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ScienceDirect
Procedia Engineering 72 (2014) 527 – 532
Procedia Engineering
www.elsevier.com/locate/procedia

The 2014 conference of the International Sports Engineering Association

Finite element modeling of wood bat profiles for durability

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Abstract

The bats used in Major League Baseball (MLB) are required to be turned from a single piece of wood. Northern white ash had been the wood of choice until the introduction of hard maple in the late 1990s. Since the introduction of maple to the game, there was a perceived increase in the rate of bats to exhibit multiple piece failures (MPF)—both ash and maple. These failures introduced a new aspect to the game that can be a significant factor during play, i.e. pieces of bats going into the field of play, thereby distracting fielders while reacting to the batted ball. Observations of bat breakage in the field and lab testing of bats in controlled conditions have shown the bat durability is a function of wood quality and bat profile. Wood quality is described by the density and the slope of grain of the wood used in the bat. The density and the slope of grain determine the effective strength of the wood. The bat profile is described by the variation in the diameter of the bat along its length. The wood densities and bat profiles which are preferred by players, are typically in direct contradiction with what makes for a durable bat. In this paper, the finite element method is used to develop calibrated models of the breaking of wood bats in controlled lab conditions. The modeling approach is then used to explore how bat profile influences bat durability and what potential changes can be made in bat profile to satisfy player desires while increasing bat durability.

Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University

Keywords: Baseball; bat; durability; bat profile; modeling

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doi:10.1016/j.proeng.2014.06.091

1. Introduction

Wood baseball bats have been breaking in Major League Baseball (MLB) games since the league originated over 140 years ago. With today's major league players having grown up using relatively thin-handle aluminum and composite bats and wanting the same relatively small handle size in their wood bats, the wood-bat breakage rate has been qualitatively perceived to increase during the last decade. Looking back in time, handle diameter is relatively smaller today than it was during the first 100 years of MLB. Because breakage rates were not tracked before July 2008, when MLB commenced a study on wood bat breakage in response to the perception of an increase in breakage rate, there are no data to describe if and how the breakage rate has evolved over time. [Ruggiero *et al.* (2012)]

Wood bat failures are classified as either single-piece failure (SPF) or multi-piece failure (MPF). An SPF is defined as when a bat cracks but remains intact, while an MPF is defined as when a bat breaks into two or more significant pieces. Both wood quality and bat profile affect bat durability and the types of failures that are induced. The quality of the wood is described by the slope of grain and density of the wood, and the profile is described by the variation in the diameter of the bat along the length. The respective durabilities for four bat profiles are investigated in this paper. Bats of similar weight and density are studied to isolate the profile effect for bat durability. Both experimental testing and finite element model simulation of a few popular bat models used by MLB players are used to examine this topic.

2. Testing Methodology

2.1. Finite Element Modeling

All finite element models (FEMs) used for this study were constructed using HyperMesh Version 11.0. Accurate and robust FEMs of several different components, including common baseball bat geometries, baseball, and ADC testing fixture were needed to conduct baseball bat durability analysis. The geometries of several bat models were generated, and the material properties to be prescribed within the FEMs were identified. [Ruggiero (2013)]

Finite Element Models (FEMs) of several popular bat models used by professional players were constructed to perform finite element analysis. These bat models include uncupped versions of the C243, C271, I13 and C353 models. These FEMs were constructed using solid 8-noded brick elements containing a single Gauss point for analysis in LS-DYNA. The geometry of the four FEMs that were used for this research are shown in Figure 1, and the number of nodes and elements that comprise each bat FEM and the volume of each profile are summarized in Table 1. [Ruggiero (2013)]

