An Investigation into the Relationship between Wood Bat Durability and Bat Taper Geometry using LS-DYNA®

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Abstract

Changes in the Wooden Baseball Bat Standards (WBBS) by the Office of the Commissioner of Baseball in cooperation with the MLB Players Association in response to recommendations made by a task force comprised wood and baseball science experts have produced a 65% reduction in the rate of multi-piece failures (MPFs) of bats since 2008. It is hypothesized that the rate of MPFs can be further reduced if regulations on the allowable geometries of the taper region for the bats used by MLB teams are implemented in the WBBS. To develop a fundamental understanding of the relationship among (1) the angle of the taper region of the bat, (2) the starting point of the taper along the length of the bat, and (3) wood density, a series of actual and generic bat profiles was investigated using LS-DYNA for bat/ball impacts. In this paper, the results of these bat/ball impact simulations are shared, and a summary of the various combinations of these geometric parameters on bat stress and strain is presented. The durability information gained from these studies is then used to develop an understanding of why certain bat profiles used in professional baseball have relatively high rates of MPFs while other profiles exhibit relatively low rates of MPFs.

Introduction

Two broad categories of wood bat failures exist: single-piece failure (SPF) and multi-piece failure (MPF). An SPF is a failure where the bat stays intact or mainly in one piece. An MPF is a failure where the bat separates on failure into two or more significant-size pieces. The Office of the Commissioner of Baseball implemented changes to the Wooden Baseball Bat Specifications (WBBS) [1] in December 2008. Additional changes to the WBBS [2-5] from 2010-1014 have gradually increased the minimum allowable wood density of maple bats and have resulted in a 65% reduction in the MPFs relative to the 2008 season [6]. It is believed that the level of MPFs can be further reduced if the geometries of the bats are regulated so as to increase bat durability through a reduction in the stresses and strains experienced by the bat during bat/ball impacts.

There are four main regions of a bat: the knob, the handle, the taper, and the barrel. Each of these regions is denoted in Figure 1. The handle is the thinnest section of the bat, and as a consequence, is very susceptible to breaking. However, players are very sensitive to any increase in the diameter of the handle, so any effort to increase the diameter is going to be met with resistance by the players. The next important section of the bat with respect to durability is the taper region of the bat. It is hypothesized that by invoking restrictions on the slope and diameter of the taper then bat durability can be further improved over what it is today.

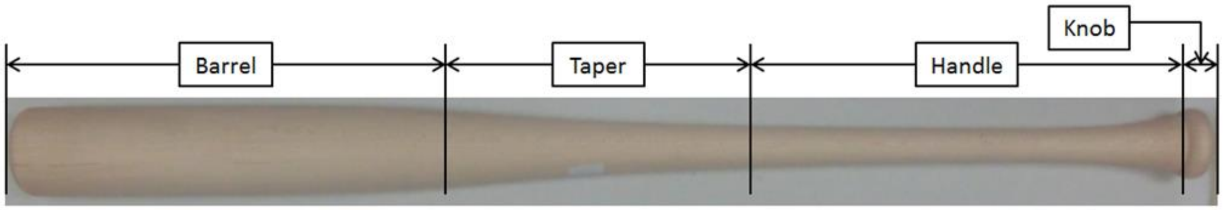


Figure 1: Baseball bat with bat regions specified

Bat Performance

The performance of a wooden baseball bat is dependent on a number of factors: wood properties, impact location, slope of grain, and bat profile.

<u>Wood Properties</u>

Wood is a naturally occurring composite composed of cellulose fibers and a lignin matrix. The cellulose acts as the reinforcement and the lignin serves as the matrix material, similar to the glass fibers and the polymer resin, respectively, in fiber-reinforced polymer matrix engineering composites [7].

Two mechanical properties that are important to consider when evaluating a wood species for use in baseball bats are (1) the modulus of elasticity (MOE) and (2) the modulus of rupture (MOR). The MOE quantifies the stiffness of a material in the elastic region of its stress-strain response while MOR is a measure of the breaking strength of the wood. The MOE and MOR of wood are generally inferior to those of metals and engineered composites.

The growth of a tree is at the mercy of Mother Nature. As a result there is high variability in the properties of wood. No two trees, even if they are of the same species, or two sections of the same tree will produce identical material properties. This high variability in material properties is demonstrated in Figures 2 and 3 which show the distribution of MOE and MOR, respectively, in ash wood as a function of density. The data in these figures were collected from four-point bend testing of wood dowels at the USDA Forest Products Lab in Madison, WI [8].

