Effect of Knots on Horizontal Shear Strength in Southern Yellow Pine

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Knots are inevitable components found in wood that can adversely affect the mechanical properties of the lumber. The objective of this study was to investigate the effect of knots on the horizontal shear strength of southern yellow pine. Knot condition (sound/unsound) and shear plane (radial/tangential face) were studied as the factors of shear strength. The standard ASTM D143-94 (2014) was used to compare 120 pairs of clear shear blocks and shear blocks containing knots. Paired t-test results showed that regardless of the direction of the grain compared with the shear plane (perpendicular or parallel), sound knots increased the shear strength and the unsound knots decreased shear strength. Based on this study, the unsound knot volume was found to be a significant factor in decreasing the shear strength in the radial or tangential face direction. Furthermore, no significant relationship between the knot angle and shear strength was found. Shear failure occurred in the wood when an encased knot sample was tested and shear failure occurred in the knot when an intergrown knot sample was tested.

Keywords: Shear strength; Knots; Angle; Volume; Shear failure; Southern yellow pine

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INTRODUCTION

Branches are essential for tree growth so that leaves can propagate on a tree for photosynthesis. Knots found in lumber are the remnants of those branches. These knots can appear as encased knots or intergrown knots. An encased knot can form when a tree grows around a dead branch, and these type of knots are usually surrounded by a dark ring with a decaying center. Encased knots are also referred to as "loose" knots because the bark inhibits the knot from tightly binding to its surrounding wood. Encased knots are those whose rings of annual growth are not intergrown with those of the surrounding wood. An intergrown knot typically refers to the base of a living branch on a tree. Intergrown knots are usually surrounded by a halo of circular growth rings. These intergrown knots are also referred to as "tight" knots because these knots are securely bound to the wood surrounding them. Encased and intergrown knots can further be divided into sound and unsound knots. Unsound knots tend to have decay, while sound knots are solid across the face and show no symptoms of decay. Examples of these classifications can be seen in Table 2,

In general, the branch tissue of softwoods is characterized as material that has a higher density than the stem wood, small or incomplete annual rings, a high proportion of compression wood, an increased microfibril angle, increased lignin content, and a decreased fiber length (Shigo 1985). Knots have been widely considered as defects in regard to wood quality, which can adversely affect the strength properties (USDA 1999). Guindos and Polocoser (2015) investigated the influence of the slope of the grain on the strength-reducing effect of face knots. They claimed that the modulus of rupture (MOR) of beams containing knots could be reduced by up to 50%. In addition, knots were shown to significantly affect the modulus of elasticity (MOE) (Hossein *et al.* 2011). Dávalos-Sotelo and Ordóñez Candelaria (2011) stated that knots negatively affected the bending strength of pine wood and their presence significantly decreased the value of the wood.

Douglas fir shear blocks have been previously tested to determine their shear strength (Gupta *et al.* 2004). Specimens tested included those with knots parallel and perpendicular to the shear plane, as well as those with no knots. The results showed that there was no significant difference in the mean shear strength of clear and knotted specimens, regardless of their orientation. Baño *et al.* (2013) used the finite element analysis method to investigate the effect that knots have on the bending strength of beams using the knot condition, size, and position as variables. Their research considered knot sizes with diameters of 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm. It was discovered that the bending strength of the beams decreased as the knot size increased, and this bending strength decrease was enhanced when the distance from the neutral axis was increased. A theoretical model (Ping 2000) revealed that knots negatively affected the stiffness (MOE) of pine lumber. To date, the influence of knot angles and the influence of sound and unsound knots on the shear strength of southern yellow pine have not been widely researched.

The objective of this study is to investigate the effects of knots on horizontal shear strength when the shear plane is parallel to the tangential and radial face of southern yellow pine. The knot size, knot condition, and the knot angle are investigated using shear blocks to determine how these factors affect shear strength. This study involves the consideration of various knot conditions (Fig. 2, Table 2) using shear block analysis of southern yellow pine for the first time.

