QUANTITATIVE WOOD ANATOMY—RELATING ANATOMY TO TRANSVERSE TENSILE STRENGTH

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ABSTRACT

The tension perpendicular-to-grain properties of eight North American hardwood species were determined and related to their anatomy. Stereological techniques based on countings of points and intersections were used to quantitatively characterize the anatomy of each species. Modulus of elasticity and proportional limit stress values were found to be more dependent on specific gravity than anatomy. However, the properties associated with failure were closely associated with anatomical features. Earlywood vessel area fraction negatively influenced radial maximum stress and strain, whereas the ray width and area fraction were positively related to the maximum radial properties. Analysis showed that the rays significantly affected the transverse stiffness.

Keywords: Tension perpendicular-to-grain, wood anatomy, stereology.

INTRODUCTION

The influence of anatomical structure on the mechanical properties of wood has been of interest to wood scientists for some time. However, transverse tensile strength properties have been studied only by a limited number of investigators. This is somewhat surprising since perpendicular-to-grain tensile strength of wood plays an important role in the development of surface checks and honeycomb during drying of lumber. In addition, modeling failure of wood around knots in loaded beams and design of curved glulam products require the knowledge of this important strength property. Consequently, a better knowledge of how anatomical structure may affect transverse tensile strength properties should result in more efficient processing and utilization of wood. This may have particular importance in the substitution of underutilized species for those more traditionally employed in structural products.

The most thorough study of transverse strength properties of the various tissues in wood has been conducted by Schniewind (1959). He tested isolated earlywood and latewood tissues of California black oak as well as excised ray tissues in the radial direction to develop his model for the prediction of shrinkage of that species. Schniewind (1959) found that tangential strength, i.e. strength when the load is applied in the tangential direction, was a function of the relative latewood proportion, whereas radial strength was dependent upon the relative proportion of rays. He concluded that the difference between the tangential and radial moduli of elasticity (MOE) was due primarily to the high MOE of the ray tissues, and the difference between tangential and radial maximum strength values was a result of the high radial strength of the rays.

Transverse compression has received greater attention in the scientific litera-

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TABLE 1. *Eight North American hardwood species studied and their basic physical and anatomical classifications.*

Common name (scientific name)	Specific gravity class[1]	Growth increment type	Ray size
Beech (*Fagus grandifolia* Ehrh.)	>0.52	diffuse porous	large
Yellow Poplar (*Liriodendron tulipifera* L.)	<0.42	diffuse porous	small
Birch (*Betula* spp.)	>0.52	diffuse porous	small
Sycamore (*Platanus occidentalis* L.)	0.45–0.50	diffuse porous	large
White Ash (*Fraxinus americana* L.)	>0.52	ring porous	small
Catalpa (*Catalpa speciosa* Wardner)	<0.42	ring porous	small
Hackberry (*Celtis occidentalis* L.)	0.45–0.50	ring porous	small
Red Oak (*Quercus* spp.)	>0.52	ring porous	large

[1] Based on oven-dry weight and green volume.

ture than tension perpendicular to the grain. Consequently, the influence of anatomy on transverse compression is somewhat better known. Bodig (1965) studied the transverse compression properties of several hardwood and softwood species and found that ray size and latewood percentage accounted for the largest part of the between-species differences. Kennedy (1968) reported that ray volume had an important positive effect on radial proportional limit stress but had no influence on MOE. As in many studies on strength variation of wood, specific gravity has been found to be the most important single factor affecting transverse strength properties.

One of the limitations to studying structure-property relationships for wood has been the lack of quick and efficient methods suitable for quantitative characterization of anatomical structure. Recent reports in the literature (Steele et al. 1976; Ifju et al. 1978; Ifju 1983) have introduced a relatively simple method for quantifying wood anatomy. These techniques, based on the principles of stereology, appear to open new avenues for determining structure-property relationships.

The objective of this study was to characterize the anatomical structure of selected angiosperm wood species using a stereological method (Ifju 1983) and to relate structural variables to transverse tensile strength and stiffness properties.

MATERIAL AND METHODS

Eight North American hardwoods were chosen for this study on the basis of their growth ring structure, relative proportion or area fraction of rays, vessel distribution, and specific gravity. The species studied are listed in Table 1, along with their comparative features. Of the eight species, four were ring porous and four were diffuse porous, three had large rays while five had small rays, and specific gravity (oven-dry weight, green volume) fell into three categories—less than 0.42, 0.45–0.50, and greater than 0.52.

