6th International LS-DYNA Users Conference
Detroit, MI
April 9-10, 2000

Using LS-DYNA to Develop a Baseball Bat Performance and Design Tool

Timothy J. Mustone
James Sherwood (james_sherwood@uml.edu)

Baseball Research Center
Department of Mechanical Engineering
University of Massachusetts – Lowell
One University Avenue
Lowell, MA 01854

ABSTRACT

Ever since the introduction of metal bats into collegiate and high school baseball, each of the bat manufacturers has been in an “arms race” to outperform its competition. These metal bats do reduce the overall operating costs to teams in comparison to solid northern white ash bats, but this economic benefit does not come without a price. The batted ball speed off the metal bats is 5 to 10% faster than off wood. This increased speed has the potential to increase batted-ball injuries to players and to change the integrity of the game of baseball.

While there is very little that an engineer can do to enhance the performance of wood bats, other than modify the bat profile; engineers can exploit metals to achieve a wide range of bat performances. Until recently, the typical process to evaluate bat performance was to make a bat and then do field-testing with players. However, with the advent of the Baum Hitting Machine (BHM), a state-of-the-art hitting machine for testing baseball bats and measuring batted ball speeds, this process is changing. UMass-Lowell has one of the two BHM’s available in the world.

With the BHM, the differences in bat performance due to changes in wall thickness, handle flex, material properties and weight distribution can be measured. By using the BHM test data to calibrate finite element models of bats, a very powerful design tool would be available. The process of using the test data to develop such calibrated models and thereby predict the performance of new bat designs is the goal of this research.

INTRODUCTION

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 coarse 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 non-wood 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 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 metal bat are good, slanting the balance of the game towards a more offensive, rather than defensive game.

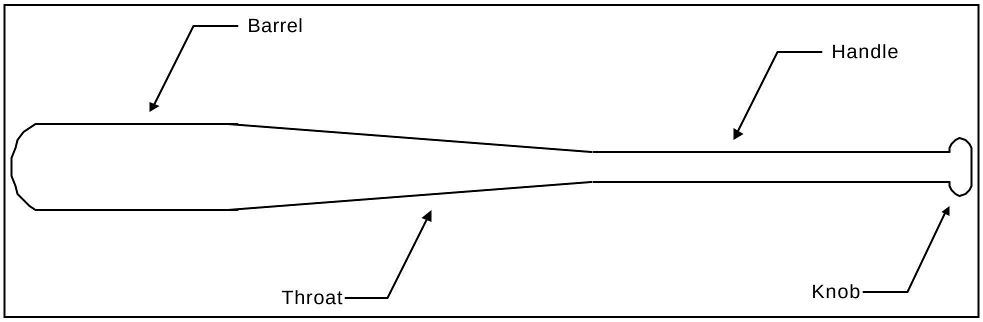

Figure 1- Terminology of a baseball bat.

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 non-wood bats that are even better than what are currently available.

With the introduction of aluminum bats, competition amongst the bat manufacturers increased, causing the levels of bat performance and price to also increase. 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 2¾ inches and the bat must be unaltered, i.e. no corking allowed (the practice of drilling an axial hole in the barrel end of the bat and inserting cork or rubber balls to make the bat lighter).

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-grade 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 Figure 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).

Figure 2 - Cross section of aluminum bat.

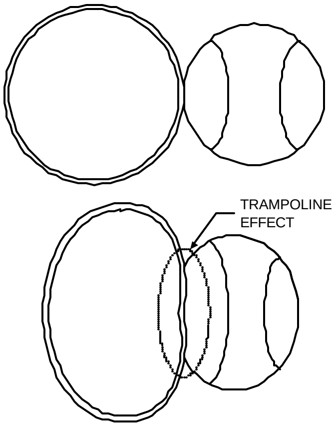

Figure 3 - Hoop deformation during impact.

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 Figure 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. It is very important when comparing bat performance between different bats that an "apples-to-apples" comparison is made, comparing bats of equal length and weight. Bats are also classified by the unit difference between the length, in inches, and the weight, in ounces. For example a bat whose length is 34 inches and weighs 29 ounces, would be classified as a minus 5 (-5) bat. A single model of a 33-in wood bat typically weighs 30 to 33 oz; the weight variation in a wood bat is a consequence of the variation in wood density. On the other hand, the weight variation amongst the same length metal bats is minimal. This minimal variation is a consequence of the engineer controlling the density and distribution of the material in a metal bat. By controlling the weight distribution of the metal bat, the engineer is controlling the mass moment of inertia. 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).

