LABORATORY AND FIELD EXPERIMENTAL INVESTIGATIONS OF THE RELATIONSHIP OF BASEBALL BAT PROPERTIES ON BATTED-BALL SPEED

BY

REBECCA H. SHAW
B.ENG. MCGILL UNIVERSITY (2004)

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE
DEPARTMENT OF MECHANICAL ENGINEERING
UNIVERSITY OF MASSACHUSETTS LOWELL

Signature of Author:

REBECCA SHAW Date: JULY 31, 2006

Signature of Thesis Supervisor:

JAMES A. SHERWOOD, PH.D. MECHANICAL ENGINEERING DEPARTMENT, UMASS LOWELL

Signature of Thesis Committee Members:

PETER AVITABILE, PH.D. MECHANICAL ENGINEERING DEPARTMENT, UMASS LOWELL

ALAN NATHAN, PH.D. PHYSICS DEPARTMENT, UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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Thesis Supervisor: James A. Sherwood, Ph.D.
Professor, Department of Mechanical Engineering

ABSTRACT

This research uses experimental methods to examine five baseball-bat design parameters and their relationship to batted-ball speed. The properties studied were barrel stiffness, moment of inertia, handle stiffness, barrel construction (single wall vs. double wall) and weight. Where possible, these properties were studied for both aluminum and composite bats. All of the bats used in the study were manufactured to isolate a particular property for variation while keeping the other four properties as close to the same as possible. A series of nondestructive tests was performed to quantify the physical properties of each bat before performance testing. Laboratory performance testing was done using an air cannon for projecting the baseball at a stationary bat and followed the 2005 NCAA Certification Test Protocol where possible. Limited field testing was done using batted-ball distance as the performance metric. It was found that for the properties studied, barrel stiffness and MOI contributed most to batted-ball speed. When considering MOI, a swing-speed model must be used to predict field performance.

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1 Introduction

Aluminum bats were introduced into the game of baseball in the 1970s as a cost saving measure. Although the initial cost of aluminum bats was greater than that of wood bats, the enhanced durability and useful life led to an overall reduction in the cost of ownership. This economic advantage made the aluminum bats an attractive option for leagues and town recreation organizations, and their use soon propagated through all levels of amateur baseball, e.g. Little League, high school and college.

The first aluminum bats allegedly performed very similar to wood. However, in the 1990s, companies started to produce aluminum bats that could far outperform wood. The use of high-strength aluminum alloys enabled manufacturers to create bats that were lighter than their wood counterparts and with relatively thin walls. Decreasing the swing weight of the aluminum bats enabled players to generate higher swing speeds and gave players more bat control than was possible with wood bats. Increased swing speeds allow hitters to wait longer before initiating their swing, giving the batter more time to see and adjust to the pitch. Thinning the walls of aluminum bats introduced a trampoline effect which increases the efficiency of the bat/ball collision in comparison to wood. Thinner walls also allowed manufacturers to adjust the weight distribution of the bat without increasing the overall weight.

Recently, composite materials have been introduced into the baseball bat market. Composite materials give manufacturers even more control over the specific properties of their bats than aluminum. Certain properties can be "tweaked" locally on the bat without changing other bat properties.

Major League Baseball allows only solid wood bats. However, leagues from Little League through college allow the use of nonwood bats. In response to concerns that nonwood bats were compromising the integrity of the game, the National Collegiate Athletic Association (NCAA) decided to regulate the performance of bats used in collegiate competition. In an effort to reduce the performance of nonwood bats, the NCAA has set minimum weight and moment of inertia (MOI) requirements for each bat length that force nonwood bats to have swing weights tied to those for wood bats. Additionally, a laboratory performance test was implemented to certify each model of bat used in NCAA competition. To ensure the testing was unbiased, an independent facility, the UMass-Lowell Baseball Research Center, was commissioned to conduct the performance testing.

1.1 Motivation

A fundamental understanding of the relationship of baseball bat properties on performance is important for multiple reasons. Bat manufacturers can use this information to understand how these properties can be incorporated in a design to achieve a desired bat performance and hence, to capture market share. Governing bodies can use this fundamental understanding to know how various properties contribute to batted-ball performance and then use this information to decide what should be regulated and how to regulate it to ensure a range of allowable performances for bats used in their respective testing. The results for each set of isolated-property bats will be compared, and the effect of each property on batted-ball performance will be quantified.

2 Background

In this chapter, some previous research related to this thesis will be presented. Russell (2004) and Nathan (2004) have studied the effect of hoop frequency on performance. Russell observed a correlation between hoop frequency and batted-ball speed in commercially available softball bats. The Ball Exit Speed Ratio (BESR) equation was developed by Carroll (2000). Crisco and Greenwald (1999) and Nathan (2003) have examined the effect of moment of inertia on player swing speed. Nathan (2000) investigated the effect of bending vibrations on performance. For the other properties investigated in the current study: weight, handle flex and barrel construction, there are no published data relating to performance in the open literature.

2.1 Barrel Stiffness and the Trampoline Effect

One of the reasons hollow bats can outperform wood bats is the so-called "trampoline effect". When a baseball impacts a solid wood bat there is essentially no deformation of the barrel and a large amount of deformation in the ball. When the ball deforms, a large amount of energy is lost to internal mechanisms. Up to 75% of the ball's initial energy can be lost in a collision with a wood bat (Russell 2006). In a hollow bat, the barrel of the bat will compress during the bat-ball collision thereby decreasing the amount of deformation in the baseball in comparison to what is observed for the ball impacting a solid wood bat. In the hollow bat, some of the energy can be stored in hoop deformation and returned to the ball, thereby creating the trampoline effect. Therefore, for a high-performing bat, it is desired to minimize ball deformation and maximize the amount of energy stored in the bat, which is subsequently transferred back to the ball.

The efficiency with which energy is transferred back to the ball depends on the hoop frequency of the bat. A model relating hoop frequency to softball-bat performance was developed by Russell (2004), and Figure 1 shows the results of this model. The collision efficiency is defined as the ratio of final to initial ball speed. The collision-efficiency values have been normalized to a rigid bat.

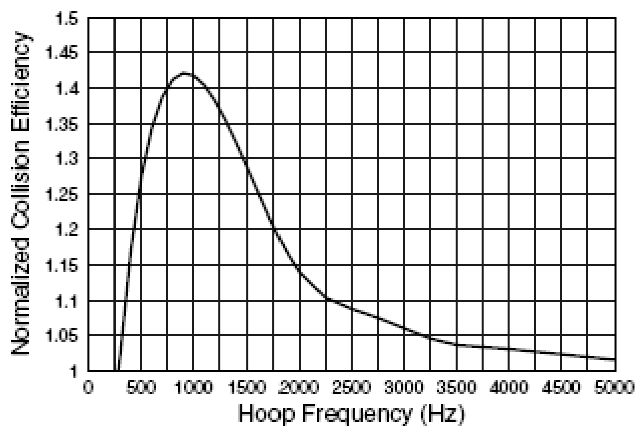

Figure 1 Normalized collision efficiency as a function of hoop frequency (Russell 2004)

The maximum efficiency is shown to be at a hoop frequency of just less than 1000 Hz. Because the bat-ball collision time is approximately 0.001 s, a frequency of 1000 Hz would correspond to the barrel moving in and out in harmony with the ball contacting the bat. It is assumed that the efficiency vs. hoop frequency curve for baseball bats would be similar to that of the softball bats as shown in Figure 1. However, the peak would shift slightly due to a difference in collision time between baseballs and softballs. Russell presented some experimental data showing this trend for a variety of adult slow-pitch softball bats. These data are shown in Figure 2.

