WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

TESTING OF SMALL CLEAR TENSION PERPENDICULAR TO GRAIN SAMPLES OF SUGAR MAPLE FOR RADIAL, TANGENCIAL AND 45 DEGREE LOADING ORIENTATIONS

David E. Kretschmann[1], Nilson T. Mascia[2]

ABSTRACT: Sugar Maple is an important material for use in baseball bats. It currently represents over 78% of all bats used in major league play. Since 2008 a technical team has started an investigation on the perpendicular tension strength. Moreover, the discussion of the importance of the perpendicular tension strength to better understand the wood's mechanical behavior in several situations, such as shrinkage analysis, glued laminated beam failure analysis, has become clear that more basic input information on tension perpendicular to grain is needed.

This work investigated tension perpendicular to grain properties for radial, tangential and 45-degree directions, using Sugar Maple specimens, and testing methodology according to ASTM D143. From the statistical analysis, it can be concluded that the experimental results of tension perpendicular to grain strength loaded in the radial and tangential directions show a significant statistical difference. Strengths obtained at 45-degrees differ significantly from the other directions.

KEYWORDS: Tension perpendicular, Radial, Tangential 45-degree orientation, (*Acer saccharum*) Sugar Maple

1 INTRODUCTION

During the 2008 regular season the Safety and Health Advisory Committee (SHAC) of Major League Baseball (MLB) agreed to use an interdisciplinary technical team of external experts to investigate bat breakage in MLB games. The team was comprised of experts in wood science, risk and statistical analyses, and laboratory testing of baseball bats. The objectives for the team were to develop recommendations to be considered by Major League Baseball's and the Major League Baseball Players Association's SHAC to reduce the frequency of multi-piece bat failures and to propose future research projects for continued analysis of the problem. During this time an initiative was also started, the investigation of finite element modeling of various bat profiles.

The importance of the perpendicular tension strength in understanding the wood mechanical behavior in several situations, such as shrinkage analysis, glued laminated beam failure analysis and others is well known. The modeling we conducted indicated that more basic input information on tension perpendicular to grain on Sugar Maple (*Acer saccharum*) was needed.

In this context, this work investigates tension perpendicular to grain strengths for radial, tangential and 45-degree ring orientations of Sugar Maple and the anatomical characteristics that may cause the differences.

2 BACKGROUND

Knowledge of the perpendicular tension strength is important information for better understanding of the wood's physical and mechanical behavior. Wood shrinkage analysis, for example in a drying process, may be analyzed from the point of view of the influence of stresses in radial and tangential directions of wood and the strengths in these directions. Certain types of ruptures occur when stress generated by drying can reach levels greater than the perpendicular to grain strength [1] A prior study of Loblolly Pine (*P. taeda*) tension perpendicular strength [2] for different ring orientations of the following angles, 0°, 22.5°, 45°, 62.5° and 90°, illustrated that tension perpendicular to grain is very sensitive to ring orientation, reaching a minimum at the 45-degree orientation in Loblolly Pine.

In structures or structural elements there are several examples related to the tension perpendicular to grain strength [3] highlighted by the tension perpendicular to grain on various elements, such as glued laminated beams, straight or curves ones, in the local vinicity of a joint, with reduced section parts near supports, multiple notches, parts tensioned with notches and so on. In general, to evaluate the design or to verify the structural elements of wood as well, failure criteria are used [4]. Already, [5] presents an expression that combines both tension perpendicular to grain and shear stresses to verify or size the glued laminated timber pieces.

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The theoretical basis of these criteria involves the knowledge of the tension perpendicular to grain strengths and, for wood one of these strengths is related to tension perpendicular to the grain, noting that not only the orthotropic directions but also off axis directions should be taken into account.

Another issue to be considered in this study is related with the influence of the density on perpendicular to grain strength values, obtained with different load orientation, such as, in the radial, tangential and other direction.

In this context, this research evaluated the tension perpendicular to grain and used specimens, [6], in three different orientations, in the radial, in the tangential and in the 45-degree directions and also analyzed the influence of the density in these strengths.

3 MATERIALS AND METHODOLOGY

3.1 MATERIALS

The Sugar Maple (*Acer saccharum*) was collected from two sources. Leatherstockings in New York and Louisville Slugger in Louisville Kentucky.

An inventory of sugar maple billets supplied by Leaterstocking (L) and Louisville Slugger (S) was created to assess the overall density distribution for the maple billets and the distribution of density from each supplier. The material from Leatherstockings was represented by an L or L-Group) and the material from Louisville Slugger will be represented by an S (or S-Group).