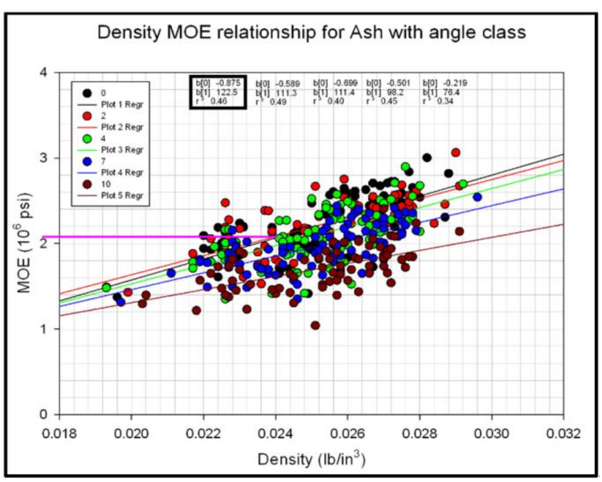


Figure 2: MOE variance with density for ash wood dowel testing

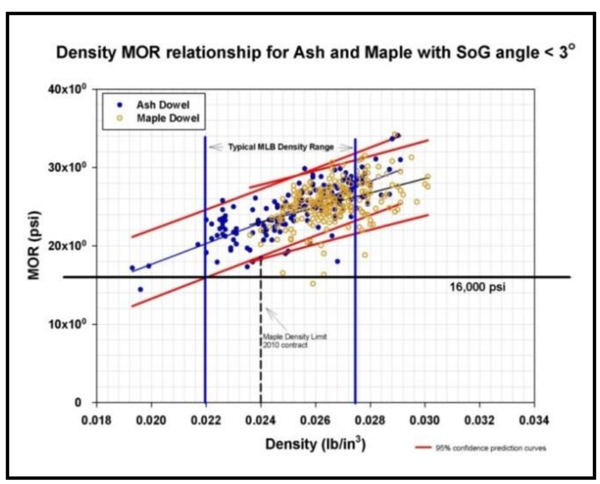


Figure 3: MOR variance with density for ash and maple wood dowel testing

Impact Location

Impact location refers to the point on the bat where a baseball contacts the bat during a bat/ball collision. The location of the impact affects the batted-ball speed, the vibration response of the bat, and the strain field in the bat. Impact is desired to occur in the last 10.2-20.4 cm (4-8 in.) of the barrel region, which is the thickest portion of the bat. When the bat is impacted in the taper region, higher strains are induced in the bat than would occur during an impact in the barrel area of the bat. Thus, impacts in the taper have a high probability to induce wood fracture and thereby compromise bat durability.

Baseball bat failure

There are two classes of failure; single-piece failure (SPF) and multi-piece failure (MPF). SPF occurs when the bat fails but remains in a single piece. This mode is the preferred failure mode because the bat remains intact after the failure occurs, thereby reducing the risk of injury from projectiles. An example of a single-piece failure is given in Figure 4. A multi-piece failure occurs when the bat breaks into two or more pieces. An example of MPF is shown in Figure 5. Previous research at the UMass Lowell Baseball Research Center where ash and maple bats were tested in a specially designed bat durability test machine showed that while maple and ash bats were equally likely to fail, maple bats were three times more prone to MPFs than ash bats [9].

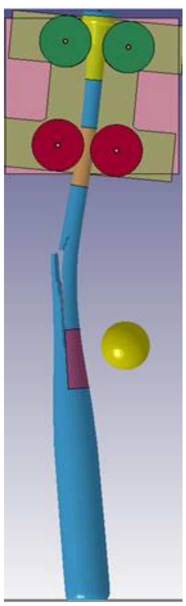


Figure 4: Single-piece failure of a baseball bat.

Figure 5: Multi-piece bat failure.

Bat Profiles

For the current research, a select group of common professional profiles of varying perceived on-field durability was examined. The three MLB bat profiles selected for this study are summarized in Table 1, and the specific name for each of these profiles has been blinded by replacing the profile name with a letter designation.