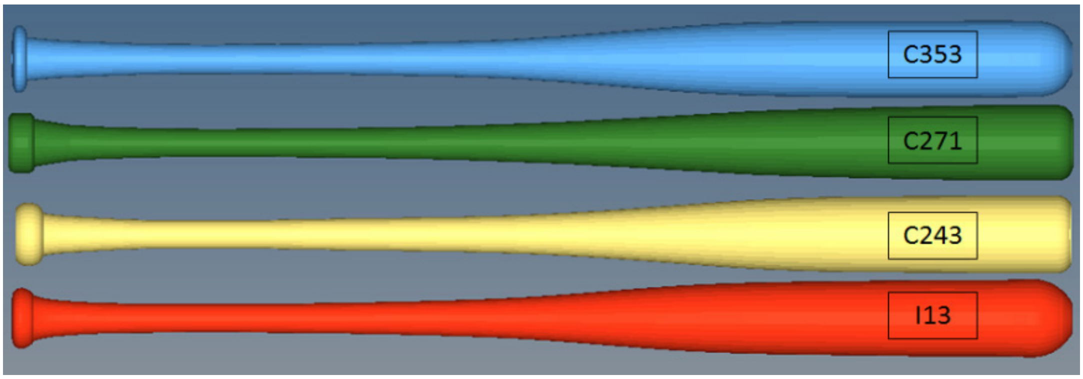

Figure 1. C353, C271, C243, and I13 bat profiles for this research

Table 1. Number of elements and nodes created in construction of bat models

Model	Cup	Elements	Nodes	Volume [in^3 (cm^3)]
C243	No	159984	179533	84.256 (1380.856)
C271	No	130554	140540	76.812 (1258.723)
C353	No	137430	145684	86.853 (1423.266)
I13	No	127665	134604	84.957 (1392.196)

2.2. Durability Testing

Durability testing was performed by Ruggiero *et al.* (2012) in the UMass-Lowell Baseball Research Center (UMLBRC) using the Automated Design Corporation (ADC) air cannon. Two different durability testing processes were used. The majority of the testing was conducted using the standard durability testing procedure, for which the test speed of the ADC was set to the initial test-speed threshold anticipated for a specific impact location. The testing then continued in 5-mph (8-km/hr) increments (as long as the recorded speed was greater than the target speed minus 2.5 mph (4 km/hr)) up to the peak testing speed. A total of five impacts at the peak testing speed were made if the bat had not broken during the process of moving from the initial to peak test speeds. The testing ended when the bat initially cracked or the test sequence was completed, i.e. the five impacts at the peak testing speed. One-strike durability testing was performed on some low-density ash bats to identify what impact velocities induce MPF at each impact location.

2.3. Bat Model Properties

The materials properties, including MOE (Modulus of Elasticity), MOR (Modulus of Rupture), density and slope of grain, were prescribed for each model. The MOE and MOR values were determined from four-point bend test data of clear dowel samples of both wood species by Kretschmann *et al.* (2010). These dowel tests showed that there is an essentially linear relationship between the wood density and the MOE and MOR of each species. Regression analyses were used so that the MOE and MOR values that are associated with each density class could applied to the appropriate models.

An important modeling input is the failure strain during a bat-ball impact, but this strain cannot be easily determined through dowel testing as the dowel test occurs at a much lower strain rate than a bat-ball impact. For this reason, multiple bat models with different failure strains were run. The failure strain that gave good correlation between the model and the bat durability test was concluded to be the effective high-speed failure strain for that wood density. Failure strains were estimated to the nearest 0.1% strain.

3. Results

Finite element models of the C271, C243, C353 and I13 bat profiles were constructed. Initially, all models were prescribed the material properties of ash with a density of 0.0225 lb/in^3 (623 kg/m^3). The models were then impacted at the 14- and 16-in. (35.6- and 40.6-cm) locations, as measured from the barrel end of the bat, to investigate the relative durability of each profile. The results were then analyzed by investigating a contour plot of the first principal strain to the bat model using an animation of the impact and subsequent motion of the bat. The location of peak maximum strain induced by the impact as well as the time at which this peak strain occurs were then identified. The results of maximum strain as a function of time were plotted for this most critical point on the bat. The results can be seen in Figure 2 for the 14- and 16-in. (35.6- and 40.6-cm) impact locations. Figure 3 shows a high-speed image of a bat-ball impact at the 14-in. (35.6-cm) location with an annotation showing the 14- and 16-in. (35.6- and 40.6-cm) impact locations.

