

Characterizing the performance of baseball bats using experimental and finite element methods

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ABSTRACT: Technology has provided the sporting goods industry with the means to manufacture ever better performing equipment, such as the introduction of high-performance aluminum alloys into baseball and softball bats. While the technological advances can enhance a player's performance, there is concern on how technology is affecting the sport overall. To explore this concern in baseball, two 34-inch baseball bats—one made of C405 aluminum and the other made of wood (white ash), were studied using experimental and finite element methods to develop a model of bat behavior. The Baum Hitting Machine (BHM), a state-of-the-art bat and ball testing machine, was used to conduct the experiments. The BHM is capable of swinging a bat at speeds up to 165 km/hr and pitching a ball at speeds up to 165 km/hr. The finite element (FE) models of the bats were modally tuned, adjusting the material properties such that the weight, location of the center of gravity and the first and second natural frequencies of the models would correspond to experimental modal results. A calibrated finite element model of an official Major League baseball was also developed. The independently calibrated bat and ball FE models were then put together to examine the batted ball velocity for each bat, comparing the finite element result to experimental bat-ball impacts as measured on the BHM. The effects of rotational and translational bat motions were investigated using the calibrated model. The modeling procedure yields a credible methodology for bat designers to use FE methods to characterize baseball bat performance.

INTRODUCTION

In the United States, baseball is also known as "America's Pastime". Every spring, players of all ages can be seen on baseball fields everywhere and spectators cheer on their favorite teams. This enthusiasm continues through the summer and into the fall when the Major League Baseball World Series is the climax and culmination of this sport.

When Abner Doubleday first developed the game of baseball in the 1839, players used wood bats to hit the ball. The profile of the bat has changed in the course of 160 years. The early bats were relatively heavy in comparison to the wood bats used today, and the older bats had fatter handles. The sole use of wood bats continued into the early 1970's. However, with the advent of aluminum and composite bats being developed by engineers, players were given an alternative to wood bats.

In 1974, the NCAA (National Collegiate Athletic Association) permitted the use of aluminum bats in collegiate baseball games of its member institutions. About the same time the NFHS (National Federation of High Schools) allowed aluminum bats to be used by its member schools and this move to nonwood bats trickled down to other youth baseball leagues.

The initial intent for this change from traditional solid wood to aluminum was to reduce operating costs due to broken bats. A common baseball strategy is for a pitcher to throw inside and "saw off the bat." By pitching inside, the hitter is forced to hit the ball with the handle or throat of the baseball bat, shown in Fig. 1, often causing the wooden bat to break, and resulting in a harmless ground ball or pop-fly. When the batter is using a more durable aluminum bat, this tactic is rendered useless because the pitcher cannot break the bat and the batter's chances of getting a hit after making contact anywhere on the metal bat are good.

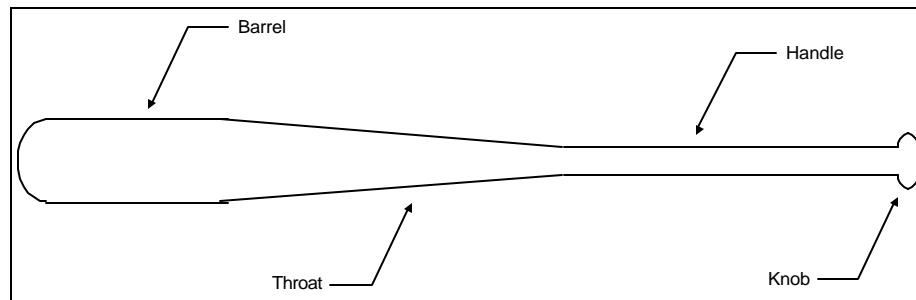


Fig. 1 Terminology of a baseball bat

BATS AND ENGINEERING DESIGN

With the introduction of aluminum bats, another facet was introduced into college baseball—a battle amongst the bat manufacturers for increased bat performance. Along with this increase in performance came an increase in bat prices. There is little a bat manufacturer can do to engineer better wood bats. The performance of a solid-wood bat is primarily a function of the type of wood used, usually northern white ash, and the quality of the wood, which is a consequence of Mother Nature. The only engineering is in the design of the taper from the barrel to the handle, which tends to be more of an artistic design as opposed to a structural design. The official rules of Major League Baseball dictate that a bat be manufactured from a solid piece of wood, the barrel diameter can be no more than $2\frac{3}{4}$ inches and the bat must be unaltered, i.e. no corking allowed.