Rectangular test specimens tested in the radial and tangential directions as shown in Fig. 1 were cut from green boards of each species. The test specimen blanks were first conditioned to approximately 12% moisture content and then machined to their final dimensions. Twenty-five radial and twenty-five tangential

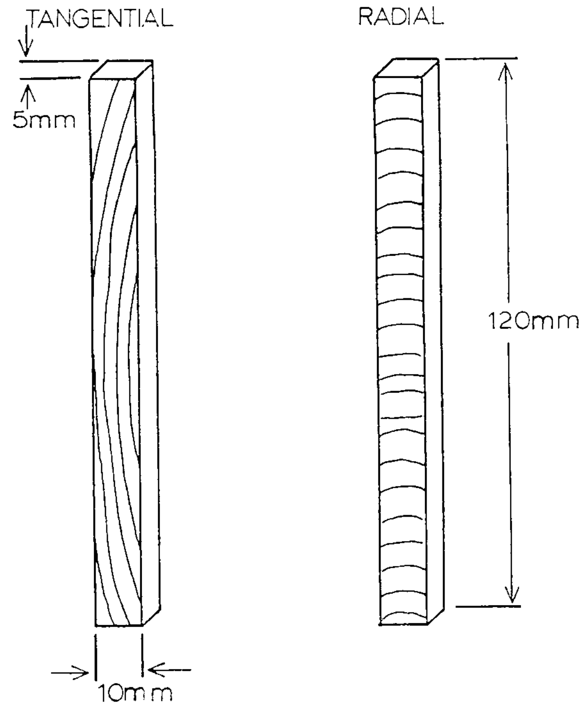

FIG. 1. Tension perpendicular-to-grain test specimens.

specimens of each species were loaded to failure in a 100-kg Instron machine over a 60-mm span with a crosshead speed of 1 mm/min. The specimens were tested with standard, smooth, rubber-coated grips clamped to a uniform torque. The few samples that failed in the grips were discarded. Strain measurements were based upon the crosshead movement and the 60-mm span. Extreme care was exercised to minimize any moisture content fluctuation during test. From this data, and the individual specimen geometry, four tensile properties were calculated—maximum stress, maximum strain, modulus of elasticity (MOE) and proportional limit stress.

Immediately after failure, two samples were cut from each test specimen: one specific gravity/moisture content sample, and one sample from the failure region of the specimen. The failure region sample provided material for microtome sections of the transverse and tangential planes, which were stained and permanently mounted on glass slides. These stained sections were analyzed using the stereological technique described by Ifju (1983) and Steele et al. (1976). Dot grids were used to determine area fractions (P_p) of anatomical elements and oriented segments of predetermined length were used to determine the number of elements per unit length of test line in the radial and tangential directions (NL_R, NL_T) (Fig. 2). Standard areas were used to determine the number of elements per unit area (N_A). These basic counts were then used to derive other parameters such as element diameters, heights, widths, and distances between elements.

