ULTIMATE TENSILE STRESS AND MODULUS OF ELASTICITY OF FAST-GROWN PLANTATION LOBLOLLY PINE LUMBER

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ABSTRACT

The purpose of our study was to define the influence of juvenile wood on the tensile structural performance of dimension lumber from fast-grown plantation pine wood. Ultimate tensile stress and modulus of elasticity were measured on nominal 2- by 4-in. (standard 38- by 89-mm) lumber from a 28-year-old fast-grown loblolly pine plantation in North Carolina. We compared four grades of lumber and two lumber lengths. Strength and stiffness decreased with increasing amounts of juvenile wood. Average ultimate tensile stress and stiffness values of pieces composed entirely of juvenile wood were from 45 to 63% of those pieces composed entirely of mature wood, depending on grade and property.

We used physical properties as grading criteria to conform our test material to 1988 National Design Specifications (NDS) allowable design values. For our test material, percentage of latewood, number of rings per inch (25.4 mm), specific gravity, and presence or absence of pith could not be used individually as successful criteria for assuring conformance to design values. We compared data on mechanical properties to 1988 NDS allowable design values and to In-Grade test values. The performance of the Select Structural lumber conformed closest to the NDS design values; in the three lower grades tested—No. 1, No. 2, and No. 3—about 20% of the lumber did not conform to the design values. Compared to In-Grade test values for southern pine, the 5th-percentile strength, average stiffness, and specific gravity values of our material fell below the In-Grade test values for all grades. For both the NDS and In-Grade comparisons, strength values of our material could be raised above the 5th-percentile cut-off level by removing a given proportion of juvenile material from the analysis.

The correlation between ultimate tensile stress and modulus of elasticity of test material was about equivalent to that of southern pine lumber reported in the literature. Apparently, fast-grown pine plantation lumber with high proportions of juvenile wood can be machine stress-rated using techniques normally applied to traditionally used southern pine lumber. However, there does appear to be a pattern of decreasing slope in the strength-stiffness relationship with increasing juvenile wood content.

The results reported here are not representative of the global population of southern pine lumber on the market. However, the significant differences between juvenile and mature wood indicate that as the industry moves to a faster grown, shorter rotation resource, grading rules and allowable design stress values will need to be modified to accommodate this changing resource.

Keywords: Ultimate tensile stress, modulus of elasticity, juvenile wood, loblolly pine, plantation.

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

INTRODUCTION

To satisfy the increased demand for forest products, much of the future timber supply will come from plantations. This resource will tend to be harvested in short rotation cycles and will consequently contain higher proportions of juvenile wood than does wood currently harvested for dimension lumber. It is likely that fast-grown plantation lumber will not support current design stresses. In anticipation of this resource, definitive information is needed on the influence of juvenile wood on lumber properties so that grading rules and the associated allowable design stresses can be modified as needed.

The purpose of our study was to determine: (1) how the ultimate tensile stress (UTS) and modulus of elasticity (MOE) of fast-grown plantation loblolly pine (*Pinus taeda*) nominal 2- by 4-in. (standard 38- by 89-mm) lumber (called 2 by 4 lumber in this report) are influenced by varying proportions of juvenile wood; (2) whether or not the growth rate and percentage of latewood of such lumber can be used to identify low strength-stiffness pieces; and (3) whether or not the relationship between UTS and MOE can be used as a criterion for machine stress-rating this material.

BACKGROUND

Early research that helped draw attention to the problems associated with plantation-grown wood was conducted on 8-year-old plantation Caribbean pine from Puerto Rico (Boone and Chudnoff 1972). In this study, the specific gravity, bending stiffness, and strength of small clear specimens of plantation-grown wood were less than 50% of the published values for virgin timber of the same species. Many were surprised that the properties of plantation-grown wood should be so much lower than those of virgin timber, not realizing that the study was not a comparison of plantation wood and virgin timber but one of juvenile and mature wood. In this study, differences between juvenile and mature wood were probably accented because the trees were very young; early juvenile wood has distinctly lower properties than juvenile wood that is formed later. Research conducted at North Carolina State University on clear wood of loblolly pine clearly demonstrated that low properties could be attributed to juvenile wood, not plantation wood per se (Pearson and Gilmore 1971). This research demonstrated that juvenile wood is substantially lower in mechanical properties than is mature wood, which generally accounts for the inferior properties of plantation wood compared to that of virgin timber.

The reduced mechanical properties of juvenile wood in structural lumber were first observed by Koch (1966). Southern pine veneer-core studs had lower bending strength and stiffness than that expected for southern pine stud grade in general, but Koch concluded that veneer cores can yield 2 by 4s with properties adequate to support loads normally imposed on studs.

More evidence for the deleterious effect of juvenile wood was found in a study of finger joints in southern pine, No. 1 or better, nominal 2- by 6-in. (standard 38- by 140-mm) lumber (Moody 1970). In control specimens without finger joints, 2 by 6 lumber with pith had substantially lower strength and stiffness than lumber without pith. Similar results were observed in a study of the effect of high-temperature drying on Douglas-fir 2 by 4s (Gerhards 1979). Although these studies suggest differences between juvenile and mature wood, neither was designed to measure the difference. Actual differences in lumber with and without juvenile wood may be greater than the equal to or less than 50% reduction for pith-associated material observed by Gerhards and Moody because the pith-associated material in those studies may have contained some mature wood; conversely, the material without pith may have contained some juvenile wood.

As a result of research results like those cited, concern developed in the United States and elsewhere that allowable stresses assigned to lumber do not adequately reflect the changing resource. In the 1980s, researchers began to assess the mechanical properties of plantation-grown lumber. In New Zealand, In-Grade testing was completed on *Radiata* pine lumber cut from 40- to 60-year-old stands, the primary resource in the past (Walford 1982), and from 28-year-old stands, the anticipated future resource (Bier and Collins 1984). For the Engineering grade, bending strength of the young plantation material was 14% lower than that of the older timber, but it still exceeded code values. However, MOE of the young material was 10% below code values. In the lower No. 1 grade, there was essentially no difference in the bending properties of the lumber from the two sources.

