Performance Evaluation of Wood and Aluminum Baseball Bats Using
Finite Element Analysis

by
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Approved:

 ____________________________________________
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# LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
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<tbody>
<tr>
<td>$m_1$</td>
<td>Baseball mass</td>
<td>lbm</td>
</tr>
<tr>
<td>$m_2$</td>
<td>Bat mass</td>
<td>lbm</td>
</tr>
<tr>
<td>$v_{lb}$</td>
<td>Baseball initial velocity</td>
<td>in/s</td>
</tr>
<tr>
<td>$v_{la}$</td>
<td>Baseball final velocity</td>
<td>in/s</td>
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<td>$v_{2b}$</td>
<td>Bat initial velocity</td>
<td>in/s</td>
</tr>
<tr>
<td>$v_{2a}$</td>
<td>Bat final velocity</td>
<td>in/s</td>
</tr>
<tr>
<td>$I$</td>
<td>Moment of inertia</td>
<td>lbm*in²</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass of the body</td>
<td>lbm</td>
</tr>
<tr>
<td>$r$</td>
<td>Distance from the center of mass to the pivot point</td>
<td>in</td>
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<tr>
<td>$e_A$</td>
<td>Collision efficiency</td>
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<td>$V_{in}$</td>
<td>Incoming ball speed</td>
<td>in/s</td>
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<td>$V_{out}$</td>
<td>Outgoing ball speed</td>
<td>in/s</td>
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## KEYWORDS

<table>
<thead>
<tr>
<th>Keyword</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Bat Performance</td>
<td>Defined in this project as the batted ball speed off of the baseball bat</td>
</tr>
<tr>
<td>Moment of Inertia (MOI)</td>
<td>A quantity expressing a body’s tendency to resist angular acceleration</td>
</tr>
<tr>
<td>Sweet Spot</td>
<td>Defined in this project as the location on the bat which produces the maximum batted ball speed</td>
</tr>
<tr>
<td>Center of Percussion (COP)</td>
<td>The impact point on the baseball bat that produces zero net force at the bat’s pivot point and minimal sting in the batter’s hands</td>
</tr>
<tr>
<td>Finite Element Model (FEM)</td>
<td>Representation of an object using finite elements</td>
</tr>
</tbody>
</table>
ACKNOWLEDGMENT

I would like to thank Professor Ernesto Gutierrez-Miravete for his guidance in these early stages of my master’s project. I would also like to thank my family and friends for their guidance and encouragement throughout my academic career.
ABSTRACT

The purpose of this project was to perform a finite element analysis to compare the performance of wood and aluminum baseball bats. In this project, the performance of the baseball bat was quantified as the batted ball speed off of the bat. Baseball bats vary in size, weight, and material, and the change in these properties can greatly affect the performance of the bat. This project focused on creating a finite element model that will simulate the dynamics of the bat-ball interaction and on comparing the effects that the material, weight, swing speed, and ball impact location have on bat performance.
1. INTRODUCTION

1.1 Background

Baseball is a popular American sport that is being played and gaining popularity across the world. The game of baseball evolved from two English games: rounders and cricket. Variations of these two games were played in schoolyards and college campuses as early as the American Revolution, becoming more popular in the mid-19th century in newly industrialized cities. The first official baseball club, the New York Knickerbocker Baseball Club, was founded in September 1845, and one of its members, Alexander Cartwright, established a set of rules for the game that would form the basis for modern baseball. Nine months later on June 19, 1846, the Knickerbockers played the first official game of baseball in Hoboken, New Jersey against a team of cricket players, losing by a score of 23-1.

Since that day in 1846, baseball has changed dramatically into the game we know today. One component of the game that has undergone many changes is the baseball bat. In the early days of baseball, there were no regulations on bats, so players used many different types of wood bats from long, heavy, round ones to short, flat bats that were similar to cricket bats. Today, bat geometry is tightly regulated in all levels of play. Furthermore, new technologies have afforded the use of new bat materials in the form of aluminum alloys. Although the professional league, Major League Baseball (MLB), uses wood bats, metal bats are primarily used in levels of play up to and through collegiate baseball in the NCAA.

