MECHANICAL PROPERTIES OF INDIVIDUAL SOUTHERN PINE FIBERS. PART II. COMPARISON OF EARLYWOOD AND LATEWOOD FIBERS WITH RESPECT TO TREE HEIGHT AND JUVENILITY

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ABSTRACT

This paper reports variations in mechanical properties of individual southern pine fibers and compares engineering properties of earlywood and latewood tracheids with respect to tree height and juvenility. Results indicate that latewood fibers exhibit greater strength and stiffness than earlywood fibers irrespective of tree height or juvenility. Average earlywood loblolly pine fibers had modulus of elasticity and ultimate tensile stress values of 14.8 GPa and 604 MPa, respectively. Corresponding latewood fibers had modulus of elasticity and ultimate tensile stress values that were, respectively, 33 and 73% higher. These differences are attributable to microfibril angles and pitting. Juvenility as defined by the mechanical properties of individual wood fibers is not a cylindrical cone surrounding the pith but appears to be biconical, tapering from the base to below the live crown and then again from the live crown to the apex.

Keywords: Loblolly pine, stiffness, strength, microfibril angle, modulus of elasticity, ultimate tensile stress, whole tree variation, juvenile wood.

INTRODUCTION

A good understanding of the relationship between wood fiber mechanical properties and basic cell morphology is comparatively new. While the influence of dominant microfibril angle (MFA) on both longitudinal stiffness and strength is now well documented, less well understood are the contribution of defects to variations in fiber properties (Mott et al. 1996) and the extent of natural variations in fiber properties within large populations, e.g., whole tree variation. An improved understanding of (whole tree) variation in fiber properties is widely regarded as fundamental to improving the quality and properties of wood-fiber based composites, including paper (Clarke 1995).

Within most common commercial trees,

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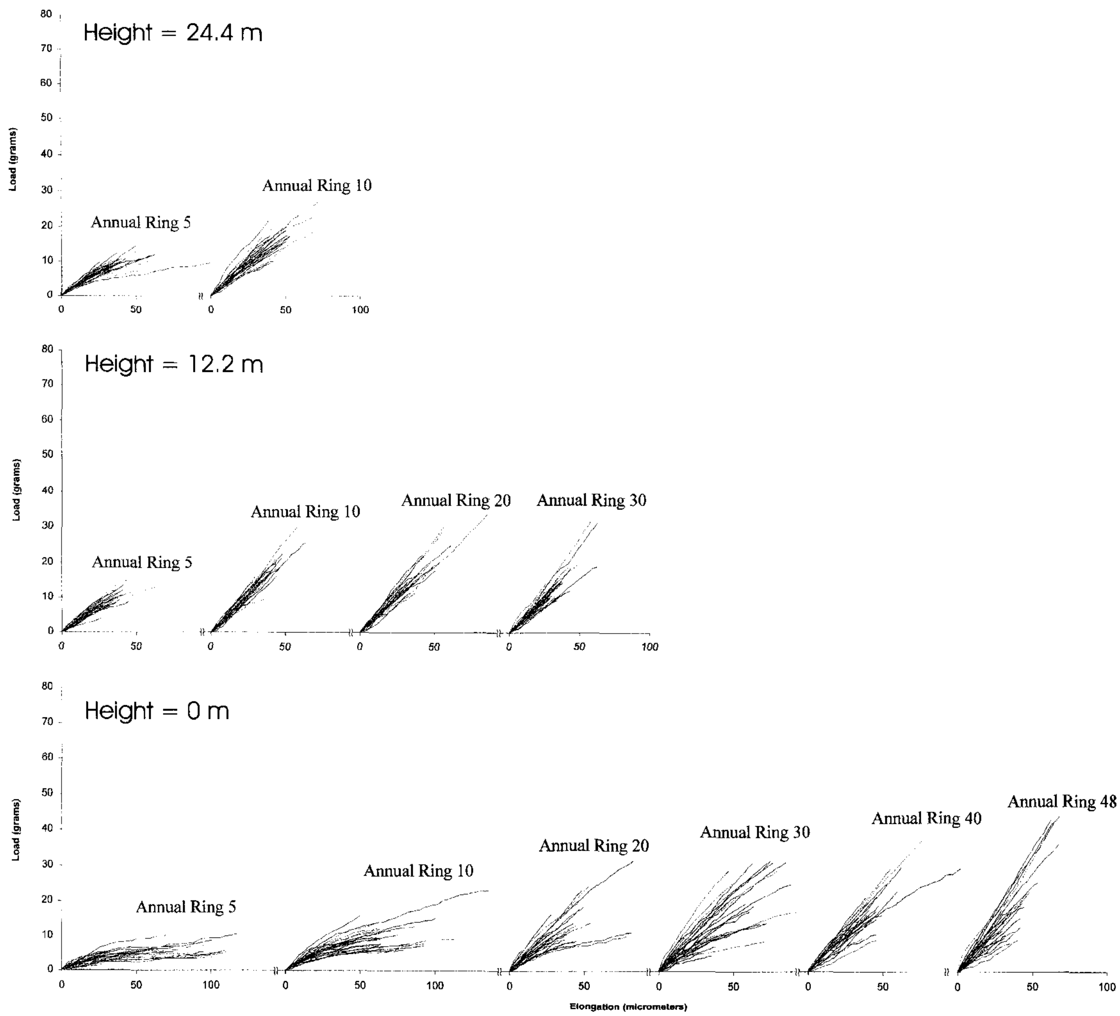

FIG. 1. Load-elongation traces for various growth rings of individual earlywood fibers located at: (a) stump height, (b) 12.2 m from stump height, and (c) 24.4 m from stump height. Every tensile test (n = 30) for each growth ring and vertical location is shown.

there exists a distribution of fiber (tracheid) types, commonly characterized by nomenclature such as latewood (LW) or earlywood (EW) or quantitatively by cell-wall thickness, length, or fibril angle. Until recently, however, it has not been possible to determine the whole-tree distributions of fiber engineering properties such as modulus of elasticity (MOE) and ultimate tensile stress (UTS).

Determining such engineering properties requires a complex protocol. Suitable techniques must be developed and practiced to obtain and isolate single fibers that are undamaged by the extraction procedure or by subsequent drying (Groom et al. 1995). The fiber must then be mounted and fixed into a sufficiently sensitive tensile-test apparatus under controlled atmospheric conditions. Post-test, the fiber must be recovered and the cross-sectional area adjacent to the failure zone measured with reliable precision. Only then can useful engineering properties of a single fiber be calculated.