Table 1: Profile Diameter and Volume Dimensions

Profile	**Handle Dia.** cm (in.)	**Taper Dia.** 30.5 cm (12 in.) from knob (in.)	**Taper Dia.** 38.1 cm (15 in.) from knob (in.)	**Barrel Dia.** cm (in.)	**Bat Volume** cm^3 (in^3)
A	2.408 (0.948)	2.573 (1.013)	2.883 (1.135)	6.241 (2.457)	1231 (75.10)
B	2.377 (0.936)	2.751 (1.083)	3.035 (1.195)	6.507 (2.562)	1394 (85.09)
C	2.441 (0.961)	2.819 (1.110)	3.274 (1.289)	6.500 (2.559)	1478 (90.19)

Table 1 highlights some of the geometrical properties for each of these three popular bat profiles. Profile A is a small volume bat that is known to be one of the most durable profiles available and has the smallest barrel of the three profiles. Profile B is a moderate volume bat that is known to exhibit relatively average durability during gameplay and has the largest barrel of the three profiles. Profile C is known to exhibit the poorest durability of the three profiles and has the largest volume of the three profiles. Table 1 also includes the diameters at two locations along the taper region of each bat and the minimum diameter in the handle region.

Finite Element Modeling

To assist in understanding the relationship between the bat profile and bat durability, finite element modeling studies were conducted using LS-DYNA. These LS-DYNA studies were separated into three major approaches. The first approach utilized two base profiles and six different variations of these base profiles to investigate how restricting the bat diameter at a location 41.9 cm (16.5-inches) as measured from the base of the knob would influence durability. The second approach investigated how changes in the slope of the taper region and in the starting position of the taper region influenced the stress state in a bat as a result of a bat/ball impact. For these studies all of the bats were of the same weight (0.88 Kg (31 oz.)). For this portion of the study, the wood density varied as a function of the volume of the bat so as to achieve the overall target weight. The third approach examined how the maximum strain level in the three professional profiles differed when the same wood density was used. Because the mechanical properties vary as a function of wood density, the use of the same density left the mechanical properties to be the same for this set of analyses. The finite element models were constructed following the lessons learned and experiences gained from prior work conducted for investigating bat durability in LS-DYNA [8].

41.9-cm (16.5-in.) Diameter study

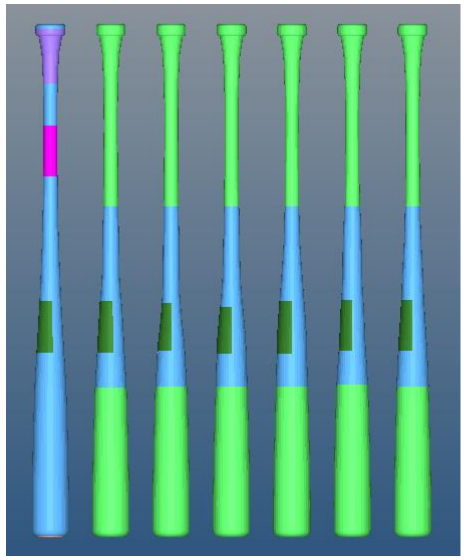
The results of broken-bat data suggested that the diameter at the 41.9-cm (16.5-in.) location as measured from the base of the knob may influence the durability of bats. Therefore, the 41.9-cm (16.5-in) location was used as the starting point for exploring how modifications to the taper of bat profiles could influence bat durability. All bats were 86.4-cm (34-in.) long.

The base profile chosen for this investigation was Profile A. Profile A is one of the most popular as well as most durable low-volume bat profiles used by MLB players. From the initial profile, six variations were created by using the morphing tool in HyperMesh. These new profiles are denoted as X1 through X6. The dimensions for base profile A as well as the various modified profile variations are given in Table 2. The X1, X2 and X3 models started with a 2.97-cm (1.17-in.) diameter at the 41.91-cm (16.5-in.) location, and the X4, X5 and X6 models started with a 3.68-cm (1.45-in.) diameter at the 41.9-cm (16.5-in.) location. The baseline profile was modified such that each profile would remain the same between 0-30.5 cm (0-12 in.) and 61.0-86.4 (24-34 in.) as measured from the base of knob but have variations in the taper section on either side of the 41.9-cm (16.5-in.) location.