To save money over the cost of constantly breaking wooden baseball bats, the NCAA implemented the use of metal bats in 1974. Since then, the number of homeruns has increased from 0.42 per game in 1973 to as high as 1.06 per game in 1998. The increase in homeruns and offensive statistics in general is attributed to the use of metal bats. However, due to the increased number of injuries to pitchers attributed to the high batted ball speeds of the ball off of a metal bat, the NCAA implemented a stricter Ball-Bat Coefficient of Restitution (BBCOR) standard in 2011. This stricter standard dropped the number of homeruns per game to 0.52 in 2011, shown in Figure 1 below.
Figure 1 - Graph Displaying Year vs. Homeruns Per Game in NCAA Games
1.2 Problem Description

In this project, finite element analysis (FEA) was used to assess the performances of wood and aluminum bats. The performance of the bat was evaluated by the batted ball speed off of the bat. Models of a baseball and a baseball bat were created in Abaqus/CAE and a dynamic analysis on the bat-ball interaction was performed in Abaqus/Explicit. After the modeling was accomplished and the dynamic analysis was performed, the models were modified with different physical properties such as barrel diameter, and the analysis was rerun. This project also compared the effects that swing speeds and ball impact locations have on both wood and aluminum bats.

The performance of baseball bats is a topic that has been studied many times [1]-[3]. These studies observed the performance of bats based on ball impact locations, MOI, bat stiffness, and other properties. These studies, using experimental and analytical results, all show that aluminum bats outperform wood bats.

![Figure 2 - Baseball Player Making Contact with the Baseball](image-url)
2. THEORY/METHODOLOGY

2.1 Theory

A baseball bat is a round object that can be made from many different types of materials. The bottom part of the bat is known as the handle. This is where the batter grips the bat. The top part is known as the barrel; this is where the bat strikes the ball. Figure 3 below shows the nomenclature of a baseball bat.

![Figure 3 - Anatomy of a Baseball Bat](image)

The interaction between a baseball and a bat is a collision of two objects with different masses and different velocities. This interaction can be explained by the law of conservation of momentum, which states that total momentum is constant in a closed system. The ball and bat have masses $m_1$ and $m_2$, respectively, and initial velocities $v_{1b}$ and $v_{2b}$, respectively, where the ball’s velocity is negative. After the collision, the ball and bat have positive velocities $v_{1a}$ and $v_{2a}$, respectively. This is shown in Figure 4 below. The masses and initial and final velocities are related to each other through the law of conservation of momentum. Momentum is a product of mass and velocity, and the law of conservation of momentum states that the total momentum before the impact must be equal to the total momentum after the impact. This relationship is shown in Equation [1] below.

$$m_1 * v_{1b} + m_2 * v_{2b} = m_1 * v_{1a} + m_2 * v_{2a} \quad [1]$$
One can see from Equation [1] that a heavier bat and a faster initial bat velocity will increase the momentum of a baseball after impact, therefore increasing the batted ball speed. However, the effect of increasing the bat mass is not the same as the effect of increasing bat velocity. A set of experiments [5] demonstrates the effects of increasing bat mass and velocity. In one experiment, the ball mass, ball initial velocity, and bat initial velocity were kept constant; the only variable changed was the bat weight. This experiment concluded that if the bat mass was doubled, the batted ball speed increased by 12 mph. The second experiment kept the ball mass, ball initial velocity, and bat mass constant, only changing the bat initial velocity. This experiment concluded that if the bat velocity is doubled, the batted ball speed is increased by 22 mph. From these experiments, one can see that bat velocity has more of an impact on the performance of a bat than bat mass. However, these two variables of bat mass and velocity are not the only two variables that affect bat performance. The moment of inertia (MOI) and sweet spot also play a large role in the performance of baseball bats.

### 2.1.1 Moment of Inertia

Moment of inertia (MOI) is a quantity expressing a body’s tendency to resist angular acceleration. The MOI of a body is a measure of the mass distribution along the body’s length relative to an axis of rotation. It is the sum of the products of the mass of each particle in the body with the square of its distance from the axis of rotation. This relationship is shown in Equation [2] below where \( I \) is the moment of inertia, \( m \) is the mass of the body, and \( r \) is the distance from the center of mass to the pivot point.
In baseball, MOI is referred to as swing weight. Bats of the same weight and length can have different swing weights; this is attributed to the distribution of the mass along the length of the bat, or the bat’s moment of inertia. A larger moment of inertia around an axis requires more torque to either increase or stop the rotation of the body about that axis; therefore, the larger the MOI of a baseball bat is, the more difficult it is to swing that bat quickly. Baseball bats with smaller MOIs have lighter swing weights and more control than bats with larger MOIs.

2.1.2 Sweet Spot

The sweet spot on a baseball bat has many definitions. Two of the most popular definitions are 1.) the location on the bat which produces minimum sting in the batter’s hands, and 2.) the location on the bat which produces the maximum batted ball speed. The sweet spot is different on all baseball bats, but is generally located 5”-7” from the end of the barrel where the sting in the batter’s hands is at a minimum and where the batted ball speed is at its highest.

