

# TENSILE PROPERTIES OF LOBLOLLY PINE GROWTH ZONES

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## ABSTRACT

For the determination of tensile properties of the earlywood or latewood zone of loblolly pine, modified standard ASTM tensile specimens were machined so that the critical sections at mid-length of specimens (2½ inches length of uniform cross section) consisted entirely of either earlywood or latewood. Specimens were tested to failure in both the green and air-dry condition.

Specific stress and specific stiffness of latewood in the air-dry condition are more than 50% and 63% higher, respectively, than corresponding values for earlywood. More than one-third of the tensile strength of latewood is attributed to factors other than density. Moisture affects the specific strength of latewood more than the specific strength of earlywood. The moisture effect on specific stiffness is approximately the same for both earlywood and latewood. The property affected most by moisture is the specific stress at proportional limit.

Same growth zones were tested by microtome sections of approximately 100 μm in thickness. Maximum tensile properties of any growth zone obtained from microtome sections were approximately one-half of the values obtained for the same zone from modified standard tensile specimens.

This paper presents partial results of a large study that concerns several mechanical properties of earlywood and latewood zones of southern yellow pine in relation to anatomical characteristics. More specifically this paper concerns the following objectives:

1) To determine and compare the tensile properties of earlywood and latewood zones of loblolly pine (*Pinus taeda* L.), in the green and air-dry conditions, by testing modified standard ASTM tensile specimens.

2) To determine the tensile properties of loblolly solidwood by standard clear tensile specimens and to establish a combined relationship between tensile properties and specific gravity for earlywood, latewood, and solidwood.

3) To compare the tensile properties of each growth zone obtained by modified standard specimens with tensile properties of the same zone previously obtained from matched microtome sections.

## BACKGROUND

Wood exhibits its greatest strength in tension parallel to the grain. Tensile strength parallel to the grain of small clear specimens is approximately 2 to 3 times

greater than compressive strength parallel to the grain, about 1½ times greater than static bending strength and 10 to 12 times greater than shear strength (Biblis 1966; Wangaard 1950; Werren 1964). Wood is anisotropic; the ratio of tensile strength parallel to the grain to that of perpendicular to the grain is frequently as high as 40 to 1 (Biblis 1966; Wangaard 1950). This high degree of anisotropy may explain the effects of grain slope on tensile strength parallel to the grain.

Tension parallel to the grain is an important property since it occurs in cases of structural uses of wood and wood products, either alone or in combination with compression and shear, as in static bending. Nevertheless, the tensile parallel to the grain properties have not been fully determined for all commercially structural woods. The reason for this is that although the importance and magnitude of tensile strength have been long recognized, the mechanical fastenings of tension structural members were governing the allowable working stresses which were appreciably smaller than the tensile stresses. The determination of the allowable tensile stresses for various commercially structural species

was not needed. Instead, the static bending allowable working stress of the same grade and species was used for tensile members. With the development of better mechanical fasteners and synthetic adhesives for wood bonding, a high proportion of the tensile strength of wood can now be used in modern design of wood structures. The need for determining the tensile parallel to the grain properties of all commercially structural species for the most efficient structural utilization of wood was emphasized (Werren 1964).

In recent years, attempts have been made not only to determine tension properties of structural grades and sizes of several softwoods, but also to establish relationship between maximum tensile strength and stiffness for grading purposes. The relationship between maximum tensile strength and modulus of elasticity is not as well defined as is the relationship between static bending strength (modulus of rupture) and modulus of elasticity. Doyle and Markwardt (1967) found the correlation coefficient of the relationship between tension parallel to grain and pure modulus of elasticity (combining three structural grades and three sizes of southern pine) to be only 0.65. On the other hand, Kramer (1964) after testing 540 southern yellow pine specimens representing three structural grades and three sizes, found a much higher correlation coefficient (0.875) for the relationship between modulus of rupture and pure modulus of elasticity.

Wood from southern yellow pine, like most other conifers and ring porous hardwoods, is highly heterogeneous in structure. Coniferous wood can be considered a natural laminate-composite in which the alternating laminae of earlywood and latewood zones, in a radial direction, constitute a periodic type of heterogeneity. The average specific gravity of southern yellow pine latewood is approximately three times greater than that of earlywood (Fitzgerald 1968; Forsaith 1933).

