Using LS-DYNA to Characterize the Performance of Baseball Bats

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Key Words: Baseball, Bats, Coefficient of Restitution, Impact

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 were studied in LS-DYNA to develop a calibrated model of bat behavior–one made of C405 aluminum and the other made of wood (white ash). A finite element model of an official Major League baseball was also made, and its material behavior was characterized using a Mooney-Rivlin material model. The models were built in HyperMesh and postprocessed in LS-TAURUS and FEMB. The material parameters were tuned so that the results of the models would match those of experimental bat/ball impacts as measured on a prototype hitting machine. The effects of rotational and translational bat motions were investigated using the calibrated model.

INTRODUCTION

In 1974, the NCAA permitted the use of aluminum bats in collegiate baseball games under its jurisdiction. The initial purpose 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 Figure 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 bat are good.

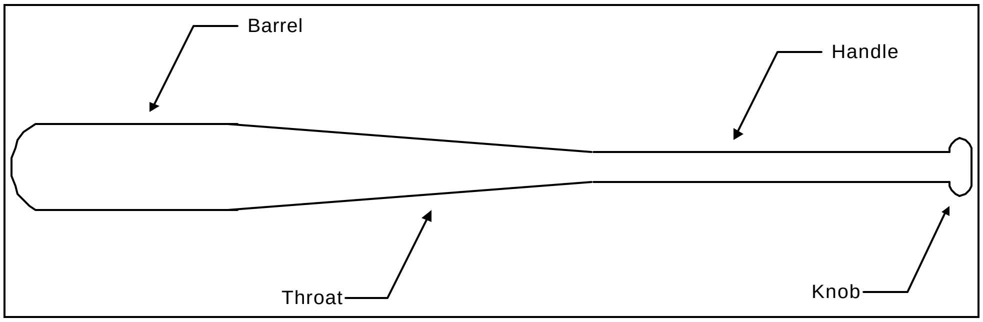

Figure 1. Terminology of a Baseball Bat

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 has come 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 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 ¾ 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 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 effect the modal and structural behaviors of the bat, the location of the center of gravity, and the mass moment of inertia (MOI).

In addition to the swing of the batter, 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 relaxes. The hollow barrel of the metal bat exhibits a hoop-deformation mode which provides an additional source of strain energy which does not exist in the solid bat. In lieu of a hoop-deformation, the wooden bat deforms the ball more than an aluminum bat, and this ball deformation lowers the overall energy transmission of the impact. The hollow barrel's hoop-mode can also develop a trampoline effect during the 1 to 1.5 ms contact period.

A metal bat is typically lighter and has a lower MOI than its wood counterpart. Thus, the aluminum bat can be swung and moved up and down to meet the ball faster than a similarly sized wood bat. A recent study by Thurston (1997) showed that the same players in 1997 had a drop of 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 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 ball-in and bat-swing speeds. By further exploiting the fundamental physics of bat design, engineers can make non-wood bats that are even better than what are currently available.

While lightweight, durable bats are good news 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 from 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 non-wood bats to be within a certain percentage of the best wood 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 Figures 2 and 3, 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 ball contact point is prescribed by the operator. A set of light cells and speed gates measures the exit velocity of the ball as it moves away from the impact. Major League Baseball commissioned Sports Engineering of Cambridge, MA and the Advanced Composites Materials and Textile Research Lab at UMass-Lowell to evaluate this proposed test methodology.

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.