The variations in profile are shown in Table 2 and illustrated in Figure 6. For example, the X1 profile increases the diameter at the 45.7-cm (18.0-in.) axial position, while the X3 modification delays the increase in diameter until the 53.3-cm (21.0-in) axial position. The same types of modifications were repeated for the X4, X5 and X6 models while having a larger starting diameter at the 41.9-cm (16.5-in.) location.

Table 2: The dimension of Profile A and modified A profiles.

Bat Profile	Diameter at different locations as measured from the base of knob [cm (in.)]					
	30.5 (12.0)	38.1 (15.0)	41.9 (16.5)	45.7 (18.0)	53.3 (21.0)	61.0 (24.0)
Profile A	2.654 (1.045)	3.035 (1.195)	3.299 (1.299)	3.670 (1.445)	4.445 (1.750)	5.398 (2.125)
A-X1	2.654 (1.045)	2.845 (1.12)	2.972 (1.17)	3.632 (1.43)	4.445 (1.75)	5.398 (2.125)
A-X2	2.654 (1.045)	2.845 (1.12)	2.972 (1.17)	3.099 (1.22)	4.445 (1.75)	5.398 (2.125)
A-X3	2.654 (1.045)	2.845 (1.12)	2.972 (1.17)	3.632 (1.43)	4.902 (1.93)	5.398 (2.125)
A-X4	2.654 (1.045)	3.023 (1.19)	3.683 (1.45)	4.343 (1.71)	5.08 (2.00)	5.398 (2.125)
A-X5	2.654 (1.045)	3.556 (1.40)	3.683 (1.45)	3.81 (1.50)	4.394 (1.73)	5.398 (2.125)
A-X6	2.654 (1.045)	3.251 (1.28)	3.683 (1.45)	3.937 (1.55)	4.775 (1.88)	5.398 (2.125)



Base X1 X2 X3 X4 X5 X6

Figure 6: Model for baseline and modified versions of Profile A.

To determine the influence of the profile modifications on durability, simulations were run for impacts at locations 5.1, 15.2, 25.4, 35.6, and 40.6-cm (2, 6, 10, 14, and 16-in.) as measured from the tip of the barrel. Using this range of impact locations covers a span from outside to inside impacts that are typically seen during gameplay. The impact velocity was varied by impact location to simulate an 80% maximum velocity impact assuming a 40.2 m/s (90 mph) pitch and 40.2 m/s (90 mph) swing speed. The velocities at the respective impact locations are listed in Table 3.

Table 3: 80% Maximum Impact Velocities by Impact Location

Impact Location cm from Barrel Tip (in)	Impact velocity m/s (mph)
5.1 (2)	64.8 (145)
15.2 (6)	62.6 (140)
25.4 (10)	58.1 (130)
35.6 (14)	53.6 (120)
40.6 (16)	51.4 (115)

The maple wood properties used in the models were derived from the Wood Handbook [10], and a series of four-point bending dowel tests at the USDA Forest Products Lab. Bats were prescribed a density so as to model a 0.879-kg (31-oz.) bat, and the mechanical properties were scaled based on that density, e.g. the elastic modulus is linearly proportional to density. The MAT143 wood material was used to prescribe the wood properties which were kept purely elastic for this set of models [11]. The maximum stresses for the various profiles are shown in Figure 7.

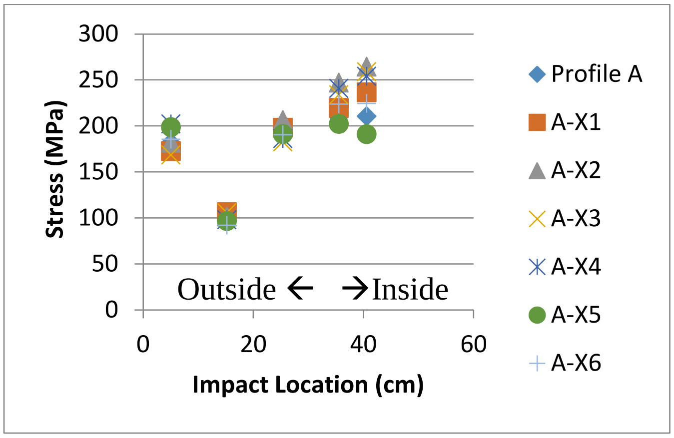


Figure 7: Max stress as a function of impact location for purely elastic models of Profile A and modified profiles.

