Studies were conducted to determine the mode I (opening) and mode II (forward shear) stress intensity factors $K_{IcTL}$ and $K_{IIcTL}$ for Southern Pine as a function of moisture content (MC). Compact-tension (mode I) and center-split beam (mode II) specimens were cut from standard 38- by 140-min (nominal 2- by 6-in.) boards. Specimens were sorted into five matched groups based on specific gravity. One group of specimens was saturated with water and four groups were equilibrated to MC levels of 4%, 8%, 12%, and 18%. Results indicate that both mode I and mode II stress intensity factors increase with decreasing MC from green to about 8% to 12%. Upon further drying, the stress intensity factors decrease. Stress intensity is also observed to be highly correlated to specific gravity.

INTRODUCTION

In the past few years, several studies have been conducted in the United States and Canada on the effect of moisture content (MC) on the bending, tensile, and compressive strength of standard 38-mm- (nominal 2-in.-) thick lumber (6). This work refutes traditional assumptions that strength always increases as lumber dries. This is especially true for tensile strength parallel to the grain. The strength for most percentile levels was found to first increase with decreasing MC down to approximately 12% to 15%, then strength began to decrease with further drying. Based on previous work, new empirical models for adjusting the strength of lumber for changes in MC are being incorporated into American Society for Testing and Materials (ASTM) standards (1). The experimental basis for this work was driven by the needs of the In Grade Testing Program (5). The lowest MC level studied was limited to 8%, because little lumber is intentionally dried below this level.

In the United States, lumber is used at a wide range of MC levels. For example, lumber installed green in timber bridges may remain at or near the fiber saturation point for several years after bridge installation. In contrast, lumber used in attics in the dry U.S. Southwest may be reduced to moisture levels as low as 2% to 4% within a year of installation. Additional experimental studies are needed to develop adjustments for allowable engineering design properties for lumber at low MC levels. However, such studies are expensive and time consuming. To understand this phenomena and to efficiently design experimental studies, a better understanding of the basic mechanisms controlling moisture property relationships is needed. Analytical models capable of predicting the strength of lumber are available (4).

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These models can quantify the relative importance of fundamental mechanisms on lumber behavior. However, the models require data on the relationship between MC and a wide range of fundamental properties.

This paper reports the relationship between MC and mode I (opening) and mode II (forward shear) stress intensity factors for Southern Pine. It also presents information on specific gravity-stress intensity factor relationships as a function of MC.

**BACKGROUND**

Fracture theory is based on the assumption of the existence of critical flaws that initiate failure in materials. The theory originated with the work by Griffith (7). Three types of stress fields, and associated stress intensity factors, can be defined at a crack tip: opening mode (I), forward shear mode (II), and transverse shear mode (III) (Fig. 1a). Wood exhibits distinct properties in each of its three principal orthogonal directions: longitudinal (L), radial (R), and tangential (T). A crack in one of the three planes may propagate in one of the two directions in each plane. This gives rise to six propagation systems: RL, TL, LR, TR, LT, and RT (Fig. 1b). The first letter indicates the axis perpendicular to the crack plane, and the second indicates the direction of crack propagation. Of these six propagation systems, four are of practical importance: RL, TR, RT, and TL (3). Because of the low strength and stiffness values of wood perpendicular to the grain, the TL and RL orientations are the systems that have been studied the most.

The concepts of fracture mechanics were first applied to wood by Atack in 1961 (2). Since this initial work, numerous studies have been completed on fracture mechanics. Summaries can be found in the reviews by Patton-Mallory and Cramer (10), RILEM TC 110-TFM (11), and Kretschmann and others (8). Much of this work was on mode I, with a limited amount of work on the other two modes. Most information on the effect of MC on stress intensity factors has been limited to MC levels of approximately 10% (8). Preliminary data for Southern Pine indicate that the mode I stress intensity factor increases with decreasing MC to approximately 8% but with further drying, mode I decreases (8).
EXPERIMENTAL METHODS

Material selection

One hundred fifty 3.7-m (12-ft) Southern Pine (Pinus echinata or Pinus taeda) standard 38- by 140-mm (nominal 2- by 6-in.) boards were obtained from local suppliers in Madison, Wisconsin. Care was taken to obtain flat sawn lumber that did not contain the pith. The lumber was either KD15 2200f machine-stress-rated lumber or No. 1 Dense visually graded lumber (12).

The 150 2 by 6's were numbered sequentially and specific gravities based on oven-dry weight and volume were obtained for each piece. The 2 by 6's were then sorted into five groups rising specific gravity as the sorting criteria. From each of the 150 2 by 6's, at least one and possibly two 204.7-mm (52-in.) sections, straight grain and free from noticeable defects, were cut.

The smaller sections were placed into conditioning chambers with the appropriate temperature and relative humidity (RH) to bring the sections to equilibrium at a target MC of 4% (32°C (90°F) and 20% RH), 8% (27°C (80°F) and 30% RH), 12% (26°C (78°F) and 65% RH), and 18% (27°C (80°F) and 90% RH). The saturated material was obtained by water soaking under a vacuum. To prevent excessive stain and the possibility of decay prior to testing, the saturated material was stored in sealed bags at 2°C (36°F) and 82% RH.

Specimen preparation

After the 1.3-in. (52-in.) sections had equilibrated, they were planed to a thickness of 20 mm (0.787 in.). Eight different, specimen blanks were cut from the conditioned 1.3-m sections: mode I fracture, mode II fracture, compression parallel to the grain, compression perpendicular to the grain, tension parallel to the grain, tension perpendicular to the grain, bending, and shear parallel to the grain.

