Breaking Bad(ly) – Investigation of the Durability of Wood Bats in Major League Baseball using LS-DYNA®

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Abstract

The bats used in Major League Baseball (MLB) are turned from a single piece of wood. Northern white ash had been the wood of choice until the introduction of hard rock maple in the late 1990s. Since the introduction of maple, there has been a measurable increase in the number of bats breaking into multiple pieces. These failures can be a significant factor during play, i.e. pieces of bats landing flying into the field of play, thereby distracting fielders from making the appropriate play for the given game situation. Observations of bat breakage in the field and in controlled conditions of lab testing of bats 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. The bat profile is described by the variation in the diameter of the bat along its length. The bat properties that are preferred by players, i.e. low-density wood and a bat profile of a big barrel and a slender handle, are in direct contradiction with what makes for a durable bat. In this paper, LS-DYNA is used to develop calibrated models of the breaking of yellow birch wood bats in controlled lab conditions. The WOOD material model in combination with the ADD EROSION option using a maximum principal strain failure criterion was found to produce a credible simulation of the failure modes seen in wood baseball bats.

Introduction

In the early years of the baseball, bats were made from a large variety of wood species. White ash became the wood of choice in the late 19th century after the Hillerich family in Louisville, Kentucky manufactured ash bats for a number of professional teams. Ash remained the wood species of choice until the late 1990s when maple bats were introduced to players, and a small number of players transitioned from ash to this new species of wood. In 2001, Barry Bonds broke the Major League Baseball (MLB) single-season home run record using maple bats. This feat caused the popularity of maple bats to increase dramatically as other players thought maple bats would magically increase their batting statistics.

As the popularity of maple bats increased, the rate at which bats were breaking into multiple pieces during games was perceived to have increased as well. In July 2008, experts in the scientific analysis of baseball, statistics, and the mechanical behavior of different wood species were appointed by MLB in cooperation with the MLB Players Association to examine the perceived bat durability issues and report findings to the MLB Safety and Health Advisory Committee at the end of the season. Over a 2½-month portion of the 2008 MLB season, 2232 bats were broken during game play, and 756 of these bats broke into multiple pieces **Error! Reference source not found.**. Research showed that, among other factors, the slope-of-grain (SOG) of the wood played a major role in the likelihood of a bat breaking into multiple large fragments. The slope of grain of a wood describes the orientation of the wood grain with respect to the longitudinal centerline of the bat. Research also showed that while maple and ash bats were equally likely to break, maple bats were three times more prone to break into multiple pieces than ash bats.

New manufacturing regulations with respect to (1) SOG and (2) changing the hitting surface for maple bats from edge grain to face grain were implemented after the 2008 season, and as a result, the rate of these multiple-piece failure (MPF) occurrences decreased by 30% 0. After the 2009 season, additional regulations were implemented to restrict the species of wood that can be used to manufacture baseball bats, which reduced the amount of MPF occurrences by an additional 14% during the 2010 season 2. All of the new regulations had the benefit that the improvements in bat durability came with changes that were fairly transparent to the players, i.e. there were no bat geometries or popular wood species that were prohibited from use.

Before the introduction of maple to the game in the 1990s, ash had been the wood of choice for over 100 years, and bat durability had not been a serious concern. To avoid any wood durability problems in the future should another new wood species be proposed for use in the game, Major League Baseball was interested in developing a scientific process for evaluating the durability and batted-ball performance of a new species of wood before it could be added to the list of approved species. Additionally, other species of wood with performance and durability characteristics similar to ash are being sought because of concerns that the emerald ash borer threatens to eradicate the ash forests from the United States within the next decade. If new species of wood are not introduced into Major League Baseball before ash is no longer available, then maple and the MPF risks associated with it may become even more prevalent than they are today. Northern white ash is taken to be the gold standard to which all other species will be compared for this proposed wood-certification methodology.

The scientific wood-evaluation process was proposed to be a combination of experimental and finite element methods. The experimental results are used to quantify the durability of a wood species relative to ash and to assist in the calibration of the wood material models used in the finite element analyses. The finite element analyses can be used to explore the relationship of the bat profile to durability and to determine the potential of a species to meet the durability criteria required for approval. The use of the finite element models reduces the number of wood bats that need to be used for the test phase of the evaluation. The finite element models also allow for case studies to be run, which can identify what bat properties positively or adversely affect bat durability.

