The Effect of Multiple Knots in Close Proximity on Southern Pine Lumber Properties

Marcela Cordeiro Barbosa
Jason Street
Frank C. Owens
Rubin Shmulsky

Abstract

Lumber grade rules address well-spaced single-knot and combination-knot sizes. Information is lacking, however, with respect to multiple knots in close proximity. The term ''well-spaced'' appears to lack quantitation. This research investigates the effect that knots in close proximity (not necessarily combination knots) have on the strength properties of southern yellow pine (SYP; *Pinus* spp.) lumber. This study attempts to use a statistical model to determine the modulus of rupture (MOR) for SYP having multiple knots in close proximity using variables including the knot diameter (KD), amount of clear wood (CW) present, knot area (KA), and modulus of elasticity (MOE) of the lumber. This study investigated specimens of 2 by 4-inch SYP dimensional lumber exhibiting multiple knots in close proximity. The basic density (D) was determined by dividing the entire specimen weight by its volume. Third-point bending tests were used in flatwise orientation to quantify the MOR and MOE. There were significant correlations among all parameters analyzed. Multiple regression analysis with one dependent variable, MOR, and three independent variables, KD, MOE, and D, resulted in a coefficient of determination value (r^2) of 0.702. When using only the MOE to predict MOR, an r^2 value of 0.564 was found.

As lumber is sawn from a log, the blade cuts through cross sections of ingrown branches, thereby leaving round, often dark-colored masses called knots. The impact of knots on the strength of lumber depends on the knot size, location, shape, soundness, and type (Green et al. 1999). The shape of a knot on a sawn surface depends largely on how the lumber was sawn from the log. For example, in flat- or plain-sawn lumber, the knots typically have a round shape.

Mechanical properties of lumber that contains knots are usually inferior when compared with lumber that is composed of clear, straight-grained wood. Lumber with knots has wood-grain fibers around the knot, which are distorted, and this grain deviation or discontinuity of the wood fiber leads to stress concentrations. Shrinkage-induced checking frequently happens around the knots during drying because of stress concentrations and a load that develops perpendicular to the fiber along the weakest axis (Green et al. 1999). Guindos and Polocoser (2015) analyzed the influence of the slope of grain on the effect of the knots. The results showed that knots in beams could reduce the modulus of rupture (MOR) by 50 percent. In addition, knots are generally classified as either intergrown or encased. In cases where the branch was alive at the time the tree was harvested, there is continuous growth at the connection of the branch and the stem of the tree, and the resulting knot is known as an intergrown knot. In cases where the branch died well before the tree was harvested, extra circumferential growth of the trunk encloses the dead branch stub or remnant. This action results in an encased knot. In that type of situation, the fibers in the stem are not continuous with the fibers of the encased knot. Encased knots tend to be accompanied by less cross grain than intergrown knots. Therefore, they are often less detrimental to mechanical properties as compared with intergrown knots (Green et al. 1999).

The mechanical properties of clear wood (CW) have been well established. The quantitative effects that knots have on

The authors are, respectively, Graduate Student (mc3115@msstate.edu), Assistant Professor (jason.street@msstate.edu [corresponding author]), Assistant Professor (fco7@msstate.edu), and Professor and Dept. Head (rs26@msstate.edu), Dept. of Sustainable Bioproducts, Mississippi State Univ., Starkville. This paper was received for publication in June 2019. Article no. 19-00027.

Forest Prod. J. 69(4):278–282.
doi:10.13073/FPJ-D-19-00027

mechanical properties have not, however, been extensively covered in the literature (Nardin et al. 2000). The sole influence of knots on the mechanical strength of lumber is difficult to study because the knots typically have substantial differences through the cross section, may be difficult to visually assess on the surface, and are generally accompanied by grain deviation. Knots are often detrimental to tension and bending properties but may improve compression properties. Therefore, the simulation of most real specimens or cases is either not possible or requires simplifications (Guindos and Guaita 2013). Grade rules speak to singular well-spaced knots and combination knots. However, often knots occur in close proximity; that is, they may not be obviously well spaced. Herein, these are called ''multiple knots in close proximity.'' In cases in which on-grade lumber contains multiple knots in close proximity, its performance may be less than expected as compared with a case in which only the largest singular knot is considered. This study considered multiple knots in close proximity as any group of at least two knots that fell within 6 inches of a specimen's length (longitudinal axis). This 6-inch value comes from the concept of the Southern Pine Inspection Bureau's definition of well-spaced knots. Well-spaced knots refer to knots where the sum of the sizes of all knots in any 6-inch section of the longitudinal axis of a piece of lumber must not exceed twice the size of the largest knot permitted. More than one knot of maximum permissible size must not be in the same 6-inch lengthwise spacing, and the combination of knots must not be mechanically detrimental. In reality, there is likely some type of continuum regarding multiple knots in close proximity; that is, the absolute 6-inch cutoff for consideration is important for rapid visual grading but may lack the precision and accuracy needed to maximize lumber production. This study attempts to determine a more precise statistical model to determine the MOR for southern yellow pine (SYP) (*Pinus* spp.) having multiple knots in close proximity using variables including the knot diameter (KD), amount of CW present, knot area (KA), and modulus of elasticity (MOE) of the lumber.

