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EFFECT OF CHANGING SLOPE OF GRAIN ON ASH, MAPLE, AND YELLOW BIRCH BENDING STRENGTH

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ABSTRACT: The presence of slope of grain (SoG) in wood can severely reduce the bending strength in wood. Failure to recognize the degree to which SoG can reduce strength can be catastrophic if wood is in single member use. In the United States, a growing concern in the sport of baseball relates to the high frequency of multi-piece broken wood bats. It was observed that hard maple bats tended to break explosively, whereas white ash bats were more likely to stay intact. An examination of bats collected during the last three months of the 2008 baseball season indicated that for that time period the majority of catastrophic multi-piece failures (MPF) involved SoG failures. This paper reports the edgewise loading results of a study conducted to investigate the influence of SoG on wood properties for three species (white ash, sugar maple, and yellow birch) that are commonly used in baseball bats. The study conducted 2,200 tests to investigate the changes in bending strength with five different slope of grain (0, 2, 4, 7, and 10 degree) angles painstakingly manufactured from the same board for three different (21.4-, 23.9-, 26.6-mm- (0.84-, 0.94-, 1.04-in-)) diameter category 457-mm- (18-in-) long dowels. Results show that in general, edgewise MOE and MOR for all three species is reduced by a similar amount as SoG increases. Maximum reduction in MOE was 20–25% at a SoG category of 10 degrees. Maximum reduction in MOR was shown to be about 25–30% at a SoG category of 10 degrees. Density changes affected the three species differently in the density range of interest to baseball manufacturing. For maple, MOE is less sensitive to changes in density than for the other two species, whereas maple's MOR is affected most by changes in density. Face-grain loading of diffuse porous maple and yellow birch at higher SoG angles had higher MOR values than matched edge-grain loaded samples. Finally, SoG may have slightly less effect on yellow birch bending properties than on ash and maple.

KEYWORDS: Slope of Grain, Bending strength, White Ash, Sugar Maple, Yellow Birch, Baseball Bats

1 INTRODUCTION

White ash (*Fraxinus americana*) has been the preferred wood for making baseball bats, because it has high impact bending strength and the correct density to make popular bat shapes in the appropriate weight for athletes to swing. Other species, such as hickory (*Carya tomentosa*) and red oak (*Quercus rubra*), have also been used as well. When sugar maple (*Acer saccharinum*) baseball bat companies started appearing in the early 1990s, it was believed that this diffuse porous hardwood was higher performing than white ash. When Barry Bonds used a maple bat to surpass the single-season homerun record in 2001, a maple bat's reputation as the high-performance bat was cemented. Yellow birch (*Betula alleghaniensis*), another diffuse porous hardwood, has also been gaining in popularity. Currently the three most popular species, in order of popularity, are white ash, sugar maple, and yellow birch.

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During the years that followed Bonds' homerun record, there was a noticeable increase in both the use of maple in Major League Baseball and the frequency of multi-piece baseball bat failures (MPF). The Office of the Commissioner of Baseball and the Major League Baseball Players Association, as part of their collective bargaining agreement, established a Safety and Health Advisory Committee (SHAC) in 2007 to examine the issue of player and fan safety in terms of broken bats and batted or thrown balls. The SHAC is investigating, among other things, factors that cause wood bats to have catastrophic failures (i.e., break into multiple pieces) in order to make recommendations to improve the safety of bats. As part of that work, studies into the effect of slope of grain (SoG) on white ash, sugar maple, and yellow birch (the most common species for bat manufacture) have been conducted to provide property information for finite element modelling. In the past two years, more than 2,200 dowel tests have been conducted. The largest number of those dowel tests looked at three dowel diameters for the three species at five different SoG targets. Side studies have also been conducted looking at face-grain versus edge-grain loading, fracture properties, compressive properties, and rate of loading. Because of space limitations, only the edgewise loaded bending test results for three dowel diameters will be reported in detail in this paper. Results of face-grain versus edge-grain loading testing, which resulted in a change in the recommended bat orientation, will be briefly mentioned.

2 BACKGROUND

It is well known that SoG has a dramatic impact on strength of clear wood. This is caused by the extreme differences in wood strength parallel and perpendicular to the grain. Figure 1 illustrates the two primary SoG measures that need to be considered in wood: the radial "Edge" SoG and the tangential "Face" SoG. A common measure of slope of grain in the United States is "1 in X," referring to how many centimeters of length is traveled before 1 centimeter of change has occurred perpendicular to the length of the tree. Figure 1 illustrates a SoG of 1 in 6. In many woods, particularly diffuse hardwoods, the tangential SoG can be difficult to observe.

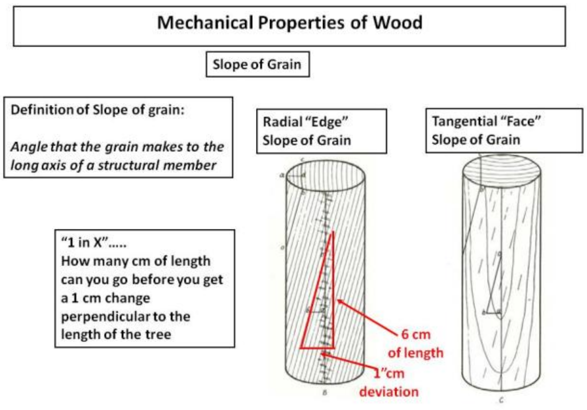

Figure 1: *Illustration of slope of grain in wooden dowels*

2.1 PRIOR LITERATURE

In 1921, T.R.C. Wilson published information, developed by Luxford in 1919, in the Journal of Forestry about the influence of spiral grain on strength [1]. In this publication, values for Sitka spruce, Douglas-fir, and white ash were tabulated and the average effects were reported. The average information for these three species is the basis for the information tabulated in table 4-12 of the current USDA FS *Wood Handbook* [2]. Others, such as Markwardt and Wilson, Kieth, and Fagan and McLain also conducted studies looking at the effect of orientation of annual layers on the resistance of wood to impact loading [5–7]. Only one of the species that are currently used in making wooden bats was used to determine this relationship. Hankinson's equation, shown graphically in Figure 2 and described mathematically as Equation (1) below, has been used to describe SoG affect on properties [3,4].