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 non-wood 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 non-wood 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 non-wood 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 (2¾ inches) has been reduced to a maximum of 2 5/8 inches. This barrel 2 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 non-wood bats to also have a swing weight comparable to their wood counterparts.

MEASURING AND LIMITING BATTED BALL SPEED

In addition to making the non-wood 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 non-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. Once such test methodology included using the Baum Hitting Machine. In 1997, Larry Fallon of Sports Engineering, Dr. James Sherwood of the University of Massachusetts, Lowell and consultant Dr. Robert Collier, were commissioned by MLB to perform a complete and thoroughly independent evaluation of the BHM. This UMass Lowell group also proposed a standard protocol using the BHM to evaluate the performance of baseball bats. They concluded that the BHM is a state-of-the-art machine capable of accurately measuring ball exit velocity. The BHM, shown in Figure 4 has the capability of swinging a bat at speeds up to 100-mph at the contact point and pitching a ball at up to 100-mph.

Figure 4 - Assorted views of the BHM.

The operator controls the BHM's movements, by setting the coordinates of the bat-ball impact and individual speeds of the bat and ball, and records the impact data from the control area, in Figure 4(a). The bat-ball impact is observed as shown in Figure 4(b). A baseball bat is mounted in the bat holding fixture that sits atop one of the motors while the ball is held in place in the ball "tuning fork" fixture attached to the other motor shown in Figure 4(c). A set of light cells and speed gates measure the exit velocity of the ball as it moves away from the impact, where the ball is eventually stopped by a collection net shown in Figure 4(d).

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.

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 cross setion of a baseball is shown in Figure 5. 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 as shown in the compression testing results are shown in Figure 6.

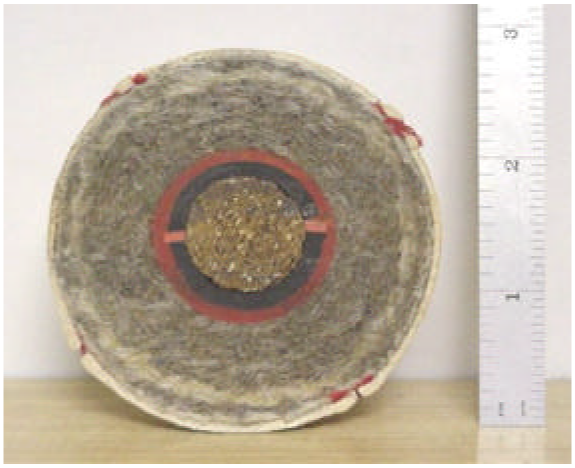

Figure 5 - Cross section of a baseball.

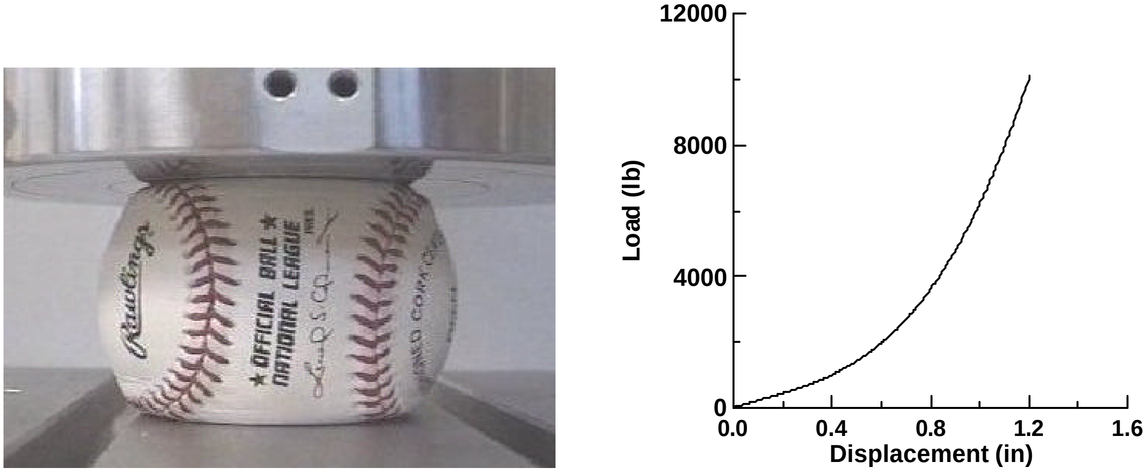

Figure 6 – Compression testing of the baseball, with results.

The Mooney-Rivlin material model (Type 27) 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 non-linear rubber-like materials. 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 spherical boundaries of an official Major League baseball.

