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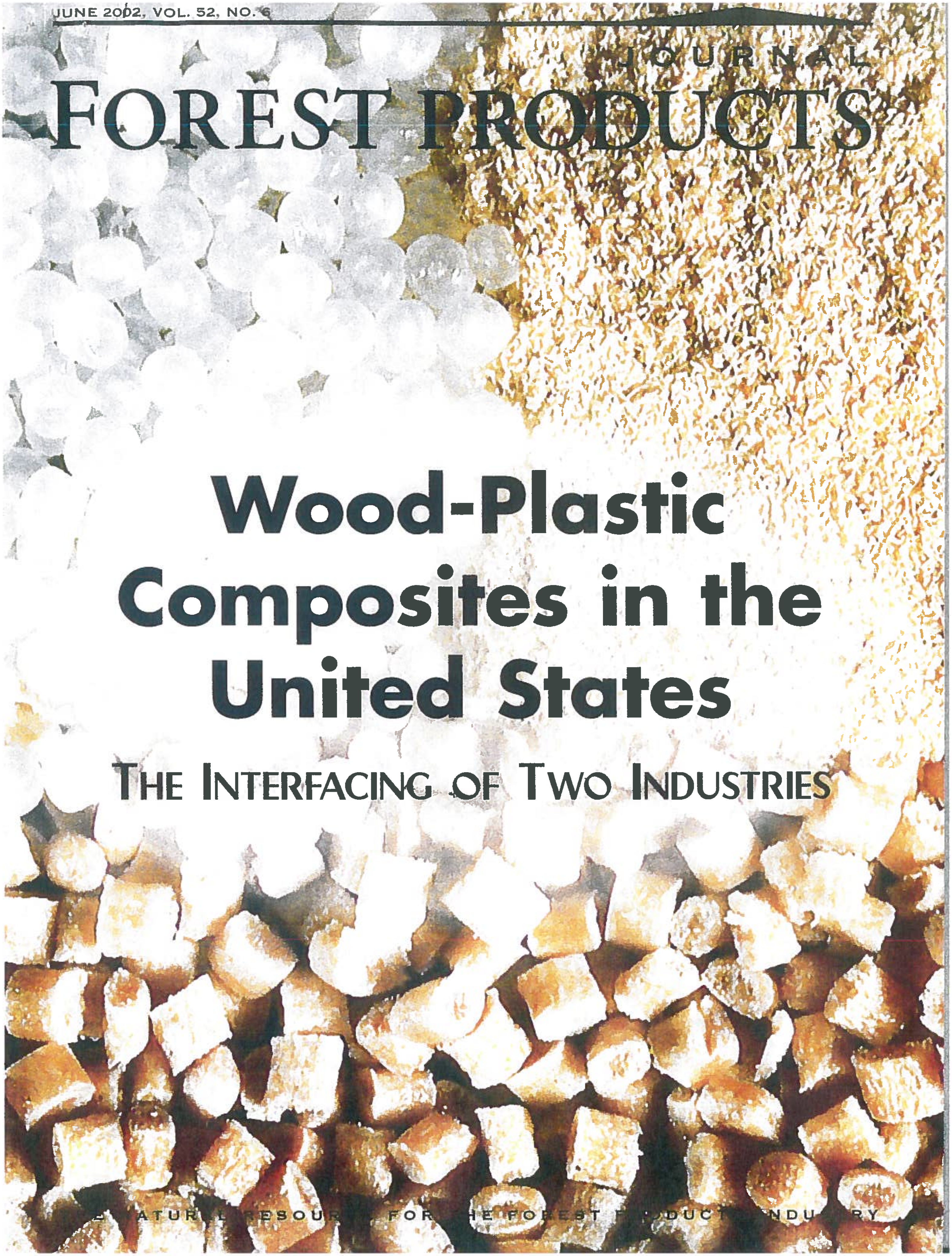

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COMPARISON OF STRENGTH PROPERTIES AND FAILURE CHARACTERISTICS BETWEEN FIRE-RETARDANT-TREATED AND UNTREATED ROOF FRAMING LUMBER AFTER LONG-TERM EXPOSURE: A SOUTH CAROLINA CASE STUDY