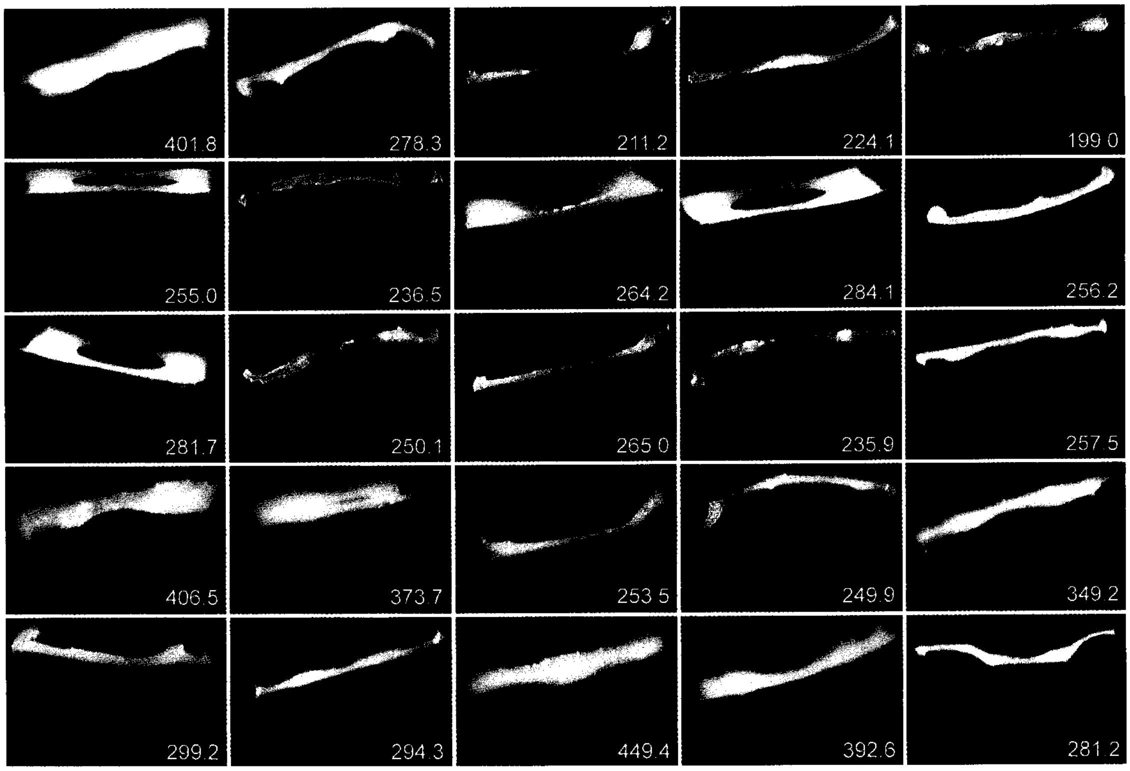

FIG. 2. Twenty-five confocal scanning laser microscope images of earlywood fiber cross sections from the 20th growth ring at a tree height of 9.1 m.

In order to test large numbers of fibers, batch testing and preparation protocols must be developed. By adapting previously developed techniques, the authors have obtained a rapid single fiber testing protocol. This enables the acquisition of engineering data for an unprecedented number of fibers. Thus, it has been possible for the first time to map whole tree variations in fiber mechanical properties.

TABLE 1. *Average cross-sectional area of earlywood and latewood fibers as a function of tree height and growth ring.*

Disk height (m)	Growth ring number											
	Earlywood cross-sectional area (μ^2)						Latewood cross-sectional area (μ^2)					
	5	10	20	30	40	48	5	10	20	30	40	48
0	177	172	237	321	283	255	191	241	339	374	313	402
3.0	225	244	267	279	256		234	426	373	451	343	
6.1	223	262	282	216	261		242	498	425	340	383	
9.1	249	260	289	263			251	394	427	408		
12.2	187	254	243	233			287	402	431	402		
15.2	216	276	282	283			304	336	437	403		
18.3	184	267	249				249	321	393			
21.3	207	243	244				303	344	393			
24.4	174	238					236	293				
Average	205	246	262	266	267	255	255	362	402	396	346	402

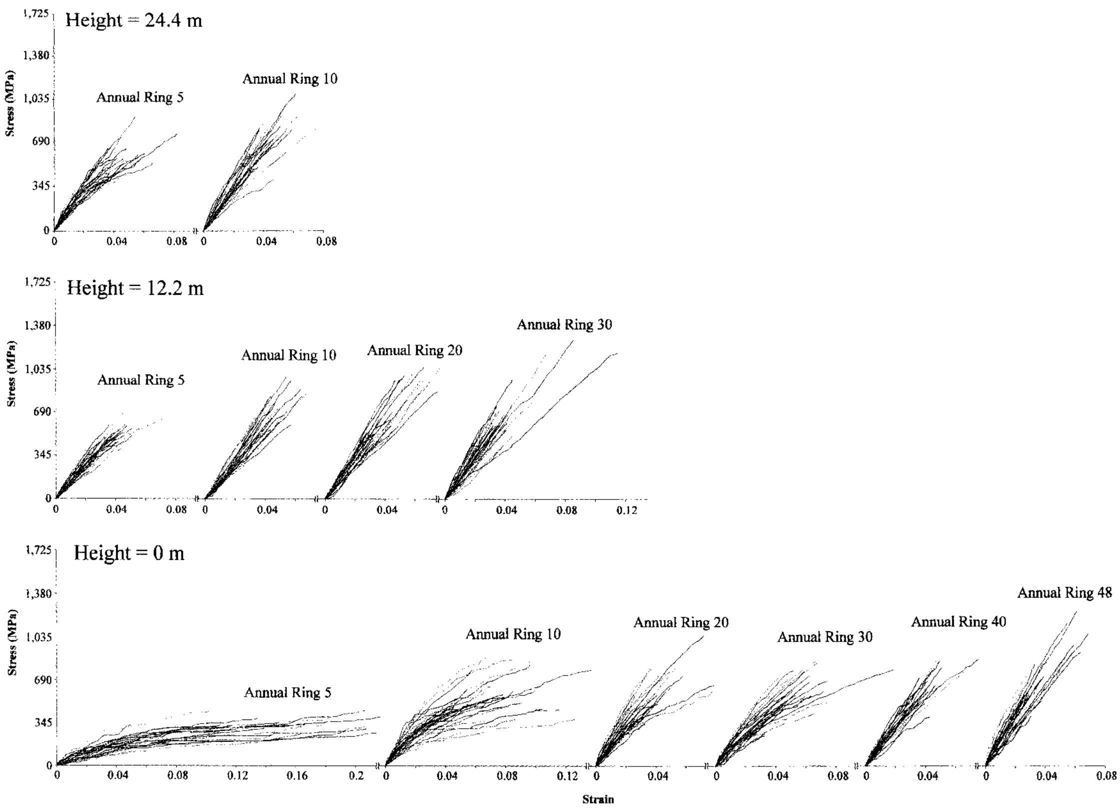

FIG. 3. Stress-strain curves for individual wood fibers taken from the latewood band of growth rings 5, 10, 20, 30, 40, and 48 at stump height. Each trace is the average of 30 individual stress-strain curves.

LITERATURE REVIEW

Jayne (1959) determined the mechanical properties of fibers from 10 softwood species. Results indicated that fibers were generally Hookean in nature, displaying a proportional stress-strain relationship. A limit was found to exist for this region—evidence that wood fibers were viscoeleastic in nature. Jayne (1959)

TABLE 2. *Average modulus of elasticity of earlywood and latewood fibers as a function of tree height and growth ring.*

Disk height (m)	Growth ring number: Earlywood modulus of elasticity (GPa) 5	10	20	30	40	48	Latewood modulus of elasticity (GPa) 5	10	20	30	40	48
0	5.1	15.2	17.9	15.1	17.8	21.1	6.6	13.4	24.5	19.2	27.5	24.6
3.0	10.3	15.7	15.5	13.7	12.3		17.2	19.8	23.9	19.0	26.7	
6.1	12.2	15.9	15.7	16.3	15.3		12.9	13.9	16.5	19.0	21.9	
9.1	12.2	16.1	16.1	14.7			16.3	23.5	22.2	22.9		
12.2	13.9	14.2	15.5	16.9			20.0	21.3	21.5	20.3		
15.2	13.7	16.6	15.2	15.2			18.5	22.3	20.8	23.1		
18.3	12.0	12.8	15.9				15.2	20.3	21.9			
21.3	11.2	15.9	16.7				12.1	20.2	21.4			
24.4	17.0	17.0					19.5	20.4				
Average	11.9	15.5	16.1	15.3	15.2	21.1	15.4	19.4	21.6	20.6	25.4	24.6

TABLE 3. *Average ultimate tensile stress of earlywood and latewood fibers as a function of tree height and growth ring.*

Disk height (m)	Earlywood ultimate tensile stress (MPa)						Latewood ultimate tensile stress (MPa)					
	5	10	20	30	40	48	5	10	20	30	40	48
0	303	581	574	573	597	718	410	716	1,011	895	1,263	1,201
3.0	443	525	514	591	590		864	1,206	1,232	1,263	1,350	
6.1	510	610	567	624	666		723	987	1,048	1,150	1,288	
9.1	579	643	708	712			643	1,083	1,231	1,335		
12.2	526	649	697	673			918	1,151	1,170	1,422		
15.2	666	697	667	581			994	1,220	1,209	1,297		
18.3	469	635	761				742	951	1,179			
21.3	436	640	705				641	1,076	984			
24.4	574	721					785	942				
Average	501	633	649	626	618	718	747	1,037	1,133	1,227	1,300	1,201

(Growth ring number)