In order to analyze mathematically the mechanical behavior in tension parallel to grain of coniferous wood, and particularly the relative contribution of earlywood and

latewood to the properties of the "natural laminate-composite," it is necessary to determine accurately the periodic variations in tensile strength and elastic properties in consecutive growth rings. The same data also could be used for an experimental verification of the theory of transverse anisotropy of wood and of radial shrinkage.

Determination of tensile strength variation in successive growth rings of several conifers was first attempted by Wardrop (1951). This study, however, was concerned more with the relationships between tensile strength and various anatomical characteristics of tracheids than it was with the strength variation. The strength parameter in his study was breaking loads of tangential microtome sections 80  $\mu\text{m}$  in thickness. Since the thickness of these microspecimens could have varied as much as  $\pm 10$  per cent from the nominal thickness of 80  $\mu\text{m}$ , the determined relationships could be only qualitatively justifiable. Wardrop concluded, from observations of failures in the microspecimens, that tension failure occurs within cell walls rather in the middle lamella, and he stated the following: "This does not necessarily imply that the intercellular adhesion per unit area of contact surface between cells is greater than the strength of the tracheids, because the line of failure involved in the separation of cells is very much greater than that involved in the rupture of the cell walls." Wardrop's conclusion, with respect to the failure location, was not justified by his test. He did not consider the fact that his microspecimens contained several longitudinally and/or obliquely cut tracheids. Such a surface exposes several weak points in cell walls where failure can be initiated.

Kloot (1952), who first tested wood microspecimens in tension, was more cautious in his conclusions. He seriously questioned the effect of cut tracheids on the tensile strength and on the nature and occurrence of failures. He actually observed a different type of failure in earlywood than he did in latewood microspecimens. The observed failures in earlywood indicated a rupture of cell walls, while failures in the latewood microspecimens

occurred in the middle lamella. The same differentiation in failures between earlywood and latewood microspecimens of Douglas fir was observed by Wellwood (1962) and Kennedy and Ifju (1962).

With respect to the influence of cut fibers on the strength of microspecimens, Kloot (1952) questioned the ability of cut fibers to carry proportional load and stated that "the effective cross section of the specimen is in doubt and thus also is the computed maximum tensile stress." Wellwood (1962), on the other hand, believed that microtome specimens give greater tensile strengths than standard specimens of the same materials. He specifically stated with regard to Douglas fir that, "Springwood microtensile samples appear to be about 23 per cent stronger than conventional samples of comparable density. Summerwood, on the same basis, is about 27 per cent stronger." Wellwood (1962) compared the tensile strength of Douglas fir microspecimens with the tensile strength obtained by Van Vliet (1959) on standard (ASTM) tension specimens of the same species. Wellwood's conclusion, however, was not justified since his comparison of microspecimen tensile strength with that of standard specimens is not valid for the following reasons: Van Vliet (1959) did not test specimens with specific gravities equal to those of the earlywood microspecimens; therefore an extrapolation of Van Vliet's data could represent only an imaginary material. Furthermore, Wellwood's specimens were not matched with Van Vliet's specimens. It is well known that strength properties of unmatched specimens, from the same species, can vary more than 100 per cent; therefore, the comparisons were not justified.

Relationships between tensile strength and specific gravity as well as between stiffness and specific gravity for microspecimens of Douglas fir were accepted as being linear by Ifju, Wellwood, and Wilson (1965). However, it appears that a curvilinear relationship (with a decreasing rate of change of curve slope as the specific gravity increases) would have fitted their plotted data even better than a linear relationship. The author (1968) found, from

the analysis of variance and F-test of the relationship between tensile strength and specific gravity of loblolly pine microspecimens, that a curvilinear relationship fits the data significantly better than does a linear relationship. It also was shown that a curvilinear relationship between stiffness and specific gravity of the same microspecimens was significantly better than was a linear relationship.

#### EXPERIMENTAL PROCEDURE

A 38-year-old loblolly pine was selected in Lee County, Alabama, for this study. The tree was healthy, straight, and clear to  $\frac{3}{4}$  of the height. The annual growth rings were approximately cylindrical with narrow transition zones between earlywood and latewood. The width of the growth rings varied from  $\frac{3}{16}$  inch to  $\frac{5}{16}$  inch; widths of earlywood and latewood zones were approximately equal.