EXPERIMENTAL

Materials

Sample preparation

Southern yellow pine (*Pinus spp.*) lumber was obtained from the Shuqualak Lumber Company located in Shuqualak, MS, USA. A table saw, an arm saw, and a band saw were used to cut the Southern yellow pine lumber into blocks with the specifications shown in Fig. 1. The samples were produced with dimensions of 1.5 in × 1.5 in × 2.5 in (modified ASTM D143-94 (2014)). Literature suggests that although these dimensions reduced shear area when compared to the ASTM D143-94 (2014) standard, this modification has an insignificant effect on the ultimate shear strength (Bendtsen and Porter 1978; Lang and Kovacs 2001). A total of 120 paired shear blocks were prepared. Each pair included one clear sample and one sample containing a knot. These samples were cut adjacent to one another to perform a comparison. They were assembled into four groups based on the knot condition and the shear plane direction. Group A contained 30 pairs of clear samples and sound knot samples in which the shear plane was parallel to the tangential face.

The knot condition was visually classified. Sound knots were solid from face to face with no decay symptoms. Unsound knots had noticeable decayed characteristics according to the Southern Pine Inspection Bureau. Group B contained 30 pairs of clear samples and unsound knot samples in which the shear plane was parallel to the tangential face. Group C contained 30 pairs of clear samples and sound knot samples in which the shear plane was parallel to the radial face. Group D contained 30 pairs of clear samples and unsound knot samples in which the shear plane was parallel to the radial face. Groups A, B, C, and D are shown in Figs. 2a, 2b, 2c, and 2d, respectively. Figure 2 shows that Groups A and B had growth rings positioned parallel to the shear tool (tangential), and Groups C and D had the growth rings positioned perpendicular to the shear tool (radial). The southern yellow pine lumber, which was used for this study, was conditioned at 20 °C ± 2 °C and 65% ± 5% air relative humidity for one month. All knots were classified as Type 3 knots as stated by the ASTM D4761-13 (2013) standard.

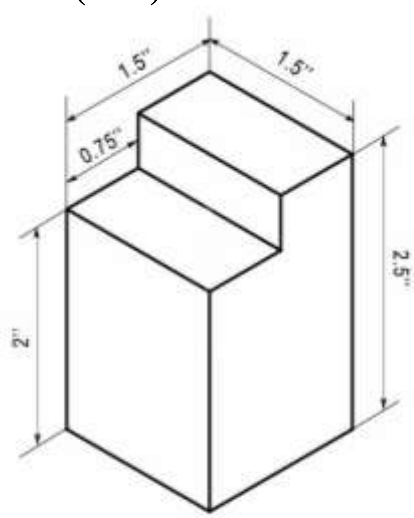


Fig. 1. Shear block sample dimensions

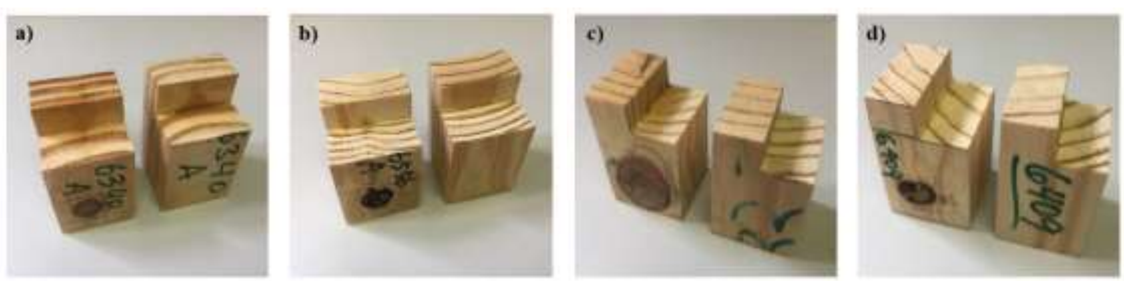


Fig. 2. Each group was tested with a matched clear sample. a: Group A, tangential testing with sound knot; b: Group B, tangential testing with unsound knot; c: Group C, radial testing with sound knot; d: Group D radial testing with unsound. Groups A and B - growth rings parallel to shear tool (tangential); Groups C and D - growth rings positioned perpendicular to shear tool (radial).