$$N = \frac{PQ}{P\sin^n\theta + Q\cos^n\theta} \qquad (1)$$

where N is the strength at an angle θ to the fiber direction. P is the strength perpendicular to the fiber, Q is the strength parallel to the fiber, and n is an empirically determined constant.

Different properties have been shown to follow different curves (Figure 2). These curves are average relationships developed across many species. The *Wood Handbook* specifically states that modulus of rupture fall very close to the curve Q/P = 0.1 and n = 1.5 and the impact bending properties fall close to the curve having Q/P = 0.05 and n = 1.5. Modulus of elasticity is close to the curve Q/P = 0.1 and n = 2. In Figure 2, the curve that best represents impact bending (Q/P = 0.05, n = 1.5) is the absolute bottom curve having the steepest slope (bending). From this figure, it is clear that SoG can have a significant impact on properties with little change in angle to the fiber direction.

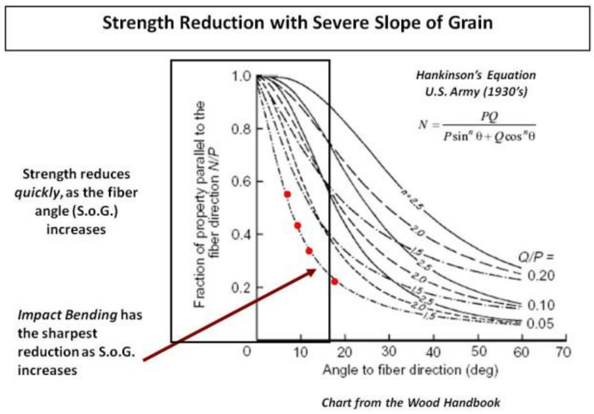

Figure 2: *Illustration of Hankinson's equation [2]*

2.2 2008 MLB BROKEN BAT STUDY

In July 2008, the SHAC formed an interdisciplinary team of external experts to investigate broken bat incidents in Major League Baseball (MLB) games. The team was composed of experts in wood science, industrial wood product certification, risk and statistical analyses, and laboratory and field testing of baseball bats. The objectives for the team were to develop a set of recommendations that could be considered by Major League Baseball, the Major League Baseball Players Association, and the Safety and Health Advisory Committee to reduce the frequency of multi-piece failures of bats broken in games in 2009 and to propose additional research priorities to further reduce the frequency of broken bats in subsequent seasons.

Between July and September 2008, 2,232 bats that broke during Major League games were collected and analyzed by the interdisciplinary team. These broken bats included cracked bats that stayed in one piece and bats that broke into multiple pieces.

Of the 2,232 broken bats, 756 had broken into multiple pieces. Failure analyses concluded that the two primary modes for these multi-piece breaks were due to poor-quality SoG ("slope of grain" failures) and/or ruptures caused by excessive bending ("rupture" failures). As the straightness of the grain decreases, the durability of the bat declines.

The team of experts made on-site visits to five bat manufacturers that were on the MLB-approved bat-supplier list for 2008. The team had technical discussions with company officials and factory workers, observed the respective manufacturing and quality control processes, shared basic techniques for grading of wood quality, and examined a representative sample of ash and maple billets during each of the visits. The team of experts also reviewed videos supplied by MLB.com of 325 multi-piece bat failures and reviewed information obtained from surveys of all MLB-approved bat suppliers, players, and equipment managers. Finally, the team conducted laboratory testing of bats and dowels.

Maple bats were found to be more likely than ash bats to break into two or more pieces. This greater probability for multi-piece failure of “diffuse porous” maple bats is partly due to the greater difficulty in the sorting and removal of poor-quality SoG maple billets than similarly deficient SoG ash billets. The failed bats showed that the maple bats were four times more likely to have broken due to poor-quality SoG than ash bats failing in the same manner.

Less visual grading for SoG was being conducted on maple than on ash for manufacturers that produce both ash and maple bats. The increased frequency for poor-quality tangential SoG in maple bats is not necessarily an indication that maple is more prone to poor-quality SoG than is ash. Rather, the increased frequency of poor-quality SoG in maple bats is a consequence of the relative greater difficulty in seeing the SoG in maple billets than in ash billets. Thus, poor-quality SoG maple billets are more likely to be made into baseball bats than are poor-quality SoG ash billets.

A histogram of the MPF SoG results of the 2008 MLB-Broken Bat Study is shown superimposed on the Hankinson curves in Figure 3.