This paper summarizes the finite element modeling that was used to investigate yellow birch baseball bats subject to ball impacts that induce SPFs (single piece failures) and MPFs. A single-piece failure of a wood baseball bat occurs when the bat cracks, but does not break into multiple large pieces. This type of failure is preferred over a multiple-piece failure because the bat remains intact, and no fragments of the bat leave the batter’s hands. Figure 1 shows an example of an SPF, for which a crack initiated but did not propagate fully across the diameter of the bat or fully down the length of the bat. A multiple-piece failure of a wood baseball bat occurs when the bat breaks into two or more large pieces. This type of failure is undesirable, as large and potentially sharp fragments can split from the bat and fly into the field or into spectator areas. MPFs typically require higher impact velocities to be induced than SPFs. Figure 2 shows an example of an MPF where a crack propagated down the length of the bat and almost entirely across the width of the bat along a diagonal line.

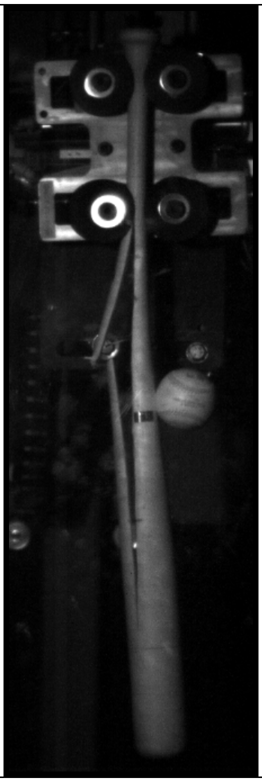


Figure 1. An example of an SPF

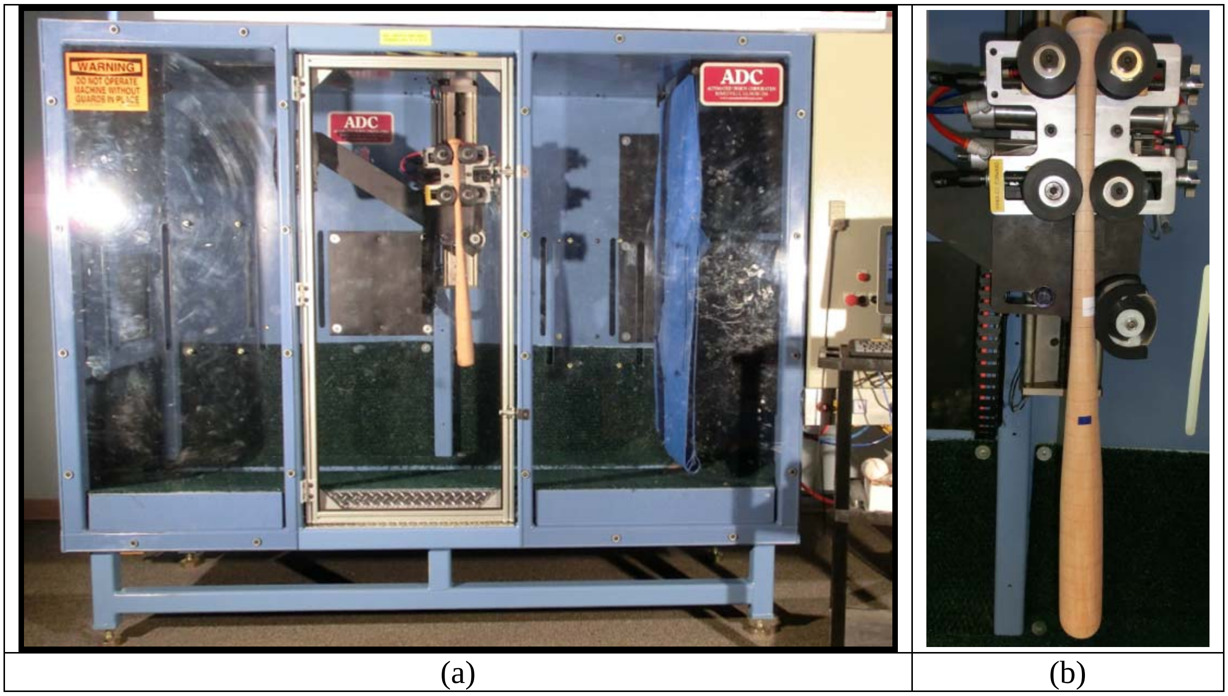
Figure 2. An example of an MPF

Note: Baseball is an American game where the dimensions of baseballs and bats are measured in inches and their weights are measured in ounces and batted-ball speeds are stated in mph. Thus, U.S standard units will be used throughout this paper as opposed to SI units—unless specified otherwise.