Hard Maple billets that were 6.985 cm in diameter and 78.74 or 93.98 cm long were supplied to the carpenter shop at Forest Products Laboratory, Madison, WI, US. For 83 billets matched samples were cut up into 5.08-cm by 5.08-cm by 6.35- cm specimens for tension perpendicular to grain testing.

The cut out pattern is illustrated in Figure 1.

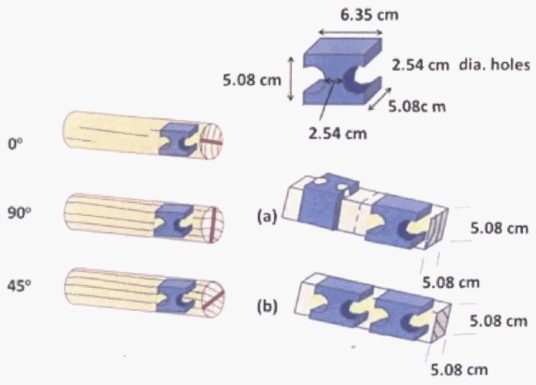

Figure 1: *Tension perpendicular to grain specimens*

3.2 PREPARATION OF SPECIMENS

3.2.1 Preparation of Specimens

The tension perpendicular to the grain samples came from the short sections of the billet illustrated in Figure 1. The orientation denoted by 0° or 90° corresponded to radial or tangential orientations (Figure 1 (a)), and for 45-degree orientation (Figure 1 (b)) two specimens were prepared, denoted by A and B for the 45-degree orientation.

The average moisture content for the specimens was 13% and the density range was 0.5749 to 0,7421 g/cm³, which histogram of the density is shown by Figure 2.

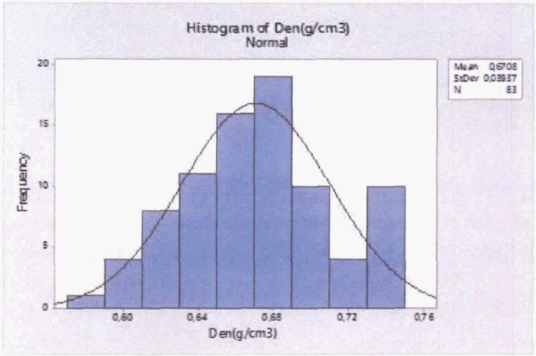

Figure 2: *Histogram of the density range of the total specimens.*

Histograms showing the density range for the 65 data for L-Group L and 18 for the S-Group, is presented in Figure 3 to highlight the variation between the densities of each group (Den(g/cm3)_L and Den(g/cm3)_S) It is noted that the S-Group mean density is 5.68% greater than the L-Group.

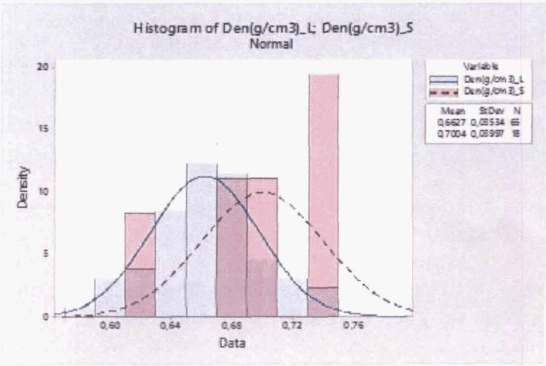

Figure 3: *Histogram of the density range of the specimens, for each group L and S.*

3.3 METHODOLOGY

3.3.1 Tension perpendicular to grain tests

The tension perpendicular to grain specimens were tested according to ASTM D143 [6]. The tests were conducted on specimens of the size and shape in accordance with Figure 1. The load was applied continuously throughout the test at a rate of motion of the movable crosshead of 2.5 mm/min as shown by Figure 4. Also it is included in Figure 4 to the specimen and the system of applying load details.

