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Predict the relationship between wood baseball bat profile and durability

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Abstract

Major League Baseball (MLB) currently has few restrictions on the bat profiles allowed for use during gameplay. Although current multi-piece failure (MPF) rates are at their lowest in years, there is still room for further improvement by regulating the bat profiles allowed in games. The influence of bat profile tapering was analyzed utilizing finite element models of various known profile geometries to determine the effect on bat durability. LS-DYNA simulations were processed for profiles over a range of maple wood densities that would be currently allowed by MLB regulations. This paper will describe the various modelling studies conducted to determine the factors that comprise a bat profile of good durability. The results of the modelling are compared to on-field data of bat failures during gameplay of known profiles used by MLB players. A profile scoring formula is proposed that is a combination of bat geometrical characteristics and bat wood density. This score is shown to be a good predictor of the relative durability of a given set of bat configurations.

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Keywords: Baseball bat; profile, durability, modeling

1. Introduction

In response to a perceived increase in multi-piece failures (MPFs) in professional baseball bats, the Office of the Commissioner of Baseball implemented changes to the Wooden Baseball Bat Specifications (WBBS) [1] in December of 2008. These changes introduced bat-supplier regulations that outlined strict quantitative requirements for wood quality and instituted a third-party inspection of professional wooden baseball bats. Additional changes to the WBBS [2, 3, 4] for the 2010, 2011, and 2012 seasons targeted increasing the density of the wood used to make maple bats, thereby increasing the minimum breaking strength of the wood allowed for these bats and restricting the process of introducing new wood species for baseball bats. By the completion of the 2015 season, these changes had driven a 65% reduction in MPFs relative to the 2008 season [6]. It is believed that the level of multi-piece failures (MPF) can be further reduced if regulations on the allowable geometries of the taper region for the bats used by MLB teams are implemented.

A baseball bat has a smooth profile that is typically defined by the sections presented in Figure 1. The handle is the thinnest section and is where the batter holds the bat. The barrel is the thickest section and is where the ball typically makes contact. The taper region can vary significantly among bats in shape, length, and axial position; and though not desirable, can be impacted during gameplay. This paper will focus on the characteristics of the bat profile that relate to the durability of the bat.

Figure 1: Baseball bat with bat regions specified

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2. Background

The need exists to have a process that can effectively sort the relative durability of bat profiles, especially those that are being used in professional gameplay. For this paper, the term durability is identified by the ability of the bat to survive a single-strike impact at an elevated relative bat/ball velocity threshold without fracture. Thus, durability is then quantified by the max relative bat/ball speed that the bat can tolerate without breaking—the higher the speed, the better the durability.

Table 1 lists several identifying characteristics of the five bat profiles presented throughout this paper. The research included the investigation of more than 15 bat profiles. However, the five-profile subset that has been selected for this paper is sufficient to demonstrate the principle outcome of the current research. The relative on-field durabilities of these bat profiles were considered in the analysis, but modeling was utilized to understand how the profiles were susceptible to breakage. Among the five bats, identified as A, B, C, D, and E, Profile A is the most durable and Profile E is the least durable. The overall relative durabilities are ordered as A > B > C > D > E. Throughout the current research, the findings and lessons learned have led to the development of a function that has been proposed for use in the WBBS to sort bats as being eligible or ineligible for on-field play. The differences among the five bat profiles shown in Table 1 are subtle but important. For example, Profile A has the smallest handle diameter but transitions slowly to the barrel and therefore results in the smallest volume of the group. The finite element images of the profiles are included to allow for visual comparison of the subtle variations in the profiles.

Table 1: Geometric characteristics of the five bat profiles

Profile	A	B	C	D	E
					
Minimum handle diameter (cm) (in.)	2.408 (0.948)	2.677 (1.054)	2.377 (0.936)	2.441 (0.961)	2.248 (0.885)
Diameter at 30.5-cm (12-in.) location (cm) (in.)	2.573 (1.013)	2.883 (1.135)	2.751 (1.083)	2.819 (1.110)	2.588 (1.019)
Diameter at 38.1-cm (15-in.) location (cm) (in.)	2.883 (1.135)	3.172 (1.249)	3.035 (1.195)	3.274 (1.289)	3.002 (1.182)
Maximum barrel diameter (cm) (in.)	6.241 (2.457)	6.553 (2.580)	6.507 (2.562)	6.500 (2.559)	6.467 (2.546)
Bat Volume–no cup (cm^3) (in^3)	1230 (75.1)	1406 (85.8)	1394 (85.1)	1478 (90.2)	1337 (81.6)
Bat Volume–with cup (cm^3) (in^3)	1208 (73.7)	1377 (84.0)	1377 (84.0)	1449 (88.4)	1319 (80.5)