Materials and Methods

This study used kiln-dried 2 by 4-inch SYP dimensional lumber obtained from a regional commercial sawmill/lumber producer. Specimens 3.81 cm thick by 8.89 cm wide by 72.4 cm long were prepared per ASTM D198-15 (ASTM International 2015). Specimens were then sorted visually based on the number of knots located in close proximity and conditioned to 12 percent moisture content. The specimens were weighed to an accuracy of 0.01 g, and dimensions were measured to an accuracy of 0.01 cm using a digital caliper. One photo was taken of each face and edge of each specimen in order to subsequently measure the dimensions of each knot and knot pattern in each specimen. The total number of samples analyzed in this study was 278. Specimen pictures were visually analyzed using the software Digimizer Version 4.6.1 (MedCalc Software, Ostend, Belgium). The knots located in the central portion area of each specimen between the two load heads were measured using the image software. Subsequently, each knot's diameter, parallel to the cross section, was measured.

In this study, each specimen had at least two knots in close proximity on the wide face. The portion of CW in the cross section was considered as the part of the cross section not covered by knots. The amount of CW was determined by using one of two categories of knots. The specimens were divided into two groups: single knots only and cluster knots. In each case, a line was traced at 90° to the specimen length and across the wide face as shown in Figure 1. If only one knot intersected the line, then this knot was considered a single knot. In cases where two knots or more intersected this line, they were considered cluster knots (Fig. 2). The CW was found by subtracting the specimen width by the diameter of the knot made at a right angle to the edge at the widest part of the knot as shown. If the specimen had both single and cluster knots, the group with the biggest KD was chosen to determine the CW for that specimen. Figure 2 illustrates a specimen with a single knot and cluster knots. The diameter of Knot 1 was bigger than the aggregate diameter of Knots 2 and 3; thus, the CW for this specimen was calculated as the difference between the specimen width (approximately 8.89 cm) and the diameter of Knot 1. In this manner, for each specimen, the maximum reduction in cross-sectional area as caused by knots was considered. KA was determined by the sum of the area of all knots found between the load heads on the wide face.

The KD was measured at a right angle to the edge at the widest part of the knot as shown in the Figure 2. For the single knots, only the biggest knot was measured. For the cluster knots, the diameters of the knots intersecting the same line were totaled. For specimens with cluster knots and single knots, the largest total KD was used (Fig. 2). For each spike knot, the length of the knot projected on the wide face was measured as well as the widest part at 90° to the edge of the lumber; these dimensions were summed then divided by two to determine the KD. The density (D) was measured in units of kg/m^3 using the dimensions of the entire specimen at 12 percent moisture content according to ASTM D2395 (ASTM International 2017).

Differing groups of variables concerning a specimen were used to build two stepwise linear regression statistical models. Model 1 involved variables CW, KA, D, and MOE while Model 2 involved variables KD, D, and MOE. One goal of this study was to use variables that could be easily measured using machine vision with the use of machine stress-rating equipment. The difference between both models is the knot variables used. Thus, the comparison of these two models was used to indicate which knot measurement would be more adequate to predict the MOR.

Static bending test

A Tinius Olsen (Horsham, Pennsylvania) universal testing machine along with the standard ASTM D198-15 (ASTM International 2015) was used to determine the flatwise MOE and MOR of all specimens. The flatwise test made it possible to orient each specimen such that the face with the maximum KD was in tension. The machine was set up in a third-point loading configuration with a span:depth ratio of 17:1. A third-point loading system was used to eliminate shear forces between the two loading heads. The standard 17:1 span:depth ratio was used per ASTM guidance. Thus the span was approximately 64.8 cm. The specimens were placed in the testing fixture such that the knotted section of interest was between the load heads and thus received the maximum bending moment. The rate of loading was constant at 7.6 mm/min and followed ASTM

