MODELING CHANGES IN STRENGTH AND STIFFNESS OF LOBLOLLY PINE WOOD

by

XIONGFEI WANG

(Under the direction of Richard F. Daniels and Christopher J. Cieszewski)

ABSTRACT

Many landowners manage their plantations using intensive treatments to accelerate tree growth rate. Forest industry and wood buyers realize that intensively grown pine produces large volumes of juvenile wood and, as a result, may reduce certain wood properties. In this study, two prediction models for bending strength, modulus of rupture (MOR), or bending stiffness, modulus of elasticity (MOE) were developed to describe how these two important mechanical properties of wood change in individual trees. MOR and MOE are modeled as a function of specific gravity, wood type, height, number of rings, the product of number of rings per inch and diameter at breast height, and physiographic region. The ability to predict these MOR and MOE will allow timber growers and buyers to compare the wood based value of these two properties among different forest management regimes.

INDEX WORDS: wood quality, strength, Modulus of Rupture, stiffness, Modulus of Elasticity, static bending, loblolly pine, prediction model, silviculture, regression.

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B.S., The Capital Normal University, P.R. China, 1995

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2003

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DEDICATION

To my mother, Yumin Wang, who took care of me and saved time for me to study. To my husband, Jianping Zhu, and my daughter, Xueqi Zhu, who encouraged me.

ACKNOWLEDGMENTS

I thank Dr. Richard F. Daniels, my major professors, who took his time to help me in the preparation of this thesis and reviewed my manuscript. I am grateful to Dr. Christopher J. Cieszewski, Dr. Barry D. Shiver and Dr. William P McCormick, for their helpful suggestions. I would like to thank my friends who give me good ideas and explanations, including Dehai Zhao, Mike Harrison, Chengcai Ni, Shangbin Liu, Lewis Jordan. I also thank to the UGA Wood Quality Consortium for providing data and the Traditional Industry Program 3 for providing financial assistance.

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CHAPTER 1

INTRODUCTION

Loblolly pine (*Pinus taeda L.*) is considered the most important species in the South for fiber and solid wood products. Many landowners manage their plantations with intensive treatments to accelerate growth rates and to increase timber volumes. These intensive treatments, including combinations of competition control, genetic improvement, thinning, pruning, and fertilizations, are leading to dramatic increases in overall wood quantities (Daniels and Clark 2002). However, lumber producers and users are noticeably avoiding the use of timber from intensively managed loblolly pine plantations (Carino *et al.* 2002). Intensively managed loblolly pines grow rapidly and achieve excellent size at a young age. Wood from these trees contains a high proportion of juvenile wood, known to be weaker and less stiff than mature wood. Buyers' preferences, therefore, lead the timber markets to seek older loblolly pine. "There is no doubt that older stands of loblolly pine plantation timber yield higher expected income for the owners" (Carino *et al.* 2002). Quantifying the wood quality for plantations, including old plantations and intensively managed plantations, will provide a useful tool for landowners, wood buyers and forest industries.

The Wood Quality Consortium (WQC) at the University of Georgia is a research partnership of industry members and institutional research partners. Its objective is to research subjects of wood quality in southern pine plantations. Much of the expected output from the WQC will be in the form of predictive models. Those models will help growers and wood users to factor wood quality into inventory and procurement systems, growth and yield predictions, and forest management decision tools (WQC annual report 2001). Models will be developed to predict wood quality within the tree, from stump to tip and from pith to bark.

In structural applications, mechanical properties are usually the most essential characteristics of wood products (Haygreen 1996). Bending strength, represented by modulus of rupture (MOR) and bending stiffness, represented by modulus of elasticity (MOE) are two substantial mechanical properties. MOR measures the load a beam will carry before rupture and MOE corresponds to how much a beam will bend under load (Haygreen 1996).

Intensively managed trees grow faster than do those in unmanaged plantations. They reach merchantability at a younger age with more juvenile wood (Daniels and Clark 2000). Stiffness and strength of structural lumber containing juvenile wood is significantly lower than that of lumber from mature wood and may not meet design specifications (Daniels and Clark 2000). Strength and stiffness of dimension lumber cut from juvenile wood is only fifty to seventy percent of that cut from mature wood (Kretschmann 1998). Quantifying the effects of environmental conditions and silviculture treatments on these two properties of wood will provide the forest products industry with a powerful tool for managing plantations.

This study addresses MOR and MOE of loblolly pine wood from plantations without any intensive management. This will be considered a baseline. Trees were chosen from five different physiographic regions. Juvenile specimens and mature specimens were sawn from three different height levels of the trees. Individual tree models are presented to describe how MOR and MOE change within an individual tree by height level for juvenile and mature wood, considering the effects of stand variables, tree variables, and sample variables on wood strength and stiffness. These models provide quantitative tools for predicting MOR or MOE using several variables, such as specific gravity (SG), diameter at breast height (DBH), height (HT), and number of rings in each specimen (NR). In these models, physiographic factors and wood type are used as indicator variables.

With such models, wood strength and stiffness can be added into current forestry yield prediction systems, aiding the landowner to consider wood quality for managing his/her plantations. Later, when data from intensively managed plantations are available, these baseline models can be tested and modified to provide the basis for comparisons of wood properties under various silviculture management regimes.

Project Objectives:

To develop models to predict wood strength (MOR) and stiffness (MOE) within loblolly pine trees in the southern United States, given tree size, stand history and other properties.

Specific objectives were to analyze Wood Quality Consortium baseline data and build models to describe and model the changes in MOR values and MOE values within a tree. The following variables were considered:

1. Physiographic region;
2. Stand variables, such as stand age, stand density, and site index;
3. Tree size, such as total height and diameter at breast height;
4. Specimen properties, such as specific gravity, number of rings, and height of the wood sample.

Models were built using the SAS software for statistical analysis (SAS/STAT User's Guide version 8).

CHAPTER 2

LITERATURE REVIEW

2.1 General Background:

Loblolly pine is the most commercially important species of timber in the southern United States. It is an ideal species for site restoration and forest management, largely because of its hardiness and ability to reproduce and grow rapidly on diverse sites. The wood of loblolly pine is generally straight-grained and has medium texture. Compared with other pines relatively, it is dense, strong, stiff, and hard. Typical physical and mechanical properties of loblolly pine are described in the Wood Handbook (Table 2.1).

Table 2.1. Average clear wood properties of loblolly pine trees.

Moisture Content	Specific gravity	Modulus of rupture (psi)	Modulus of elasticity (10^6 psi)
Green	.47	7300	1.40
12%	.51	12800	1.79

(Adapted from wood Handbook, 1974 Table 4-2)

Mechanical (strength) properties are important wood properties for solid product applications. They have far-ranging impacts on the use of wood in many applications. Mechanical properties, including strength and elastic properties, determine wood engineering and design applications (Haygreen

1996). Bending strength (MOR), compression strength parallel to the grain, compression perpendicular to the grain, etc. are strength properties, while modulus of elasticity (MOE) and modulus of elasticity parallel to the grain (Young's modulus), etc. are elastic properties (Haygreen 1996). This study focuses on bending strength (MOR) and stiffness (MOE).

MOR is a measure of the maximum bending strength of a specimen when loaded as a beam (Haygreen 1996). Modulus of elasticity represents resistance of a specimen under load to deflection (Haygreen 1996). Elasticity allows a beam to resist a load changing its shape and to resume its original shape when the load is removed (Brown 1952). In some instances, a beam may not be in danger of failing when loaded but could deflect markedly without failing; hence, deflection is an important design aspect (Haygreen 1996). The following review identifies some factors affecting MOR and MOE.

2.2 Specific Gravity (SG):

The specific gravity of wood is a comparison of its density to that of water at $4\,^{\circ}C$ (Haygreen 1996). Since 1880, specific gravity was the main research subject of wood quality evaluation. The early years of research on specific gravity also revealed some characterizations of wood strength and stiffness. It is known that both wood strength and stiffness increase with increasing specific gravity (Haygreen *et al.* 1996). Pearson *et al.* (1971) found MOR or MOE were highly correlated with specific gravity with correlation coefficients of 0.93 and

0.89 respectively. They also found neither height in tree nor wood type has effect for these results.

Microfibril angle was found to be more highly correlated with MOE than for specific gravity at the 1 m height level on trees, with the reverse trend is true at the 5 m height level (Megraw *et al.* 1999).

2.3 Wood Type: Juvenile Wood And Mature Wood

In trees, the wood near the pith is called juvenile wood. During the first years of growth, a tree produces juvenile wood. It will take several years for an individual tree to transition from juvenile wood to mature wood. Therefore, there is no definite line of demarcation between juvenile wood and mature wood. It is widely believed that juvenile wood, compared with mature wood, has lower quality wood properties (Larson *et al.* 2001). Juvenile wood in most species has a noticeably lower modulus of elasticity and modulus of rupture than mature wood (Bao *et al.* 1999). Bao *et al.* (1999) compared wood anatomical properties, chemical properties, physical properties, and mechanical properties for juvenile and mature wood in both plantation-grown trees and naturally grown trees. For loblolly pine, their results are that (1) there is limited difference on chemical properties between juvenile wood and mature wood; (2) juvenile and mature wood have considerably different anatomical properties, such as cell wall and microfibril angle, different physical properties, and different mechanical properties, such as MOR and MOE.

Both wood strength and wood stiffness increase from juvenile wood to mature wood, but they increase at different rates. Bendtsen and Senft (1984) studied mechanical and anatomical properties of loblolly pine specimens from the 6-foot butt log. They did bending tests and obtained MOR and MOE values for every annual ring specimen. The average MOE values of mature wood were about a fivefold increase over that of juvenile wood and average MOR values of mature wood were about threefold increase to that of juvenile wood. The increase in specific gravity from juvenile wood to mature wood was 40%.

2.4 Rotation Age:

Modulus of rupture and modulus of elasticity generally increase with increasing age. Pearson and Ross (1984) studied trees from 15, 25, and 41 years old plantations and found that for a given distance from the pith, the bending properties were, on average, higher in older trees than in younger trees. Considering the differences between juvenile wood and mature wood, it is evident that the longer the rotation age, the lower the juvenile wood proportion, and the stronger the mechanical properties of the wood (Bao *et al.* 1999). McAlister *et al.* (1996) studied unthinned loblolly pine stands in the Coastal Plain of Georgia. Six stands were sampled with rotation ages of 22, 28, and 40. They found: 1) the samples with the highest MOE values were from the 40-year rotation ages. Modulus of elasticity significantly increased with the increasing age. 2) Modulus of rupture increased with the increasing rotation age but not significantly at the 0.05 probability level. 3) Specific gravity also appeared to increase slightly with rotation age, but not significantly (McAlister *et al.* 1996).

2.5 Geographic Location:

Usually, wood from the Atlantic Coastal Plain and Gulf Coastal Plain have the higher specific gravity than wood grown futher inland (McAlister and Clark 1990). Due to the high correlation of modulus of rupture or modulus of elasticity to specific gravity, the regionwhere the wood is grown should have some effects on mechanical properties. McAlister and Clark (1990) studied the effect of geographic location on mechanical properties of juvenile wood and mature wood. Samples were from three locations: Dooly County, GA., Atlantic Coastal Plain with deep sandy loam soil; Spalding County, GA., Piedmont with heavy red clay soil; Clark County, AR., Upper Coastal Plain. They concluded that geographic location was a significant factor in the bending properties of both juvenile and mature wood of loblolly pine. The Atlantic Coastal plain (Dooly County, GA.) had the highest MOR and MOE.

Although the recent relative studies showed that geographic factor is significant on wood strength and stiffness, there are not any models that can give quantitative predictions of MOR values or MOE values based on different physiographic region.

2.6 Height (HT):

Only a few studies focused on effects of height. A study by Pearson *et al.* in 1971 indicated that the butt log (3 feet from ground) wood had considerably lower values of MOR and MOE, compared to materials of the same SG from higher part of the trees. Later, Megraw *et al.* (1999) designed a study to determine the relationship of modulus of elasticity to microfibril angle and specific gravity. In that study, bending tests were done and MOE was measured on specimens with only one ring from six height levels and six ring positions. They found that MOE in loblolly pine is a function of cambial age and vertical location in the tree. For example, for the inner 10 rings from pith MOE values increase with height up to 3 m (about 9.8 feet) above stump and stiffness is lowest at the base of the stump. They focused on the height under 5 m (about 16.4 feet). Static bending properties on upper height levels do not appear to have been studied previously.

2.7 MOR-MOE Relationship:

Wood strength and stiffness are closely correlated. Walters *et al.* (1976) analyzed MOR values and MOE values for 1200 small clear specimens of red oak and cottonwood in 1976. They found that curvilinear models for predicting MOR and MOE are only slightly better than a linear model. Due to the simplicity, they chose linear model. Pearson *et al.* (1971) studied the strength and stiffness of wood specimens from loblolly pine. Test materials with dimensions 1.25 by 1.25 by 17 inches were from Piedmont and Coastal Plain of North Carolina. They did regressions for MOR and MOE of juvenile and mature wood specimens, including those from butt logs, and found that the correlation coefficient is low. They also did regressions for MOR and MOE of all specimens except those from butt logs and found that MOR and MOE are highly correlated ($|r|$ = 0.8 to 0.9) for both juvenile wood and mature wood (Pearson *et al.* 1971). Wood mechanical properties for limbwood are much different from normal wood. McAlister *et al.* (1999) even found that there is a near perfect correlation between strength and stiffness of the limbwood of loblolly pine. In contrast, some researches concluded that predicting MOR by logarithmic MOE is better for some species or for some specific geographic origin wood (Verkasalo *et al.* 2002).