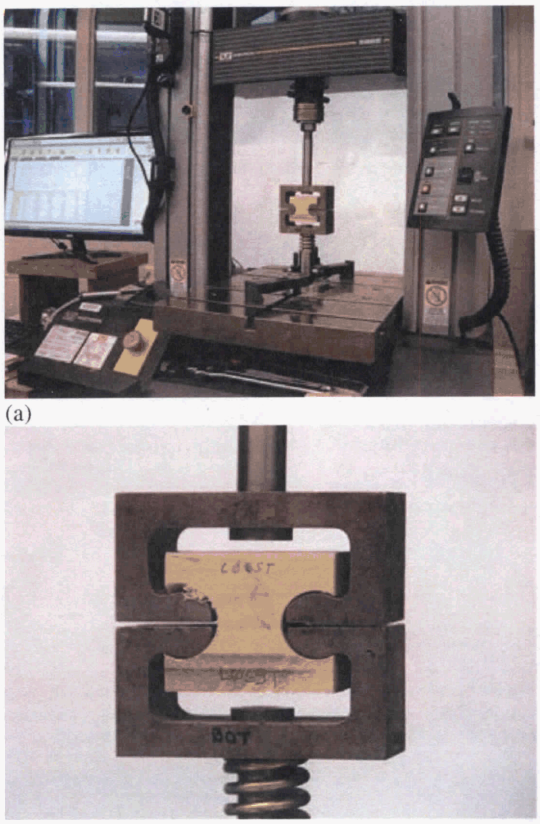

Figure 4: *(a) Tension perpendicular to grain loading system; (b) Detail of the specimen and the system of applying load.*

4 RESULTS

4.1 Tension perpendicular to grain

The strength for tension perpendicular to grain samples of Sugar Maple for radial, tangential and 45-degree (A and B) loading orientations, the results that were obtained are presented in Figures 5-8. The total sample is constituted by specimens from two different locations, L-Group and S-Group, the results were plotted in order to be shown the bias (tendency) of each group. In addition, it is presented the histogram of results of the entire sample [7].

Figure 5 exhibits the radial, tangential strengths for L-Group, whereas Figure 6 exhibits the radial, tangential strengths for L-Group, Figure 7 the 45-degree (A and B) loading orientations (A and B) loading orientations strengths for L-Group, Figure 8 the 45-degree (A and B) loading orientations (A and B) loading orientations strengths for S-Group.

The following symbology was adopted in this analysis:

- RTenS(MPa) is the tension perpendicular to grain strength in radial direction for S sample.
- TTenS(MPa) is the tension perpendicular to grain strength in tangential direction for S sample.
- RTenL(MPa) is the tension perpendicular to grain strength in radial direction for L sample.
- TTenL(MPa) is the tension perpendicular to grain strength in tangential direction for L sample.
- ATenL(MPa) is the tension perpendicular to grain strength in 45-degree orientation direction for S sample, specimen A.
- BTenS(MPa) is the tension perpendicular to grain strength in 45-degree orientation direction for S sample, specimen B
- ATenL(MPa) is the tension perpendicular to grain strength in 45-degree orientation direction for L sample, specimen A.
- BTenL(MPa) is the tension perpendicular to grain strength in 45-degree orientation direction for L sample, specimen B.

