ON FRACTURE-RELATED CAUSES FOR REDUCTION IN TENSILE STRENGTH OF SOUTHERN PINE LUMBER AT LOW MOISTURE CONTENT

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ABSTRACT

A combination of lumber testing and finite element–fracturemechanics simulation was used to determine the influence of moisture content on the tensile strength of southern pine dimension lumber. This research confirmed that tensile strength degrades as equilibrium moisture content drops below 12%. The simulations allowed tracking of the individual influence of different clear wood properties on the tensile strength of lumber specimens. The finite element results suggest that lumber containing knots more closely approaches idealized linear elastic behavior as the wood becomes extremely dry. For green lumber, the model appears to be overly conservative, possibly because stress concentrations are reduced by inelastic response perpendicular to the grain.

Keywords: Tensile strength, lumber, moisture content, computer simulation.

INTRODUCTION

It has traditionally been accepted that the ultimate tensile stress (UTS) of lumber parallel to the grain, or tensile strength, increases as moisture content (MC) decreases (Green and Evans 2001). However, more recent research has shown that while UTS may initially increase as lumber is dried from the green condition, UTS may decrease with further drying below about 12% to 15% MC (Green et al. 1990). However, this latter research was limited to lumber that had MC above about 10%. Subsequent studies on clear wood and lumber confirm that UTS may decrease when the lum-

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ber is dried to very low MC (Green and Kretschmann 1994; Green et al. 2002). These studies, along with some reports of failures in lumber in commercial buildings subjected to very low MC, emphasize the need to better understand the effect of MC on the tensile strength of lumber. A previously developed finite element program called GASPP (grain angle strength prediction program) has been used successfully to predict UTS and fracture patterns for lumber containing a single wide-face knot (Cramer and McDonald 1989). This program depends on clear wood properties derived from density and grain angles to model a board and predict strength. In this study, the GASPP model was modified and used to gain a more fundamental understanding of the relationship between lumber properties and changes in clear wood properties induced by MC.

The objectives of this research were to

1. Investigate the tensile strength of southern pine nominal 2- by 4-in. (standard 38- by 89-mm) dimensional lumber (2 by' 4s) at very low MC.
2. Investigate the degree to which lumber quality affects the MC–tensile strength relationship.
3. Further quantify the applicability of the GASPP modeling approach for predicting the UTS of lumber.
4. Gain a fundamental understanding of how MC-induced changes in clear wood properties affect the tensile strength of lumber.

BACKGROUND

In this section, we will briefly review the development of the GASPP computer model and previous literature on the effect of MC on tensile strength. For more complete discussion, the reader is referred to the literature cited.

The GASPP model

GASPP is a finite element–fracture mechanics analysis program developed at the University of Wisconsin for predicting the tensile strength of lumber (Cramer and McDonald 1989; Stahl et al. 1990; Cramer and Fohrell 1989). The program considers point-by-point fiber directions relative to the board axes and density patterns. A density map and grain angle map are established for the wide-face surfaces of each board analyzed. Using this information, the program generates a two-dimensional finite element mesh where orthotropic elastic and strength properties are assigned from the input information to each finite element. The effects of grain distortion surrounding knots as well as the knot material itself are considered in the linear elastic orthotropic analysis. Linear-elastic fracture mechanics are employed with localized stress-based criteria to predict the onset and propagation of cracks. Crack initiation occurs when any of the following criteria are satisfied:

$$\frac{\sigma_{perpendicular}}{UTS_{perpendicular}} = 1 \qquad \frac{\tau}{Shear_{parallel}} = 1$$

$$\frac{\sigma_{parallel}}{UTS_{parallel}} = 1$$

where $s_{perpendicular}$ = normal stress perpendicular to grain; $UTS_{perpendicular}$ = tensile strength perpendicular to grain; t = shear stress parallel to grain; $Shear_{parallel}$ = shear strength parallel to grain; $s_{parallel}$ = normal stress parallel to grain; and $UTS_{parallel}$ = tensile strength parallel to grain.

When one of the first two criteria is deemed critical, a perpendicular-to-grain or shear-fracture initiation is modeled as a small finite-sized separation of nodal points along the grain line. When the third criterion is satisfied, a parallel-to-grain fracture is modeled as with a cross-grain separation of nodes bounded by parallel-to-grain separation of nodes to simulate the splintering action of fractures induced by parallel-to-grain stresses.

Singular elements are placed around the crack tips, and crack tip displacements are computed. These displacements are employed with orthotropic, linear-elastic fracture equations to compute mode I and mode II stress intensity factors. The stress intensity factors

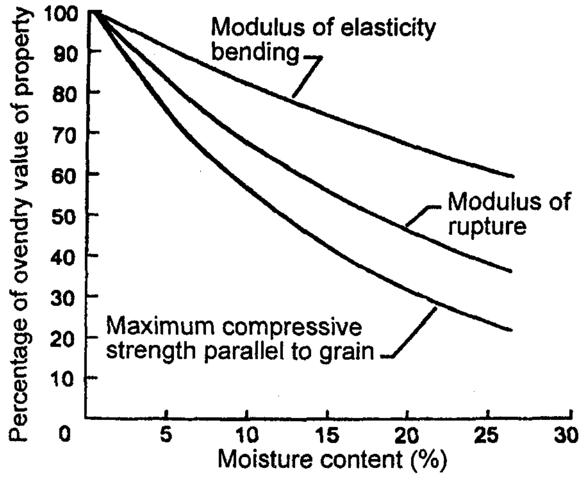

FIG. 1. Typical representation of the effect of moisture content on the properties of clear wood (Panshin and de Zeeuw 1964)

are then evaluated in Wu's fracture criterion (Wu 1967) to determine if crack growth will occur. If a crack is determined to grow, the finite element mesh is extended and the analysis increments in a step-wise manner with increasing displacement. Details of this modeling have been presented before (Cramer and Fohrell 1989).