2.8 Summary:

1. Modulus of rupture is highly affected by specific gravity.
2. Modulus of elasticity is strongly correlated to specific gravity and microfibril angle. In addition, modulus of elasticity is a function of cambial age and height.
3. Wood type, height and region have effects on wood mechanical properties.
4. Modulus of rupture and modulus of elasticity are highly correlated positively and linearly to each other.
5. Most studies on wood mechanical properties focused on identifying the effects of one or more specific potential factors, such as physiographic factors, wood type, number of rings, age, diameter of breast height (DBH), or height. Few of the studies incorporate those factors as a quantitative element in a prediction model for MOE or MOR.

CHAPTER 3

METHODS

3.1 Data:

Data were collected by University of Georgia and U.S.D.A. Forest Service crews from 1999 to 2002. Data collection included two parts: field sampling procedures and laboratory procedures.

3.1.1 Field sampling procedures:

Samples were collected from 291 loblolly pine trees with the same history in five physiographic regions, covering nine states in the southern United States (Table 3.1 and Figure 3.1). On these sites, there was no fertilization at planting except for P on P-deficient sites. Initial planting density was from 500 to 900 trees per acre (TPA). There was no competition control, no wildfire history, no pruning, up to one thinning with residual density of at least 250 trees per acre. Stands age ranged from 20 to 31.

In each stand, only trees with 5-inches diameter at breast height or larger were sampled. They were dominant or co-dominant trees and single stem trees. Three trees in each stand were felled. Measurements of felled trees were recorded, including total tree height, diameter at breast height (DBH) (Table 3.2).

Table 3.1 Base line study sites

Region	Stands
Atlantic Coastal Plain	35
Gulf Coastal Plain	11
Hilly Coastal Plain	15
Upper Coastal Plain	12
Piedmont	24

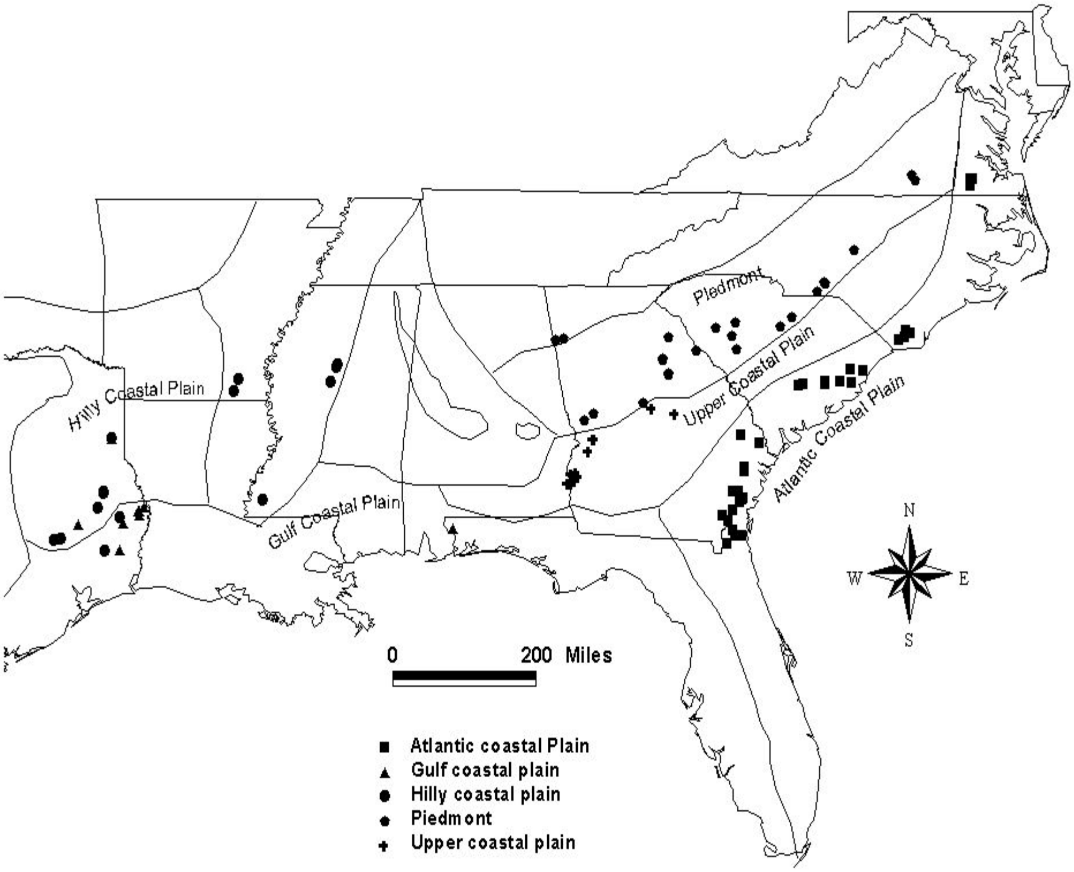


Figure 3.1 Map of baseline study sites for MOR and MOE sampling

Table 3.2Average tree characteristics

Region	Tree Sampled (No.)	DBH (in)	Total Height (ft)	Tree Age (years)
Atlantic Coastal Plain	105	10	70	23
		(6-14)	(40-84)	(20-25)
Gulf Coastal Plain	33	10	64	23
		(6-14)	(42-81)	(20-25)
Hilly Coastal Plain	45	10	60	23
		(6-14)	(44-76)	(20-26)
Upper Coastal Plain	36	9	66	24
		(6-12)	(41-77)	(10-29)
Piedmont	72	9	66	24
		(6-12)	(37-99)	(20-31)

3.1.2 Laboratory procedures*:*

Figure 3.2 demonstrates the procedure of obtaining specimens from felled trees. Two-foot long logs were cut from heights of 8 feet, 24 feet, and 40 feet from felled trees (Some trees were not tall enough for the 40 ft sample). Up to four clear and straight specimens for static bending were obtained from a board, which was sawn through the center of the log. The board was marked with side A and side B. Juvenile wood specimens were sawn with 1-inch width from first ring from the pith of trees. Mature wood specimens were sawn with 1-inch width from one inch from the bark. A total of 1144 specimens were obtained and tested.

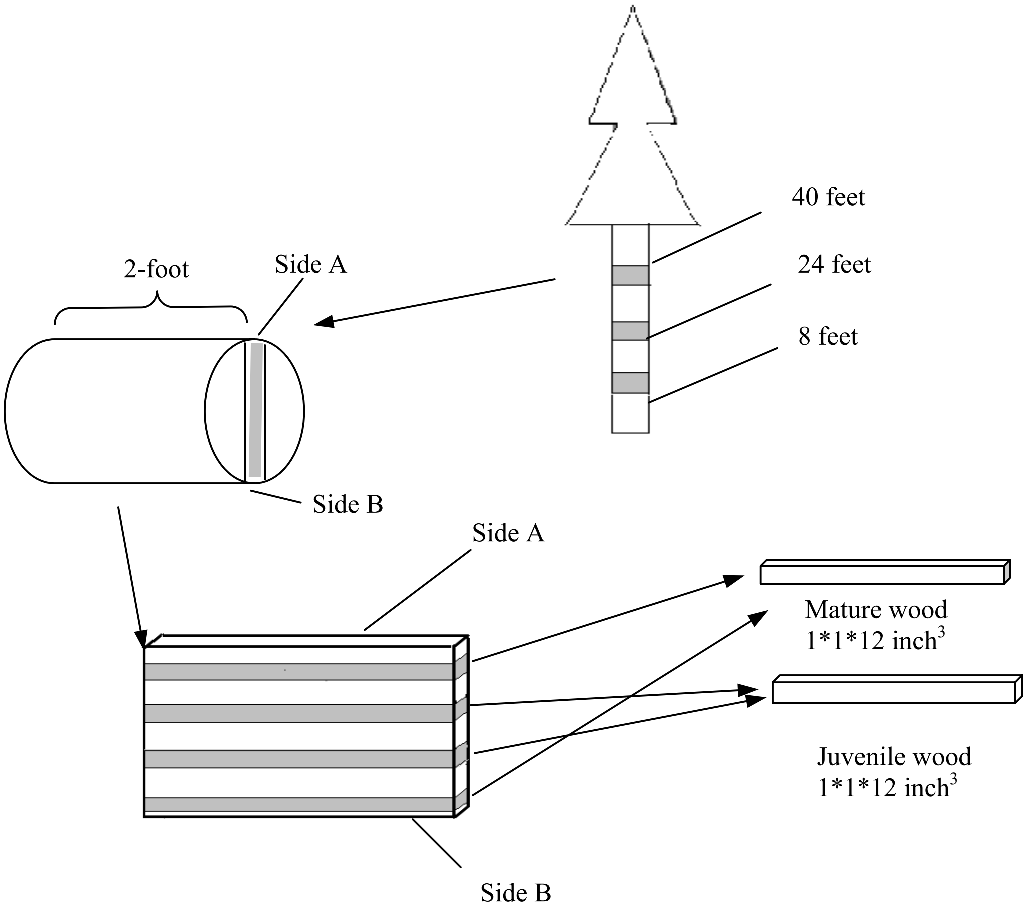


Figure 3.2 Schematic for obtaining clear wood specimens from felled trees

Specimens were 16 in long, 1 in wide, and 1 in deep. In the laboratory, bending tests were conducted on a Tinius-Olsen five-thousand pound load frame. Static bending tests were conducted using a center-point load on 14 in span by using the standard ASTM D 143 bending test, which is the standard designated procedure for testing clear wood specified by the American Society for Testing and Materials. When a specimen was tested to failure, its ultimate strength *P*, *i.e.*, its modulus of rupture, was obtained. At the same time, work to maximum load and information from the load form were sent into a computer database and edited by software in this computer. MOR and MOE of a specimen were obtained and saved.

The bending strength was calculated by the formula (Haygreen 1996):

$$MOR = 1.5PL/bd^2\,(psi)$$

Where,

P = the maximum load in pounds

L = the test span (14 in)

b = the width of the sample (1 in)

d = the depth of the sample (1 in)

The bending stiffness was calculated from the following equation (Haygreen 1996):

$$MOE = PL^3/48ID(psi)$$

Where

P = the concentrated center load in pounds

D = the deflection at midspan in inches resulting from P (Deflection is the amount of bending at the midpoint of the beam under a certain load.)

L = the span (14 in)

I = (width* depth^3)/12, (in this case, 1/12 in^4)

This equation is valid only for center-point load test (Haygreen 1996).

3.2 Modeling Procedures:

- The whole set of data was imported into the Statistical Analysis System (SAS) database.
- Q-Q plots were used for checking the normality assumption for the variables. Straightness of the outcome demonstrated that variables were normally distributed. The Shapiro-Wilk tests were also used to examine the normality of variables.
- A lot of information could be found in scatter plots. Scatter plots of each pair of variables were prepared with a specific categorical variable. Outliers were deleted. Pattern displayed the relationship between pairs of variables. A straight line implies a linear relationship, while a cured line implies a nonlinear relationship, or the need for transformations. Depending on the pattern, several potential equations were chosen. From scatter plots by categorical variables, patterns revealed the effects of this categorical variable on MOE and MOR.
- Hypothesis tests (F-tests) were used to give further evidence of results observed from plots. Effects of some categorical variables, which were difficult to observe from scatter plots, were found with F-tests. Alpha was defined as 0.05. When a categorical variable with significant effects was found, indicator variables were used to distinguish each level of that variable in models.

- PROC CORR in SAS is a procedure for examining the simple linear relationship of variables by calculating the correlation coefficients ($|r|<1$) and examining if that relationship is significant by checking p-value.
- Procedure "PROC MODEL" in SAS was used to estimate regression model parameters.
- To evaluate and compare models some fit statistics were considered.
    1. R^2 (Fit index for nonlinear models)

       R^2 = Fit Index = $1-\sum\left(Y_i-\hat{Y}_i\right)^2 \Big/ \sum\left(Y_i-\overline{Y}_i\right)^2$

       For models with the same number of parameters, larger fit index values indicate models that explain a greater proportion of the variability.
    2. Mean square error (MSE)

       $\mathrm{MSE}=\mathrm{SSE}/(\mathrm{n}-\mathrm{p})=\sum\left(Y_i-\hat{Y}_i\right)^2 \Big/ (n-p)$ Where SSE is sum of squares of error, n is sample size and p is number of parameters estimated. For models with same numbers of parameters, smaller MSE values indicate a better fitting model.
    3. Plots of predicted MOR values (or MOE values) versus observed MOR values (or MOE values). With small residuals between predicted value and observed value, plots should be straight lines through origin with slope one. Patterns with narrower range around that line indicate a better model.