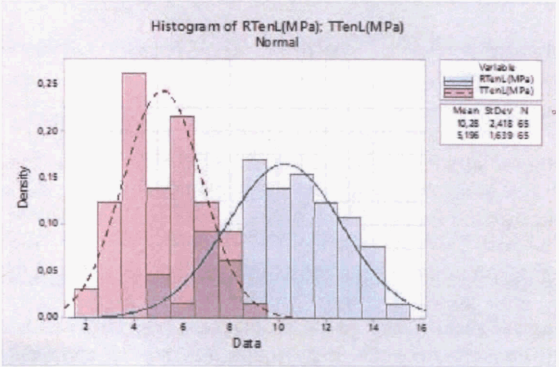

Figure 5: *Radial, Tangential strengths for L-Group.*

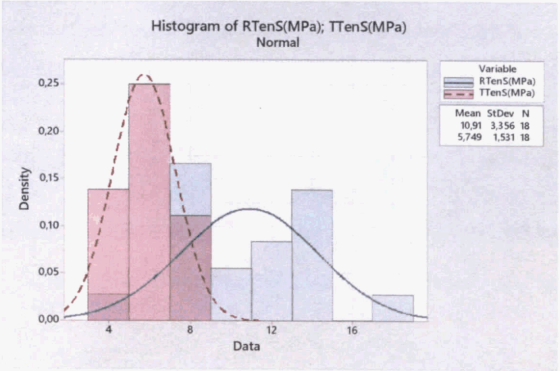

Figure 6: *Radial, Tangential strengths for S-Group.*

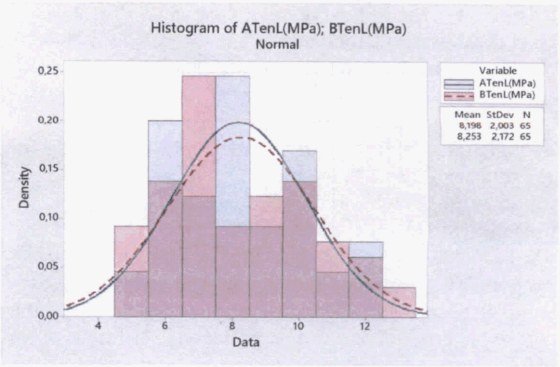

Figure 7: *45-degree (A and B) loading orientation strengths for L-Group.*

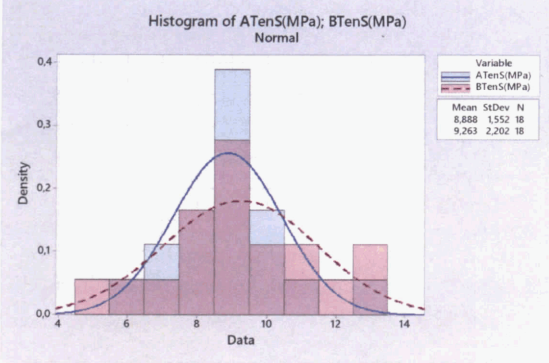

Figure 8: *45-degree (A and B) loading orientation strengths for S-Group.*

In order to verify the relationship between the tangential and radial strengths is presented the next figure showing the scatter plot of the results separated by groups of specimens, L-type and S type. It is possible to denote that both have the same tendency, and L-type by having a larger amount of data (66 sample results L compared to 17 samples S) denotes a greater dispersion of data or values. Thus, Figure 9 displays more clearly the differences between the groups L and S, and, the regression analysis, which follows, emphasizes statistically the tendency of each group.

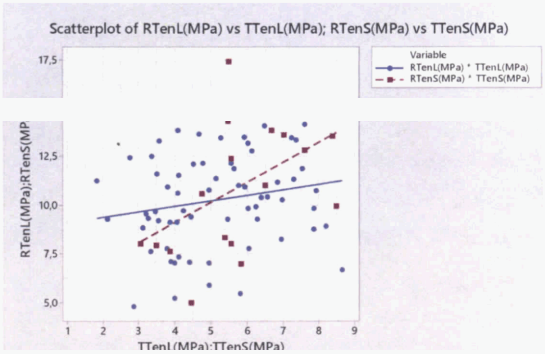

Figure 9: *Plotting of experimental results with the two separate groups of specimens, type L and S.*

In Tables 1-7 the following notation was used:
DF is the degree of freedoms.
S is an estimate of the standard deviation of the error term in the model.
R-sq (or R^2) is the coefficient of determination.
R-sq(adj) is a modified Ri-sq that has been adjusted for the number of terms in the model.
Adj SS is the regression mean square.
Adj.Ms is the residual mean square.
F-Val is used in hypothesis testing to determine whether two population variances are equal
P-Val is used the P-Value to analyze whether the regression coefficients are significantly different from zero.

The Regression Analysis of RTenL(MPa) versus TTenL(MPa) is shown in Table 1.

Table 1: *Analysis of Variance*

Source	DF	Adj SS	Adj MS	F-Val.	P-Val.
Regress	1	13.83	13.830	2.42	0.125
TTenL	1	13,83	13,830	2,42	0,125
Error	63	360.34	5.720		
Total	64	374.17			

Model Summary

S	R-sq	R-sq(adj)
2.3915	3.70%	2.17%

Regression Equation:

$$RTenL(MPa) = 8{,}810 + 0{,}284\ TTenL(MPa) \qquad (1)$$

The regression analysis of RTenS(MPa) versus TTenS(MPa) is shown in Table 2.

Table 2: *Analysis of Variance*

Source	DF	Adj SS	Adj MS	F-Val.	P-Val.
Regress	1	42.11	42.115	4.51	0.050
TTenS	1	42.11	42.115	4.51	0.050
Error	16	149.31	9.332		
Total	17	191,42			

Model Summary

S	R-sq	R-sq(adj)
3.0548	22.00%	17.13%

Regression Equation:

$$RTenS(MPa) = 5{,}00 + 1{,}028\ TTenS(MPa) \qquad (2)$$

The regression analysis between the total radial and tangential strengths is presented Figure 10, illustrating the plot of the strengths, followed by the corresponding the regression analysis.