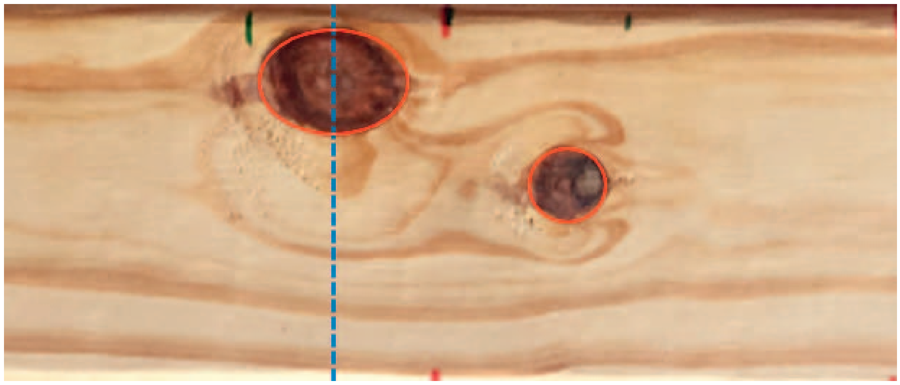

Figure 1.—The line perpendicular to the specimen length and across the wide face intersects only one knot. There are two single knots in this figure.

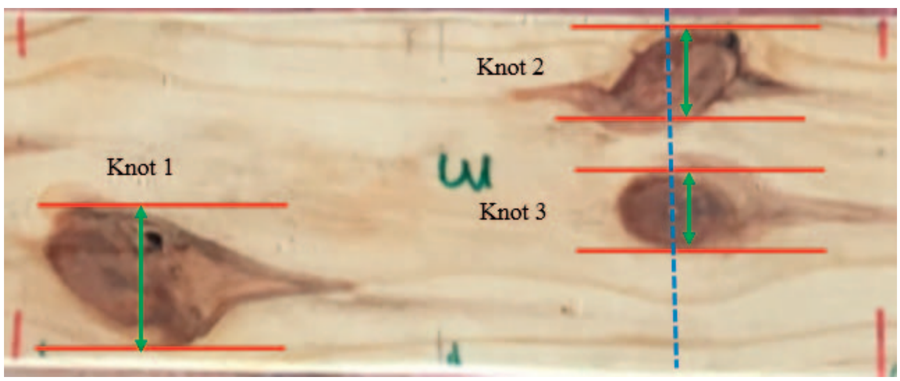

Figure 2.—Knot 1 is a single knot and Knots 2 and 3 are cluster knots.

D4761 (ASTM International 2019). The MOE was obtained from the linear elastic portion of the stress versus the strain-loading curve. The MOR was calculated from the load at failure (Castéra et al. 1996).

Statistical analysis

Pearson's correlation was performed for both statistical models. The correlation coefficients indicated the relative importance of the variables and served as a basis to decide how the independent variables affected the dependent variable. The Pearson correlation matrix was used to determine the relationship or the strength of the association between variables. A Pearson correlation matrix was created dealing with each variable outlined in regression Models 1 and 2, which can be seen in Tables 2 and 3. Linear stepwise multiple regression was performed using MOR as the dependent variable and MOE, D, CW, and KA as the independent variables for Model 1. The MOE, D, and KD were used as the independent variables for Model 2. A higher level of correlation was sought, so each step of the regression model added an independent variable to improve the correlation to the dependent variable, MOR. The statistical analyses were performed using the software IBM SPSS statistics, version 24 (IBM 2016).

Table 1.—Summary statistics for 2 by 4-inch southern yellow pine dimensional lumber specimens.

Property[a]	*N*	Minimum	Maximum	Mean	SD
MOR (MPa)	278	12.29	74.72	36.51	12.89
MOE (GPa)	278	0.44	13.14	7.35	2.34
D (kg/m^3)	278	396.94	676.30	496.02	49.40

[a] MOR = modulus of rupture; MOE = modulus of elasticity; D = density.

Results and Discussion

Table 1 summarizes the basic characteristics of the 2 by 4-inch SYP dimensional lumber specimens. Pearson's correlation (r) analysis was used to examine the strength of linear association between different parameters. The correlations between the parameters for Models 1 and 2 are shown in Tables 2 and 3, respectively.

Table 2.—Pearson's correlation matrix for stepwise linear regression Model 1 parameters.