In contrast to wood, a metal-bat design can benefit from several areas of engineering science. The designer has the freedom to choose from a variety of alloys and material-processing methods. Aircraft quality aluminum alloys, such as C405 and Scandium—an alloy only available from the Ukraine, are the current materials of choice. The extension of metal to include fiber (as can be seen in Fig. 2) and air-bladder reinforcements adds another dimension to the material selection aspect of the

design. The wall thickness and outer diameter can be varied along the bat to affect the modal and structural behaviors of the bat, the location of the center of gravity and the mass moment of inertia (MOI).



Fig. 2 Cut hollow aluminum bat

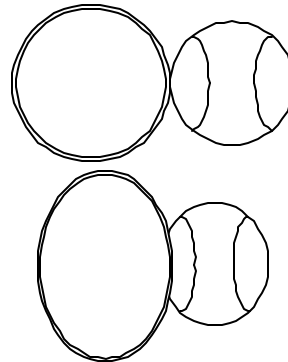


Fig. 3 Hoop deformation during impact

In addition to the bat swing speed, the deformation of the bat assists in dictating the exit velocity of the ball. As a wood or metal bat contacts the ball, the barrel end of the bat bends backward. This strain energy is transmitted to the ball as the bat rebounds. The hollow barrel of the metal bat exhibits a hoop-deformation mode, which provides an additional source of strain energy that does not exist in the solid bat. This hoop deformation is depicted in Fig. 3. In lieu of a hoop-deformation, the wooden bat deforms the ball more than an aluminum bat, and this additional ball deformation lowers the overall energy transmission of the impact. The hollow barrel's hoop-mode can also develop a local trampoline effect during the 1 to 1.5 ms contact period.

PHYSICAL DIFFERENCES BETWEEN WOOD AND ALUMINUM BATS

Bats are classified by their length and weight. A single model of a 33-in wood bat typically weighs 30 to 33 oz. The weight variation is a consequence of the variation in wood density. On the other hand, the weight variation amongst the same length and model aluminum bats is minimal. This minimal variation is a consequence of the engineer controlling the density and distribution of the material in an aluminum bat. Until recently, an NCAA 33-in aluminum bat was allowed to weigh as little as 28 oz. Bats are also classified using a length-to-weight-unit differential system, where the length of the bat is reported in inches and the weight of the bat is reported in oz. Using the unit difference terminology to describe a metal bat that is 33-in long and weighs 28 oz., the bat would be classified as a minus 5 (-5) bat.

A metal bat is typically lighter and has a lower MOI (mass moment of inertia) than its wood counterpart of the same length. Thus, the aluminum bat can be swung faster and moved up and down to meet the baseball quicker than an equal length wood bat (Watts and Bahill, 1990). Fig. 5 shows a sample of MOI values for a range of bat lengths from 31 to 36 inches. The open diamond symbols denote the wood bats, which have a weight that is at most 3 units (ounces) less than the bat length units (inches). The filled diamond symbols denote wood bats that are 4 to 5 units in weight

below their length. The filled circles denote the MOI values as a function of length for aluminum bats. The solid line denotes a recommended minimum MOI for aluminum bats so that these bats will swing like their wood counterparts.

Recent annual studies by Thurston (1998, 1999 and 1999) showed that the same players had a drop of approximately 100 points in their batting averages as they changed from using aluminum bats during the college season to using wood bats in the Cape Cod League. A similar drop was observed in the homeruns per at bat by these players—from one per 25 at bats for aluminum to one per 75 at bats for wood. These observations highlight the fact that it is easier to get a big hit with metal bats as compared to wood. The current high-performance metal bats outperform the best wood bats by about 10% in measured exit velocities under the same pitch and bat-swing speeds. By further exploiting the fundamental physics of bat design, engineers can make nonwood bats that are even better than what are currently available.

While lightweight bats are attractive for batters, they are an increasing danger to pitchers and infielders. The increasing exit velocities of balls off the metal bats reduce the time a pitcher or infielder has to react to a line drive hit. The dimensions of the baseball field were based on human speed and batters hitting with wood bats. Any increase in exit velocity over that of wood changes the game. Major League Baseball recognizes this fact and will never allow the use of high-performance metal bats in its games.