The model has predicted tensile strengths of a variety of knot-containing lumber specimens with a standard error of 630 1b/in.[2] (4.3 MPa). Effects of changes in clear wood properties can be examined for a given board geometry. This capability of the model made it ideal for considering the influence of moisture-induced clear wood property changes on overall lumber tensile strength.

Effect of moisture content on wood properties

Properties of clear wood.—An extensive amount of research has been conducted on the effect of MC on the mechanical properties of clear wood. General discussions can be found in Panshin and de Zeeuw (1970) and in Forest Products Laboratory (1999). These discussions indicate that clear wood strength for a number of properties increases with decreasing MC and is often shown as increasing continuously from green to 0% MC (Fig. 1). However, a more critical analysis of the available literature suggests that not all properties necessarily increase with drying to such low MC levels (Gerhards 1982; Green and Kretschmann 1994).

The data from the world literature summarized by Gerhards (1982) were evaluated for possible use with the current study. However, there were many limitations to its use for our purposes. The most significant limitation was that for most studies, the original data were not available for further analysis. Experimentally, individual studies were often limited in the number of properties evaluated, in the number of specimens sampled, or in the range of MC evaluated. To overcome these limitations, a study was conducted on the effect of MC on a wide range of properties using small, clear specimens of southern pine (Green and Kretschmann 1994). Specimens for this study were cut from commercially dried nominal 2- by 6-in. (standard 38- by 140-mm) (2 by 6s) southern pine lumber and sorted, based on specific gravity, into five matched MC groups of approximately 40 specimens each. These specimens were conditioned to equilibrium MC levels of approximately 4%, 8%, 12%, and 18%. The last group was saturated with water and tested green.

Results indicated that tensile stress parallel and perpendicular to the grain and both mode I and mode II stress intensity factors for fracture toughness increase with decreasing MC from green to a peak between 7% and 13% MC, depending upon the property. Upon additional drying, these properties decrease. Maximum fiber stress in bending, compression parallel and perpendicular to the grain, and all elastic moduli increase with decreasing MC from green to 4% MC. For some of these properties, the increase is not linear at low MC levels. Empirical equations were developed relating eight different strength properties and seven elastic properties to change in MC (Kretschmann and Green 1996). The point at which these properties cease to decrease with increasing MC (Mp) was found to be remarkably constant across properties and averaged

23% MC. Equations were also developed between these properties and both MC and specific gravity. Selected relationships between properties and MC and specific gravity are shown in Fig. 2. The dots on the figure indicate the location of the data points on the fitted surface.

Tensile strength of lumber.—Historically, the procedures used for adjusting the bending strength of lumber for changes in MC were also used to adjust UTS for changes in MC (Green and Evans 2001). Although the technical justification was not apparent, it was consistent with the historical practice of relating tensile strength to bending strength when deriving allowable properties. Research by Hoffmeyer (1978) and Madsen and Nelsen (1981) established that this practice was invalid, but these studies were either limited in the number of MC levels studied or the number of grades tested. In 1990, a study was completed on the effect of MC on the tensile properties of Douglas-fir dimension lumber (Green et al. 1990). In that study, lumber of three grades and two sizes was tested at MC levels of green, 20%, 15%, and 10%. There were approximately 110 specimens per grade, size, and MC category. An empirical quadratic surface model (QSM) fit to these data clearly indicated that UTS did not always increase, and might decrease, as MC decreased from green to 10% (Fig. 3; Green and Evans 1989).

Eskelsen et al. (1993) explored the effects of drying on the ultimate tensile capacity (product of UTS and cross-sectional area) of mechanically graded 2100f Douglas-fir 2 by 6s. They assumed that decreases in UTS of the type predicted from the QSM (Green and Evans 1989) were correct for carefully dried lumber but were not necessarily applicable to lumber dried by commercial schedules. They divided 5 10 pieces of lumber into three groups matched by modulus of elasticity (MOE) and knot characteristics. Two of the groups were carefully dried to approximately 13.5% MC using a mild kiln schedule, and one group was dried to about 8.5% by a commercial schedule. From the results of the study, the authors concluded that the QSM accounted for the drying effects for lumber with strength values between the 10th and 60th percentile levels of their data but was conservative for values up to the 5th percentile. Unfortunately, loss of the actual dimensions of the commercially dried lumber and failure to achieve a target MC of about 7% somewhat clouded the conclusions from an otherwise excellent study. Thus, the reduction in UTS when drying to a very low MC is still an open question.