Methods

Measurements – Knot angle

The branches that form the knots in lumber begin growing from the pith and continue to radially grow outwards, such that when lumber is cut closer to the pith, the knots contained in the lumber are smaller and more numerous. The shear block dimensions used in this study were 1.5 in × 1.5 in × 2.5 in, and all the knots used in this project were characterized as Type 3 (face to face) knots. There were no knots on any one surface larger than 1.5 in × 2.5 in. The knot angle was measured by connecting the centers of the knot in two faces.

Knot volume

The outer surface of the lumber from which the shear block sample was taken was used to characterize the knots as sound or unsound. For example, if the inner side (from the lumber) of the sampled knot was sound and the outer side was unsound, then the overall sample was classified as an unsound knot sample. The knot sizes on both surfaces were measured according to ASTM 4761-13 (2013). In addition, all dimensions were measured to calculate the volume of the shear block using Eq. 1,

$$V = \frac{1}{3}\, d\, (S1 + \sqrt{S1S2} + S2) \tag{1}$$

where V is knot volume (mm^3), $S1$ is the area of the knot located on surface 1 (mm^2), $S2$ is the area of the knot located on surface 2 (mm^2), and d is the thickness of the shear block (mm).

Shear strength

All specimens were tested on a Tinius-Olsen universal testing machine (Tinius Olsen Testing Machine Company, Horsham, PA, USA) at a loading rate of 0.6 mm/min (0.024 in/min) in accordance with the ASTM D143-94 (2014) standard. The width and thickness of the shear plane were measured and recorded before the tests were performed. Ultimate loads and specimen failure modes were recorded. The shear strength was calculated by dividing the ultimate load by the shear plane area. After testing, the specific gravity (SG) was determined for each specimen according to ASTM D2395-14 (2014). The SG was adjusted to 12% moisture content using equations given in the Wood Handbook (1999).

Fig. 3. Shear block testing apparatus

Analysis

The software SAS 9.4 (SAS Institute Inc., version 9.4, Cary, NC) was used in this study to perform the statistical analysis. A paired t-test with a significance level of 0.05 was used to analyze the difference between the clear samples and samples containing knots. The correlation analyzation was based on a significance level of 0.05 to investigate the relationship between knot volume and knot angle with shear strength.

RESULTS AND DISCUSSION

Influence of Knot Condition on Shear Strength

The mean shear strength of each of the four groups is shown in Table 1. The average SG of all specimens was 0.53 with a full range of 0.36 to 0.85. The samples that contained knots had a SG of approximately 0.61 (ranging from 0.45 to 0.85), while the matched clear samples had a SG of approximately 0.44 (ranging from 0.36 to 0.55).

Table 1. Mean Shear Strength of Four Groups

Groups/Parameter	Knot Condition	N [a]	Mean Shear Strength [b] (MPa)	Specific Gravity
Group A (shear plane parallel to tangential face)	Sound	30	12.50 (0.17)[c]	0.63 (0.14)
	Matched clear	30	9.91 (0.17)	0.44 (0.10)
Group B (shear plane parallel to tangential face)	Unsound	30	9.91 (0.25)	0.61 (0.12)
	Matched clear	30	10.70 (0.13)	0.46 (0.06)
Group C (shear plane parallel to radial face)	Sound	30	10.50 (0.17)	0.61 (0.14)
	Matched clear	30	9.59 (0.17)	0.42 (0.10)
Group D (shear plane parallel to radial face)	Unsound	30	9.34 (0.23)	0.59 (0.11)
	Matched clear	30	10.90 (0.14)	0.45 (0.10)