Experimental Program

The apparatus used to conduct durability testing is the Automated Design Corporation (ADC) Bat Durability Testing System. This system is capable of firing baseballs at velocities up to 200 mph. In this testing apparatus, the bat is stationary prior to impact. A pair of ADC iBeam Screen Sensors and an ADC Velocigraph Speed Chronograph are used to measure the inbound velocity of the baseball by determining how long it takes the ball to travel through the 12-in. distance between the sensors. The sensors are accurate to within ±0.5 mph. The ADC machine is shown in Figure 3.

The baseball bat being tested is held stationary in the ADC machine by two pairs of roller grips constructed of two different rubber materials. The top set of rollers is made of a Tecamid Molybdenum Disulfide nylon material **Error! Reference source not found.**, and the rollers are clamped relatively tightly. The bottom set of rollers is made from a polyurethane material 4, and these rollers are loosely in contact with bat. This combination of rollers is intended to simulate a player’s grip. Bat durability tests using this setup have shown good correlation with bats broken in the field of play. Figure 3 and Figure 3b show images of the baseball bat sitting in the ADC machine and a close-up of the baseball bat sitting in the rollers, respectively.



(a) (b)

Figure 3. ADC machine (a) with a baseball bat sitting in it and
(b) with a close-up view of a baseball bat gripped by rollers

Finite Element Models

All finite element models (FEMs) used for this research were constructed using HyperMesh Version 11.0. FEMs of several popular bat models used by professional players were constructed. These bat models include cupped and uncupped versions of the C243, and uncupped models of the C271, I13, and C353. 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 uncupped FEMs that were used for this research are shopwn in Figure 4, and the number of nodes and elements that comprise each bat FEM and the volume of each profile are summarized in Table 1.

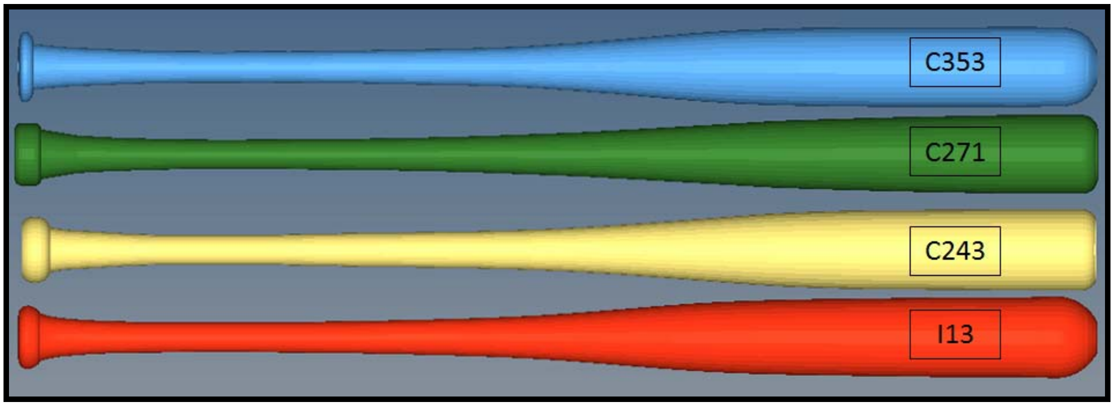


Figure 4. C353, C271, C243, and I13 FEMs created for this research

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

Model	Cup	Elements	Nodes	Volume [in^3]
C243	Yes	156078	163132	82.197
C243	No	159984	179533	84.256
C271	No	130554	140540	76.812
C353	No	137430	145684	86.853
I13	No	127665	134604	84.957

Wood Material Model

The LS-DYNA Wood Material Model 143, which was developed for the Federal Highway Administration **Error! Reference source not found.** was used as the basic material model. This material model allows for all essential material properties of wood to be implemented, e.g. MOE in the three principal directions for wood, density, MOR as a function of direction, and SoG (using AOPT). As used in this research, the slope-of-grain was assumed to be in one plane and uniform along the entire length of the bat. This material definition also has several other properties which can be input, e.g. to capture the strain-rate effects on the yield stress. However, these other options were left at the default values because their values as they apply to the woods considered in this current research were unknown when this research was performed.