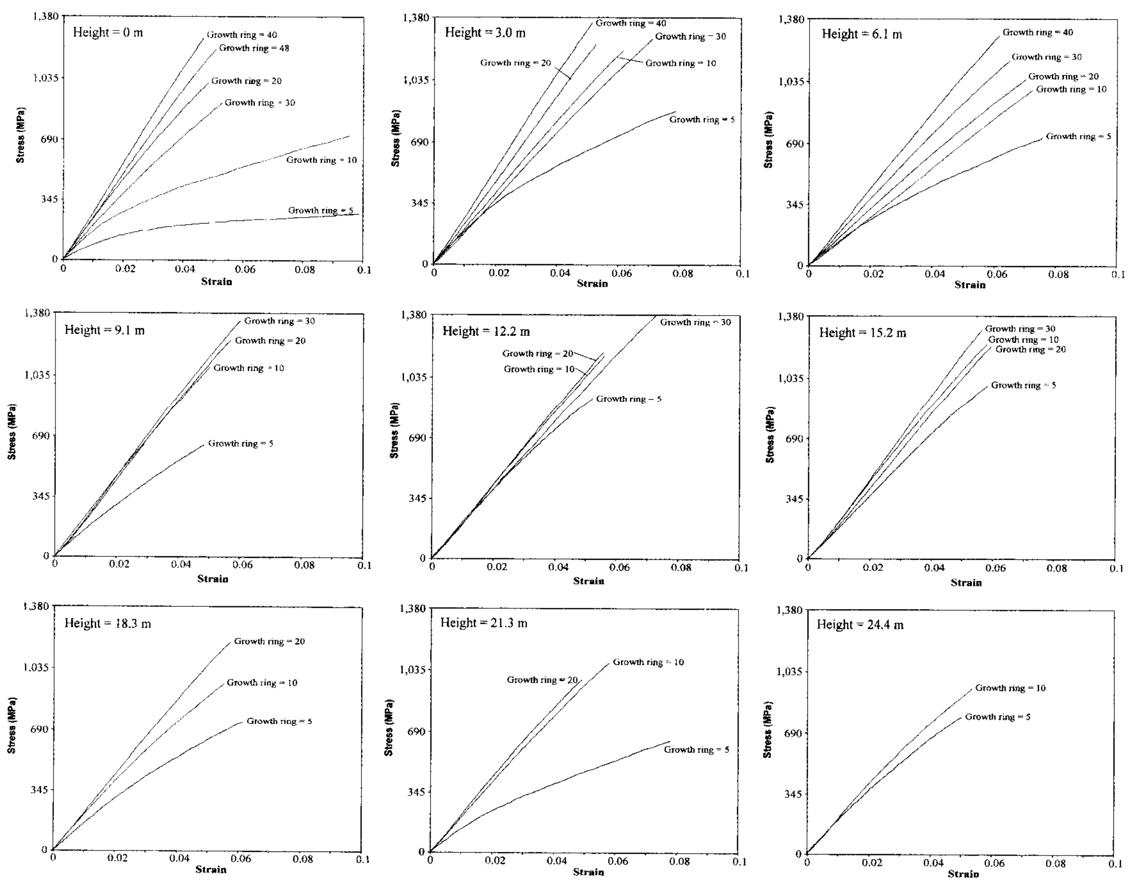

FIG. 4. Average (n = 30) stress-strain curves for individual latewood fibers for various rings from stump height to 24.4-m height at approximately 3-m intervals.

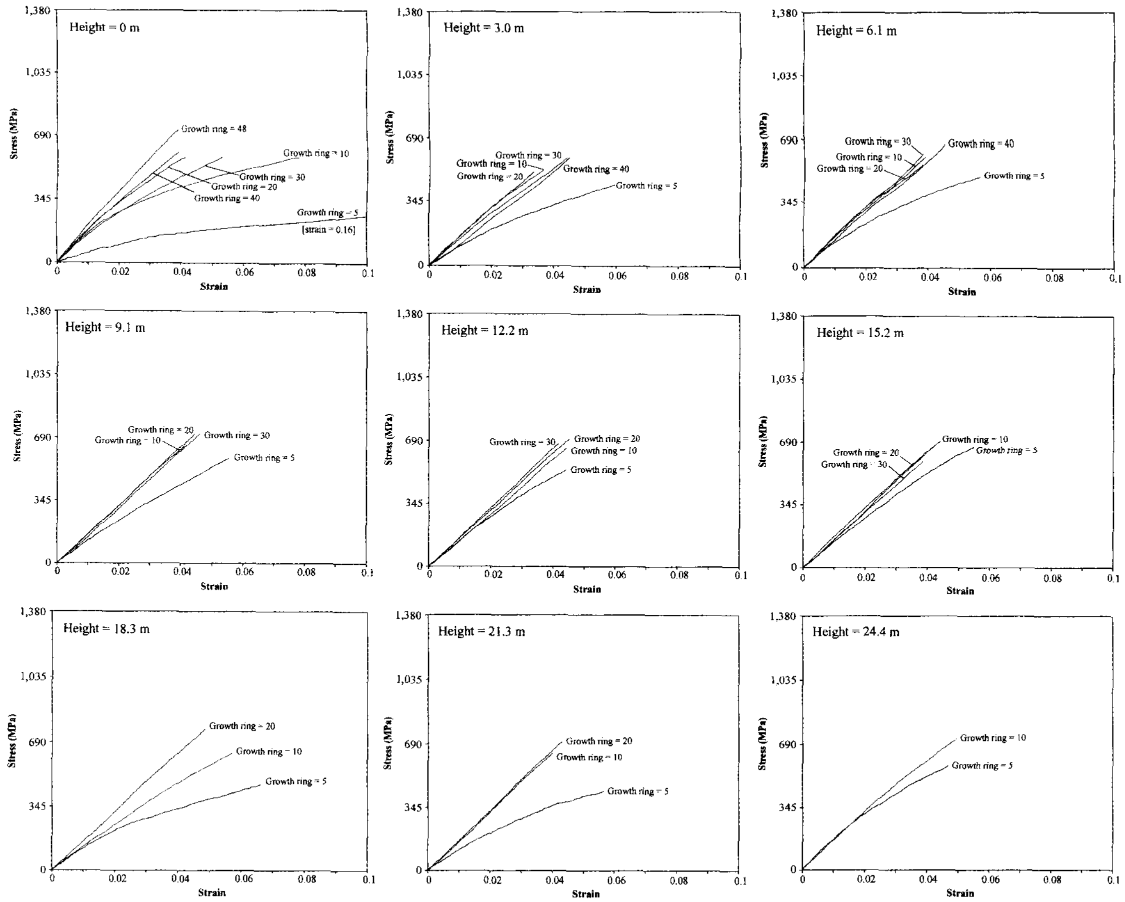

FIG. 5. Average (n = 30) stress-strain curves for individual earlywood fibers for various rings from stump height to 24.4-m height at approximately 3-m intervals.

also reported that proportional limits varied considerably both between and within each specie group. Subsequently many authors conducted similar fiber tensile-tests, reporting a variety of test methods, but in reality only adopting minor changes in test protocol (Tamolang et al. 1967; Kellogg and Wangaard 1964; Hartler et al. 1963; Luner et al. 1967; Duncker and Nordman 1965). Understandably these tests often resulted in similar findings to those of Jayne (1959). Test populations were usually small—typically less than 100 fibers, and conclusions as to the nature of mechanical properties and the influence of morphology or growth characteristics were difficult to make.

Various attempts were made to explain the viscoeleastic behavior of wood fibers. Most conceded that test method in some way influenced test results. This subsequently led to Kersavage (1973) proposing that curvilinearity in Jayne's (1959) original stress-strain curves was due only to slippage at the fiber grips. Various authors have examined fiber tensile-test methodology critically (Kersavage 1973; Page et al. 1972; Kim et al. 1975; Ehrnrooth and Kolseth 1984). Collectively they have proved that fiber misalignment, slippage of the fiber through the gripping assembly (glue or mechanical fixing), and pre-test damage of individual fibers during handling can confound the true stress-strain relationship.