[a] N = number of observations; [b] Adjusted to 12% moisture content; [c] Values in parentheses are coefficients of variation

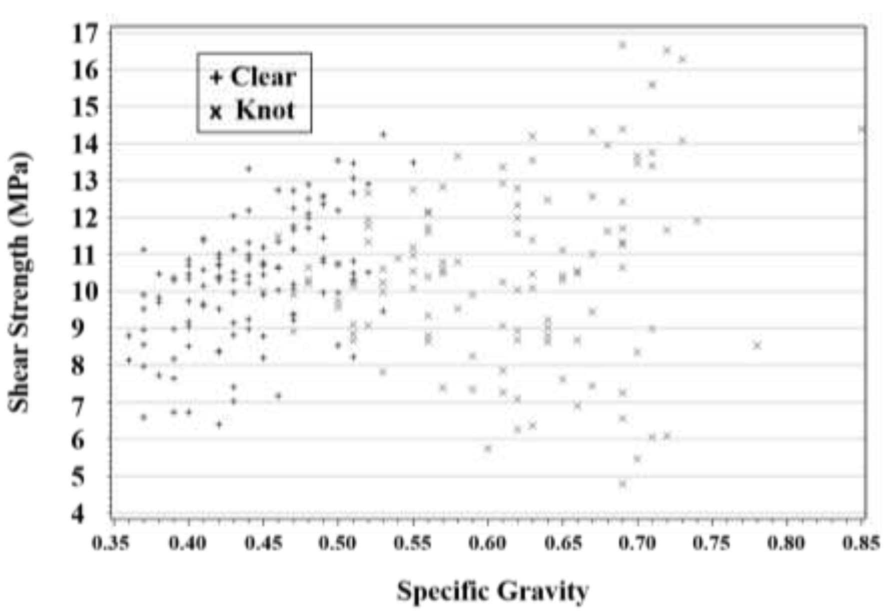


Fig. 4. Distribution of SG and shear strength by type of sample

In addition, as Fig. 4 shows, the clear samples and knot samples did not have much overlap on the SG *versus* shear strength graph. This result revealed that the SG of knot samples and clear samples had a considerable difference. The difference of SG between the knot samples and the matched clear samples was primarily an effect of the knots. This difference occurred because knots may contain many extractives including polyphenols, such as lignans, oligolignans, and stilbenes (Willför *et al.* 2003). Therefore, the SG was not considered as an independent factor when analyzing the differences between the knot samples and clear samples in this study.

The paired profile in the shear strength between the clear samples and the samples containing knots of each group are shown in Fig. 5. According to the paired t-test results, there were significant differences ($\alpha = 0.05$) in all groups with respect to mean shear strength when the samples containing knots was compared with the matched clear samples. Specifically, in Groups A and C, the sound knot samples had a significantly higher shear strength than the clear samples; while in Groups B and D, the clear samples had a significantly higher shear strength than the unsound knot samples. Therefore, it can be summarized as regardless of the direction of the grain compared with the shear plane (radial or tangential face), the sound knots increased the shear strength and the unsound knots decreased shear strength.