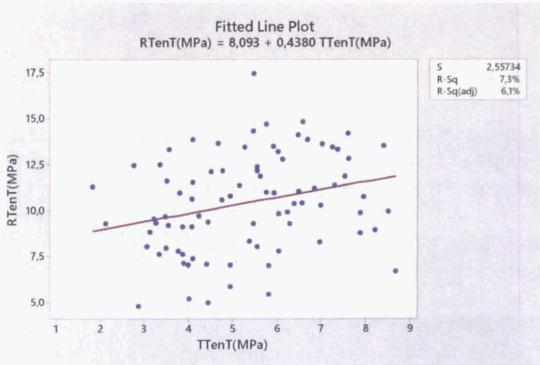

Figure 10: *Plotting of the total results for radial and tangential tension perpendicular to grain strengths.*

The regression analysis of RTenT(MPa) versus TTenT(MPa) is shown in Table 3.

Table 3: Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Val.	P-Val.
Regress	1	41.44	41.439	6.34	0.014
TTenS	1	41.44	41.439	6.34	0.014
Error	81	529.74	6.540		
Total	82	571.18			

Model Summary		
S	R-sq	R-sq(adj)
2.5573	7.25%	6.11%

Regression Equation:

$$RTenT(MPa) = 8{,}093 + 0{,}438\ TTenT(MPa) \qquad (3)$$

Where: RTenT(MPa) is the tension perpendicular to grain strength in radial direction for the total sample and TTenT(MPa) is the tension perpendicular to grain strength in radial direction for the total sample.

In light of the analysis of variance, it can be concluded that with a p = 1.4% the regression is not significant with the value F, and the coefficient of determination R^2 = 0.0725 the relationship between the parameters is small.

The Boxplot summary of matched samples for each loading direction is shown in Figure 11 [7].

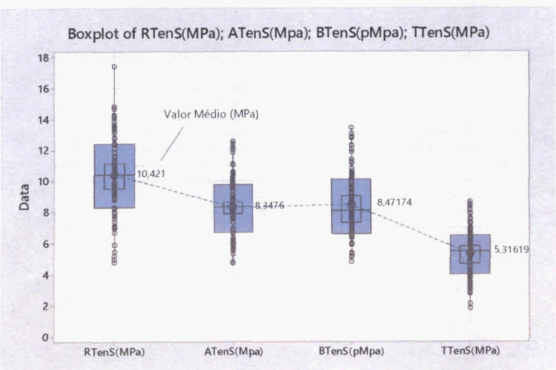

Figure 11: *Boxplot of radial, tangential and 45-degree orientation tension perpendicular to grain strengths for all data.*

From Figure 11 data it is possible to point out that the tension perpendicular strength with loading in the tangential direction is almost 51 % of the strength when loaded in the radial direction. In addition, the 45-degree orientation for A or B specimen results were located 6% above the mean value between the radial and tangential strength mean value.

A Mann-Whitney Rank Sum Test was conducted on the matched samples indicated that the radial and tangential tension perpendicular stress results. The results for the t-tests of various combinations are shown in Table 4. There is not a statistically significant difference (P = 0.989) in the median values between the A and B groups. There is not great enough to exclude the possibility that the difference is due to random sampling variability. There are however statistically significant differences between (P = <0.001) the median values of the Tangential, 45 degree, and the Radial samples. The difference between groups are greater than would be expected by chance. there is a statistically significant difference tangential and radial samples

Table 4: *Mann-Whitney Rank Sum Test Results in MPa*

Group	N	Missing	Median	25%	75%
RTenT	88	0	10.61	8.81	12.42
ATenS	88	0	8.38	6.73	9.97
BTenS	87	2	8.13	6.66	10.15
TTenT	88	2	5.48	4.01	6.61

Comparison RTenT vs TTenT
Mann-Whitney U Statistic = 378
T=4119 n(small)=86 n(big)=88 (P=<0.001)

Comparison RTenT vs ATenS
Mann-Whitney U Statistic = 2120
T=9540 n(small)=88 n(big)=88 (P=<0.001)

Comparison ATent vs BTenT
Mann-Whitney U Statistic = 3735
T=7390 n(small)= 85 n(big)=88 (P=0.989)

4.2 Tension perpendicular to grain and density analysis

The Figures 12-15 amd Tables 5-7 present an analysis on the influence of the density on perpendicular to grain strength values in the radial, tangential and 45-degree orientation, for A or B directions, as follows:

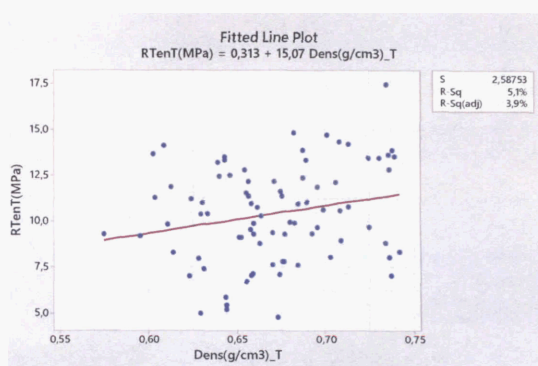

Figure 12: *Plotting of the radial tension perpendicular to grain strengths and density for total sample.*