Eight-foot logs were cut from the bole and quarter-sawn into planks 3 inches in thickness. The planks were then cross-cut into 4 ft lengths. The first (lower) 4 ft sections were designated as material for green specimens and then immersed in a tank with running clean water. The second 4 ft sections were end-coated, stickered, air-dried, and designated as material for air-dry specimens.

#### *Modified ASTM Standard Tensile Specimens*

Tensile specimens used in this study were similar to standard tension specimens described in ASTM Standards D-143-52 with the following exception. For specimens machined to test earlywood or latewood alone, critical sections of the specimen ( $2\frac{1}{2}$  inch length of uniform cross section) consisted entirely of either earlywood or latewood, Fig. 1. Thickness of critical sections of these specimens was variable (depending upon the width of the zone tested). Care was taken during machining not to include the transition zone in test sections.

Specimens were taken to represent the entire tree length. Juvenile wood was

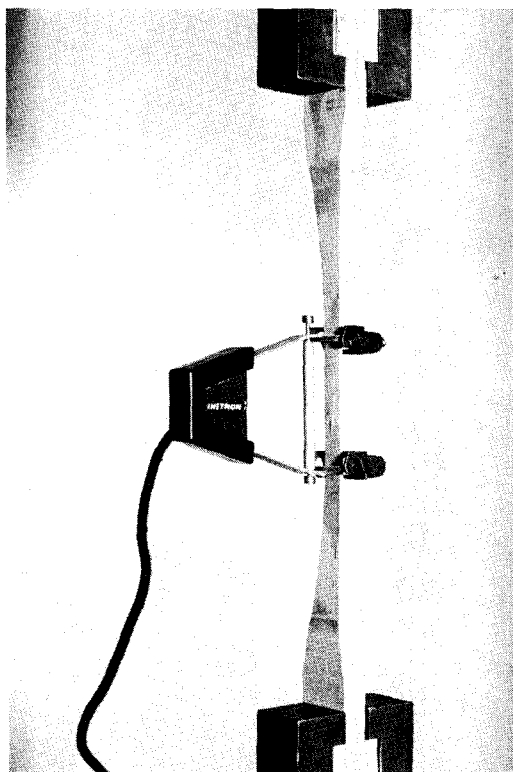


FIG. 1. Modified tension specimen for testing individual zones of earlywood or latewood. Note that minimum cross section area in middle length of specimen consists of only one growth zone, latewood in this case.

avoided. The last six rings near the bark were also not utilized because of insufficient width. Specimens generally were taken from wood included between the 16th and 32nd rings. Replications varied for various zones and rings.

For individual zones, 125 specimens were machined. Approximately one-half were in the green condition, while the others were in the air-dry condition. Approximately one-half represented the latewood zones.

In addition, 25 standard ASTM solid-wood specimens were machined in the air-dry condition. Their uniform cross section area (at middle span) was  $\frac{3}{8}$  inch  $\times$   $\frac{3}{16}$  inch. The uniform cross section areas consisted of three zones with the following two combinations: 1) either an earlywood zone at the middle of the  $\frac{3}{8}$  inch width with latewood zones on either side, or 2) a late-

wood zone in the middle with earlywood zones on either side. The actual width of each zone for each specimen was measured with a linear micrometer through a dissecting microscope and was expressed as a percentage of the total width of the cross section.

Air-dry specimens were conditioned to E.M.C. at 73F and 50% R.H. before testing. All specimens were tested to failure with an Instron testing machine. Standard testing speeds of 0.05 inch/min were used. Strains were measured with an Instron strain gage extensometer 2 inches in length with 10% maximum extension. Strains were simultaneously recorded with the corresponding load on the chart of an X-Y recorder. After testing, a small sample was taken from the vicinity of failure for moisture and specific gravity determination.

#### *Microtome Sections*

Material used for microtome sections was matched either end to end or side by side with the tested growth zone of certain modified ASTM tension specimens. Portions that included matched zones were removed from the tree while still green and kept saturated in a 0.1% formaldehyde solution at 36F until the microtome section was cut.