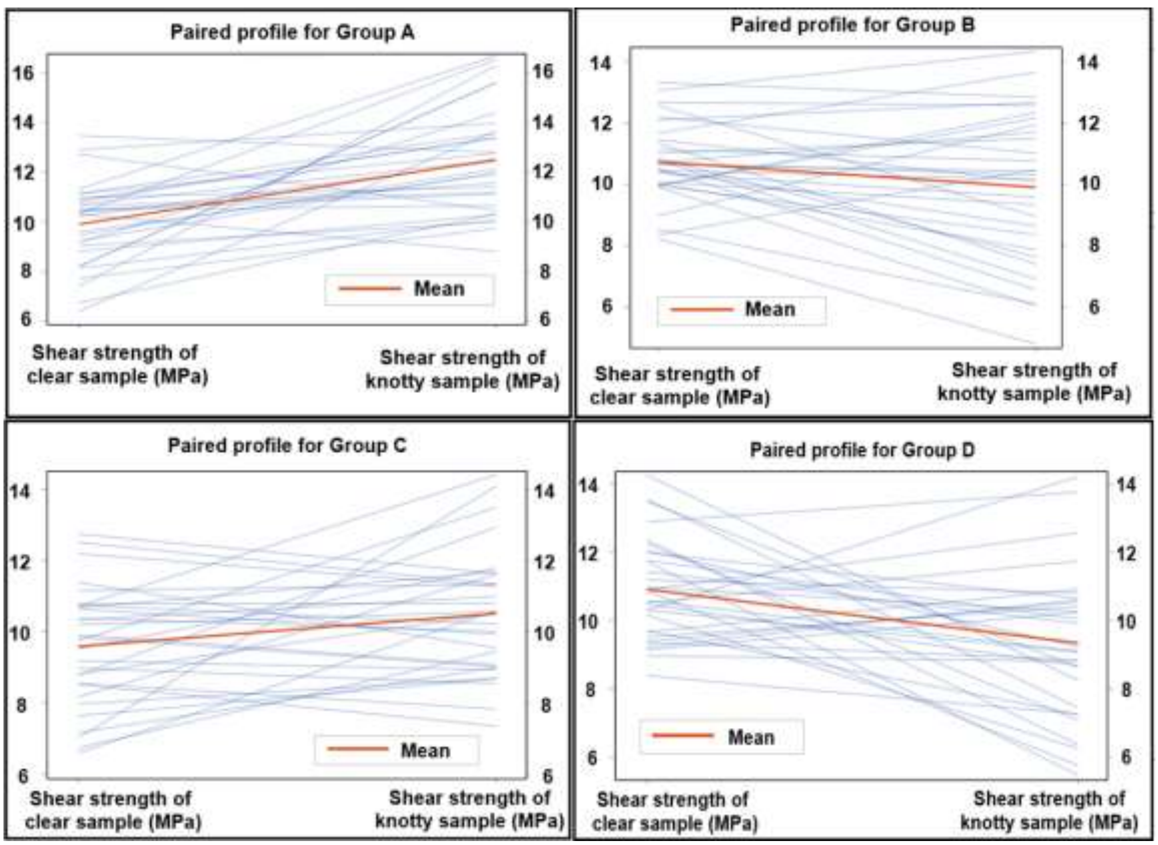


Fig. 5. Paired profiles of Group A, B, C, and D

Sound knots enhanced the shear strength 26.2% when oriented and loaded through the tangential face (Group A). When the shear plane was oriented through the radial face (Group C), sound knots increased the shear strength 9.6%.

Unsound knots can be considered as a defect with respect to horizontal shear strength. When present, the shear strength decreased 7.6% when the shear plane was through the tangential face (Group B), and decreased 14.4% when the shear plane was through the radial face (Group D).

