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Design Implementation of Baseball Bats: Reinforced Bats—A Case Study

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An analysis of the physics of baseball bats is presented in this study. In particular, the analysis focuses on the safety of various types of baseball bats and the numerous approaches that have been taken in the industry to improve their safety. In order to evaluate their safety, several factors have been analyzed including the baseball bat coefficient of restitution, the trampoline effect, the durability of the bat and its constituent materials. In this study, a novel, patented, reinforced wooden baseball bat has been examined to determine its durability and safety relative to traditional wooden bats. Results based on a finite element analysis using ANSYS software have demonstrated that this reinforced bat reduces the stress of impact with a baseball, increasing the useable lifespan of the bat. Furthermore, after thorough and consistent use, results suggest that the reinforced bat is both more durable and safer because it takes longer to break than a traditional bat and, when it does break, it cracks instead of splintering and becoming a projectile.

INTRODUCTION

Baseball is one of the oldest sports in America, dating back to the mid-1800s. As would be expected with any sport that has been around for more than 150 years, there have been many advances made in baseball through the years. Probably the biggest advancements have been in the area of equipment. In the early years of baseball, there were not very many rules regarding equipment, as most equipment was generally very rudimentary. However, as the equipment began to advance, rules were implemented by organized baseball leagues to maintain a competitive balance between the teams and the players. These rules were more focused on achieving competitive balance than increasing safety, largely because the equipment was not advanced enough to cause major safety concerns.

Starting in the 1970s, metal baseball bats, especially aluminum bats, became increasingly popular due to their extreme durability and improved performance over traditional wooden bats. More recently, bats made of composite materials, which offer even better performance, have also become common. As the metal and composite bat performance continued to improve over the years, the competitive balance between hitters and pitchers was increasingly disrupted, and more importantly, safety began to be a major concern. For example, given an average pitch speed and bat speed, the pitcher could have as little as 0.33 seconds to react to a ball hit back at them in little league baseball, and as little as 0.26 seconds in major league baseball. Another safety concern is that when wooden bats break during play, they often splinter, and a large chunk of the bat becomes a projectile which can potentially come very close to one of the fielders. In fact, 13 people were killed playing youth baseball between 1987 and 1996 and there were over 29,000 injuries, including over 15,000 ball-related mishaps.[1]

As these incidents grew in frequency, more rules about baseball equipment, especially regarding baseball bats, were introduced at various levels of play to help make the game safer. The rules that have been implemented are not completely consistent and often vary from one league to another. In Little League and collegiate baseball where metal bats are prevalent, more and stricter rules have been implemented. The Little League Association of America, for example, recently outlawed all bats made of composite materials and also has rules regarding the maximum length of the bat as well as its maximum diameter.[2] The NCAA has gone even further regarding rules for the safety of baseball bats. In addition to length and diameter restrictions, there are also rules regarding the difference between the length and weight of the bat as well as the bat's moment of inertia.[3] Until recently, the National Collegiate Athletic Association (NCAA) also had a rule which required that all approved bats be tested to determine the ball exit speed ratio (BESR), which compared the speed of the ball before and after collision with the bat. Bats with a BESR of more than 0.728 were not allowed in play.[4] Recently, however, a new, more stringent statistic called the baseball bat coefficient of restitution (BBCOR) has been implemented by the NCAA which also takes into account the "trampoline effect" caused by metallic and composite baseball bats. Bats with BBCOR ratings of more than 0.50 are not allowed in competition.[3]

In Major League Baseball as well as professional Minor League Baseball, where wooden bats are used exclusively, fewer rules are present regarding baseball bats. While this is understandable in the sense that these leagues do not have to be concerned with the negative effects of metal and composite bats, it still poses the potential danger of a broken wooden bat injuring a fielder.