Small rectangular blocks were cut from these sections with a high quality carbide-tipped saw that produced very smooth surfaces. These blocks were 2.25 inches in length longitudinally, 0.25 inch in width tangentially and 0.50 inch to 0.75 inch in depth radially. Care was taken in cutting the blocks to have true tangential and radial sides. The blocks were sawn so that the growth zones, from which tangential microtome sections were cut, coincided with tangential sides of the blocks.

Several factors were considered in selecting the portions of growth zones from which microtome specimens were to be taken. The most important of these were the frequency and distribution of resin ducts and canals.

Before the microspecimens were cut, the radial sides of each rectangular block were

TABLE 1. *Tensile properties of loblolly pine earlywood, solidwood, and latewood tested in the green and air-dry conditions by modified ASTM standard tensile specimens*

Group (1)	Range (2)	Specific gravity (O.D. Vol.) (3)	Stress at P.L. p.s.i. (4)	Maximum tensile stress p.s.i. (5)	Modulus of elasticity p.s.i. (6)	Specific stress at P.L. p.s.i. (7)	Specific <sup>1</sup> maximum stress p.s.i. (8)	Specific <sup>2</sup> stiffness p.s.i. (9)	Strain at P.L. in. (10)	Maximum strain in. (11)
Earlywood green	Max.	0.361	3,950	10,880	900,900	14,100	36,990	3,064,290	0.0056	0.0266
	Min.	0.260	1,880	5,510	395,170	5,210	20,470	1,158,850	0.0031	0.0123
	S.d.	0.026	560	1,380	139,760	2,040	5,610	507,130	0.0006	0.0035
	Mean	0.304	2,640	7,930	683,490	8,700	26,100	2,248,330	0.0041	0.0187
Earlywood air-dry 12% M.C.	Max.	0.346	6,880	11,030	1,234,200	20,850	33,420	3,868,970	0.0075	0.0189
	Min.	0.283	3,740	8,180	609,350	12,630	26,560	1,578,630	0.0045	0.0075
	S.d.	0.023	740	870	132,250	2,740	2,430	457,130	0.0011	0.0036
	Mean	0.311	4,960	9,360	902,540	15,960	30,100	2,902,050	0.0064	0.0115
Latewood green	Max.	1.013	16,080	37,580	4,910,500	16,730	38,940	5,088,600	0.0053	0.0226
	Min.	0.756	5,350	15,010	2,050,000	6,000	15,570	2,300,790	0.0028	0.0076
	S.d.	0.068	6,084	6,800	963,167	6,200	6,530	881,790	0.0073	0.0060
	Mean	0.911	10,570	25,380	3,327,140	11,610	27,860	3,652,180	0.0038	0.0135
Latewood air-dry 12% M.C.	Max.	1.007	28,920	48,420	5,633,300	32,060	53,680	5,886,420	0.0074	0.0216
	Min.	0.899	17,650	38,000	3,491,800	18,220	38,500	3,548,580	0.0035	0.0071
	S.d.	0.056	4,310	3,580	712,310	5,040	4,840	860,930	0.0035	0.0013
	Mean	0.919	22,610	41,830	4,360,970	24,610	45,520	4,745,340	0.0051	0.0125
Solidwood air-dry 12% M.C.	Max.	0.679	14,520	24,610	3,267,450	23,270	39,430	5,236,300	0.0076	0.0183
	Min.	0.434	5,330	13,350	1,150,220	10,470	26,230	2,495,050	0.0033	0.0079
	S.d.	0.065	2,820	3,320	518,480	5,250	6,530	885,060	0.0010	0.0031
	Mean	0.536	9,270	17,860	1,853,710	17,300	33,320	3,458,420	0.0053	0.0095

<sup>1</sup> Specific maximum stress is defined as the ratio of maximum stress to specific gravity.

<sup>2</sup> Specific stiffness is defined as the ratio of stiffness to specific gravity.

S.d. designates the sample standard deviation.

surfaced in a microtome. With a plane-level, the two sides were surfaced to be almost parallel. Afterwards, each rectangular block was attached securely to the microtome with its tangential surface facing the knife. Each block was oriented so that the true tangential plane would be parallel to the plane formed by the moving knife edge. This was done to minimize the number of cut fibers on the tangential surfaces. Microtome sections were cut to a nominal thickness of approximately 100  $\mu\text{m}$ . Sections were cut consecutively and placed immediately, in sequence, into bottles with water (36 F) so that their positions within the ring could be easily determined at a later time. Selection of microspecimens for testing was based on their quality rather than on their position within the ring. Many microspecimens were rejected because of imperfections caused by resin canals.