An interesting trend to take away from Figure 10 is that there are different stress behaviors for inside- and outside-impact locations. It can be seen in this figure that impacts at the 15.2-cm (6-in.) position, have the lowest level of maximum stress. This location is often referred to as the "sweet spot" because it induces the least vibration transmission to the hands of the batter, thereby giving the batter a "good feeling". The maximum stress levels are observed for ball strikes that are inside of the sweet spot with the maximum stress occurring from strikes at the 40.6-cm (16-in.) positions followed by strikes at the 35.6-cm (14-in.) location.

The results of this modeling study show that the modifications that improve durability for an inside pitch and an outside pitch differ. Modified profiles with the 3.68-cm (1.45-in.) diameter at the 41.9-cm (16.5-in.) location performed superior for inside impacts when compared to the models with the 2.97-cm (1.17- in.) diameter at this location. This distinction is important because roughly 2/3 of all MPFs occur due to an inside impact. In particular, the X5 modification proved to exhibit the lowest maximum stress level of all profile modifications. This profile had the smallest rate of diameter change, or taper slope, into and out of the 41.9-cm (16.5-in) location as well as the largest diameters near the handle of the bat. These results led to the hypothesis that the slope of the taper angle of a bat profile might be an indicator of its durability.

Investigation of taper starting position with constant taper angle

Three series of generic bat profiles were developed using HyperMesh and subsequently analyzed in LS-DYNA. These generic bats were configured to have a constant-slope (3^o, 4^o, or 5^o) in the taper region in combination with a prescribed axial position for the start of the taper (25.4, 30.5, and 35.6 cm (10, 12, and 14 in.) as measured from the base of the knob). The models generated for the 25.4 cm (10-in.) can be seen in Figure 8. The black arrows denote the starting point of the taper. All bats were 86.4-cm (34-in.) long.

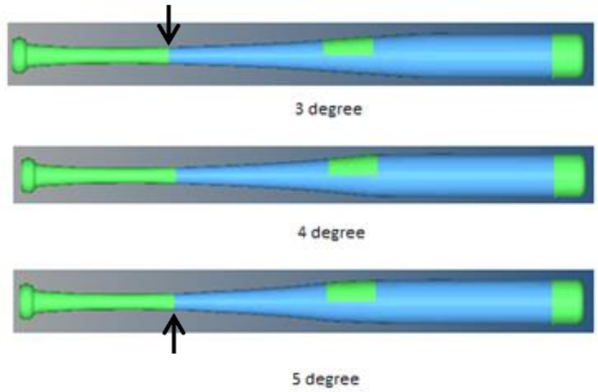


Figure 8: Finite element models of bats with 3^o, 4^o, and 5^o constant taper slopes and taper starting at 25.4 cm (10 in.) as measured from the base of the knob

All of the bats in the study were made of maple, and the same location along the length of the bat was used for all impact analyses. The maple wood properties used in the models were derived from the Wood Handbook [10]. Bats were prescribed a density so as to model a 0.879-kg (31-oz.) bat, and the mechanical properties were scaled based on that density, e.g. the elastic modulus is linearly proportional to density. All simulations utilized an impact location of 35.6 cm (14 in.) as measured from the tip of the barrel with an impact velocity of 53.6 m/s (120 mph). These parameters were chosen because the 35.6-cm (14-in.) location lies within the taper region of the bat and 53.6 m/s (120 mph) represents 80% of maximum bat/ball impact at the 35.6-cm (14-in.) location assuming a swing speed of 35.7 m/s (80 mph) at the tip of the barrel and a pitch speed of 40.2 m/s (90 mph). This position on the bat corresponds to a typical inside-pitch impact that is known to be detrimental to the bat. For this study, no failure criteria were used in the models. After the simulations were run to completion, they were postprocessed in LS-PrePost® to analyze the resulting maximum stress levels in the bats after impact.