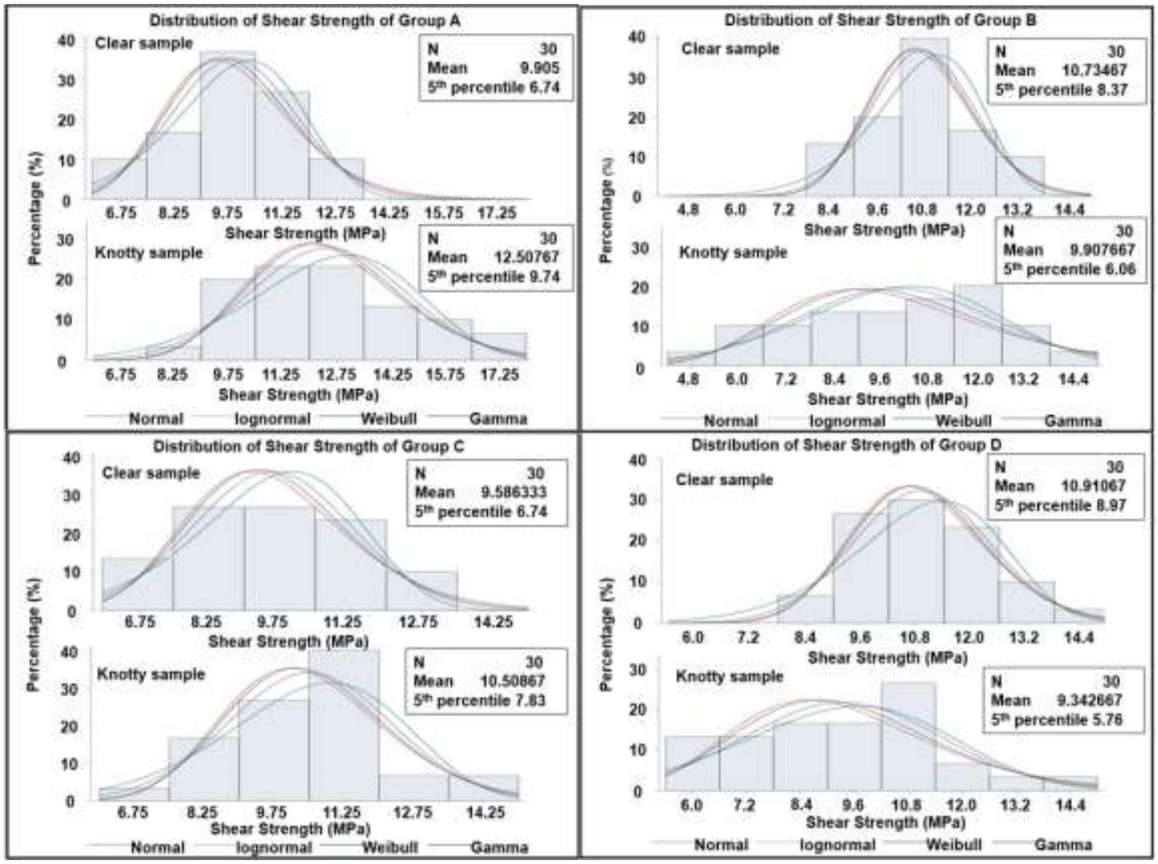
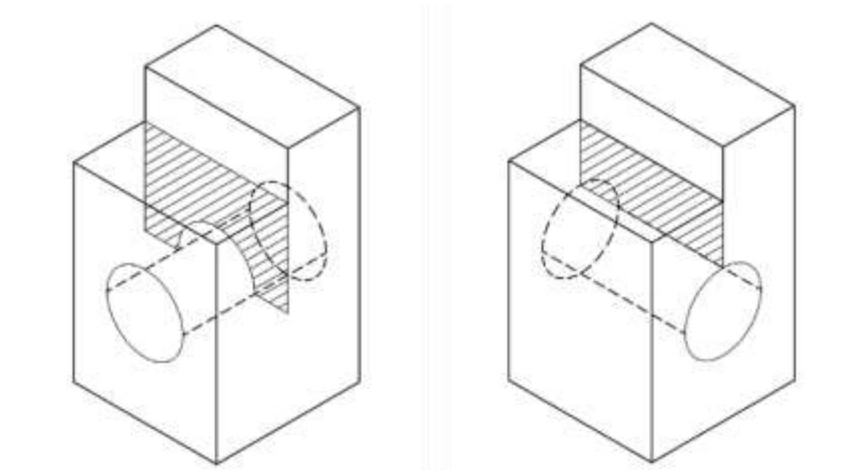


Fig. 6. Shear strength distribution of clear sample and knotty sample in Group A, B, C, and D.