The collegiate and high school governing bodies for baseball are beginning to recognize this change. As a consequence, they are looking to limit the performance of nonwood bats to be within a certain percentage of the best wood bats. The NCAA and NFHS do not want to abandon the overall benefit of cost savings that nonwood bats bring to the game. However, these groups do want to ensure the safety of the players and maintain the integrity of the game of baseball. Thus, as a first effort to make nonwood bats be physically more like their wood counterparts, these governing bodies have recently reduced the unit difference in length to weight from being up to 5 units to only 3 units. Likewise, the use of relatively larger barrels ($2\frac{3}{4}$ inches) has been reduced to a maximum of $2\frac{5}{8}$ inches. This barrel $2\frac{5}{8}$ -in size is similar to that of wood bats. The NFHS has also implemented a minimum MOI rule (as denoted by the solid line in Fig. 5). This NFHS rule will force the nonwood bats to also have a swing weight comparable to their wood counterparts.

MEASURING AND LIMITING BATTED BALL SPEED

In addition to making the nonwood bats be similar to their wood counterparts in length to weight differential and MOI, the batted-ball speed also has to be controlled to be like that off of wood bats. Engineers can exploit the material properties and the hollow bat barrel to achieve relatively high batted-ball speeds off nonwood bats. To achieve this limitation on performance, a credible and repeatable test methodology needs to be available to the governing bodies, who make the rules and set the limits on performance, and to the bat manufacturers. One proposed test machine, the Baum Hitting Machine (BHM) shown in Figs. 6 and 7, has the capability of swinging a bat at speeds up to 100 mph (162 km/hr) at the contact point and pitching a ball at up to 100 mph (162 km/hr). The operator prescribes the ball contact point. A set of light cells and speed gates measures the exit velocity of the ball as it moves away from the impact. In 1997, Major League Baseball commissioned Sports Engineering of Cambridge, MA and the Baseball Research Lab at UMass-Lowell to evaluate this proposed test methodology. The UMass-Lowell Baseball Research Center now has a Baum Hitting Machine in its test lab.

The evaluation included the comparison of computer models of impacts run in LS-DYNA to test results from the hitting machine. These computer models also provide insight to the physics of the impact between the bat and ball. This paper discusses the issues associated with these models and the test versus simulation responses.

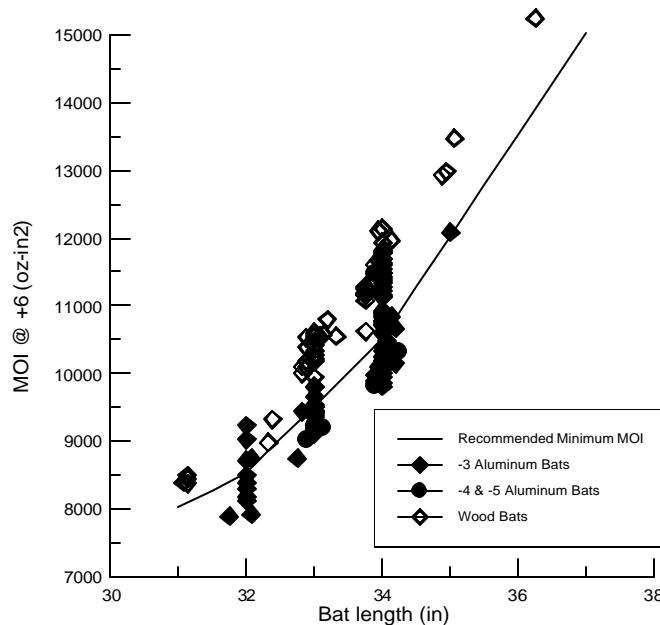


Fig. 5 Sample of MOI variation amongst wood and aluminum baseball bats

MODELING THE BASEBALL

Finite element models of a bat-ball collision were developed to better understand the mechanics of a bat-ball collision in general. More specifically, they were needed to understand the mechanics of the Baum Hitting Machine and to validate some of the experimental data. The first part of modeling the impact was to develop a realistic model for the baseball.

A baseball is a complex object consisting of many nonlinear materials such as leather, twine or yarn and cork/rubber pill. A purely linear-elastic ball cannot be used in the modeling because it does not account for the nonlinear properties that a real ball exhibits with respect to the stiffness of the ball. In reality, a baseball gets stiffer the more it deforms. The Mooney-Rivlin material model in the LS-DYNA finite element code provides the option of prescribing a load curve for the material model. Past experience has shown that it is an excellent material model for rubber-like materials.