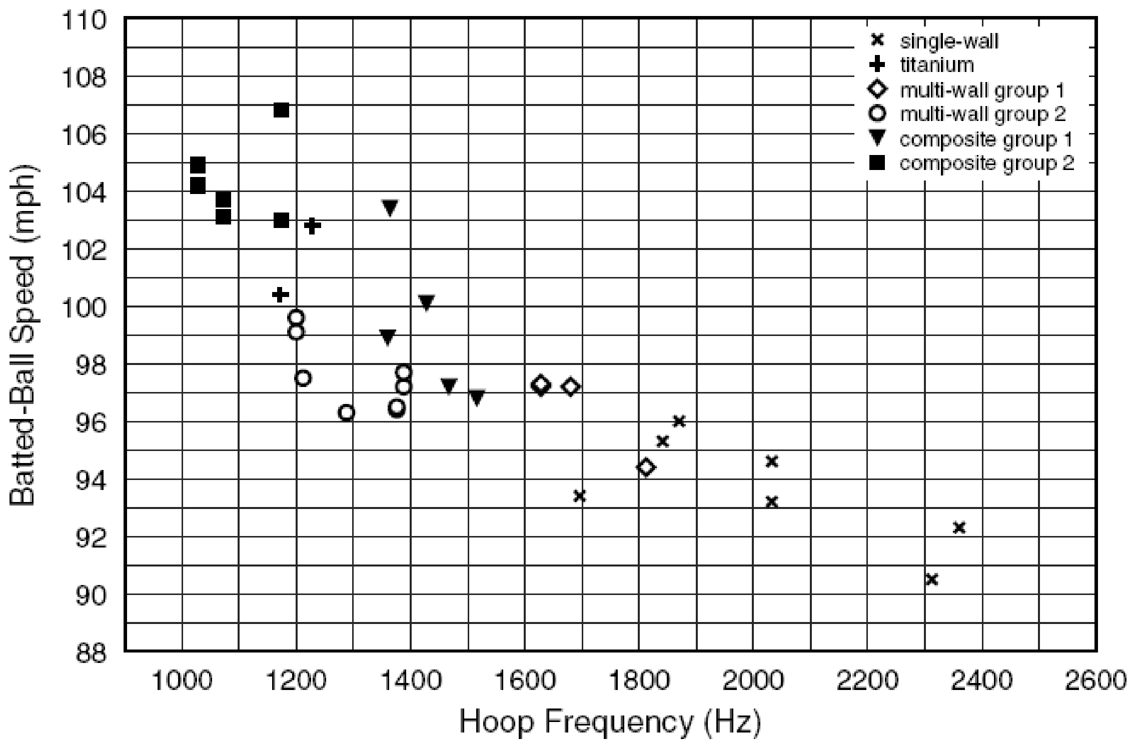

Figure 2 **Measured batted-ball speed versus hoop-mode frequency for a variety of adult slow-pitch softball bats (Russell 2004)**

A mass-spring-damper model was developed by Nathan *et al.* (2004) to describe the trampoline effect. In their model, both the bat and the ball were given mass and stiffness. By adjusting the stiffness of the bat, the exit velocity of the ball can be changed. One of their conclusions was that the bat-ball coefficient of restitution (BBCOR) depends on both mass and stiffness of the bat. Therefore, hoop frequency is not the sole predictor of the trampoline effect of a bat.

2.2 BESR

One metric used to measure baseball bat performance is the ball exit speed ratio (BESR) (Carroll 2000). There are two interpretations for the BESR, one is the physics-based "true" BESR, and the other is adjusted to account for variations in bat speed along the length of the bat. The second version is used by the NCAA for certification purposes and is summarized in Appendix A. The "true" BESR is given by,

$$BESR = \frac{V_R}{V_I} + 0.5 \tag{1}$$

where V_I is the ball inbound speed and V_R is the ball rebound speed for a test with a moving ball and stationary bat. The ball impact speed V_I, or $V_{Contact}$ is adjusted to account for bat-speed variation along the length of the bat:

$$V_{\text{Contact}} = (66\text{ mph})\left(\frac{L-6-z}{L-12}\right) + 70\text{ mph} \tag{2}$$

where 66 mph represents the speed of the swung bat (as measured 6 in. from the end of the barrel), 70 mph represents the speed of the incoming pitch, L is the length of the bat (in inches) and z is the impact location measured in inches from the end of the barrel. The *BESR* equation can also be written as,

$$BESR = \frac{1+2e-\mu^*}{2(1+\mu^*)} \tag{3}$$

where e is the bat-ball coefficient of restitution (BBCOR) and,

$$\mu^* = \frac{m_b x^2}{I} \tag{4}$$

where I is the mass moment of inertia measured about the axis of rotation, m_b is the mass of the ball and x is the distance from the axis of rotation to the impact location. If the *BESR* is measured, then e can be calculated:

$$e = \frac{2BESR(1+\mu^*) - 1 + \mu^*}{2} \tag{5}$$

and substituting in for μ^*,

$$e = \frac{2BESR\left(1+\left(\frac{m_b x^2}{I}\right)\right) - 1 + \left(\frac{m_b x^2}{I}\right)}{2} \tag{6}$$

For the analyses in this thesis, the physics interpretation of the *BESR* will be used, and performance values will be expressed in terms of batted-ball speed (BBS),

$$BBS = v(BESR - 0.5) + V(BESR + 0.5) \tag{7}$$

where v is the ball pitch speed (in mph) and V is the bat swing speed (in mph). For all lab BBS calculations, a 70-mph pitch speed is used, and the swing speed is adjusted for impact location such that the speed at the 6-in. location is 66 mph,

$$V = 66\left[\frac{(L-6-z)}{(L-12)}\right] \tag{8}$$

The BESR equation can be broken down into two components: inertial effects (μ*) and BBCOR. The moment of inertia of the bat, the mass of the ball and the distance from the impact location to the axis of rotation determine the value of μ*. Each of these components can be measured prior to testing, and their effect on BESR can be calculated. The BBCOR is a more complex term and can only be measured directly if the speed of the bat immediately after impact is measured. Alternatively, the BBCOR can be obtained experimentally by measuring BESR (using only the ball inbound and rebound speeds) and the components that make up μ*. The BBCOR can then be backcalculated from the experimental data. One of the goals of this thesis is to determine how each specific bat property affects the value of BBCOR, so this ability to backcalculate the BBCOR from the experimental data is critical to this thesis.

2.3 Moment of Inertia

The effect of moment of inertia on BESR can be found directly from Equations 3 and 4 if the BBCOR, ball mass and axis-to-impact distance remain constant. The effect of MOI on BBS is a little complicated because pitch and swing speeds enter into the equation. For the testing in the lab, a pitch speed of 70 mph and a swing speed of 66 mph at the 6-in. location were always assumed to be constant. In the field, the MOI of a bat will affect how fast the player is able to swing the bat. Thus, assuming the same swing speed for bats of varying MOI will not reflect accurate field-performance observations. According to Equations 3 and 4, increasing MOI will increase the BESR. However, increasing MOI will also decrease swing speed in the field, which will result in a lower BBS for a given BESR. Therefore, increasing MOI causes an increase in BESR for the bat but a decrease in swing speed for the player.

Several models for the dependence of swing speed on MOI have been developed (Nathan 2003, Bahill 2004, Fleisig 2002, Adair 2002), but relatively little experimental data have been collected. A batting cage study was done by Crisco et. al. (1999) using high school, college and professional players. Video analysis was used to determine player swing speed. Their data were subsequently analyzed by Nathan (2003), and a relationship between MOI and swing speed was determined,

$$\omega \propto {I_{knob}}^{-n} \tag{9}$$

where $n = 0.3$ for the range of MOIs of interest, ω is the angular swing speed and I_{knob} is measured about a point one inch from the end of the knob (one inch up the handle towards the barrel).

Bahill (2004) developed a system to measure swing speed over a range of moments of inertia. His Bat Chooser^{TM} uses two vertical laser beams to measure bat swing speed at the estimated point of maximum bat speed (the point where the batter's front foot hits the ground). In his study, Bahill used 20 "serious" male baseball and softball players and the University of Arizona women's softball team over the course of a 12-year period beginning prior to 1994. He had each player swing five times each with four bats of different moments of inertia. The average swing speed for each bat was recorded. Using a batted-ball speed equation similar to that presented in Sec. 2.2, Bahill calculated batted-ball speed as a function of swing speed. He found that over the range of bat MOIs studied, all players would benefit from using an end-loaded bat. However, the moments of inertia studied by Bahill were all in the normal aluminum bat range (before the NCAA implemented an MOI limit) which is lower than the range studied here.

In 2000, the NCAA established a minimum MOI requirement for each length bat. The purpose of this requirement was to ensure that the weight distributions of aluminum and composite bats were tied to those of wood bats. However, the respective limit is still lower than the MOI of a -3 wood bat of the same length. Figure 3 is a plot of MOI vs. length. The solid line denotes the NCAA minimum allowable MOI values. The symbols are a sample of -3 wood bats. It can be clearly seen in this graph that the NCAA minimum allowable MOI is lower than that of comparable-length wood.