In this paper, the impact of the new rules regarding metal and composite bats on bat performance is analyzed. A new reinforced wooden bat aimed at improving the safety of wooden bats is presented. A finite element analysis (FEA) using the ANSYS software is performed to compare the stress experienced during collision by a regular wooden bat as well as the reinforced bat.

REVIEW OF THE LITERATURE

There have been a number of articles analyzing the physics of baseball bats with a variety of motivations and applications. These articles can be separated into three distinct categories: articles that try to understand the bat-ball collision, articles comparing metal and wood bats, and articles that present ways of improving various characteristics of baseball bats.

Among the studies attempting to understand the bat-ball collision, a major topic of interest was the so-called "sweet spot." Cross tried to locate the sweet spot in terms of vibration nodes or a center of percussion[5] while Noble also attempted to quantitatively describe the location of the sweet spot as a combination of vibrational factors, the center of percussion, and the coefficient of restitution.[6] Another study which sought to understand the bat-ball collision was Nathan, Russell, and Smith, which analyzed the trampoline effect using the coefficient of restitution.[7] Finally, Drane and Sherwood (2004) found that there was a 4% decrease in performance when the baseball was cooled significantly prior to use.[8]

The studies that focused on comparing the performance between metal and wood bats unanimously agreed that metal bats gave better performance. Shenoy, Smith, and Axtell[9] as well as Greenwald, Penna, and Crisco[10] found that the ball's velocity was 4–9 mph higher after colliding with a metal bat compared to a wooden bat.[11] Meanwhile, Crisco et al.[12] analyzed a number of factors to determine the reasons for better performance of metal bats.

In regards to the studies attempting to improve aspects of baseball bats, Ashley[13] developed two predominantly composite bats, one of which had performance similar to hardwood bats but with improved durability and the other with performance that exceeded even that of aluminum bats. Both of these bats contain a high-strength inner core made from resin-impregnated synthetic fibers and yarns surrounded by a wood outer surface. Axtell, Smith, and Shenoy[14] also developed a composite reinforcement for wooden bats to improve durability. This composite reinforcement consisted of an e-glass braided sleeve which was placed around a regular laminated wood bat.

However, the main problem with both of these studies is that since they use composite materials, they would not be allowed in leagues that permit only traditional wood bats.

THEORETICAL BACKGROUND

There are several important factors to consider when analyzing both metal and wooden baseball bats. These factors include the bat's coefficient of restitution, its moment of inertia, and the mechanical properties of its constituent materials. For metal and composite bats, the so-called "trampoline effect" is also important.

Coefficient of Restitution

Beginning in 2005, the NCAA implemented the BESR statistic to limit the performance of metal and composite bats by placing restrictions on the ratio of the ball speed before and after collision. This statistic, however, did not provide enough safety, and several pitchers were seriously injured after it was implemented. In response, the NCAA implemented the BBCOR statistic in 2011, which represents the coefficient of restitution between the baseball and each metal or composite bat model.

Instead of comparing the velocity of the ball before and after impact, the BBCOR statistic measures the bounciness or give of an aluminum or composite bat at the moment of contact with a ball.[3] To determine a bat's BBCOR rating, the NCAA has developed a specific testing procedure.[3] A ball cannon fires regulation baseballs at a stationary bat, and the velocity of the ball before and after impact is recorded, similarly to the BESR statistic. The difference, however, is how these velocities are used in the respective calculations. The equation for the BESR statistic[4] is given by the following expression:

$$\text{BESR} = \frac{V_R - \delta v}{V_I + \delta v} + 0.5 + < \varepsilon > \quad (1)$$

where, V_I and V_R are the ball inbound and rebound speeds, ε is a correction factor, and

$$\delta v = 136 \text{ mph} - V_{Contact} \quad (2)$$

The BBCOR statistic is represented as:

$$\text{BBCOR} = \frac{V_R}{V_I}(1+r) + r + C_{ball} \quad (3)$$

where, V_I and V_R are the ball inbound and rebound speeds respectively. The r and C_{ball} values are calculated from the following formulae:

$$C_{ball} = 0.528 - \text{BBCOR} \quad (4)$$

$$r = m\left[\frac{1}{W} + \frac{(L - BP - z)^2}{1 - W(BP - 6)^2}\right] \quad (5)$$

where, m is the mass of the ball in ounces, z is measured in inches from the barrel end of the bat, W is the weight of the bat, L is the length of the bat, and BP is the balance point relative to the knob of the bat.