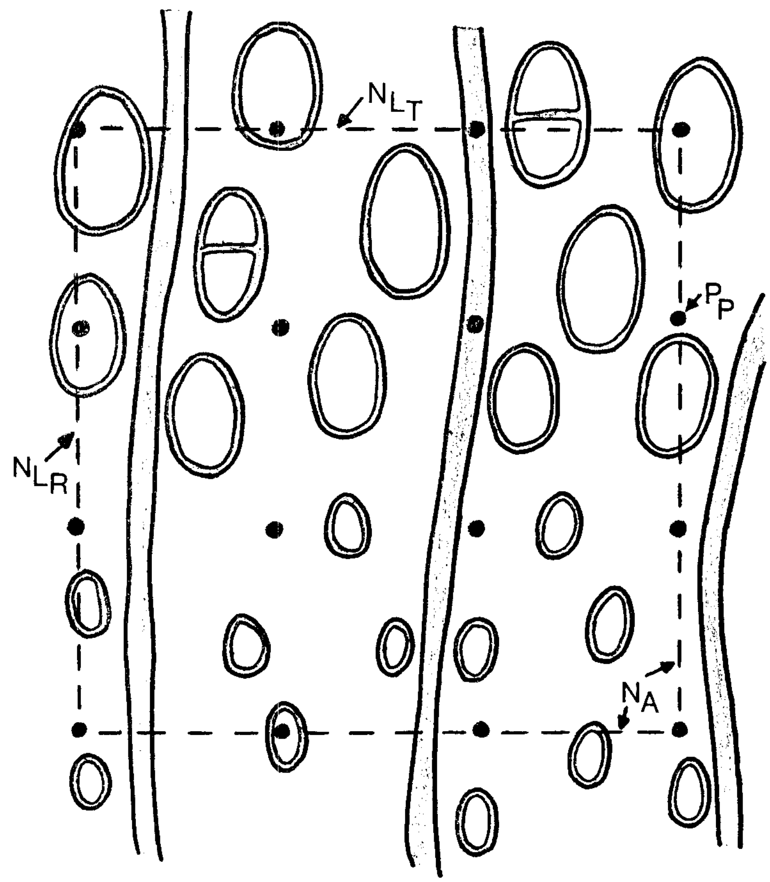

FIG. 2. Counting grid used for stereological counts.

RESULTS AND DISCUSSION

Transverse tensile strength properties

It is well known that most mechanical properties of wood are highly dependent on specific gravity. Although the range of specific gravity of the eight species was relatively narrow, statistical analysis showed coefficients of determination (R^2) ranging from 0.42 to 0.82 for linear regression of strength properties against specific gravity. The only strength-related property not related to wood density was ultimate strain.

To eliminate the significant influence of specific gravity on the variations in maximum tensile strength, modulus of elasticity and proportional limit stress, the respective specific strength values were calculated. Since nonlinear regression of the properties and specific gravity was not substantially more effective than a linear regression, the latter was used. Consequently, the specific properties were calculated from simple division by specific gravity. The specific properties, ultimate strain values, and ratios of radial/tangential strength are given in Table 2 for the eight species.

TABLE 2. *Means and ratios of specific transverse tensile properties (except maximum strain) and specific gravity.*

Species and orientation[1]		Growth increment type	Specific maximum stress (kPa)	Specific MOE (MPa)	Specific prop. limit stress (kPa)	Maximum strain (mm/mm)	Specific gravity
Beech	R	DP	29700	1727	14000	0.022	0.57
	T		18500	1198	6800	0.021	0.52
	R/T		1.61	1.44	2.08	1.05	
Yellow Poplar	R	DP	25100	1599	13900	0.018	0.34
	T		14500	872	5800	0.020	0.36
	R/T		2.15	1.65	2.38	0.90	
Birch	R	DP	31900	1570	12800	0.030	0.46
	T		14900	954	6400	0.023	0.53
	R/T		2.15	1.65	2.01	1.30	
Sycamore	R	DP	33500	1741	13700	0.026	0.50
	T		17600	1201	8700	0.018	0.51
	R/T		1.90	1.45	1.57	1.44	
White Ash	R	RP	19700	1589	12800	0.013	0.51
	T		19000	1097	6200	0.029	0.48
	R/T		1.03	1.45	2.08	0.45	
Catalpa	R	RP	20500	1797	13000	0.012	0.41
	T		16200	856	7600	0.025	0.42
	R/T		1.27	2.10	1.72	0.48	
Hackberry	R	RP	24000	1429	11100	0.021	0.48
	T		20000	1174	7700	0.026	0.51
	R/T		1.20	1.22	1.44	0.81	
Red Oak	R	RP	22900	1839	14700	0.014	0.53
	T		14300	1198	8300	0.014	0.55
	R/T		1.60	1.54	1.77	1.00	

[1] R = Radial, T = Tangential.
[2] DP = Diffuse Porous, RP = Ring Porous.

Specific MOE, in both radial and tangential directions, was greatest for the three species with large rays (beech, sycamore, and red oak), indicating a positive influence on tensile stiffness. The diffuse porous species had higher specific radial maximum stress values than the ring porous species, indicating that the large open earlywood zones in the latter had a negative effect on specific maximum stress.

The ratio of radial to tangential (R/T) specific properties also shows the dependence of transverse tensile behavior on anatomy. In general, the R/T ratios were greater than 1.0, demonstrating that radially loaded specimens were stronger and stiffer than tangential specimens. This is consistent with past findings (Kennedy 1968; Schniewind 1959). The R/T ratio for specific maximum stress was greater for diffuse porous species than ring porous species as a consequence of the large weak earlywood zones in the latter. For the diffuse porous species, the R/T ratios of MOE were lower for species with large rays. This was due primarily to the higher tangential specific MOE values for the species with large rays, indicating that large rays were substantially stiffer than small rays when loaded tangentially. A similar trend was not found in the ring porous species, presumably because of an interaction between large open earlywood zones and the rays.