3. Durability score development

Finite element studies were used to investigate the effects of bat profile taper on durability [7, 8, 9] and to provide insight into what constitutes a durable profile. Using the results of these finite element analyses and applying the lessons learned to popular profiles that are currently used by MLB players, a durability criterion was developed. The objectives in developing the durability criterion (score) was to identify the simplest relationship possible by using one or more physical characteristics to conclude durability score. Therefore, this paper presents several potential criteria that were investigated, but many of them proved to be too simple to capture the major parameters that influence bat breakage.

3.1. Initial profile scores that were investigated

The results of the finite element studies indicated that profiles with relatively large diameters near the handle exhibited lower stress and strain levels during impact than profiles with smaller diameters in this vicinity. On-field data that had been collected over several years indicate that large-volume bats are more likely to exhibit an MPF in comparison to profiles of low-volume bats. By taking both of these findings into account, the initial attempt at a relationship to predict on field durability was,

$$\frac{1}{Durability} \propto \frac{Bat\ Volume}{Diameter\ (x)} \qquad (1)$$

In Equation 1, x represents a location at 30.5 (12), 35.6 (14), 40.6 (16) or 45.7 (18) cm (in.) as measured from the base of the knob. By using this criterion, a bat with a lower score would be deemed more durable. Profile C is used as a baseline for comparison as this profile is a popular profile that exhibits moderate durability. This criterion was applied to 20 bats commonly used by MLB players, the results for the five profiles that were selected for this paper are summarized in Table 2—where the lower score, the better the durability. Among these five profiles, the results included in Table 2 show the 30.5-cm (12-in.) location to sort the profiles well. The other locations were not as representative of the durability of each profile from gameplay. Unfortunately, further investigation of additional profiles did not provide confidence in moving forward with this simple relationship.

Table 2: Tabulation of the scores calculated from Equation 1 (Score in English Units (in and lbs))

Location from knob end	Profile A	Profile B	Profile C	Profile D	Profile E
30.5 cm (12 in.)	74	76	79	81	80
35.6 cm (14 in.)	69	71	74	74	73
40.6 cm (16 in.)	62	66	67	66	65
45.7 cm (18 in.)	55	58	58	58	54

Wood density has been a key factor in much of the research related to bat durability. Therefore, as the research progressed, wood density was added as a factor into the relationship. With the objective of having a low score represent good durability, density was incorporated into the denominator of the next attempted relationship, which is presented in Equation 2, so that a higher-density wood will improve a bat profile's score.

$$\frac{1}{Durability} \propto \frac{Bat\ Volume}{Diameter(x) * Wood\ Density} \qquad (2)$$

Including density in the score, as shown in Equation 2, would allow for higher-density wood to be used in larger volume bats. Many of the bats that have large volume have a low perceived durability. The result of implementing a score that includes wood density would require bat manufacturers to use higher-density wood for bats that would not have been allowed by the score calculated in Equation 1. Likewise with this method, lower-density woods would be able to be used in bat profiles that scored sufficiently lower than what would have been the cut-off limit using Equation 1. Profile C again was used as a baseline for comparison. This criterion was applied to 20 bats commonly used by MLB players, the results of the five selected profiles are summarized in Table 3, where a lower score is intended to represent better durability.