The ball model, consisting of 1,296 solid elements, was then impacted against a stationary wood block (as shown in Fig. 7) to calibrate it to known coefficient of restitution (COR) values. The COR is a measure of the elasticity of a collision between two bodies. Experimental data show that a baseball impacting a stationary wood block at 58 mph has a COR of approximately 0.56 (Adair, 1994), meaning that 56% of the energy is returned back to the ball. In order to achieve this value of 0.56, mass damping was added to the model. High-speed video of a baseball-bat impact was also used as a visual guide to judge the amount of damping needed. Automatic surface-to-surface contact was prescribed.

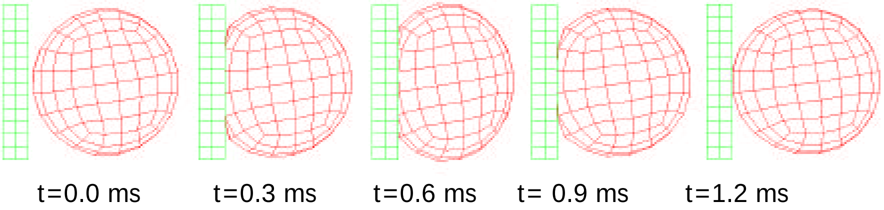

Fig. 7 - Sequence of ball deformation during contact with flat surface.

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. 8 and 9. All finite element models were created using HyperMesh 2.1a. The mesh for the hollow aluminum bat consisted of 2,054 shell elements with a uniform thickness of 0.100 in. The C405 alloy was modeled using an elastic-plastic material model with kinematic hardening (Type XX), recommended for use with shell elements. The mesh for the solid wood bat consisted of 3,840 8-noded brick elements. An orthotropic elastic material model (Type 2) was used to model the directional properties of the wood. The bats were then calibrated using modal analysis. Previous work (Mustone, 1998) had used un-calibrated bat models to quantify the relative performance between the aluminum bat and wood bat, but did not compare well to experimental data.

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 using an impact hammer and a dynamic signal analyzer. MSC/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. Note that the cg location is measured from the barrel end of the bat.

Table 1 Aluminum bat calibrated data

	Weight (oz)	Length (in)	Center of Gravity (in)	1st Mode (Hz)	2nd 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)	1st Mode (Hz)	2nd 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 have an inbound velocity of 70 mph and at the point of impact on the bat, it will have a linear velocity of 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 FEMB 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. 10 Profile of the aluminum bat model

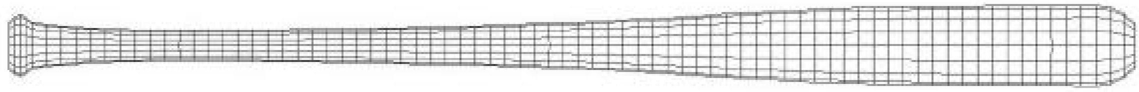

Fig. 11. Profile of the wood bat model

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 - 0.4 mph. 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 same location of the impact at 6-in from the barrel end. 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.

