EFFECT OF CCA PRESERVATIVE TREATMENT AND REDRYING ON FRACTURE TOUGHNESS OF LOBLOLLY PINE

Jerrold E. Winandy
Research Wood Scientist

David E. Kretschmann
Research Engineer

USDA Forest Service
Forest Products Laboratory[1]
Madison, WI 53705-2398

Abstract

The influence of treatment with chromated copper arsenate (CCA) and redrying after treatment is apparently dictated by physical changes in the chemical composition and cellular character of the treated wood. Linear elastic fracture mechanics (LEFM) was evaluated to determine if this method is more sensitive than conventional static-mechanical test methods in assessing the effect of CCA treatment on wood strength.

When compared to untreated controls, the fracture toughness of CCA-treated loblolly pine (*Pinus taeda* L.) was reduced by 1 to 12 percent when redried at 160°F and by 11 to 23 percent when redried at ≥190°F. These losses in fracture toughness were comparable in magnitude to those found in previous work using clear wood specimens and conventional static-mechanical test methods. This would suggest that results derived using LEFM are directly comparable to those derived using conventional static-mechanical test methods.

Introduction

Waterborne-preservative treatments have revolutionized the wood-preserving industry. Chromated copper arsenate (CCA) preservative accounts for over 90 percent of the waterborne-preservative market. Annually, 40-45 percent of the southern pine dimension lumber produced in the United States is treated with CCA (9). Lumber treated with CCA is popular because it is clean, paintable, and highly leach resistant. These desirable properties are a result of fixation, a chemical process in which the CCA components either react with various phenolic and carbohydrate wood components or react among themselves to form water-insoluble precipitates.

As a result of fixation reactions, CCA treatments may reduce the strength of many types of treated products (3,5,11,12,22-24). This strength loss is caused by hydrolytic chemical activity upon the molecular and microfibril structure of wood. As with most hydrolytic processes involving wood, the extent of chemical degradation is a function of wood species and pH, temperature, and duration of the chemical process.

The effect of CCA treatment and redrying on strength is apparently dictated by physical changes in the chemical composition and cellular character of the treated wood. The failure theory on which linear elastic fracture mechanics (LEFM) is based assumes that preexisting flaws within a brittle material initiate failure. In the study reported here, LEFM methods were evaluated to determine their sensitivity in assessing the effect of CCA treatments on wood strength. The results were compared to previously reported results from conventional static-mechanical test methods. While the application of LEFM to wood is an approximate method, it is believed to give reasonable approximations of the toughness of the wood (4,20,21). Linear elastic fracture mechanics would seem especially pertinent when used for comparative purposes, rather than for establishing definitive baseline values.

Background

The concepts of LEFM were first applied to wood by Atack et al. (2). Porter (15) studied fracture toughness in depth for a variety of species in various grain orientations. The general theory of LEFM for brittle materials is that fracture initiates at a preexisting flaw. When stresses build to some ultimate level at the crack (flaw) tip, the crack extends forward some incremental distance, releasing energy. The level of intensity of the stress field in the vicinity of the crack is called fracture toughness or stress intensity factor K. Three types of stress fields and thereby stress intensity factors can exist at a crack tip, each associated with a local mode of deformation. These factors are the opening (I), forward shear (II). and transverse shear (III) modes (Fig. 1). Because of the ease of testing, much of the previous work with wood has been done with the opening mode (Mode I) fracture. The work described in this paper dealt only with the stress intensity factor in the opening mode (K_I). The application of fracture mechanics to characterize the fracture process in wood is difficult because wood is an orthotropic material which exhibits distinct properties in each of its three principal orthogonal directions (longitudinal (L), radial (R), and tangential (T)). A crack may lie in one of these planes and propagate in one of two directions. Thus, there are six crack-propagation systems: RL, TL, LR, TR, LT, and RT (Fig. 1). Of these systems, four are of practical importance: RL, TR, RT, and TL. Each of these four systems allows for propagation of the crack along the low-strength path perpendicular to the grain (4). The TL orientation in wood (where T is direction of load and L is direction in which the crack propagates) is the least resistant orientation for crack growth (18).