4. Residual plot

Assumptions for regression models are that residuals are identical, independent, and homogeneous; and their mean is zero. The expected residual plots for a good regression model are the residuals should fall within a horizontal band centered on zero, displaying no systematic tendencies to be positive or negative.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

4.1.1 Continuous Variables

Based on the literature review and these investigations, there are three continuous variables that are good predictors of static bending properties. They are specific gravity, number of rings in the sample specimen, and DBH, along with various transformations of these variables.

4.1.2 Categorical variables

- Side: side A and side B

  In the laboratory, if a board sawn from each log is clear and straight, we could get up to two juvenile wood specimens or two mature wood specimens. These two specimens had a same source except that one was from side A and the other was from side B of the board. The Tukey T-test results showed that side (A or B) have no significant effects on modulus of rupture, modulus of elasticity, number of rings, or specific gravity. Means of side A and B (for modulus of rupture, modulus of elasticity, number of rings, or specific gravity) were obtained and used in subsequent analyses.

- Wood Type: Mature wood and Juvenile wood

The mean values of mechanical properties and specific gravity for juvenile wood specimens are significantly different than the mean values of properties for mature wood (Table 4.1.1). Sample sizes for wood types were unequal. Least square means (LSMEAN) was used here because of the unbalanced experiment design.

Table 4.1.1 Bending property values are higher for mature wood than for juvenile wood.

WOODTYPE	MOR LSMEAN	MOE LSMEAN	SG LSMEAN
Juvenile	8202.6744	813268.53	0.40020629
Mature	13196.7388	1487914.65	0.54424679

Both MOR and MOE values of mature wood specimens are considerably higher than those of juvenile wood specimens (Figure 4.1.1).

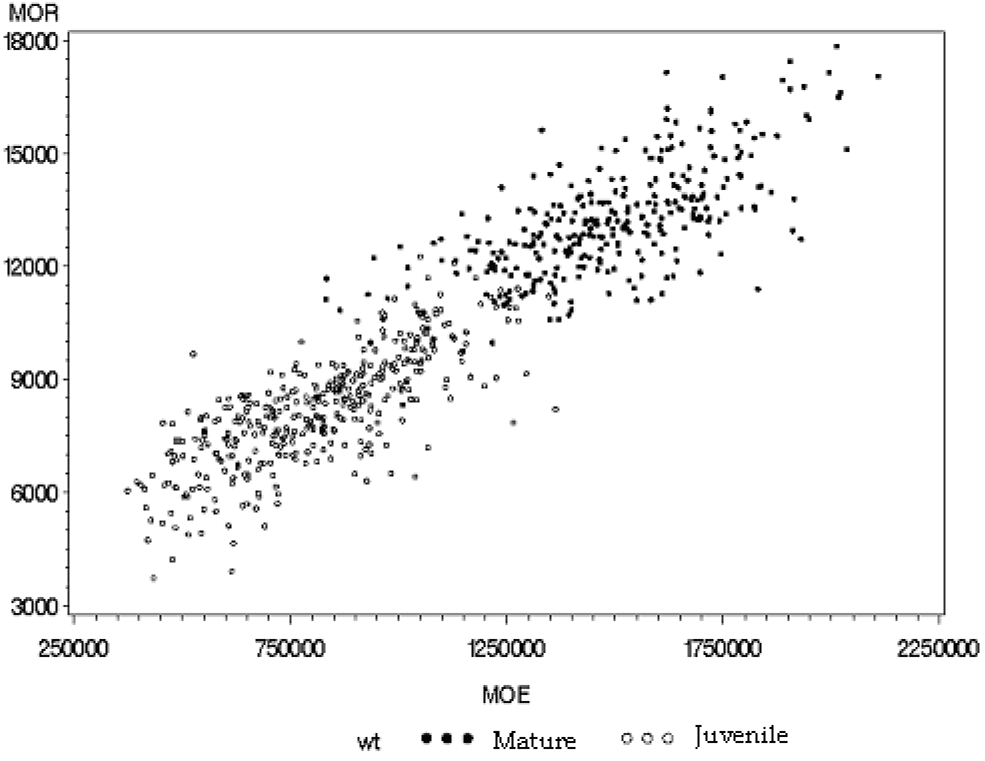


Figure 4.1.1 Scatter plot of MOR versus MOE: Mature wood has higher MOR or MOE than Juvenile wood

Juvenile wood is formed during the first few years, while mature wood is formed later, generally after 8-12 years of growth. Juvenile wood has wide rings and a narrow proportion of late wood. That leads to a relatively low specific gravity. Mature wood has narrower rings, high proportion of late wood, and a relatively high specific gravity. It is believed that both MOR and MOE are a function of specific gravity. Therefore, mature wood tends to have larger MOR or MOE values due to its higher density.

- Height level and the interaction of height level with wood type:

Usually, logs are cut into lengths of 16 feet. 8 feet, 24 feet, and 40 feet height are median points of first three logs in a tree, respectively. We want to know if logs from different heights of the same tree have different static bending properties and if there are any interaction of height and wood type. To determine if these effects exist, F-tests were conducted for MOR, MOE, and SG. In Table 4.1.2, results of tests are listed. In Table 4.1.3, pair wise interaction effects comparison results are listed.

For MOR, if the wood type and the interaction of wood type with height are in the model, then the effect of height is not significant (Table 4.1.2A). Table 4.1.3A shows that MOR values from juvenile wood specimens are affected by height level. Materials from 8 feet have significantly lower MOR values than those from higher height levels. In contrast, Table 4.1.3A shows that wood strength of mature wood decreases when height increase, but this difference is not significant.

For modulus of elasticity, height, wood type, and the interaction have significantly effects on MOE values (Table 4.1.2B). In Table 4.1.3B, it is evident that only juvenile wood is significantly affected by height and that specimens from 8 feet have notably lower MOE values than those from higher height. For mature wood, MOE has the highest values at 24 feet and difference among three height levels is not significant.

Specific gravity shows the same results as modulus of elasticity (Table 4.1.2C). Height, wood type, and the interaction all significantly affect SG. Nevertheless, Table 4.1.3C makes obvious that no matter which wood type, juvenile wood or mature wood, materials from 8 feet have significantly larger specific gravity than those from 24 feet or 40 feet.

Table 4.1.2 Results of F tests for effects of wood type, height, and their interaction.

A: MOR

Source	DF	Type III SS	Mean Square	F Value	Pr > F
WOODTYPE	1	2259713283	2259713283	1088.82	<.0001
HEIGHT	2	6389113	3194557	1.54	0.2153
HEIGHT(WOODTYPE)	2	115733135	57866568	27.88	<.0001

B: MOE

Source	DF	Type III SS	Mean Square	F Value	Pr > F
WOODTYPE	1	4.490742E13	4.490742E13	1063.89	<.0001
HEIGHT	2	1.8341607E12	917080344919	21.73	<.0001
HEIGHT(WOODTYPE)	2	1.8160656E12	908032782246	21.51	<.0001

C: SG

Source	DF	Type III SS	Mean Square	F Value	Pr > F
WOODTYPE	1	1.80568255	1.80568255	1291.65	<.0001
HEIGHT	2	0.14987327	0.07493663	53.60	<.0001
HEIGHT (WOODTYPE)	2	0.03683632	0.01841816	13.17	<.0001

Table 4.1.3 Least Squares Means of MOR, MOE, and SG at each height level by wood type for multiple comparison (Tukey-Kramer Tests: **Pr > |t| for H0: LSMean(i)=LSMean(j)** *).*

Height	WoodType	MOR LSmean	MOE LSmean	SG LSmean	LSmean Number
8	J	7645.9321	696887.56	0.40893569	1
24	J	8597.2807	906464.29	0.39326190	2
40	J	8851.2879	923581.23	0.39311472	3
8	M	13335.5380	1483836.99	0.55859793	4
24	M	12852.7534	1492459.47	0.51439726	5
40	M	12525.5192	1478613.02	0.50882692	6

A: MOR

i/j	1	2	3	4	5	6
1		<.0001	<.0001	<.0001	<.0001	<.0001
2	<.0001		0.8105	<.0001	<.0001	<.0001
3	<.0001	0.8105		<.0001	<.0001	<.0001
4	<.0001	<.0001	<.0001		0.0613	0.0431
5	<.0001	<.0001	<.0001	0.0613		0.9197
6	<.0001	<.0001	<.0001	0.0431	0.9197	

B: MOE

i/j	1	2	3	4	5	6
1		<.0001	<.0001	<.0001	<.0001	<.0001
2	<.0001		0.9926	<.0001	<.0001	<.0001
3	<.0001	0.9926		<.0001	<.0001	<.0001
4	<.0001	<.0001	<.0001		1.0000	0.9999
5	<.0001	<.0001	<.0001	1.0000		0.9997
6	<.0001	<.0001	<.0001	0.9999	0.9997	

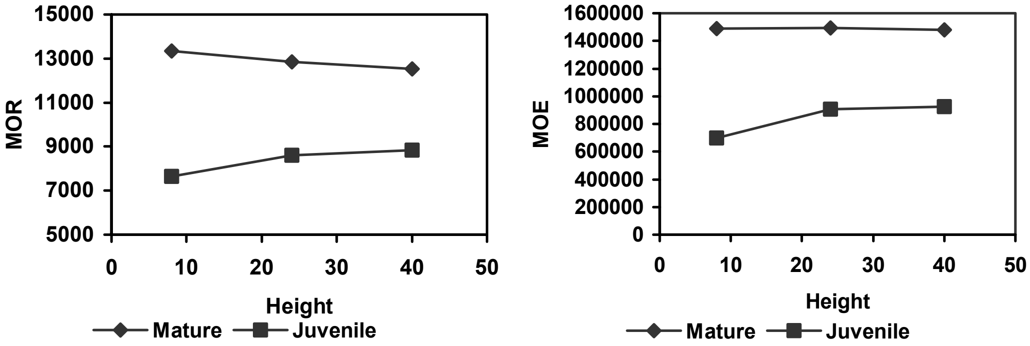
C: SG

i/j	1	2	3	4	5	6
1		0.0040	0.0301	<.0001	<.0001	<.0001
2	0.0040		1.0000	<.0001	<.0001	<.0001
3	0.0301	1.0000		<.0001	<.0001	<.0001
4	<.0001	<.0001	<.0001		<.0001	<.0001
5	<.0001	<.0001	<.0001	<.0001		0.9868
6	<.0001	<.0001	<.0001	<.0001	0.9868	

Juvenile wood bending properties from the 8-foot height are lower than those from 24-foot and 40-foot height (Figure 4.1.2). Mechanical properties from the three height levels are similar for mature wood.

Height has a notably different effect on mechanical properties than it does on specific gravity, indicating that mechanical properties depend on more than specific gravity, but other anatomical factors as well. For modulus of rupture, it seems that the height level effect is more favorable in juvenile wood. For modulus of elasticity, height has effects on each wood type.

Consequently, logs from the bottom of trees containing a high proportion of juvenile wood have the lowest modulus of rupture and modulus of elasticity values. The first logs may have less value than other for certain products due to the poorer mechanical properties.



A **B**

Figure 4.1.2 MOR (A) or MOE (B) versus height by wood type

Indicator variables were used in models to represent the effects of the interaction of wood type and height level (Table 4.1.3).

Table 4.1.4 Indicator variables of the interaction of wood type and height.

Wood Type	Height Level	Indicator variables
Mature	8-foot-height	mh8 = 1, other wise mh8 = 0
Wood	24, 40-foot-height	mh4 = 1, other wise mh4 = 0
Juvenile	8-foot-height	mh8 = mh4 = jh4 = 0
Wood	24, 40-foot-height	jh4 = 1, other wise jh4 = 0

- Physiographic factors:

Selected trees were from five physiographic regions (Atlantic Lower Coastal Plain, Atlantic Upper Coastal Plain, Piedmont, Gulf Coastal Plain and Hilly Gulf Coastal Plain). F-tests demonstrated that MOR means of are not all equal by region. Similarly, region had significant effects on MOE and SG. In Table 4.1.4, mean values show that wood from Atlantic Coastal Plain, Gulf Coastal Plain, and Hilly Coastal Plain have higher MOR value and higher MOE values than the Upper Coastal Plain and Piedmont. Wood from the Atlantic Coastal Plain and Gulf Coastal Plain have higher specific gravity than wood from the other regions.

Indicator variables of regions in models are listed in Table 4.1.5. The Atlantic Coastal Plain was used as the base line.

Table 4.1.5 Least Squares Means of MOR and MOE in each region

REGION	MOR LSMEAN	MOE LSMEAN	SG LSMEAN
Atlantic Coastal Plain	10677.2473	1143758.86	0.47623132
Upper Coastal Plain	9850.1073	1041192.71	0.44783067
Piedmont	9852.8410	1009422.76	0.45390857
Gulf Coastal Plain	11362.3485	1292103.45	0.48175000
Hilly Coastal Plain	10523.2606	1149922.95	0.45390957

Table 4.1.6 Indicator variables of physiographic factors.