The first definition of the sweet spot above refers to the bat’s center of percussion (COP). The COP is the impact point on the baseball bat that produces zero net force at the bat’s pivot point and minimal sting in the batter’s hands. Impacts closer to the handle of the bat will result in translational force at the pivot point and impacts closer to the barrel end of the bat will make the bat rotate about its center of mass and cause a force in the opposite direction at the pivot point. For impacts at the COP, however, the translational and rotational accelerations in the opposite direction would cancel each other out, resulting in zero net force and no sting in the batter’s hands. The COP is not a fixed point on a baseball bat as it depends on the location of the pivot point and is heavily influenced by the bat’s MOI and distance from the pivot point to the bat’s center of mass. The COP is determined by pivoting the bat about a point on the handle 6” from the knob and measuring the period of oscillation required for the bat to swing back and forth through one cycle. All current methods of testing bat performance use

\[ I = m \cdot r^2 \]
this 6” distance from the knob as a reference for locating the COP. However, two studies [6-7] have shown that the actual pivot point during a bat-ball interaction is 2.5” off of the knob of the bat and 2.5” off of the axis of the bat. Therefore, the pivot point traditionally used to identify the COP and the actual pivot point during a bat-ball interaction are not the same and the COP referenced to the 6” pivot point has no relevance in the performance of a baseball bat. Although the COP meets the first definition of the sweet spot above, it is not the location that produces the highest batted ball speeds.

The location of the bat that produces maximum batted ball speeds is different on every bat; it cannot be calculated as a single location for all bats and must be measured for each individual bat. One metric used for comparing the performance of baseball bats is the Batted-Ball Speed (BBS). The BBS is calculated from the collision efficiency, which is determined by firing a ball from a cannon towards a bat and measuring the incoming and outgoing speeds of the ball, $V_{in}$ and $V_{out}$, respectively. The collision efficiency is given in Equation [3].

$$e_A = \frac{V_{out}}{V_{in}}$$  \[3\]

The BBS is calculated from the collision efficiency and also depends on the bat’s MOI and the impact location of the ball on the bat.

In this project, the sweet spot is referred to as the location on the bat which produces the maximum batted ball speed.
2.2 Finite Element Analysis Methodology

Finite element analysis (FEA) is a numerical method for finding an approximate solution to engineering and mathematical boundary value problems. FEA is very useful for problems with complex geometries, loads, and material properties where it is difficult to obtain an analytical solution. FEA allows for a large system to be divided into an equivalent system composed of many small sections called finite elements that are interconnected at common points called nodes. Once element types are defined, the material and geometric properties of the elements are applied. Boundary conditions are then applied to the entire system. Equations are then generated after loads are specified, which allows for the results of the equations to be generated at each node. These results at the nodes allow for an approximation of a much more complex equation over the larger system. The FEA softwares utilized in this project are Abaqus/CAE and, Abaqus 6.13 and Abaqus/Explicit, Abaqus 6.13. Abaqus/CAE will be used to develop the models of the ball and bats whereas Abaqus/Explicit will be used to solve the dynamic simulation of the bat-ball interaction.

2.2.1 Part Geometry

Three-dimensional models of a baseball, wood bat, and aluminum bat were created using Abaqus/CAE. Per MLB’s official rules [8], a baseball shall “measure not less than nine nor more than 9 ¼ inches in circumference.” This works out to be a ball diameter between 2.86” and 2.94”. For this project, the average ball diameter of 2.90” was chosen. The finite element model (FEM) of the baseball is shown in Figure 5 below.
Also per MLB’s official rules [8], “the bat shall be a smooth, round stick not more than 2 ¾ inches in diameter at the thickest part and not more than 42 inches in length.” For this project, a bat length of 34”, a barrel diameter of 2.5”, and a handle diameter of 1” are initially assumed. The bat length, barrel diameter, and handle diameter are the same for both the wood and aluminum bats. The wooden bat is modeled as a solid bat whereas the aluminum bat is modeled with a solid handle and a hollow barrel with a 0.10” thick wall. Further analysis was performed with the barrel diameters of 2.25” and 2.75” to determine what effect bat mass had on bat performance. The FEM of the bats is shown in Figure 6 below.
2.2.2 Materials

A baseball is a composite consisting of 4 different materials: cork, rubber, yarn, and cowhide [8]. The core of the baseball, or “pill,” is made of cork and surrounded by two thin wrappings of rubber. The rubber and cork are then wound with 370 yards of wool yarn, and then the wool yarn is covered by two pieces of cowhide stitched together with 216 stitches. A cross-section view of a baseball can be seen in Figure 7 below. The baseball is modeled as a viscoelastic material due to the ball’s time dependent material properties. There is a time-dependent energy loss associated with baseballs; therefore, a simple elastic model cannot properly represent a baseball. The properties for a baseball are given in Table 1 below and were obtained from experimental results [2], [9].