The load curve data were collected from static testing at elevated crosshead speeds (3, 6 and 30 in/sec) using an Instron 1332 testing machine. The data, shown in Fig. 8, were recorded using a PC-based data acquisition system collecting data in a streaming fashion. The Mooney-Rivlin material card provides an option for the deformation behavior to be a load versus deflection curve given specimen dimensions, or a stress versus strain curve setting the specimen dimensions to 1.0. Because this

ball model is developed as a preliminary approximation, the data was not converted to a stress versus strain curve. The baseball was approximated as a cube with a side length of 2.4 inches, which will fit inside of the boundaries of an official Major League baseball.

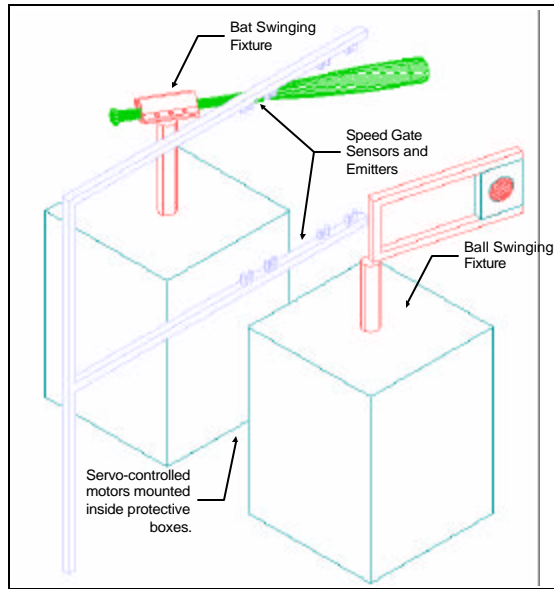


Fig. 6 Schematic of Baum Hitting Machine

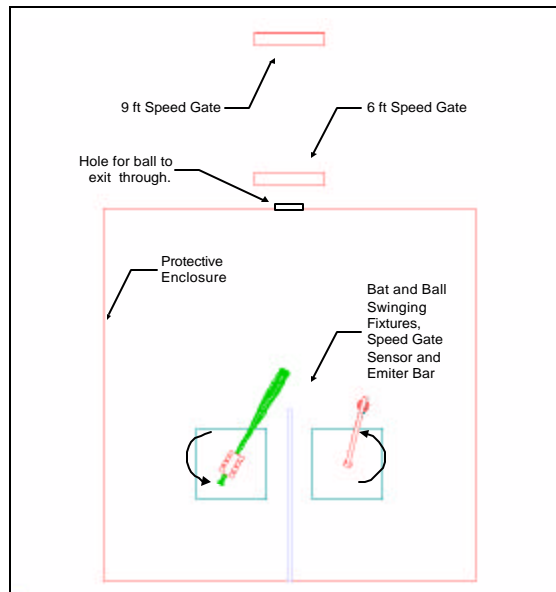


Fig. 7 Top View of Baum Hitting Machine

The ball model was then impacted against a stationary wood block (as shown in Fig. 9) to calibrate it to known coefficient of restitution (COR) values. Experimental data show that a baseball impacting a stationary wood block at 60 mph has a COR of approximately 0.56 (Adair, 1994). In order to achieve this, mass damping was added to the model. It was added using a unit step function and a scale factor of 550. High-speed video of a baseball-bat impact was also used as a visual guide to judge the amount of damping needed.

MODELING THE BASEBALL BAT

Finite element models of the aluminum and wood bats were built from bat profiling measurements. The finite element meshes are shown in Figs. 10 and 11. All finite element models were created using HyperMesh 2.1a. The mesh for the hollow aluminum bat consisted of shell elements with a uniform thickness of 0.100 in. The mesh for the solid wood bat consisted of 8-noded brick elements. Both bats were modeled as purely elastic materials (material model Type 1 in LS-DYNA). The bats were then calibrated using modal analysis.