PROCEDURES

Development of the GASPP model

In this study, analyses under different MC scenarios were conducted on sets of 15 southern pine 2 by 4s and 2 by 6s representing a range of lumber grades. The quality of each piece of lumber was classified as clear, small edge knot, large edge knot, and large center knot. Density maps of each board were obtained using digital X-ray density scanning and mapping (Suryoatmono et al. 1994). This information was put into GASPP, along with scanned grain angle data (Cramer and McDonald 1989). Density variations and assumed constant MC provided a basis for determining the variation in specific gravity within each lumber specimen at various MC levels using ASTM D2395 (ASTM 1999). With MC input and specific gravity maps, properties at any point in a board were estimated using the information presented in Kretschmann and Green (1996). Table 1 gives the regression equations used in this study. For Poisson's ratio, the mean values at individual MC levels were used (Table 2). Differential shrinkage and the potential resulting stresses were not assessed or modeled. The subject lumber specimens were equilibrated for an extended period to minimize these effects.

Sixty GASPP finite element analyses were conducted for some representative southern pine knot situations (Table 3). While statistically valid conclusions may not be possible from this limited data set, the objective was really to observe general trends in the data and

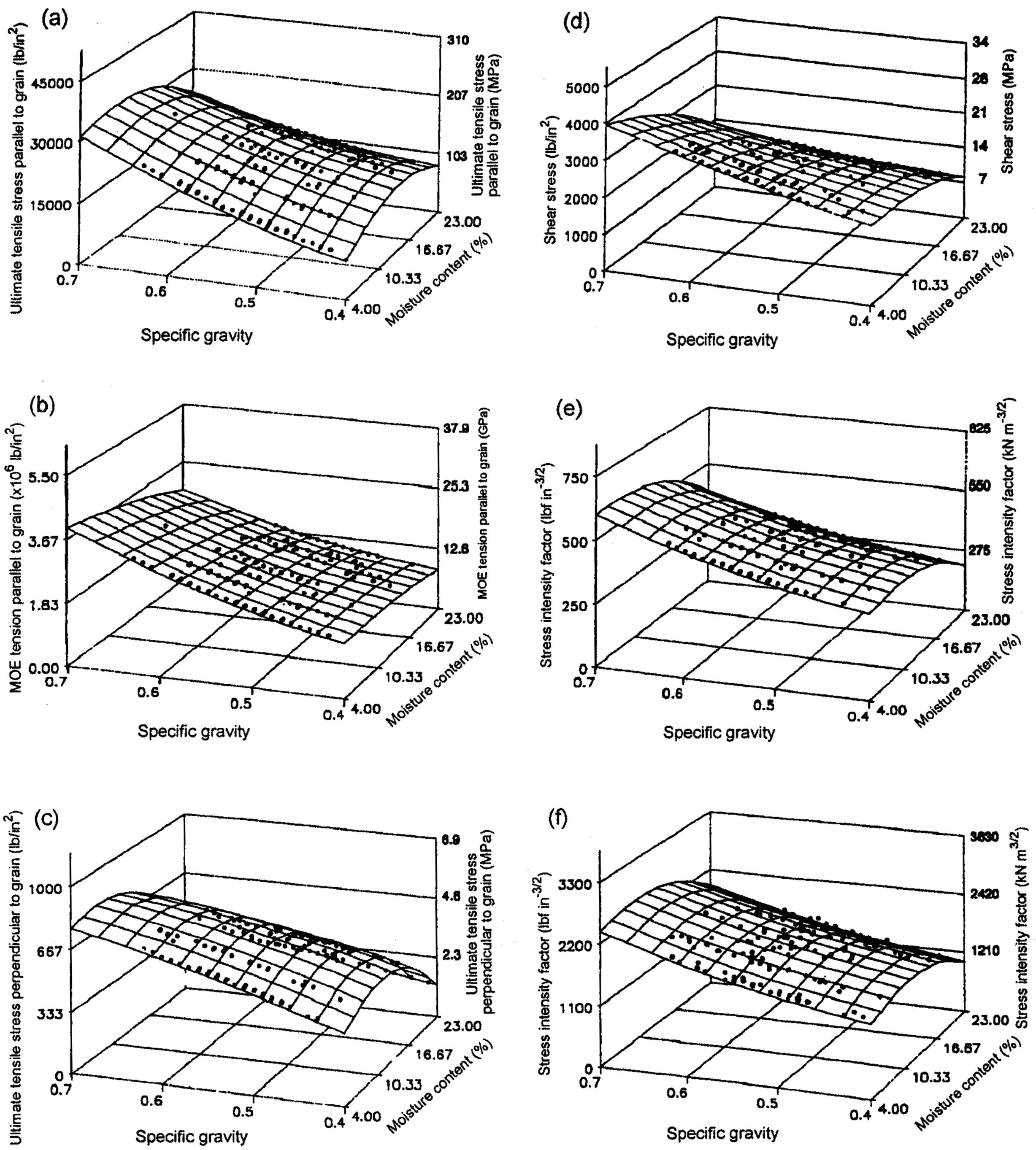

FIG. 2. Relationship between property, moisture content, and specific gravity for clear southern pine (Kretschmann and Green 1996). Dots on surface represent x–y location of test data on surface. (a) modulus of elasticity in tension parallel to the grain, (b) ultimate tensile stress parallel to the grain, (c) ultimate tensile stress perpendicular to the grain, (d) shear stress parallel to the grain, (e) mode I stress intensity factor for fracture toughness, (f) mode II stress intensity factor for fracture toughness.