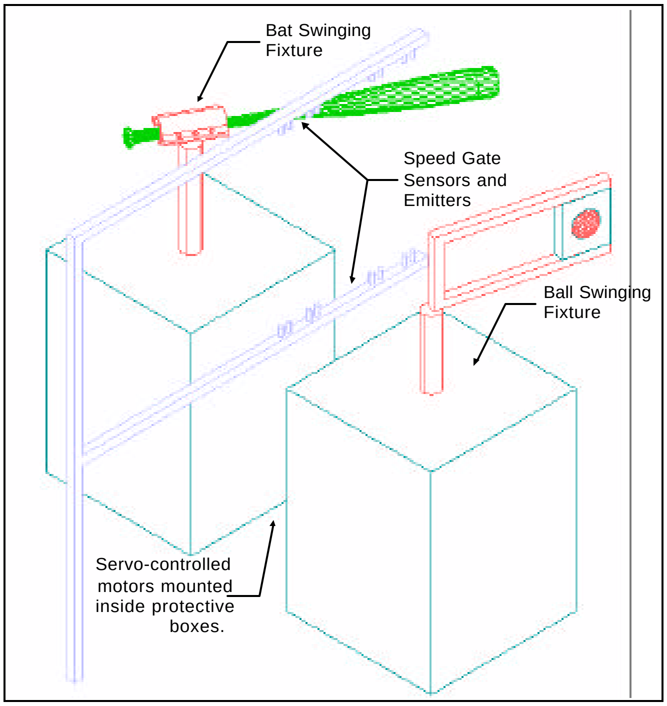

Figure 2. Schematic of Proposed Test Machine

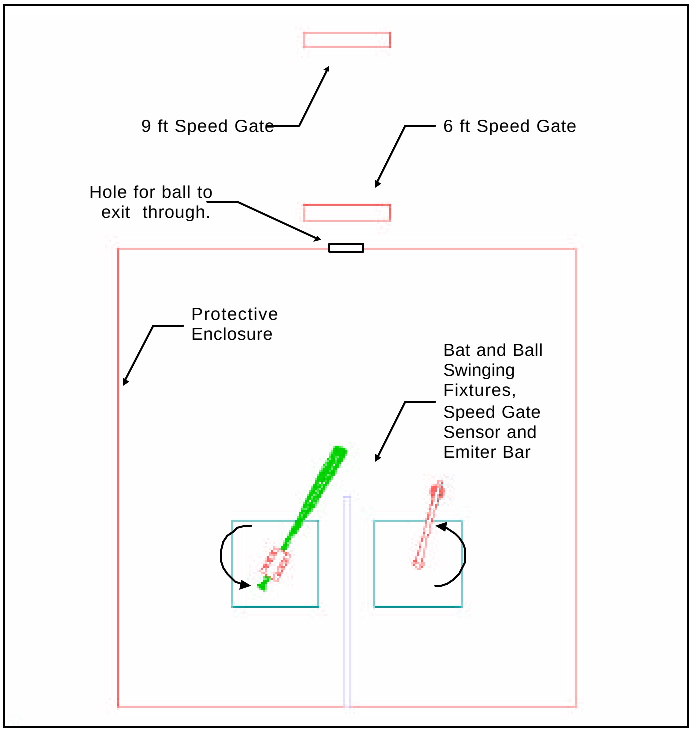

Figure 3. Top View of Proposed Test Machine

APPROACH

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 is 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. A purely linear-elastic ball cannot be used in the modeling because it doesn't 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. A Mooney-Rivlin material model, Type 27, 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.

The load curve data were collected from static testing at elevated cross-head speeds (3, 6 and 30 in/sec) using an Instron 1332 testing machine. The data, shown in Figure 4, 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.

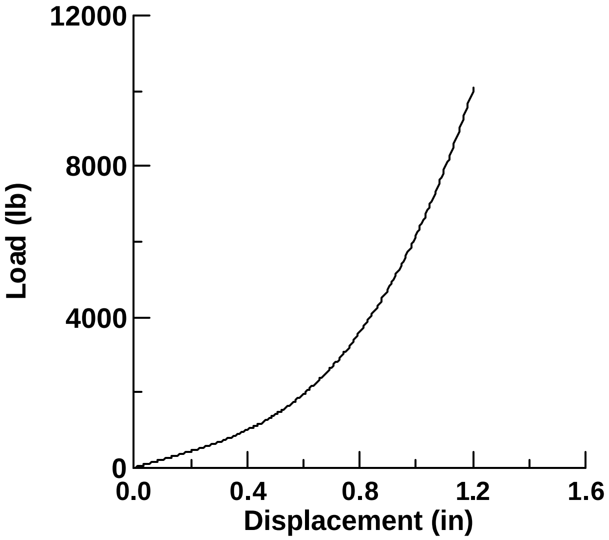

Figure 4. Compression Test Data for a Baseball

The ball model was then impacted against a stationary wood block in order 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.

The calibrated ball model was then added to finite element models of a C405 aluminum alloy bat and a wood bat. 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 using material model Type 1. These models simulated a 70-70 impact, i.e. the ball will be traveling at 70 mph and the point of impact on the bat will be travelling 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 travelling ball. The rotational speed of the servo-motor 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 LS-TAURUS and FEMB. Profiles of the aluminum and wood bats are shown in Figures 5 and 6.

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

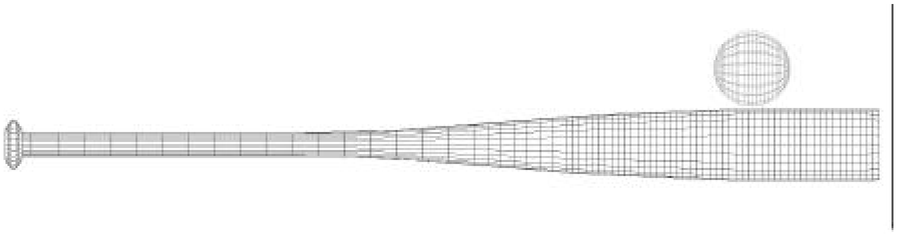

Figure 5. Profile of the Aluminum Bat Model

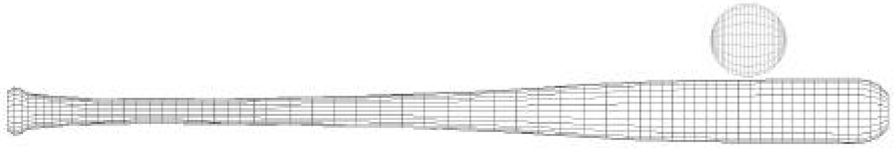

Figure 6. Profile of the Wood Bat Model

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 impact 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 99.07 mph off the wood bat and 108.89 mph off the aluminum bat–a 9% difference in the exit velocities. A plot of the ball exit velocities of the two models is shown in Figure 7. The original ball-damping factor of 500 was decreased to 300 because the ball was over-damped in the aluminum bat model. In order to take this into account with the wood bat model, mass damping was added to the wood bat similar to the ball. The scale factor was 650. The COR for these new damping factors was reanalyzed using the stationary wood block model and found to be 0.71, which is higher than the accepted 0.56.