In a study of the properties of lumber cut from 45- and 50-year-old Douglas-fir plantations in Canada (Barrett and Kellogg 1984), bending strength was about 8 to 27% lower than design values recommended by the National Lumber Grades Authority of Canada (1980). Differences in MOE between the plantation material and design recommendations were inconsistent among different grades and sizes and did not appear to be significant. Ratios of modulus of rupture (MOR) and MOE values for juvenile wood compared to those for mature wood ranged from 0.62 to 0.97, depending upon property, grade, and size. The low values for juvenile wood may explain why the plantation wood generally did not support the recommended design values.

In the United States, several studies have been conducted on the properties of Douglas-fir and southern pine dimension lumber cut from plantations. In lumber cut from a 75-year-old Douglas-fir plantation, UTS and MOE of 2 by 4s composed entirely of juvenile wood were about 60 and 72%, respectively, of those properties of 2 by 4s without juvenile wood (Bendtsen et al. 1988). Overall, the sample material was in conformance with allowable design stresses (NFPA 1988). However, about 10% of the material with equal to or more than 80% juvenile wood had less than 2.1 times (combined adjustment factor for duration of load and safety) the allowable design stress in tension. These results indicate that a modified medium-grain definition might be an effective criterion for maintaining conformance with design stresses in lumber cut from younger plantations.

The MOR and MOE of No. 2 and No. 3 grade 2 by 4 and 2 by 6 lumber cut from a 20-year-old slash pine plantation averaged about one-half the MOR and MOE of similar material from a 50-year-old plantation (MacPeak et al. 1990). The lumber from the older plantation exceeded 1988 design requirements for southern pine (NFPA 1988) in both strength and stiffness. However, for the younger plantation material, only a small percentage of pieces in four grade-size categories met design MOE. For the No. 2 grade, 23% of the 2 by 4s did not meet design requirements for design strength; other grades and sizes from the younger plantation were in conformance with bending design stresses. Slash pine is considered the strongest and stiffest species of the major southern pine group. If similar results were obtained for the other species in the group, they would likely be less favorable in terms of conformance with design stresses than those shown here for slash pine.

In a study of 22-year-old loblolly pine, MOR and MOE increased markedly from pith to bark in 2 by 6s cut from butt bolts (Pearson 1984). Because the strength ratio or lumber quality level decreased slightly from the pith outward, radial increases in MOR and MOE apparently reflected differences between juvenile and mature wood. Lumber from upper bolts showed no radial gradient in MOR and MOE, apparently because there was no mature wood. These results cannot be directly compared to design stress values because the material was not graded. However, observed MOE values were lower than expected, even for the No. 3 grade wood. With the exception of the values for the outer two positions in the butt bolt, MOR values were considerably less than those expected for the strength ratios observed.

North American lumber cut from the juvenile wood zone of logs from young plantations, at least for Douglas-fir and southern pine, apparently will not meet 1988 National Design Specifications (NDS) allowable properties for visually graded lumber. Grading rules in the

United States and Canada attempt to address this question with restrictions on growth characteristics and lightweight wood. The effect of juvenile wood appears to be more severe in the southern pines than in Douglas-fir, and several studies indicate that juvenile wood has a greater effect on MOE than on strength (Pearson 1984; Bendtsen and Senft 1986; Bendtsen et al. 1988). This agrees with results reported for *Radiata* pine lumber from New Zealand (Bier and Collins 1984).

EXPERIMENTAL

Test material

The 2 by 4s in our study were previously used in a study that compared press drying and the Saw-Dry-Rip (SDR) process in reducing warp in fast-grown loblolly pine lumber. For the study reported here, we evaluated 1,680 pieces of lumber. The test material included 701 8-ft (2.4-m) press-dried 2 by 4s, the length limited by the size of the press available, and 991 16-ft (4.9-m) 2 by 4s processed by the SDR method. The results of tests on twelve 2 by 4s were deleted for various reasons, ranging from machine failure to missing data values.

The lumber was obtained from 100 trees cut from a 28-year-old plantation in Beaufort County, North Carolina, owned by the Weyerhaeuser Company. Although the exact seed source is unknown, we do know that the seeds did not come from a genetically improved source. The plantation site was an old farm field, not a forested site, with a site index of 69. The plantation was thinned twice (1973 and 1981) and fertilized at least once (1979–1980). This management regime is typical of that anticipated by the Weyerhaeuser Company for the production of sawtimber trees in the future, although 28 years is 2 to 4 years shorter than the expected rotation time for trees on this site.

The sample trees averaged 16.1 in. (409 mm) in breast-height diameter (dbh) and ranged from 11 to 19.3 in. (279 to 490 mm) dbh. About half the trees fell in the diameter range of 14 to 16.5 in. (356 to 419 mm). A 36-ft (11-m) long log was cut from each tree, end-painted to prevent moisture loss, and shipped to Madison, Wisconsin, for processing.

Specimen preparation and testing

Before the logs were sawn into lumber, the 8th annual ring from the pith was delineated with a felt-tip pen on both ends of the logs. The surface area inside this ring was then spray-painted. The choice of the 8th ring as the delineation between juvenile and mature wood was somewhat arbitrary. Loblolly pine has been reported to have from 6 to 14 or more rings of juvenile wood (Hallock 1968; Clark and Saucier 1989; Bendtsen and Senft 1986). The logs were sawn into 2 by 4s, dried, and planed according to different press-drying regimes or the SDR process. For the press-dried material, the processing conditions were two different pressures [25 or 50 lb/in.^{2} (172 or 345 kPa)], platen temperature of 350 F (171 C), and two cooling techniques (restrained and unrestrained) with each pressure. The SDR material was processed by cant or SDR sawing technique and dried with or without conditioning (Simpson et al. 1988).

The 2 by 4s were visually graded by a quality supervisor from the Southern Pine Inspection Bureau according to the National Grading Rule (SPIB 1977), except that appearance characteristics such as wane were not considered. Also, defects in the first 30 in. (762 mm) from each end were not considered in grading because these areas were to be covered by the tension grips during testing.