DEREK A. HODGIN*
ANDY W.C. LEE*

ABSTRACT

The degradation of strength properties related to the presence of fire retardant treatment (FRT) in wood has been previously documented. This degradation process is directly associated with environmental conditions of temperature and humidity. The FRT chemicals react with the wood during cyclical changes in temperature and humidity causing changes in pH such that the wood becomes brittle. This process is most commonly associated with plywood roof sheathing, where exposure to radiant heat is most significant. However, a recent case study in South Carolina indicates that the effects on southern pine dimension lumber used in roof framing can be equally dramatic. This study included strength testing of both FRT and untreated roof framing lumber after 22 to 31 years of exposure. Analysis of modulus of elasticity (MOE) and the bending modulus of rupture (MOR) of these samples revealed no appreciable loss of bending strength in the untreated lumber. In contrast, the treated wood samples had significant losses in both MOE and MOR. The failure of the FRT wood samples occurred suddenly with a marked absence of toughness, which is a reflection of their brittle condition.

Seven buildings on the campus of Chesterfield Marlboro Technical College (CMTC) in Cheraw, South Carolina, provided the materials for this study. The first three buildings (100, 400, and 500) were constructed in 1969. The remaining buildings (200, 300, 600, and 700) were constructed in 1974. In the fall of 1996, a partial roof collapse occurred at Building 700. The roof framing consisted of prefabricated metal-plate-connected No. 2 southern pine wood trusses and plywood roof sheathing. Both the dimension lumber in the trusses and the plywood roof sheathing were treated with fire retardant chemicals. However, this paper addresses the dimension lumber only. Shortly after the collapse occurred, the wood roof framing of the subject building was found to be severely damaged to the extent that partial removal and replacement was considered necessary. In 1997, a comprehensive damage survey was performed on the remaining portions of the subject building, the six other buildings on campus, and covered walkways that connected the buildings. This survey revealed that similar damages existed in all of the structures (1). Eventually, the roof of every building and walkway on campus was completely removed and replaced. The purpose of this paper is to report the difference in selected properties between fire-retardant-treated (FRT) lumber and untreated lumber after long-term service.

TESTING OF FIRE-RETARDANT-TREATED LUMBER

ORIGINAL TESTING

Seventeen wood samples, with nominal sizes of 2 by 4 inches and 2 by 6 inches, were removed from trusses in the seven buildings on the CMTC campus in 1996 (two or more samples from each building) for testing purposes (12). The in-service life of the wood samples ranged from 22 to 27 years. The specimens were prepared and natural defects (knots and cross-grain) were avoided as much as possible. Specimens measuring 1 by 1 by 16 inches were conditioned at

The authors are, respectively, Professional Engineer (P.E.), Campbell, Schneider and Associates, LLC, 218 East Main St., Westminster, SC 29693; and Professor, Dept. of Forest Resources, Clemson Univ., Clemson, SC 29634-0331. This paper was received for publication in December 2000. Reprint No. 9232.
*Forest Products Society Member.

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72°F and 65 percent relative humidity (RH) until they reached equilibrium moisture content (MC). Actual MC was measured immediately after the bending test. Bending tests included determination of the bending modulus of elasticity (MOE) and the modulus of rupture (MOR) in accordance with applicable ASTM standards (2). These tests revealed significant losses in MOE and MOR (**Table 1**) when compared to published values. These tests found the average MOE for treated wood to be approximately 1,262,000 psi. This average MOE value represents a loss of approximately 21 percent when compared to 1,600,000 psi for untreated No. 2 grade southern pine (10). The average MOR value of 8,100 psi for the treated wood samples represents a loss of approximately 37 percent when compared to 12,800 psi for untreated loblolly pine (4).

The average toughness of the treated and untreated specimens (0.79 by 0.79 by 11 in.) was measured and reported to be approximately 90 and 268 in.-lb., respectively (**Table 1**). These data indicate that the toughness of the untreated wood was approximately three times the toughness of the treated samples. The loss of toughness is directly related to the brash failure mode associated with FRT lumber.

A chemical assay (3) was performed with a plasma emission spectrometer for element analysis to determine the basic chemical constituents of the FRT (**Table 2**). The chemical analysis identified the presence of mono-ammonium phosphate. A previous study (8) suggested that this particular FRT formulation is significant in terms of wood strength loss over time. The pH of the treated samples was also measured and found to be 3.2. There is a strong relationship between changes in pH of treated wood and reduction in mechanical properties (8). Mono-ammonium phosphate is an inorganic salt that dissociates more readily at elevated temperatures, thereby increasing the acid concentration and decreasing the strength properties of wood (8).