Figure 12 shows a trend towards increasing ratial tension perpendicular to grain strength with increasing density. The regression analysis of RTenT(MPa) versus Dens(g/cm3)) is shown in Table 5,

Table 5: *Analysis of Variance*

Source	DF	Adj SS	Adj MS	F-Val.	P-Val.
Regress	1	28.86	28.859	4,31	0.041
Dens	1	28.86	28,859	4.31	0.041
Error	81	542.32	6.695		
Total	82	571.18			

Model Summary		
S	R-sq	R-sq(adj)
2.5875	5.05%	3.88%

Regression Equation:

RTenT(MPa) = 0.31 + 15.07 Dens(g/cm3)_T (4)

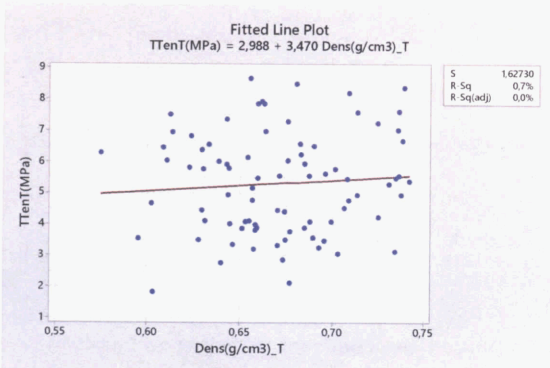

Figure 13: *Plotting of the tangential tension perpendicular tu grain strengths and density for total sample.*

Figure 13 demonstrates that the impact of density on the tangential tension perpendicular to grain strength is minimal. The regression analysis of TTenT(MPa) versus Dens(g/cm3) is given in Table 6.

Table 6: *Analysis of Variance*

Source	DF	Adj SS	Adj MS	F-Val.	P-Val.
Regress	1	1.531	1.531	0,58	0.449
Den	I	1.531	1.531	0,58	0.449
Error	81	214.49	2.648		
Total	82	216.026			

Model Summary		
S	R-sq	R-sq(adj)
1.6273	0.718	0.00%

Regression Equation

TTenT(MPa) = 2,99 + 3,47 Dens(g/cm3)_T (5)

Figure 14 suggests that as density increases so does the tension perpendicular to grain strength of the A samples. The regression analysis of ATenT(MPa) versus Dens(g/cm3) is given in Table 7.

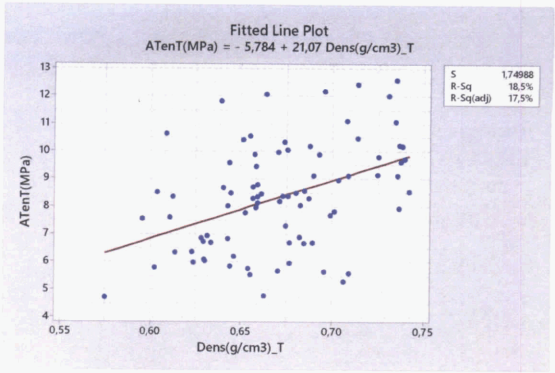

Figure 14: *Plotting of the 45-degree orientation tension perpendicular to grain strengths, for A specimens and density for total sample.*

Table 7: *Analysis of Variance*

Source	DF	Adj SS	Adj MS	F-Val.	P-Val.
Regress	1	56.41	56.410	18.42	0.00
Den	1	56.41	56.410	18,42	0,00
Error	81	248.03	3.062		
Total	82	304.44			

Model Summary		
S	R-sq	R-sq(adj)
1.7498	18.53%	17.52%

Regression Equation:

ATenT(MPa) = - 5,784 + 21 ,07 Dens(g/cm3)_T (6)

Figure 15 suggests that as density increases so dose the tension perpendicular to grain strength of the B samples. The regression analysis of BTenT(MPa) versus Dens(g/cm3) is given in Table 8.