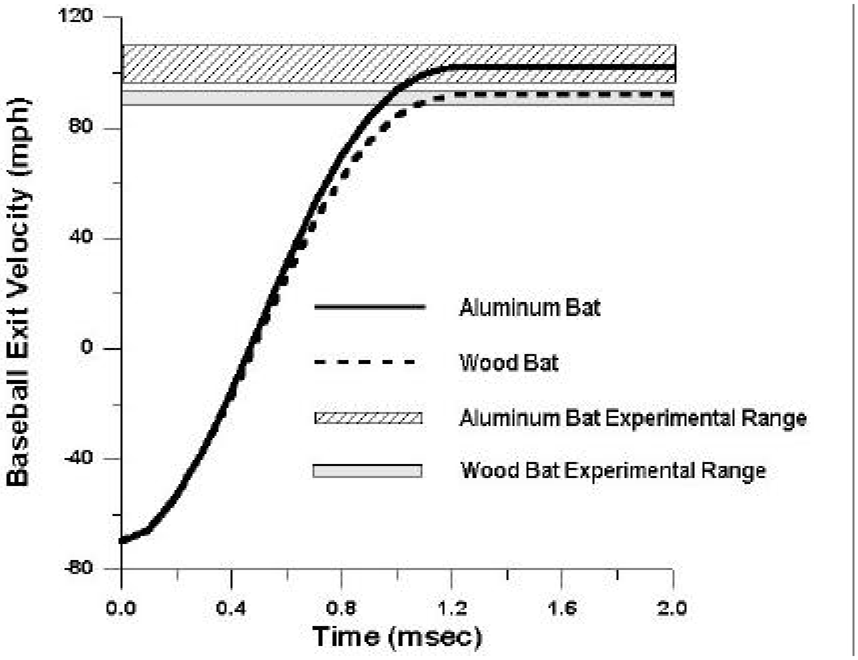

Fig. 12 Baseball velocities for the aluminum and the wood bats

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. Figures 13 and 14 show the stress contour plots for the aluminum and wood bat impact animations, respectively. Notice that in the aluminum bat, the hoop mode in the barrel is present at impact with the ball, followed by the impulse traveling down the length of the bat to the handle and in the wood bat, only the impulse is present.

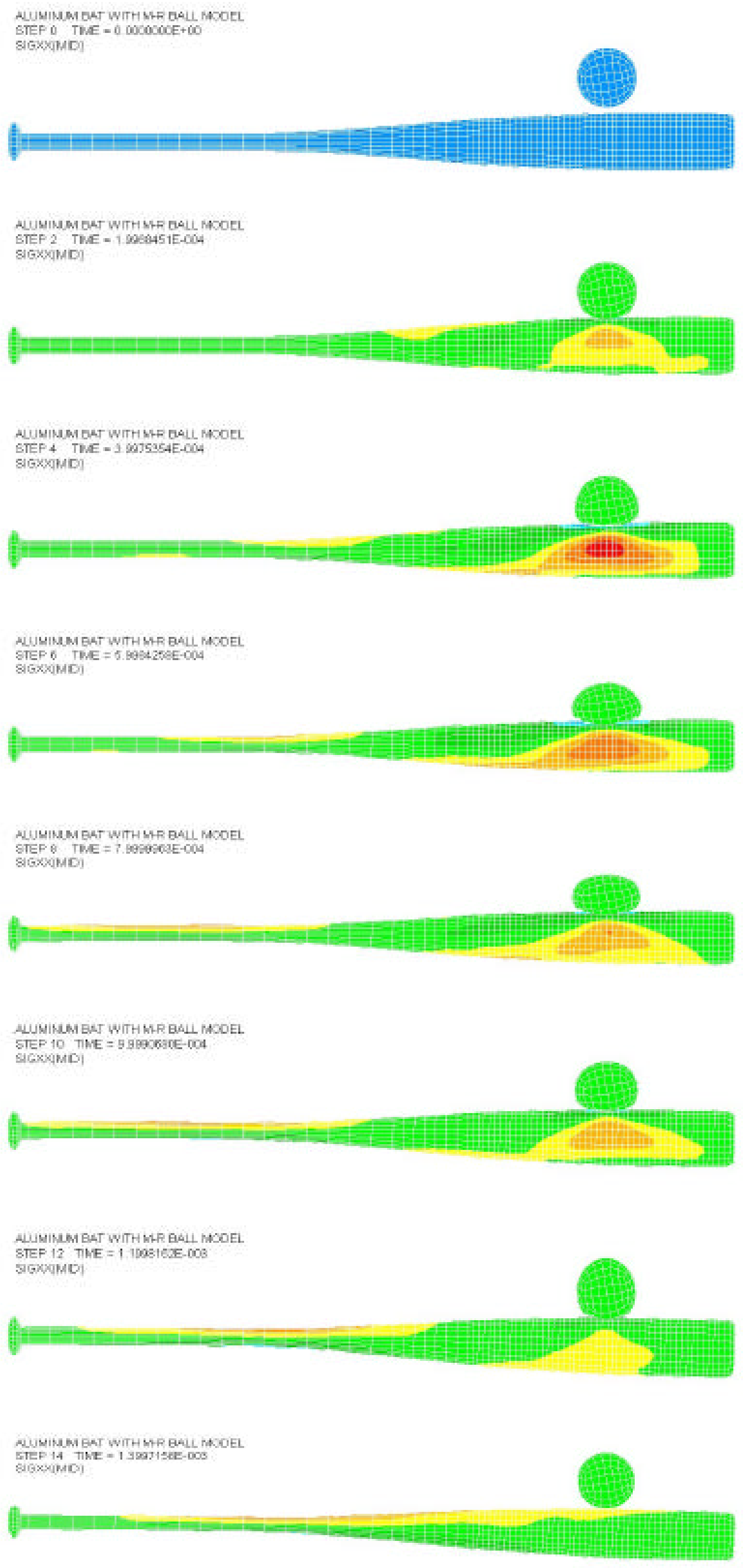

Figure 13 – Stress contour plots of aluminum bat animation.