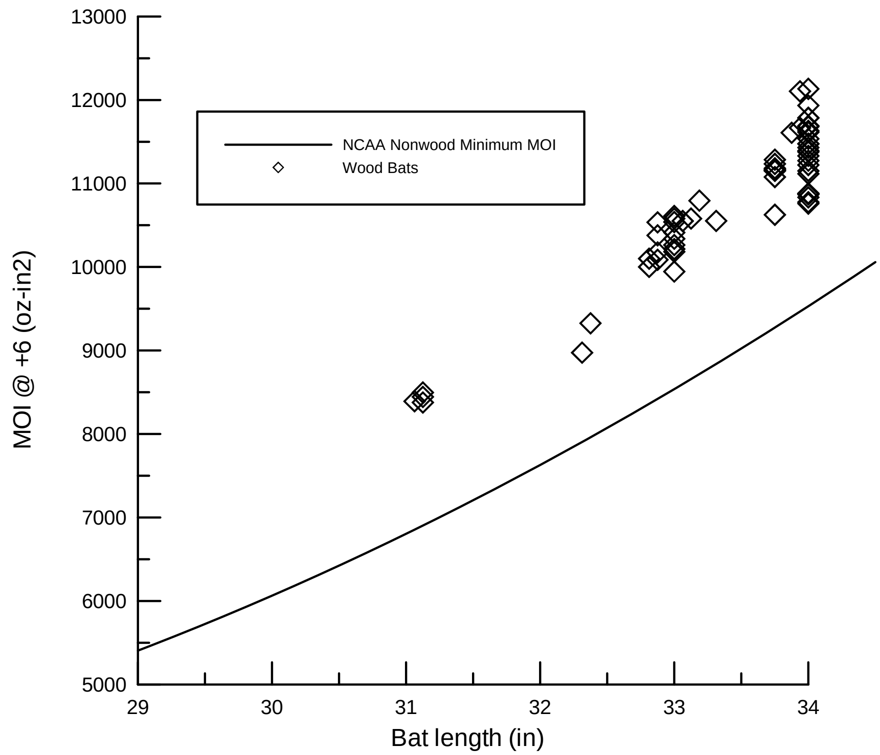

Figure 3 MOI vs. length for a selection of -3 wood bats

2.4 Handle Stiffness

Nathan (2000) developed a mathematical model that incorporates bending vibrations to predict batted-ball speed. Energy that goes into low-order bending vibrations is energy that cannot be transferred back to the ball. It is expected that handle stiffness will affect batted-ball performance to the extent that bending vibrations affect batted-ball performance. Lower handle stiffness will result in lower natural frequencies of the bending modes which will result in more collision energy transferred to bending vibrations and therefore lower potential batted-ball speed.

In Nathan's model, the natural frequencies of the bending modes of the bat are incorporated into the calculation of the "effective mass" of the bat, or the amount of mass that is "seen" by the ball during the collision. As bat flexibility increases, the "effective mass" in the collision decreases—resulting in lower batted-ball speeds. The amount of energy lost to bending vibrations depends on the location of the impact. For impacts close to the nodes of the first two bending modes (the nodes are usually within two inches of each other in the sweet-spot region of the bat), there will be very little vibration, so the effect of the bat flexibility will be small. For impacts away from the nodes of the first two bending modes, the flexibility of the bat has a large effect on batted-ball speed.

2.5 Barrel Construction

Some of the highest performing softball and baseball bats are double-wall bats. Double-wall bats tend to have lower hoop frequencies than single-wall bats, as can be seen in Figure 2. The double wall allows for a thinner outer wall without losing the strength exhibited in a single-wall bat. The bats used in this study were manufactured to have similar barrel stiffnesses and hoop frequencies, so the double-wall bat may or may not have a performance advantage relative to the single-wall bats.

2.6 Weight

One of the first rules established by the NCAA to limit aluminum-bat performance was a weight restriction. The NCAA realized that players are able to generate higher bat speeds with lightweight aluminum bats than they can with wood bats. In response, the NCAA established the "-5 rule" and then the "-3 rule". The "-5 rule" stated that the weight of the bat (in ounces, with the grip) minus the length of the bat (in inches) must be no less than -5. Similarly, the "-3 rule" stated that the weight of the bat (in ounces, without the grip) minus the length of the bat (in inches) must be no less that -3. The intent of these rules was to keep aluminum bats from getting much lighter than wood bats. The "-3 rule" came out of the 1998 bat summit (Hagwell 1999) where it was decided to also establish a limit on batted-ball speed once more data were collected.

The effective bat mass in the bat-ball collision is an important factor in determining bat performance. Bats with relatively higher effective mass will typically be relatively higher performing. However, effective mass is not simply related to the overall weight of the bat. Effective mass will depend on several factors including overall weight, weight distribution and flexibility.

3 Methods

To quantify the bat properties examined in this thesis, several measurements were made on each bat before performance testing. The bat preparation, MOI measurement, and performance testing follow procedures developed for NCAA certification testing. In addition, measurements were made to quantify the handle stiffness and barrel stiffness of each bat. Each of these test methods is described in this chapter.

3.1 Model Numbers

Each bat was labeled with a model number using the following format:

P-M-T

Where, P identifies which property the set of bats isolates:

- 1 = barrel stiffness
- 2 = MOI
- 3 = handle stiffness
- 5 = barrel construction
- 6 = weight

M identifies the material:

- M = Composite
- W = Aluminum

and T identifies the particular bat type:

H = High for stiffness bats; or Handle loaded for MOI and weight bats
M = Medium
L = Low
E = End-loaded
B = Balanced
S = Single-wall
D = Double wall

For example, a composite low-handle-stiffness bat would have model number 3-M-L.

3.2 Conditioning

All baseballs and bats were stored in an environmentally controlled lab at the University of Massachusetts Lowell Baseball Research Center. The lab conditions were maintained at 70±2°F and 50±5% relative humidity. Baseballs were held in lab conditions for at least two weeks before testing, and bats were held in lab conditions for at least 24 hours before testing.

3.3 Bat Preparation

Before any testing was done with the bats, several measurements were taken. These measurements included: length, weight, center of gravity (CG) and diameter measurements at eight positions along the length of the bat. Length was measured to the nearest 1/16 in. using a yardstick with 1/16-in. divisions. Weight was measured to the nearest 0.005 oz using a digital scale. Rings were drawn on the bat at 3, 4, 5, 6, 7, 8 and 9 in. from the end of the barrel and at 6 in. from the end of the knob. Dial calipers were used to measure the diameter to the nearest 0.001 in. at each of the marked locations. The CG was found by balancing the bat on a knife-edge and was recorded as the distance from the barrel end of the bat. A 0^o location was chosen arbitrarily and marked with a line down the length of the barrel. Axial lines were also drawn at 120^o and 240^o around the barrel measured from the 0^o line. The 0^o, 120^o and 240^o reference lines were used in the barrel compression tests and modal tests to ensure that the barrel was tested at three equally spaced locations around the barrel.

3.4 Moment of Inertia

Moment of inertia was measured following ASTM standard F2398, Standard Test Method for Measuring Moment of Inertia and Center of Percussion of a Baseball or Softball Bat (ASTM 2004). The MOI fixture is shown in Figure 4.

Figure 4 MOI fixture

3.5 Barrel Stiffness

Barrel stiffness was measured two ways:

- barrel compression test
- hoop frequency test

The barrel compression test squeezes the barrel between two 1-in. diameter cylindrical loading noses. A picture of the barrel compression setup is shown in Figure 5. The handle of the bat was supported to ensure that the bat remained perpendicular to the load. A Miken protocol was followed (see Appendix B). An Instron 8511 with a 5000-lb load cell was used.