The specimens were placed on stickers and allowed to come to equilibrium in an environment controlled at 74 F (23 C) and 65% relative humidity [approximately 12% equilibrium moisture content (EMC)]. Selected specimens were periodically weighed to determine when equilibrium was reached.

Full-length MOE was measured on each specimen with a Metriguard E-Computer;[2] the

[2] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

width and thickness of each specimen was measured near the center to the nearest 0.01 in. (0.25 mm). The 2 by 4s were failed in tension, placing the outer 30 in. (762 mm) in the tension grips. Testing was in accordance with standard procedures (ASTM D-4761-88; ASTM 1989) except that no elongation data were recorded. The ultimate load was recorded.

After failure, the 2 by 4s were cross-cut at an intact area as near the failure zone as possible. One surface of the cross-cut was color-coded for juvenile wood by tracing the color codes on the ends of the specimens through the annual rings to the cross-cut surface. The percentage of the cross section comprised of juvenile wood was determined by laying a 0.25-in. (6.4-mm) transparent grid over the end and counting the number of grid squares falling inside and outside the color-coded area. Interpolating or estimating was required at the juvenile-mature wood interface because some squares covered both juvenile and mature wood.

A 1-in. (25.4-mm) section was cut from the failure end of the cross-cut piece and used to determine the growth rate (rings per unit length), percentage of latewood, specific gravity (oven-dry weight/test volume), moisture content, and presence or absence of pith.

Grading of lumber

The 2 by 4s were distributed among four structural grades as follows:

Grade	Number of pieces
Select Structural	515
No. 1	424
No. 2	463
No. 3	278

None of the pieces was graded DENSE [as defined by the SPIB (1977)].

Pooling of data

For the purposes of the study reported here, we wanted to pool the data. Because the lumber had been processed by different regimes, we needed to determine if one or more of these regimes affected UTS or MOE, either positively or negatively, and if this effect was different in juvenile wood compared to mature wood. Either effect would tend to mask or exaggerate the influence of proportion of juvenile wood on mechanical properties.

To address this concern, we plotted and tabulated average UTS and MOE as a function of percentage of juvenile wood for lumber processed by different regimes. This was done separately for each lumber grade. The plots showed considerable variability because of small sample sizes (two or fewer specimens in some instances) (see Fig. 1 for plot of data from No. 2 lumber). As a result of the high variability, differences between treatments were difficult to detect. Consistent slopes suggest that juvenile and mature woods were not affected differently by the processing regime used. In addition, processing regime did not affect mechanical properties, although the press-dried

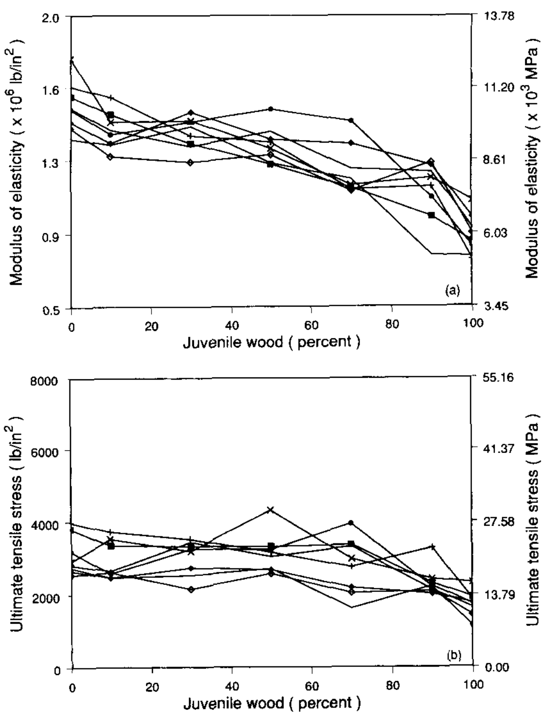
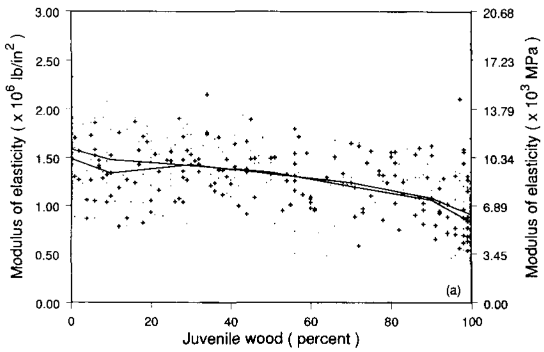


FIG. 1. Effect of processing regime on the relationship between percentage of juvenile wood and (a) modulus of elasticity (MOE) and (b) ultimate tensile stress (UTS) for No. 2 grade 2 by 4s.



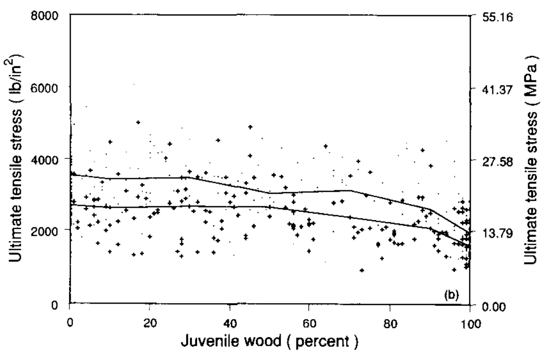


FIG. 2. Effect of lumber length on relationship between percentage of juvenile wood and (a) MOE and (b) UTS for No. 2 grade 2 by 4s. Dots, 8-ft (1.4-m) lumber; plus signs, 16-ft (4.9-m) lumber.

material tended to have the highest strength and stiffness values. Increases in strength and stiffness caused by densification during press drying have been reported by others (Tang and Simpson 1989). However, even though press-drying results in an apparent increase in strength and stiffness, this method has a drawback: the densified boards must have greater green thickness than boards dried by other methods to produce lumber of the same dimension for final use.

We were also concerned about the effect of lumber length. For all grades, no consistent pattern was noticed between MOE of 8-ft (2.4-m) and 16-ft (4.9-m) specimens (Fig. 2a). Length did have a noticeable effect on UTS (Fig. 2b). The UTS for 8-ft (2.4-m) specimens was approximately 20% greater on average than that for 16-ft (4.9-m) specimens. The percentage of juvenile wood had a similar effect on 8-ft (2.4-m) and 16-ft (4.9-m) specimens. Therefore, the two lengths of lumber were pooled for subsequent analyses. When we compared our test results to allowable design stress values and In-Grade test data, data for the two lengths were separated.