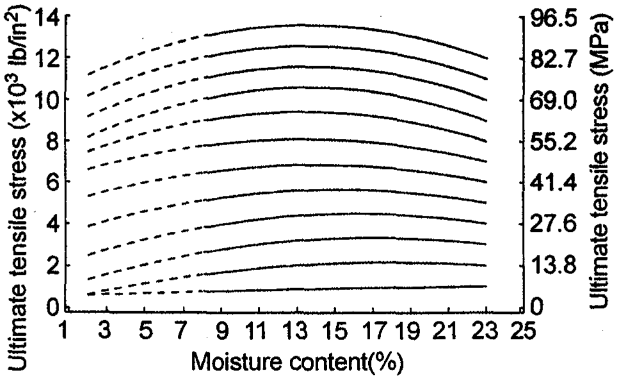

FIG. 3. Ultimate tensile stress parallel to grain for dimension lumber as influenced by moisture content (Green and Evans 1989).

to identify those clear wood properties that predominate in certain grade categories. For example, it was hypothesized that clear wood strength in tension perpendicular to grain and decreases in this strength caused by moisture changes would play a greater role in edge knot situations compared with its role in determining properties of relatively clear lumber.

Tensile strength of southern pine at low moisture content

To verify the loss in lumber UTS at low MC levels inferred from Fig. 3 and observed for clear wood in Fig. 2, we tested 52 southern pine 2 by 4s, 12 ft (3.7 m) long, at approximately 12% and 4% MC (Table 4). This data set was independent of the lumber specimens used in the finite element simulation. The lumber was a mixture of several machine-stress-rated (MSR) grades with grade-stamped MOE values between 1.6E and 2.0E that were available from FPL surplus. The lumber had been commercially kiln-dried to a maximum MC of 15% by conventional (that is, not high temperature) schedules. All the lumber was equilibrated to 12% MC at 73°F (23°C), and an MOE was determined by transverse vibration. Within a grade, the MOEs were ranked and adjacent pairs randomly assigned to be tested at 12% or 4% MC. The pieces to be tested at 4% were equilibrated at 85°F (32°C). An MOE was obtained for the lumber by transverse vibration after equilibration to 4%. The lumber was tested according to ASTM D198 using a clear span of 6 ft (1.8 m) (ASTM 1999).

RESULTS AND DISCUSSION

Before discussing the effect of clear wood properties on changes in UTS with varying MC, we must validate the changes in lumber UTS values predicted by the GASPP model. To do this, we have two pieces of information: the experimental results for southern pine MSR lumber at 12% and 4% MC, and the change in UTS with change in MC predicted by the QSM. The MSR data establish a lower reference point well below the minimum MC level used in deriving the QSM (Green and Evans 1989; Green et al. 1990). The QSM provides property trends for MC ranging from 10% to green for comparison with GASPP predictions. After verification of the general trends predicted by the GASPP model, the effects of lumber quality and clear wood properties that can be gleaned from the GASPP simulations are discussed.

Lumber tests

Table 4 summarizes the results of the tensile tests at target MCs of 4% and 12% for southern pine 2 by 4s. The values are based on the actual dimensions at time of test. The average MCs were approximately 4% and 11%. The average UTS value for this material decreased 9% in drying from 11% to 4%. This is a reduction similar to that found for Douglas-fir MSR in a companion study (Green and Evans 2002). Reductions tended to be larger for lower strength levels than they were at the mean. However, this lumber is a mix of three MSR grades, and therefore, these results do not necessarily translate directly to specific percentiles of a single grade.

The QSM shown in Fig. 3 (Green and Evans 1989; Evans et al. 1990) was also used to predict the change in UTS at 3.7% MC (Table 4). The QSM predicted a mean reduction of 13% and did a reasonable job of predicting change in UTS throughout most of the

TABLE 1. *Regression equations of clear wood properties as functions of moisture content (MC) and specific gravity (SG) (Kretschmann and Green 1996)*[a].

	Property = Int + a(MC) + b(MC)^2 + c(DN) + d(DN)^2 + e(MC)(DN)[b] (Property = Int + a(MC) + b(MC)^2 + c(SG) + d(SG)^2 + e(MC)(SG))[c]					
	Int	*a*	*b*	*c*	*d*	*e*
UTS parallel	– 16.16	17.354	– 0.422	– 0.158	0.000539	– 0.01129
	(–2.344)	(2.5184)	(–0.06127)	– 25.595	(98.009)	(– 1.833)
UTS perpendicular	– 4.785	0.462	– 0.0155	0.01663	– 0.00000583	– 0.000262
	(–0.694)	(0.067)	(– 0.00224)	(2.7011)	(– 1.0611)	(– 0.0425)
Shear parallel	3.0033	0.8299	– 0.02232	0.013746	0.0000242	– 0.001295
	(0.4356)	(0.12036)	(– 0.003238)	(2.2329)	(4.4097)	(– 0.2104)
K_{Ic} TL	284.8	21.20	– 0.918	– 0.395	0.00106	– 0.0113
	(259.2)	(19.30)	(–0.836)	(– 403.1)	(1,210.0)	(– 11.52)
K_{IIc} TL	870.9	110.5	– 4.494	– 1.290	0.00408	– 0.0251
	(792.6)	(100.6)	(– 4.081)	(– 1,315.1)	(4,662.3)	(– 25.60)
MOE tension parallel	9,164.9	499.0	– 8.723	– 25.256	0.064	– 0.9012
	(1,329.2)	(72.37)	(– 1.265)	(– 4,102.4)	(11.647)	(– 146.4)
MOE tension	–503.1	54.7	– 1.834	2.718	– 0.000287	– 0.0734
perpendicular	(–72.0)	(7.83)	(– 0.263)	(435.8)	(– 51.63)	(– 11.77)