Variable[a]	D	CW	KA	MOE	MOR
D	1	0.076	−0.018	0.492*	0.506*
CW	0.076	1	−0.683*	0.210*	0.357*
KA	−0.018	−0.683*	1	−0.284*	−0.431*
MOE	0.492*	0.210*	−0.284*	1	0.751*
MOR	0.506*	0.357*	−0.431*	0.751*	1

[a] D = density; CW = clear wood; KA = knot area; MOE = modulus of elasticity; MOR = modulus of rupture.
* Correlation is significant at the 0.01 level (2-tailed).

Table 3.—Pearson's correlation matrix for stepwise linear regression Model 2 parameters.

Variable[a]	D	KD	MOE	MOR
D	1	−0.200*	0.492*	0.506*
KD	−0.200*	1	−0.446*	−0.633*
MOE	0.492*	−0.446*	1	0.751*
MOR	0.506*	−0.633*	0.751*	1

[a] D = density; KD = knot diameter; MOE = modulus of elasticity; MOR = modulus of rupture.
* Correlation is significant at the 0.01 level (2-tailed).

The correlations between D, MOR, and MOE were equal for both models because the data used to determine these parameters were the same. The relationships between these three variables and the MOR were all significant at the 0.01 level. The results determined herein are similar with other softwood studies. Not unexpectedly, the highest correlation was between MOE and MOR. Castéra et al. (1996) analyzed maritime pine (*Pinus pinaster* Aiton) timber properties and found $r = 0.775$ between MOE and MOR, which is very close to the r value of 0.751 obtained in this study. D usually shows significant correlations with the mechanical properties of wood (Kretschmann 2010). However, the significance level of correlation is affected by specific lumber characteristics (juvenile or mature wood, proportion of defects, etc.; Castéra et al. 1996). A previous study (Senft et al. 1962) investigated Douglas-fir and reported $r = 0.435$ between D and MOR. The correlation between D and MOR obtained in this study was 0.506. Castéra et al. (1996) obtained a higher correlation of 0.625 for the marine pine timber between D and MOR.

Model 1 included the variables KA and CW. KA is a variation of the KA ratio (KAR, not measured in this study) which is measured as a projection of the knots located within a certain length to the cross section of the lumber under scrutiny. Previous authors have used KAR to investigate the strength reduction created by knots (Johansson et al. 1992, Castéra et al. 1996). Table 2 shows a correlation between KA and MOR of –0.431. As expected, the negative correlation between KA and MOR demonstrates and confirms that knots contribute to potentially quantifiable strength reduction. Johansson et al. (1992) obtained $r = –0.51$ for Nordic spruce (*Picea* sp.) lumber for the correlation between KAR and MOR. Castéra et al. (1996) obtained a correlation of –0.644 for correlation between KAR and MOR. The KAR method counts all the projection of the knots on the cross section while the KA method counts the area projected on the wide face. Therefore, the correlations are higher for KAR than for KA. However, KA appears to be a good predictor of MOR, and it can be easily obtained despite KA being a parameter that is based on estimations. CW was the other variable used in Model 1 to predict the MOR. The correlation between CW and MOR was 0.357. Although this value was statistically significant, it was the lowest coefficient among the correlations between the other variables and MOR. Model 2 included only one parameter to describe the knots, KD. As shown in Table 3, the correlation between KD and MOR was –0.633. Compared with the knot parameters of Model 1, KD had the strongest correlation with MOR. The method used to determine the KD was similar to the method used to grade SYP.

The stepwise regression method was used to determine the order in which each variable was added to the models. To avoid potential issues with multicollinearity due to the high correlation between CW and KA, the variable CW was excluded from Model 1, shown in Table 4. As seen in the correlation matrix (Tables 2 and 3), the MOE had a strong correlation with MOR. In Model 2 (Table 5), KD had a higher contribution than KA when compared with Model 1. The additional variance explained by D was small (0.027); however, the simplicity of its measurement justifies its use. Model 2 showed better results than Model 1 for predicting the MOR value. The coefficient of determination when using all variables contained in Model 2 was 0.702 when contrasted with 0.564 obtained by using MOE alone to predict MOR. Quadratic and cubic regressions were conducted for the variables using MOR as dependent variable. The variance of the coefficient of determination (lower than 5%) did not justify making the model more complex.

Table 4.—Stepwise linear regression for Model 1 parameters to determine modulus of rupture.

Step	Independent variables[a]	r	r^2	Adjusted r^2	SE of the estimate	r^2 change	F change	df	F change significance
1	MOE	0.751	0.564	0.562	80.53	0.564	356.62	276	0.000
2	MOE, KA	0.784	0.615	0.613	80.03	0.052	36.90	275	0.000
3	MOE, KA, D	0.808	0.652	0.648	70.65	0.037	28.98	274	0.000

[a] MOE = modulus of elasticity; KA = knot area; D = density.