REGION	INDICATOR VARIABLES
Atlantic Coastal Plain	rg2 = rg3 = rg4 = rg5 =0
Upper Coastal Plain	rg2 = 1, other wise rg2 = 0
Piedmont	rg3 = 1, other wise rg3 = 0
Gulf Coastal Plain	rg4 = 1, other wise rg4 = 0
Hilly Coastal Pain	rg5 = 1, other wise rg5 = 0

<u>4.2 Modeling for Relationship between MOR and MOE</u>

Modulus of rupture and modulus of elasticity are linearly related with high correlation coefficient ($|r|=0.9225$). Scatter plots of MOR against MOE (Figure 4.1.1) and the high correlation coefficient show a linear equation may describe well the relationship of them. Other multiple linear models and nonlinear models were tried, but did not provide a better result. Candidate models after adding height are shown in Table 4.2.1:

Table 4.2.1 Candidate models for MOR = f (MOE, HT)

Models	Equation Number	MSE	R-Square
$MOR = \theta_1 + (\theta_2 + \theta_3 * h4) * MOE + \varepsilon$	(1)	1178234	0.8607
$MOR = \theta_1 + \theta_2 * MOE + \theta_3 * HT + \varepsilon$	(2)	1206337	0.8574
$MOR = \theta_1 + \theta_2 * MOE + \theta_3 * Rh + \varepsilon$	(3)	1194540	0.8588

Where: height = the height in a tree;

h4 = an indicator. h4 = 1, if height = 24 or 40; h4 = 0, other wise;

Rh represent the relative height of source, i.e. Rh = height of the source divided by HT.

All three models describe the linear association of MOR and MOE with height in the models. Wood from 8 feet high in a tree is significantly different than wood from upper heights based on mechanical properties. Therefore, the model (1) with indicator variable h4 is the best one. This model has the smallest MSE and largest R-Square.

If other effects, such as wood type, interaction of wood type with height, and region were considered in these three models, model (1) is still the best one. Model (4) is a full model with MSE = 1010380, R-Square = 0.8809, Adjusted R-Square = 0.8802. Parameter estimates are listed in Table 4.2.2.

In the full model (4), region had no significant effect. The relationship between MOR and MOE are almost same in all five regions. Materials from different height of trees with each wood type have different parameter values.

$$
\begin{aligned}
&MOR = \theta_1 + \theta_2 * MOE + \varepsilon \\
&where, \\
&\theta_1 = \theta_{11} + \theta_{12} * mh8 + \theta_{13} * mh4 \\
&\theta_2 = \theta_{21} + \theta_{22} * mh4
\end{aligned}
\tag{4}
$$

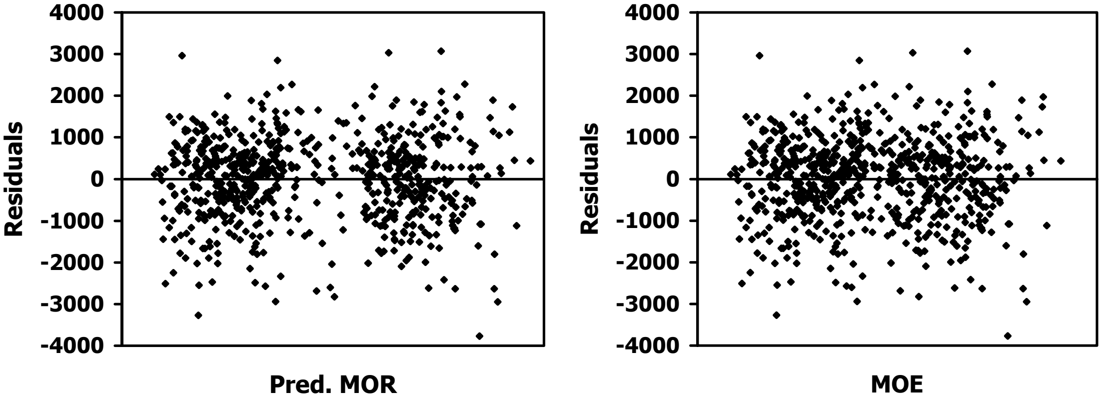
Table 4.2.2 Parameter estimates for $MOR = \theta_1 + \theta_2 * MOE + \varepsilon$ **:**

Parameter	Estimate	Approx Std Err	t value	Approx Pr > |t|
θ_{11}	3993.313	157.2	25.40	<.0001
θ_{12}	3823.354	838.1	4.56	<.0001
θ_{13}	1710.065	150.0	11.40	<.0001
θ_{21}	0.005172	0.000183	28.32	<.0001
θ_{22}	-0.00185	0.000578	-3.19	0.0015

Plots residuals versus $\hat{MOR}$ and MOE (Figure 4.2.1, A for MOR and B for MOE) display 'shotgun' patterns that all residual errors are around the zero line, there are no trends to indicate bias are heteroskedasticity. The assumptions of $\varepsilon \xrightarrow{iid} N\left(0, \sigma^2\right)$ are assumed to have seen met.

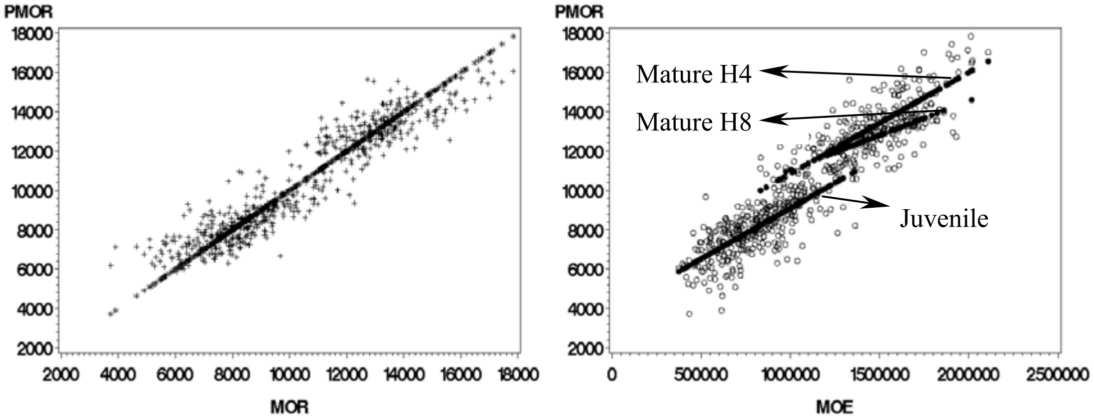
In Figure 4.2.2A, plot of predicted $\hat{MOR}$ values versus observed MOR values, displays a straight-line pattern around the line, which is through origin with slope of one. Predicted MOR values were also plotted against MOE values (Figure 4.2.2B). For juvenile wood specimens, the height level did not affect the relationship of MOR and MOE. One regression line fit

the data very well. For mature wood specimens, two regression lines with different intercept and different slope were fitted to express the relationship of MOR and MOE for mature wood, and the differences due to height level.



A B

Figure 4.2.1 Residual plots against Predicted MOR (A) and MOE (B)



A B

Figure 4.2.2 Predicted MOR versus actual MOR (A) and MOE (B)

4.3 Predict Modulus of Rupture

4.3.1 With SG as a predictor

Modulus of rupture is strongly correlated with specific gravity (Figure 4.3.1) with correlation coefficient R = 0.8889. Although SG explains a large proportion of the variation of MOR, there are other anatomical factors which have effects on MOR, such as microfibril angle. Because those anatomical data are not available we hope to improve the prediction outcome by using measurable variables. In a scatter plot of SG versus MOR (Figure 4.3.1), there are two groups: the larger values are from mature wood specimens while the smaller values are from juvenile wood specimens. In addition, MOR of material from 8 feet obviously has lower values than MOR of materials from upper heights (Figure 4.3.1).

Number of rings in the specimen was a good predictor for MOR and logarithm of number of rings was better (Figure 4.3.2). The correlation coefficient is 0.8054. Number of rings in the specimen indicates growth rate. Because specimen is 1 in thick, it can be thought of as number of rings per inch.

DBH is the diameter at breast height of a tree. It is hard to tell any variant trend of MOR with DBH from the scatter plot. An inconsistent variation exists between modulus of rupture and diameter. However, the product of number of rings and diameter (rtd) is a good predictor, where $rtd = NR * DBH$. In Figure 4.3.3, the scatter plot of MOR versus rtd shows that there is an approximate linear pattern. That indicates a positive linear relationship between modulus of rupture and NR*DBH. The correlation coefficient is 0.7968.

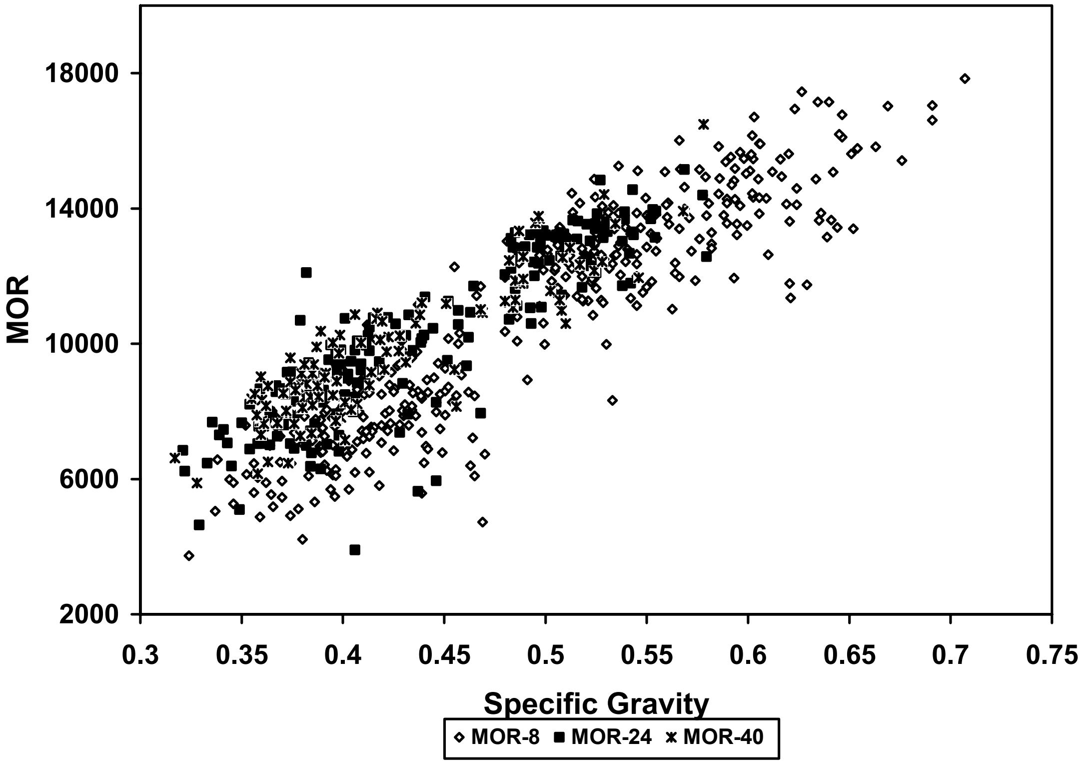


Figure 4.3.1 Scatter plot of MOR versus SG by height

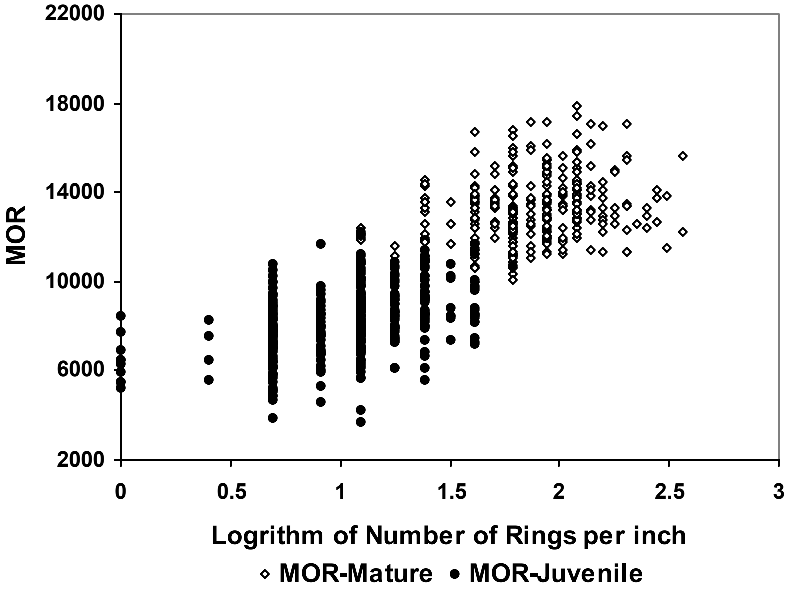


Figure 4.3.2 Scatter plot of MOR against logarithm of number of rings per inch by wood type

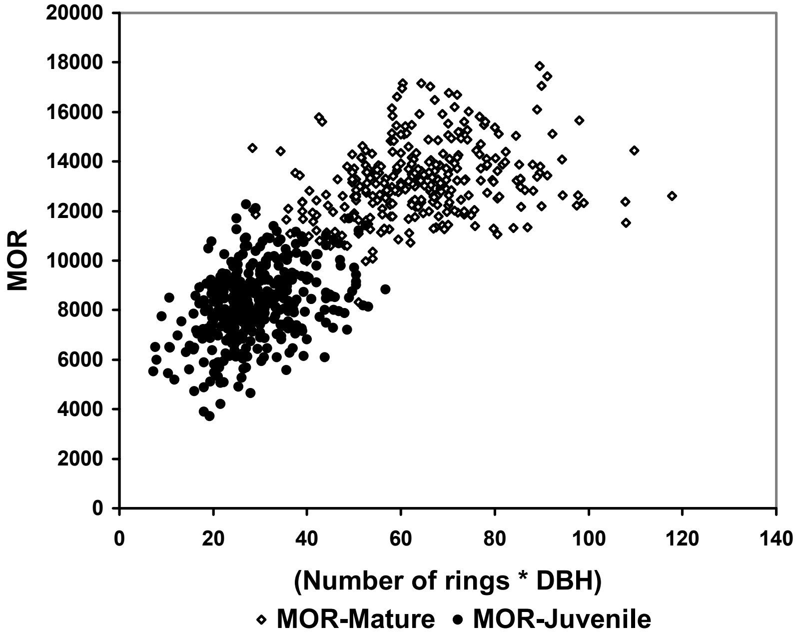


Figure 4.3.3 Scatter plot of MOR versus NR*DBH by wood type

MOR also varies among different regions (Table 4.1.3). If wood type and number of rings are predictors for modulus of rupture, region effects were significant, but were reduced (Table 4.1.3). Based on the literature review, rotation age should be a good predictor. Rotation age in this study is around 25 and the range is from 20 to 31. The effect of rotation age on MOR and MOE was hard to tell due to the small range.