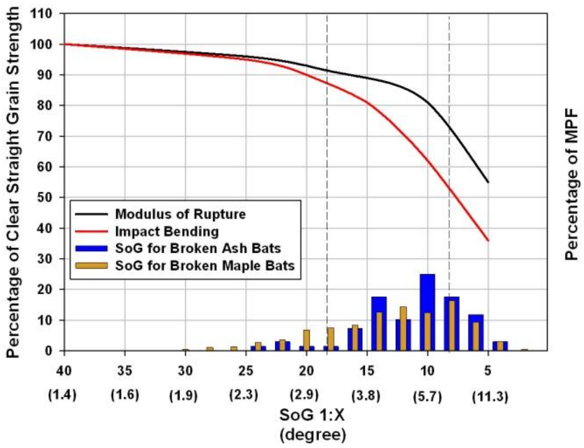

Figure 3: *The Wood Handbook Hankinson relationship for modulus of rupture and impact bending overlaid on the distribution of MPF SoG in 2008 MLB-Broken Bat Study SoG Data*

Analysis of the data found that over 50% of multi-piece failures are caused by poor SoG. It was determined that improving the SoG of the billets used to make bats would significantly reduce the frequency of multi-piece failures. In addition, because bats made with billets having a poor SoG are also more prone to rupture (which is the second most common cause of multi-piece bat failure), improving the SoG of billets used to make bats should also reduce the number of bats that fail due to SoG and/or rupture.

2.3 TESTING NEEDS

Based on the review of existing literature and the evidence of SoG issues with MPF in the 2008 MLB broken bat study, it became apparent that it was important to gather more information on magnitude of property decreases with increasing SoG for the three most popular wood species in MLB in order to make an informed decision about revisions that needed to be made in the baseball bat supplier’s regulations. The primary focus of the testing was looking at three dowel diameters for the three species at five different SoG targets. Side studies were also conducted on face-grain versus edge-grain loading, compressive properties, and rate of loading. The information gathered is to be used to further develop finite element analysis methods for various wood bat models [8,9].

3 METHODS

Conventionally kiln-dried boards were obtained from a commercial supplier, matched, cut into sections, split, marked with a template, cut into blanks, turned into dowels, and tested. The process of producing the blanks for the dowels and testing is traced in Figure 4.

3.1 MATERIAL

The boards for this study were obtained from a commercial supplier in Hurley, WI, USA. A minimum of 90 2.5-m-long boards with a minimum width of 150 mm and thickness of 30 mm and having two or more 510-mm-long straight-grained sections in the radial direction were hand selected for each species (Figure 4a). Straight-grained material in this study was taken to be material with radial SoG judged to have a slope less than 1 in 30, or 2 degrees.

3.2 SAMPLE PREPARATION

The test samples were prepared at a commercial hardwood manufacturing facility in Antigo, WI, USA.

3.2.1 Matching

For each species, the selected boards were assigned an identification number and the density determined. The boards were ranked by density and assigned systematically to one of the three diameter categories to ensure equal density distributions for each category. The diameter categories 26.6 mm (1.04 in), 23.9 mm (0.94 in) and 21.4 mm (0.84 in) represented the high, average, and minimum diameters used by players observed in the 2008 MLB broken bat study. The targeted edgewise loading test matrix for a single species is shown in Table 1. A total of 1,350 edgewise tests were planned for the three species.

Table 1: *Single species edgewise testing test matrix*

With 2^{o} or less radial SoG	Tangential SoG Angle (1:X) Number of Dowels Tested					
Dowel Dia. (mm)	0^{o}	2^{o} (1:28.6)	4.0^{o} (1:14)	7.0^{o} (1:8)	10.0^{o} (1:5.7)	Total
26.6	30	30	30	30	30	150
23.9	30	30	30	30	30	150
21.4	30	30	30	30	30	150
Total	90	90	90	90	90	450

3.2.2 Board Sectioning and Splitting

Each board was marked into two to four clear straight-grained 510-mm- (20-in-) long sections. Additional sections were also marked with radial SoG angles greater than 2 degrees for testing in side studies. The sections were then cross cut from each board. Each section was hand split along the grain (Figure 4b) and then marked with one of the five angular templates which had been aligned to the split edge (Figure 4c). The boards were then cut along the template markings to produce five matched sets of 30- by 30- by 510-mm blanks having 0, 2, 4, 7, and 10 degree tangential slope-of-grain angles for each board. In addition to these blanks, duplicate blanks were produced when possible to provide additional material for side studies.

Figure 4: *Summary photo of dowel preparation: a) board selection, b) section splitting, c) marking section with template, d) dowel manufacture, e) universal test setup*

3.2.3 Dowel Manufacture

All dowels were turned on an automated back-knife lathe (Figure 4d). Prior to dowel manufacture, identification numbers from the blanks were transferred to the ends of each blank. The ash and maple blanks were processed first; the yellow birch blanks were processed one week later. Some ash boards were thinner than expected, so the largest diameter category for the ash and maple dowels was reduced slightly to 25.6 mm (1.008 in). The largest size category was successfully produced at the full 26.6 mm (1.04 in) diameter for the yellow birch dowels.

3.2.4 Conditioning and Pre-test Measurements

The dowels were shipped to the USDA FS Forest Products Laboratory (FPL) and placed in a 23°C and 50% relative humidity (RH) conditioned room. The dowels were stored until weight stabilized. Prior to testing, each test specimen was measured for length, radial and tangential diameter at center, weight, number of rings, and radial and tangential SoG. Using a technique suggested by Koehler, an ink dot was applied to the tangential face of the dowels to assist in measuring the tangential SoG for the maple and yellow birch dowels [10]. A true SoG was also calculated for each specimen. The true SoG was determined by using the radial and tangential SoG and substituting them into Equation (2).

$$TrueSoG = \sqrt{raSoG^{2} + taSoG^{2}} \qquad (2)$$

where *TrueSoG* = the true slope of grain, *raSoG* = the measured radial SoG, and *taSoG* is the measured tangential SoG. Table 2 summarizes the average diameter of the three target categories for each species.

The dowels diameters produced by the commercial lather were very consistent, with an average coefficient of variation of 0.2%. A summary of average dowel diameters compared with the target is shown in Table 2.