RESULTS AND DISCUSSION

Table 1 shows average results of all measurements for the various grades of lumber with different amounts of juvenile wood.

Effect of juvenile wood on mechanical properties

The average UTS and MOE of the 2 by 4s of four structural grades—Select Structural (SS), No. 1, No. 2, and No. 3—decreased markedly as the amount of juvenile wood in the cross section increased; these properties were maximum for 2 by 4s composed of all-mature wood and minimum for those composed of all-juvenile wood (Table 1 and Figs. 1–3). For example, the average UTS of the SS grade, all-mature-wood 2 by 4s was 6,100 lb/in.^{2} (42 MPa) and that of all-juvenile-wood 2 by 4s 2,740 lb/in.^{2} (18.9 MPa); MOE was 1.70 and 1.00×10^6 lb/in.^{2} (11,722 and 6,895 MPa) for the all-mature and all-juvenile wood, respectively.

The trends in the relationship between the average mechanical property values and the percentage of juvenile wood are remarkably consistent for both UTS and MOE and for all four grades, considering the variability normally associated with tests of structural lumber (Figs. 3, 4). The coefficients of variation showed no consistent pattern; they are quite typical for structural lumber, generally ranging from 20 to 30% for MOE and 25 to 40% for UTS, depending upon grade and the percentage of juvenile wood. The major inconsistency occurred in MOE: MOE values for different grades of lumber were very similar when the amount of juvenile wood in the cross section exceeded about 50%. There is no obvious reason for this result; apparently, strength ratio has little influence on the MOE of lumber composed primarily of juvenile wood.

TABLE 1. *Physical and mechanical properties of various grades of loblolly pine 2 by 4s by percentage of juvenile wood.*

Juvenile wood class[a]	Sample size	Modulus of elasticity: Average ($\times 10^6$ lb/in.)	($\times 10^3$ MPa)	SD	Tensile strength: Average (lb/in.^{2})	(MPa)	SD	Rings/ inch[b]	Late-wood (percent)	Specific gravity[c]	Pith[d]
					Select Structural						
0	237	1.711	(11.8)	0.338	6,102	(42.1)	2,169	4.3	37.0	0.499	0/237
1–20	125	1.684	(11.6)	0.307	6,439	(44.4)	2,016	4.7	36.3	0.496	0/125
21–40	57	1.577	(10.9)	0.330	6,016	(41.5)	1,843	5.0	34.5	0.483	0/57
41–60	35	1.478	(10.2)	0.332	5,361	(37.0)	1,644	4.5	37.4	0.496	0/35
61–80	14	1.177	(8.1)	0.401	4,617	(31.8)	911	4.0	31.6	0.442	0/14
81–99	20	1.088	(7.5)	0.382	3,718	(25.6)	1,318	3.4	24.4	0.418	2/20
100	27	0.986	(6.8)	0.274	2,737	(18.9)	1,114	2.8	19.1	0.392	15/27
(Average)	515	1.597	(11.0)	0.388	5,815	(40.1)	2,167	4.4	35.0	0.486	17/515
					No. 1						
0	76	1.655	(11.4)	0.387	4,202	(42.1)	1,270	4.3	31.6	0.470	0/76
1–20	66	1.527	(10.5)	0.299	4,218	(44.4)	1,251	4.6	31.9	0.462	0/66
21–40	54	1.545	(10.7)	0.308	4,013	(41.5)	1,039	4.7	29.9	0.458	0/54
41–60	49	1.446	(10.0)	0.304	3,998	(37.0)	1,344	4.4	31.6	0.464	0/49
61–80	34	1.221	(8.4)	0.340	3,367	(31.8)	1,374	4.2	28.4	0.432	2/34
81–99	68	1.054	(7.3)	0.311	2,837	(25.6)	916	3.6	26.1	0.417	24/68
100	77	0.840	(5.8)	0.252	2,168	(18.9)	613	2.6	17.8	0.386	53/77
(Average)	424	1.318	(9.1)	0.433	3,502	(40.1)	1,357	4.0	27.8	0.440	79/424
					No. 2						
0	75	1.532	(10.6)	0.266	3,055	(42.1)	908	4.1	30.4	0.456	0/57
1–20	72	1.416	(9.8)	0.325	3,043	(44.4)	973	4.2	29.7	0.450	0/72
21–40	58	1.424	(9.8)	0.275	3,012	(41.5)	907	4.3	30.4	0.455	0/58
41–60	50	1.339	(9.2)	0.301	2,807	(37.0)	786	4.2	31.2	0.447	0/50
61–80	39	1.222	(8.4)	0.297	2,707	(31.8)	929	4.1	27.6	0.423	5/39
81–99	85	1.069	(7.3)	0.320	2,315	(25.6)	825	3.4	23.3	0.396	23/85
100	84	0.867	(6.0)	0.260	1,789	(18.9)	488	2.6	17.8	0.387	53/84
(Average)	463	1.248	(8.6)	0.373	2,626	(40.1)	952	3.7	26.5	0.428	81/463
					No. 3						
0	41	1.380	(9.5)	0.253	2,297	(42.1)	973	3.9	29.1	0.441	0/41
1–20	54	1.385	(9.5)	0.262	2,113	(44.4)	740	4.0	29.3	0.444	0/54
21–40	29	1.307	(9.0)	0.270	2,289	(41.5)	784	4.1	28.1	0.427	0/29
41–60	33	1.322	(9.1)	0.287	1,755	(37.0)	659	4.2	29.4	0.438	0/33
61–80	33	1.215	(8.4)	0.319	1,923	(31.8)	665	3.6	27.6	0.417	3/33
81–99	47	1.092	(7.5)	0.268	1,690	(25.6)	629	3.5	20.9	0.398	12/47
100	41	0.864	(6.0)	0.242	1,317	(18.9)	367	2.6	17.5	0.390	21/41
(Average)	278	1.222	(8.4)	0.323	1,904	(40.1)	773	3.7	25.8	0.422	36/278

[a] Percentage of juvenile wood.
[b] 1 in. = 25.4 mm.
[c] Based on oven-dry weight and test volume.
[d] Number of pieces with pith per total number of pieces.