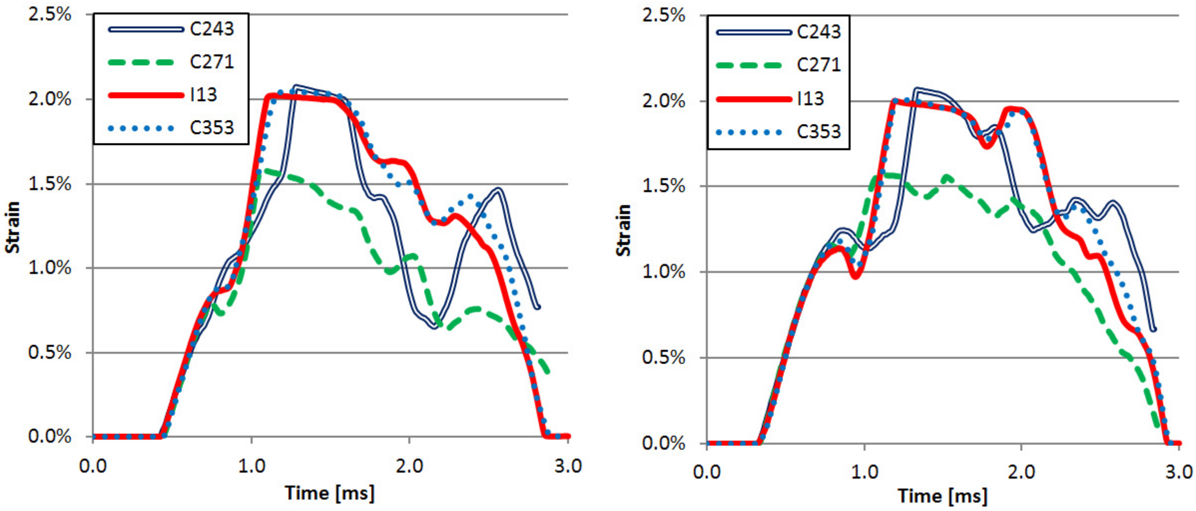

Figure 2. Plots of the maximum first principal strain for different profiles versus time at an impact location of 14 in. (35.6-cm) (left) and 16 in. (40.6-cm) (right). The same density and MOE are prescribed for each of the bats.

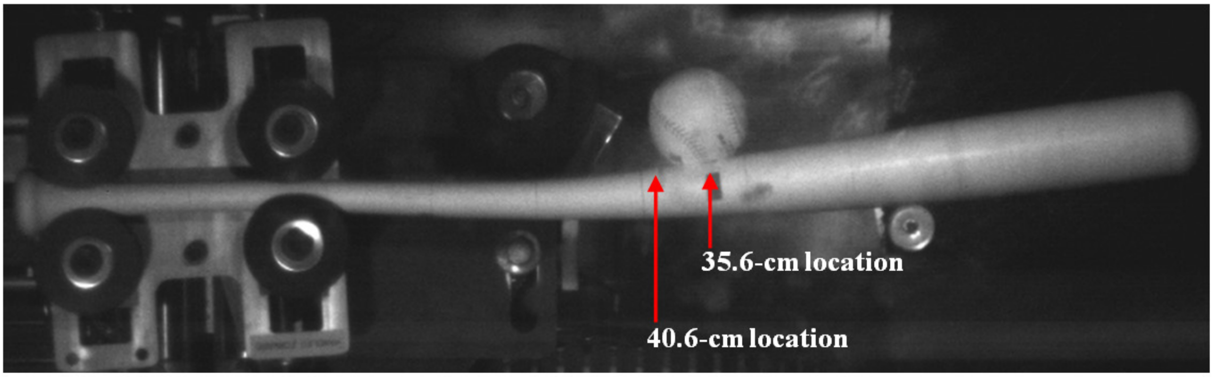

Figure 3. High-speed image of bat-ball impact at 14-in. (35.6-cm) location. Annotation showing the 14- and 16-in. (35.6- and 40.6-cm) impact locations.

Figure 2 shows the strain as a function of time for an impact of 110 mph (177 km/hr) at the 14-in (35.6-cm) location and 105 mph (169 km/hr) at the 16-in (40.6-cm) location. The strain-time responses for the C243, C353 and I13 bat profiles are similar, which is expected as these profiles have a large barrel relative to the C271 profile and are elsewhere similar in geometry for the taper and the handle. The C353 and I13 profiles experienced peak strains for a longer period of time in comparison to the C243 profiles which leads to the belief that the C243 model exhibits greater durability than the other two models. This belief is also supported by field data that has been collected by the research team assembled by MLB in 2008 as identified by Ruggiero (2013). Overall, the C271 profile exhibited the lowest peak strain of the profiles tested and helps to explain why, experimentally, the C271 profile demonstrates superior durability, i.e. has a higher breaking speed, in comparison to the C243, C353, and I13 profiles. The smaller barrel of the C271 is the likely primary source of the lower effective peak strain, i.e. less mass out at the tip of the bat.