The radial penetration of CCA occurs primarily through the ray cells and causes swelling, which induces stress in the RL plane. Accordingly, we anticipated the TL orientation would be the most sensitive to chemical effects, and on that basis, we studied only that orientation.

---

[1] The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Stress intensity is used as a failure criterion. Unstable crack growth or catastrophic failure occurs when K_I reaches a critical value (K_{IC}). K_{IC} represents the critical stress intensity factor for an isotropic material in Mode I failure. Previous work using the Mode I compact-tension specimen (CTS) consistently showed a range for K_{IC} values of 260-320 psi x $in^{1/2}$ for the TL orientation for several wood species or wood-based composite materials (4,13,14,16,17,19,20,25).

In our tests, the polynomial for plane-strain Mode I fracture toughness for a CTS of metallic materials (8) was the basis for the geometric correction factor used to calculate K_{IcTL}.

$$K_{IcTL} = P_Q/BW^{1/2} \times [29.6(a/W)^{1/2} - 185.5(a/W)^{3/2} + 655.7(a/W)^{5/2} - 1017.0(a/W)^{7/2} + 638.9\,(a/W)^{9/2}] \quad [1]$$

where P_Q = load required to propagate crack (lb) (pop-in load)
B = specimen thickness (in)
a = crack length (in)
W = specimen width between center line of load application and specimen edge (3.3 in)

This isotropic polynomial solution is considered a reasonable approximation to the orthotropic value for K_{IcTL} (4,21,25). Because our objective was to evaluate treatment effects rather than to establish true orthotropic K values, the use of these simplifying assumptions seems acceptable.

Experimental Method

Short sections (4.5 in long), free of defects, were cut from undamaged sections of 2 by 6 loblolly pine (Pinus taeda L.) lumber tested in an earlier study (23). The lumber had been treated with CCA-Type-C to a target retention of 0.4 or 0.6 pcf (water-treated and untreated controls included) and redried after treatment using various redrying temperatures (air-dried or kiln-dried at 160°, 190°, or 240°F) The levels of CCA retention were chosen to represent standard CCA retentions for structural lumber. The drying temperatures were chosen to represent a range of industrial redrying temperatures.

The short sections were stored in a climate-controlled room with the temperature maintained at 74°F and the relative humidity at 65 percent, producing an equilibrium moisture content of about 11.5 percent. After equilibrating, the sections were inspected and only those free from observable heartwood, checks, and shakes were selected. Heartwood sections were avoided to insure even distribution of CCA within the specimens and to limit the possible inclusion of juvenile wood. Finally, only blocks exhibiting ideal TL orientation were chosen. Examples of this TL orientation and the range of ring curvature used in this study are shown in Figure 2.

Specimen Preparation

The compact-tension specimen (CTS) was selected as the test specimen configuration because much of the recent work on wood fracture has used this configuration. The dimensions for the CTS (Fig. 3) were chosen to correspond to ASTM Standard E 399 (1).

The specimens were prepared in three stages. First, a block 4.0 by 4.2 in, with full thickness (about 1.5 in), was machined so that the location for the crack was positioned at the optimum TL orientation in the specimen's height (Fig. 2). Second, holes were drilled for loading, and the notch for mounting the crack-opening displacement (COD) gauge was cut. Finally, a sharp-tipped crack notch was cut to a predetermined depth., A starter notch (2.3 in deep) was cut and three marks were scribed at 0.1-in increments starting at 2.4 in from the edge (Fig. 3). The distance between a line drawn between the center of the two loading holes and the scribe marks (shown as "a" in Fig. 3 and Eq. [1]) determined the relative positioning of the three crack lengths that would be tested for each CTS specimen. The three crack lengths to be tested for each specimen were 1.575, 1.675, and 1.775 in. To produce the initial crack (1.575 in), the material just short of the first scribe mark was removed with a band saw. Next, the crack tip was sharpened with a specially machined blade with adjustable stops. The blade was placed in contact with the specimen and then softly impacted with a hammer to sharpen the crack tip to achieve the crack length of 1.575 in. This procedure was conducted just seconds before testing. The procedure used to produce the second and third cracks will be discussed in Test Procedure.