Approximately 650 microspecimens were

cut. Of these, only 146 were considered of suitable quality and subsequently tested. Prior to testing, length and width of each wet microsection were measured to 0.0001 cm with a microscope equipped with a measuring stage. Section thickness was measured with a dial indicator sensitive to 0.00005 inch at zero dial pressure.

An Instron testing machine (Model TT-D-L) was used for testing the microspecimens. Each microspecimen was securely gripped with rubberfaced jaws at a span of 1.50 inches tested with a speed of 0.01 inch/min. The test was conducted at 72 F. During tests, microspecimens were kept saturated by a continuous flow of a thin water film over both surfaces. Water was applied at upper ends of the specimens at the rate of 30 drops per minute. Total elongation of the 1.50-inch span was recorded simultaneously with the corresponding load on a chart of an X-Y recorder.

TABLE 2. Ratios of latewood to earlywood tensile properties in the air-dry and green condition

Growth zones and moisture condition	Ratios of specific stresses at P.L.	Ratios of specific maximum stresses	Ratios of specific stiffness
Latewood/earlywood green condition	1.33	1.07	1.63
Latewood/earlywood air-dry condition 12% M.C.	1.54	1.51	1.64

## RESULTS AND DISCUSSION

*Modified ASTM Standard Tension Specimen*

Tensile properties of the two growth zones and of the solidwood obtained by testing modified ASTM standard tension specimens in both green and air-dry condition are shown in Table 1. Average M.C.% of green specimens (water saturated) was 300% for earlywood and 67% for latewood. Average moisture content of air-dry specimens after being conditioned at 73 F and 50% R.H. was 9.6% for earlywood and 10.4% for latewood. Properties of all air-dry specimens were adjusted to 12% moisture content. Since the relationships between tensile properties and moisture have not yet been established for southern yellow pine, the moisture adjustment was made by the use of Wilson's (1932) equation. This method for adjustment is considered justified since the equation is applicable for adjusting static bending properties which are partially depending on the tension properties.

Table 1 shows maximum and minimum values, means and sample standard deviations, of each group and condition. Table 2, constructed from data in Table 1, shows tensile property ratios of latewood to earlywood zones in both green and air-dry conditions.

Specific stresses of latewood in the air-dry condition were more than 50% higher than specific stresses of earlywood. The difference in specific stiffness was even higher, amounting to more than 63% in favor of the latewood. This indicates that

the amount of wood substance per unit volume is not the only contributing factor to tensile strength of latewood zone. It is evident that the quality of the wood substance contributes significantly to strength and stiffness. On the basis of earlywood specific strength, one-third of the air-dry (12% M.C.) tensile strength of latewood can be attributed to factors other than specific gravity. These quality factors very probably are related to some anatomical, chemical, and structural characteristics of the latewood zone. Since quality factors of wood substance can affect utilization properties of wood to such a great degree, a real challenge is presented to forest tree geneticists, physiologists, and silviculturists.

In the green condition, the specific maximum stress of latewood is only 6% higher than that of earlywood. At the proportional limit, specific stress of latewood was 33% higher than that of earlywood. Specific stiffness of latewood in the green condition was 62% higher than that of earlywood.

It is evident that moisture affects the tensile strength properties of latewood more than those of earlywood. The reduction in specific ultimate stress of latewood from air-dry (12% M.C.) to green condition is more than 38%; the reduction corresponding to a similar change in moisture of earlywood is only 13%. This might be explained by a probable disproportional weakening of the middle lamella by moisture rather than by a weakening of cell walls of latewood tracheids. In the green condition, the retained strengths by both earlywood and latewood tracheids are irrelevant if the middle lamella is weakened sufficiently to initiate failure. Since the specific maximum stress of the latewood zone in the air-dry condition (12% M.C.) is 33% higher than that of the earlywood, the percentage reduction of latewood strength would be expected to be higher than the percentage reduction of earlywood.