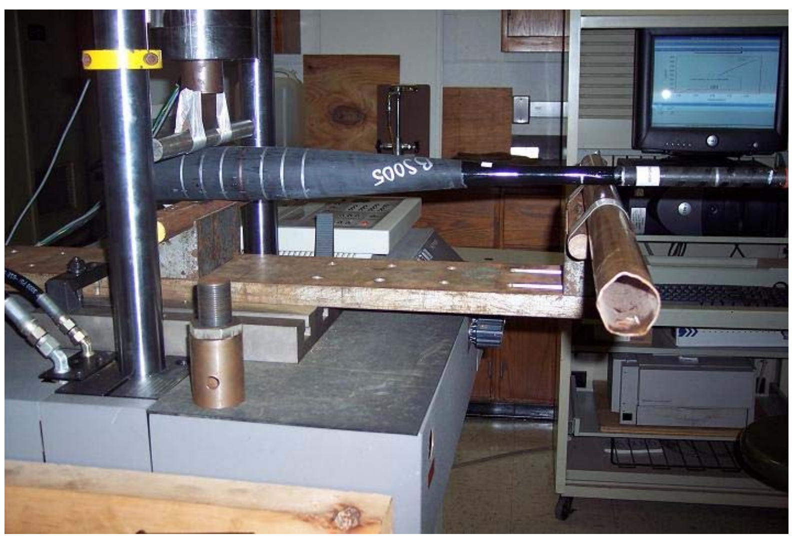

Figure 5 Barrel compression test setup

The barrel was compressed 0.07 in. using a load rate of 1 in./min. The first 0.02 in. of deflection tended to be nonlinear and was subtracted from the data. The load-deflection data from 0.02 to 0.07 in. was fit with a linear trend line in Excel, and the slope of the line was used to calculate the amount of force needed to deflect the barrel 0.05 in. A sample calculation is shown in Figure 6. Bats were compressed at the 4-, 5- and 6-in. locations along the barrel (measured from the tip of the barrel) at three equally spaced positions around the barrel as denoted in Sec. 3.3. The three values at each axial location were averaged to give a value for deflection at the 4-, 5- and 6-in. locations.

For some of the high-barrel-stiffness composite bats, the load-deflection curves appeared to be nonlinear after a deflection of about 0.04 in. For these bats, the tests were stopped at 0.04 in. to prevent any damage to the bat. The data from 0.02 to 0.04 in. were fit with a trend line in Excel, and the slope was used to calculate the amount of force that would be needed to deflect the bat 0.05 in. if the load-deflection relationship remained linear. A sample calculation is shown in Figure 7 for a test terminated at a low displacement.

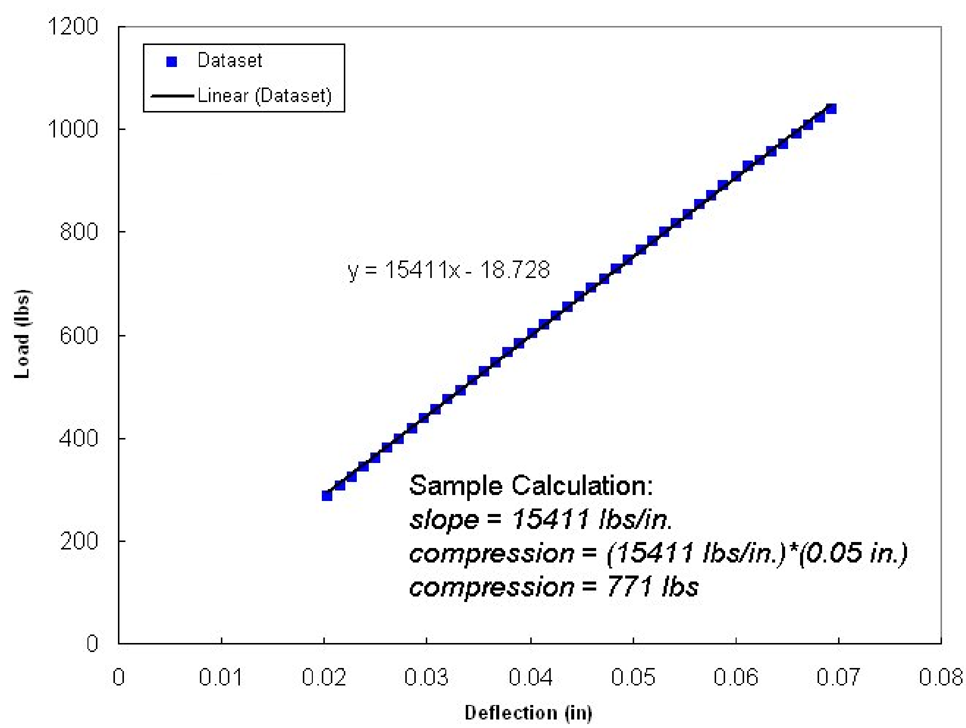

Figure 6 Sample barrel-compression calculation for a complete compression test

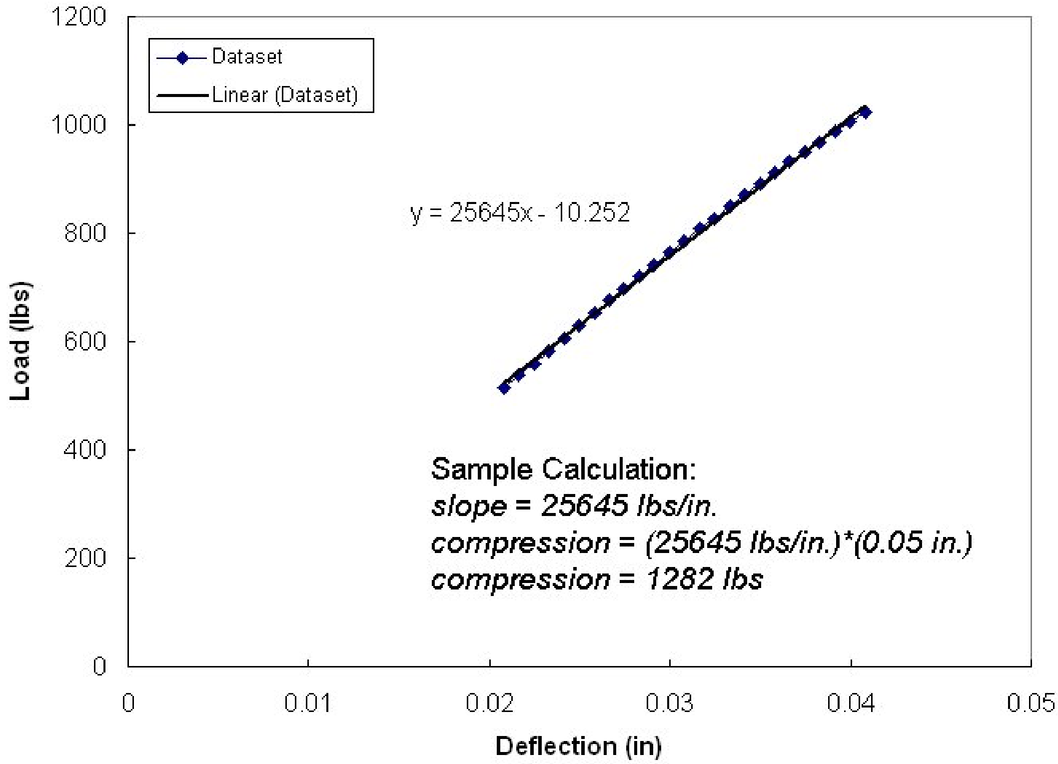

Figure 7 Sample barrel-compression calculation for a shortened compression test

3.6 Modal Analysis

Modal analysis was used to measure the natural frequencies of the first two bending modes and the first hoop mode of each bat. Two accelerometers (Model PCB 303A) were used with a Zonic Medallion Mobile FFT Analyzer and Bobcat DAQ Version 5.21 software. Data analysis was performed using ME'Scope (Vibrant Technology 2005). Each bat was freely hung to simulate a free-free boundary condition. The two accelerometers were placed on the barrel of the bat, one at the 4-in. location at 240^o and one at the 6-in. location at 0^o. The bat was impacted at 19 locations, 15 around the barrel of the bat (at the 3-in., 4-in, 5-in, 6-in and 7-in. locations at 0^o, 120^o and 240^o) and four locations along the taper and handle of the bat (all at 0^o). It was necessary to have accelerometers placed around the barrel to measure the hoop-mode frequency. The four accelerometers placed along the taper and handle were sufficient to identify the bending modes. Five impacts were averaged at each location. A simple structure was built in ME'Scope to represent the bat. The curve-fitting tools in ME'Scope were used to identify the natural frequencies and mode shapes. The animation tool was used to identify which modes were bending modes and which were hoop modes. A sample Frequency Response Function (Log Magnitude vs. Frequency) from ME'Scope is shown in Figure 8. Each peak represents a natural frequency of the bat. The simple structure built in ME'Scope is shown in Figure 9. Each point on the structure represents one of the 19 impact locations on the bat.