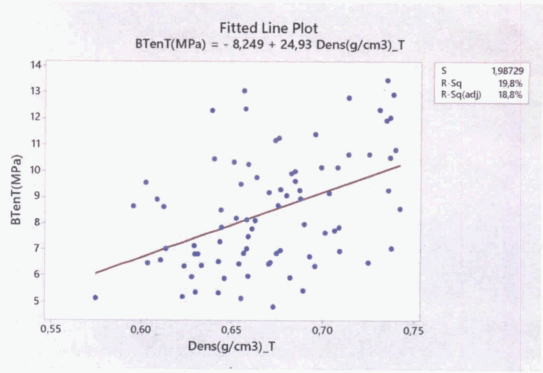

Figure 15: *Plotting of the 45-degree orientation tension perpendicular to grain strength, for B specimens, and density for total sample.*

Table 8: *Analysis of Variance*

Source	DF	Adj SS	Adj MS	F-Val.	P-Val.
Regress	1	78.98	78.975	20,00	0.00
Den	1	78.98	78.975	20.00	0.00
Error	81	319.90	3.949		
Total	82	398.87			

Model Summary		
S	R-sq	R-sq(adj)
1.9872	19.80%	18.81%

Regression Equation:

BTenT(MPa) = - 8,249 + 24,93 Dens(g/cm3)_T (7)

It is noted that from the statistical analysis developed in this item the influence of the density on perpendicular to grain strength values in radial and tangential directions can be considered not significant (even that it is not possible to reject the null hypothesis) for radial and tangential tension perpendicular to grain. On the other hand, in the cases of 45-degree inclined specimens certain relationship is verified.

5 INFLUENCE OF MEDULLARY RAYS IN TENSION PERPENDICULAR TO GRAIN STRENGTH

Test results indicated that the tension perpendicular strength in the tangential direction is almost ½ the strength when loaded in the radial direction, it is our belief that this is related to the influence of the medullary rays on this wood's mechanical property.

In technical literature, there are many studies demonstrating the importance in wood strength associated to radial direction, the presence of rays. Already [8] presented a study on the solid mechanics cell, in which a cell model proposed for the timber, to check the positioning of the medullary rays in relation to a stress applied, and the contributions to strength in compression or tension.

Also, [9] took microscopic images using computed tomography to observe the orthotropic planes of the following species wood, Spruce Noroega, *Picea Abies [L.]* and European Beech, *Fagus sylvatica [L.]*, the former is a conifer while the latter is a hardwood. [9] verified the rupture of medullary rays and the importance of the presence of them in wood strength in compression and tension tests.

[IO] stated for the resistance of medullary rays of the wood, a significantly high value of about 75 MPa, rated by test micro tension in low humidity conditions, but highlighting the contribution of underestimated the parenchyma, constituents of medullary rays in wood strength as a whole. The medullary rays in the case of this research for various wood species ranging from 8 to 40%, indicating that the strength in the radial direction is greater than in the tangential direction, as can be illustrated by Figure 16. Considering now the relationship between modulus of elasticity and strength, for example higher values in radial direction relative to the tangential, [11] stated the mechanical behavior of wood is induced by its orthotropic direction properties.

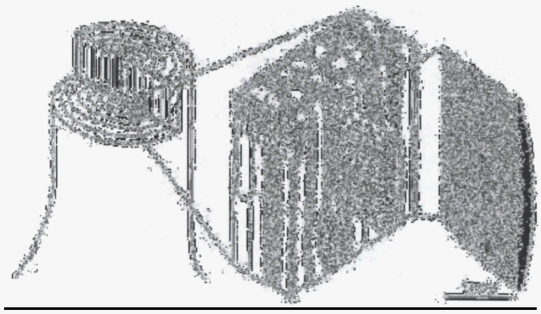

Figure 16: *Wood sample illustrating presence of the meddulary rays, indicating influence in the strength in the radial direction [12].*

Yet [12] noted that the presence and proportion in volume of medullary rays in the wood of the studied species may influence stiffness timber in the radial direction, regardless of its size and that the radial modulus of elasticity is both dependent on the volume fraction of rays and the apparent density wood. In the tangential direction, the apparent density is the factor that influences the timber rigidity.

Focusing on this present research, in which Sugar Maple (Acer saccharum) medullary was used, and considering Figures 17 and 18 show the radial-longitudinal plane (the radial direction is the horizontal direction, and the longitudinal direction is the vertical one) and the tangential-longitudinal plane (the tangential direction is the horizontal direction, and the longitudinal direction is the vertical one) of this wood species, a significant presence of medullary rays can be noted.