Table 4.3.1 ANOVA table for MOR = f (region, wood type, NR)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	28	4592688480	164024589	85.72	<.0001
Error	668	1278216648	1913498		
Corrected Total	696	5870905128			

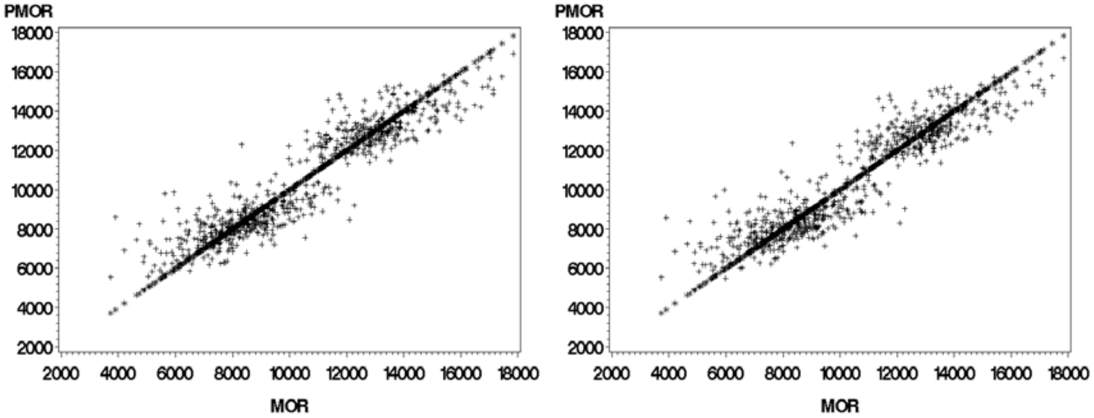
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REGION	4	27617780.9	6904445.2	3.61	0.0064
WOODTYPE	1	426138143.1	426138143.1	222.70	<.0001
NR	23	261011148.5	11348310.8	5.93	<.0001

With all of these candidate variables in mind, many models were fit, including simple linear models, multiple linear models, and nonlinear models (Ratkowsky 1990). Both multiple linear equations and the Logistic nonlinear model predicts MOR very well. The multiple linear equation is a function of specific gravity and logarithm of number of rings (log(NR)). The Logistic equation is a function of specific gravity and logarithm of NR*DBH. The Logistic model has slightly better fit statistics than linear model (Table 4.3.2).

Table 4.3.2 Candidate models for MOR = f (SG, NR, DBH)

Models		MSE	R-Square	Adj R-Sq
$MOR = \theta_1 + \theta_2 * SG + \theta_3 * \log(NR) + \varepsilon$	(5)	1551174	0.8166	0.8161
$MOR = \dfrac{\theta_1}{1 + \theta_2 * \exp(-\theta_3 * SG - \theta_4 * \log(NR * DBH))} + \varepsilon$	(6)	1497795	0.8232	0.8224

Predicted MOR values and observed MOR values for both full models are plotted: (Figure 4.3.4, (A) is multiple linear model and (B) is Logistic model). There are no big differences between the results.



A **B**

Figure 4.3.4 Predicted MOR versus Observed MOR using (A) linear regression and (B) Logistic model

The effect of the categorical variables improves the model. A multiple linear model (7) was chosen due to its simplicity. It has R-Square 0.8649 (Adjusted R-Square 0.8636) and MSE 1150944. Parameter estimates are listed in Table 4.3.3.

$$\begin{aligned}&MOR = \theta_1 + \theta_2 * SG + \theta_3 * \log(NR) + \varepsilon\\&where,\\&\theta_2 = \theta_{21} + \theta_{22} * mh4 + \theta_{23} * mh8 + \theta_{24} * jh4 + \theta_{25} * rg4 + \theta_{26} * rg5\end{aligned} \tag{7}$$

In model (7), mature wood from 24 or 40 feet high has largest predicted MOR values, followed by mature wood from 8 feet high, juvenile wood from 24 or 40 feet high, and the juvenile wood from 8 feet, with the smallest predicted MOR. The Gulf Coastal Plain (rg4) has the largest predicted values followed by the Hilly Coastal Plain (rg5). With logarithm of number of rings, wood type, height, and regions in the model, the fit index (R^2) for MOR was improved from 79 percent (with only specific gravity) to 86 percent.

Table 4.3.3 Parameter estimates for $MOR = \theta_1 + \theta_2 * SG + \theta_3 * \log(NR) + \varepsilon$**:**

Parameter	Estimate	Approx Std Err	t value	Approx Pr > |t|
θ_1	-1520.08	523.2	-2.91	0.0038
θ_{21}	19997.88	1309.3	15.27	<.0001
θ_{22}	4741.059	408.6	11.60	<.0001
θ_{23}	3399.557	446.8	7.61	<.0001
θ_{24}	3413.425	278.9	12.24	<.0001
θ_{25}	1056.707	270.2	3.91	0.0001
θ_{26}	814.3358	291.3	2.80	0.0053
θ_3	883.1248	145.5	6.07	<.0001

The residual plot against predicted MOR values (Figure 4.3.5) does not display a pattern of heteroskedasticity.

Predicted MOR values were plotted against observed MOR values (Figure 4.3.4) and predictor variables (Figure 4.3.6). In Figure 4.3.4, residual points are distributed around the line that is through the origin with slope one. The narrow pattern indicates showed the differences between the predicted MOR values and observed MOR values were small. Predicted values closely align were observed values when plotted over SG and NR indicating good prediction ability (Figure 4.3.6).

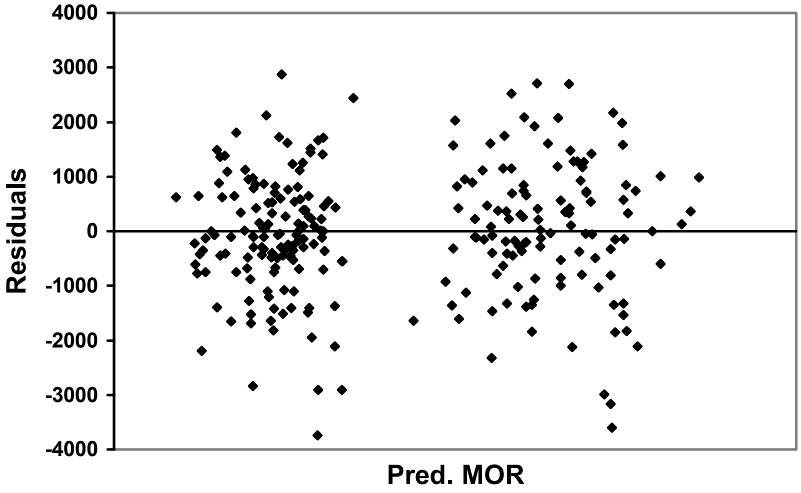
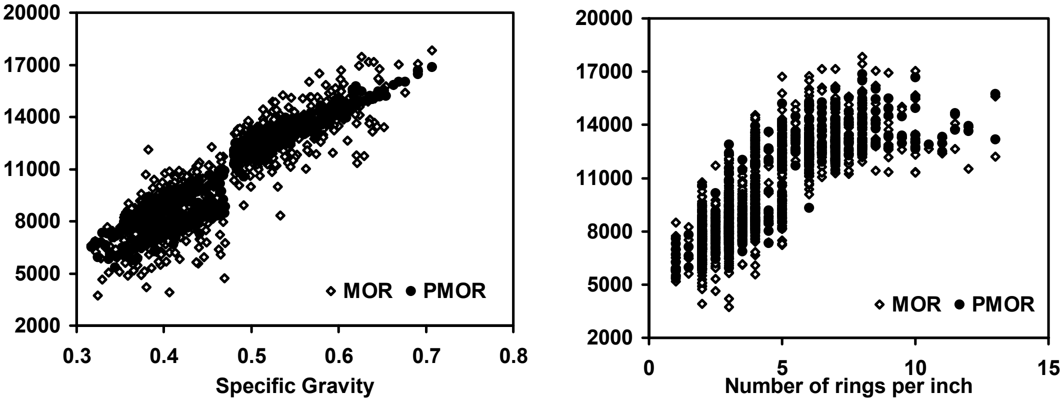


Figure 4.3.5 Residual plot of model (7) against predicted MOR



A **B**

Figure 4.3.6 Predicted MOR values versus (A) Specific Gravity and (B) Number of Rings

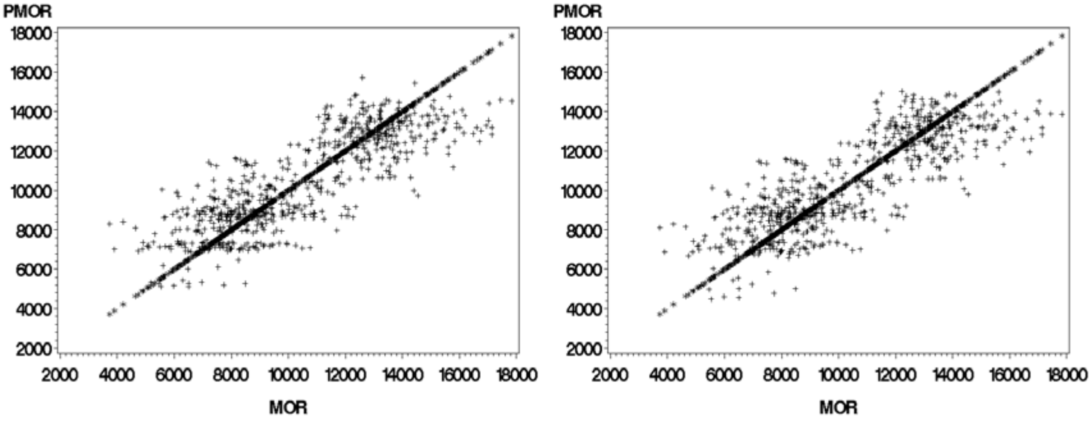
<u>4.3.2 Without SG as predictor</u>

Specific gravity accounts for large proportion of variation of modulus of rupture but it is not an available predictor in many cases. SG is expensive to obtain. Although there are several methods to estimate SG, predicting MOR only by available variables may be more useful in some applications. Other predictors in model (7) are much easier to obtain, but they explain relatively little of the variation in MOR. A prediction model without specific gravity as a predictor was built for application.

Many linear and nonlinear models were tried fitting the raw data. The best candidate models are presented in Table 4.3.4. The linear model (8) is slightly better than the Logistic model (9) (Figure 4.3.7).