[a] Int, intercept; UTS, ultimate tensile stress; K_I, mole I stress intensity factor; K_{II}, mode II stress intensity factor; TL, transverse longitudinal plane; MOE, modulus of elasticity.
[b] MC as a percentage; Dn, density in Kg/m^3 at 12% MC; *a, b. c, d, e,* modeled coefficients: units for K_I and K_{II} are kN·mr$^{-3/2}$; values remaining are in Mpa.
[c] MC as a percentage; SG based on oven-dry weight and volume at 12% MC; *a, b, c, d, e* are modeled coefficients; units for K_I and K_{II} are lb·in.$^{-3/2}$;values remaining are in X 103 lb/in.^{2}.

strength distribution. The data confirm previous hypotheses that UTS may decrease at very low MCs.

GASPP simulations

Predictions versus test data.—Simulated tensile strengths (UTS) for each of the 15 representative southern pine specimens, and averages for each group, are shown in Table 5. In all cases, the strength was defined as the peak load sustained by the simulated specimen. For the clear specimens, ultimate tensile stress was assumed to be at the formation of the first crack. For the specimens containing knots, the tensile strength was realized after the formation and propagation of multiple cracks, with the first predicted crack formation occurring as early as loads that were 25% of the specimen peak load. Moisture content changes, and the resulting changes in clear wood properties, caused some change in the predicted crack formation and propagation process for each specimen, but no clear trends for the fracture patterns were identified.

First, we compare the ratios of the UTS values at 12% and 4% MC obtained from the GASPP model with the ratios actually measured experimentally. With the GASPP model, the values for the ratio of 4% to 12% are 0.81 for large edge knots, 0.95 for small edge

TABLE 2. *Moisture content effects on Poisson's ratio*[a] *(Kretschmann and Green 1996).*

MC level (%)	Sample size	Mean		COV (%)	
		^{v}LT	^{v}LR	^{v}LT	^{v}LR
4	41	0.291	0.158	23.4	32.9
8	39	0.270	0.133	28.9	37.6
12	38	0.260	0.126	23.1	51.6
18	38	0.183	0.078	33.3	73.1
FSP[b]	40	0.162	0.038	32.1	94.7

[a] L, longitudinal. T, tangential, R, radial. The first letter indicates the axis perpendicular to the crack plane, and the second indicates the direction of crack propagation.
[b] FSP, fiber saturation point.

TABLE 3. *Simulation cases investigated.*

Type of specimen	Moisture content level				Number of simulations
	4%	8%	12%	23%	
Clear specimen			4444		16
Small edge knot	3	3	3	3	12
Large edge knot	4	4	4	4	16
Large center knot	4	4	4	4	16
Total					60

TABLE 4. *Experimental change in ultimate tensile stress of southern pine lumber when dried to 4% moisture content.*

Moisture content (%)	Sample size	Specific gravity[a]	Ultimate tensile stress (lb/in.^{2} (MPa)) Mean	COV (%)	5th	25th	50th	75th	95th
3.7	52	0.71	7,160 (49.4)	39.5	2,189 (15.1)	5,377 (37.1)	7,005 (48.3)	9,090 (62.7)	11,462 (79.0)
10.9	52	0.72	7,860 (54.2)	33.8	2,919 (20.1)	6,297 (43.4)	7,790 (53.7)	9,584 (66.1)	12,813 (88.3)
Ratio, 3.7/10.9									
Actual	—	—	0.91	—	0.75	0.85	0.90	0.95	0.90
Predicted[b]	—	—	0.87	—	0.58	0.83	0.87	0.85	0.87

[a] Specific gravity based on oven-dry weight and volume.
[b] Predicted by quadratic surface model (Green and Evans 1989).

knots, 0.96 for large centerline knots, and 0.71 for clear lumber (Table 5). Lumber with large edge knots exhibits a larger loss in UTS upon drying to 4% MC than does lumber with small edge knots or centerline knots. This trend is consistent with the MSR data where a greater loss is seen at the 5th percentile than at the median (Table 4). At the 50th percentile (median value), the experimental ratio is 0.90, and for the 25th and 75th percentiles, it ranges from 0.85 to 0.95, respectively (Table 4). Thus, the ratios predicted by GASPP for the lumber containing knots are similar to those measured in the middle portion of the UTS distribution. The 0.7 1 ratio predicted by GASPP for clear wood is much lower than the experimentally measured median values for MSR lumber. However, the trend predicted by GASPP that clear wood UTS values should be more sensitive to change in MC than are lumber UTS values is consistent with independent observations. For softwoods, the ratio of UTS at 12% MC to UTS for green clear wood averages 1.13 (Forest Products Laboratory

TABLE 5. *Ultimate stress for each sample at four moisture content (MC) conditions predicted by the GASPP model.*