Table 2: *Average diameters for the three target diameter categories.*

Species	Diameter categories (mm)		
	21.4	**23.9**	**26.6**
Ash	21.5	23.9	25.6
Maple	21.4	23.9	25.6
Yellow Birch	21.6	24.0	26.6

3.3 TESTING

Testing was conducted in the FPL Engineering Mechanics and Remote Sensing Laboratory. Tests were conducted on a universal test machine in a portable conditioning chamber (Fig. 4e) that had its climate controlled to maintain a temperature of 23°C and 50% RH. At the time of test, ovendry weight/ovendry volume was determined using ASTM D 2395, Method A, and MC was determined using ASTM D 4442 [11].

The test span was 406 mm (16 in). The dowels were tested using a third point loading configuration creating a constant moment zone of 135.4 mm. The test setup is shown in Figure 5. An accelerated test speed of 510 mm/min (20 in/min), to more closely simulate actual loading conditions, was used for testing. Load and displacement were recorded electronically. Moisture content samples were measured at the time of test.

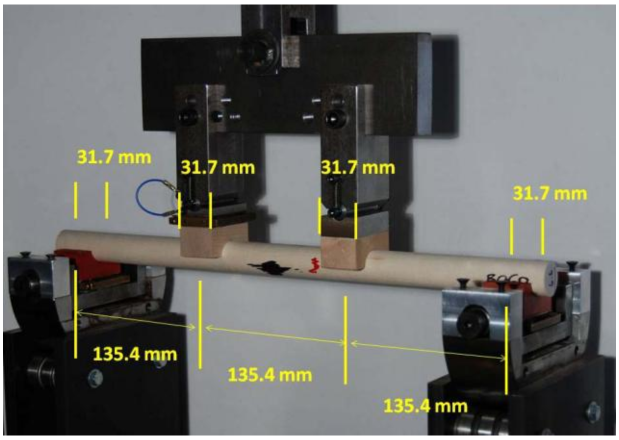

Figure 5: *Dowel bending test setup*

4 RESULTS

The properties of particular interest in this study were density distributions for each species, maximum load (Pmax), modulus of elasticity (MOE), modulus of rupture (MOR), mode of failure, relationships between SoG and MOE and MOR, and interactions of density, SoG, and MOR for the density range of interest to baseball bat manufacturers.

4.1 MOISTURE CONTENT AND DENSITY

Average moisture contents for the specimens were 8.3%, 9.0%, and 9.4% for ash, maple, and yellow birch, respectively. Density distributions for the entire set of test data for the three species are shown in Figure 6. Average density was 0.69, 0.72, and 0.76 g/cm^3 for yellow birch, ash, and maple, respectively. Maple had the least variability, whereas ash had the greatest. The typical range of density used in baseball bat manufacturing is between 0.55 and 0.75 g/cm^3 (range shown between the vertical red lines). Figure 5 illustrates how difficult it is to obtain low weight maple for baseball manufacturing.

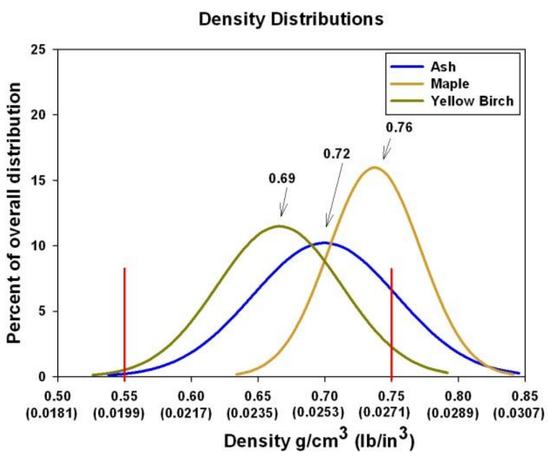

Figure 6: *Density distributions for all ash, maple, and yellow birch samples. The red vertical lines represent typical ranges of density for baseball bat manufacture.*

4.2 FAILURE MODES

A very clear failure mode shift was observed while testing. Specimens with SoG angles in the 0 and 2 degree group tended to remain intact. As the SoG angle increased, the failures tended to become more and more dramatic. Specimens with SoG greater than 7 degrees almost always separated explosively. Of the three species tested, maple was the most explosive in its mode of failures and ash the least. Figure 7 illustrates the changing failure mode with increasing SoG for one set of matched dowels. The SoG values of the test specimens increase from top to bottom of the picture. The target angle category for each dowel is shown in yellow at the right of the photograph.

Figure 7: *Example of the changing failure mode with increasing SoG. The SoG of the test specimens increase from top to bottom. The target angle category for each dowel is shown in yellow.*

4.3 TABULATED TEST RESULTS

The data summarized in this section are for the edgewise bending tests for specimens with a radial SoG angle less than or equal to 2 degrees. There was no detectable size effect in the test results. The percentage change in maximum load as the sample reduced in size matched the theoretically expected reductions caused by reduced section modulus.

Table 3 shows the ratios of Pmax, MOE, and MOR of samples when the smaller diameter results are compared with the larger diameter results. Because of the change in diameter having a direct impact on the moment of inertia (MOI) for the bending member, there was an expected ratio of 0.81 between the 23.9 and 25.6 mm diameter, 0.75 between 24.0 and 26.6 mm diameter, 0.72 between the 23.9 and 21.4 mm diameter, 0.58 between 21.4 and 25.6 mm, and 0.53 between 23.9 and 26.6 mm diameter for Pmax values. The values for maple and yellow birch in Table 3 reflect the expected results. The ash dowels had a slightly larger ratio than expected going from the largest to the middle diameter category. The ratio of the MOE and MOR values for the different diameters are close to 1 for ash, maple, and yellow birch.