Test Procedure

Specimen thickness at the crack tip and specimen weight were recorded prior to testing. The test setup is illustrated in Figure 4. The specimens were suspended in hangers by two clevises, and a steel sleeve was inserted into each loading hole to provide a smooth bearing surface. A block of wood was used to support the specimen until the load was applied. Because the block remained in place during testing, a strip of soft foam was placed between the supporting block and the specimen to keep the load imposed by the supporting block to a minimum during testing. Testing was conducted in a 12,000-lb universal test machine at a cross-head speed of 0.02 in/min, resulting in a time to failure of 1.5-2.5 min. Loads were recorded with a 500-lb load cell and COD measurements were obtained with a clip gauge extensometer. Crack-opening displacements and load were recorded simultaneously on an X-Y plotter and an interfaced microcomputer.

Load was applied until the first pop-in (drop in load) occurred, as evaluated from the X-Y plot. Then, the specimen was rapidly unloaded to arrest the growth of the crack before it reached the next length. Preliminary experimentation had visually shown that loading at a 0.2 in/min rate of load could be stopped and released before the new crack tip passed the next target crack length. After the test was completed, the specimen was prepared for the next crack length by using a band saw to remove material along the crack notch nearly to the next scribe mark. The new crack tip was then sharpened with the blade. Testing for the second crack length (1.675 in) was the same as testing for the first. Testing for the third crack length (1.775 in) was allowed to run out to maximum loading. After testing, the critical K_{IC} values for each crack length (K_{575} = 1.575-in, K_{675} = 1.675-in, K_{775} = 1.775-in crack) were calculated using Eq. [1] and the pop-in load (P_Q), which represented the load that produced an ultimate stress in the vicinity of the crack tip for each crack length. If a distinct pop-in load was not present, the point at which the first major change in compliance occurred was taken as P_Q. Specific gravity (ovendry weight and volume at test) and moisture content were also calculated.

Results and Discussion

Equilibrium moisture content was related to the level of CCA treatment and redrying temperatures employed; CCA treatment increased moisture content, whereas at any CCA level, moisture content was decreased by an increase in kiln dried after treatment temperature (Table 1). We did not adjust K_{IC} values for moisture content because the effect of treatment and drying on moisture content can be considered as part of the overall treatment and redrying effect on strength.

Based on the results of preliminary experiments, we tested three crack lengths for each specimen. However, we were concerned that the initial crack or cracks might run past the initiation point of a later crack or cracks. Visual observation of each crack did not reveal any problems, but previous work had shown that crack fronts can tunnel into the center of a specimen (6,7). While tunneling is less of a problem in static tests (such as ours) than in fatigue tests (6,7), tunneling is not readily apparent from a visual observation of the exterior of a specimen. To learn whether the first crack interfered with the results of the second, we statistically tested the hypothesis that no difference existed between the first two critical K_{IC} values (H_0 : $K_{575} - K_{675} = 0$) using Student's t-test. The results of the test indicated that for all nine treatment-redrying combinations the average K_{575} value was less than the K_{675} value, and in seven of nine cases it was significantly less. The two exceptions were for specimens that were treated with CCA to 0.4 pcf or treated with water and then redried at 240°F. A t-test of H_0: $K_{575} - K_{775} = 0$ yielded similar results. Thus, for material redried at. 190°F or less, the 0.1-in difference between the three cracks was apparently sufficient to preclude interference between replicated crack lengths. Nevertheless, the exceptions (where K_{575} was greater than K_{675} or K_{775}) could present unknown pitfalls because the true length of the initial crack or cracks could not be measured. The uncertainty about crack length limits the statistical independence of data of the second crack length from the first and of the third from the second and first. Thus, although we report the results from the second and third crack lengths, these results are not discussed any further. The trends discussed for the initial K_{575} values were virtually identical to those found with K_{675} and K_{775}.