TABLE 3. *Mean vessel area fractions (P_p), feature counts (N_A), and intercept counts (N_L) on transverse microtome sections.*

		Earlywood						Latewood					
		P_P						P_P					
Species	Type[2]	Lumen (%)	Wall (%)	Total (%)	N_A (mm^{-2})	N_{L_T}[1] (mm^{-1})	N_{L_R} (mm^{-1})	Lumen (%)	Wall (%)	Total (%)	N_A (mm^{-2})	N_{L_T} (mm^{-1})	N_{L_R} (mm^{-1})
Beech	DP	36.9	7.5	44.4	128	8.1	6.4	15.1	4.5	19.6	109	4.8	4.4
Yellow Poplar	DP	47.5	9.4	56.9	143	10.8	7.8	30.2	8.3	38.5	143	8.0	6.8
Birch	DP	19.8	4.3	24.1	23	2.9	2.0	16.4	5.2	21.6	39	3.1	2.9
Sycamore	DP	32.8	8.9	41.7	135	7.9	7.0	19.3	3.9	23.2	82	4.7	4.2
White Ash	RP	35.3	6.1	41.4	10	2.6	1.9	2.5	3.2	5.7	15	1.2	1.1
Catalpa	RP	34.0	6.6	40.6	17	3.0	2.7	11.8	4.5	16.3	83	3.6	3.5
Hackberry	RP	30.3	5.3	35.6	18	2.7	2.4	18.5	6.0	24.5	165	7.5	5.5
Red Oak	RP	38.8	3.8	42.6	5	1.8	1.5	5.1	2.8	7.9	15	1.3	1.3

[1] R = Radial, T = Tangential.
[2] DP = Diffuse Porous, RP = Ring Porous.

Since maximum strain was not strongly correlated with specific gravity, specific maximum strain was not calculated. Table 2 indicates that diffuse porous species generally had larger elongation at failure than the ring porous species when loaded radially. Apparently the large open earlywood zones in the ring porous species caused failure to occur before much elongation took place. This may also be the result of a nonuniform strain distribution inherent in the radially tested samples similar to that shown by Bodig (1966). For tangentially loaded specimens, the species with small rays generally had higher maximum strain values than the species with large rays, indicating that large rays hindered elongation under tangential load. The effect of ray size is further emphasized by examining R/T ratios of maximum strain. The R/T ratios were greater than 1.0 for the species with large rays, while the R/T ratios were less than 1.0 for all species with small rays except birch.

Quantitative anatomical parameters

Stereological analysis of the microtome sections produced quantitative anatomical parameters which were used to test relationships between tensile properties and anatomical features. One main parameter was the area fraction of various elements. Table 3 contains average vessel area fractions for the eight species in both earlywood and latewood. Earlywood vessel area fractions were quite similar for diffuse porous (24–57%) and ring porous (36–43%) species, but most of the ring porous species had lower latewood vessel area fractions than the diffuse porous species.

Intercept (N_L) and feature (N_A) counts were also made on cross sections, and the vessel counts are tabulated in Table 3. One obvious difference between ring porous and diffuse porous species was the number of vessels per mm^2 in the earlywood—all ring porous species had fewer than 20, but the diffuse porous species had more than 120 (except birch). These differences in vessel counts undoubtedly contributed to the lower maximum stress values found in the ring porous species when loaded radially.

Results of the stereological counts on fibers are tabulated in Table 4. Both the

TABLE 4. *Mean fiber area fractions (P_P) feature counts (N_A), and intercept counts (N_L) on transverse microtome sections.*

Species	Type[2]	Earlywood P_P Lumen (%)	Earlywood P_P Wall (%)	Earlywood P_P Total (%)	Earlywood N_A (mm^{-2})	Earlywood N_{L_T}[1] (mm^{-1})	Earlywood N_{L_R} (mm^{-1})	Latewood P_P Lumen (%)	Latewood P_P Wall (%)	Latewood P_P Total (%)	Latewood N_A (mm^{-2})	Latewood N_{L_T} (mm^{-1})	Latewood N_{L_R} (mm^{-1})
Beech	DP	9.9	24.5	34.4	1819	29	27	14.8	39.8	54.6	2471	41	36
Yellow Poplar	DP	13.0	16.2	29.2	887	15	15	13.6	25.5	39.1	1093	22	20
Birch	DP	26.3	33.8	60.1	2617	39	36	26.6	35.1	61.7	2719	40	36
Sycamore	DP	8.8	14.7	23.5	1461	21	21	13.0	26.5	39.5	2283	32	29
White Ash	RP	21.3	18.0	39.3	1139	25	18	33.0	43.8	76.8	2734	50	47
Catalpa	RP	24.8	20.0	44.8	1655	33	22	33.0	36.0	69.0	3112	51	41
Hackberry	RP	19.9	26.1	46.0	2641	41	32	22.0	33.6	55.6	3566	49	42
Red Oak	RP	18.5	18.2	36.7	1151	24	19	25.9	41.8	67.7	2576	46	41