In the constructed finite element model, a positive slope-of-grain is angled towards the surface impacted by the ball, whereas a negative slope-of-grain is angled towards the face opposite of the impact. This interpretation is shown visually in Figure 5.

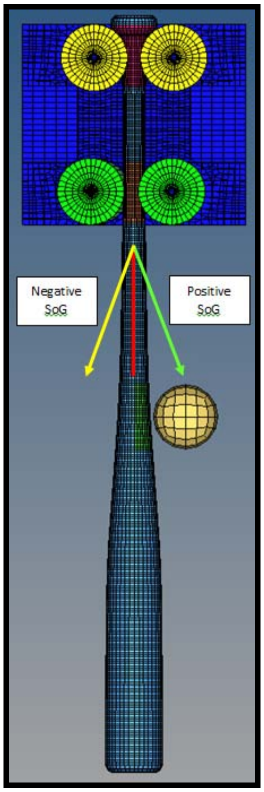


Figure 5. Orientation of positive and negative slopes-of-grain in bat model

Baseball FEM Construction

The baseball FEM that was used for this research was constructed for a currently ongoing MS thesis by Connolly **Error! Reference source not found.**. The ball FEM construction involved correlating modeling and experimental results of a baseball impacting an aluminum baseball bat, and tuning the properties of the baseball so the modeling results of the baseball rebounding off the baseball bat correlated with the experimental velocities. These experimental and modeling bat-ball collisions occurred between 110-140 mph, which is roughly the same range that was being examined for the modeling performed in this study. The geometry of the ball model is a sphere of 1.4-in. radius, and consists of 12,096 solid elements and 12,589 nodes. The material prescribed to this ball FEM was LS-DYNA Material Type 6, which is a viscoelastic material.

ADC Fixture FEM Construction

The experimental dynamic durability testing of the bats are performed in the ADC Durability Testing System which supports bats between two sets of rubber rollers, and the two sets have different material properties. These rollers constitute the boundary conditions which support the bats in the ADC system. In the experimental system, the two sets of rollers have different material properties and are tightened differently. These rollers are mounted on an aluminum plate, which is free to rotate about a pivot point.

Failure Criterion

One of the most significant properties that must be implemented into the baseball bat model to capture the bat breakage is the material failure criterion. The MOR is a failure criterion that, when implemented, causes failure to occur when the effective stress induced by a bat-ball collision exceeds the prescribed MOR value in one or more directions. While MOR can be calculated from the dowel test data that is performed, preliminary models showed that implementing these MOR values does not allow for the bat models to break as observed during experimental bat durability testing. This lack of correlation between MOR from dowel testing and durability testing is likely due to the slower loading rate of the machine used to perform the dowel testing relative the very high impact velocities of the bat-ball collisions. Therefore, a strain-to-failure criterion was implemented into the models though the use of the Add Ersion material option in LS-DYNA, which resulted in excellent correlation between the models and the test. This strain-to-failure criterion specifies that if the maximum principle strain induced by a bat-ball collision exceeded a specified value, then failure will occur at the location where this set strain-to-failure value is exceeded.

Tuning of Strain-to-Failure through Correlation

The strain-to-failure of a species of wood was determined by implementing some strain-to-failure value into a baseball bat model then correlating modeling and experimental results. The strain-to-failure is also treated as dependent on the density of the wood being tested, as several other properties that define a species' material strength are also dependent on wood density.

FEMs of tested baseball bats were constructed by implementing the measured SoG and calculated density, as well as the MOE and MOR values determined through dowel testing which are associated with the density of the bat tested. The baseball FEM is positioned to impact the bat model at the same impact location and impact velocity that induced failure of the tested bat. Strain-to-failure values are then implemented into the model to determine what strain value, to the nearest tenth of a percent, produces the best correlation between modeling and experimental results.