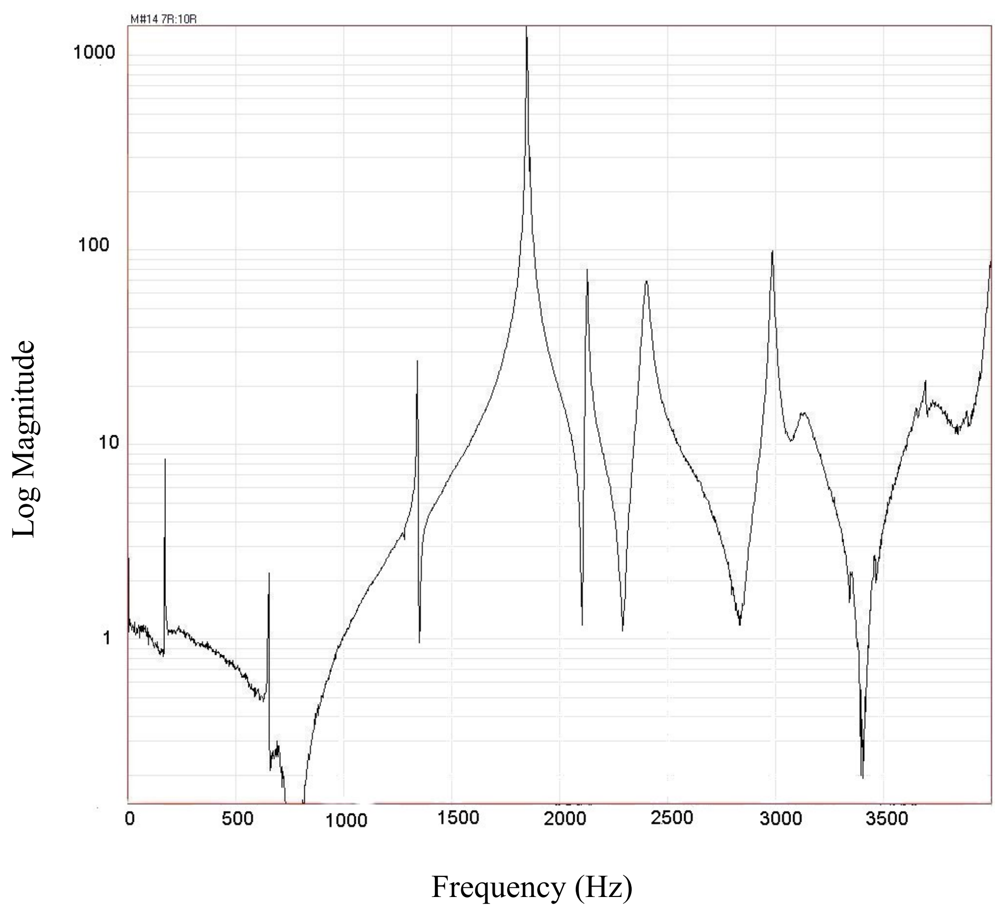

Figure 8 Sample FRF displayed in ME'Scope

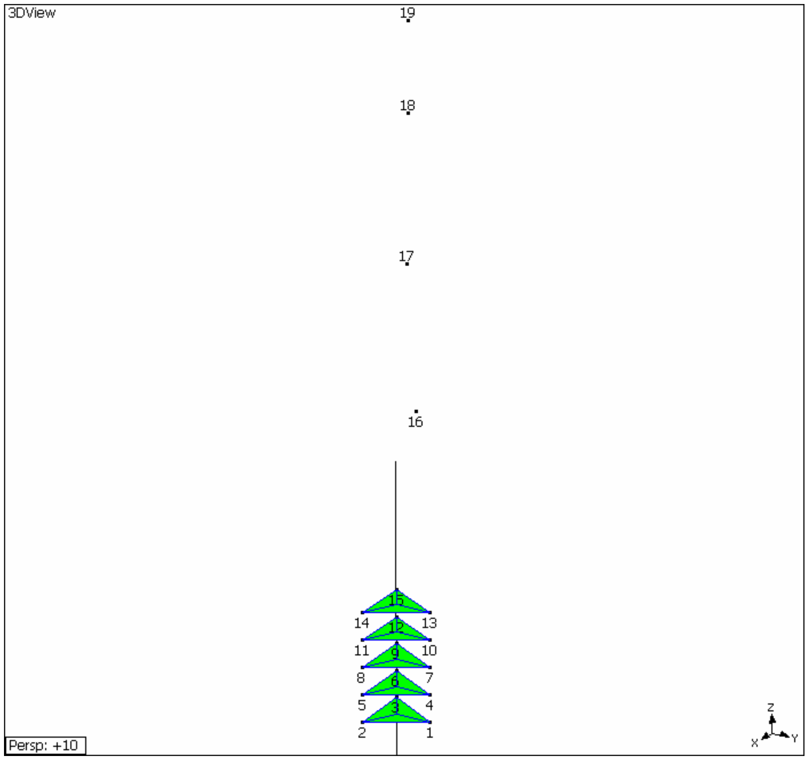

Figure 9 Structure built in ME'Scope

To find the nodes of the first bending mode, an accelerometer was placed at the tip of the bat. The bat was impacted along the length until there was no response at the natural frequency of the first bending mode (~180 Hz). The nodes of a baseball bat tend to be about 6 in. in from each end of the bat.

3.7 Handle Stiffness

Handle Stiffness was characterized two ways:

- three-point bend tests
- modal tests

The three-point bend tests were done following the protocol provided by Miken (see Appendix C) and using an Instron 8511 with a 5000-lb load cell. The bat was supported just inside the knob and at a point on the barrel 26.5 in. from the first support. The bat was loaded 12 in. from the end of the knob of the bat with a 1-in. diameter cylindrical loading nose. A preload of 5 lbs was applied, and the bat was flexed to a deflection of 0.25 in. using a load rate of 1 in./min. Figure 10 shows a bat loaded in the three-point bend fixture. Stiffness was measured as the load needed to flex the bat to 0.25 in.

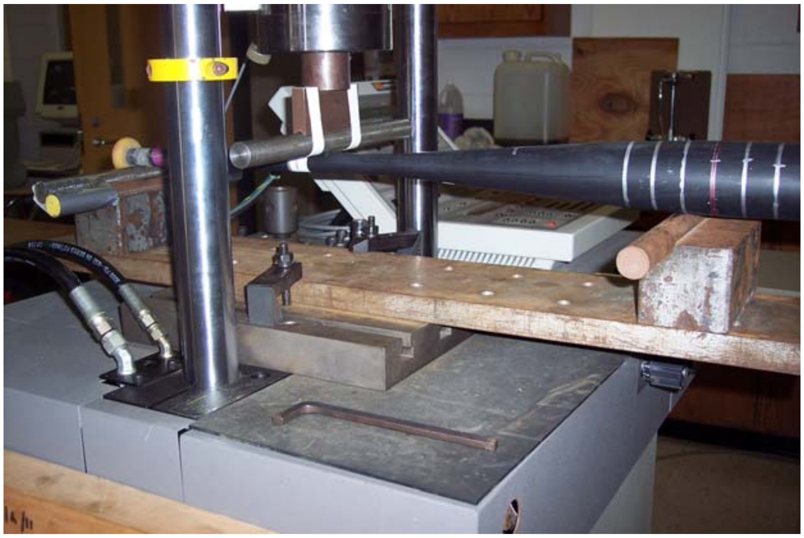

Figure 10 Three-point bend fixture

The natural frequencies of the first two bending modes were measured using modal analysis. The modal analysis procedure was described in Sec. 3.6. The nodes of the first bending mode were also found. This process was also described in Sec. 3.6.

3.8 Performance Testing

Performance testing was done per the 2005 NCAA Certification Protocol (NCAA 2005). The air cannon for this test is capable of firing a baseball at speeds up to 150 mph at a stationary bat. The bat is clamped 6 in. from the knob end in a fixture that is free to rotate after impact. A schematic and a photo of the setup are shown Figure 11 and Figure

12, respectively. The ball inbound and rebound speeds are measured using three sets of light gates, as shown in Figure 13. The bat grip fixture is shown in Figure 14.