Table 4: Summary of results for taper study models

Taper Slope	**Max stress (MPa) and taper start position**		
	25.4-cm start	**30.5-cm start**	**35.6-cm start**
3^o	166.37	205.84	245.32
4^o	161.22	199.89	225.11
5^o	171.89	206.42	226.29

The results of the finite element simulations are summarized in Table 4. The results show that the maximum stresses were essentially the same for all combinations of taper slope at a given taper starting position. However, the maximum stress did vary significantly with respect to taper starting position. This result suggests that durability improves as the start of the taper moves toward the knob. Figure 9 shows the finite element models at the point of maximum stress for the 4^o taper slope starting at 25.4, 30.5, and 35.6 cm (10, 12, and 14 in.) as measured from the base of the knob when impacted at 35.6 cm (14 in.) from the tip of the barrel. All fringe levels in the illustrations are on the same scale for ease of comparison. Note how the shift in position of maximum stress follows the movement of the taper starting point. The maximum stress for the 25.4 cm (10-in.) taper start is closer to the knob and has a lower maximum stress in comparison to the 35.6 cm (14-in.) taper start.

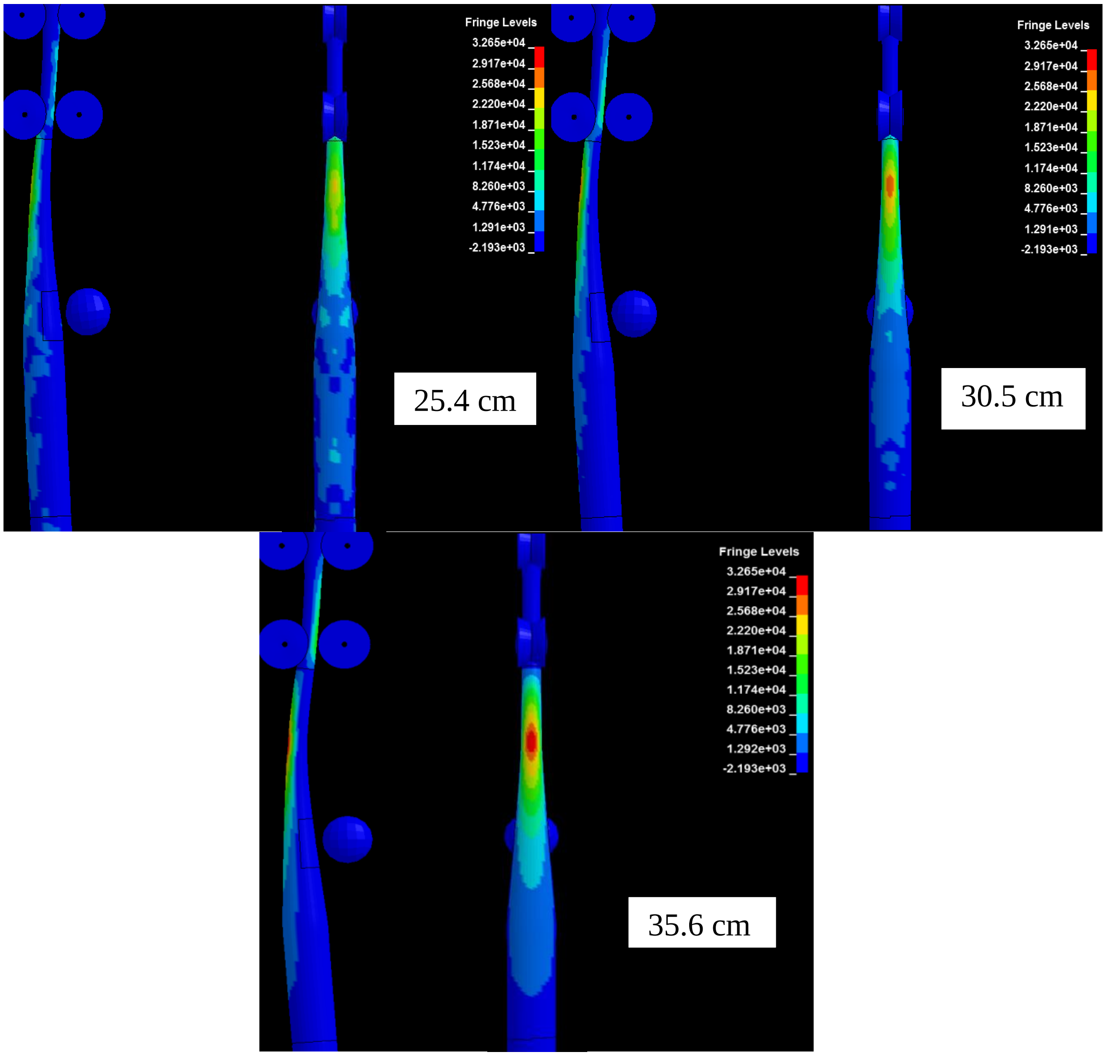


Figure 9: The 4^{o} constant taper slope models showing stress contours. The dimension in the figure is the taper starting position as measured from the base of the knob.