The results of this new rule have been very significant, with scoring dropping by over 1 run per team per game and batting average dropping from .305 to .279.[15]

Moment of Inertia

Another important factor in determining a bat's performance is its moment of inertia, or in other words, the distribution of its weight. With bats made out of a single piece of wood, the distribution of the bat's weight is obvi-

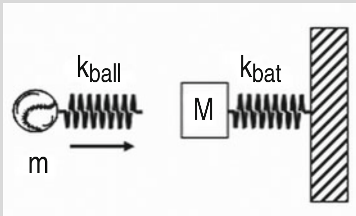

Figure 1. A bat-ball collision modeled as two springs.[7]

ously fixed, meaning that any gains from re-positioning the bat's weight cannot be realized. With metal and composite bats, however, the amount of material at different points along the length of the bat can be varied and optimized.

Bahill[16] analyzed various metal and wood baseball and softball bats to determine their respective moments of inertia. In his analysis, he found that, as expected, the metal bats had higher moments of inertia. To realize an increase in the moment of inertia of a bat, Bahill recommended adding weight near the end of the bat while lightening the area close to the handle. This so called "end-loading" effect caused a slight decrease in swing speed but increased the batted ball speed, improving a given batter's game performance.

The moment of inertia for baseball bats is only mandated in one major organized baseball league—the NCAA. Interestingly, the NCAA mandates a minimum moment of inertia but makes no mention of a maximum moment of inertia. The stated goal of this rule is to force players to use heavier bats, thus reducing their swing speeds and improving safety. According to Bahill's work, however, it seems that a maximum moment of inertia should also be mandated.

Trampoline Effect

While the coefficient of restitution, the bat's mass, and its moment of inertia are all important factors in bat performance and safety, a thorough analysis of the topic would not be complete without also considering the trampoline effect.

The collision between a baseball and a bat can be simplified to be considered as a collision between two linear springs, as in Figure 1, which have different spring constants. As such, both objects absorb some finite amount of energy from each other.

While the mass of the two objects and their velocities have an impact on the speed with which the ball leaves the bat, in this model, the spring constant also plays a significant role. This spring constant can be quantified by considering it to be the elastic modulus, or Young's Modulus, of the bat material. The Young's Modulus of some common bat materials are: ash, 12; hickory, 14; maple, 13; and aluminum, 69.

A larger Young's Modulus number means that the material requires a larger force to deform by the same amount. Given the much larger Young's Modulus value for aluminum compared to the various types of wood, it is obvious that the various types of wood deform much more than the aluminum, absorbing much more energy and lowering the velocity of the ball as it leaves the bat. Meanwhile, this lack of deformation in the aluminum represents the so-called "trampoline effect" which causes the ball to collide more elastically and have a higher velocity after collision.

The result of this trampoline effect is twofold. First, because the ball rebounds off of the bat with a higher velocity, the pitcher has less time to react, which is one reason why so many injuries to pitchers have occurred in leagues where metal bats are used. The other major result is that the ball tends to fly farther with bats that have a large trampoline effect. This extra distance causes more home runs to occur and games to be higher scoring, negating the effect of skilled pitchers and upsetting the balance of the game.