Table 4.3.4 Candidate models for MOR = f (NR, DBH)

Models	MSE	R-Square	Adj R-Squ
$MOR = \theta_1 + \theta_2 * NR + \theta_3 * NR^2 + \theta_4 * NR * DBH + \varepsilon$ (8)	2586405	0.6947	0.6934
$MOR = \dfrac{\theta_1}{1 + \theta_2 * \exp(-\theta_3 * NR - \theta_4 * \log(NR * DBH))} + \varepsilon$ (9)	2658423	0.6862	0.6848



A **B**

Figure 4.3.7 Predicted MOR versus observed MOR for (A) linear model and (B) Logistic model

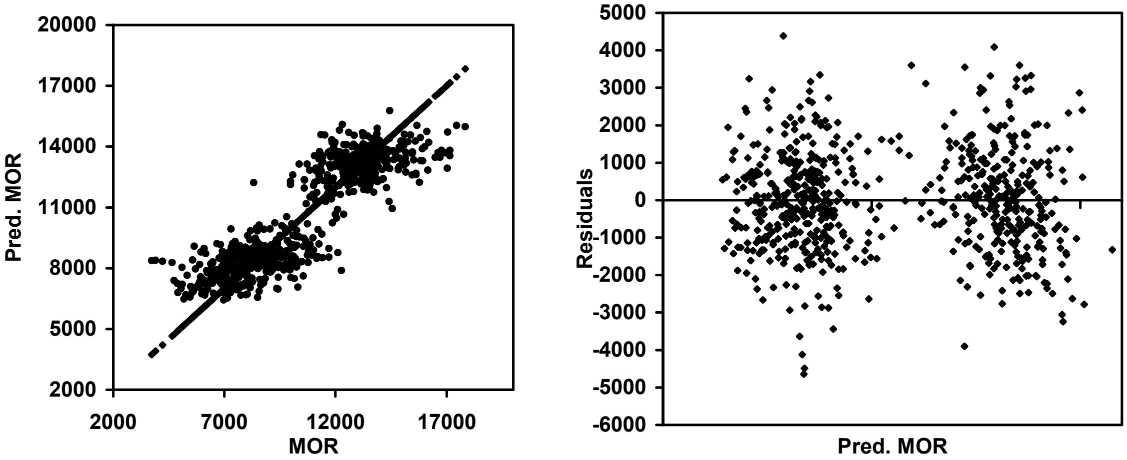
The effect of number of rings was significantly different when the specimens were from different regions and if the wood type or height of the specimens were not same. After adding these effects into both models, the linear model (8) was the simplest and had the best fit statistics. This full model (10) had R-Square 0.7826 (adjusted R-Square 0.7794) and MSE 1860849 and was chosen as at the best one for describing the variation of MOR without SG as a predictor. Parameter estimates are listed in Table 4.3.5.

$$
\begin{aligned}
&MOR = \theta_1 + \theta_2 * NR + \theta_3 * NR^2 + \theta_4 * NR * DBH + \varepsilon \\
&where, \\
&\theta_1 = \theta_{11} + \theta_{12} * jh4 \qquad (10) \\
&\theta_3 = \theta_{31} * mh4 + \theta_{32} * mh8 + \theta_{33} * rg2 + \theta_{34} * rg3 + \theta_{35} * rg5 \\
&\theta_4 = \theta_{41} + \theta_{42} * mh4 + \theta_{43} * mh8
\end{aligned}
$$

Table 4.3.5 Parameter estimates for $MOR = \theta_1 + \theta_2 * NR + \theta_3 * NR^2 + \varepsilon$**:**

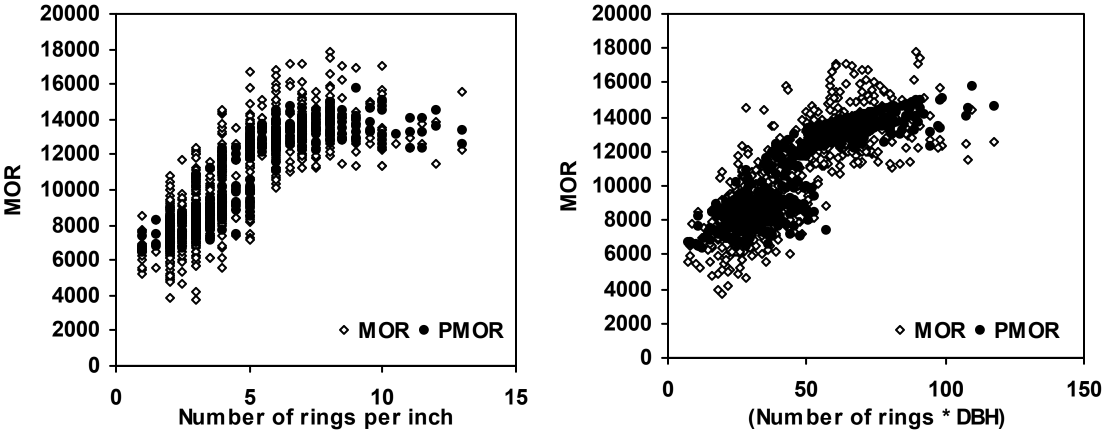
Parameter	Estimate	Approx Std Err	t value	Approx Pr > |t|
θ_{11}	6021.393	245.5	24.53	<.0001
θ_{12}	1081.5	144.8	7.47	<.0001
θ_2	1278.734	104.0	12.30	<.0001
θ_{31}	-113.329	16.2609	-6.97	<.0001
θ_{32}	-78.7898	7.2113	-10.93	<.0001
θ_{33}	-14.5098	4.4470	-3.26	0.0012
θ_{34}	-14.5567	4.0964	-3.55	0.0004
θ_{35}	-8.1875	3.8307	-2.14	0.0329
θ_{41}	-70.3915	9.4710	-7.43	<.0001
θ_{42}	127.6854	9.9135	12.88	<.0001
θ_{43}	112.4778	6.2656	17.95	<.0001

This model is better at predicting MOR of juvenile wood than that of mature wood (Figure 4.3.8 A). We had sufficient juvenile wood specimens to identify prediction relationships. Number of rings of these specimens was uniform at each height level (Figure 4.3.10). Both number of rings and height had significant effects (Figure 4.1.2) and they are independent. Therefore, both number of rings and height are good predictors for modulus of rupture of juvenile wood.



A **B**

Figure 4.3.8 Predicted MOR versus observed MOR (A) and Residual plot against predicted MOR values (B)



A B

Figure 4.3.9 Predicted MOR versus NR (A) and (NR*DBH) (B)

Due to the nature of wood formation fewer mature wood specimens with number of rings more than 10 at 24 feet high or more than 8 at 40 feet high were available. MOR of mature wood specimens was not affected by height (Figure 4.1.2), while the effect of number of rings was significantly different at each height level. Thus the prediction model for MOR as a function of number of rings, height, and region, without specific gravity, is better for materials from juvenile wood than for materials from mature wood.

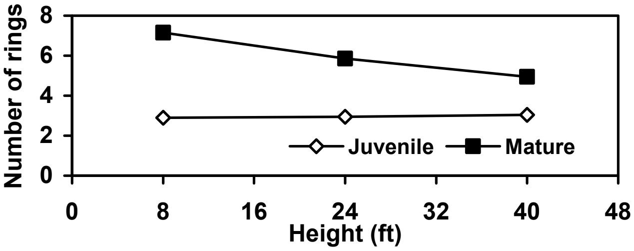


Figure 4.3.10 Juvenile wood had uniform number of rings at each height level while number of rings of mature wood decrease with height increase.

In model 10, Upper Coastal Plain (rg2) and Piedmont (rg3) had smaller predicted values than did the other three regions.

Specific gravity is an expensive piece of information to collect. It is easy to identify the number of rings and wood type of the cut lumber. The manufacturer also could know from which region the logs originated and the height level from which the lumber was cut. Height levels in these models represent the median position of each of the first three logs. Therefore, to predict MOR of beams from first log, we should use the parameter values of indicator variables with '8', like mh8 or jh8.

4.4 Predict Modulus of Elasticity

4.4.1 SG as predictor

In this section, a prediction model for MOE will be introduced. There are two clusters of data points for MOE versus SG (Figure 4.4.1). The mature wood specimens have high MOE and SG while juvenile wood specimens have lower MOE and SG values. It is also obvious that materials from 8 feet of trees, represented by black dots, have generally lower MOE values than materials from upper heights, represented by circles or triangles.

MOE values are positively and linearly related to specific gravity (Figure 4.4.1), but the pattern is wider than that for MOR. Specific gravity explains about 67 percent of variation of modulus of elasticity, while it accounts for more than 79 percent of variation of modulus of rupture. There may be at least one more anatomical factor that accounts for variation of MOE. Based on literature review, microfibril angle explains a large proportion of the variation of MOE. Microfibril angle data are not available for these samples.

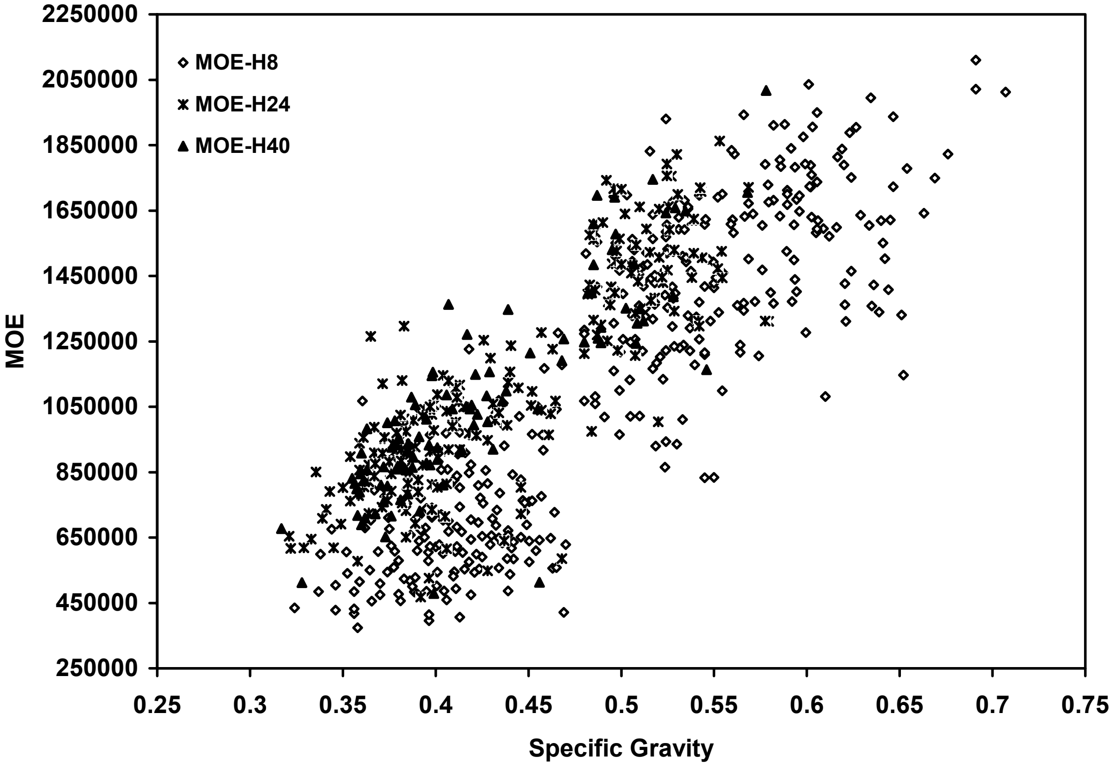


Figure 4.4.1 Scatter plot of MOE against SG by height

The relationship between modulus of elasticity and the product of number of rings and DBH is positive and linear (Figure 4.4.2). The correlation coefficient between MOE and NR*DBH is 0.7744. Although results of these analyses are similar to results of analyses for modulus of rupture, the relationships for MOE are weaker.

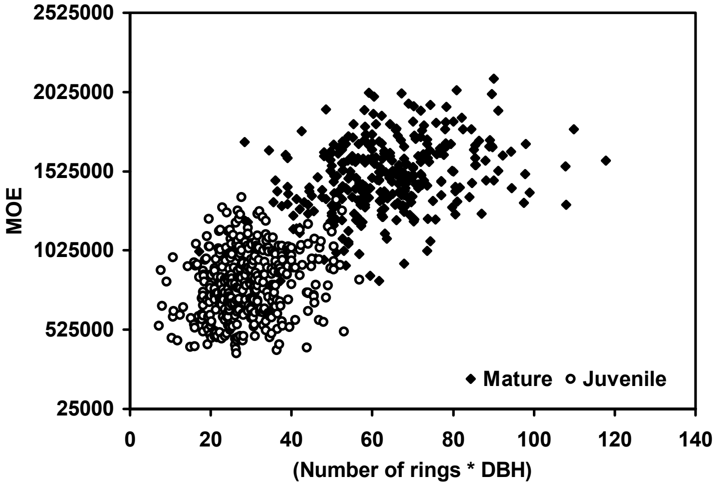


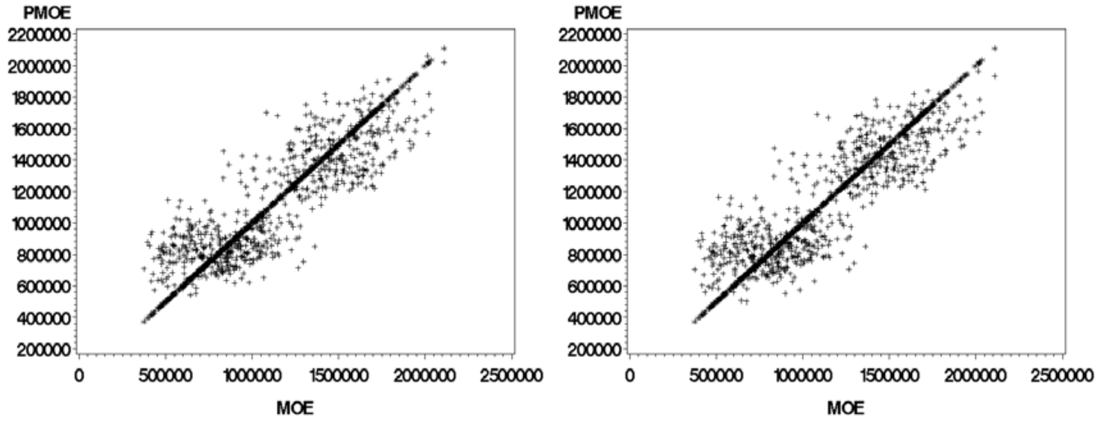
Figure 4.4.2 Scatter plot of MOE against NR*DBH by wood type

Two candidate models, a linear and a nonlinear model, are presented in Table 4.4.1. The values of R-Square and MSE show that Logistic model (12) is slightly better than linear model.