Effects of Treatments and Redrying

Table 1 shows the average fracture toughness of each crack length (K_{Ic575}, K_{Ic675}, K_{Ic775}), coefficient of variation, percentage difference from untreated controls, moisture content, and specific gravity for each treatment group. The K_{Ic575} value for the 18 untreated control specimens was 301 psi x $in^{1/2}$ with a coefficient of variation of 11.9 percent. Previous research showed KIc values of 270-326 psi x $in^{1/2}$ for the TL orientation of Douglas-fir CTS (4,14,16) and values of 300.3 psi x $in^{1/2}$ for Scots pine (20). Thus, our results compare favorably with previous results of studies with untreated wood.

We expected that ring count, latewood percentage, and specific gravity would influence fracture toughness. However, an analysis of covariance showed that none of these were significant ($\alpha \leq .05$). Although no significant interactions between treatment and redrying were identified by an analysis of variance, the eventual loss or reduction in fracture toughness depends on consideration of the treatment and redrying level. Overall, several significant trends can be identified by reviewing the results of an analysis of variance and of the Tukey test of means on K_{Ic575} for all nine treatment-redrying combinations together and individually for CCA treatment at the 0.06-pcf level and two redrying levels (160' and 240°F) (Table 2). In general, air drying after CCA treatment and kiln drying after water treatment at 160°F either did not affect or slightly increased K_{Ic575} (7% to 12%). Kiln drying at 240°F after water treatment and kiln drying at 160°F after CCA treatment usually reduced K_{Ic575} (1% to 12%), but not significantly so. However, kiln drying at $\geq$190°F after CCA treatment at 0.6 pcf significantly lowered K_{Ic575} (16% to 23%) (Table 2). The percentages of property loss with kiln drying at temperatures $\geq$190°F after treatment with CCA were similar to or slightly greater in magnitude than those found in previous work by Bendtsen et al. (5), Winandy et al. (24), and Mitchell and Barnes (12) using clear wood specimens tested in bending.

Table 1.--FRACTURE TOUGHNESS, SPECIFIC GRAVITY, AND MOISTURE CONTENT OF TREATED AND CONTROL SPECIMENS.

Treatment	Post-treatment drying temperature (°F)	Number of specimens	Stress intensity factor[a] K_{Ic575} Mean (psi x	CV[b]	Variation[c] (%)	K_{Ic675} Mean (psi x $in^{1/2}$)	CV	Variation (%)	K_{Ic775} Mean (psi x $in^{1/2}$)	CV	Variation	SG[d]	MC[e]
Control	--	18	301	11.9	--	323	10.4	--	324	12.8	--	0.46	11.1
Water	160	23	322	11.9	+7	340	10.6	+5	331	23.2	+2	0.45	11.4
	240	16	295	13.6	-2	307	13.5	-5	303	14.0	-6	0.46	11.3
GRD[f]	160	12	267	13.3	-12	289	11.1	-11	293	12.0	-10	0.46	11.5
	240	13	269	15.8	-11	276	15.5	-15	281	10.9	-13	0.45	11.3
FDN[f]	Air	22	336	9.8	+12	354	10.2	+10	356	10.9	+10	0.46	11.7
	160	21	297	9.1	-1	321	8.9	-1	326	10.0	+1	0.46	11.4
	190	22	232	17.8	-23	253	17.1	-22	255	18.6	-21	0.46	11.3
	240	18	253	15.8	-16	274	14.2	-15	276	14.7	-15	0.47	11.3

[a] K_{Ic} is critical stress intensity factor that designates fracture toughness.
Superscripted numbers refer to crack length (1.575, 1.675, 1.775 in).
[b] Coefficient of variation.
[c] Difference from untreated controls.
[d] Specific gravity (ovendry weight/volume at test).
[e] Moisture content.
[f] GRD = 0.4 pcf CCA. FDN = 0.6 pcf CCA.

Table 2.--NONPARAMETRIC ANALYSIS OF VARIANCE AND TUKEY TEST OF RANKED OBSERVATIONS OF K_{Ic575}.