THE REINFORCED BAT

The force generated from the impact of a baseball on a wooden bat can often be quite large, on the order of several thousand Newtons. This violent collision occasionally has the effect of breaking the bat to a degree that it is no longer useable. Sometimes when this occurs, part of the bat becomes a sharply pointed projectile which flies towards one or more of the fielders, causing a tremendous safety risk. To help remedy this safety risk, in this study, a reinforced wooden baseball bat has been investigated to see if it could be made more durable and safer than regular wooden bats. This reinforced bat was designed and patented by Leonard Smalley.[17]

In this design, as in Figure 2, four small and shallow grooves are cut circumferentially around the bat. These grooves are roughly evenly distributed throughout the length of the bat with the first one close to the handle of the bat, the second one approximately at the middle of the bat, and the other two near the end of the bat straddling the "sweet spot." Then, a sealant is put in each groove as well as at least one strand of polymeric string. The location of each groove was determined empirically through significant real-world testing. The end result is that the bat looks exactly the same as a traditional bat, but is intended to be more durable and safer.

The theory behind this design is that the grooves will focus excessive vibrations created from the bat-ball collision which would otherwise propagate throughout the entire length of the bat. By focusing these vibrations, the goal of this design is to prolong the life of

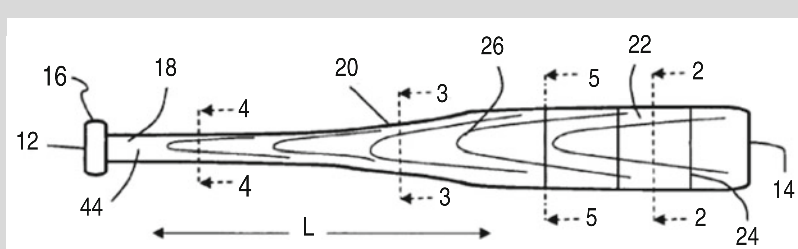

Figure 2. Schematic of a reinforced baseball bat.

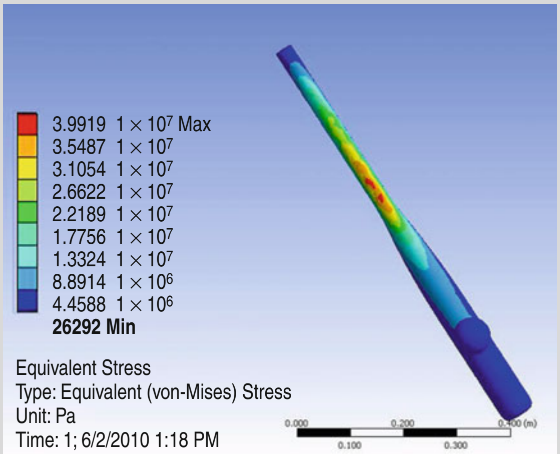

Figure 3. Stress concentration for a traditional baseball bat.

wooden baseball bats. Also, when the bat finally tends to break, the goal is to limit the crack to just the area between two such grooves so that the bat does not completely shear and become a projectile.

FINITE ELEMENT ANALYSIS

As a part of this study, a finite element analysis was performed using ANSYS software to analyze the stress distribution along the length of both a traditional wooden bat and the reinforced bat during collision. Finite element analysis uses a complex system of points called nodes which make a grid called a mesh. This mesh is programmed to contain the material and structural properties which define how the structure will react to certain loading conditions. Nodes are assigned at a certain density throughout the material depending on the anticipated stress levels of a particular area. Regions which will receive large amounts of stress usually have a higher node density than those which experience little or no stress.[18]

In this analysis, a number of parameters were specified. First, a three-dimensional version of both the standard bat and the reinforced bat were developed. Based on previous calculations, the force on the ball due to the pitcher was determined to be 3.94 kN and the force on the bat due to the batter's swing was determined to be 3.40 kN. These values, along with the following material constants, were included in the model: Baseball bat (maple wood)—Young's modulus, 1.22×10^{10} Pa, Poisson's Ratio, 0.371, and density, 600 kg/m^3; baseball—young's modulus, 1×10^8 Pa. Poisson's Ratio, 0.45; density, 4,000 kg/m^3.