A reliable fiber tensile-test method, includ-

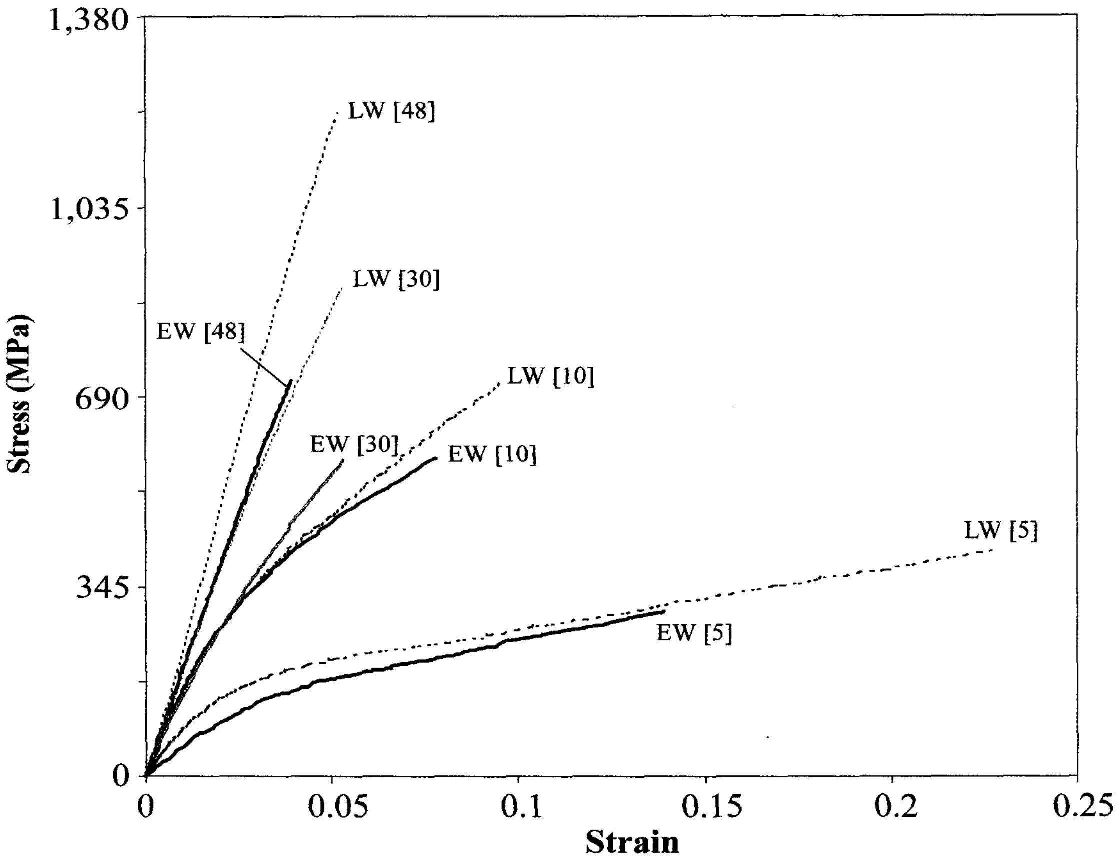

FIG. 6. Average (n = 30) stress-strain curves for individual fibers tested at stump height and from growth rings 5, 10, 30, and 48. Latewood curves are shown as solid lines, earlywood curves are shown as dashed lines.

TABLE 4. *Average microfibril angle of earlywood and latewood fibers as a function of tree height and growth ring.*

Disk height (m)	Growth ring number											
	Earlywood microfibril angle (degrees)						Latewood microfibril angle (degrees)					
	5	10	20	30	40	48	5	10	20	30	40	48
0	43.6	30.2	13.9	10.8	8.4	5.8	37.0	26.2	12.3	11.3	7.1	6.4
3.0	28.2	24.2	9.1	15.2	10.0		27.3	18.7	8.8	7.5	7.8	
6.1	30.5	20.1	16.0	8.5	8.2		26.6	9.7	9.7	7.9	5.9	
9.1	27.4	16.9	10.8	7.2			24.8	14.6	9.4	5.3		
12.2	24.7	14.4	10.9	8.7			21.2	8.3	7.3	7.4		
15.2	16.2	9.4	10.9	8.9			18.8	17.3	10.2	6.2		
18.3	30.4	25.8	6.6				25.5	17.1	9.6			
21.3	32.2	16.9	7.1				30.1	13.7	7.8			
24.4	18.0	7.5					20.3	11.4				
Average	27.9	18.4	10.7	9.9	8.9	5.8	25.7	15.2	9.4	7.6	6.9	6.4

ing a protocol for the isolation of individual fibers that minimized tracheid damage, was developed by Page et al. (1972); El-Hosseiny and Page (1975); Kim et al. (1975); Page and El-Hosseiny (1976); and Page et al. (1977). These authors confirmed that the MFA of the S_2 cell-wall layer had a controlling influence over mechanical properties of the entire fiber, and that all fibers irrespective of species are stiffest and strongest in tension when the MFA approaches zero degrees. Page et al. (1972), El-Hosseiny and Page (1975), Kim et al. (1975), Page and El-Hosseiny (1976), and Page et al. (1977) were also able to confirm that subtleties in test method could influence test results, e.g., that increased fiber gauge length also resulted in reduced mechanical properties. Page and El-Hosseiny (1976) also confirmed that fibers of comparable MFA exhibited large variations in fiber properties. These were attributed to the presence of fiber defects such as crimps, kinks, and microcompressions. Mott et al. (1996) reported a method to characterize such defects, but this technique cannot be applied to large populations of fibers to aid in determining large-scale variations in moduli, for example.

There exists a strong correlation between MFA and fiber length (Panshin and De Zeeuw 1980), and MFA and fiber strength (Page et al. 1977). Earlywood fibers are generally shorter than LW fibers of the same growth increment but exhibit a higher MFA (Panshin and De Zeeuw 1980). This explains EW fiber reduced stiffness and strength. Unfortunately, limited reliable data are available to characterize (whole-tree) variations in MFA (Panshin and De Zeeuw 1980); thus few clues are provided as to true whole-tree variations in fiber mechanical properties. However, fiber length is more commonly measured and models describing variations in fiber length do exist. These can provide insight as to whole-tree variation in mechanical properties.

Bisset and Dadswell (1949) provided data for Panshin and De Zeeuw's (1980) classic model that clearly showed fiber length generally increasing from pith to bark and from stump to a mid-point height, before decreasing towards the crown. Groom et al. (1995) provided a basic model of single fiber load-carrying capacity that displayed similar trends i.e., low load-bearing fibers towards the tree pith and in proximity to the crown. Until now no models have demonstrated such relationships for fiber stiffness and strength.

EXPERIMENTAL PROCEDURES

The first phase of this study involved the mechanical properties of LW fibers, with a detailed description of the experimental procedures found in the corresponding paper (Groom et al. 2001). The following section outlines the additional material as well as providing an abbreviated description of the material selection, material preparation, and experimental procedures.

Material selection

A 48-year-old loblolly pine (*Pinus taeda* L.) tree was selected and felled from a conventional plantation stand located at the Crossett Experimental Forest, Crossett, Arkansas. The tree was straight in form with a diameter at breast height of 42.2 cm, overall height equal to 30.3 m, and height to live crown of 21.2 m. Immediately upon felling, a disk approximately 2.5 cm thick was removed every 3.05 m in height, starting from the stump and proceeding to a 10-cm top.