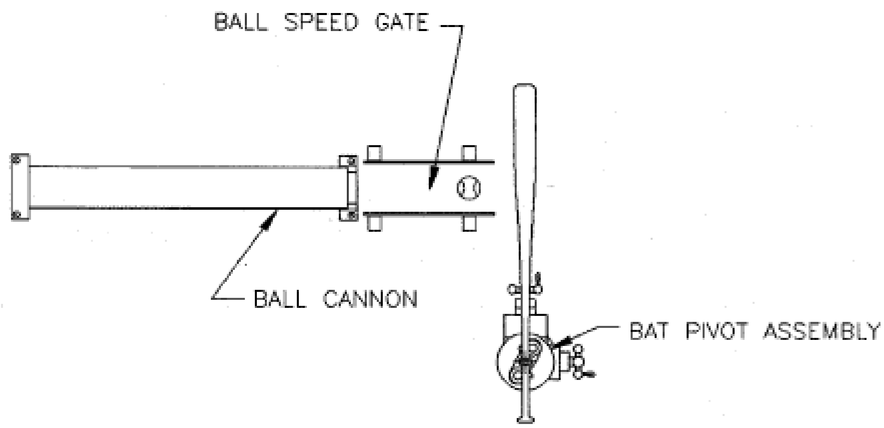

Figure 11 Performance test setup [ASTM 2219]

Figure 12 Air cannon test setup

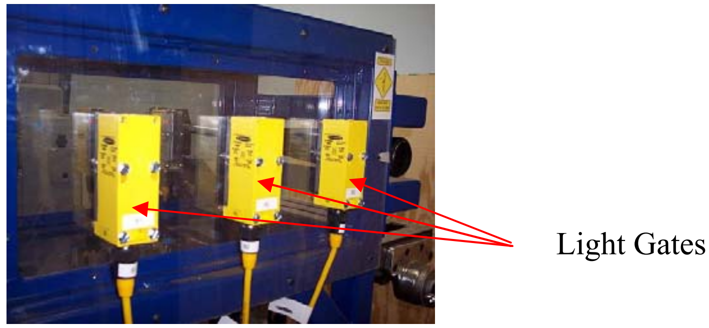

Figure 13 Light gates on air canon

Figure 14 Grip fixture on air cannon

In this thesis, performance results will be reported in terms of BBS, as discussed in Sec. 2.2. The NCAA protocol calls for testing to begin at the 6-in. location, then move to the 5-in., then the 7-in., and then isolate the sweet spot using ½-in. increments from there with six impacts at each location. Because some of the composite bats used in this study were prone to cracking, it was desired to minimize the total number of hits on each composite bat. Therefore, for this research, testing always began at the 6-in., then moved to the 5-in. If the 5-in. position had a higher BBS than the 6-in. position, testing moved to the 5.5-in. location to isolate the sweet spot with a minimum number of impacts. For most of the bats, three hits were taken at each location to identify the sweet spot, and then three additional hits were taken at the sweet spot and the locations ½-in. to either side of the sweet spot. Depending on the performance results and the condition of the bat, additional hits were taken at other locations as well.

Impact speeds were varied according to Equation 2 with an inbound speed tolerance of ±2 mph. A high-speed video camera capturing at the rate of 250 frames per second was used to capture the impact. The high-speed video was used to ensure that the ball was rebounding straight through the speed sensors (i.e., within a $\pm 5^{o}$ cone). Performance testing was stopped once the sweet spot was isolated with six impacts at the sweet spot and the two positions ½-in. on either side of the sweet spot, or when the performance of the bat changed due to a visible crack. Only the bats that successfully had six valid impacts at the sweet spot and the locations ½-in. on either side of the sweet spot were included in the data analysis for the study.

3.9 Baseballs

All baseballs used in this study were Rawlings R1NCAA baseballs. Only balls that weighed 5.129±0.053 oz (145.4±1.5 g) were used. Before each hit, the ball was marked with its weight and moisture content. The moisture content was measured using a Delmhorst moisture meter with 5/16-in. long probes. Each lot of balls was tested with the same wood bat so that balls lots could be compared. A Rawlings model 456B ash bat (33.875 in., 31.48 oz, 11,529 oz-in^2 as measured with respect to an axis +6 in. in front of the knob) was used for comparison of ball lots. Each ball lot consisted of approximately 100 baseballs. The sweet spot of the ash bat was found to be at the 5.5-in. location. Once the sweet spot was isolated, 20 valid hits were taken at the 5.5-in. location for each ball lot, and the BBS values for each ball lot were compared.

4 Results and Discussion

In this chapter, the results from all the preliminary tests and the performance tests are presented. The data are organized by the property that is investigated.

4.1 Ball Lot Comparisons

Three ball lots were used for the performance testing in this study. The lots were labeled RBS1, RBS2 and RBS3. A set of 20 baseballs from each lot was performance tested with a Rawlings model 456B ash bat. The results are presented in Table 1.

Table 1 Ball lot comparison data

Ball Lot	Avg. BESR	Avg. BBS (mph)	Standard Deviation of the Mean (mph)
RBS1	0.714	96.9	0.2
RBS2	0.713	96.8	0.2
RBS3	0.715	97.0	0.2

The BBS values for the three ball lots were essentially equal, so no correction factors were needed when comparing bats that were tested with different ball lots. For the majority of the bats tested in this study, each bat of the same set was tested with the same ball lot.

4.2 Barrel Stiffness

The first set of bats tested had different barrel stiffnesses. Both composite and aluminum bats were tested. The composite and aluminum bat results will be presented separately.

4.2.1 Composite

The composite bats consist of carbon fiber and epoxy resin. The barrel stiffness was varied by changing the angle and density of the carbon fibers with respect to the hoop direction of the barrel.

4.2.1.1 Preliminary Results for Composite Barrel-Stiffness Bats

Barrel stiffness was measured with a barrel compression test and with a hoop frequency test. The results of these two tests for the composite bats are presented in Table 2. Recall the barrel compression is the force required to squeeze the barrel 0.05 in.

Table 2 Barrel stiffness measurements for composite bats

Bat ID	Model	Barrel Compression at Axial Location (lbs)			Hoop Freq (Hz)
		4 in.	5 in.	6 in.	
BS002	1-M-H	1220	1239	1346	3950
BS038	1-M-H	1286	1297	1392	4070
BS006	1-M-M	831	873	981	2670
BS036	1-M-L	739	775	862	2430

The barrel stiffness measurements in Table 2 show three levels of stiffness: high (1-M-H), medium (1-M-M), and low (1-M-L). Unfortunately the stiffness levels were not evenly distributed over the 500-lb stiffness range. There was only a small difference in stiffness between the low- and medium-stiffness bats (~100 lbs) and a large difference between the medium- and high-stiffness bats (~400 lbs). For these bats, the masses and mass distributions should be the same so as to isolate this portion of the study to exploring how variations in barrel stiffness affect batted-ball speeds with all other design parameters being equal. Consequently, the hoop frequencies should correspond directly to changes in barrel compression values – which they do here. Based on the respective works done by Russell and Nathan, it is expected that batted-ball speed will increase as barrel stiffness decreases due to increased trampoline effects. For these particular bats, the low- and medium-stiffness bats should have a small difference in performance, and the high-stiffness bats should be much lower performing than the low- and medium-stiffness bats.

The results of the weight, MOI and handle-flex measurements are shown in Table 3. All bats are 33.875 in. in length. Table 3 shows the measured values for all the properties that are intended to be equal. The only properties with significant differences between bats are the moments of inertia and the weights. The moments of inertia for the medium- and low-stiffness bats are very close, but the high-stiffness-bats' MOI values are about 700 to 900 oz-in^2 higher than the other two bats. It is expected that this difference in MOI will cause an increase in the batted-ball speed of the high-stiffness bats in comparison to the other two bats. The differences in batted-ball speeds between high- and medium-stiffness bats will be smaller than if their MOI values were equal.

Table 3 Weight, MOI and handle-flex measurements for the composite barrel-stiffness bats

Bat ID	Model	Wt. (oz.)	CG (in.)	MOI (oz-in^2)	Handle Flex (lbs)	1st Bend Freq (Hz)	2nd Bend Freq (Hz)	Handle Node (in.)	Barrel Node (in.)
BS002	1-M-H	32.80	14.438	10,923	238	176	647	5.5	5.9
BS038	1-M-H	30.56	12.375	10,772	222	177	653	5.7	6.2
BS006	1-M-M	31.21	13.875	10,007	261	189	698	5.3	6.2
BS036	1-M-L	31.37	13.750	10,167	230	183	680	5.1	6.3

4.2.1.2 Performance Results for Composite Barrel-Stiffness Bats

The performance test results are shown in Table 4 along with the significant bat properties that relate to these test results. The performance results do not necessarily show the expected trend: as barrel stiffness decreases the hoop frequency decreases (recall frequency is proportional to stiffness/mass) and consequently BBS increases. The performances of the high-stiffness bats were almost equal to the performance of the medium- and low-stiffness bats. The BBS results shown here were calculated using Eq. 7 with a 70-mph pitch speed and a 66-mph swing speed at the 6-in. location.