![Cross-Section View of a Baseball](image)

**Figure 7 - Cross-Section View of a Baseball [10]**

**Table 1 - Material Properties of a Baseball**

<table>
<thead>
<tr>
<th>Material Properties of a Baseball [2],[9]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (lb/in³)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>.028</td>
</tr>
</tbody>
</table>
Ash is the most popular wood bat material; therefore, the wood bat in this analysis will use material properties based on ash. The wood bat is modeled as an orthotropic material. The properties for the ash bat are given in Table 2 below.

<table>
<thead>
<tr>
<th>Material Properties of Ash [2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (lb/in$^3$)</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
</tbody>
</table>
|                      | $E_1$                 | $E_2$               | $E_3$           | $G_{12}$ | $G_{23}$ | $G_{13}$ | $
u_{12}$ | $
u_{23}$ | $
u_{13}$ |
| 0.028                | $2.02 \times 10^6$   | $1.93 \times 10^6$ | $2.13 \times 10^5$ | $1.78 \times 10^5$ | $2.03 \times 10^4$ | $1.20 \times 10^5$ | 0.4 | 0.5 | 0.5 |

The aluminum bat is modeled with elastic material properties. Elastic material properties for aluminum are shown in Table 3.

<table>
<thead>
<tr>
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<tr>
<td>Density (lb/in$^3$)</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>0.0975</td>
</tr>
</tbody>
</table>

2.2.4 Assembly and Steps

A reference point was created at the global FEM origin (0,0,0). This reference point is the pivot point of the baseball bat. The bat was offset 2.5” in the positive x-direction from the pivot point and 2.5” in the negative x-direction from the pivot point. This offset corresponds to the pivot point of the bat during bat-ball interaction as was discussed in section 2.1.2 above. The baseball was initially offset 30.5” in the positive x-direction and 0.2” inches in the positive z-direction so that it would contact the bat barrel at the assumed sweet spot 6” away from the end cap. Figure 8 shows a view of the FEM assembly.
Two steps were created in the FEM. The first step is the Initial Step and the second step is the Impact Step, which is a dynamic, explicit step. Details about what is performed during these steps will be discussed in the following sections.

2.2.5 Interactions, Contact, and Constraints

The general contact (explicit) interaction was chosen in this analysis to simulate the bat-ball interaction. This contact is applied during the Impact Step. The interaction properties used are tangential behavior and normal behavior. The ball contacts the bat at the assumed sweet spot 6” from the end of the barrel. Further analysis was performed with the ball contacting the bat 5” and 7” from the end of the barrel to determine what effect impact location had on bat performance.

A 6” long section on the handle of the bat was connected to the rotation point reference point using a rigid body tie constraint. This was done to represent the rigidity of the batters hands during the swinging of a baseball bat and to ensure that the bat rotates around the pivot point defined in Section 2.1.2 above. Figure 9 shows the rigid body tie constraint on the bat about the rotation point.
2.2.6 Boundary Conditions and Predefined Fields

One boundary condition is used in this analysis. The boundary condition is applied at the rotation point reference point to only allow the bat to rotate about the y-axis. This boundary condition is applied in both the Initial and Impact Steps.

Two predefined fields are used in this analysis. The first predefined field is a velocity field that is applied to the bat and the rotation point reference point. This predefined field allows both the bat and rotation point to rotate about the y-axis at an initial angular velocity of 32 rad/s. Further analysis was performed with angular velocities of 28 rad/s and 36 rad/s to determine the effect of bat swing speed on bat performance. This field is applied during the Initial Step.

The second predefined field is also a velocity applied to the baseball. This field allows the ball to translate along the z-axis at an initial velocity of 90 mph. This field is also applied during the Initial Step.

Figure 9 - Rigid Body Tie Constraint
2.2.7 Mesh

The bat is meshed using hexahedral elements whereas the baseball is meshed using tetrahedral elements. The element type for the bat is the C3D8 element, which is an 8-noded linear brick element from the Abaqus/Explicit library. The element type for the baseball is the C3D10M element, which is a 10-node modified quadratic tetrahedron from the Abaqus/Explicit library. Figures 10 and 11 show meshed images of the ball and the bat, respectively.