Because the modal response of the bat contributes significantly to the resulting batted-ball speed, the bats were calibrated using experimental and analytical modal analyses. The first and second natural frequencies of the bats were measured experimentally. NASTRAN was used to calculate these same modes for each of the bats. The refinement of the mesh and the distribution of the mass in finite element models were tuned so that the analytical natural frequencies correlated closely with the experimentally determined values. Tables 1 and 2 summarize the calibration data for the aluminum and wood bats, respectively.

Table 1 Aluminum bat calibrated data

| | Weight (oz) | Length (in) | Center of Gravity (in) | 1 st Mode (Hz) | 2 nd Mode (Hz) |
|----------------------|----------------|----------------|---------------------------|------------------------------|------------------------------|
| Experimental | 29.49 | 34 | 12.63 | 182 | 656 |
| Finite Element Model | 29.44 | 34 | 12.62 | 196 | 682 |

Table 2 Wood bat calibrated data

| | Weight (oz) | Length (in) | Center of Gravity (in) | 1 st Mode (Hz) | 2 nd Mode (Hz) |
|----------------------|----------------|----------------|---------------------------|------------------------------|------------------------------|
| Experimental | 31.90 | 34 | 11.25 | 143 | 481 |
| Finite Element Model | 31.89 | 34 | 11.22 | 145 | 490 |

MODELING THE BAT/BALL IMPACT

The calibrated ball model was then added to the calibrated finite element models of the C405 aluminum alloy bat and the wood bat. These models simulated a 70-70 impact, i.e. the pitched ball will be traveling at 70 mph and the point of impact on the bat will be traveling at 70 mph also. The ball impacted the bat 27.625 inches from the end of the knob. To simulate the hitting machine, the bat was pinned at 6 inches from the handle end such that it was only allowed to rotate about an axis perpendicular to the traveling ball. The rotational speed of the servomotor was converted to an initial linear velocity along the length of the bat corresponding to achieve a swing speed of

70 mph at the impact point. The ball was given an initial linear velocity of 70 mph. The models were then analyzed using LS-DYNA. The results were interpreted using the LS-TAURUS and IEMB postprocessors. Profiles of the aluminum and wood bats are shown in Figs. 10 and 11, respectively.

Using these bat models, comparisons between the ball-exit velocities off the wood and aluminum bats were made. Also, differences between a bat rotating or translating to the ball were investigated.