TABLE 1. — Summary of strength properties for FRT and untreated roof framing lumber subjected to 22 to 31 years exposure in South Carolina.[a]

Static bending test						
Type of treatment	No. of specimens	Specific gravity	MC	MOE	MOR	Reference No.
			(%)	(1000 psi)	(psi)	
FRT (original)	17	0.53	8.26	1,262 (411)	8,100 (3358)	(12)
FRT (additional)	16	0.52	8.39	1,275 (487)	6,200 (3276)	(6)
Untreated	8	0.53	9.71	1,399 (190)	13,200 (1498)	(7)

Toughness test			
Type of treatment	No. of specimens	Toughness	Reference
		(in.-lb.)	
FRT	9	90 (50)	(12)
Untreated	10	268 (83)	(12)

[a] Values in parentheses indicate standard deviation.

TABLE 2. — Summary of chemical assay results of FRT wood from Benton Laboratories, Inc. (3).[a]

Element or compound	Measured concentration	
Boron	649 ppm	816 ppm
Phosphorus	8,552 ppm	8,911 ppm
Sulfur	1.76 %	1.75 %
Nitrogen	1.53 %	1.42 %
Mono-Ammonium Phosphate	3.07 %	3.20 %
pH	3.2	3.2

[a] Two samples were tested for each property.

Additional testing

Sixteen additional No. 2 southern pine samples were removed from the trusses during the 1997 damage survey for purposes of further independent testing. The in-service life of the wood samples ranged from 23 to 28 years. Specimen size and conditioning were identical to those described in the original testing. This testing also included determination of the MOE and the MOR in accordance with applicable ASTM standards (2). The average MOE and MOR were approximately 1,275,000 and 6,200 psi, respectively (**Table 1**) (6). This average MOE value represents a loss of approximately 20 percent when compared to 1,600,000 psi for untreated No. 2 grade southern pine (10). The average MOR for treated wood represents a loss of approximately 51 percent when compared to 12,800 psi for untreated loblolly pine (4).

The plots (stress vs. strain) of the test data for the treated wood samples just described typically showed an abrupt mode of failure (**Fig. 1**). These plots included a relatively linear and proportional stress/strain relationship early in the test. However, when failure occurred, the load-carrying capacity of the treated specimens dropped suddenly. The abrupt failure of the treated specimens is depicted by a sharp truncation on the final stage of the test plot. This portion of the test plot typically includes a nearly vertical drop indicating the rapid loss of the specimen's load-carrying capacity. This sharp truncation reduces the area below the stress/strain curve, which is directly related to toughness. The brash and sudden failure contributes to the reduced toughness of the treated specimens (**Fig. 2**).

Testing of untreated lumber

As the CMTC project entered into the litigation phase, numerous experts testified regarding the cause and extent of damages to the FRT dimension lumber. In the summer of 2000, it was suggested by an expert witness that the reductions in MOE and MOR were primarily the result of thermal degradation of natural wood. The contribution of the FRT was discounted to represent only 10 percent of the degradation, based on the early versions of the National Design Standard publication (9). This suggestion prompted further investigation. Fortunately, a small portion of an original roof section remained in place at the CMTC campus. This roof area extends over the entrance of Building 100 and was framed with untreated dimension lumber, which was exposed to similar conditions (i.e. structural loads, roof covering, solar shade, and ventilation).