Several EW slivers were removed from each disk at growth rings 5, 10, 20, 30, 40, and 48. The slivers measured approximately 2 by 2 by 25 mm. The number of growth rings

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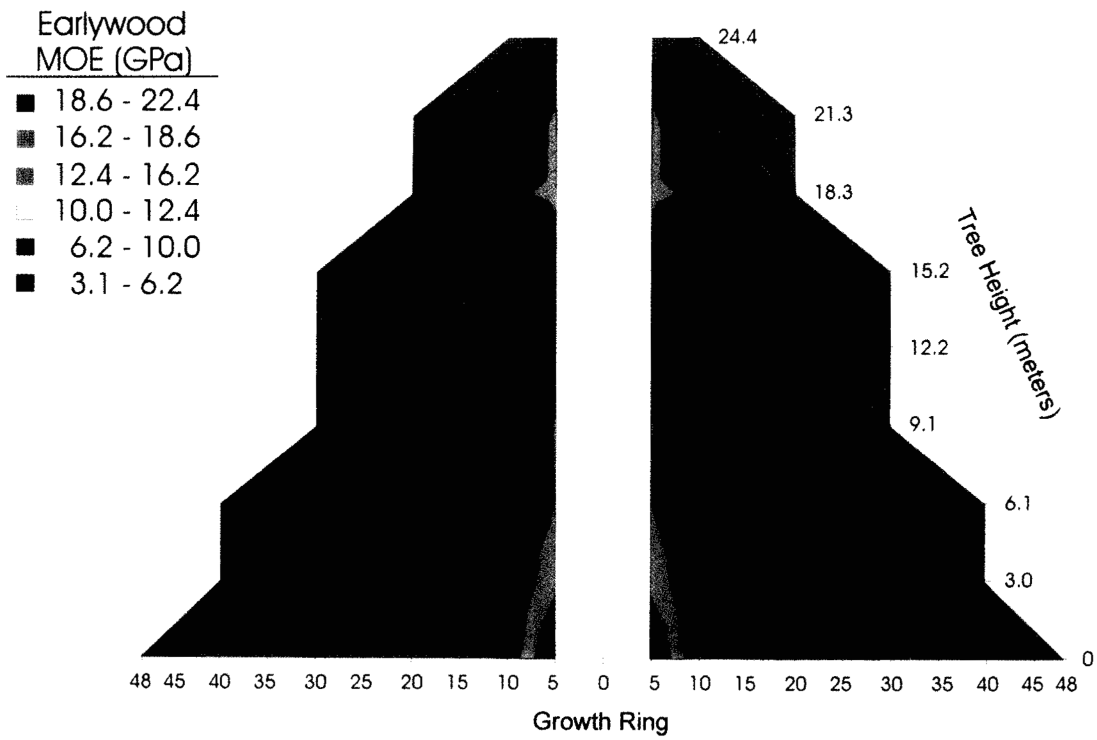
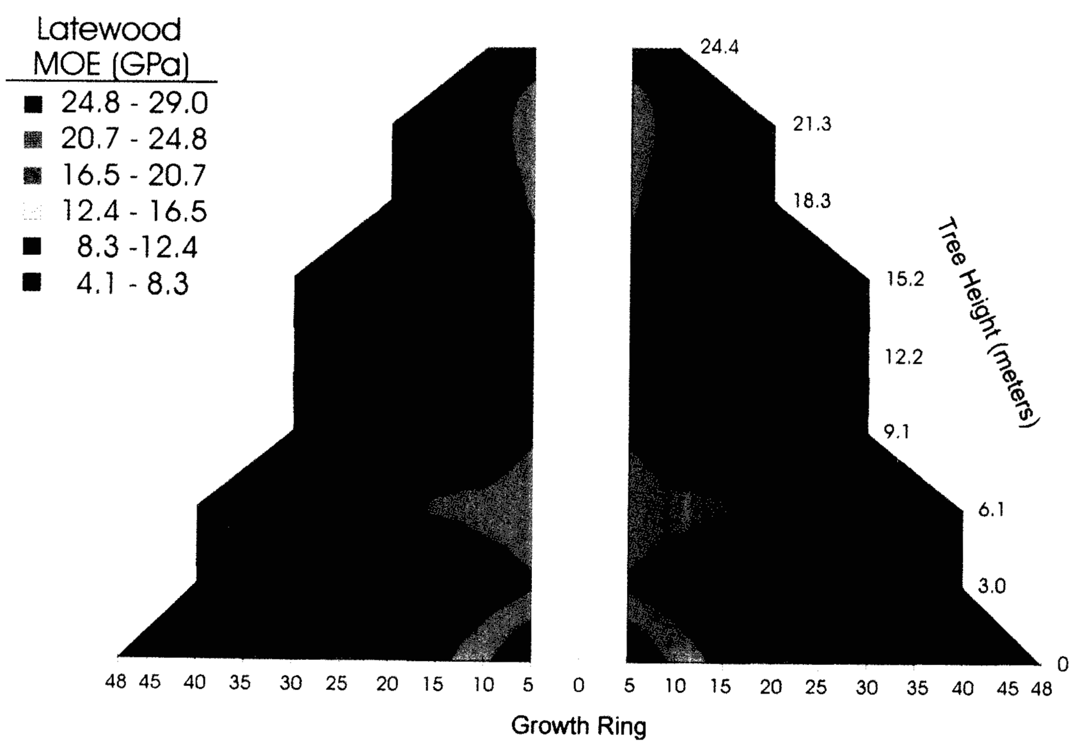
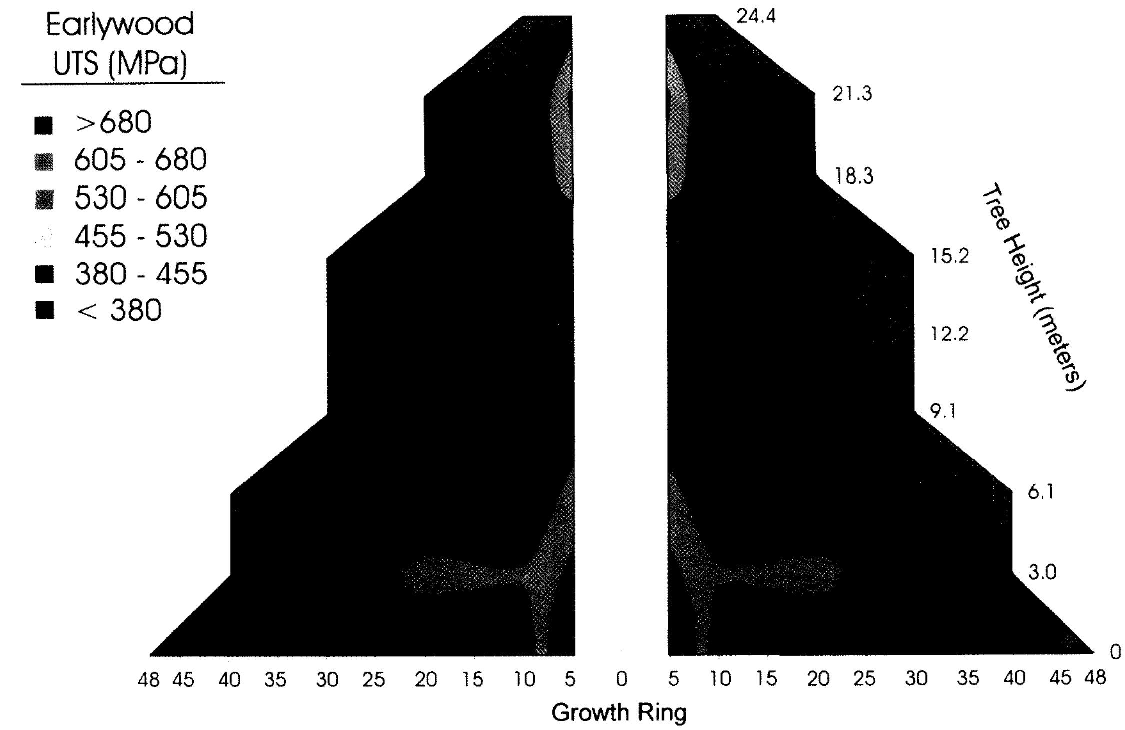
FIG. 7. Modulus of elasticity of individual fibers shown as function of tree location for: (a) earlywood fibers, and (b) latewood fibers.