The shear strength distribution and population means of knotty samples and matched clear samples of each group with each's mean shear strength (μ) values are shown in Fig. 6. Each population fit a normal distribution based on the Anderson-Darling test. The knotty samples had a larger variation in each group due to different knot characteristics, including the knot volume, knot angle, and knot soundness (Fig. 5). The paired t-test showed that in Group A and Group C, the mean shear strength of the sound knot blocks was significantly higher than the mean shear strength of the matched clear blocks based on the significance level of 0.05, with p-values of less than 0.0001 and 0.0237, respectively.

In this study, the results from the sound knots were similar to the results from Rajput *et al.* (1980), in which the knots drastically increased the shear strength of *Cedrus deodara* in both directions. They reported that the reductions in strength can be mainly attributed to the grain pattern in the wood. Their study did show some differences when comparing the radial and tangential shear planes. The reinforcement was stronger when the shear plane was parallel to the radial face. However, in the present study, the reinforcement was stronger when the shear plane was through the tangential face.

The type of species tested does tend to have an effect on the shear strength to a certain extent. A shear block study (Okkonen and River 1989) of full size samples which were double notched showed that samples tested in the tangential direction were stronger when compared to the radial direction for southern pine, and the opposite was true for Douglas-fir. At this time there is not enough data available to come to a conclusion regarding the effect that knots have among differing species, so future studies are needed to determine how varying types of knots affect various species.



a b

Fig. 7. Clear wood amount in shear plane when shear plane parallel to tangential face (a) and radial face (b)

A contributing factor to the strength of the sample was the amount of clear wood available in the shear plane to support the load, as well as the orientation of the clear wood. In Group A and Group B knots were perpendicular to the shear plane in the axial direction (Fig. 7a) and clear wood was available in this plane to help support the loading. However, when the shear plane was parallel to the knots (Group C, Group D, Fig. 7b), more of the knot volume was located within the shear plane. Hence, more clear wood would contribute to the strength of knots oriented in Group A and Group B, and not as much clear wood was available in Group C and Group D. This is why sound and unsound knotty samples had a higher mean shear strength in Group A and Group B. The intergrown and encased knots within the sound knot group of this study were not separated into two sub-groups before testing. This separation will be considered in future studies.

Influence of Knot Size and Angle on Shear Strength

The knot condition, size, and angle are the basic characteristics that define a knot and can be factors that affect the shear strength. The branches that form knots in lumber begin growing from the pith and continue to grow radially outwards, such that when the lumber is cut closer to the pith, the knots contained in the lumber are smaller and more numerous. The shear block dimensions were 1.5 in × 1.5 in × 2.5 in, and all the knots used in this project were characterized as Type 3 (face to face) knots. There were no knots on any one surface larger than 1.5 in × 2.5 in. Based on this and the fact that the knot surface area was not uniform on both sides of each specimen, this study attempted to have a more consistent knot characterization by using the knot volume instead of the knot size on either surface.

According to correlation analyzation based on a 0.05 significance level, in Group A both knot angle (R = 0.53) and knot volume (R = 0.57) were positive factors of shear strength; in Group B, only knot volume had a negative coefficient of correlation (R = -0.69); in Group C, both knot angle and volume were not significant, and only SG had a slightly positive effect on shear strength (R = 0.39); in Group D, knot volume had a negative correlation coefficient (R = -0.44). The SG of the knot samples used in the correlation analysis was the SG of matched clear samples because the SG of clear wood located in the shear block samples with knots was assumed to be similar to the matched clear samples.

As the results showed, when it comes to sound knots, if the shear plane was through the tangential face (Group A), the horizontal shear strength increased with increasing knot angle and knot volume. In this study, knot samples were randomly chosen, and the data revealed that the knot angle and knot volume had a strong positive relationship in Group A, according to the correlation analysis. Some samples that had large knot volumes also had large knot angles, so it cannot be definitively stated that both knot angle and knot volume were positive factors of shear strength in Group A. If the shear plane was parallel to the radial face (Group C), both knot volume and knot angle were not influential toward shear strength.