Table 4.4.1 Candidate models for MOE = f (SG, NR, DBH)

Models		MSE	R-Square
$MOE = \theta_1 + \theta_2 * SG + \theta_3 * (NR * DBH) + \varepsilon$	(11)	4.571E10	0.7166
$MOE = \dfrac{\theta_1}{1 + \exp(-\theta_2 * \log(SG) - \theta_3 * \log^2(NR * DBH))} + \varepsilon$	(12)	4.509E10	0.7204

Figure 4.4.3A and B are plots of predicted MOE values versus observed MOE values for linear model and for the Logistic model, separately. Although, the difference between the two plots is not great, one can see that Logistic model is better at predicting wood stiffness for mature wood.

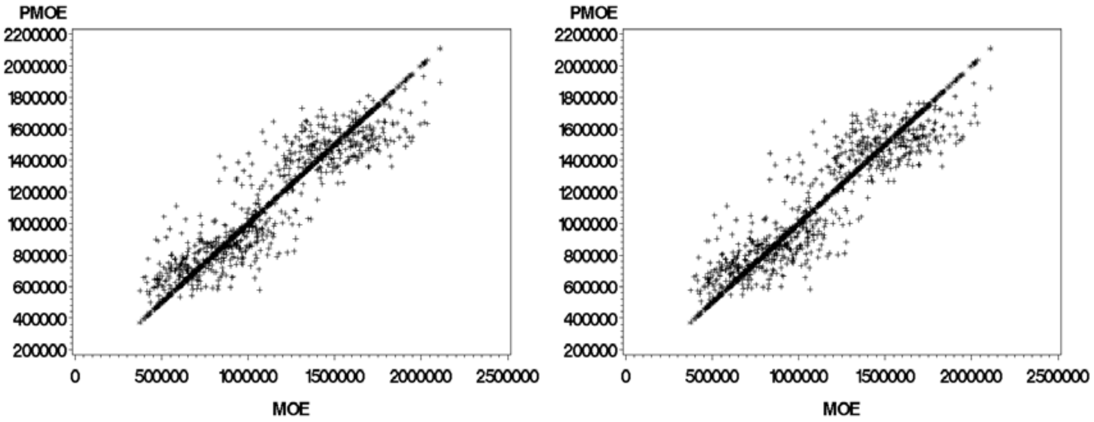


A **B**

Figure 4.4.3 Predicted MOE values versus observed MOE values: A is for the multiple linear model, B is for Logistic model.

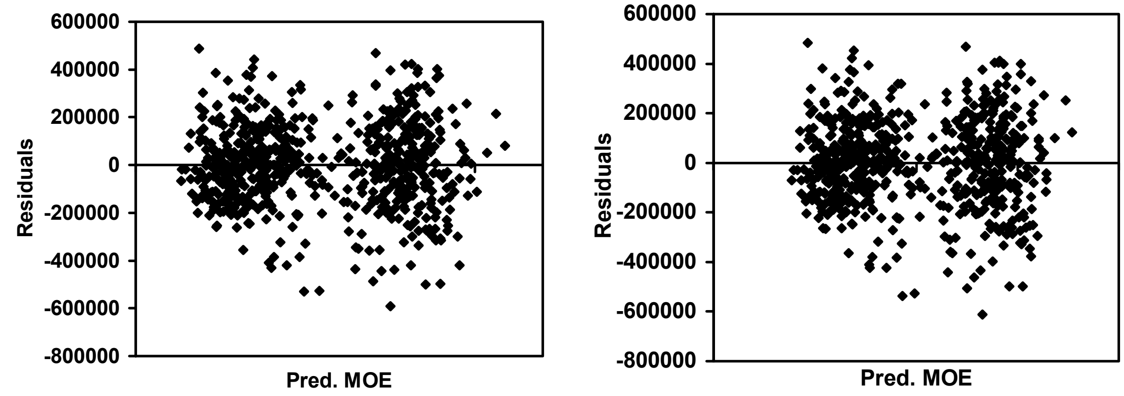
Categorical variables representing factors of height, wood type and physiographic region were added into both models as indicator variables. The linear and nonlinear models have the same number of parameters. The linear model has larger R-Square, smaller MSE. Plots of predicted MOE values versus observed MOE values shows that the multiple linear model has a better performance on predicting for both two wood types (Figure 4.4.4). The residual plot from the linear model is much better than that of the Logistic model.

The best full model (13) is displayed following. It has R-Square 0.8206 (adjusted R-Square is 0.8182) and MSE 2.9E10. Parameter estimates are listed in Table 4.4.2. Height, number of rings, wood type, and region have large effects on specific gravity. That is the reason why there is only a little improvement on predicting MOE.



A B

Figure 4.4.4 Scatter plot of predicted MOE values versus observed MOE values: (A) is for linear model; (B) is for Logistic model



A B

Figure 4.4.5 Residual plot against predicted MOE values: (A) is for linear model; (B) is for Logistic model

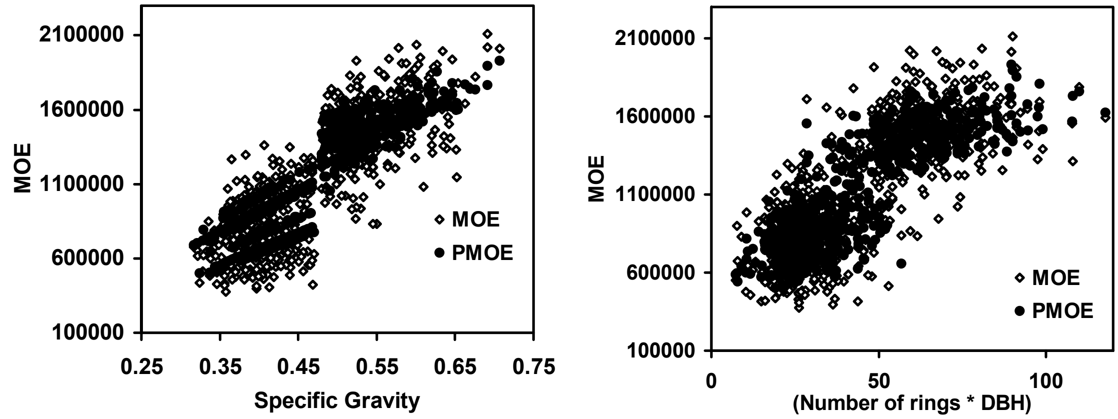
$$MOE = \theta_1 + \theta_2 * SG + \theta_3 * (NR * DBH) + \varepsilon$$

$$\begin{aligned} &where, \\ &\theta_1 = \theta_{11} + \theta_{12} * mh4 + \theta_{13} * rg4 \\ &\theta_2 = \theta_{21} + \theta_{22} * mh8 + \theta_{23} * jh4 + \theta_{24} * rg3 + \theta_{25} * rg5 \\ &\theta_3 = \theta_{31} * mh4 + \theta_{32} * mh8 \end{aligned} \qquad (13)$$

Table 4.4.2 Parameter estimates for

$MOE = \theta_1 + \theta_2 * SG + \theta_3 * (NR * DBH) + \varepsilon$:

Parameter	Estimate	Approx Std Err	t value	Approx Pr > |t|
θ_{11}	-192161	83209.5	-2.31	0.0212
θ_{12}	373719.8	92487.4	4.04	<.0001
θ_{13}	115301.4	22962.9	5.02	<.0001
θ_{21}	2139548	202738	10.55	<.0001
θ_{22}	331197.8	114848	2.88	0.0041
θ_{23}	645604.7	44281.3	14.58	<.0001
θ_{24}	-75911.9	34587.2	-2.19	0.0285
θ_{25}	213118.6	43752.3	4.87	<.0001
θ_{31}	3316.846	1493.7	2.22	0.0267
θ_{32}	4209.007	745.1	5.65	<.0001



A **B**

Figure 4.4.6 Predicted MOR versus SG (A) and (NR*DBH) (B)

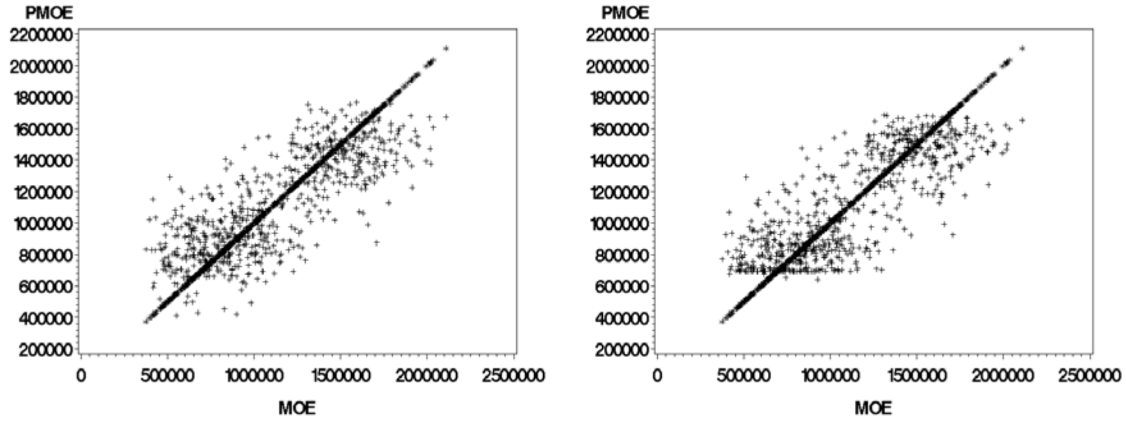
4.4.2 Without SG as predictor

Both specific gravity and microfibril angle are expensive to obtain. We hope to find a useful prediction model for MOE as a function of readily available variables.

Candidate models are listed in Table 4.4.3. From MSE and R-square, the Logistic model is slightly better than linear model. From scatter plots of predicted values versus observed values, the predictions from the linear model are closer to the line, which is through the origin zero with slope one (Figure 4.4.7).

Table 4.4.3 Candidate models for MOE = f (NR, DBH)

Models	MSE	R-Square
$MOE = \theta_1 + \theta_2 * (NR * DBH) + \theta_3 * (NR * DBH)^2 + \theta_4 * NR + \theta_5 * NR^2 + \varepsilon$ (14)	5.946E10	0.6424
$MOE = \frac{\theta_1}{1 + \exp(-\theta_2 * \log(NR * DBH) - \theta_3 * \log^2(NR * DBH) - \theta_4 * NR - \theta_5)} + \varepsilon$ (15)	5.702E10	0.6475

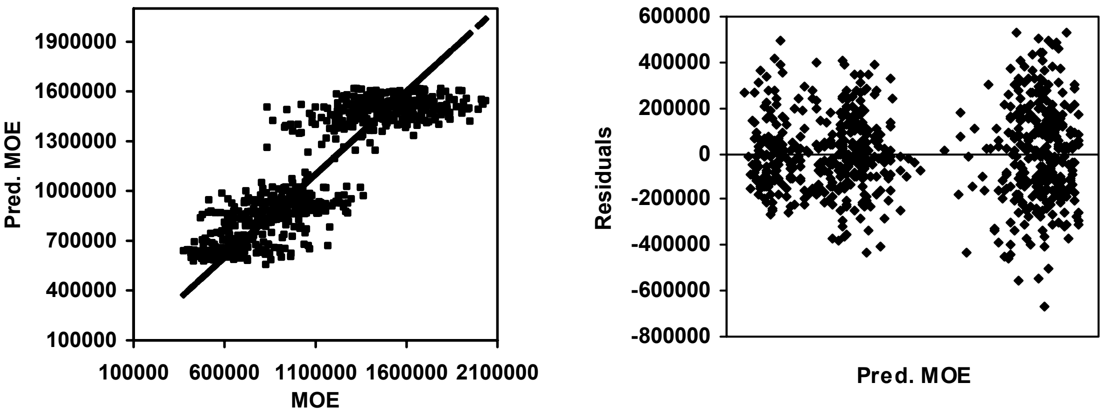


A B

Figure 4.4.7 Predicted MOE values versus observed MOE values: A is for linear model and B is for Logistic model

After adding height, wood type, and region factors into these two models as indicator variables, the linear model appears better according to scatter plots of predicted versus observed values. Residuals plotted against predicted MOE values (Figure 4.4.8) show residual errors have mean zero. The full model (16) has R-Square of 0.7828 (adjusted R-Square 0.7780). Wood type explains large proportion of the variation. MSE of this model is 3.57E10. The relatively large variance indicates that available variables in this study could not predict MOE as well as specific gravity did. However, this model may be more applicable because the predictors are easy to obtain. Parameter estimates are listed in Table 4.4.4.