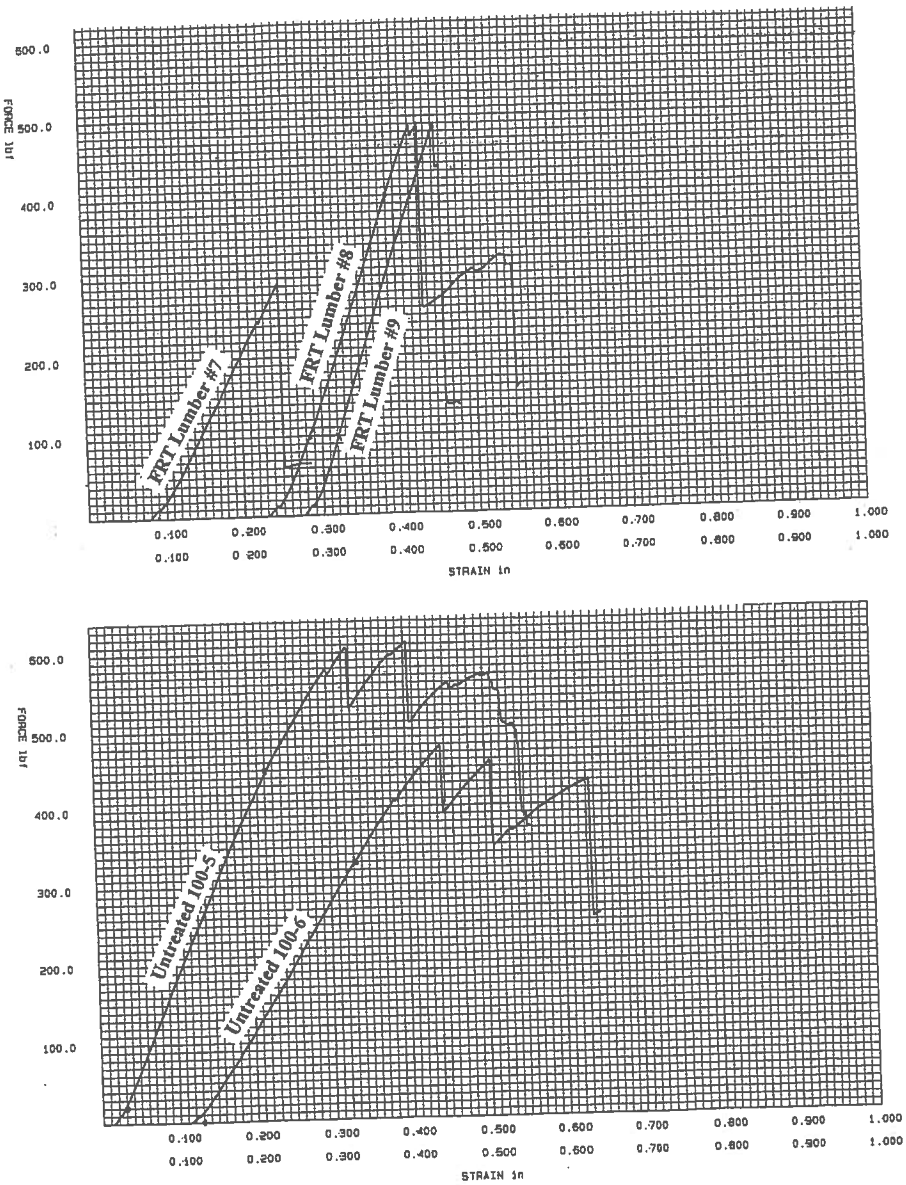

Figure 1. — Recording plots of static bending tests of FRT wood samples (top) and untreated wood samples (bottom).

All remaining roof areas were framed with FRT lumber and were removed and replaced in 1997. The presence of untreated lumber provided a unique opportunity for testing and comparison with the FRT lumber.

Samples of untreated wood roof framing were retrieved for testing in August of 2000 (7). The in-service life of the wood samples was 31 years. Four samples were removed from each of the two slopes of the gable roof, which provided a total of eight wood samples for testing. Specimen size and conditioning were identical to those described in the original testing. Testing of the untreated wood samples was performed in accordance with the applicable ASTM Standard (2). The average MOE was approximately 1,399,000 psi (**Table 1**), representing a 13 percent loss when compared to 1,600,000 psi for untreated No. 2 grade southern pine (10). The average MOR is approximately 13,200 psi, indicating no loss of MOR in the untreated samples when compared to 12,800 psi for untreated loblolly pine (4).

The plots (stress vs. strain) of the untreated wood samples just described typically showed a less abrupt mode of failure (**Fig. 1**). Specifically, failure occurred more gradually with the load-carrying capacity of the specimen dropping in a more "stepped" fashion on the final stage of the test plot. The ability of the untreated specimens to continue carrying load after initial failure greatly increased the area below the stress/strain curves, which represents the toughness of the samples. Therefore, these test plots indicate that the toughness of the untreated samples is much greater than that of the treated samples. The more gradual and less brash mode of failure of the untreated samples (**Fig. 2**) is attributed to the increased toughness.