Table 3: *Change in SOG 2^o or less edgewise dowel result with diameter changes*

	Change in property going from larger diameter to smaller diameter		
	25.6 to 23.9 mm	**23.9 to 21.5 mm**	**25.6 to 21.4 mm**
	Ash		
Pmax	0.85	0.72	0.62
MOE	1.04	1.02	1.06
MOR	1.04	1.00	1.04
	Maple		
	25.6 to 23.9 mm	**23.9 to 21.4 mm**	**25.6 to 21.4 mm**
Pmax	0.81	0.74	0.60
MOE	1.00	1.03	1.03
MOR	0.98	1.04	1.02
	Yellow Birch		
	26.6 to 24.0 mm	**23.9 to 21.4 mm**	**26.6 to 21.4 mm**
Pmax	0.71	0.74	0.52
MOE	1.00	0.99	0.99
MOR	0.96	1.02	0.98

Table 4 shows the ratio of the 10 degree category dowel test results to the 0 degree category test results. There was a fairly consistent 25% to 30% reduction in strength. Plots of the different quartiles of the data confirmed that this behaviour was consistent throughout the distribution.

Because of the lack of a clear size effect, the data from all three sizes were combined for analysis. The rest of the analysis presented in this paper is for all sizes combined. Table 5 summarizes the results for the combined diameter data. The average values for true SoG, sample size, MOE, and MOR data for dowels with radial SoG less than or equal to 2 degrees for edgewise loading are reported. Both MOR and MOR have a substantial reduction in value as the true SOG increases.

Table 4: *Change in edgewise dowel result with diameter changes*

	Change in property going from 0 to 10 degree tangential slope of grain		
Dia. (mm)	**21.4**	**23.9**	**25.6**
Property	**Ash**		
MOE	0.78	0.75	0.76
MOR	0.73	0.75	0.73
	Maple		
MOE	0.76	0.80	0.80
MOR	0.70	0.73	0.80
	Yellow Birch		
Dia. (mm)	**21.4**	**23.9**	**26.6**
MOE	0.79	0.80	0.81
MOR	0.76	0.73	0.80

Table 5: *Average results for combined diameter data with radial SoG less than or equal to 2 degrees for the edgewise loading bending tests*

SoG angle (degree)			Average Results (combined diameters)	
target	**true**	**n**	**MOE (GPa)**	**MOR (MPa)**
Ash				
0	1.37	111	15.5	173.4
2	2.38	83	15.4	168.9
4	4.11	96	14.6	162.4
7	6.87	87	13.6	147.8
10	9.23	84	11.8	127.1
Maple				
0	1.83	132	16.2	178.4
2	2.51	84	16.0	172.5
4	3.60	87	15.6	167.6
7	6.07	87	14.1	151.3
10	8.68	90	12.7	133.2
Yellow Birch				
0	2.15	102	16.2	169.9
2	2.79	87	15.8	161.9
4	3.96	89	15.0	153.2
7	6.22	89	14.0	140.1
10	8.88	89	12.7	124.0

4.4 MODULUS OF ELASTICTY

Box plots of MOE results for all samples with a radial SOG less than or equal to 2 degrees are given in Figure 8. The box plots are centered on the average true SoG for each SoG category. There is little detectable change in properties until SoG exceeds 3 degrees. Values for MOE at that point decrease at an increasing rate by as much as 25% at the largest angles.

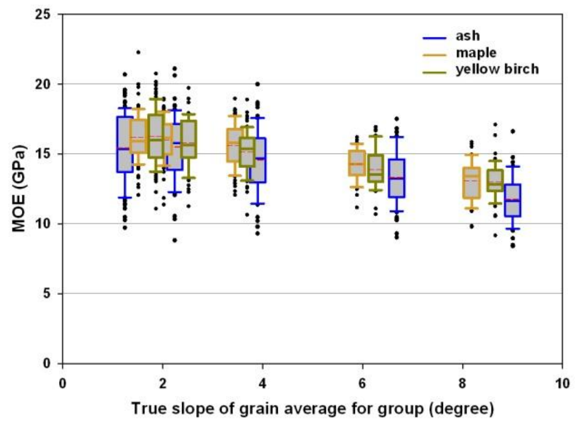

Figure 8: *MOE box plots of the five categories of angles for ash, maple, yellow birch*

4.5 MODULUS OF RUPTURE

Box plots of MOR results for all samples with a radial SOG less than or equal to 2 degrees are given in Figure 9. The box plots are centered on the average true

SoG for each SoG category. As for MOE, there is little detectable reduction in MOR until SoG exceeds 3 degrees. Values for MOR decrease by about 30% at the largest angles. This is the reduction that would be suggested by Hankinson's equation. All three species behave in a similar manner.

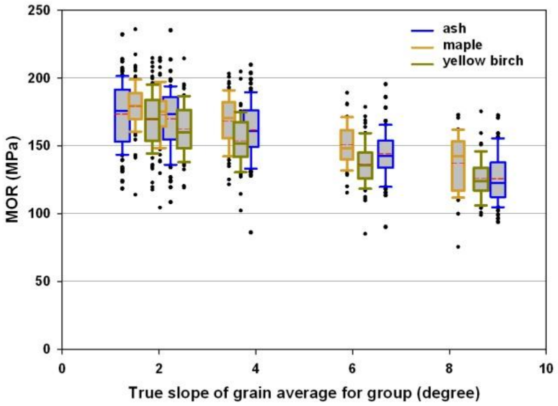

Figure 9: *MOR box plots of the five categories of angles for ash, maple, yellow birch*

4.6 EFFECT OF DENSITY ON MOE AND MOR

Scatter plots of 0 and 2 degree angle category density versus MOE and MOR are shown in Figures 10 and 11, respectively. The spread in the density data reflects the spread illustrated in Figure 6. A very small portion of the maple tested has ultralow density. It was observed that MOE changed less for a given change in density than did ash and yellow birch. The increasing trend for MOR with increased density is consistent across species for MOR.