Results

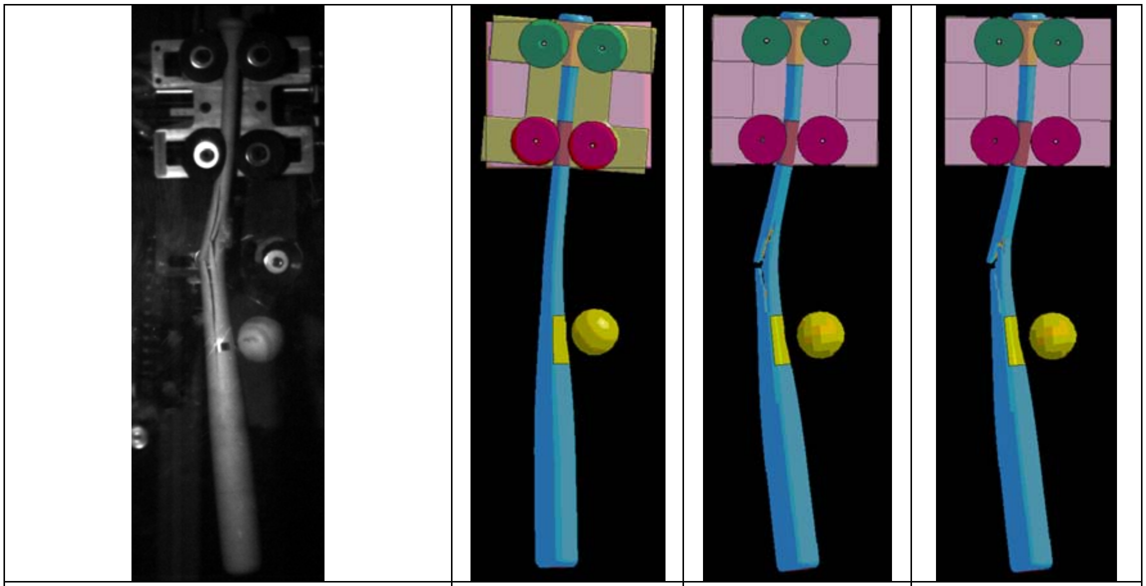
While the dowel test data was valuable in quantifying the MOE as a function of density, the dowel testing was unable to be performed at strain rates that are comparable to those experienced by the wood during a bat/ball impact. Because wood is a viscoelastic material, the strain to failure can be a function of the strain rate. Thus, for this research, the strain-to-failure of a wood species had to be determined through correlating modeling and experimental results of bat/ball impacts. This approach ensured that the strain-to-failure was determined using test data that were collected at a strain rate in the order of magnitude associated with bat durability.

The parameters of a tested baseball bat, including profile, density (and corresponding MOE and MOR values), and slope-of-grain, are all included in the finite element model. The speed of the ball in the models is prescribed to be the speed that induced failure in the associated experiment to which the model is to be correlated. Parametric studies were then run to explore different prescribed strain-to-failure values, and the results were visually compared with what was observed experimentally, i.e. initiation point and path of the crack. The strain-to-failure value that results in the best visual correlation is considered the strain-to-failure of the combination of the yellow birch and density that was analyzed.

Finite element models of tested yellow birch bats were constructed, and strain-to-failure values were prescribed to determine what strain-to-failure in the finite element model produced results that correlated well with the high-speed video of the durability test. The bats that were chosen to be modeled broke in a manner that was expected for the impacted location. For example, bats impacted at the 14-in. location typically experience crack initiation around 6 in. above where the impact occurs and on the surface opposite of the impacted surface. .

