds. Similar results were obtained by Walsh (1971) for three Australian species.

The average $K_{Ic}$ value for specimens with varying notch sizes was 283 psi $\sqrt{\text{inch}}$ and the the average time to failure was 1.49 min. The $K_{Ic}$ value computed from the regression line in Fig. 4 at 1.49 min to failure is 275 psi $\sqrt{\text{inch}}$. The mean value, or 279 psi $\sqrt{\text{inch}}$, was taken as the 100% level for subsequent long-term tests under constant load.

Figures 5, 6, 7, and 8 show survival probability as a function of load duration of specimens loaded at the levels indicated under constant environmental conditions. Some specimens failed almost instantaneously at 90 and 85% load levels. Mean and standard deviation values were estimated by the method of censored distribution (Hald 1952), with the assumption that the time to failure in these specimens was shorter than could be measured. At 80% load level all specimens could be tested, and at 70% load level testing was discontinued after 100,000 min of loading. Here, also, the censored distribution method was used.

Survival probability plots indicate considerable variability of the data. At 90% load level (Fig. 5) the times to failure ex-

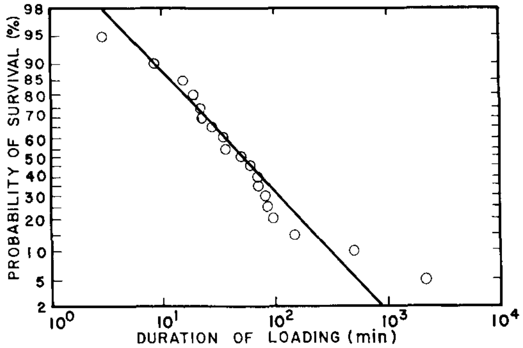


FIG. 10. Survival probability as a function of load duration at 70% load level in the TL system under humidity cycling.

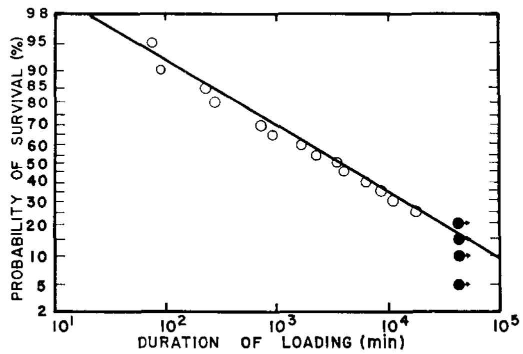


FIG. 11. Survival probability as a function of load duration at 50% load level in the TL system under humidity cycling.

tend over six decades. However, the data points in each case are grouped closely about a straight line and thus can be considered normally distributed.

Figure 9 shows mean time to failure as a function of load level. The points fall on a straight line and extrapolate to 1.8 min to failure at 100% survival probability, which agrees closely with the 1.49 min obtained with ramp loading in the static tests. Figure 9 also shows the regression line computed by Pearson (1972) for modulus of rupture based on a comprehensive compilation of data from the literature. The average time to failure is less for the notched specimens, thus indicating that duration of load effect for the TL system of crack propagation is somewhat more severe as compared to modulus of rupture. The two lines are nearly parallel, however, indicating that after adjustment for the difference in testing speed at the 100% level the data would agree much better with Pearson's regression line. Walsh (1971) made similar tests on three Australian species, one softwood and two hardwoods. One of the hardwoods showed a shorter time, and the other two species somewhat longer times to failure at a given load level as compared to the equivalent curve for modulus of rupture.

Figure 10 shows survival probability for tests made at 70% load level under cyclic environmental conditions. Only one specimen survived the first complete cycle, and in less than 2 days all specimens had failed. All of the specimens failing during the first cycle failed during the initial drying period. Early failures can no doubt be attributed to the superposition of drying stresses that would tend to augment the stress intensity factor. The notch itself would probably tend to promote check development, even in the absence of loads, and the nucleation of a drying check could then be followed by rapid crack propagation and complete failure of the specimen. Unnotched beams of Douglas-fir also showed reduced times to failure under cyclic environmental changes but the reductions were less severe (Schniewind 1967).

Figure 11 shows data similar to those of Fig. 10 but at a load level of 50%. Tests were discontinued at 40,000 min of loading, by which time all but four of the 19 specimens had already failed. Mean time to failure computed according to the method of censored distribution was only 3690 min (less than 3 days). It is evident that the test conditions are very severe for the TL system investigated. Results at the two load levels indicate that under cyclic environmental conditions only low load levels can be tolerated in the TL system.

## CONCLUSIONS

In wood, six principal systems of crack propagation can be distinguished. For air-dry Douglas-fir, critical stress intensity factors of all but two of the systems were significantly different from each other. The six systems can be divided into three groups according to the location of the crack plane and the direction of crack propagation with respect to grain direction. For practical purposes, a two-way grouping may be a suitable approximation. The LT and LR systems ($K_{Ic}$ values of 2200 and 2450 psi $\sqrt{\text{inch}}$) would constitute one group, and the other four systems ($K_{Ic}$ values ranging from 281 to 373 psi $\sqrt{\text{inch}}$) would constitute the other group. This would be equivalent to the practice of using a single value for allowable shear stress parallel to the grain, even though two different shear planes and often somewhat different average values are involved.

The duration of load factor for the critical stress intensity factor for air-dry Douglas-fir in the TL system is about the same or somewhat more severe, as compared to modulus of rupture, when the environmental conditions are held constant. Cyclic changes in relative humidity cause a drastic reduction in time to failure. In essence this system entails loading in tension perpendicular to the grain, a practice which is avoided whenever possible in structural applications. Our findings thus serve to further emphasize the uncertainties and dangers associated with significant loading perpendicular to the grain.

With respect to application in structural design, the LT and LR systems are of greatest importance. Long-term testing of these systems, however, presents particular problems of experimental procedure associated with the arrest and 90-degree divergence of the crack. The duration of load factor for these systems will be the subject of another report in this series.

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