Figure 10 - Meshed Baseball

Figure 11 - Meshed Bat
3. RESULTS

3.1 Wood Bat Performance

This section discusses the results of the analyses performed on the wood baseball bat. The three scenarios investigated were changes to bat mass, swing speed, and ball impact location.

3.1.1 Bat Mass

In this section, the performances of wood bats of bat barrel diameters of 2.25”, 2.50”, and 2.75” are compared. A change in the diameter of the barrel results in a change in the mass of the bat. The weight of the 2.25” diameter barrel bat is 36 oz, the weight of the 2.50” diameter barrel bat is 43 oz, and the weight of the 2.75” diameter barrel bat is 50 oz. Each bat was given a swing speed on ball impact of 32 rad/s. The baseball in all three scenarios was given a speed of 90 mph on impact and contacted the bat 6” from the end of the barrel. Table 4 shows the input variables and results and Figure 12 displays the results.

Table 4 - Wood Bat Performance for Varying Bat Barrel Diameters and Masses

<table>
<thead>
<tr>
<th>Barrel Diameter (in)</th>
<th>Bat Mass (oz)</th>
<th>Ball Speed (mph)</th>
<th>Bat Speed (rad/s)</th>
<th>Impact Location from End of Barrel (in)</th>
<th>Batted Ball Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.25</td>
<td>36</td>
<td>90</td>
<td>32</td>
<td>6</td>
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<td>2.50</td>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td>100.4</td>
</tr>
<tr>
<td>2.75</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td>102.5</td>
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</table>
From Table 4 and Figure 12, one can see that as the bat barrel diameter and mass increase, the batted ball speed increases. This is an expected result as it is shown in Equation [1] from the law of conservation of momentum. The performance of the wood bat relative to a change in mass is parabolic. The 10.1 mph increase in batted ball speed from the 2.25” diameter barrel to the 2.50” diameter barrel is very steep when compared to the 2.1 mph increase in batted ball speed from the 2.50” diameter barrel to the 2.75” diameter barrel bat.
3.1.2 Swing Speed

In this section, the performances of wood bats with swing speeds of 28 rad/s, 32 rad/s, and 36 rad/s are compared. Each bat in this analysis was a 2.50” barrel diameter, 43 oz wood bat. The baseball in all three scenarios was given a speed of 90 mph on impact and contacted the bat 6” from the end of the barrel. Table 5 shows the input variables and results and Figure 13 displays the results.

Table 5 - Wood Bat Performance for Varying Bat Swing Speeds

<table>
<thead>
<tr>
<th>Barrel Diameter (in)</th>
<th>Bat Mass (oz)</th>
<th>Ball Speed (mph)</th>
<th>Bat Speed (rad/s)</th>
<th>Impact Location from End of Barrel (in)</th>
<th>Batted Ball Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.50</td>
<td>43</td>
<td>90</td>
<td>28</td>
<td>6</td>
<td>89.2</td>
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<td></td>
<td>32</td>
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<td>100.4</td>
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<td></td>
<td></td>
<td></td>
<td>36</td>
<td></td>
<td>111.6</td>
</tr>
</tbody>
</table>

Figure 13 - Batted Ball Speed vs. Bat Swing Speed for Wood Bat
From Table 5 and Figure 13, one can see that as the bat swing speed increases, the batted ball speed increases. This is an expected result as it is shown in Equation [1] from the law of conservation of momentum. The performance of the wood bat relative to changes in swing speed displays a linear trend as is seen in Figure 13.

3.1.3 Impact Location

In this section, the performances of wood bats with impact locations of 5”, 6”, and 7” relative to the end of the barrel diameter are compared. Each bat in this analysis was a 2.50” barrel diameter, 43 oz wood bat and was given a swing speed of 32 rad/s on impact of the baseball. The baseball in all three scenarios was given a speed of 90 mph on impact with the bat. Table 6 shows the input variables and results and Figure 14 displays the results.