Sample type	Sample	SG	Ultimate stress (lb/in.^{2} (MPa)) 4% MC	8% MC	12% MC	23% MC
Clear	1	0.49	12,560 (86.6)	14,860 (109.0)	15,810 (109.0)	11,150 (76.9)
	2	0.46	9,150 (63.1)	12,940 (89.2)	15,400 (106.2)	11,610 (80.0)
	3	0.50	10,820 (74.6)	14,150 (97.6)	15,780 (108.8)	11,190 (77.2)
	4	0.50	13,640 (94.0)	16,740 (115.4)	18,000 (124.1)	12,250 (84.5)
Average		0.49	11,540 (79.6)	14,670 (101.2)	16,250 (1 12.0)	1 1,550 (79.6)
Small edge knot	5	0.45	4,870 (33.6)	5,330 (36.8)	5,180 (35.7)	2,110 (14.5)
	6	0.50	6,150 (42.4)	6,300 (43.5)	5,900 (40.7)	2,130 (14.7)
	7	0.61	6,440 (44.4)	6,980 (48.1)	7,370 (50.8)	3,030 (20.9)
Average		0.52	5,820 (40.1)	6,200 (42.8)	6,150 (41.7)	2,420 (16.7)
Large edge knot	8	0.53	4,460 (30.8)	4,930 (34.0)	4,810 (33.2)	2,600 (1 8.0)
	9	0.51	3,200 (22.0)	3,720 (25.7)	3,730 (25.7)	1,750 (12.1)
	10	0.50	870 (6.0)	910 (6.3)	750 (5.1)	520 (3.6)
	11	0.60	5,000 (34.5)	7,530 (51.9)	7,340 (50.6)	120 (0.8)
Average		0.53	3,380 (23.3)	4,270 (29.5)	4,160 (28.7)	1,250 (86.)
Large center knot	12	0.58	2,300 (15.8)	2,690 (18.5)	2,180 (15.0)	1,310 (9.0)
	13	0.51	1,070 (7.4)	2,690 (1 8.6)	2,280 (15.7)	1,370 (9.4)
	14	0.59	4,620 (3 1.8)	4,470 (30.8)	4,530 (31.3)	2,160 (14.9)
	15	0.62	4,420 (30.5)	5,020 (34.6)	3,900 (26.9)	2,170 (14.9)
Average		0.58	3,100 (21.4)	3,720 (25.6)	3,220 (22.2)	1,750 (12.1)

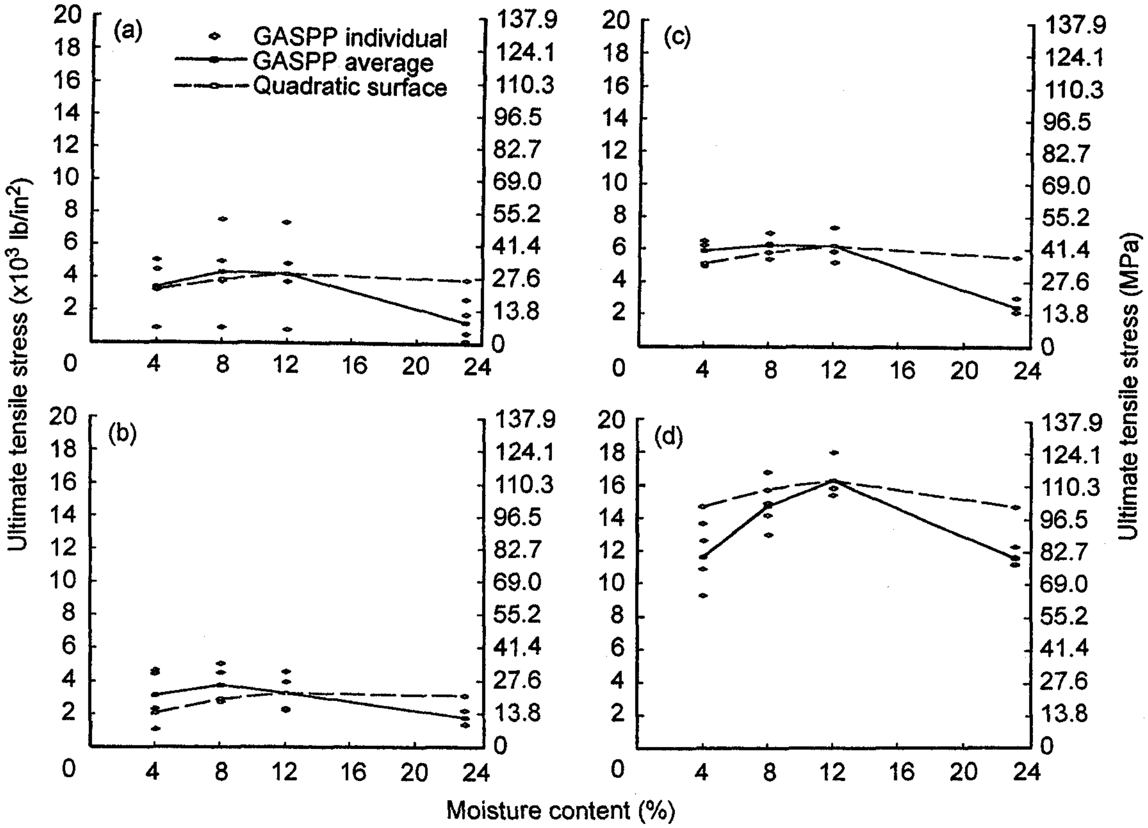

FIG. 4. Average effect of moisture content on the ultimate tensile stress of lumber predicted by the GASPP MC model compared with the trends expected from the lumber model of Green and Evans (1989). (a) lumber with large edge knots, (b) lumber with large centerline knots, (c) lumber with small edge knots, (d) clear lumber.