Condition	ANOVA Level of significance	Factor	Tukey results[a] (low to high)								
All nine groups	<.0001	Treat[b]	FDN	FDN	GRD	GRD	H_2O	FDN	CTL	H_2O	FDN
		Dry[c]	190	240	160	240	240	160	--	160	AIR
Redrying at 160°F only	<.0004	Treat	GRD	FDN	CTL	H_2O					
Redrying at 240°F only	<.0016	Treat	FDN	GRD	H_2O	CTL					
FDN treatment only	<.0001	Dry	190	240	160	CTL	AIR				

[a] Each bar represents mean values equivalent at 95 percent probability level.
[b] FDN = 0.6 pcf CCA, GRD = 0.4 pcf CCA, H_2O = water-treated control, CTL = untreated control.
[c] Posttreatment drying temperature (°F).

Utility of LEFM

The assumptions required to apply LEFM methods to an anisotropic, heterogeneous material like wood appear acceptable for detecting chemical and processing effects for treated wood. Our values for K_{Ic} for the control group compare favorably with previous Mode I fracture studies with wood (4,14,16). In addition, the relative effect of LEFM on fracture toughness results for each treatment-redrying combination appears comparable to the effect of using more conventional static-mechanical test methods such as those described in ASTM D 143 and D 198 (1). Therefore, LEFM appears to provide an effective testing methodology for accurately assessing the effects of chemical treatment. However, the use of LEFM results to address specific engineering design concerns will require further research.

Concluding Remarks

We investigated the effects of treatment with water or preservative (0.4 or 0.6 pcf CCA) and posttreatment air drying or kiln drying (160°, 190°, or 240°F) using LEFM as opposed to conventional static-mechanical test methods. No significant interactions were found between factors of the incomplete factoral design. Treatment with CCA followed by redrying temperatures $\geq$190°F significantly reduced fracture toughness or critical stress intensity factor (K_{Ic}) in the TL orientation for loblolly pine. This effect is comparable to previous results from conventional static-mechanical test methods.

References

1. American Society for Testing and Materials. 1984. Standard method of test for plane-strain fracture toughness of metallic materials (E 399-74). Annual Book of Standards, Part 10, Philadelphia, PA.

2. Atack, D., W. D. May, E. L. Morris, and R. M. Sproule. 1961. The energy of tensile and cleavage fracture of black spruce. Tappi 44(8):556-567.

3. Barnes, H. M., and P. H. Mitchell. 1984. Effects of post-treatment drying schedule on the strength of CCA-treated southern pine dimension lumber. Forest Prod. J. 34(6):29-33.

4. Barrett, J. D. 1976. Effect of crack-front width on fracture toughness of Douglas-fir. Eng. Fracture Mech. 8:711-717.

5. Bendtsen, B. A., L. R. Gjovik, and S. P. Verrill. 1983. Mechanical properties of Longleaf pine treated with waterborne preservatives. USDA Forest Serv. Res. Pap. FPL 434. Forest Prod. Lab., Madison, WI.

6. Boatright, S.W.J., and G. G. Garrett. 1980. On the statistical approach to fracture toughness variations with specimen size in wood. Eng. Fracture Mech. 13:107-110.

7. Boatright, S.W.J., and G. G. Garrett. 1983. The effect of microstructure and stress state on the fracture behaviour of wood. J. Mater. Sci. 18:2181-2199.

8. Broek, D. 1982. Elementary Engineering Fracture Mechanics. Martinus Nijhoff Publishers.

9. Data Resources, Inc. 1983. The markets for treated lumber, timbers and plywood: Recent developments and prospects for the future. Special report to Amer. Wood Preserv. Inst., Vienna, VA.

10. Johnson, J. A. 1973. Crack initiation in wood plates. Wood Sci. 6(2): 151-158.

11. Knuffel, W. E. 1985. The effect of CCA preservative treatment on the compression strength of South African pine structural timber. Holzforschung 37(5):96-99.