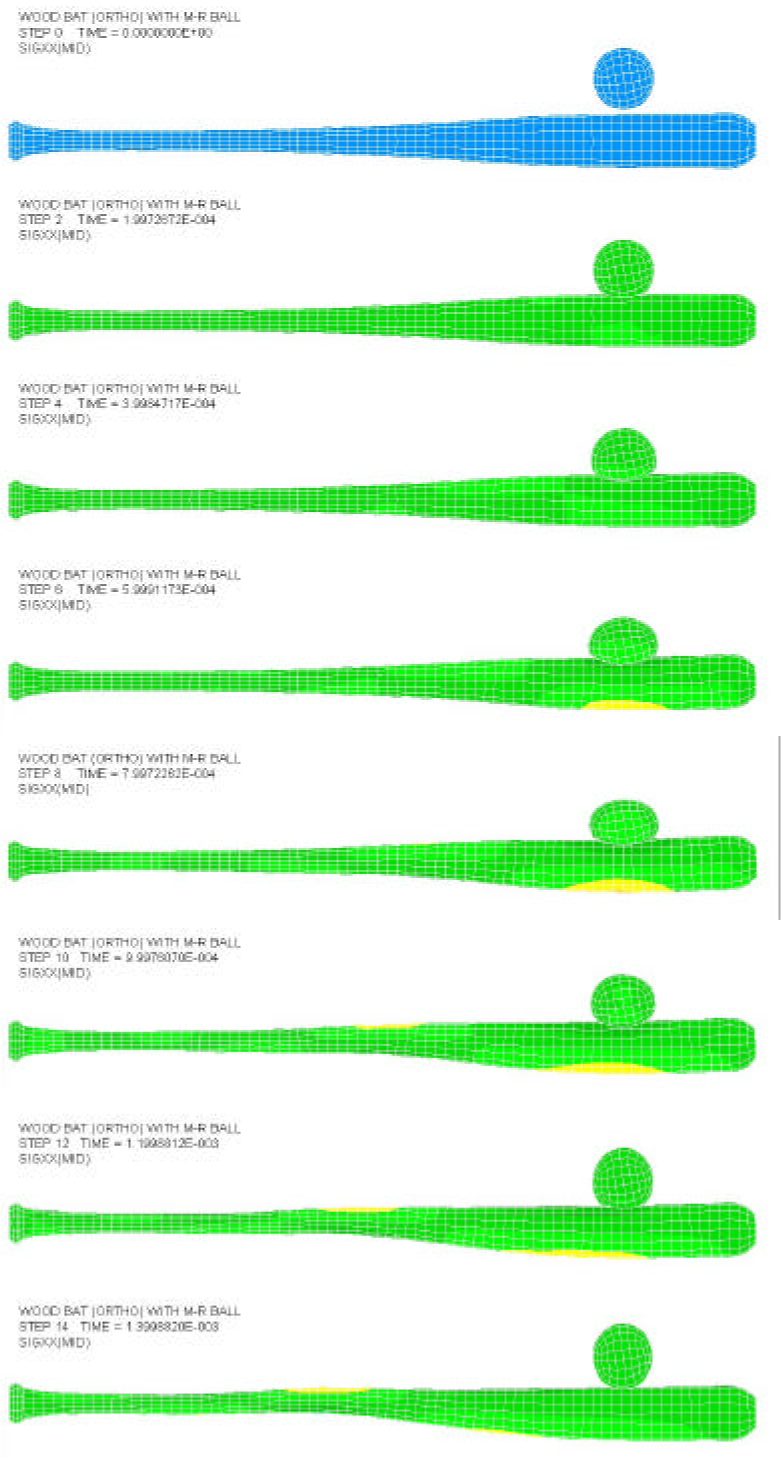

Figure 14 – Stress contour plots of wood bat animation.

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 second-generation 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.

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.

REFERENCES

Adair, R. (1994) *The Physics of Baseball*, Harper and Row
Thurston, W. (1998) *Collegiate Baseball*
Thurston, W. (1999) *Collegiate Baseball*
Thurston, W. (1999) *Personal Communication*
Watts, R. and Bahill, T. (1990) *Keep Your Eye on the Ball*, W. H. Freeman and Company

Fallon, Lawrence P. , Sherwood, James A., Collier, Robert D., "Program to Develop Baseball Bat Performance Procedures using the Baum Hitting Machine and Provide Verification using Laboratory Test Methods, FINAL REPORT," October 1997