Table 3: Tabulation of scores calculated from Equation 2 (Score in English Units (in and lbs))

Location from knob end	Profile A	Profile B	Profile C	Profile D	Profile E
30.5 cm (12 in.)	2936	3332	3413	3818	3497
35.6 cm (14 in.)	2730	3143	3231	3460	3189
40.6 cm (16 in.)	2456	2906	2890	3105	2829
45.7 cm (18 in.)	2176	2543	2500	2719	2371

The result of incorporating density into the criterion led to an improved distribution among the profiles that are durable (lower score) and the lesser-durable (higher score). Among these five profiles, the results included in Table 3 show the 30.5-cm (12-in.) location to sort the profiles the best, but other locations were not as representative of the relative durability of each profile from gameplay. Again, further investigation of additional profiles did not provide confidence in this relationship. To further improve this distribution, the diameter of the profile at the "x" location would be given more weight in the equation by squaring that term. This decision was supported by the conclusion that bats with a taper starting closer to the handle, and thus a larger diameter closer to the knob exhibit better durability. This modification led to,

$$\frac{1}{Durability} \propto \frac{Bat\ Volume}{\left(Diameter(x)\right)^2 * Wood\ Density} \qquad (3)$$

At this point in the analysis, it was determined that "x" would be either 30.5 (12) or 35.6 (14) cm (in.) as measured from the base of the knob. This location range was chosen as it is the most common region of initial bat failure for inside pitches. The result of applying this criterion to the five profiles is summarized in Table 3. Among the five profiles, the results included in Table 4 show the 30.5-cm location to sort the profiles the best. Therefore, the terms in Equation 3 were determined to have the ability to capture the relative durability of a bat profile.

Table 4: Tabulation of scores calculated from Equation 3 (Score in English Units (in and lbs))

Location from knob end	Profile A	Profile B	Profile C	Profile D	Profile E
30.5 cm (12 in.)	2900	2937	3153	3440	3432
35.6 cm (14 in.)	2507	2614	2825	2824	2854

3.2. Improving profile score through finite element modeling

To analyse the relationship between bat profile and wood density as it relates to the failure mode of the bat, bat profiles were constructed of varying wood densities for impact analysis in finite element modelling using LS-DYNA. The finite element models were configured for a baseball to impact the bat at a location 35.6 cm (14 in.) from the barrel end of the bat at a velocity of 64.8 m/s (145 mph). The 35.6-cm (14-in.) impact location was chosen because this location is known to be among the most severe locations of MPF for an inside pitch impact. An impact velocity of 64.8 m/s (145 mph) was used for the study as this is the maximum velocity for an impact at the 35.6-cm (14-in.) location assuming both a pitch and swing speed of 40.2 m/s (90 mph). The density range used in this study varied from 622.80-747.360 kg/m^3 (0225-0.0270 lb/in^3). Eleven bat profiles were analysed, but the same five profiles are presented in this section. Once the finite element analyses were completed, the models were postprocessed to determine the failure mode of the profile. A bat profile was classified to have failed either MPF, single-piece failure (SPF) or no failure (NF). A MPF is classified as any bat failure in which the bat splits into two or more pieces greater than an ounce in weight. If the bat fractures or cracks without splitting into multiple pieces, then it is deemed a SPF. Examples of the three failure types are shown in Figure 2. The results of the modelling studies are summarized in Table 5. This table helps to show the relationship among failure type, the bat profile, wood density and how the bat profile, volume and density affect the bat weight as included in the parentheses within each cell of the table.

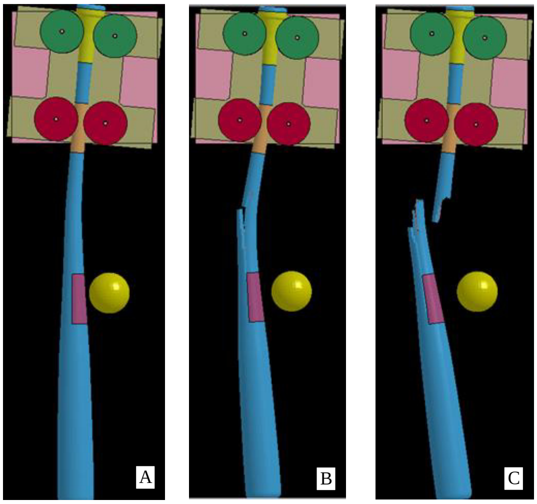

Figure 2: Bat failure modes: (a) no failure (NF), (b) single-piece failure (SPF), and (c) multi-piece failure (MPF)

Table 5: Density failure results based on FE modelling (including resulting bat weight (oz.) based on density, volume and maximum 2-oz. cup)