12. Mitchell, P. H., and H. M. Barnes. 1986. Effect of drying temperature on the clear wood strength of southern pine treated with CCA-Type A. Forest Prod. J. 36(3):8-12.

13. Parhizgar, S., L. W. Zachary, and C. T. Sun. 1982. Application of the principles of linear fracture mechanics to the composite materials. Int. J. Fracture 20:3-15.

14. Petterson, R. W., and J. Bodig. 1983. Prediction of fracture toughness of conifers. Wood Fiber Sci. 15(4):302-316. Oct.

15. Porter, A. W. 1964. On the mechanics of fracture in wood. Forest Prod. J., Vol. XIV.3. Aug.

16. Ruedy, T. C., and Jay A. Johnson. 1978. Glueline fracture of wood adhesive compact-tension specimens at various grain orientation configurations. First International Conference on Wood Fracture, Banff, Alberta, Canada, Aug. 14-16, 1978.

17. Sadd, M. H., and D. R. Curran. 1982. Mode I fracture toughness of epoxy impregnated wood. Mech. Res. Commun. 9(5):331-336.

18. Schniewind, A. P., and J. C. Centeno. 1973. Fracture toughness and duration of load factor I. Six principal systems of crack propagation and the duration factor for cracks propagating parallel to the grain. Wood and Fiber 5(2):152-159.

19. Schniewind, A. P., and P. A. Pozniak. 1971. On the fracture toughness of Douglas Fir wood. Eng. Fracture Mech. 2:223-233.

20. VVT Technical Research Centre of Finland. 1986. Fracture toughness of Finnish wood. Laboratory of Structural Engineering, Research Newsletter, 86-06-09.

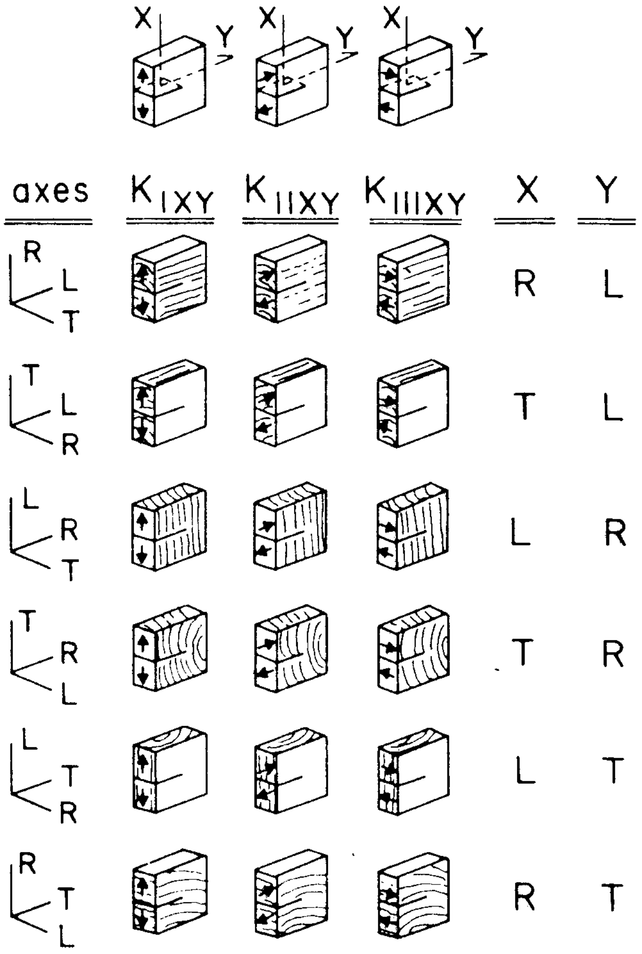
21. White, M. S., and D. W. Green. 1980. The effect of substrate on the fracture toughness of wood-adhesive bonds. Wood Sci. 12(3).

22. Winandy, J. E., B. A. Bendtsen, and R. S. Boone. 1983. Effect of delay between treatment and drying on toughness of CCA-treated southern pine. Forest Prod. J. 33(6):53-58.