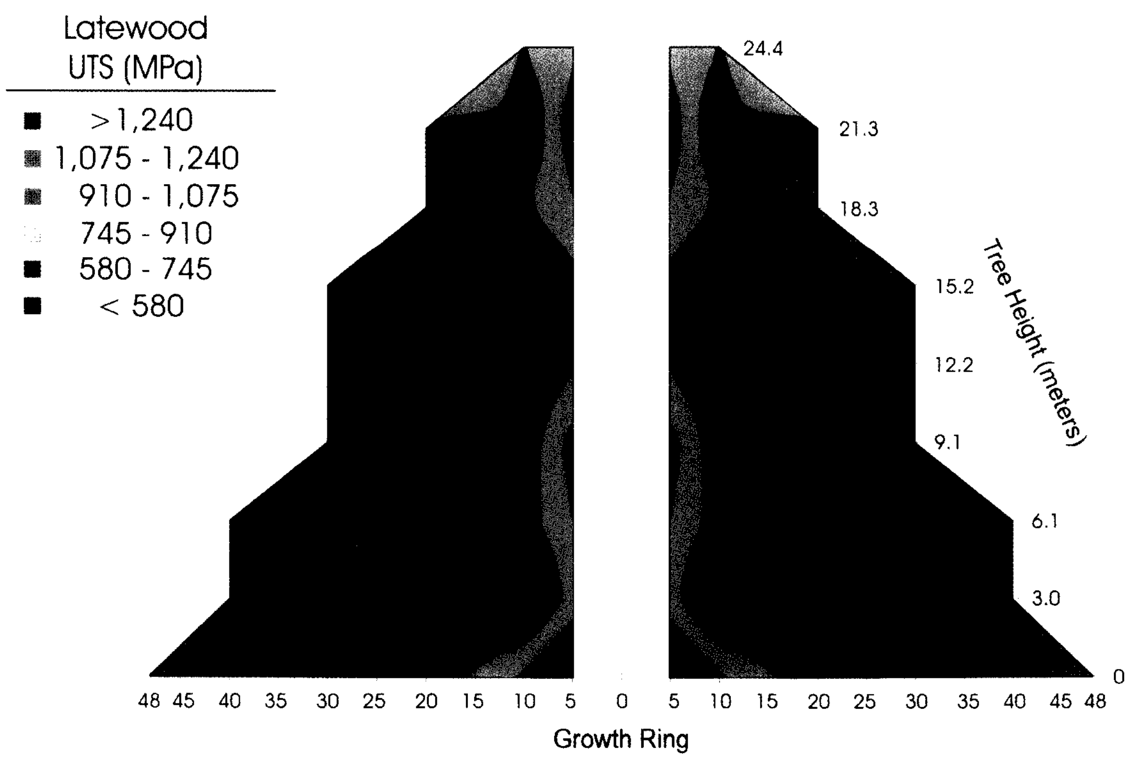


Earlywood MOE (GPa)
18.6 - 22.4
16.2 - 18.6
12.4 - 16.2
10.0 - 12.4
6.2 - 10.0
3.1 - 6.2
24.4
21.3
18.3
15.2
12.2
9.1
6.1
3.0
0
Tree Height (meters)
48 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 48
Growth Ring



Latewood MOE (GPa)
24.8 - 29.0
20.7 - 24.8
16.5 - 20.7
12.4 - 16.5
8.3 -12.4
4.1 - 8.3
24.4
21.3
18.3
15.2
12.2
9.1
6.1
3.0
0
Tree Height (meters)
48 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 48
Growth Ring


Earlywood
UTS (MPa)
>680
605 - 680
530 - 605
455 - 530
380 - 455
< 380
24.4
21.3
18.3
15.2
12.2
9.1
6.1
3.0
0
Tree Height (meters)
48 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 48
Growth Ring


Latewood
UTS (MPa)
>1,240
1,075 - 1,240
910 - 1,075
745 - 910
580 - 745
< 580
24.4
21.3
18.3
15.2
12.2
9.1
6.1
3.0
0
Tree Height (meters)
48 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 48
Growth Ring

analyzed for each disk varied as a function of tree height, with the uppermost disk consisting of only growth rings 5 and 10. Approximately three slivers per growth ring and tree height were macerated in a solution comprised of 1 part 30% hydrogen peroxide, 4 parts distilled water, and 5 parts glacial acetic acid. Macerated fibers were washed with distilled water and placed between glass slides to minimize twisting during drying. Two epoxy droplets were placed in the center portion of each fiber via forceps with an approximate spacing of 1 mm. The epoxy was allowed to cure at 60°C for 24 h, followed by a minimum of an additional 24 h at 22°C.

Tensile tests

A more detailed discussion of the tensile tests can be found in Groom et al. (2001), but is summarized as follows. Individual fibers were tested in tension to failure with a custom gripping assembly attached to a miniature materials tester. Load was acquired with a 5-N capacity load cell; elongation was taken as crosshead movement. The crosshead rate of elongation was 80 micrometers per minute. Cross-sectional areas of tensile-failed fibers were ascertained with the aid of a confocal scanning laser microscope (CSLM). Thirty fibers were tested for each sample.

Confocal scanning laser microscopy

Failed fibers were stained with a dilute concentration of acridine orange (10 mg/300ml of distilled water), attached to a glass slide, mounted with permount, and covered with a number 1 cover slip. Fiber cross-sectional (XS) areas were imaged with a Biorad Model 600 CSLM using a 100× oil-immersion objective. The XS images were constructed from a series of vertical line scans adjacent to the failure location. A standard image analysis software program was used to quantify the XS area from each reconstructed vertical line scan image. The XS area and span length were then used to convert the load-elongation curves into stress-strain curves. In addition to XS area, the CSLM was used to ascertain MFA on 10 of the failed fiber specimens per sample. The MFA was determined by measuring the deviation from the longitudinal fiber axis of microfibrils of the S_2 cell-wall layer on the failed fiber ends.

RESULTS AND DISCUSSION

Physical and mechanical properties

Earlywood fibers.—A summary of load-elongation traces for various fiber types is shown in Fig. 1. The average tensile span for all fibers tested was 0.98 mm. The tensile span of fibers from growth rings 5 and 10 averaged 0.9 mm, whereas the span of fibers from growth rings beyond and including the 30th growth ring averaged 1.0 mm. Individual EW fibers located in the distinctly juvenile region of growth ring 5 typically had load-carrying capacities of between 5 and 15 grams. Elongation to failure varied tremendously in EW juvenile fibers but was generally limited to between 30 and 100 microns.

Cross-sectional images of one set of fibers obtained with the CSLM are shown in Fig. 2. In most cases, measurements of lumens were not applicable due to the thin-walled nature of EW fibers and their subsequent propensity to collapse. The average cross-sectional area of EW fibers tested in this study is shown in Table 1. The overall average of all EW fibers was 244 microns^2, but ranged from approximately 175 microns^2 near the stump and pith to around 280 microns^2 in the mature regions. The overall coefficient of variation for EW fibers was 19.6%, comparable to the 19.2% for similar LW fibers (Groom et al. 2001).

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FIG. 8. Ultimate tensile stress of individual fibers shown as function of tree location for: (a) earlywood fibers, and (b) latewood fibers.

The stress-strain curves of several sets of EW fibers are shown in Fig. 3. Modulus of elasticity and UTS for LW fibers are summarized in Tables 2 and 3. The average MOE and UTS for all EW fibers tested were 14.8 GPa and 604 MPa, respectively. Previous researchers reported MOE values for various softwood species: slash pine EW equal to 11.4 GPa (Jayne 1960) and Douglas-fir EW of 8.8 GPa (Hardacker 1970). Values for UTS have also been reported as: slash pine EW equal to 324 MPa (Jayne 1960), Douglas-fir EW of 471 MPa (Hardacker 1970), and white spruce EW equal to 520 MPa (Page et al. 1972). The values reported in this study are slightly higher than previous researchers have found for other softwoods attributable to either reduction of stress concentrations during tensile testing, species differences, or various degrees of juvenility of test specimens. The coefficients of variation for MOE and UTS were 24.8 and 26.9%. These coefficients of variation are somewhat higher than those reported for LW fibers (Groom et al. 2001). This variability can be linked to the higher degree of pitting inherent in EW fibers.

The average MFA for all EW fibers tested in this study was 16.5 degrees. Juvenile fibers had MFAs of approximately 25 to 30 degrees. Comparable mature fibers had MFAs of between 5 and 10 degrees.

Earlywood/latewood comparison

Stress-strain curves for all 36 EW and LW fiber types based on juvenility and height are shown in Figs. 4 and 5, respectively. The most noteworthy similarity was that in all cases tested, the stress-strain curves of the fifth growth ring fibers are the weakest and most compliant of those fibers tested. Similarly of interest was that the fibers from the nearby tenth growth ring behave much more like mature fibers than their closer juvenile neighbors. This transition is dependent on the height of the fibers in the tree; fibers located near the stump and in the crown mature at a much slower rate than those fibers below the live crown. In the central portion of the main bole, the transition of juvenility to maturity as defined by fiber mechanical properties is abrupt and occurs before the tenth growth ring.