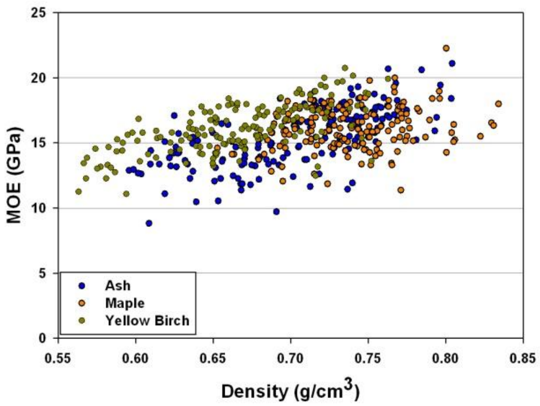

Figure 10: *Scatter plot of 0 and 2 degree angle category density versus MOE*

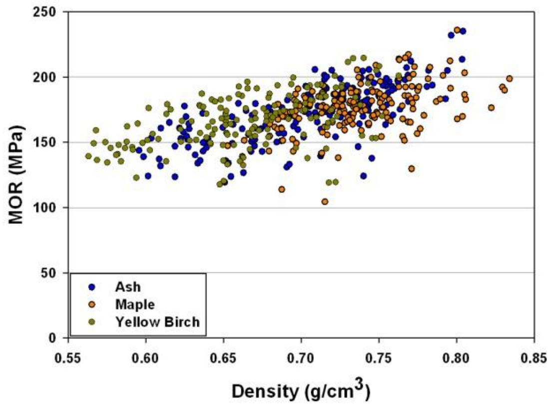

Figure 11: *Scatter plot of 0 and 2 degree angle category density versus MOR*

4.7 REGRESSION RESULTS FOR PRACTICAL RANGE OF DENSITY

A wide range of densities were tested. The density range of 0.5 to 0.75 g/cm^3 is, however, of particular interest in baseball bat manufacturing because it is the range for which most major league bats are being produced. Box plot results for MOE and MOR with the data only from this practical range of densities are shown in Figures 12 and 13. Inspection of data from this range when compared with Figures 8 and 9 suggests that there is little change in the overall trend for decreases in MOR and MOE with increases in SoG for a restricted range of density.

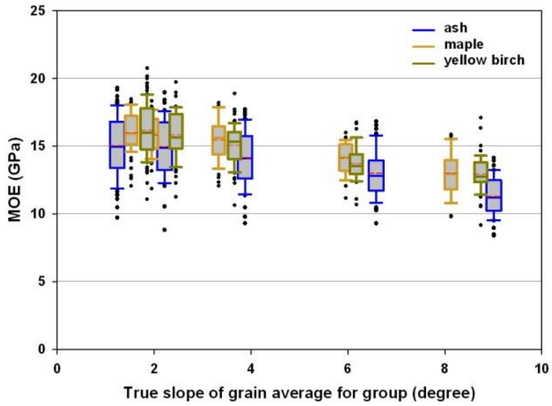

Figure 12: *MOE box plots of five categories of angles for ash, maple, yellow birch for practical density range*

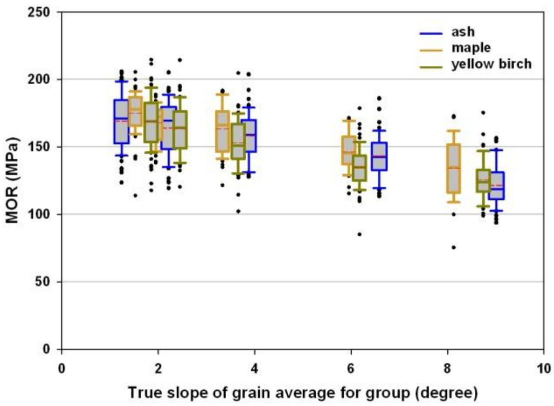

Figure 13: *MOR box plots of five categories of angles for ash, maple, yellow birch for practical density range*

Regression relationships of density with MOE and MOR, as determined from our 0 and 2 degree angle category data for this practical range of density, are given in Table 6. Figures 14–19 show these relationships superimposed over our data. In Figures 14–16, maple MOE is less sensitive to changes in density; in Figures 17–19, the maple MOR is impacted most by changes in density.

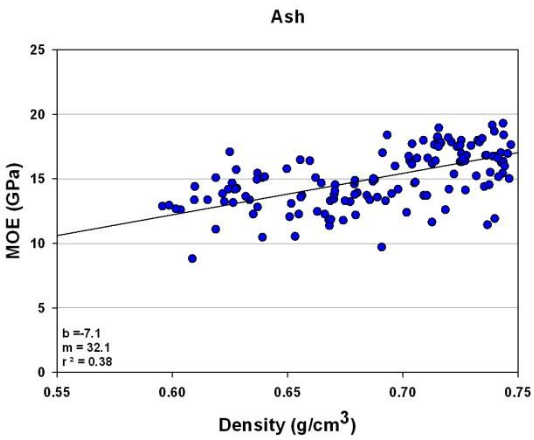

Figure 14: *Linear regression fit of 0 and 2 degree angle category density versus MOE data for practical range of density for ash*