23. Winandy, J. E., and R. S. Boone. 1987. The effects of CCA preservative treatment and redrying on the bending properties of 2 x 6 Southern Pine dimension lumber. Forest Prod. J. (in press).

24. Winandy, J. E., R. S. Boone, and B. A. Bendtsen. 1985. Interaction of CCA preservative treatment and redrying: effect on the mechanical properties of southern pine. Forest Prod. J. 35(10):62-68.

25. Wright, K., and M. Fonselius. 1986. Fracture toughness of wood--Mode I. ClB-W18/19-6-3. International Council for Building Research, Commission W18--Timber Structures, Florence, Italy.



(J. A. Johnson, 1973)

Figure 1. Principal stress intensity factors for wood: I-opening mode, II-forward shear mode, III-transverse shear mode, X-normal crack plane, and Y-crack propagation direction. L = longitudinal, R = radial, T = tangential (10). (ML87 5456)

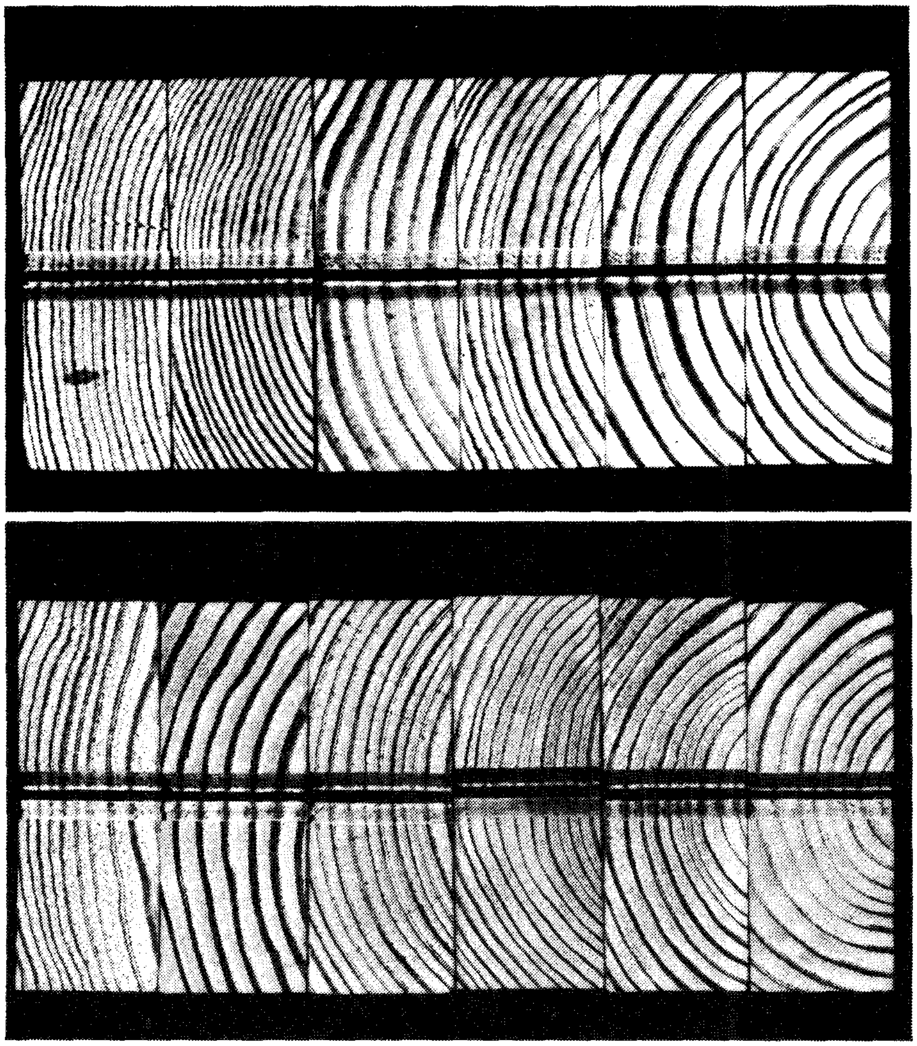


Figure 2. Range of specimen TL ring curvature; ideal on left and extreme deviation from ideal on right. Top, untreated specimens; bottom, CCA-treated specimens. (M86-0146 & M86-0147)