Table 6 - Wood Bat Performance for Varying Ball Impact Locations

<table>
<thead>
<tr>
<th>Barrel Diameter (in)</th>
<th>Bat Mass (oz)</th>
<th>Ball Speed (mph)</th>
<th>Bat Speed (rad/s)</th>
<th>Impact Location from End of Barrel (in)</th>
<th>Batted Ball Speed (mph)</th>
</tr>
</thead>
<tbody>
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<td>6</td>
<td>100.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>98.4</td>
</tr>
</tbody>
</table>
From Table 6 and Figure 14, one can see that the bat performance is greatest when the ball impacts the bat 6” from the end of the barrel. Also, the bat performance is greater at 5” from the end of the barrel than it is at 7” from the end of the barrel. The performance of the wood bat relative to changes in ball impact location displays a parabolic trend as is seen in Figure 14.
3.2 Aluminum Bat Performance

This section discusses the results of the analyses performed on the aluminum baseball bat. The three scenarios investigated were changes to barrel diameter, swing speed, and ball impact location.

3.2.1 Bat Mass

In this section, the performances of aluminum bats of bat barrel diameters of 2.25”, 2.50”, and 2.75” are compared. A change in the diameter of the barrel results in a change in the mass of the bat. The weight of the 2.25” diameter barrel bat is 29 oz, the weight of the 2.50” diameter barrel bat is 34 oz, and the weight of the 2.75” diameter barrel bat is 40 oz. Each bat was given a swing speed on ball impact of 32 rad/s. The baseball in all three scenarios was given a speed of 90 mph on impact and impacted the bat 6” from the end of the barrel. Table 7 shows the input variables and results and Figure 15 displays the results.

<table>
<thead>
<tr>
<th>Barrel Diameter (in)</th>
<th>Bat Mass (oz)</th>
<th>Ball Speed (mph)</th>
<th>Bat Speed (rad/s)</th>
<th>Impact Location from End of Barrel (in)</th>
<th>Batted Ball Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.25</td>
<td>29</td>
<td>90</td>
<td>32</td>
<td>6</td>
<td>92.0</td>
</tr>
<tr>
<td>2.50</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td>99.0</td>
</tr>
<tr>
<td>2.75</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td>103.1</td>
</tr>
</tbody>
</table>
From Table 7 and Figure 15, one can see that as the bat barrel diameter and mass increase, the batted ball speed increases. This is an expected result as it is shown in Equation [1] from the law of conservation of momentum. The performance of the aluminum bat relative to a change in mass is parabolic. The 7.0 mph increase in batted ball speed from the 2.25” diameter barrel to the 2.50” diameter barrel is steeper when compared to the 4.1 mph increase in batted ball speed from the 2.50” diameter barrel to the 2.75” diameter barrel bat.
3.2.2 Swing Speed

In this section, the performances of aluminum bats with swing speeds of 28 rad/s, 32 rad/s, and 36 rad/s are compared. Each bat in this analysis was a 2.50” barrel diameter, 34 oz aluminum bat. The baseball in all three scenarios was given a speed of 90 mph on impact and contacted the bat 6” from the end of the barrel. Table 8 shows the input variables and results and Figure 16 displays the results.

Table 8 - Aluminum Bat Performance for Varying Bat Swing Speeds

<table>
<thead>
<tr>
<th>Barrel Diameter (in)</th>
<th>Bat Mass (oz)</th>
<th>Ball Speed (mph)</th>
<th>Bat Speed (rad/s)</th>
<th>Impact Location from End of Barrel (in)</th>
<th>Batted Ball Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.50</td>
<td>34</td>
<td>90</td>
<td>28</td>
<td>6</td>
<td>88.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>32</td>
<td></td>
<td>99.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>36</td>
<td></td>
<td>109.7</td>
</tr>
</tbody>
</table>

Figure 16 - Batted Ball Speed vs. Bat Swing Speed for Aluminum Bat
From Table 8 and Figure 16, one can see that as the bat swing speed increases, the batted ball speed increases. This is an expected result as it is shown in Equation [1] from the law of conservation of momentum. The performance of the aluminum bat relative to changes in swing speed displays a linear trend as shown in Figure 16.

### 3.2.3 Impact Location

In this section, the performances of aluminum bats with impact locations of 5”, 6”, and 7” relative to the end of the barrel diameter are compared. Each bat in this analysis was a 2.50” barrel diameter, 34 oz aluminum bat and was given a swing speed of 32 rad/s on impact of the baseball. The baseball in all three scenarios was given a speed of 90 mph on impact with the bat. Table 9 shows the input variables and results and Figure 17 displays the results.