The average UTS and MOE of all-juvenile-wood 2 by 4s were substantially lower than those of all-mature wood (Table 2). The low ratio (0.45) of UTS for juvenile to mature wood for SS lumber may be explained by the better quality of the mature wood; the strength ratio of SS lumber may range from 65 to 100%.

In a similar study of plantation-grown Douglas-fir, juvenile to mature wood ratios of about 59 and 72% were observed for UTS and MOE, respectively (Bendtsen et al. 1988). However, the Douglas-fir plantation evaluated was older than the plantation evaluated in the study reported here (75 years compared to 28

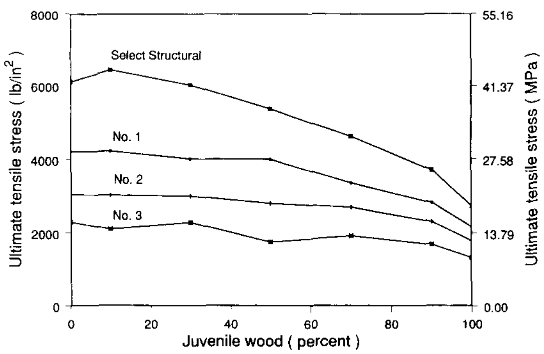


FIG. 3. Ultimate tensile stress (UTS) as a function of percentage of juvenile wood for four grades of southern pine 2 by 4 lumber.

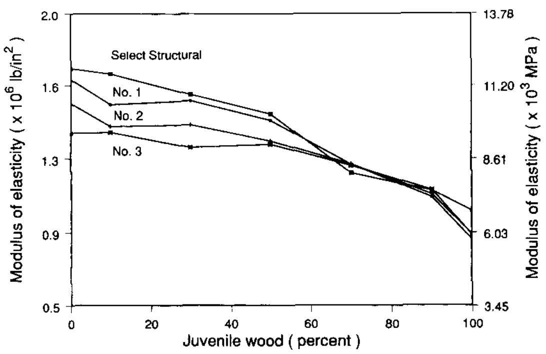


FIG. 4. Modulus of elasticity as a function of percentage of juvenile wood for four grades of southern pine 2 by 4 lumber.

years) and its rate of growth was slower, as shown by the average number of annual rings per inch (25.4 mm) (7.5 rings compared to 4.0 rings). If the plantations were more similar in age and growth rate, the ratios of mechanical properties in juvenile and mature wood would possibly be more similar.

Our results are in close agreement with those from tests of clear wood of the same species. Average juvenile/mature wood ratios of 0.47 for MOE and 0.59 for MOR were reported for very small, clear wood specimens prepared from individual annual rings of six plantation-grown loblolly pine trees (Bendtsen and Senft 1986). Pearson and Gilmore (1971) also found significant differences between the clear wood values of juvenile and mature wood in loblolly pine, although they did not calculate average values for the two kinds of wood.

Physical properties as grading criteria for design values

We used our physical property data as grading criteria to conform our test material to design values listed in the 1988 NDS (NFPA 1988) for southern pine KD-15 (used at 15% maximum moisture content).

The percentage of latewood, rings per inch (25.4 mm), and specific gravity were highest in the SS lumber and lower in each succeeding grade (Table 1). Also, the percentage of SS lumber with pith (3%) was much lower than that of lumber in the other three grades (19, 17, and 13% for No. 1, No. 2, and No. 3, respectively). These data indicate that the SS grade contains less juvenile wood than do the lower grades, which may explain why the UTS values for the SS lumber were in conformance with allowable stress values.

The physical properties tested also showed a relationship to the amount of juvenile wood in the cross section. These properties were relatively constant in lumber with 0 to 60% juvenile wood but declined sharply in lumber with a higher percentage. Nearly all the pieces that contained pith had at least 80% juvenile wood. The data suggest that certain physical properties—including percentage of latewood, rings per inch (25.4 mm), specific gravity, and presence or absence of pith—can be used singly or in combination to identify lumber that contains juvenile wood. Thus, these properties also have the potential to be used as grading or sorting criteria for maintaining conformance with allowable design properties.

In our study, growth rate, percentage of late-

TABLE 2. *Ratio of mechanical properties in all-juvenile wood to those in all-mature wood for various grades of lumber.*

Grade	Ultimate tensile stress	Modulus of elasticity
Select Structural	0.45	0.58
No. 1	0.52	0.51
No. 2	0.59	0.57
No. 3	0.57	0.63

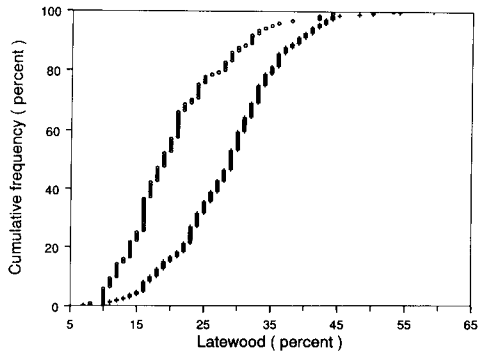


FIG. 5. Cumulative distribution functions for percentage of latewood in No. 2 grade 2 by 4s that do (+) and do not (O) conform to allowable tensile stress values for the grade.

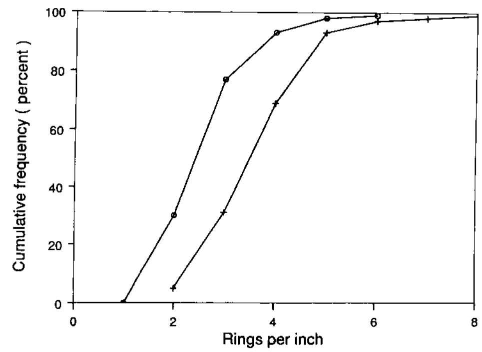


FIG. 7. Cumulative distribution functions for growth rate of No. 2 grade 2 by 4s that do (+) and do not (O) conform to allowable tensile stress values for the grade. Plotted values are the average cumulative frequency for each discrete growth rate measurement. 1 in. = 25.4 mm.

wood, and specific gravity used singly lacked good sorting capability because of the overlap of property distributions for pieces that conformed to design and those that did not. To illustrate, we will examine the No. 2 lumber because this grade had the largest percentage of pieces (33%) that did not conform to the allowable tensile stress value.