Figures 4 and 5 show that the mechanical properties of mature EW fibers are more heterogeneous than those of their corresponding LW fibers, attributable to the numerous and variable pitting of EW fibers. This heterogeneity is greatest at stump level and inversely proportional to tree height.

Stress-strain curves of all EW and LW fibers for various growth rings regardless of vertical location in the tree are summarized in Fig. 6. There is no difference in the shape of stress-strain curves between EW and LW fibers. The stress-strain curves of fifth growth ring fibers are initially linear and then become curvilinear. The response changes back from curvilinearity to linearity at approximately 50% of maximum load. This is similar to findings from Navi (1998). However, fully mature fibers with low MFAs displayed linear behavior to failure. This will be discussed in further detail in the third paper of this series.

Figure 6 also illustrates two additional differences between EW and LW fibers. For a given fiber type, the slope of EW fiber stress-strain curves is less than that of their corresponding LW fibers. The difference in EW and LW fiber MOE values (Table 2) can be explained by the differences in MFA. The MFA of pine fibers is generally greater in EW fibers than in LW fibers from the same growth ring, and has been documented in radiata pine (Evans 1998) and loblolly pine (Megraw 1985). It has also been shown by past researchers (Page et al. 1972) that MFA and MOE are inversely related. The average MFAs

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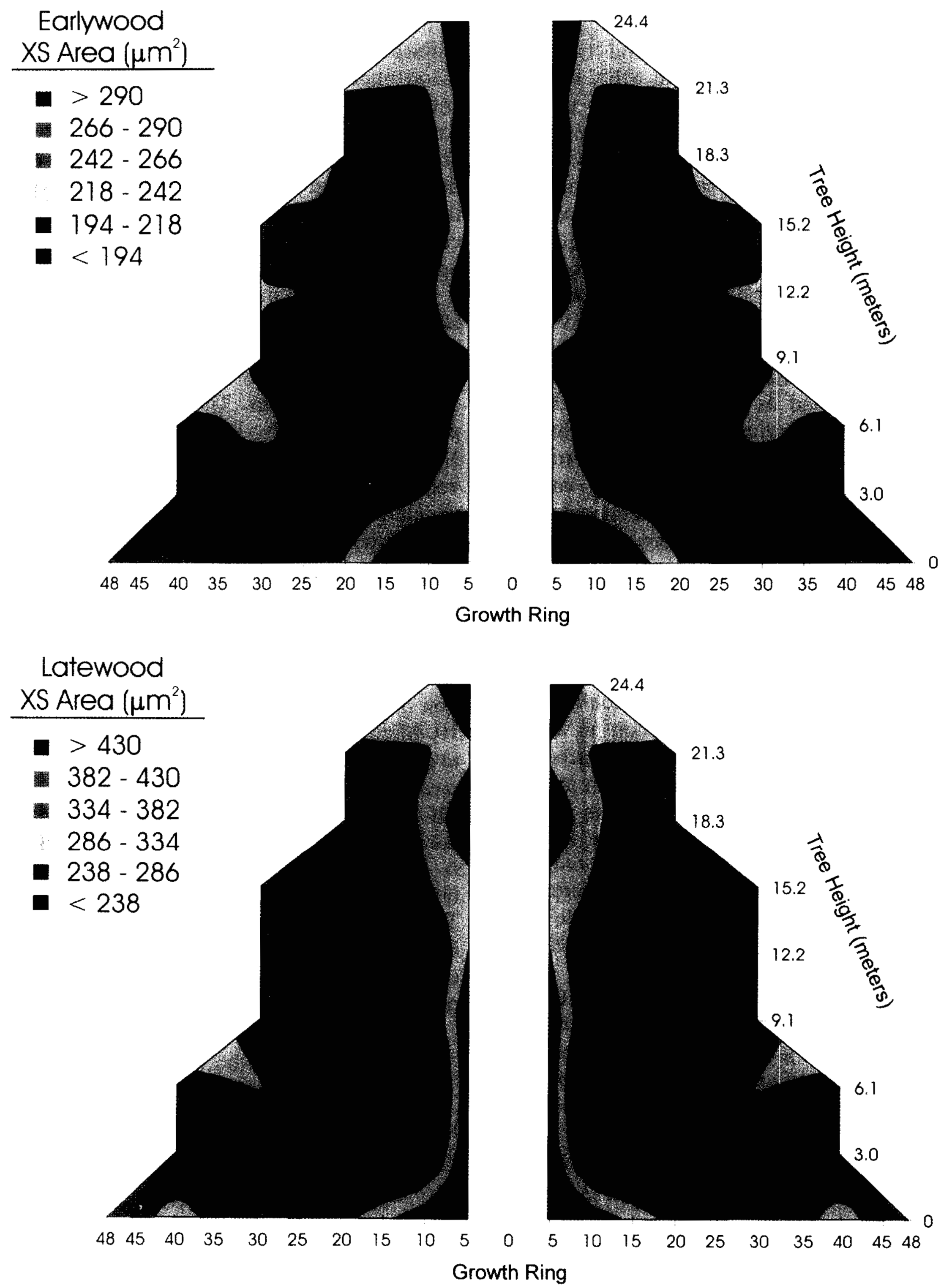
FIG. 9. Microfibril angle of individual fibers shown as function of tree location for: (a) earlywood fibers, and (b) latewood fibers.


Earlywood
XS Area (μm²)
> 290
266 - 290
242 - 266
218 - 242
194 - 218
< 194
24.4
21.3
18.3
15.2
12.2
9.1
6.1
3.0
0
Tree Height (meters)
48 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 48
Growth Ring
Latewood
XS Area (μm²)
> 430
382 - 430
334 - 382
286 - 334
238 - 286
< 238
24.4
21.3
18.3
15.2
12.2
9.1
6.1
3.0
0
Tree Height (meters)
48 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 48
Growth Ring

for EW and LW fibers in this study, summarized in Table 4, were 16.5 and 14.3%, respectively. This difference in MFA is consistent with past research and thus is the basis for MOE differences in EW and LW fibers.

The second difference between EW and LW fibers is the ultimate stress level each fiber type can endure. The EW/LW disparity is greater for UTS (Table 3) as compared to MOE values. The MOE for LW fibers is 33% greater than that for EW fibers; the increase of UTS for LW fibers as compared to EW fibers is 73%. This disparity is attributable to more than MFA. Ultimate tensile stress is a measure of strength and as such is governed by two factors: the carrying capacity of defect-free material coupled with any strength-reducing variables. These strength-reducing variables either reduce the effect cross-sectional area or result in stress concentrations. The carrying capacity of the wood fiber is governed by the microfibril crystallinity and orientation and is closely associated with fiber stiffness. The strength-reducing variables in wood fibers are disruptions in the cellulosic chain or orientation, the most noteworthy of which is the pit. Intertracheal pitting is common in loblolly pine, especially in EW fibers. Intertracheal pits on the radial walls of EW are much more numerous, conspicuous, and larger in diameter than in LW (Panshin and deZeeuw 1980). In addition to reducing the effective cross-sectional area of the wood fiber, the intertracheal pits have been shown to produce tensile strains 300 times greater than defect-free cell wall material (Mott 1995).

A graphical summary of fiber MOE and UTS is shown in Figs. 7 and 8, respectively. The effect of juvenility on the stiffness and strength of individual wood fibers is most marked at locations near the base as well as in the vicinity of and above the live crown. Juvenility is least pronounced at heights above 9 m and below the live crown. Maturation as defined by mechanical properties of individual wood fibers is less dependent on tree height and increases proportionally with distance from the pith. Juvenility does not appear to be confined to a cylindrical cone coincident with the pith. Rather the juvenile zone is biconical, tapering from the stump to just below the live crown and then from the live crown to the apex of the bole.

The juvenility and maturity of fiber cross-sectional area, shown in Fig. 9, paralleled the mechanical property response (Figs. 7 and 8). Cross-sectional area was least within the first 5 to 10 growth rings. This is consistent with previous research by Larsen et al. (2001) and McMillan (1968) showing that, in general, juvenile fibers are thinner than their mature counterparts. This study shows that no particular patterns exist regarding maturation of cell-wall cross-sectional area below the live crown. However, the cross-sectional areas of fibers within the live crown are much less than those outside of the live crown.