Professional Profile Study

Finite element models of the three professional profiles that are cited in Table 1 were analysed. To limit the study to examine the effect of geometry on bat durability, all of the material properties were based on a wood density of 678.2 kg/m^3 (0.0245 lb/in^3), which is currently the minimum-allowed maple density of bats for use in gameplay. Having held the density the same for all the profiles, it is assumed that the individual profile effect after impact can be analysed in isolation from the effect of wood density. Recall in the previous section all bat modelling varied the densities of the bat models so that the weight of the bat was 0.879-kg (31-oz.).

The models were analysed for impacts at the 35.6 cm (14-in.) location to simulate the same inside pitch as was considered in the taper-study models. The impact velocities were set at 80% maximum velocity which is 53.6 m/s (120 mph) for an impact at the 35.6 cm (14-in.) location. No failure criteria were used in these models. Previous modelling studies focused on analysing the maximum stress in the bat after impact. However, it was thought that the maximum strain level in the bats might be a better parameter to indicate bat durability. The results of the modelling simulations after postprocessing are summarized in Table 5.

Table 5: Professional profiles modelled with same density and mechanical properties

Profile	Max Strain	Bat Weight Kg (oz.)	Bat Volume cm^3 (in^3)	Wood Density Kg/m^3 (lb/in^3) for 0.879-Kg (31-oz.) target weight
A	0.0233	0.850 (30.0)	1231 (75.10)	714.1 (0.0258)
B	0.0226	0.967 (34.1)	1394 (85.09)	631.1 (0.0228)
C	0.0177	1.010 (35.7)	1478 (90.19)	595.1 (0.0215)

The results of the simulations were surprising. Profile A, which is the most durable of the three profiles, exhibited the largest strain at 0.0233. Profile C, which is the least durable of the three profiles, exhibited the smallest strain at 0.0177. Based on field-experience data, one would expect for Profile A to exhibit the lowest strain of the three profiles and for Profile C to have the highest. Because the density and mechanical properties are the same for all of the models in this portion of the study, the only reasonable explanation for the unexpected differences in maximum strain is the geometry of the profile.

Table 1 can help to understand the contradiction of the modelling results from what is seen on the field for the relative durability of these three profiles. In Table 1, it can be seen that the two diameters in the taper region for Profile C are much larger than these same diameters in Profiles A and B. Profile A has the smallest diameters for all the locations, which would indicate that the disparity in diameter size could explain the difference in the strain levels, i.e. the max strain decreased with increasing diameter. Essentially these results show that if a profile is generated from the same piece of wood, the profile with larger diameters up through the taper region will exhibit superior durability. While this result is intuitively correct, i.e. bigger is better, and underwhelming, it brings to the forefront one of the true sources for the on-field relative durability of these three profiles.

For the current study, each of the A, B and C bat profiles was modelled using the same density. This same-density approach results in a wide span of overall bat weights as summarized in Table 5. For the case of each of these profiles being used for on-field play, the target weight would be 0.879 Kg (31 oz.). Table 5 lists the respective wood densities required to achieve the target weight for each of the profiles. As the volume of the bat increases from Profiles A to B to C, the wood density decreases to meet the target weight. The on-field poor durability of Profile C implies that wood density may play a larger role in the relative durability of a bat than does the size of the taper region of the bat. Thus, there is trade-off between the geometry of the taper and the wood density for the roles that each plays with respect to bat durability.

Conclusions

The finite element studies provided insight into the profile geometry parameters that influence relative bat durability. Modifications made to base Profile A showed that variations which improve durability for inside-pitch impacts do not improve durability for outside-pitch impacts. Specifically profiles with a larger diameter at the 41.9 cm (16.5-in) location will exhibit a lower maximum stress level for an inside impact. For the range of taper angles considered (3^o to 5^o), no appreciable trend with respect to increasing or decreasing durability was observed as a function of taper angle. Significant durability change was observed for changing the taper start position– the closer to handle the taper begins the better the durability. Bat profiles with larger diameters closer to the handle exhibit lower maximum strain during impact than profiles with smaller diameters near the handle when considering the same wood density.

Acknowledgements

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