The objective of sorting is to downgrade those pieces that do not conform to design values and, at the same time, to minimize the downgrade of pieces that do meet design values. In regard to percentage of latewood (Fig. 5), if the 5th percentile (about 15% latewood) of the distribution of pieces that conform to the allowable tensile stress value is the sorting level, this level identifies about 30% of the

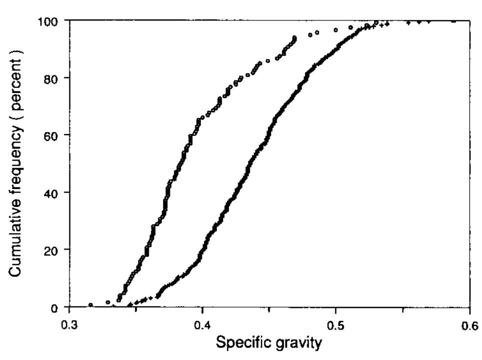


FIG. 6. Cumulative distribution functions for specific gravity of No. 2 grade 2 by 4s that do (+) and do not (O) conform to allowable tensile stress values for the grade.

pieces that do not meet the design value. To identify 95% of the pieces that do not conform to design would require a sorting level of about 35% latewood. However, this sorting level would also downgrade about 80% of the pieces that do conform to design.

The results for specific gravity (Fig. 6) were essentially identical to those for percentage of latewood. A 5th percentile sorting level for pieces that conform to design correctly downgraded about 30% of pieces that did not conform; a specific gravity level of about 0.48, required to identify 95% of the pieces that do not meet design, would incorrectly downgrade about 80% of the pieces that do conform to design.

For rate of growth, the 5th percentile [slightly more than 2 rings per inch (25.4 mm)] for pieces that conformed to design identified less than 20% of those that did not conform (Fig. 7). Five rings per inch (25.4 mm) identified 95% of pieces that did not conform to design and downgraded about 80% of those that did conform.

Absence of pith appears to have sorting potential about equivalent to that of both the percentage of latewood and specific gravity. For the No. 2 lumber, absence of pith correctly downgraded 43% of pieces that did not conform to design and incorrectly downgraded 8% of pieces that did conform (Table 3). At the

TABLE 3. *Relationship of pith to allowable ultimate tensile stress (UTS) in graded lumber of different lengths.*

Length and grade	Ultimate tensile stress equal to or more than 2.1 × design	Sample size	Number of pieces: Without pith	Number of pieces: With pith
8 ft (2.4 m)				
Select Structural	Yes	391	386	5
	No	17	8	9
No. 1	Yes	217	192	25
	No	59	24	35
No. 2	Yes	175	162	13
	No	37	14	23
No. 3	Yes	85	77	8
	No	5	0	5
16 ft (4.9 m)				
Select Structural	Yes	98	98	0
	No	9	6	3
No. 1	Yes	124	117	7
	No	24	12	12
No. 2	Yes	168	151	17
	No	83	55	28
No. 3	Yes	165	150	15
	No	23	15	8

43% sorting level, about 10% of pieces were incorrectly downgraded by percentage of latewood (Fig. 5) and about 8% by specific gravity (Fig. 6).

Mechanical properties compared to design values

The comparison of test UTS data to NDS values is summarized by lumber length because of the length effect detected in UTS.

Ultimate tensile stress.—The 1988 allowable design stress values for visual grades of lumber were derived under the assumption that the strength of at least 95% of the pieces, when adjusted for duration of load and safety (combined factor of 2.1), must be at least as high as the stress assigned (ASTM 1990a, b). Conversely, not more than 5% of the pieces can have strength values less than 2.1 times the design stress.

For the 8-ft (2.4-m) material tested in our study, the SS grade conformed with the allowable design stress in tension; only 4.2% of the pieces had strength values less than 2.1 times the allowable value (Table 4). For the 16-ft (4.9-m) material, none of the grades conformed with the design values (Table 4). As anticipated, the number of pieces that did not conform with the design tensile stress values generally increased as the percentage of juvenile wood increased. For lumber composed entirely of juvenile wood, the percentage of pieces not in conformance ranged from 24 to 85%, depending on grade and length.

The tabulated information suggests that restrictions on the percentage of juvenile wood content permissible would be effective in reducing the percentage of pieces that do not meet 1988 design criteria. If, for example, 8-ft (2.4-m) pieces with more than 60% juvenile wood were excluded, the lumber would meet the design criteria; 4.5% (5 of 107) of the pieces would not conform to the allowable value rather than 7.5%.

Modulus of elasticity.—Design MOE is based on an average value. In our study, the average MOE test value for all four grades was less than the allowable MOE, as shown in Table 5. In fact, even the average values for 2 by 4s of all-mature wood (Table 1) were less than the allowable values for all four grades. The failure of plantation wood to conform to design values can be attributed not only to the proportion of juvenile wood but also to the physical properties of the material.