Comparison of Treated and Untreated Test Results

The tests indicate that the presence of FRT caused a moderate loss of MOE (stiffness) and a severe loss of MOR (bending strength). In the absence of FRT, the untreated wood experienced only a minor loss of stiffness and no loss of bending strength.

The brittle condition of the treated wood samples is associated with a significant reduction of toughness. The loss of toughness in the treated wood resulted in a sudden and brash failure. In contrast, the untreated wood samples were able to continue carrying load after initial failure. The mode of failure for the untreated samples was more gradual and resilient in nature.

Discussion of Temperature Effects

Published studies have revealed that elevated temperatures above 150°F can result in permanent strength loss in wood and that continuous exposure for 72 months to elevated temperatures can result in a strength (MOR) loss of approximately 30 percent (4,5). However, the effect of elevated temperature was found to be insignificant for the MOR of the untreated wood in this case study. Based on a published report (11), these treated and untreated wood specimens in this case study were most likely exposed to temperatures above 150°F only on an infrequent and limited basis. A study of attic temperatures in Wisconsin and Mississippi revealed that temperatures above 150°F only occur for brief periods each day during the hottest summer months (11). A South Carolina location would likely be similar to Mississippi. However, the exposures remain intermittent and appear to have little long-term effect on the strength of untreated wood.

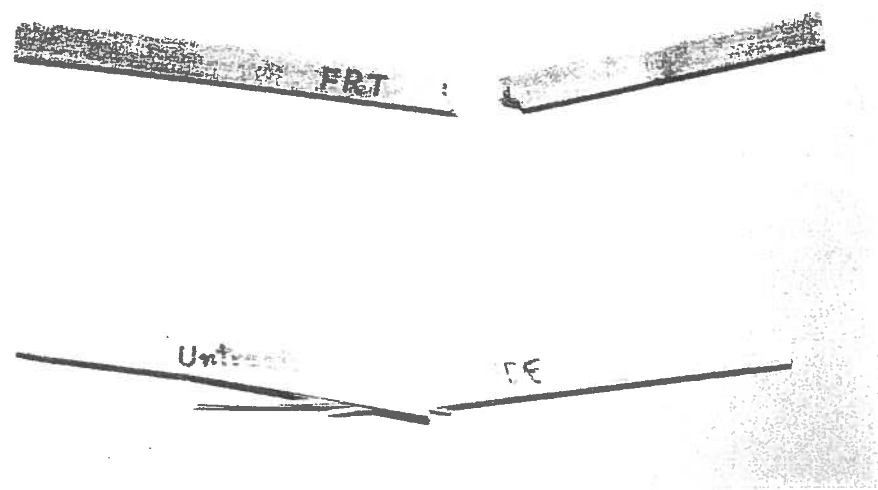

Figure 2. — Failure modes of static bending tests of FRT wood sample (top) and untreated wood sample (bottom).

Due to the limited exposure of the wood samples to elevated temperatures, it appears that a significant amount of time would be required for appreciable strength loss to occur. As an example, if wood were exposed to temperatures above 150°F for 2 hours per day for 2 months each year, it would require approximately 432 years to reach an accumulative exposure time of 72 months. Therefore, it is considered reasonable that this case study found no measurable strength loss of untreated wood samples after only 31 years of service life.

Summary

The test results of the treated and untreated wood samples showed moderate differences in loss of stiffness (MOE) and significant differences in loss of bending strength (MOR). Based on the results of these tests, it appears that the presence of FRT is the primary cause of reductions in the bending strength of wood. The FRT samples failed in an abrupt and brash manner, which was found to correspond to a reduction of toughness. In contrast, the untreated samples appeared to retain their toughness and failed in a less abrupt manner.

While permanent strength loss can result when wood is exposed to elevated temperatures above 150°F for long periods of time, this case study found no measurable strength loss in the untreated wood samples, which had remained in service for 31 years. Published literature revealed that significant losses in wood strength primarily occur in continuous and long-term exposures to elevated temperatures. The wood samples tested in this case study were likely only exposed to intermittent periods of elevated temperatures during the hottest summer months. Therefore, the exposure time of the samples to elevated temperature conditions only represents a very small fraction of the exposure time necessary to produce measurable effects.

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