1999). For lumber, the 12% to green UTS ratio ranges from 1.00 to 1.10 for green UTS values from 2,000 lb/in.[2] (13.8 MPa) to 6,000 lb/in.[2] (41.4 MPa), respectively (Green and Evans 2001).

Predictions versus quadratic surface model.—Next, we compare trends predicted by the GASPP model at several MC levels to those predicted using the QSM (Green and Evans 1989; Evans et al. 1990). Figure 4 shows the GASPP-predicted change in UTS for each piece of lumber reported in Table 5 along with a trend line connecting the average of these values at each MC level. For a given knot type, there is considerable variability in the results of the individual simulations, reflecting the variability in the individual boards that formed the basis of the study. Unfortunately, time and funds did not permit inclusion of more boards. Therefore, statistically based trends cannot be derived from the research, but general behavioral trends can still be observed.

The QSM was also used to adjust the individual GASPP values in Table 5 at 12% MC to each of the other three MC levels. The average QSM value for each knot type and MC level is shown in Fig. 4. For large edge knots (Fig. 4a), the average trend predicted by the GASPP model closely follows the expected results from the QSM at 4% and 8% MC. The GASPP prediction was significantly lower than the QSM value for green lumber. The GASPP mean value is still reasonably close to that of dry lumber with small edge knots (Fig. 4b) and large centerline knots (Fig. 4c). Again, the GASPP prediction is much lower than that of the QSM values for green lumber. For clear lumber, the prediction is not particularly good for either green or dry lumber.

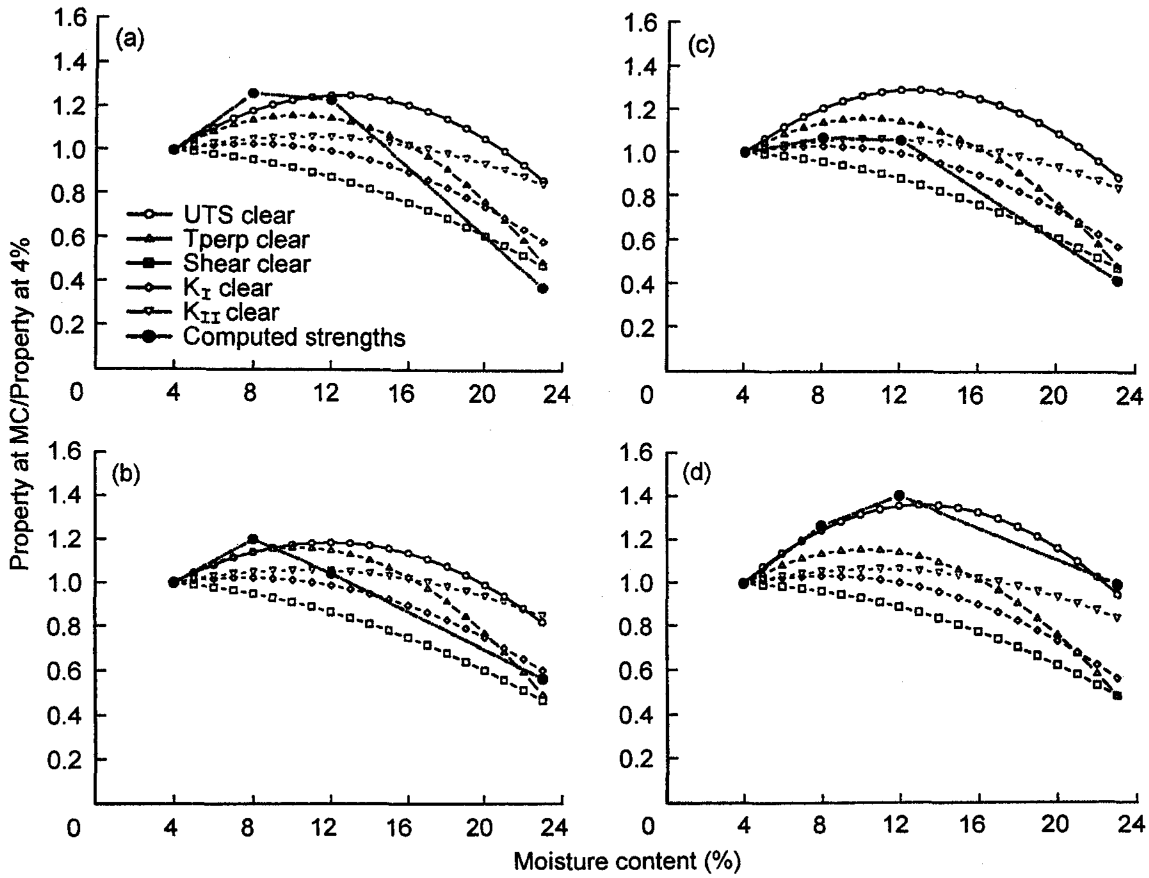

FIG. 5. Effect of moisture content on the ultimate tensile stress (UTS) of lumber predicted by the GASPP MC model compared with trends expected for selected clear wood properties. (a) lumber with large edge knots, (b) lumber with large centerline knots, (c) lumber with small edge knots, (d) clear lumber.