Table 5.—Stepwise linear regression for Model 2 parameters to determine modulus of rupture.

Step	Independent variables[a]	r	r^2	Adjusted r^2	SE of the estimate	r^2 change	F change	df	F change significance
1	MOE	0.751	0.564	0.562	8.53	0.564	356.62	276	0.000
2	MOE, KD	0.821	0.675	0.672	7.38	0.111	93.70	275	0.000
3	MOE, KD, D	0.838	0.702	0.699	7.08	0.027	25.04	274	0.000

[a] MOE = modulus of elasticity; KD = knot diameter; D = density.

Conclusions

Knots are known as characteristics that negatively affect the mechanical properties of wood. Knots have this impact because they interrupt the flow of the wood grain. The exact effect of a knot on the strength depends on the proportion of the cross section of the piece occupied by the knot, the nature and type of loading, and the knot's relative location in the piece. In this study, the effect that knots in close proximity have on the mechanical properties of SYP was investigated and quantified using simple parameters.

There was a significant correlation between all the measured independent variables and the dependent variable MOR. Both KA and KD were found to have negative correlations with MOR, confirming that knots are strength-reducing characteristics when located on the tensile face of a flexural specimen. Other parameters increased the amount of variance explained. The amount of additional variance explained by D was small (0.027); however, its ability to be easily measured likely justifies its incorporation in the statistical model. A linear regression using KD, D, and MOE achieved a coefficient of determination of 0.702 as contrasted with 0.564 obtained by only using only the MOE value to predict MOR. This study was able to demonstrate, using easily obtainable parameters, that the presence of multiple knots significantly affects the strength properties, and that these parameters can be used to better predict the MOR of lumber containing multiple knots.

Acknowledgments

The authors acknowledge the support from US Department of Agriculture (USDA) Forest Service Forest Products Laboratory (FPL) in Madison, Wisconsin, as a major contributor of technical assistance, advice, and guidance to this research. This report was made possible through a grant from the USDA Forest Service under FPL agreement number 16-JV-11111133-058. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Literature Cited

ASTM International. 2015. Standard test methods of static tests of lumber in structural sizes 1. ASTM D198-15. ASTM International, Philadelphia, Pennsylvania.

ASTM International. 2017. Standard test methods for density and specific gravity (relative density) of wood and wood-based materials. ASTM D2395-17. ASTM International, Philadelphia, Pennsylvania.

ASTM International. 2019. Standard test methods for mechanical properties of lumber and wood-based structural materials. ASTM D4761-19. ASTM International, Philadelphia, Pennsylvania.

Castéra, P., C. Faye, and A. El Ouadrani. 1996. Prevision of the bending strength of timber with a multivariate statistical approach. *Ann. Forest Sci*. 53(4):885–896.

Green, D. W., J. E. Winandy, and D. E. Kretschmann. 1999. Mechanical properties of wood. *In:* Wood Handbook: Wood as an Engineering Material. General Technical Report FPL; GTR-113. USDA Forest Service Forest Products Laboratory, Madison, Wisconsin. pp. 4.1–4.45.

Guindos, P. and M. Guaita. 2013. A three-dimensional wood material model to simulate the behavior of wood with any type of knot at the macro-scale. *Wood Sci. Technol*. 47(3):585–599.

Guindos, P. and T. Polocoser. 2015. Numerical calculations of the influence of the slope of grain on the effect of knots. *Eur. J. Wood Wood Prod*. 73(2):271–273.

IBM. 2016. IBM SPSS Statistics for Windows, version 24. IBM, Armonk, New York.

Johansson, C.-J., J. Brundin, and R. Gruber. 1992. Stress Grading of Swedish and German Timber. A Comparison of Machine Stress Grading and Three Visual Grading Systems. Swedish National Testing and Research Institute, Boras, Sweden. 92 pp.

Kretschmann, D. 2010. Mechanical properties of wood. *In:* Wood Handbook: Wood as an Engineering Material. General Technical Report FPL; GTR-190. USDA Forest Service Forest Products Laboratory, Madison, Wisconsin. pp. 1–5.

Nardin, A., L. Bostrom, and F. Zaupa. 2000. The effect of knots on the fracture of wood. Washington State University, Pullman. p. 7.

Senft, J. F., S. K. Suddarth, and H. D. Angleton. 1962. A new approach to stress grading of lumber. *Forest Prod. J*. 12:183–186.