**Table 9 - Aluminum Bat Performance for Varying Ball Impact Locations**

<table>
<thead>
<tr>
<th>Barrel Diameter (in)</th>
<th>Bat Mass (oz)</th>
<th>Ball Speed (mph)</th>
<th>Bat Speed (rad/s)</th>
<th>Impact Location from End of Barrel (in)</th>
<th>Batted Ball Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.50</td>
<td>34</td>
<td>90</td>
<td>32</td>
<td>5</td>
<td>98.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>99.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>98.7</td>
</tr>
</tbody>
</table>
From Table 9 and Figure 17, one can see that the bat performance is greatest when the ball impacts the bat 6” from the end of the barrel. Also, the bat performance is greater at 7” from the end of the barrel than it is at 5” from the end of the barrel. The performance of the wood bat relative to changes in ball impact location displays a parabolic trend as is seen in Figure 17.
3.3 Comparison of Wood and Aluminum Bat Performance

This section compares the results of the analyses performed on the wood and aluminum baseball bats. The three scenarios investigated for each bat were changes to barrel diameter, swing speed, and ball impact location.

3.3.1 Bat Mass

In this section, the performances of wood and aluminum bats of bat barrel diameters of 2.25”, 2.50”, and 2.75” are compared. For the wood bats, the weight of the 2.25” diameter barrel bat is 36 oz, the weight of the 2.50” diameter barrel bat is 43 oz, and the weight of the 2.75” diameter barrel bat is 50 oz. For the aluminum bats, the weight of the 2.25” diameter barrel bat is 29 oz, the weight of the 2.50” diameter barrel bat is 34 oz, and the weight of the 2.75” diameter barrel bat is 40 oz. As was done in Sections 3.1.1 and 3.2.1, each bat was given a swing speed on ball impact of 32 rad/s, and the baseball was given a speed of 90 mph on impact and impacted the bat 6” from the end of the barrel. Figure 18 compares the results of the analyses.

![Batted Ball Speed vs. Bat Mass for Wood and Aluminum Bats](image)

**Figure 18 - Batted Ball Speed vs. Barrel Mass for Wood and Aluminum Bats**
From Figure 18, one can see that as the bat barrel diameter and mass increase, the batted ball speed increases for both the wood and aluminum bats. These are expected results due to the law of conservation of momentum. The performances of both bat materials relative to a change in mass are parabolic. The performance of the wood bat displays a much steeper curve than that of the aluminum bat. Even though the weight of the aluminum bat is much less than that of the wood bat, it is important to note that the aluminum bat tends to outperform the wood bat.

3.3.2 Swing Speed

In this section, the performances of the wood and aluminum bats with swing speeds of 28 rad/s, 32 rad/s, and 36 rad/s are compared. The wood bat in this analysis is the 2.50” barrel diameter, 43 oz bat, and the aluminum bat is the 2.50” barrel diameter, 34 oz bat. Similar to Sections 3.1.2 and 3.2.2, the baseball was given a speed of 90 mph on impact and contacted the bat 6” from the end of the barrel. Figure 19 compares the results of the analyses.

![Batted Ball Speed vs. Bat Swing Speed for Wood and Aluminum Bats](image)

**Figure 19 - Batted Ball Speed vs. Bat Swing Speed for Wood and Aluminum Bats**
From Figure 19, one can see that as the bat swing speed increases, the batted ball speed increases for both the wood and aluminum bats. These are expected results due to the law of conservation of momentum. The performances of the both bat materials relative to changes in swing speed display linear trends. One can see from Figure 19 that the wood bat performs slightly better than the aluminum bat at the analyzed swing speeds. However, it is important to note that the analyzed wood bat is 9 oz (26%) heavier than the aluminum bat. This disproportion in weight is due to the fact that the models of both material bats were given identical dimensions, except that the aluminum bat was modeled as hollow. Due to the hollow nature of the aluminum bat and the solid nature of the wood bat, a difference in masses exists. If the mass of the wood bat was closer to the mass of the aluminum bat, or vice versa, the aluminum bat would outperform the wood bat. This is shown in Figure 20 below, where the batted ball speed per ounce of bat is displayed versus bat swing speed.

![Batted Ball Speed per Ounce vs. Bat Swing Speed for Wood and Aluminum Bats](image)

**Figure 20 - Batted Ball Speed per Ounce vs. Bat Swing Speed for Wood and Aluminum Bats**
When comparing the performances of the similar mass 2.50” barrel diameter, 34 oz aluminum bat to the 2.25” barrel diameter, 36 oz wood bat, one can clearly see that the aluminum bat outperforms the wood bat at the analyzed swing speeds. Table 10 and Figure 21 show this information.