If a player wants to use a 32-oz. (907 g) bat, they can choose a bat with a relatively large barrel, i.e. C243, C353, or I13, that is made with wood of a relatively low density, or they can choose a bat with a relatively small barrel such as the C271 that is made with wood of a relatively higher density. The fact that field data indicate that the C271 bat profile is the most durable profile of the bat profiles included in the current study may be due to a combination of the factors. The C271 profile bats are typically constructed from higher density wood because of their smaller volume compared with the C243, C353, or I13 profiles. Therefore, to examine the hypothesis that the C271 bat will continue to be more durable than the other profiles if all of the bats are the same weight, finite element analysis was used. Models of these profiles were constructed and prescribed with densities that allow for each bat profile to weigh 32 oz (907 g). The same process used to analyze the profiles with the same prescribed density was used to analyze the profiles with the same prescribed weight. The strain vs. time plots of the four bat profiles for impacts at the 14- and 16-in. (35.6- and 40.6-cm) locations are then compared in Figure 4. The results displayed in Figure 4 show similar trends to what was observed in Figure 2, i.e. the maximum first principal strains experienced by the C271 bats impacted at the 14- and 16-in. (35.6- and 40.6-cm) locations are lower than the peak strains experienced by the other profiles. Field data show that bats of C271 profile are more durable than bats of C243, C353, and I13. This study has shown that the bat profiles is influenced by the shapes of these profiles and is not entirely due to the difference in density or weight.

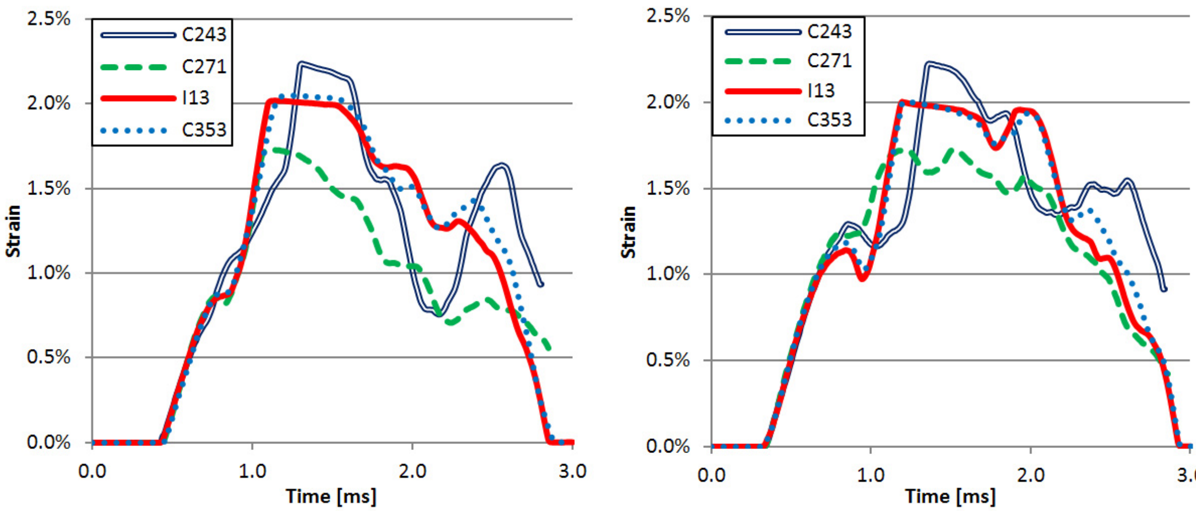

Figure 4. Plots of the maximum first principal strain for different profiles versus time at an impact location of 14 in.(35.6-cm) (left) and 16 in. (40.6-cm) (right). The bats are prescribed the same weight (32 oz) (907 g).

Next consider comparing the two plots in Figure 4 for the two impact locations. The peak strains for the C243, C353, and I13 profiles remain essentially the same between the two plots for the 14- and 16-in. (35.6- and 40.6-cm) impacts, respectively, i.e. approximately 2%. The peak strains for the C271 and C243 are slightly higher for both the 14-in. (35.6 cm) and the 16-in. (40.6 cm) locations with the prescribed weight (Figure 4) than the prescribed density (Figure 2). Thus, the peak strain can increase with increasing density, but this increase in peak strain is of little consequence because the strain to failure typically increases with increasing density.

The modeled bats of different profiles were all impacted at the 14- and 16-in. (35.6- and 40.6-cm) locations at the SPF threshold velocities of 110 mph and 105 mph (177 km/hr and 169 km/hr), respectively. Future studies will include running these models for a wide range of impact velocities and locations to determine if the duration and magnitude of strains that C271, C243, C353, and I13 bats experience are affected by these factors.

4. Conclusion

Finite element models of baseball bats that were tested experimentally were created by implementing the slope-of-grain, wood density, and MOE/MOR values associated with the wood density of the wood species that was tested. The strain-to-failure of a bat was found by determining what prescribed strain-to-failure resulted in good correlation between the durability test and modeling of the bat breakage. The effects of different choices in bat design on baseball bat durability were examined through parametric studies. Modeling results show that C271 may be more durable than C243, C353, and I13 bats. This modeling result correlates with field data that have shown the C271 is more durable than the C243, C353, and I13 profiles.

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