[1] R = Radial, T = Tangential.
[2] DP = Diffuse Porous, RP = Ring Porous.

area fraction and number of fibers per mm^2 were higher for the ring porous species than diffuse porous species in the latewood. No other general trends were distinguishable for fiber characteristics.

Tangential microtome sections were analyzed using stereological techniques providing data on ray characteristics shown in Table 5. As expected, sycamore, red oak, and beech had significantly higher ray area fractions than the other species. This indicated that this parameter may have been a major factor accounting for between species differences in specific MOE values. Counts of the number of rays per unit area showed that red oak had 41 rays per mm^2 (large and small rays combined), while sycamore had only one large ray per mm^2. This implied that the number of rays making up a given ray area fraction, in addition to the ray area fraction itself, may have affected the transverse tensile properties.

TABLE 5. *Mean ray area fractions, feature counts, and intercept counts on tangential microtome sections.*

Species	Type[1]	Area fraction (%)	Feature count (mm^{-2})	Intercept count Radial (mm^{-1})	Intercept count Tangential (mm^{-1})
Beech—small rays	DP	9	23	4.5	0.8
large rays		13	1	1.2	0.2
total		22	24	5.7	1.0
Yellow Poplar	DP	16	13	4.9	1.0
Birch	DP	15	38	7.2	1.1
Sycamore	DP	36	1	2.2	0.3
White Ash	RP	16	38	7.0	1.1
Catalpa	RP	14	30	6.1	0.9
Hackberry	RP	16	19	4.6	1.0
Red Oak—small rays	RP	12	40	7.8	1.1
large rays		11	1	0.5	0.1
total		23	41	8.3	1.2

[1] RP = Ring Porous, DP = Diffuse Porous.

TABLE 6. *Mean vessel size distribution parameters.*

Species	Type[2]	Earlywood Diameter R[1] (μm)	Earlywood Diameter T (μm)	Earlywood Diameter R/T	Earlywood Mean free path R (μm)	Earlywood Mean free path T (μm)	Latewood Diameter R (μm)	Latewood Diameter T (μm)	Latewood Diameter R/T	Latewood Mean free path R (μm)	Latewood Mean free path T (μm)	Earlywood/latewood diameter ratio R	Earlywood/latewood diameter ratio T
Beech	DP	63	50	1.26	88	70	45	42	1.07	185	170	1.40	1.19
Yellow Poplar	DP	75	55	1.36	55	41	56	48	1.17	91	77	1.34	1.14
Birch	DP	130	91	1.43	372	261	81	75	1.08	278	259	1.60	1.21
Sycamore	DP	59	52	1.13	84	75	57	51	1.12	186	166	1.03	1.02
White Ash	RP	258	198	1.30	308	236	85	75	1.33	944	831	3.03	2.64
Catalpa	RP	181	159	1.34	222	196	43	42	1.02	292	236	4.21	3.78
Hackberry	RP	156	129	1.21	288	240	45	34	1.32	136	106	3.47	3.79
Red Oak	RP	353	316	1.12	377	338	85	84	1.01	738	720	4.15	3.76

[1] R = Radial, T = Tangential, R/T = Radial/Tangential ratio.
[2] RP = Ring Porous, DP = Diffuse Porous.

One advantage of using stereological analysis is that the simple counts just described can also be used to derive other anatomical parameters that may have influenced the tensile properties. For instance, the mean earlywood vessel diameters (tangential) derived for ring porous species, shown in Table 6, ranged from 129–316 μm, while the diameters for diffuse porous species were generally less than 100 μm. Furthermore, the ratio of earlywood to latewood vessel diameters (radial), which is a measure of the ring porous nature of a species, was greater than 2.0 for ring porous species but was less than 1.6 for the diffuse porous woods. These two parameters, earlywood diameter and the earlywood-latewood diameter ratio, may account for differences in specific maximum stress between diffuse porous and ring porous species.