RESULTS

The results of the finite element analysis are shown in Figures 3 and 4, in which it is apparent that the grooves with polymeric string are able to eliminate some of the stress placed on the bat during collision. It can be seen that the maximum and the minimum equivalent stress for a traditional baseball bat is higher than that of the reinforced baseball bat. This result has the effect of relieving the stress on the rest of the bat, prolonging its usable life.

The reinforced bats (Figure 5) were also given to the New Jersey Institute of Technology (NJIT) baseball team for real-world testing. The NJIT baseball players reported that there was no noticeable difference in the look, feel, or most importantly, performance between traditional bats and the reinforced bats. Of the four bats which were tested, all the bats were able to withstand several thousand hits over the course of the season, and one of the bats made it through the entire season without being damaged. Meanwhile, the three bats that did crack (for example, Figure 6) after several thousand hits cracked such that instead of shattering and becoming projectiles, they had very slight cracks beginning at one of the grooves and ending at another one of the grooves. While these cracks still mark the end of the useful lives for the bats, it is important to note that they cracked in a completely controlled and safe way which did not injure any of the participants in the game.

CONCLUSIONS

The main advantages of bats made with metal and composite materials are that they have greater performance and they have a near infinite useable lifespan. Wooden bats, on the other hand, do not achieve the same performance and have a tendency to break or shatter under consistent heavy use. It would seem, then, that wooden bats are inferior to their metal and composite counterparts.

A deeper analysis, however, presents a much different picture. The increase in the performance of metal bats has a negative effect on other aspects of baseball. For example, by enabling such tremendous performance by bat-

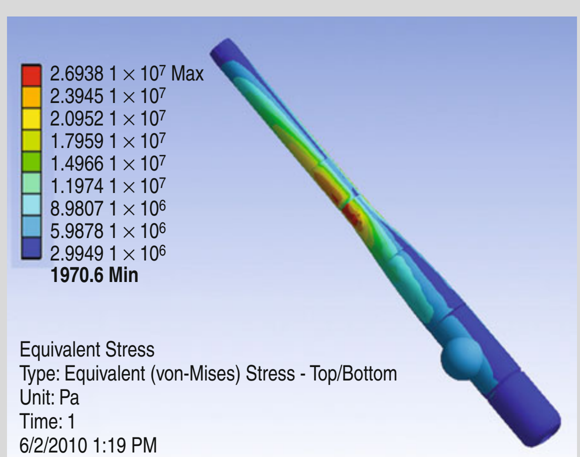

Figure 4. Stress concentration for a reinforced baseball bat.

Figure 5. A reinforced baseball bat before use.

Figure 6. A reinforced baseball bat after use.

ters, the effect of a team's pitching ability becomes almost inconsequential, upsetting the balance of the game. More importantly, the tremendous speed with which the ball leaves a metal bat causes the pitcher to have almost no time to react when a ball is hit directly at them. This lack of reaction time has caused many serious injuries through the years to pitchers at different levels of baseball.

Wooden bats, on the other hand, have maintained the gentle balance between pitchers and batters for over 150 years and their slightly less potent performance allows the pitchers a little more time to react when a ball is hit directly at them. The main concern, then, with wooden bats is that they tend to break under heavy use, potentially becoming a dangerous, sharp projectile. These disadvantages, however, are remedied by the reinforced bat which was tested as part of this study. Our results show that this bat kept the same performance standards of wooden bats but experienced dramatically less stress on impact, prolonging its lifespan. Furthermore, when the bats did finally crack, they cracked in a very controlled manner between two of the grooves as opposed to shearing along the grain of the bat and becoming a sharp projectile which could injure a player. Also, by holding the bat such that the trademark is pointed directly up or down, the ball will collide with the grain of the bat instead of against the grain,[19] increasing the lifespan of the bat. Therefore, it seems that this reinforced wooden bat is the best blend of performance, safety, and durability among the currently available types of baseball bats.

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