Microfibril angle of fibers shown as a function of location within a tree is shown in Fig. 10. Microfibril angle is inversely proportional to distance from the pith and parallels the fiber mechanical properties. The greatest range in MFA occurs at or near the base of the tree and decreases with increasing height. This pattern is similar to that found by Megraw et al. (1999) in 30-year-old stands of loblolly pine. The range of MFA in this study did, however, increase abruptly in the vicinity of the live crown and mirrored the behavior at the base of the tree.

SUMMARY AND CONCLUSIONS

The mechanical properties of individual EW loblolly pine fibers were determined at various locations within a tree. These results, in con-

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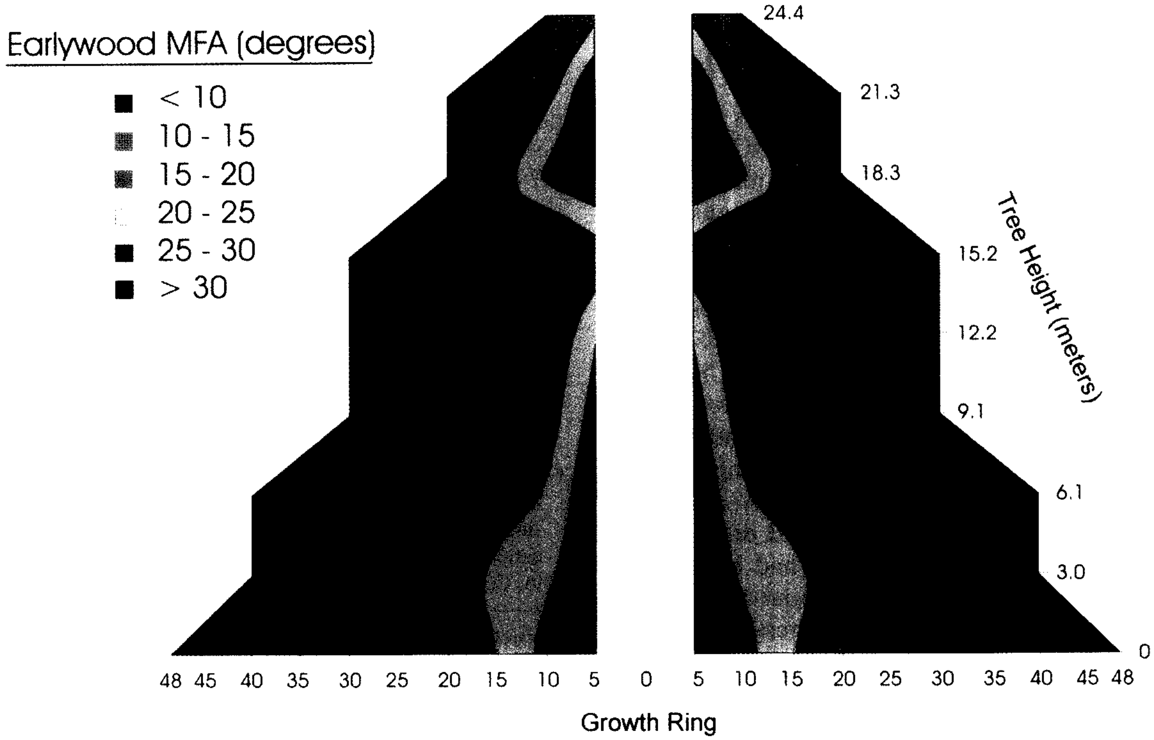
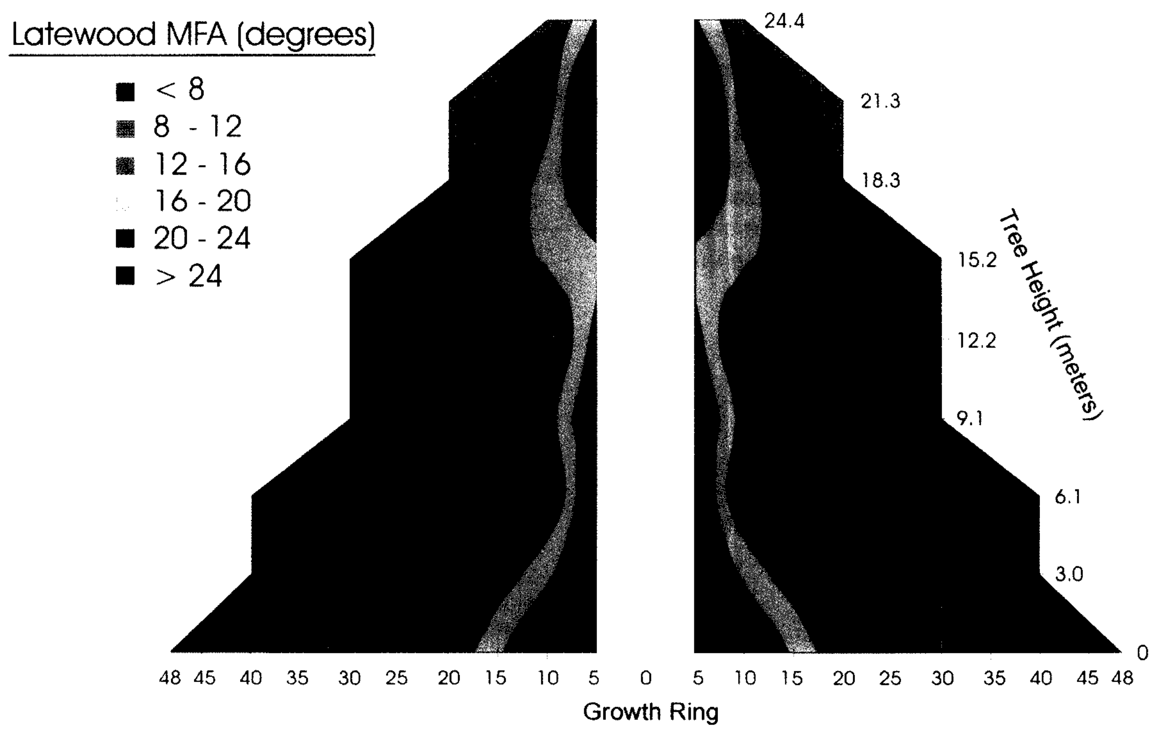
FIG. 10. Cross-sectional areas of individual fibers shown as function of tree location for: (a) earlywood fibers, and (b) latewood fibers.


Earlywood MFA (degrees)
< 10
10 - 15
15 - 20
20 - 25
25 - 30
> 30
24.4
21.3
18.3
15.2
12.2
9.1
6.1
3.0
0
Tree Height (meters)
48 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 48
Growth Ring


Latewood MFA (degrees)
< 8
8 - 12
12 - 16
16 - 20
20 - 24
> 24
24.4
21.3
18.3
15.2
12.2
9.1
6.1
3.0
0
Tree Height (meters)
48 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 48
Growth Ring

junction with physical properties, were discussed in detail and then subsequently compared to corresponding LW fibers.

The MOE of loblolly pine EW fibers was 14.8 GPa. Juvenile fibers had MOE values of approximately 11.7 GPa and a minimal value of 5.1 GPa. Mature fibers were considerably stiffer, with average MOE values of approximately 17.2 GPa and a maximal value of 21.1 GPa. The UTS of LW fibers was 604 MPa. Juvenile fibers had an average UTS of 496 MPa; mature fibers averaged 648 MPa. Average MFA was 25 to 30 degrees for juvenile fibers and 5 to 10 degrees for mature fibers, with an overall average of 16.5 degrees.

The stress-strain curves of EW and LW fibers are identical in shape and differ only in magnitude. Latewood fibers had MOE values 33% greater than their EW equivalent. This is most likely due to the differences in MFAs: the average MFA of EW fibers was 2.2 degrees higher than the LW fibers. The UTS of LW fibers were 73% greater than EW fibers, due to a combined effect of MFA and pitting characteristics.

Relationships were also established between mechanical properties and spatial location. The juvenile core is not cylindrical in nature but is a response of physiological growth sequences. Thus, the juvenile core is conical from stump to below the live crown, with this pattern being repeated in the live crown. This relationship will be expanded upon in the third and final paper of this series.

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