Vessel mean free path (MFP) is a measure of the mean distance between vessels in a given direction and is computed from the point fraction P_P and the number

TABLE 7. *Mean ray size distribution parameters.*

Species	Type[2]	Height (μm)	Width (μm)	Height/width ratio	Mean free path T[1] (μm)	Mean free path L (μm)
Beech—small	DP	400	36	11.1	203	1,150
large		1,850	179	10.3	754	3,830
Yellow Poplar	DP	808	80	10.1	172	872
Birch	DP	381	31	12.3	121	751
Sycamore	DP	3,851	278	13.9	289	2,017
White Ash	RP	382	30	12.7	126	772
Catalpa	RP	403	28	14.4	144	1,082
Hackberry	RP	472	49	9.6	185	908
Red Oak—small	RP	400	28	14.3	112	818
large		6,279	441	14.2	2,068	16,467

[1] T = Tangential, L = Longitudinal.
[2] DP = Diffuse Porous, RP = Ring Porous.

TABLE 8. *Multiple regression equations for specific transverse tensile properties.*

Model[1]		R^2
Specific maximum stress (kPa)		
Radial =	43830 − 29062 (EVAF) + 11924 (W) − 2757 (RING)	0.86
Tangential =	8034 + 1.8 (LFNA) + 33250 (RMFPT) − 8739 (RAF)	0.57
Specific modulus of elasticity (MPa)		
Radial =	2280 + 603 (W) − 614 (LVSHAPE)	0.59
Tangential =	−168 + 1423 (RAF) + 280 (EVMFPR) + 796 (LVSHAPE)	0.51
Specific proportional limit stress (kPa)		
Radial =	17451 + 5535 (W) − 4326 (LVSHAPE)	0.31
Tangential =	6559 + 316 (H)	0.27
Maximum strain (mm/mm)		
Radial =	0.0600 − 0.0292 (EVAF) − 1.602 (EFDR)	0.75
Tangential =	0.0101 − 0.0202 (W) + 0.0140 (FIBER)	0.75

[1] W = ray width (mm), H = ray height (mm), RAF = ray area fraction, EVAF = earlywood vessel area fraction, LFNA = number of latewood fibers per mm², EFDR = radial earlywood fiber diameter (mm), RMFPT = tangential mean free path between rays (mm), EVMFPR = radial mean free path between earlywood vessels (mm), LVSHAPE = ratio of radial : tangential latewood vessel diam., RING = ratio of earlywood : latewood vessel diameter. FIBER = ratio of earlywood : latewood fiber diameter.

of elements per unit length in that direction, N_L. Table 6 indicates the parameters from this study for earlywood and latewood vessels in both the radial and tangential directions. The radial MFP was larger than that in the tangential direction for all species. With the exception of birch, the vessel MFP of diffuse porous species was less than that of ring porous species, which indicates that the more vessels there were, the smaller the distances between them. Because of the orientation sensitivity of this parameter, MFP may be related to the differences between the radial and tangential properties.

Ray size parameters were derived from tangential stereological counts and are summarized in Table 7. Those rays that were qualitatively labeled "large" were found to be 2–20 times taller and 2–12 times wider than "small" rays. The smaller rays were fairly uniform in height (except for yellow poplar), ranging from 381–472 μm among the species studied. Ray size parameters, including height and width, may have a greater impact on radial tensile properties than those tangentially. The MFP between rays in the longitudinal direction was larger than in the tangential direction. Additionally, the MFP for species with large rays were much greater than that for small ray species.

Relationships between anatomical and strength properties

The final step of this study was to determine if transverse tensile strength properties were related to the measured anatomical parameters. A stepwise regression technique was used to determine the most important anatomical parameters affecting each of the specific tensile properties. Each regression was arbitrarily limited to a maximum of three variables.

The resulting regression models are shown in Table 8, which indicates that the coefficients of determination (R^2) ranged from 0.27–0.86. Specific maximum stress and maximum strain were predicted well with R^2 values of 0.57–0.86. Specific MOE was moderately well explained (R^2 = 0.51–0.59), but little of the variation