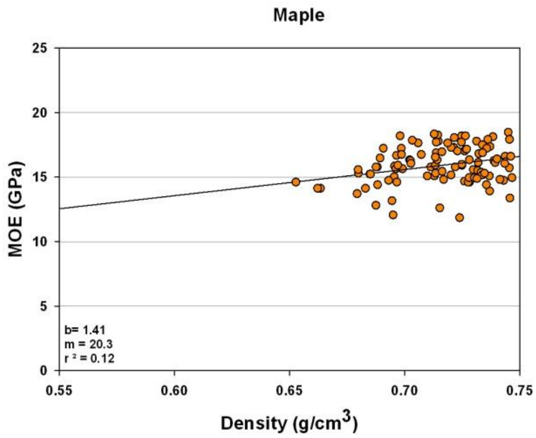

Figure 15: *Linear regression fit of 0 and 2 degree angle category density versus MOE data for practical range of density for Maple*

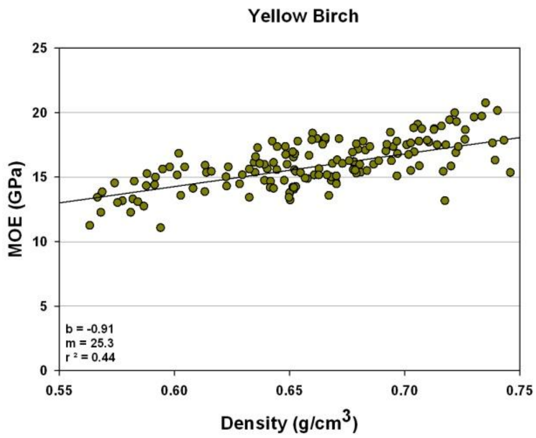

Figure 16: *Linear regression fit of 0 and 2 degree angle category density versus MOE data for practical range of density for yellow birch*

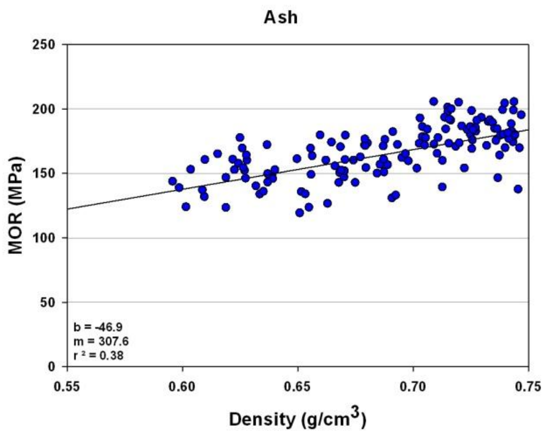

Figure 17: *Linear regression fit of 0 and 2 degree angle category density versus MOR data for practical range of density for ash*

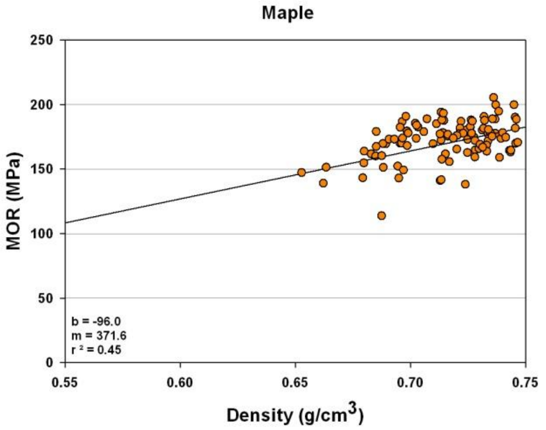

Figure 18: *Linear regression fit of 0 and 2 degree angle category density versus MOR data for practical range of density for maple*

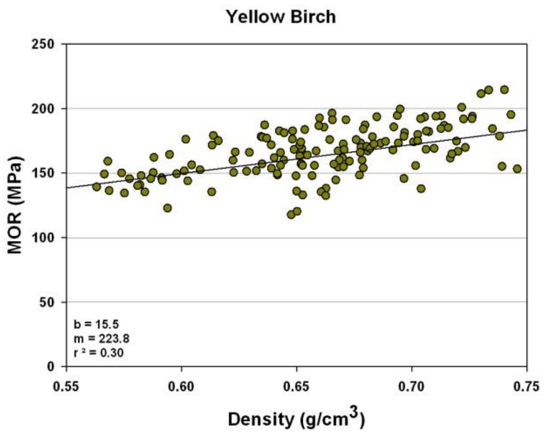

Figure 19: *Linear regression fit of 0 and 2 degree angle category density versus MOR data for practical range of density for yellow birch*

Table 6: *Regression fits to MOE and MOR density data for ash maple and yellow birch*

	Change in property going from larger diameter to smaller diameter		
	Slope	intercept	R^2
	MOE (GPa)		
Ash	32.1	-7.1	0.38
Maple	20.3	1.4	0.12
Yel. Bir.	25.3	-0.9	0.44
	MOR (MPa)		
Ash	307.6	-46.9	0.38
Maple	371.6	-96.0	0.45
Yel. Bir.	223.8	15.5	0.30

4.8 INTERACTIONS OF MOE AND MOR WITH DENSITY AND TRUE SOG FOR PRACTICAL RANGE OF DENSITY

All the dowel data collected to this point have been used to create surfaces that show interactions of MOE and MOR with density and true SoG. Portions of the MOR and MOE surfaces for the practical range of density are shown in Figures 20 and 21. In general, the surfaces suggest that the properties of all three species are quite similar for straight-grained wood in this range of density typically used to make bats. Slope of grain appears to have more of an impact on ash and maple than it does on yellow birch.