Comparison of test data to In-Grade data

The literature indicates that lumber cut from the juvenile wood zone of logs obtained from young-growth southern pine plantations may not meet 1988 NDS allowable design properties. Reported strength and stiffness ratios for 2 by 4s containing all-juvenile wood and those containing all-mature wood have ranged from 45 to 59% and 51 to 72%, respectively. However, 1988 NDS values for some species have been shown to be significantly different from the In-Grade data (Green and Evans 1987), and the NDS values will change with

TABLE 4. *Conformance of test ultimate tensile stress (UTS) values to NDS values by percentage of juvenile wood.*

Length and grade	Number (percentage) of pieces not conforming to design[a] by juvenile wood class							All specimens
	0	1–20	21–40	41–60	61–80	81–99	100	
8 ft (2.4 m)								
Select Structural	1/176	0/99	0/47	0/28	0/14	5/20	11/24	17/408
	(1)	(0)	(0)	(0)	(0)	(25)	(46)	(4)
No. 1	2/32	4/40	0/34	1/30	4/22	12/54	36/64	59/276
	(6)	(10)	(0)	(3)	(18)	(22)	(56)	(21)
No. 2	1/31	1/37	1/24	2/20	1/17	10/38	21/45	37/212
	(3)	(3)	(4)	(10)	(6)	(26)	(47)	(18)
No. 3	0/11	0/17	0/15	0/6	0/11	1/14	4/16	5/90
	(0)	(0)	(0)	(0)	(0)	(7)	(25)	(6)
16 ft (4.9 m)								
Select Structural	2/61	1/26	1/10	2/7	0/0	0/0	3/3	9/107
	(3)	(4)	(10)	(29)	(0)	(0)	(100)	(8)
No. 1	2/44	1/26	1/20	1/19	4/12	8/14	7/13	24/148
	(5)	(4)	(5)	(5)	(33)	(57)	(54)	(16)
No. 2	6/44	6/35	8/34	4/30	7/22	19/47	33/39	83/251
	(14)	(17)	(24)	(13)	(32)	(40)	(85)	(33)
No. 3	2/30	3/37	0/14	3/27	4/22	5/33	6/25	23/188
	(7)	(8)	(0)	(14)	(18)	(15)	(24)	(12)

[a] Number of pieces with UTS values less than 2.1 times the allowable design stress per total number of pieces. For example, of 8-ft (2.4-m) Select Structural grade 2 by 4s composed entirely of mature wood, 1 of 176 pieces or 0.6% had less than 2.1 times the design stress value. National Design Specification (NFPA 1988).

the implementation of the ASTM In-Grade testing standard (ASTM-D-1990-1991; ASTM 1991). Thus, not all the detected differences in testing standard (ASTM D-1990–91; ASTM 1991). Thus, not all the detected differences in test results and allowable properties can be attributed to juvenile wood characteristics alone. A better method for evaluating the effect of juvenile wood on properties is to compare our results to property values summarized in Green and Evans (1987).

Ultimate tensile stress.—Table 6 shows UTS and MOE for graded lumber in various juvenile wood classes based on normalized 5th percentile UTS parallel to grain values from Green and Evans (1987). As the percentage of juvenile wood increased, so did the percentage of pieces that fell below the normalized 5th percentile; this pattern is like that observed in the comparison of our results with NDS data. In general, the SS pieces had slightly higher values and the No. 2 pieces lower values compared to UTS values for lumber by lumber length (Table 4). Again, the percentage of juvenile wood was apparently an important consideration in making the 5th-percentile cut-off.

Modulus of elasticity.—Table 6 shows the average MOE for the two lumber lengths combined. Again, the stiffness of this particular material was considerably less than the expected average stiffness for 2 by 4 lumber in the Green and Evans In-Grade data. The percentage of pieces that fell below expected values increased with increasing percentage of juvenile wood.

Specific gravity.—Some differences between In-

TABLE 5. *Average and allowable modulus of elasticity values for various grades of 2 by 4 lumber.*

Grade	Average modulus of elasticity		Allowable modulus of elasticity	
	($\times 10^6$ lb/in.^{2})	($\times 10^3$ MPa)	($\times 10^6$ lb/in.^{2})	($\times 10^3$ MPa)
Select Structural	1.597	11.0	1.8	12.4
No. 1	1.318	9.1	1.8	12.4
No. 2	1.249	8.6	1.6	11.0
No. 3	1.223	8.4	1.5	10.3

TABLE 6. *Conformance of test mechanical properties to In-Grade results[a] by percentage of juvenile wood.*

Length and grade	Number (percentage) of pieces with lower than normalized 5th percentile values[b] by juvenile wood class: 0	1–20	21–40	41–60	61–80	81–99	100	All specimens
				Ultimate tensile stress parallel to grain				
8 ft (2.4 m)								
Select Structural	6/176 (3)	1/99 (1)	1/47 (2)	0/28 (0)	2/14 (14)	9/20 (45)	15/24 (63)	34/408 (9)
No. 2	1/31 (3)	0/37 (0)	1/24 (4)	2/20 (10)	1/17 (6)	6/38 (16)	16/45 (36)	27/212 (13)
16 ft (4.9 m)								
Select Structural	3/61 (5)	1/26 (4)	2/10 (20)	2/7 (29)	0/0 (0)	0/0 (0)	3/3 (100)	11/107 (10)
No. 2	4/44 (9)	5/35 (14)	6/34 (18)	1/30 (3)	4/22 (18)	15/47 (32)	23/39 (59)	58/251 (23)
				Modulus of elasticity				
Select Structural	165/237 (70)	95/125 (76)	47/57 (83)	33/2 (94)	14/14 (100)	20/20 (100)	27/27 (100)	401/515 (78)
No. 2	34/75 (45)	42/72 (58)	35/58 (60)	36/50 (72)	33/39 (85)	76/85 (89)	83/84 (99)	339/463 (73)

[a] Green and Evans (1987).
[b] For example, of 8-ft (2.4-m) Select Structural grade 2 by 4s composed entirely of mature wood, the UTS values of 6 of 176 pieces or 3.4% were lower than the normalized 5th percentile.

Grade test values and our juvenile test values can be attributed to differences in specific gravity. Table 7 compares average specific gravity values from our tests with those from the In-Grade test program (Green and Evans 1989). Specific gravity values of test material were approximately 20% lower in each grade than the values of In-Grade material.

Relationship between modulus of elasticity and ultimate tensile stress

Machine stress-rating is frequently offered as a solution to the stress-rating of fast-grown plantation lumber. Presumably, the machine-measured MOE can be used to correctly identify and assign stress values to low strength-stiffness lumber with juvenile wood. In our test, the correlation coefficient (r) for the least squares linear fit of UTS to MOE for all grades combined was 0.582 (Fig. 8). This compares favorably with other published values for combinations of grades and sizes of southern pine lumber (Doyle and Markwardt 1967; Green and Kretschmann 1991), as shown in Table 8.