Table 4 Performance test results and properties for composite barrel-stiffness bats

Bat ID	Model	Barrel Compression at Axial Location (lbs)			Hoop Freq (Hz)	MOI (oz-in^2)	Sweet Spot Loc. (in.)	BBS (mph)
		4 in.	5 in.	6 in.				
BS002	1-M-H	1220	1239	1346	3950	10,923	4.5~5.0	96.3
BS038	1-M-H	1286	1297	1392	4070	10,772	5.0	95.6
BS006	1-M-M	831	873	981	2670	10,007	4.0	96.4
BS036	1-M-L	739	775	862	2430	10,167	4.5~5.0	96.6

Using Equations 3 through 5, the BESR can be adjusted for differences in MOI. Using the BESR, the value for BBCOR can be calculated. Using this value for BBCOR, new BESR and BBS values can be calculated for each bat assuming a moment of inertia of 10,000 oz-in^2. The results of this analysis are presented in Table 5 and Figure 15. Additionally, BBCOR is plotted against hoop frequency in Figure 16. BBCOR represents the component of performance independent from MOI. Therefore, the effect of barrel stiffness on performance can be examined for bats with different moments of inertia.

Table 5 Performance test results for composite barrel-stiffness bats adjusted for differences in MOI

Bat ID	Model	MOI (oz-in^2)	Sweet Spot (in.)	Hoop Freq (Hz)	BBCOR	BBS (mph)
BS002	1-M-H	10,000	4.5~5.0	3950	0.490	93.1
BS038	1-M-H	10,000	5.0	4070	0.488	93.1
BS006	1-M-M	10,000	4.0	2670	0.513	96.4
BS036	1-M-L	10,000	4.5~5.0	2430	0.512	96.0

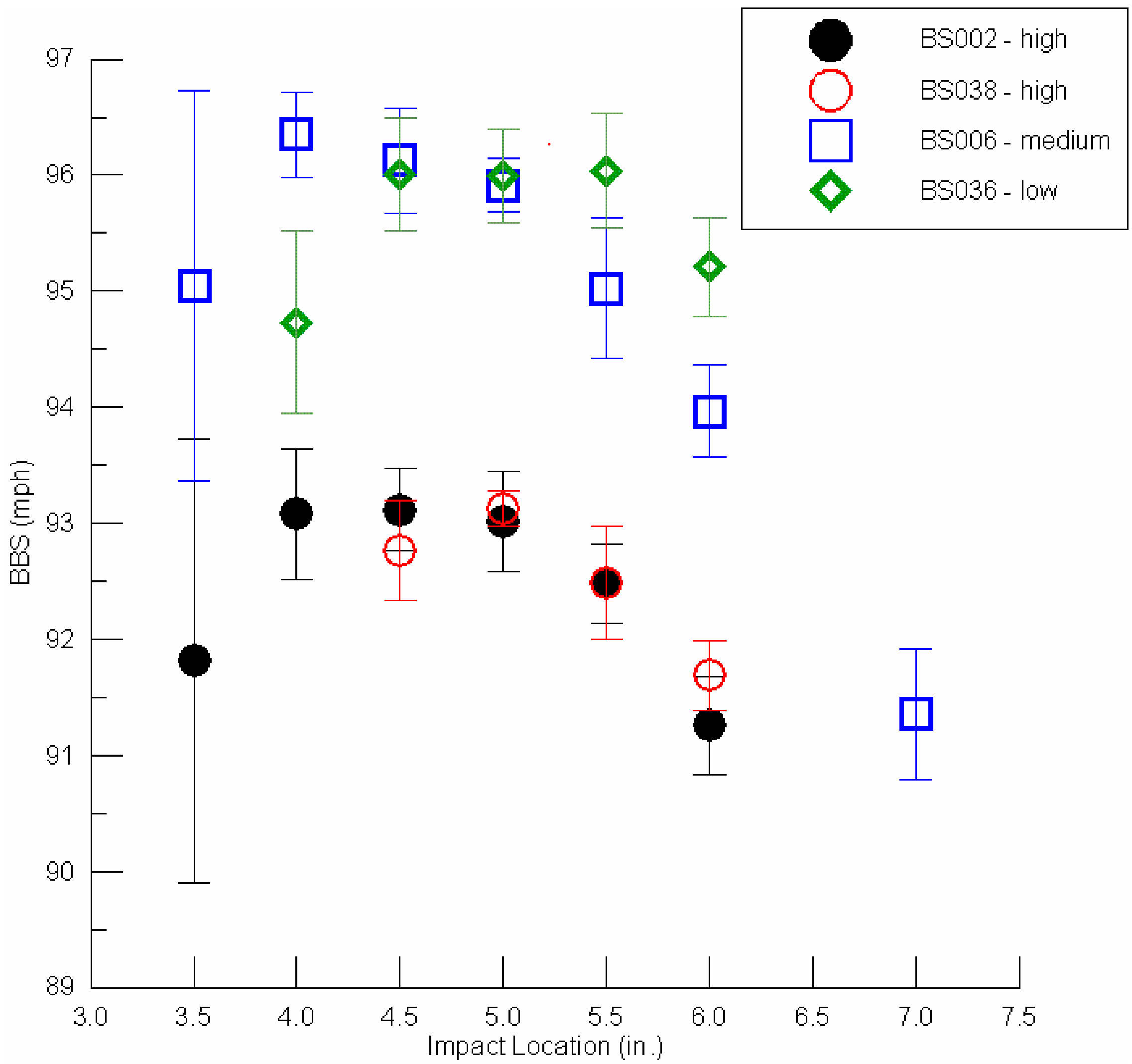

Figure 15 BBS for composite barrel-stiffness bats adjusted for differences in MOI

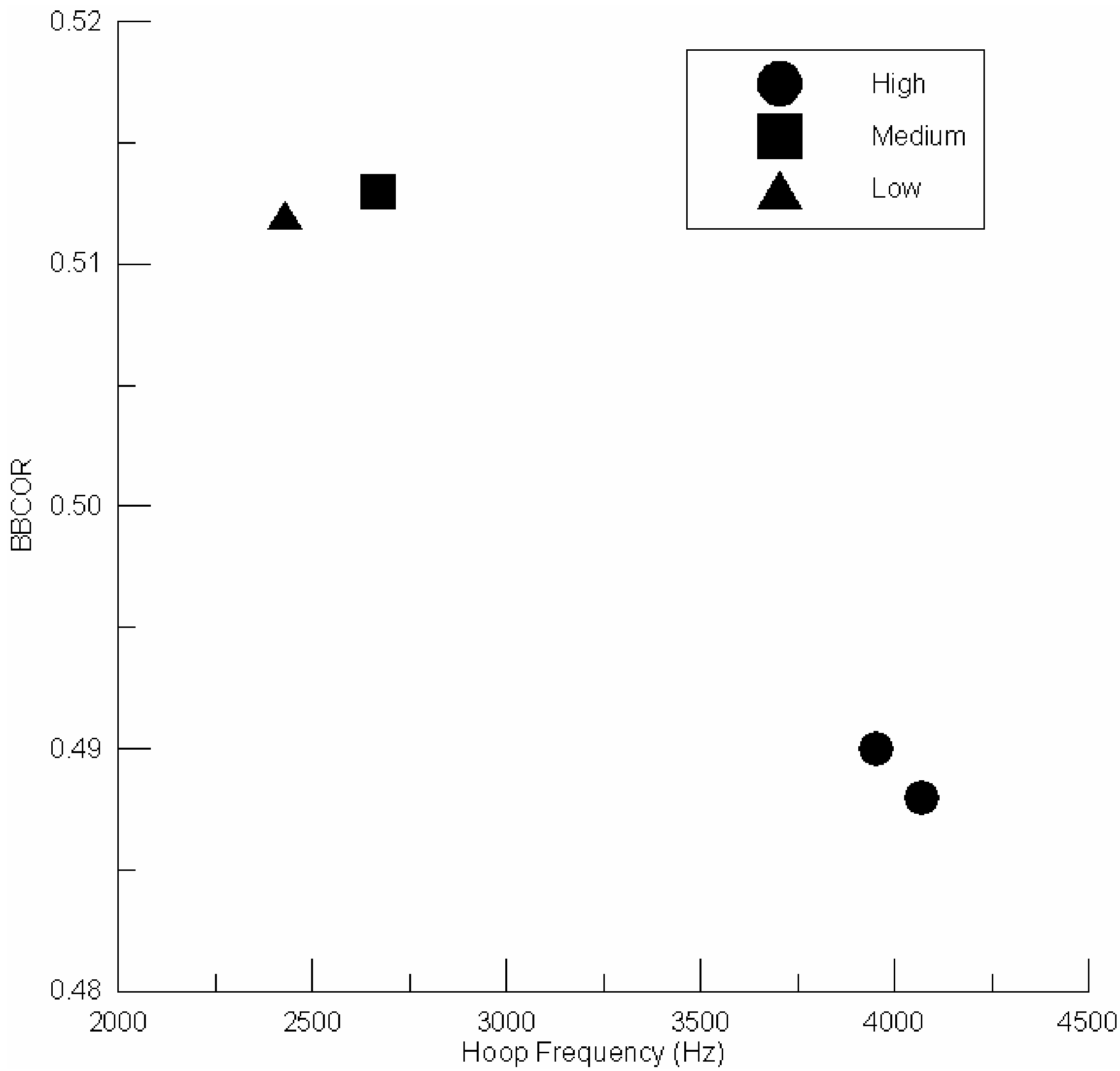

Figure 16 Sweet-spot BBCOR (*e*) vs. hoop frequency for composite barrel-stiffness bats