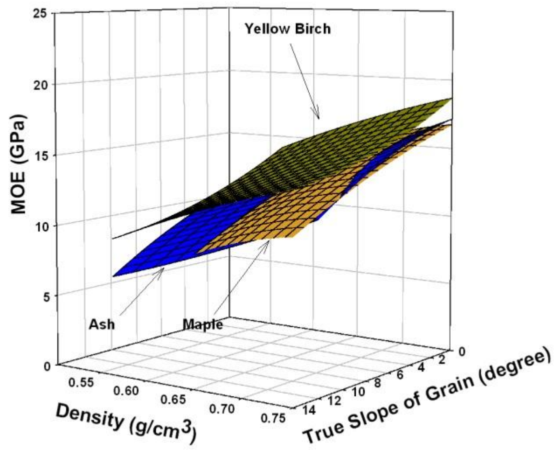

Figure 20: *Surfaces relating density, true SoG, and MOE for practical range of density*

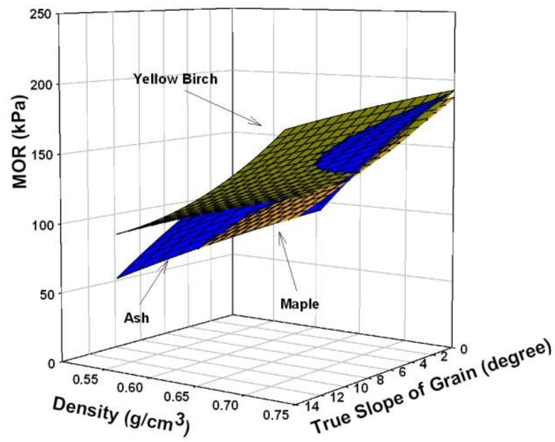

Figure 21: *Surfaces relating density, true SoG, and MOR for practical range of density*

4.9 EDGE-GRAIN vs FACE-GRAIN LOADING ORIENTATION

One of the important side studies conducted as part of this research effort was with matched samples subjected to either edge-grain or face-grain loading. A brief mention should be made of the difference between how ring porous ash and diffuse porous maple and yellow birch behave when loaded on the edge grain versus the face grain. When SoG is small, our test results suggest there is no detectible difference between edge- and face-grain loading. There was, however, a statistically significant difference between matched pairs of face- and edge-grain-loaded dowels at the higher SoG categories for both maple and yellow poplar. The face-grain-loaded matched specimens were higher in strength and stiffness than the edge-grain-loaded material. For the ash material, while statistically significantly different, there was a consistent trend towards having higher MOE and MOR values for matched material loaded on edge-grain over material loaded on the face-grain.

5 CONCLUSIONS

This paper reports the edgewise loading results of a study conducted to investigate the influence of slope of grain (SoG) on wood properties for three species (white ash, sugar maple, and yellow birch) that are commonly used in baseball bats. Results show that in general, edgewise MOE and MOR for all three species is reduced by a similar amount as the SoG increases. Maximum reduction in MOE was 20–25% at a SoG category of 10 degrees. Maximum reduction in MOR was shown to be about 25–30% at a SoG category of 10 degrees. Density changes affected the three species differently in the density range of interest to baseball manufacturing. For maple, MOE is less sensitive to changes in density than the other two species, whereas maple's MOR is affected the most by changes in density. Face-gain-loaded samples of diffuse porous maple and yellow birch at higher SoG angles had higher MOR values than matched edge-grain-loaded samples. Finally, SoG may have slightly less effect on yellow birch than on ash and maple.

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REFERENCES

[1] Wilson, T.R.C. The effect of Spiral Grain on the Strength of Wood. Jour. Forestry 19:740-747, illus. 1921.

[2] USDA Green, D. W., Winandy, J. E., and Kretschmann, *D. E.* Chapter 4: Mechanical Properties of Wood, *Wood Handbook: Wood as an Engineering Material.* General Technical Report, FPL GTR 113, Madison WI, U. S. Department of Agriculture, Forest Service, Forest Products Laboratory. 1999.

[3] United States Army, Engineering Division. Investigation of crushing strength of spruce at varying angels of grain. U.S. Air Serv. Inform. Circ. 259, 15pp**.** 1921.

[4] Hankinson, R. L. Investigation of the crushing strength of spruce at varying angles of grain. U.S. Air Sew. Inf. Cir. No. 259. 1921.

[5] Markwardt, L. J. and Wilson, T. R. C. Strength and Related Properties of Woods grown in the United States. United States Department of Agriculture, Technical Bulletin No. 479, Washingon, D. C. September 1935.

[6] Keith, C.T. Effect of orientation of annual layers on the resistance of wood to impact loading. ASTM Journal of Materials 1(4):759. 1966.

[7] Fagan, G. B. and McLain, T. E., The influence of small grain angle variation on toughness. Wood and Fiber Science, 15(2), 94-101. 1983.

[8] Mustone, Timothy J., "*A Method to Evaluate and Predict the Performance of Baseball Bats Using Finite Elements,"* MS Thesis, University of Massachusetts Lowell. 2003.

[9] Sherwood, J.A., Mustone, T.J., and Fallon, L.P., "Characterizing the Performance of Baseball Bats using Experimental and Finite Element Methods," In: Proceedings of the 3rd International Conference on the Engineering of Sport, June, Sydney, Australia. 2000.

[10] Koehler, A. Guide to Determining Slope of Grain in Lumber and Veneer. US FPL, Mimeo No. 1585, May 1955.

[11] ASTM International. *Annual Book of ASTM Standards.* Section 4, Volume 04.10, Wood, West Conshohocken, PA, 2008, p.779.

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