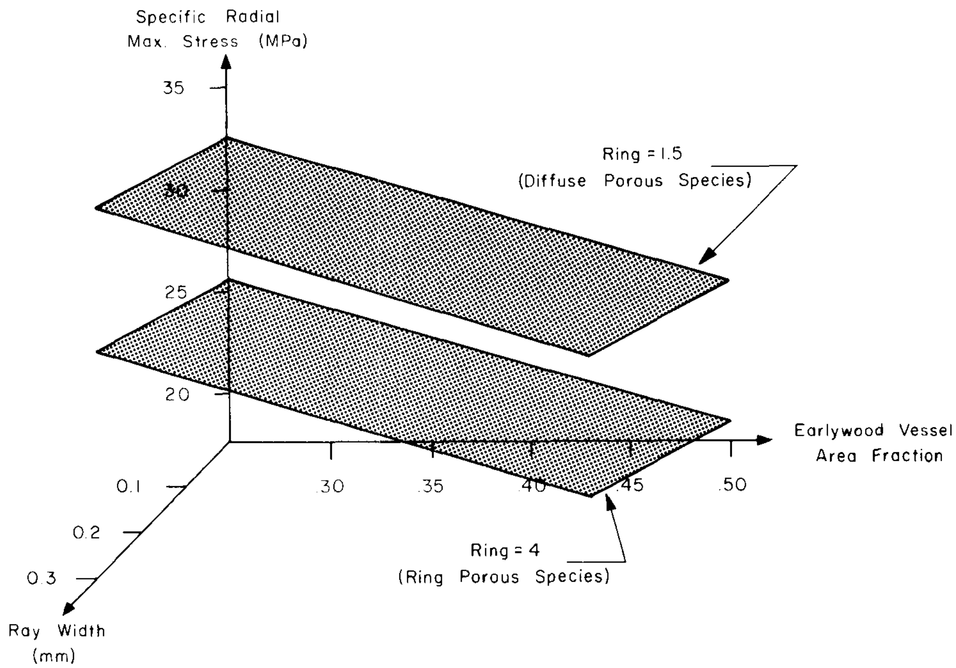

FIG. 3. Influence of certain anatomical variables on radial maximum specific tensile strength of hardwoods. (Ring: earlywood/latewood vessel ratio.)

in specific proportional limit stress could be explained by the anatomical parameters (R^2 = 0.27–0.31). It was apparent that the tensile properties associated with inelastic behavior and failure phenomena, i.e. maximum stress and maximum strain, were more dependent on anatomical features than were the properties associated with elastic behavior (MOE and proportional limit stress). Anatomical parameters describing ray size or area fraction and earlywood vessel size, shape, or area fraction were included in almost every model, thus pointing out the impact of these two anatomical elements on transverse tensile properties. Graphical illustrations of these strength–anatomy relationships are also shown in Figs. 3 and 4.

The anatomical parameters used in the regression equations confirmed several prior observations. For radial maximum specific stress and maximum strain, the earlywood vessel area fraction (EVAF) was a negative factor in the models, confirming that the large open earlywood zones of ring porous woods reduced radial strength and elongation at failure (Fig. 3). Ray width (W) was a positive factor in the maximum stress model, indicating that rays reinforced radial strength, but the earlywood radial/latewood radial diameter ratio (RING) had a negative effect (Fig. 3). Ray width was also a positive factor for radial MOE and proportional limit stress, confirming that rays influence radial stiffness. The latewood vessel shape factor (radial/tangential diameter) was a negative factor for both radial MOE and proportional limit stress, which suggests that the more elongated latewood vessels adversely affected the elastic behavior of radial test specimens.

Tangential maximum specific stress was negatively affected by ray area fraction

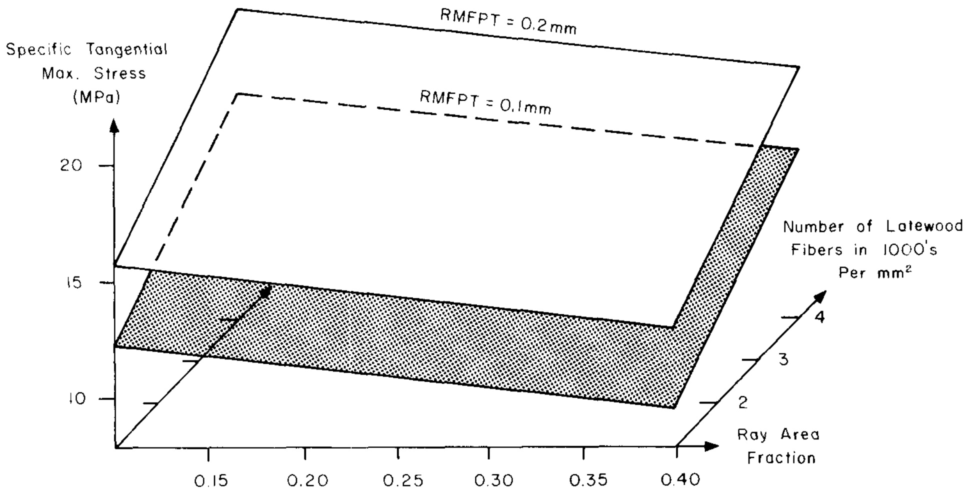

FIG. 4. Influence of certain anatomical variables on tangential maximum specific tensile strength of hardwoods. (RMFPT: Mean free tangential distance between rays.)