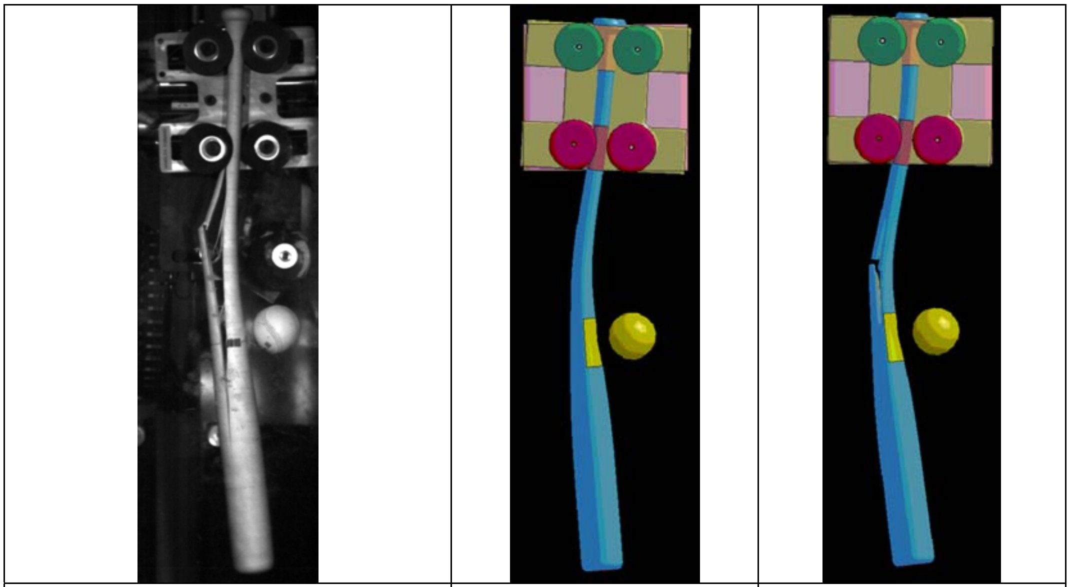
Strain-to-failure is dependent on wood density, so low-density (< 0.0225 lb/in3), medium-density (0.0225-0.0250 lb/in3) and high-density (> 0.0250 lb/in3) yellow birch bats were modeled to determine how the strain-to-failure changes with density. Models of impacts that occurred at the 14-in. location were created initially to determine what strains-to-failure were required for good modeling-experimental correlation. Figures 6 through 8 show comparisons of the model from the parametric study of varying the strain-to-failure that correlated best with the experimental results in that density class.

The results in Figures 6 through 8 show that the strain-to-failure for low- density yellow birch is 3.5%, increases to 4.6% for medium-density, and remains at 4.6% for high-density. Using these data, a plot was created to determine what strain-to-failure should be applied to a yellow birch model for any wood density. This plot is shown in Figure 9.



14-in impact Broke @ 147 mph Max vel. w/o break @ 134 mph	135 mph ε_f=3.5% [no break]	140 mph ε_f=3.5%	145 mph ε_f=3.5%

Figure 6. Strain-to-failure that resulted in good correlation for impacting 0.0217 lb/in^3 low-density yellow birch bat at 14-in. location [Bat ID 0711-045]



14-in impact Broke @ 156 mph Max vel. w/o break @ 150 mph	150 mph ε_f=4.6% [no break]	155 mph ε_f=4.6%

Figure 7. Strain-to-failure that resulted in good correlation for impacting 0.0239 lb/in^3 medium-density yellow birch bat at 14-in. location [Bat ID 1011-018]

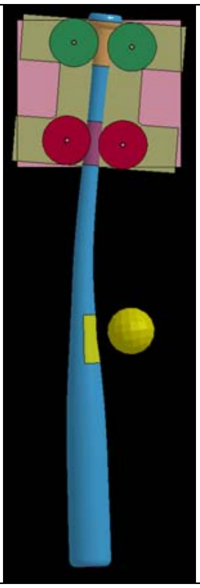
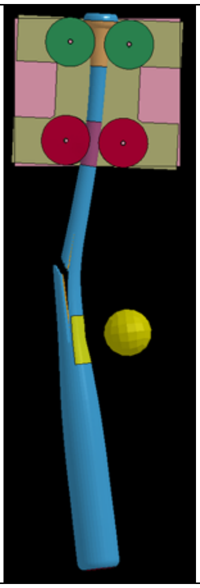
		
14-in impact Broke @ 136 mph Max vel. w/o break @ 130 mph	135 mph ε_f=4.6% [no break]	140 mph ε_f=4.6%

Figure 8. Strain-to-failure that resulted in good correlation for impacting 0.0261 lb/in^3 high-density yellow birch bat at 14-in. location [Bat ID 0711-025]