The preparation of the 76.2- by 79.4- by 20-mm (3.0- by 3.35- by 0.787-in.) compact-tension specimens (CTS) is described by Kretschmann (8). The dimensions for the center-split beam (CSB) are shown in Figure 2. The mode II test specimens were prepared in three stages. First, the oversized mode II test blank was cut to 650 by 60 by 20 mm (25.6 by 2.36 by 0.787 in.). Second, a steel guide, in conjunction with a saber saw, cut the initial center split. Finally, the blade of a scroll saw was threaded through the initial cut, and the 120-mm (4.72-in.) center split was produced by first pushing the specimen along a guide with a stop, flipping the specimen, and then repeating for the second half of the cut.

Testing procedure

Testing was conducted at the U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. The CTS testing is described by Kretschmann (8). Prior to testing, the CSBs, like the CTSs, were inspected for checks and shake and defects were recorded. Only specimens free from initial defects were used in the analysis. Small groups of specimens were transported from the conditioning chambers to the test floor in sealed hags where information on specimen weight and thickness at crack length was collected. Next, the crack tip was sharpened with a razor blade. After the sharp cracks were in place, linear variable differential transformers (LVDTs) were attached to measure vertical and horizontal displacements at the crack. Specimens were then placed within the test chamber. The environment within the chamber was controlled by a portable conditioning unit that maintained the required temperature and MC levels (4%, 8%, 12%, 18%) for each
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Figure 2 Dimensions for the center-split beam mode II specimen.

MC group. The saturated specimens were tested under controlled temperature–humidity conditions of 26°C (78°F) and 65% RH.

Testing was conducted on a universal test machine at a cross-head speed of 0.25 mm/min (0.01 in/min). This rate of cross-head movement resulted in a time to failure of 1.5 to 3.0 min. Loads were recorded with a 22.2-kN (5,000-lb) load cell. Horizontal displacements were measured for all specimens, and vertical displacements were measured for the 4%, 8%, 18%, and saturated MC groups using LVDTs. Displacements and load were recorded simultaneously on an X–Y plotter and an interfaced microcomputer. Recordings were stopped after the crack propagated explosively. After testing, one end of the CSB was removed and oven-dried to determine MC and specific gravity.

RESULTS

Grouping and conditioning effects

Specific gravity distributional information for each moisture level is summarized in Table 1. The average specific gravity adjusted to 12% MC for all MC levels is 0.53. This is slightly greater than the clear wood average of 0.51 (13). A good match is present between the specific gravities of the different moisture groups. Note that all groups also have similar ranges in specific gravity values.

We were able to obtain good separation between MC groups with no overlap in moisture levels (Table 1). The control capability of the various conditioning chambers governed the scatter present in MC results. The 4% and 8% levels had much tighter controls than did the 12% and 18% levels. The actual average moisture levels (4.4%, 7.4%, 12.0%, and 17.5%) were within 0.5% of the target moisture levels (4%, 8%, 12%, 18%) All saturated pieces were well above the fiber saturation point.
Moisture content effects on mode I

Data points and boxplots are used to illustrate data trends (Fig. 3). The boxplots show the lowest datum point, the 25th percentile, the mean, the median, the 75th percentile, and the highest datum point. The plots are centered on the average MC for each moisture level. No correction was made for MC before the percentiles were calculated. Work is underway to establish appropriate MC adjustment models. The boxplots show a definite trend toward an increase in stress intensity factor as MC decreases until a peak is reached at 7.5%, with continued drying the factor begins to decrease. Relative to the value at 12% MC, the Kc value is about 40% lower when green, 18% lower at 18% MC, 9% higher at 8% MC, and about the same at 4% MC.
Moisture content effects on mode II

In our tests, the polynomial for plane-strain mode II stress intensity factor for a CSB was taken from Murphy (9).

\[
K_{IIe} = \left[ 2.8 \left( \frac{a}{d} \right) + 0.72 \right] \frac{(s - L)/L}{P} \]  

(1)

where
- \(P\) is applied load centered over the crack (N (lb)),
- \(s\) beam length (600 mm (23.62 in.)),
- \(a\) crack length (60 mm (2.36 in.)),
- \(L\) distance between load points, or reaction points, on the same side of the beam (490 mm (19.29 in.)),
- \(b\) thickness (20 mm, (0.787 in.)), and
- \(d\) width (50 mm (1.97-in.)).

Like the mode I results, the boxplots in Figure 4 were developed from data unadjusted for MC. The plots show a definite trend toward an increase in \(K_{IIe}\) as MC decreases until a peak is reached between 10% and 7.5%. Below 7.5%, the stress intensity factor declines. Relative to the value at 12% MC, \(K_{IIe}\) value is about 30% lower when green, 10% lower at 18% MC, equal at 8% MC, and 10% lower at 4% MC.

Relationship of \(K_{IIe}\) and \(K_{IIc}\) to specific gravity

Mode II results are very similar to those reported (8) for mode I. Stress intensity has a strong positive correlation ranging from 0.5 to 0.8 with specific gravity. Our results also
CONCLUDING REMARKS

From the results of our study on the effect of MC on $K_{IC}$ for Southern Pine in the TL mode, we conclude the following:

1. $K_{IC}$ increases as MC decreases, reaching a maximum at about 8% MC. With further drying, $K_{IC}$ decreases.

2. $K_{IIc}$ increases as MC decreases, reaching a maximum between 7.5% and 10%. With further drying, $K_{IIc}$ decreases.

3. $K_{IC}$ and $K_{IIc}$ are positively correlated to specific gravity. However, the slope of the relationship is a function of MC.

REFERENCES