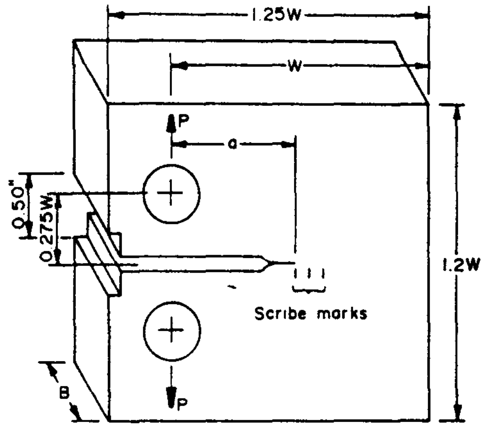


Figure 3. Dimensions for the compact-tension specimen (CTS) as governed by ASTM Standard E 399. a = crack length (1.575, 1.675, or 1.775 in); B = specimen thickness (1.5 in); W = specimen width between center line of load application and specimen edge (3.3 in); P = load (1). (ML88 5425)

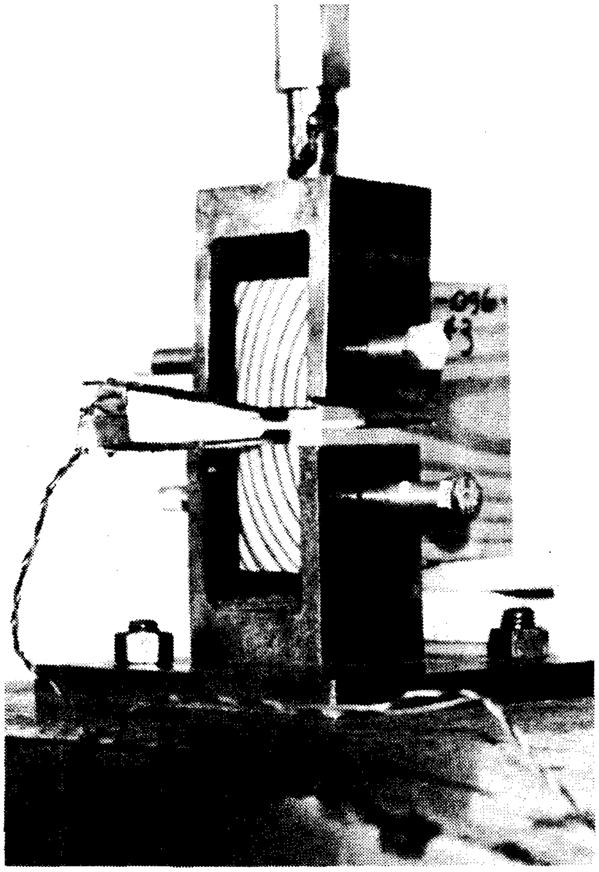


Figure 4. Closeup view of compact-tension specimen (CTS) and clip gauge used to monitor crack-opening displacement. (M86-0141)

Proceedings of the

1988 INTERNATIONAL CONFERENCE ON TIMBER ENGINEERING

Editor

Rafik Y. Itani
Professor
Washington State University

Westin Hotel
Seattle, Washington
U.S.A.

September 19-22, 1988

VOLUME 1

1988 INTERNATIONAL CONFERENCE ON TIMBER ENGINEERING

This proceedings includes papers presented at the 1988 International Conference on Timber Engineering which was held September 19-22, 1988 in Seattle, Washington, U.S.A. These papers are printed directly from camera ready manuscripts prepared by the authors. Views presented in the various papers are those of the respective authors and do not necessarily reflect those of the sponsors.

Editor

Rafik Y. Itani

Host Institution

Washington State University

Forest Products Research Society
2801 Marshall Court
Madison, Wisconsin 53705
(608) 231-1361; Fax: (608) 231-2152