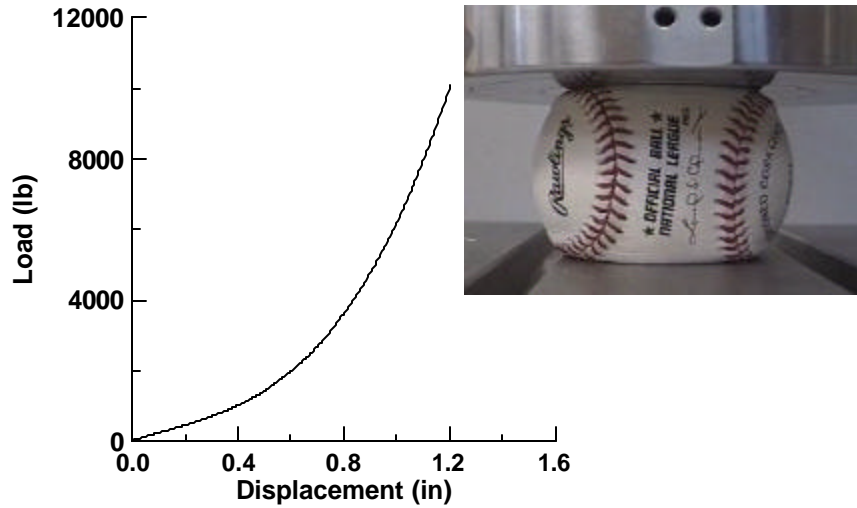


Fig. 8 Compression test for a baseball

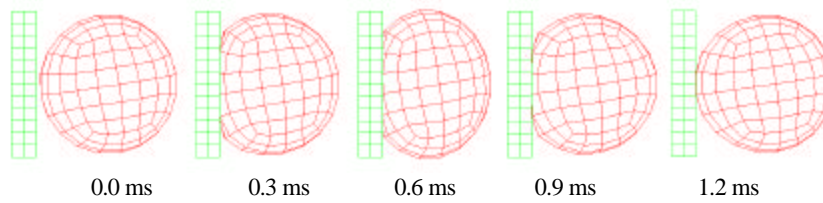


Fig. 9 Sequence of ball deformation during contact with flat surface

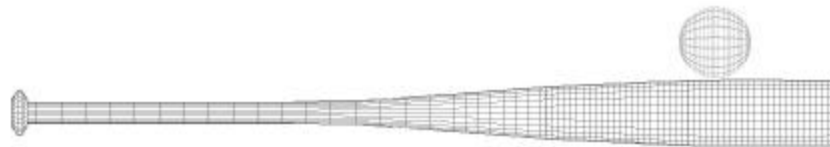


Fig. 10 Profile of the aluminum bat model



Fig. 11 Profile of the wood bat model

RESULTS

A finite element model of the hitting machine was first developed to examine any whipping effect that the bat might undergo as it is spun towards the ball. Further boundary conditions limiting the movement of the handle of the bat were imposed to simulate the fixture used on the Baum Hitting Machine to hold the baseball bat. Two models were run, one that started the bat rotation similar to the actual hitting machine, approximately 325° from the impact, and one that started the bat rotation immediately before impact. The results of the modeling showed that there was a negligible difference in the exit velocities of the ball. This negligible difference was significant because it not only showed that the minor whipping of the bat did not add to the exit velocity of the ball, but it allowed all future models of the BHM to start the bat rotation just before impact, saving hours of computer time.

Comparisons of the wood bat and the aluminum bat were then made. Each bat was subjected to the same 70-70 impacts with the location of the impact at the sweet spot. The results of the two models showed that the exit velocity of the ball was 91.3 mph off the wood bat and 101.8 mph off the aluminum bat—a 10.3% difference in the exit velocities. A plot of the ball exit velocities of the two models is shown in Fig. 12.

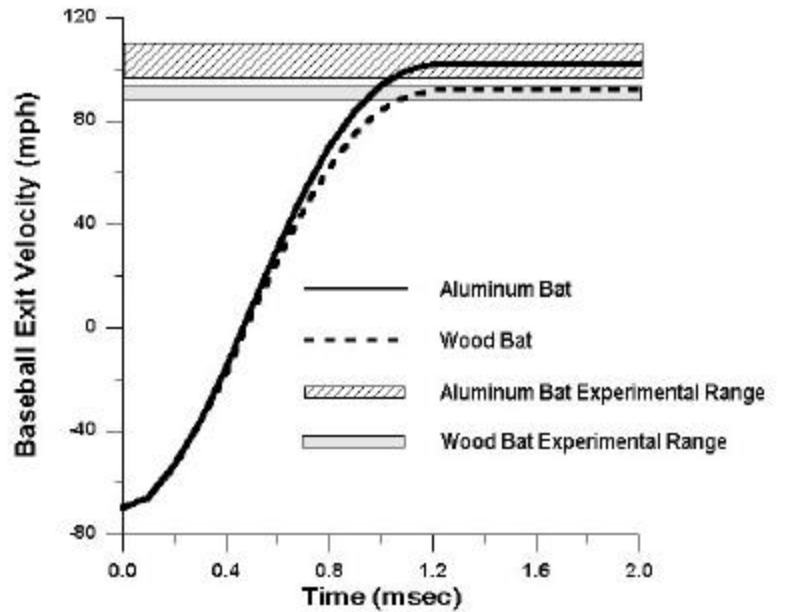


Fig. 12 Baseball velocities for the aluminum and the wood bats

Experimental data collected from the Baum Hitting Machine showed that the ball exit velocity for this particular aluminum bat ranged from 97 to 113 mph while the wood bat velocities ranged from 90 to 94 mph. The correlation of the impact models with the experimental data is very good.

Whether the bat is given an initial angular velocity pivoting about the handle or an initial linear velocity did not significantly affect the exit velocity of the ball. This negligible difference removes the concern of the machine's ability to simulate realistic batting conditions, which are some combination of rotation and translation.

CONCLUSIONS

An unrefined finite element model of a baseball has been created using a Mooney-Rivlin material model. When this ball model is used with preliminary finite element models of aluminum and a wood baseball bats, the differences in the ball exit velocity between the two bats can be quantified. These finite element models provide an excellent simulation of the bat-ball impact and can be used to investigate the effect of different properties of the bat, such as the location of the center of gravity, weight of the bat, wall thickness and the diameter profile, on the ball exit velocity. The modeling procedure yields a credible methodology for bat designers to use finite element methods to characterize baseball bat performance.

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