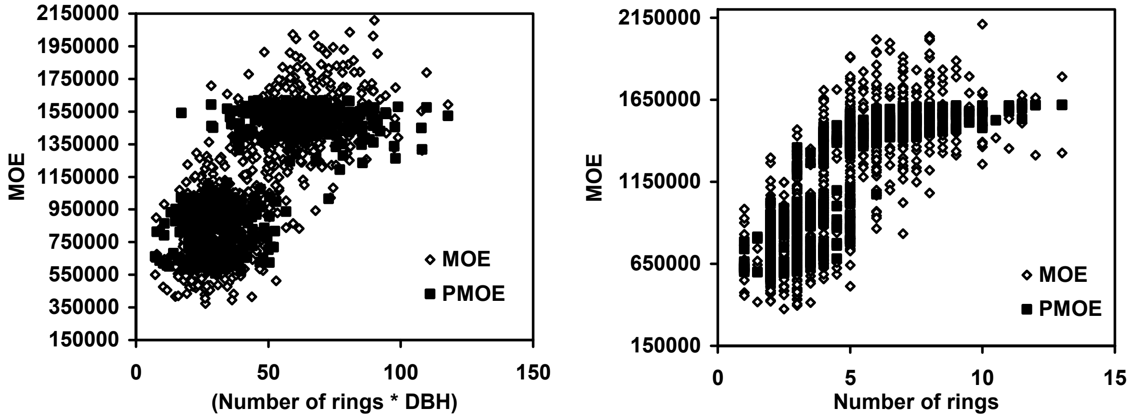
In this model, the quadratic terms are only for mature wood. From Figure 4.3.10, we know that number of rings is not uniform at height levels. Mature wood specimens that had more than 10 rings at 8 feet high had low MOE values. The linear relationship between MOE and number of rings is not suitable for mature wood. Quadratic forms here are to adjust this curvilinear trend. This model is agreement with the fact that it is rare to obtain mature wood samples with large number of rings from second or higher logs.



A B

Figure 4.4.8 Predicted MOE versus observed MOE (A) and Residual plot (B)

$$
\begin{aligned}
&MOE = \theta_1 + \theta_2 * (NR * DBH) + \theta_3 * (NR * DBH)^2 + \theta_4 * NR + \theta_5 * NR^2 + \varepsilon \\
&where, \\
&\theta_2 = \theta_{21} + \theta_{22} * mh4 + \theta_{23} * mh8 + \theta_{24} * jh4 \\
&\theta_3 = \theta_3 * mh8 \\
&\theta_4 = \theta_{41} + \theta_{42} * mh4 + \theta_{43} * mh8 + \theta_{44} * rg3 + \theta_{45} * rg4 + \theta_{46} * rg5 \\
&\theta_5 = \theta_{51} * mh4 + \theta_{52} * rg2 + \theta_{53} * rg4 + \theta_{54} * rg5
\end{aligned}
\tag{16}
$$



A B

Figure 4.4.9 predicted MOE values versus (Number of rings * DBH) (A) and Number of rings (B)

Table 4.4.4 Parameter estimates for

$$MOE = \theta_1 + \theta_2 * (NR * DBH) + \theta_3 * (NR * DBH)^2 + \theta_4 * NR + \theta_5 * NR^2 + \varepsilon:$$

Parameter	Estimate	Approx Std Err	t value	Approx Pr > |t|
θ_1	650635.4	34286.8	18.98	<.0001
θ_{21}	-6659.88	2094.9	-3.18	0.0015
θ_{22}	10127.8	3283.4	3.08	0.0021
θ_{23}	23027.61	2945.1	7.82	<.0001
θ_{24}	7192.354	669.4	10.74	<.0001
θ_3	-76.8821	16.1542	-4.76	<.0001
θ_{41}	80655.4	19764.1	4.08	<.0001
θ_{42}	151147.8	44171.0	3.42	0.0007
θ_{43}	-59740.1	23740.7	-2.52	0.0121
θ_{44}	-15825.4	3835.0	-4.13	<.0001
θ_{45}	53539.73	12209.1	4.39	<.0001
θ_{46}	31864.89	12133.3	2.63	0.0088
θ_{51}	-20111.1	3493.4	-5.76	<.0001
θ_{52}	-1794.12	653.0	-2.75	0.0062
θ_{53}	-5877.05	1428.0	-4.12	<.0001
θ_{54}	-4451.5	1614.2	-2.76	0.0060

CHAPTER 5

CONCLUSIONS

A sample of 272 loblolly pine trees were randomly chosen from baseline sites in five regions from 97 stands. Static bending tests were done for small clear and straight specimens from those trees. Five models were built (Table 5.1). The following conclusions may be drawn from the results of these investigations:

Juvenile wood and mature wood are different in modulus of rupture and modulus of elasticity. Mature wood has higher MOR and MOE values than juvenile wood. Transition wood was not sampled so there is virtually no overlap in the values for individual specimens of the two types of wood.

Material from the first log (8 ft) has lower MOR and MOE values than material from upper heights. The first logs with a large proportion of juvenile wood have lowest MOR and MOE.

Model (7) and (13) are for predicting modulus of rupture and modulus of elasticity, respectively, including specific gravity as one of predictors. Modulus of rupture and modulus of elasticity are correlated strongly and linearly with specific gravity. The correlation coefficients are 0.8889 to MOR values and 0.8199 to MOE values. Modulus of elasticity is more variable than modulus rupture.

Model (10) and (16) are prediction models for MOR and MOE, respectively, as functions of available variables without specific gravity. Both of them are better at predicting bending properties of juvenile wood that for predicting properties of mature wood.

Proportions of juvenile wood specimens from each height level are 20, 35, and 45 percent, at 8, 24 and 40 feet, respectively.. Compared with lower height levels, logs from 40 feet high are much younger and have a small proportion of mature wood with fewer numbers of rings. It is rare to get clear mature wood specimens at 40 feet of tree height. Only 7 percent of mature wood data is from 40 feet of trees, and 21 percent of it from 24 feet of trees. If there were more mature wood specimens from the upper heights, these models could be more accurate in predicting MOE and MOR for nature wood.

Table 5.1. Final models for modulus of rupture and modulus of elasticity

Models	Equation Number
$MOR = \theta_1 + \theta_2 * MOE + \varepsilon$ $where,$ $\theta_1 = \theta_{11} + \theta_{12} * mh8 + \theta_{13} * mh4$ $\theta_2 = \theta_{21} + \theta_{22} * mh4$	(4)
$MOR = \theta_1 + \theta_2 * SG + \theta_3 * \log(NR) + \varepsilon$ $where,$ $\theta_2 = \theta_{21} + \theta_{22} * mh4 + \theta_{23} * mh8 + \theta_{24} * jh4 + \theta_{25} * rg4 + \theta_{26} * rg5$	(7)
$MOR = \theta_1 + \theta_2 * NR + \theta_3 * NR^2 + \theta_4 * NR * DBH + \varepsilon$ $where,$ $\theta_1 = \theta_{11} + \theta_{12} * jh4$ $\theta_3 = \theta_{31} * mh4 + \theta_{32} * mh8 + \theta_{33} * rg2 + \theta_{34} * rg3 + \theta_{35} * rg5$ $\theta_4 = \theta_{41} + \theta_{42} * mh4 + \theta_{43} * mh8$	(10)

$$
\begin{aligned}
&MOE = \theta_1 + \theta_2 * SG + \theta_3 * (NR * DBH) + \varepsilon \\
&where, \\
&\theta_1 = \theta_{11} + \theta_{12} * mh4 + \theta_{13} * rg4 \\
&\theta_2 = \theta_{21} + \theta_{22} * mh8 + \theta_{23} * jh4 + \theta_{24} * rg3 + \theta_{25} * rg5 \\
&\theta_3 = \theta_{31} * mh4 + \theta_{32} * mh8
\end{aligned}
\tag{13}
$$

$$
\begin{aligned}
&MOE = \theta_1 + \theta_2 * (NR * DBH) + \theta_3 * (NR * DBH)^2 + \theta_4 * NR + \theta_5 * NR^2 + \varepsilon \\
&where, \\
&\theta_2 = \theta_{21} + \theta_{22} * mh4 + \theta_{23} * mh8 + \theta_{24} * jh4 \\
&\theta_3 = \theta_3 * mh8 \\
&\theta_4 = \theta_{41} + \theta_{42} * mh4 + \theta_{43} * mh8 + \theta_{44} * rg3 + \theta_{45} * rg4 + \theta_{46} * rg5 \\
&\theta_5 = \theta_{51} * mh4 + \theta_{52} * rg2 + \theta_{53} * rg4 + \theta_{54} * rg5
\end{aligned}
\tag{16}
$$

REFERENCES CITED

Adegbidi, H. G., E. J. Jokela, N. B. Comerford, and N. F. Barros. 2002. Biomass development for intensively managed loblolly pine plantations growing on spodosols in the southeastern USA. Forest Ecology and Management 167: 91-102.

Bao, F. C., Z. H. Jiang, X. M. Jiang, X. X. Lu, X. Q. Luo, and S. Y. Zhang. 1999. Differences in wood properties between juvenile wood and mature wood in 10 species grown in China. Wood Science and Technology 35: 363-375.

Bendtsen, B. A. and J. Senft. 1984. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly-pine. Wood and Fiber Science 18: 23-38.

Brown, H. P., A. J. Panshin and C. C. Forsaith. 1952. *Textbook of wood technology*. New York, McGraw-Hill, 229-370.

Carino, H. F. and E. J. Biblis. 2002. Economic desirability of deferring the harvesting of loblolly pine plantation timber for structural dimension lumber production. Forest Products Journal 52: 52-58.

Daniels, R.F. and A. Clark III. 2003. Variation in loblolly pine wood density and moisture content across the U.S. South. In: Proceedings Twelfth Biennial Southern Silvicultural Conference. Biloxi, MS. Feb 26-28, 2003. [In Press]

Groom, L, R. Newbold, and J. Guldin. 2002. Effect of silviculture on the yield and quality of veneers. USDA Forest Service. SRS–48, 170-175.

Haygreen, J. G. and J. L. Bowyer. 1996. *Forest products and wood science: an introduction*. Third edition. Iowa State University Press, Ames, IA, 213-242.

Lee, A. W. C., G. Chen, D. E. Dickens, and A. E. Miller. 1999. Selected mechanical properties of wood produced by loblolly pine trees fertilized with sludge. Forest Products Journal 49: 43-47.

Larson, P. R., D. E. Kretschmann, A. Clark III, and J. G. Isebrands. 2001. Formation and properties of juvenile wood in southern pines: a synopsis. Gen. Tech. Rep. FPL-GTR-129. USDA Forest Service. Forest Products Laboratory. Madison, WI. 42p.

McAlister, R. H. and A. Clark III. 1990. Effect of geographic location and seed source on the bending properties of juvenile and mature loblolly-pine. Forest Products Journal 41: 39-42.

McAlister, R. H., A. Clark III, and J. R. Saucier. 1996. The effect of age at harvest on bending and tensile properties of loblolly pine from the coastal plain. Forest Products Journal 47: 85-88.

McAlister, R. H., H. R. Powers, and W. D. Pepper. 1999. Mechanical properties of stemwood and limbwood of seed orchard loblolly pine. Forest Products Journal 50: 91-94.

Neter, J., M. Kutner, C. Nachtsheim, and W. Wasserman. 1996. *Applied linear statistical models*, Fourth edition., New York, McGraw-Hill.

Pearson, R. G. and R. C. Gilmore. 1971 Characterization of the strength of juvenile wood of loblolly pine. Forest Products Journal 21: 23-31.

Pearson, R. G. and B. E. Ross. 1984. Growth-rate and bending properties of selected loblolly pines. Wood and Fiber Science 16: 37-47.

Ratkowsky, D. A. 1990. *Handbook of nonlinear regression models*. M. Dekker, New York.

SAS/STAT User's Guide, Version 8, SAS institute Inc., Cary, NC, USA.

Shupe, T. F., C. Y. Hse, E. T. Choong, and L. H. Groom. 1997. Effects of silvicultural practice and moisture content level on loblolly pine veneer mechanical properties. Forest Products Journal 47: 92-96.

U.S. Forest Service. 1974. Wood Handbook: Wood as an engineering material. USDA, Forest Products Laboratory, Agriculture Handbook No. 72. U.S. Government Printing Office, Washington, D.C. Table 4.2

Verkasalo, E. and J. M. Leban. 2002. MOE and MOR in static bending of small clear specimens of Scots pine, Norway spruce and European fir from Finland and France and their prediction for the comparison of wood quality. Paperi ja Puu – Paper and Timber 84: 332-340