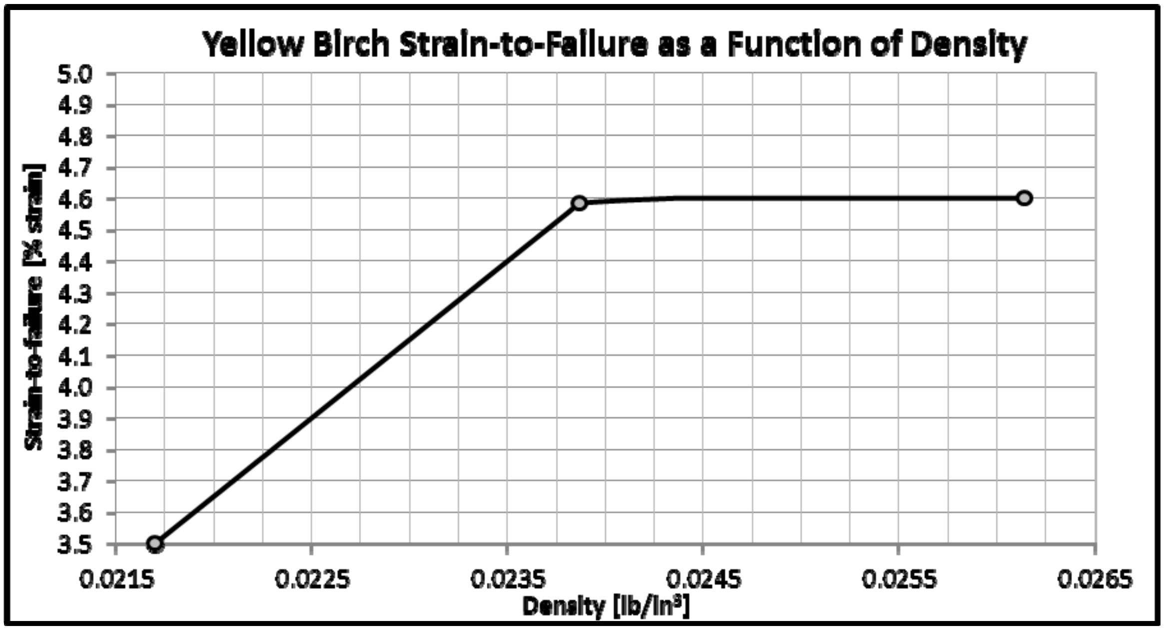
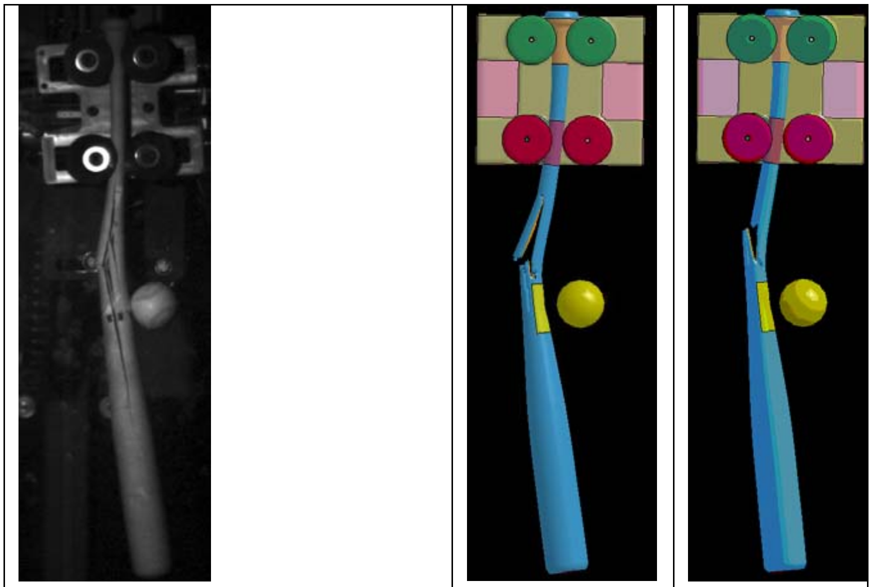


Figure 9. Yellow birch strain-to-failure as a function of density

It is important to note that the relationship between strain-to-failure and wood density of yellow birch that is shown in Figure 9 was obtained using a very limited amount of data. As experimental bat and dowel testing have shown, there can be significant variability in material properties among samples for a species of wood. The tested bats that were modeled were chosen because their properties appeared to be average for their density class. However, it is recommended that additional testing and modeling should be performed in the future to increase the number of data points that can then be used to develop a better understanding of the relationship between the strains-to-failure as a function of density for yellow birch.

With a relationship between strain-to-failure and wood density determined for yellow birch, albeit based on a limited data set, models of experimental 16-in. impacts were generated to investigate the credibility and robustness of the strain-to-failure/density relationship. The strains-to-failure prescribed to each bat model were determined using the relationship shown in Figure 9, and the results of the models were compared to the experimental results. Modeling results of these 16-in. impacts are shown in Figures 10 through 12.