Density (lb/in^3)	Profile A	Profile B	Profile C	Profile D	Profile E
0.0225	MPF (25.0)	SPF (28.9)	MPF (28.6)	MPF (30.5)	MPF (27.4)
0.0230	MPF (25.6)	SPF (29.6)	MPF (29.3)	MPF (31.2)	MPF (28.0)
0.0235	MPF (26.2)	SPF (30.3)	MPF (30.0)	MPF (31.9)	MPF (28.7)
0.0240	MPF (26.8)	SPF (30.9)	MPF (30.7)	MPF (32.6)	MPF (29.3)
0.0245	MPF (27.4)	SPF (31.6)	MPF (31.4)	NF (33.4)	MPF (30.0)
0.0250	MPF (28.0)	NF (32.3)	SPF (32.0)	NF (34.1)	MPF (30.6)
0.0255	MPF (28.6)	NF (33.0)	SPF (32.7)	NF (34.8)	MPF (31.3)
0.0260	MPF (29.2)	NF (33.7)	SPF (33.4)	NF (35.5)	NF (31.9)
0.0265	SPF (29.8)	NF (34.4)	NF (34.1)	NF (36.2)	NF (32.6)
0.0270	NF (30.4)	NF (35.1)	NF (34.8)	NF (37.0)	NF (33.3)

The results of the modelling of bat failure related to density show that profiles with large diameters near the handle and in the taper region display a larger range of NF based on density in comparison to bats with small diameters in these regions. Specifically, profiles B and D perform the best of the sample set based on density alone. However, Profile D is considered to exhibit relatively poor durability based on the perceived durability ranking. Profile D has a very large volume in comparison to the other four profiles presented, and it is hypothesized that the majority of the bats made with Profile D that are used in games are comprised of a low-density wood leading to its poor durability—not the profile geometry itself. Conversely, it was also unexpected that Profile A has the largest range of MPF through the density range investigated. Profile A has small diameters throughout the profile and has a very small volume in comparison to the rest of the profiles in the sample set. The small volume results in bats likely being made from high-density wood, and this high-density wood is believed to be the explanation for Profile A to exhibit good durability during gameplay.

The objective of the profile score is to be able to predict if a bat profile is more or less likely to result in a MPF or either a SPF or NF. Therefore, the modelling performed and presented in Table 5 was used to improve the profile score. Equation 3 had identified many of the important terms in the score, but it was challenging to determine the weight of each term in the relationship. Additionally, it was determined that the equation for the profile score would be improved by including an additional term for another diameter along the taper region and the length of the bat. The diameter characteristics of the region spanning between the 30.5-cm (12-in.) location and the barrel is important. The results of the work leading to Table 3 had identified little value in considering the diameters of the 40.6- and 45.7-cm (16- and 18-in.) locations, and the finite element analysis showed the crack initiation point to be very near the 38.1-cm (15-in.) location. Additionally, because bat volume is so dependent on bat length and the score would need to be applied to bats of varying lengths, length was added as a term in the profile score. Therefore, it was selected to make an attempt at improving the score by including terms for the bat length and the diameter at the 38.1-cm (15-in.) location and weighting the power of each term in the profile score within an equation based on the analysis of the finite element modelling in Table 5.

The finite element modelling for a range of profiles generated the failure type outcomes (MPF, SPF or NF) based on a 13.8 kg/m^3 (0.0005 lb/in^3) increments in wood density. From this tabulation, the transition from MPF to either SPF or NF is identified. Applying the criteria to the 11 profiles analysed in this study for the lowest density resulting in either a SPF or NF as well as a density 13.8 kg/m^3 (0.0005 lb/in^3) higher than the threshold difference in the two scores was analysed. By investigating the standard deviation of the bat profiles at the threshold density and by normalizing the standard deviation to that of Profile C, a credible relationship among the durability factors could be achieved. Iterating through multiple variations, it was found that the deviation amongst the group was at a minimum when the durability factors were raised to the powers shown in Table 6 and presented in Equation 4.