Reduction in specific stiffness from the air-dry to green condition is approximately the same for both latewood and earlywood zones, amounting to 22%. This is in good agreement with the findings of Markwardt

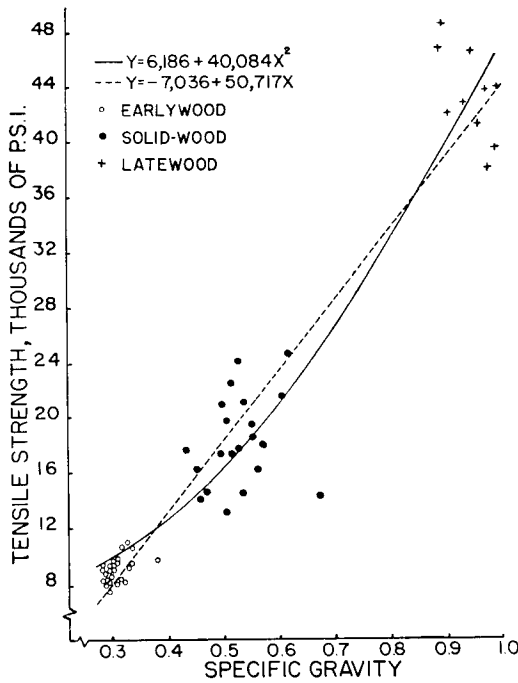


FIG. 2. Combined relationship and corresponding regression equations between tensile strength and specific gravity of earlywood, solidwood, and latewood tensile specimens in the air-dry condition.

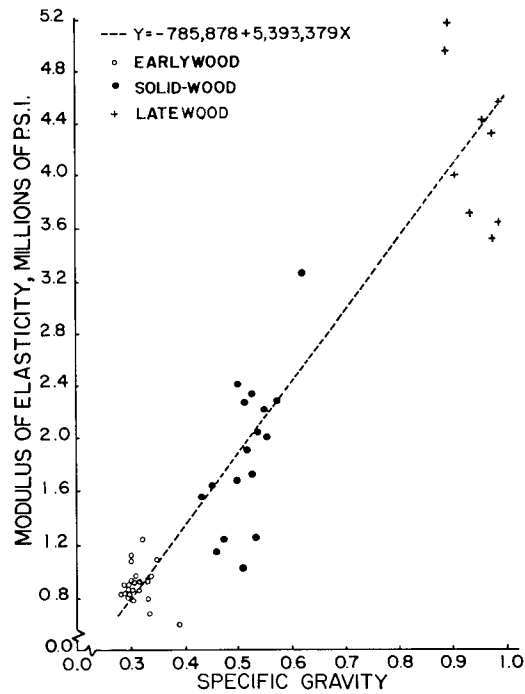


FIG. 3. Combined relationship and corresponding regression equation between modulus of elasticity and specific gravity of earlywood, solidwood, and latewood tensile specimens in the air-dry condition.

and Wilson (1935) concerning moisture effects on bending stiffness.

Results in Table 1 also indicate that moisture affects the limits of elastic region more than any other tensile property by reducing considerably the specific stress at proportional limit of both earlywood and latewood. The reduction was 53% for latewood and 45% for earlywood.

Tensile strength in p.s.i. with corresponding specific gravity of each specimen is shown in Fig. 2. An attempt was made to establish a relationship between tensile strength and specific gravity by combining earlywood, solidwood, and latewood specimens in the air-dry condition (12% M.C.). Two regression equations were fitted to the data, one linear and one curvilinear. The analysis of variance and F-test in Table 3 indicates that the gain in the reduction of the total sum of squares attributable to the  $X^2$  term is significant, leading to the

conclusion that the curvilinear expression better describes the relationship than does the linear expression. The curve is concave up where the tangent angles increase as the specific gravity increases.

The increase in specific gravity is accompanied by a continuous change of some anatomical and chemical factors that are known to influence positively the strength as they vary from earlywood to latewood. The curvilinearity of this relationship might be the result of the combined effect of all these additional factors.