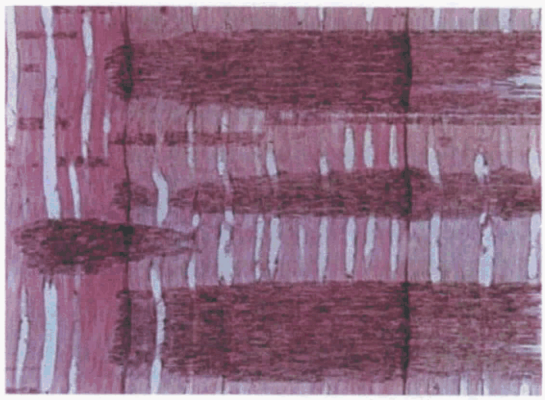

Figure 17: *The amount of medullary rays on the radial-longitudinal plane of Sugar Maple wood species. (image courtesy of Alex Wiedenhoeft)*

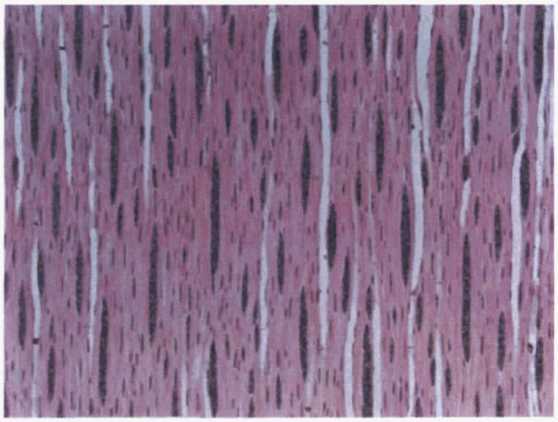

Figure 17: *The amount of medullary rays on the tangential-longitudinal plane of Sugar Maple wood species (image courtesy of Alex Wiedenhoeft)..*

The estimated percentage of the volume of medullary rays in relation to the volume of the timber is about 17.9%, and this amount of rays certainly contributed to increase the tension perpendicular to grain strength in radial direction when compared to tangential direction.

6 FAILURE MODES VERIFIED

The failure modes of radial, tangential and inclined specimens were the typical separation by tension of the fibers. In addition, the effects of shear stresses in inclined specimens due to positioning of the fibers in relation to the applied stress was observed.

Figures 18 shows an example of such failure modes for 45-degree orientation specimen, whereas Figure 19 illustrates an example for radial or tangential tension perpendicular to grain specimen.

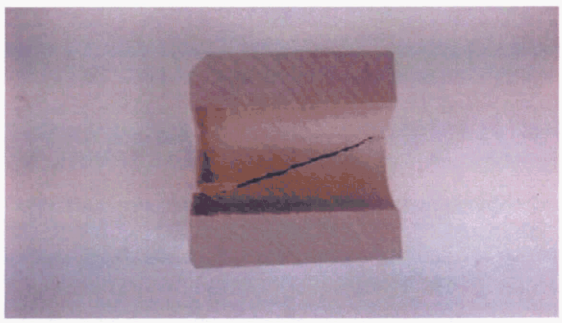

Figure 18: *Typical failure mode of 45-degree direction specimen in perpendicular tension perpendicular to grain tests.*

7 CONCLUSIONS

From the statistical analysis, it can be concluded that the experimental results for tension perpendicular to grain strengths, in the radial, 45-degree, and tangential directions, show a significant statistical difference between each other. These differences can be explained by the substantial ray packets of Sugar Maple.

Also density did not have a statistically significant influence on the perpendicular to grain strength values in radial and tangential directions. There was very little effect of influence of density on the tangential perpendicular to grain strength but there was a tendency for increased radial tension perpendicular to grain strength with increased density. Density had an even stronger influence on the 45-degree inclined specimens.

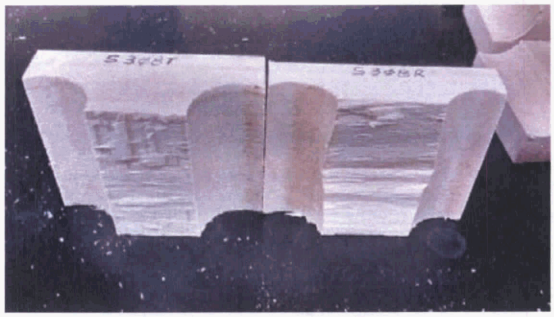

Figure 19: *Typical failure mode in, radial or tangential specimen in tension perpendicular to grain tests.*

ACKNOWLEDGEMENT

The authors thank Sara Fishwild from the Forest Products Laboratory-Madison, WI-US for her assistance in sample testing and Fapesp, Sao Paulo Research Foundation, Brazil(Project number 2014/23818-1), for the financial support to develop this research.

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