Table 6: Power weighting of profile score terms (Score in English Units (in and lbs))

Parameter	Power
Bat Volume (in^3)	0.5
Wood Density (lb/in^3)	1.8
Diameter at 30.5-cm (12-in) location (in)	2.0
Diameter at 38.1-cm (15-in) location (in)	1.0
Bat Length (in)	1.0

$$\frac{1}{Durability} \propto \frac{Bat\ Volume^{0.5}}{(Diameter_{12})^2 * Diameter_{15} * Wood\ Density^{1.8} * Length} \tag{4}$$

The durability score terms have the units of in., in^3, and lb/in^3. This relationship provides the best estimation of on-field bat durability based on the modelling work conducted to date.

4. Method for implementing profile score limit

Equation 4 offers a method for evaluating the relative durability of bat profiles. By applying this score to the five bat profiles that are investigated in this paper, Table 7 shows the profile score for each profile based on the range of typical bat weights used by MLB players. By utilizing an 86.4-cm (34-in.) length bat, the weight ranged from 0.850-0.992 kg (30-35 oz.) in 0.014-kg (0.5-oz.) increments. In Table 7, the score is applied to the bats assuming a cupped profile. A cup, material drilled out of the end of the bat, can have a significant effect on the score. The cupping of a bat can result in a weight reduction of up to 56.7 g (2 oz.) depending on the wood density. This cup reduces the volume of the bat, which directly affects the calculation of the score.

Table 7: Tabulation of scores calculated from Equation 4 (Score in English Units (in and lbs))

Bat weight	Profile A	Profile B	Profile C	Profile D	Profile E
0.850 kg (30.0 oz)	161	157	181	179	187
0.865 kg (30.5 oz)	156	153	175	174	181
0.879 kg (31.0 oz)	152	148	170	169	176
0.893 kg (31.5 oz)	147	144	165	164	171
0.907 kg (32.0 oz)	143	140	161	159	166
0.921 kg (32.5 oz)	139	136	156	155	162
0.936 kg (33.0 oz)	136	133	152	151	157
0.950 kg (33.5 oz)	132	129	148	147	153
0.964 kg (34.0 oz)	128	126	144	143	149
0.978 kg (34.5 oz)	125	122	140	139	145
0.992 kg (35.0 oz)	122	119	137	136	142

4.1. Application of profile score criterion

As an example, using a profile score limit of 150 would allow a 86.4-cm (34-in.) bat constructed to Profile A to be able to have a weight of 0.893 kg (31.5 oz) and heavier, but not 0.879 kg (31.0 oz) and lighter. The same limit would allow a 86.4-cm (34-in.) bat constructed to Profile D to be able to have a weight of 0.950 kg (33.5 oz) and heavier, but not 0.936 kg (33.0 oz) and lighter. Table 8 provides the minimum density and weight utilizing a threshold score of 153.

Table 8: Minimum density and weight limits utilizing the cutoff threshold for various known profiles

Parameter	Profile A	Profile B	Profile C	Profile D	Profile E
Min Density	725.2 kg/m^3 (0.0262 lb/in^3)	628.3 kg/m^3 (0.0227 lb/in^3)	678.2 kg/m^3 (0.0245 lb/in^3)	642.2 kg/m^3 (0.0232 lb/in^3)	719.7 kg/m^3 (0.0260 lb/in^3)
Min Weight (no cup)	0.876 kg (30.9 oz)	0.865 kg (30.5 oz)	0.933 kg (32.9 oz)	0.927 kg (32.7 oz)	0.950 kg (33.5 oz)
Min Weight (cup)	0.833 kg (29.4 oz)	0.825 kg (29.1 oz)	0.887 kg (31.3 oz)	0.890 kg (31.4 oz)	0.904 kg (31.9 oz)

5. Conclusions

Finite element modelling of baseball bat impacts facilitated the development of a profile score to assess the relationship between bat profile and the associated durability of the bat. It was determined that a reliable relationship required more than just the bat volume and a diameter at a single location. The profile score was based on the finite element modeling of 15 common profiles that are used by MLB players and that span a range of perceived durability from their use in gameplay. It was determined that profiles with low volume, large diameters at 30.5 and 38.1 cm (12 and 15 in.) as measured from the base of the knob, and composed of high-density wood exhibit the best durability during gameplay. Through a combination of these parameters, a durability criterion score was developed to predict the relative durability of a profile during gameplay. From this score, a threshold value can be set to remove the less durable combinations of bat profiles and wood densities from being used in gameplay.

Acknowledgements

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