(RAF), but the tangential mean free path (RMFPT) between rays was a positive factor (Fig. 4). Rays were apparently a weak zone when loaded tangentially; but the farther the rays were apart, the smaller this effect became. The negative influence of ray width was also evident for tangential maximum strain. The number of latewood fibers per mm^2 (LFNA) was positively related to tangential maximum stress, while the ratio of radial earlywood:latewood fiber diameters (FIBER) positively affected tangential elongation at failure. Tangential elastic properties (MOE and proportional limit stress) were positively related to ray area fraction and ray height (H), indicating that the test specimen stiffness was reinforced by rays when loaded tangentially.

It should be recalled that specific gravity alone accounted for a substantial portion of the total variation in the transverse mechanical properties. The amount of variation explained by anatomical parameters beyond that explained by specific gravity was of primary interest in this study. To obtain an estimate of this quantity regression of the mechanical properties (not specific properties) with both specific gravity and the significant anatomical parameters were developed. The R^2 values associated with specific gravity alone as an independent variable were subtracted from those including specific gravity and anatomical variables. Thus a percentage of the tensile property variation due to anatomical parameters alone could be obtained. Results of this procedure, given in Table 9, indicate that maximum stress and maximum strain were much more dependent on anatomical parameters than were MOE or proportional limit stress. In fact, MOE was shown to have less than 17% of its total variation dependent on anatomy, and proportional limit stress less than 15%, but both properties were highly dependent on specific gravity (54–82%). On the other hand, maximum strain was virtually independent of specific gravity, but almost 75% of its total variation was accounted for by anatomical parameters. Maximum stress was somewhat dependent on both specific gravity (42–53%) and anatomy (28–51%).

TABLE 9. *Fraction of explained variation from regression of the unadjusted tension perpendicular-to-grain properties of eight hardwoods and various factors.*

Property	R^2 due to SG and anatomical parameters[1]	−	R^2 due to SG alone	=	R^2 due to anatomical parameters alone
Radial properties					
Maximum stress	0.93	—	0.42	=	0.51
Modulus of elasticity	0.91	—	0.74	=	0.17
Proportional limit stress	0.73	—	0.58	=	0.15
Maximum strain[2]	—		—	=	0.75
Tangential properties					
Maximum stress	0.81	—	0.53	=	0.28
Modulus of elasticity	0.86	—	0.82	=	0.04
Proportional limit stress	0.65	—	0.54	=	0.11
Maximum strain[2]	—		—	=	0.74

[1] SG = specific gravity.
[2] Maximum strain was not related to specific gravity.

CONCLUSIONS

1. The transverse tensile properties associated with elastic behavior, i.e. modulus of elasticity and proportional limit stress, were more dependent on specific gravity than the measured anatomical characteristics. However, for those properties associated with failure, 28–51% of the total variation in maximum stress 74–75% of that in maximum strain was attributable to anatomical parameters. Apparently, elasticity was more dependent on the amount of solid wood present, while failure characteristics were a function of weak zones in wood naturally created by various anatomical elements.

2. For radially loaded specimens, the earlywood vessel area fraction was a negative factor in regression equations for maximum stress and maximum strain, showing that earlywood vessels created a weak zone under radial loads. However, ray width was a positive factor for maximum stress, indicating that the rays reinforced transverse tensile strength when loaded radially. On the other hand, ray width and ray area fraction were negative factors in regression equations for tangential maximum stress and maximum strain. Apparently, the ray material was a zone of weakness for specimens loaded perpendicular to the rays.

3. Ray width, height, and area fraction were positive factors in regressions of radial and tangential modulus of elasticity and proportional limit stress. This indicated that rays reinforced specimen stiffness when stressed either along their length or across their width.

4. Stereological data, based upon simple counting techniques, provide a means of quantifying the anatomy of hardwood species. These data may then be used to quantify the effect of anatomy on transverse tensile properties or to segregate species on the basis of anatomical characteristics.

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