Experimental data collected from the Baum Hitting Machine showed that the ball exit velocity for aluminum bats ranged from 97 to 102 mph while the wood bat velocities ranged from 90 to 94 mph. The differences in the experimental and analytical data could be a result of the ideal material models used for the bats. The high-performance C405 aluminum bats are known to dent quite easily, so as a result, an elastic-plastic material model might be a better approximation of the performance of the bat. An improved ball model would also yield better results. With respect to the cube approximation of the ball, the dimensions of the cube obviously affected the behavior of the ball. Also, the bat models could be improved by modally tuning them to experimental data, making sure that the weight, center of gravity and mass moment of inertia are equal to those values for the bats on which they are based. The bat models are currently only geometrically similar with the real material densities prescribed in the material cards.

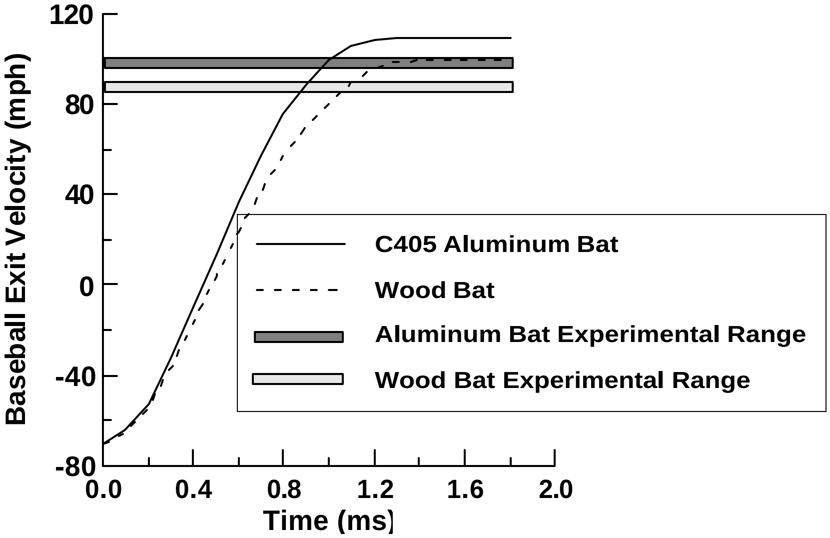

Figure 7. Baseball Velocity for the Aluminum and the Wood Bats

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. A plot of the two velocity conditions is shown in Figure 8. The baseball exit velocity for the rotating bat was 108.89 mph, while the translating-bat exit velocity was 109.20 mph. This negligible difference removes the concern of the machine's ability to simulate realistic batting conditions, which are some combination of rotation and translation. A constant linear velocity applied to the translating bat was investigated, but was deemed unrealistic because of the constant input of energy into the system for maintaining the bat velocity during impact.

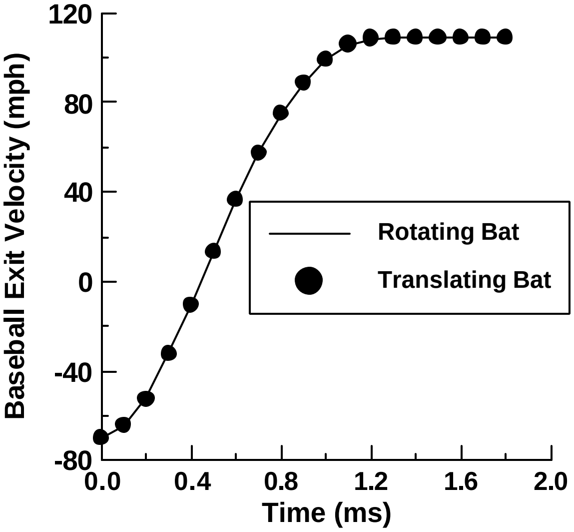

Figure 8. Comparison of the Velocity Profile for the Bat Rotating and the Bat Translating during the Impact

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. Future work should include refining both the baseball and the bat models.

ACKNOWLEDGEMENTS

The authors would like to thank Jim Kennedy and Lee Bindeman of KBS2, Inc. for their technical advice on LS-DYNA during the completion of this research. The support of Bill Murray, Director of Operations at Major League Baseball is also appreciated. The technical assistance of Larry Fallon, Bob Collier and Steve Baum was helpful

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