When it comes to an unsound knot (Groups B and D), knot volume was a negative factor of shear strength. Less clear wood around the knot in the shear block was available to support the shear load as the unsound knot volume increased. Therefore, the failure occurred at lower loading values in unsound knots as the knot volume increased.

When the shear plane was oriented parallel to the radial face (Groups C and D), the knot went through the shear plane regardless of the knot angle. Thus, it was reasonable that there was no relationship between knot angle and shear strength in Groups C and D. Only in Group C did the SG show a positive relationship with shear strength.

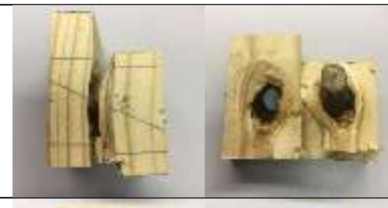
Analysis of the Shear Failure in Blocks Containing Knots

Several different types of shear failures were noted. Encased knots and intergrown knots represented different relationships between the knots and surrounding clear wood and therefore, they did affect the shear failure mode. When the shear plane was parallel to the tangential face, shear failure appeared both on the radial face and tangential face, while when shear plane was parallel to the radial face, the shear failure only appeared on the tangential face.

A detailed description with pictures is shown in Table 2, and the knot condition is discussed in detail. The study showed that if the knots in the samples were encased knots, the shear failure was determined to be wood failure only. This occurred because the rings of annual growth were not intergrown with the surrounding wood.

The intergrown knots were completely intergrown on one or both faces of the surrounding wood. Hence, the intergrown knot samples displayed failure throughout the knot. This finding likely occurred because the structural and functional arrangement of the branch and stem tissue gives the branch–trunk junction its unique properties for strength, flexibility, and resiliency (Shigo 1985). The knot pith was often the weakest area where cracks occurred.

Table 2. Shear Failure Descriptions

Direction	Type	Sound /Unsound	Description	Pictures
Tangential (shear plane parallel to the tangential face)	Encased knot sample	Sound knot sample	Wood failure. Failure along wood grain in radial section. Crack around the knots, and knots were loose.	
		Unsound knot sample	Wood failure. Failure along wood grain in radial section. Cracks appeared on tangential section.	
	Intergrown knot sample	Sound knot sample	Knot failure. Failure along wood grain in radial section. Cracks appeared in knots.	
		Unsound knot sample	Knot failure. Failure along wood grain in radial section. Some cracks appeared in the tangential section.	
Radial (shear plane parallel to the radial face)	Encased knot sample	Sound knot sample	Wood failure. Failure along the brim of knot in tangential section. No failure in the radial section.	
		Unsound knot sample	Wood failure. Cracks in the tangential section. No failure in radial section.	
	Intergrown knot sample	Sound knot sample	Knot failure, cracks appeared through the center of knot in the tangential section. No failure in radial section.	
		Unsound knot sample	Knot failure. Cracks appeared along the decayed part of knot in tangential section. No failure in radial section.	

CONCLUSIONS

1. The knot condition was a significant factor of horizontal shear strength in both planes. Specifically, a sound knot enhanced the shear strength, while an unsound knot decreased shear strength. The sound knot increased shear strength by 26.2%, and 9.6% when the shear plane was parallel to tangential face and radial face, respectively. The unsound knot decreased shear strength 7.6% and 14.4% of shear strength when the shear plane was parallel to tangential face and radial face, respectively.
2. Unsound knot volume showed a significantly negative effect on horizontal shear strength. No relationship between knot volume and shear strength was found in sound knots. In addition, no significant relationship was found between the knot angle and shear strength in this study. However, the level of knot angle and knot volume were not well distributed in this study.
3. Shear failure type was dependent on the knot condition. When the knot was encased, failure occurred in the wood, however if the knot was intergrown, failure occurred in the knot. The failure type did not change when the knotted specimens were loaded through the tangential or radial face.

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