Given the brittle, elastic fracture mechanics basis of the GASPP model, it is not surprising that it best predicts trends in UTS for dry lumber containing knots. For green lumber, the inability of the GASPP model to predict the results suggests that the constitutive relationship and failure mechanisms of green lumber do not coincide with the linear elastic assumptions in GASPP. It appears that inelastic behavior in green lumber tends to reduce stress concentrations associated with lumber that contains knots. Likewise, inferences drawn on the effect of clear wood properties on lumber UTS values are likely to be more valid for the lumber with knots than for clear lumber. The number of GASPP analyses is small, however, and definitive conclusions on the quality of the fit with experimental data cannot be made. Furthermore, the tested and experimental specimen lengths were different. The GASPP analysis considered only the critical knot-containing region (approximately 16 in. (0.4 m)) of a representative lumber sample. Also, the UTS values for the clear lumber used in the GASPP simulation (Table 5) are above the upper end of most of the data used to generate the QSM (about 10,500 lb/in.^{2} (72.4 MPa)). Thus, the QSM may not accurately predict the behavior of lumber of this quality level.

Influence of clear wood properties.—Finally, we attempted to identify the primary clear wood properties that control lumber failure and how they are predicted to change as a function of MC. Figure 5 shows the average UTS values for lumber predicted by the GASPP model at each MC level relative to their value at 4% MC. Also shown is the predicted change for each of five clear wood strength properties, relative to their value at 4% MC (Kretschmann and Green 1996).

For large edge knots with MC between 4% and 12% (Fig. 5a), the relative change in the lumber UTS value simulated by the GASPP model most closely follows the change in clear wood stress for tension parallel to the grain up to 12% MC. Tension perpendicular to the grain is the second most influential clear wood property. For green lumber, the influence of tension perpendicular to the grain and shear seem to be the predominant factors. With large centerline knots (Fig. 5b), the change in predicted lumber UTS appears to most closely follow the change in clear wood UTS to 8% MC but is closer to the mode II stress intensity factor (K_{II}) change at 12%. For green lumber with a large centerline knot, the predicted value is closest to the changes in tension perpendicular, shear, and mode I stress intensity factor (K_I). For small edge knots in dry lumber (Fig. 5c), the predicted change in UTS of the lumber with change in MC most closely follows the clear wood change for mode II fracture, with shear stress a secondary influence. For green lumber with small edge knots, the GASPP prediction is again closest to the change for tension perpendicular and shear. Not surprisingly, the change in UTS of clear lumber most closely follows the change in clear wood UTS (Fig. 5d).

We propose through discussion of Fig. 5 that lumber tensile strength is a complex weakest-link fracture process influenced by several strength and fracture modes. Because moisture influences the relative values of these strength and fracture modes differently, it is not surprising that for different MCs, different strength and fracture modes will control board strength. The interaction of these strength values may also change with MC. We cannot claim the GASPP model is a perfect predictor, and we cannot prove with this research that lumber fracture works precisely as predicted by the model. Yet, the model has been verified with a limited number of observed dry lumber fracture patterns and measured strength values (Cramer and Fohrell 1989; Stahl et al. 1990). For dry lumber, it also predicts trends in UTS with change in MC similar to those predicted by the independently established QSM. The GASPP model provides possible explanations of the complex fracture process, and from these explanations, new practical strength theories can be contemplated.

It is perhaps not surprising that clear wood tension perpendicular and fracture stresses appear to be important for dry lumber containing knots. The influence of clear wood UTS at very low MCs was evident in all situations except for small edge knots. With green lumber, the model appears to be overly sensitive to the clear wood tension perpendicular values. This could explain why the model does not follow the trend in lumber strength predicted by the lumber data of Green et al. (1990) for green lumber.

Although clear lumber strengths followed the trends of clear wood UTS, the resulting computed lumber strengths were approximately 80% of the clear wood UTS value. This reduction was attributed to density and grain angle variations within the 16-in. (0.4-m) specimens, suggesting that at least a portion of size effect factors empirically established for lumber design is the result of small variations in density and grain angle.

CONCLUSIONS

Tension tests of southern pine lumber and detailed finite element modeling of knot-containing and clear lumber specimens were used to better define the strength–MC relationship and to discern possible fundamental mechanisms that shape the relationship. From the results of this research, we conclude

1. The tensile strength of southern pine lumber is about 9% lower at 4% MC than at 12% MC.
2. For MC of 12% and less, the finite element model was generally successful in predicting average changes in tensile strength of lumber containing knots. The model predicted mean trends from 12% to 4% MC that were in agreement with the experimen-

tal values and also predicted that the UTS of lumber with large edge knots should be more sensitive to changes in MC than lumber with small edge knots. For this dry lumber, local properties would be expected to behave in a linear elastic manner, consistent with assumptions in the GASPP model.

3. The model significantly underpredicted the properties of green lumber. Local properties of green lumber would be less likely to behave in a linear elastic manner.
4. Small clear properties change at different rates with change in MC, making it unclear which properties control lumber strength for different knots and MC. Ultimate clear wood tensile stress, as expected, controlled the strength of predominately clear lumber. Mode II fracture toughness, tensile strength parallel and perpendicular to the grain, and shear all played significant roles in knot-controlled tensile strength of dry lumber.

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