The modulus of elasticity of each specimen was plotted against the corresponding specific gravity as shown in Fig. 3. This relationship was investigated by two regression equations, one linear and one curvilinear (second order polynomial). The analysis of variance and F-test indicated that the  $X^2$  term in the polynomial does not contribute significantly to the reduction

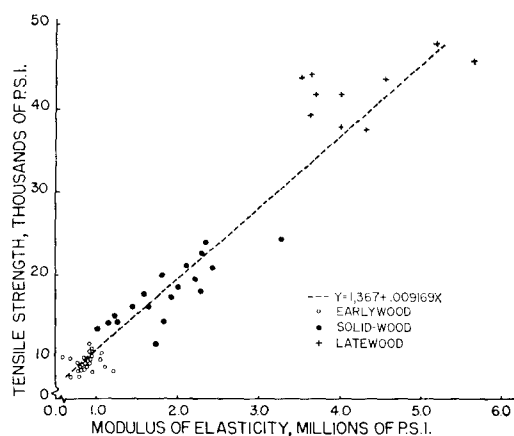


FIG. 4. Combined relationship and corresponding regression equation between ultimate tensile strength and modulus of elasticity of earlywood, solidwood, and latewood tensile specimens in the air-dry condition.

of the total sum of squares. Thus, the linear equation better describes the relationship. The same anatomical and chemical factors that affect the tensile strength also affect the stiffness. It appears, however, that the effect of these factors on stiffness is different in magnitude and/or location than it is on strength. It can be stated that the established linear relationship between stiffness and specific gravity is a result of the combined effect of specific gravity, anatomical factors, and chemical factors.

Finally, the relationship between tensile

strength and stiffness was investigated, Fig. 4. Two regression equations were calculated for the data. The analysis of variance and F-test indicated that the  $X^2$  term in the polynomial does not contribute significantly to the reduction of the total sum of squares. Thus, the linear equation better describes the relationship.

*Properties of Microtome Sections*

Results of tensile properties obtained from testing water-saturated microtome sections from earlywood and latewood zones are shown in Table 4. Also shown in Table 4 are tensile properties obtained by modified ASTM Standard tensile specimens matched to the section of the growth zones from which microspecimens were taken. Minimum tensile strength and stiffness values of microspecimens correspond to the beginning of the growth zones, while maximum values correspond to the end of zones. Generally, maximum values are more than 50% higher than minimum values.

Results in Table 4 also indicate that values of tensile properties obtained by modified ASTM standard tensile specimens are approximately double the corresponding maximum values for the same zone obtained from matched microtome specimens. It should be noted that tests of modified standard tensile specimens determined the properties of the entire width of each earlywood or latewood zone. Strength and elastic properties within each zone, how-

TABLE 3. Analysis of variance of the relationship between tensile strength and specific gravity of air-dry (12% M.C.) specimens

Source of variation	d.f.	Sum of squares	Mean square	F
X and $X^2$	2	8,000,894,700		
X alone	1	7,939,738,700		
$X^2$ after X	1	61,156,000	61,156,000	5.73*
X and $X^2$	2	8,000,894,700		
$X^2$ alone	1	7,962,126,700		
X after $X^2$	1	38,768,000	38,768,000	3.63 n.s.
Error	53	565,484,800	10,669,524	
Total	55	8,566,379,500		

\* Significant at the 95% level.  
n.s.—non-significant.



TABLE 4. *Ultimate tensile stress and modulus of elasticity of microtome sections and modified ASTM tension specimens from matched samples of the same growth zone*

Growth ring No. (1)	Microtome sections				Modified ASTM specimens	
	Ultimate tensile stress p.s.i.		Modulus of elasticity p.s.i.		Ultimate tensile stress p.s.i. (6)	Modulus of elasticity p.s.i. (7)
	Minimum (2)	Maximum (3)	Minimum (4)	Maximum (5)		
Earlywood						
17	2,570	4,350	105,230	193,450	9,220	880,600
17	2,290	3,410	79,490	127,830	8,520	732,670
18	2,480	3,400	110,640	162,380	10,880	900,900
22	2,820	5,080	143,000	266,940	9,380	791,000
22	4,950	6,900	261,610	441,160	9,120	763,090
23	4,040	6,500	180,530	399,300	7,920	761,000
26	3,170	4,590	159,300	228,900	9,360	861,750
32	3,860	5,380	165,790	251,250	9,460	752,150
Average	3,270	4,950	150,700	258,900	9,230	805,400
Latewood						
17	6,150	10,430	540,160	641,000	27,730	3,638,000
19	9,540	14,320	754,500	1,094,000	25,300	2,170,000
22	10,240	17,190	950,000	1,367,620	30,590	3,660,000
23	10,670	15,440	1,041,000	1,421,500	38,000	4,644,800
27	6,480	11,170	638,500	860,000	20,320	3,010,000
Average	8,620	13,710	777,630	1,076,820	28,390	3,424,560

ever, increase progressively from the beginning to the end of each zone. Values obtained from the modified standard tensile specimens represent rather average values of the zone and therefore should have been smaller than maximum zone values obtained from the microtome sections. Experimental results indicate the opposite. Values from every single modified standard specimen of either zone are much higher than corresponding maximum values for the zone obtained by matched microspecimens.