As indicated by Fig. 8, the MOE-UTS relationship can be a useful tool for machine stress-rating. However, the overall relationship seems to be nonlinear. A nonlinear, nonparametric correlation approach using Kendall's approach (SAS Institute 1988) produced a correlation of 0.44, which compares quite closely to the 0.48 nonparametric correlation resulting from an analysis by Doyle and Markwardt (1967). We also noted that the MOE-strength relationship is a function of the percentage of juvenile wood. The slope of the MOE-UTS relationship decreased with increasing juvenile wood content (Fig. 9). Nevertheless, for fast-grown lumber that ranges from all-mature to all-juvenile wood, our anal-

TABLE 7. *Specific gravity of graded lumber from test and In-Grade data.*

Grade	Specific gravity: Test data	In-Grade data
Select Structural	0.486	0.574
No. 1	0.440	0.524
No. 2	0.428	0.523

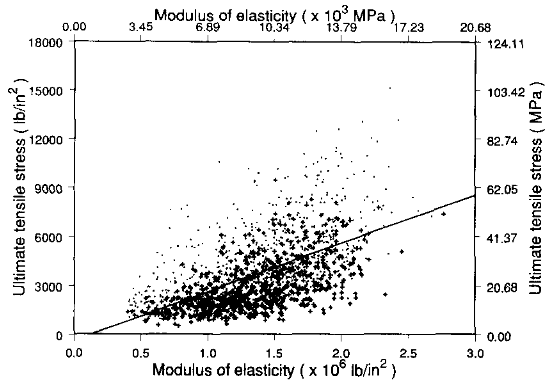


FIG. 8. Relationship between UTS and MOE for 2 by 4s of all grades and all-juvenile wood. Dots, 8-ft (1.4-m) lumber; plus signs, 16-ft (4.9-m) lumber.

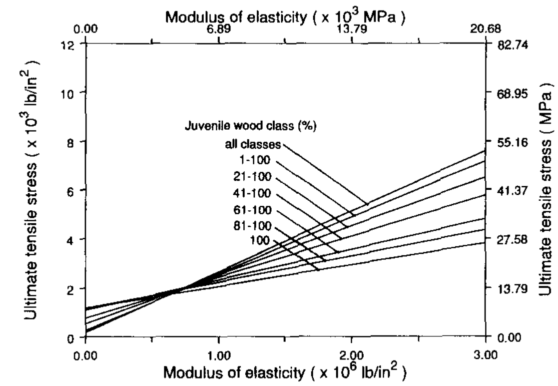


FIG. 9. Change in slope of UTS-MOE relationship as mature material is removed.

yses suggest that material with juvenile wood can be machine stress-rated as is the material traditionally used for lumber, at least in regard to UTS.

Interpretation of results

The interpretation of our results may be complicated by the low specific gravity of the test material, high-temperature drying, effect of lumber length, and processing methods used. However, we believe that these factors do not affect the conclusions drawn from our data. High-temperature drying has been shown to have a strength-reducing effect on UTS (Gerhards 1979; Price and Koch 1980). We explored the possibility that the high-temperature drying regimes and lumber length would account for the large differences noted between our test results and the 1988 NDS and In-Grade results. A conservative temperature-reduction factor was applied to the test data and analyzed by lumber length. This factor increased the number of specimens that met the conformance criteria. Despite this correction, our results of tests on No. 1 and No. 2 lumber significantly differed from the 1988 NDS and In-Grade test results.

TABLE 8. *Least-squares linear fit of tensile strength to MOE for test data compared to data in the literature.*[a]

Data source	A	B	*r*
Our test	2.967	−0.355	0.582
Doyle and Markwardt (1967)[b]	3.135	−1.735	0.651
Green and Kretschmann (1990)	3.349	−1.493	0.665

[a] UTS = A(MOE) + B.
[b] All grades combined.

CONCLUSIONS

The strength and stiffness of fast-grown plantation loblolly pine 2 by 4 lumber decreased with increasing amounts of juvenile wood in the cross section. Pieces composed entirely of juvenile wood had average ultimate tensile stress (UTS) values ranging from 45 to 59% that of pieces composed entirely of mature wood, depending upon lumber grade. For modulus of elasticity (MOE), these percentages ranged from 51 to 63%, depending on grade.

The percentage of latewood, rate of growth [rings per inch (25.4 mm)], specific gravity, and presence or absence of pith all relate to the percentage of juvenile wood. These characteristics show some potential for identifying low strength-low stiffness pieces. However, in our study these factors could not be used individually as grading criteria to assure conformance with allowable tensile stress values—criteria that correctly sorted pieces below design tended to downgrade many pieces with adequate strength.

The UTS values of the 8-ft (2.4-m) Select Structural 2 by 4s were in conformance with the 1988 NDS allowable design values. However, the percentage of 16-ft (4.9-m) lumber of lower grades (No. 1, No. 2, and No. 3) that conformed to design ranged from 5.6 to 33%. The No. 2 lumber had the poorest compliance with the NDS allowable design stress values. The average MOE for the test lumber in all four grades was considerably below the design MOE. In fact, even the average MOE for all-mature-wood lumber was below the design value.

Comparison of our results to In-Grade testing results, like the comparison to NDS values, indicates a significant reduction of UTS and MOE values with increasing juvenile wood. Here also, the No. 2 lumber had the poorest compliance with the expected 5th-percentile cut-off.

The relationship between MOE and UTS of test lumber was nearly equivalent to that for southern pine lumber reported in the literature. This suggests that fast-grown, plantation lumber with high proportions of juvenile wood can be machine stress-rated as efficiently as the traditionally used southern pine lumber. The slope of the relationship between MOE and UTS does, nevertheless, seem to be dependent on juvenile wood content.

We remind the reader that we define juvenile wood as that material within the first eight rings. If, for example, 12 rings had been chosen for the boundary, some of our conclusions might have been modified.

The results reported here are from one plantation forest and should not be interpreted as representative of southern pine lumber being marketed today. Nevertheless, as the industry moves to a faster grown, shorter rotation resource, grading rules and allowable design stresses will apparently need to be modified accordingly.

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