16-in Impact Broke @ 129 mph Max vel. w/o break @ 122 mph	130 mph ε_f=3.6%	115 mph ε_f=3.6%

Figure 10. Correlation of 0.0220 lb/in^3 (low-density) yellow birch bat impacted at the 16-in. location with 3.6% strain-to-failure prescribed [Bat ID 0711-044]

Figure 10 shows that prescribing a strain-to-failure of 3.6% for a 0.0220 lb/in^3 (low-density) model produces good correlation, although the bat model still experiences failure at an impact velocity lower than the maximum impact velocity that the bat endured without breaking. Figure 11 shows that a modeled bat of 0.0246 lb/in^3 (medium-density) does not experience failure when impacted at the maximum test velocity for a strain-to-failure of 4.6% prescribed, like was observed experimentally. Figure 12 shows that a modeled bat of 0.0258 lb/in^3 (high-density) does not experience failure at 125 mph with a prescribed strain-to-failure of 4.6%, but does experience MPF for an impact at 130 mph. The actual bat experienced SPF at 125 mph, and the failure that occurred was not significant because the crack did not propagate very far across the diameter of the bat, i.e. an impact at a slightly lower velocity may not have induced any sign of breakage. It is also plausible that if the impact occurred at 130 mph, then the bat would have experienced an MPF as shown in the modeling results. Therefore, while visual correlation between the finite element model and experimental results is not achieved for a 4.6% strain-to-failure, the modeling results show that the strain-to-failure of this 0.0258 lb/in^3 (high-density) bat may still be a good approximation.

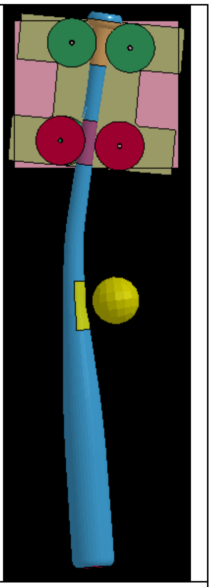
	
16-in Impact Impact shown occurred @ 144 mph Max impact vel. @ 148 mph Bat did not break during test	145 mph ε_f =4.6%

Figure 11. Correlation of 0.0246 lb/in^3 (medium-density) yellow birch bat impacted at the 16-in. location with 4.6% strain-to-failure prescribed [Bat ID 0711-054]

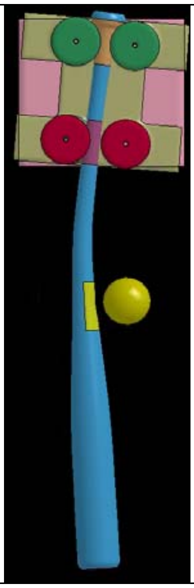
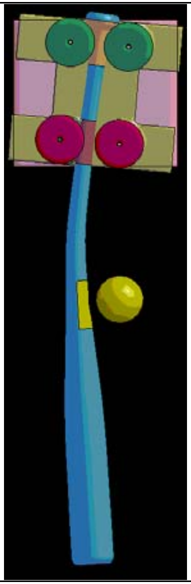
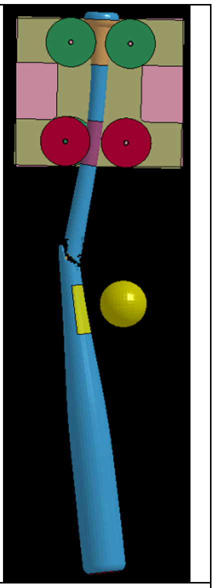
			
16-in Impact Bat broke @ 125 mph Max vel. w/o break @ 118 mph	120 mph ε_f=4.6% [no break]	125 mph ε_f=4.6% [no break]	130 mph ε_f=4.6%

Figure 12. Correlation of 0.0258 lb/in^3 (high-density) yellow birch bat impacted at the16-in. location with 4.6% strain-to-failure prescribed [Bat ID 0711-023]

Conclusions

Finite element modeling of yellow birch bats in LS-DYNA were used to develop a method for simulating bat durability. Mat 143 was used in conjunction with the Mat Add Erosion option where the maximum principal strain criterion was found to provide realistic failure modes when the failure strain varied as a function of wood density.

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