Perhaps an explanation of this discrepancy lies in the fact that microspecimens contained longitudinally or obliquely cut fibers on either side. Average radial diameter of tracheids was approximately 50  $\mu\text{m}$  (35–40  $\mu\text{m}$  for latewood and 55–60  $\mu\text{m}$  for earlywood). Since the average thickness of microspecimens was approximately 100  $\mu\text{m}$ , then most probably each microspecimen includes at any cross section either one uncut and one cut tracheid or one uncut and two cut tracheids. This type of surface apparently exposes several weak points either within the cut walls or in the exposed middle lamella, particularly at points be-

tween tracheid ends. The applied load to microspecimens, instead of subjecting the tracheid walls to uniform tension, most likely caused stress concentrations in the middle lamella. After initiation of the first failure, the developed stresses probably were no longer entirely in tension, but partially in shear and perhaps even in cleavage. These types of stresses can cause complete failure at much lower stress levels than those developed in pure tension.

Another factor that could have contributed significantly to the reduction of both tensile properties of the microspecimens is the possible inclusion of certain cutting defects "slip lines" in the microtome section. According to Kissler and Junger (1952), these defects are cell wall deformations produced in the microtome sections during sectioning. Their findings have been confirmed by Keith and Côté (1968), who refer to these sectioning defects as "slip lines."

Both-mentioned factors as a possible explanation of the reduced tensile properties obtained from the microtome sections are being investigated currently by the writer.

## SUMMARY AND CONCLUSIONS

1) Specific stress and specific stiffness of latewood in the air-dry condition are more than 50% and 63% higher, respectively than corresponding values for earlywood. This indicates that the amount of wood substance per unit volume contributes only a portion to tensile properties of the latewood zones. More than one-third of the tensile strength value is attributed to factors other than density, such as anatomical, chemical, and structural characteristics of the latewood zones. Since quality factors of wood substance can affect the utilization properties of wood to such a great degree, a real challenge is presented to forest tree geneticists, physiologists, and silviculturists.

2) Moisture affects the specific strength of latewood more than the specific strength of earlywood. Reduction in specific ultimate stress of latewood from the air-dry to green condition was found to be more than 38%, while the corresponding reduction to the same change in moisture for earlywood was only 13%. The moisture effect on specific stiffness is approximately the same for both earlywood and latewood. Reduction in specific stiffness from the air-dry to green condition was approximately 22% for both earlywood and latewood. It is evident that moisture has different effect on the various tensile properties. The elastic limit is affected, in magnitude, more than other properties. Reduction of specific stress, at proportional limit from the air-dry to green condition, was 53% for latewood and 45% for earlywood.

3) The relationship between air-dry tensile strength and specific gravity combining earlywood, latewood, and solidwood of modified standard tensile specimens was investigated. A curvilinear expression was found to describe the relationship better than a linear expression. This relationship indicates that tensile strength increases disproportionately with increasing specific gravity. The relationship between modulus of elasticity and specific gravity for the same specimens and moisture was also investigated and it was found that a linear

expression satisfactorily describes the relationship. The slope of the linear expression, however, indicates that stiffness increases disproportionately with increasing specific gravity. Finally, the relationship between tensile strength and modulus of elasticity of the same specimens was investigated and it was found that a linear expression fits the data better than a curvilinear expression.

4) Maximum tensile properties of a growth zone obtained from microtome sections, approximately 100  $\mu\text{m}$  in thickness, were found to be approximately one-half of the values obtained for the same zone from modified standard tensile specimens. It is believed that longitudinally and/or obliquely cut fibers on either side of the microspecimens and perhaps permanent deformations produced during slicing caused this reduction in properties. Further experiments to verify this assumption are in progress.

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