Table 10 - Wood Bat Performance for Varying Bat Swing Speeds - 2.25” Barrel

<table>
<thead>
<tr>
<th>Barrel Diameter (in)</th>
<th>Bat Mass (oz)</th>
<th>Ball Speed (mph)</th>
<th>Bat Speed (rad/s)</th>
<th>Impact Location from End of Barrel (in)</th>
<th>Batted Ball Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.25</td>
<td>36</td>
<td>90</td>
<td>28</td>
<td>6</td>
<td>80.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>32</td>
<td></td>
<td>90.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>36</td>
<td></td>
<td>100.2</td>
</tr>
</tbody>
</table>

Figure 21 - Batted Ball Speed vs. Bat Swing Speed for Similar Mass Wood and Aluminum Bats
3.3.3 Impact Location

In this section, the performances of the wood and aluminum bats with impact locations of 5”, 6”, and 7” relative to the end of the barrel diameter are compared. The wood bat in this analysis is the 2.50” barrel diameter, 43 oz bat, and the aluminum bat is the 2.50” barrel diameter, 34 oz bat. Similar to Sections 3.1.3 and 3.2.3, the bats were given a swing speed of 32 rad/s on impact with the baseball and the baseball was given a speed of 90 mph on impact with the bat. Figure 22 compares the results of the analyses.

**Figure 22 - Batted Ball Speed vs. Ball Impact Location for Wood and Aluminum Bat**

From Figure 22, one can see that the bat performance is greatest when the ball impacts the bat 6” from the end of the barrel. The performances of the both bat materials relative to changes in ball impact location display parabolic trends. One can see from Figure 22 that the wood bat performs better than the aluminum bat at the analyzed impact locations. Again, it is important to note that the analyzed wood bat is 9
oz (26%) heavier than the aluminum bat. If the mass of the wood bat was closer to the mass of the aluminum bat, or vice versa, the aluminum bat would outperform the wood bat. This is shown in Figure 23 below, where the batted ball speed per ounce of bat is displayed versus bat swing speed.

![Batted Ball Speed per Ounce vs. Ball Impact Location for Wood and Aluminum Bats](image)

**Figure 23 - Batted Ball Speed per Ounce vs. Ball Impact Location for Wood and Aluminum Bat**
When comparing the performances of the similar mass 2.50” barrel diameter, 34 oz aluminum bat to the 2.25” barrel diameter, 36 oz wood bat, one can clearly see that the aluminum bat outperforms the wood bat at the analyzed impact locations. Table 11 and Figure 24 show this information.

Table 11 - Wood Bat Performance for Varying Ball Impact Locations - 2.25"

Barrel

<table>
<thead>
<tr>
<th>Barrel Diameter (in)</th>
<th>Bat Mass (oz)</th>
<th>Ball Speed (mph)</th>
<th>Bat Speed (rad/s)</th>
<th>Impact Location from End of Barrel (in)</th>
<th>Batted Ball Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.25</td>
<td>36</td>
<td>90</td>
<td>32</td>
<td>5</td>
<td>90.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>90.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>88.5</td>
</tr>
</tbody>
</table>

Figure 24 - Batted Ball Speed vs. Ball Impact Location for Similar Mass Wood and Aluminum Bats
4. CONCLUSION

For this project, the performance of wood and aluminum bats was determined using finite element analysis. The performance of the bats was investigated for different bat masses, swing speeds, and ball impact locations. It was observed that the aluminum bat outperformed a wood bat of similar weight as it produced higher batted ball speeds. Much scientific data exists to back the claim that aluminum bats outperform wood bats. One reason why aluminum bats outperform wood bats is due to the distribution of mass along the length of the bat, known as moment of inertia. Since aluminum bats are hollow, their center of mass is closer to the handle, which allows for the bat to be swung quicker. Wood bats are solid and have a center of mass closer to the end of the barrel. Another reason why aluminum bats outperform wood bats is the trampoline effect. When a baseball impacts a wood bat, the ball compress to nearly half of its original diameter and loses much energy. In hollow aluminum bats, the bat barrel compress when the ball impacts it, and the ball does not compress as much and retains more energy. Then, the energy stored in the bat during the collision is returned back to the ball.

It was also observed in this project that a heavier wood bat outperforms an aluminum bat when the bats are swung at the same speed. In real life, however, it is difficult to swing a heavy wood bat at the same speed as an aluminum bat. This is due to the larger moment of inertia of the wood bat.

This project also observed the effects of ball impact location on both material bats. It was shown that for both the wood and aluminum bats, each bat performed best when the impact location was 6” from the end of the barrel.
5. REFERENCES

5. Physics of Sport, (Ginn and Company, 1980), part of the Individualized Science Instructional System for Grades 9-12, developed by Florida State University.