Figure 16 shows that there is a large difference in BBCOR for the medium- and high-stiffness bats and essentially no difference in BBCOR for the low- and medium-stiffness bats. This result corresponds with the barrel stiffness measurements. Figure 15 shows that the performance of the low-stiffness bat and the medium-stiffness bat were very close for most impact locations, and the high-stiffness bats had lower BBS values. The error bars in Figure 15 represent one standard deviation of the mean. These results agree with Russell's model (2004) which says performance increases as hoop frequency decreases. To detect a performance change using the air-canon test, the difference in barrel stiffness must be greater than the difference (~100 lbs) between the low- and medium-stiffness bats investigated in the current study.

4.2.2 Aluminum

The bats in this section were all made of C555 aluminum alloy. The wall thickness in the barrel of the bat was varied to achieve the different barrel stiffnesses.

4.2.2.1 Preliminary Results for Aluminum Barrel-Stiffness Bats

The barrel-stiffness measurements for the aluminum bats are presented in Table 6. The bats fell into three stiffness classes, low (1-W-L), medium (1-W-M) and high (1-W-H). The variation in stiffness between the classes is small compared to the composite bats. There is only a 200-lb and 200 Hz difference between low- and high-stiffness bats.

Table 6 Barrel stiffness and hoop frequency measurements for aluminum barrel-stiffness bats

Bat ID	Model	Barrel Compression at Axial Location (lbs)			Hoop Freq (Hz)
		4 in.	5 in.	6 in.	
BS045	1-W-H	954	940	941	2000
BS048	1-W-H	962	948	950	2000
BS046	1-W-M	815	796	799	1870
BS049	1-W-M	807	792	792	1860
BS047	1-W-L	744	727	729	1800

The weight, MOI and handle-stiffness measurements are shown in Table 7. There is some variation in MOI among the bats. Because there is only a small difference in barrel stiffness, the differences in MOI may dominate the performance differences as was observed for the composite bats. The handle stiffness measurements were very close for all five bats.

Table 7 Weight, MOI and handle stiffness measurements for aluminum barrel-stiffness bats

Bat ID	Model	Weight (oz)	CG (in.)	MOI (oz-in^2)	Handle Flex (lbs)	1st Bend Freq (Hz)	2nd Bend Freq (Hz)	Handle Node (in.)	Barrel Node (in.)
BS045	1-W-H	31.40	13.250	9883	189	176	611	5.8	7.2
BS048	1-W-H	32.10	12.938	10,416	188	175	612	6.0	6.9
BS046	1-W-M	31.40	13.313	9949	178	171	584	6.0	7.1
BS049	1-W-M	30.51	13.688	9318	175	170	578	5.8	7.2
BS047	1-W-L	30.52	13.875	9140	179	170	583	6.1	7.4

4.2.2.2 Performance Results for Aluminum Barrel-Stiffness Bats

Table 8 shows the performance results for the aluminum bats. The results show the high-stiffness bats to be the highest performing. The relatively high performance of these bats is most likely due to their moments of inertia.

Table 8 Performance and hoop frequency data for aluminum barrel-stiffness bats

Bat ID	Model	Sweet Spot Loc. (in.)	Hoop Freq (Hz)	MOI (oz-in^2)	BBS (mph)
BS045	1-W-H	6.0	2000	9883	99.0
BS048	1-W-H	5.5~6.0	2000	10,416	100.3
BS046	1-W-M	5.5	1870	9949	99.3
BS049	1-W-M	6.0	1860	9318	96.8
BS047	1-W-L	6.5	1800	9140	96.4

Following the procedure described in Sec. 4.2.1, the performance results were adjusted to a nominal MOI of 10,000 oz-in^2. The BBCOR values and MOI adjusted BBS values are presented in Table 9 and Figure 17. To assist in seeing the data, the points in Figure 17 were moved slightly left and right of the actual impact locations. When adjusted for differences in MOI, there is no measurable difference either in BBCOR or in BBS for these bats.

Table 9 Performance data for aluminum barrel-stiffness bats adjusted for differences in MOI

Bat ID	Model	Sweet Spot Loc. (in.)	Hoop Freq (Hz)	BBCOR	BBS (mph)
BS045	1-W-H	6.0	2000	0.549	99.3
BS048	1-W-H	5.5~6.0	2000	0.545	99.0
BS046	1-W-M	5.5	1870	0.547	99.5
BS049	1-W-M	6.0	1860	0.547	99.2
BS047	1-W-L	6.5	1800	0.553	99.4

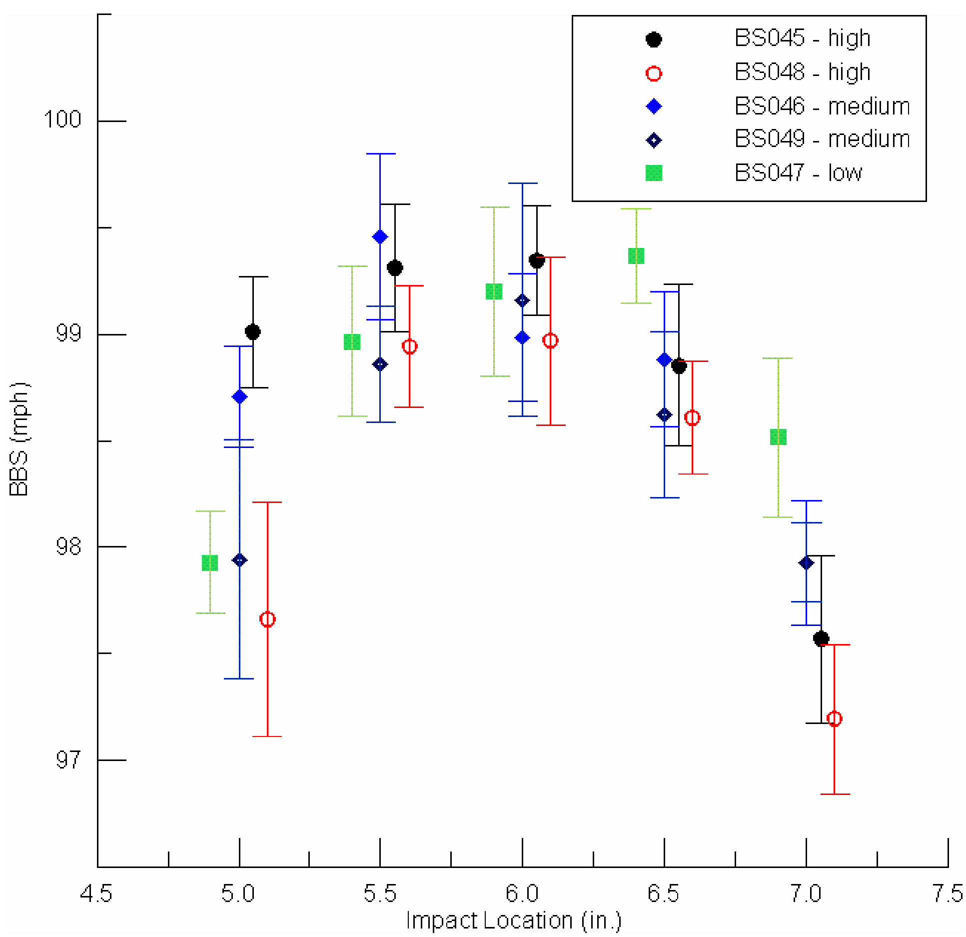

Figure 17 BBS for aluminum barrel-stiffness bats adjusted for differences in MOI

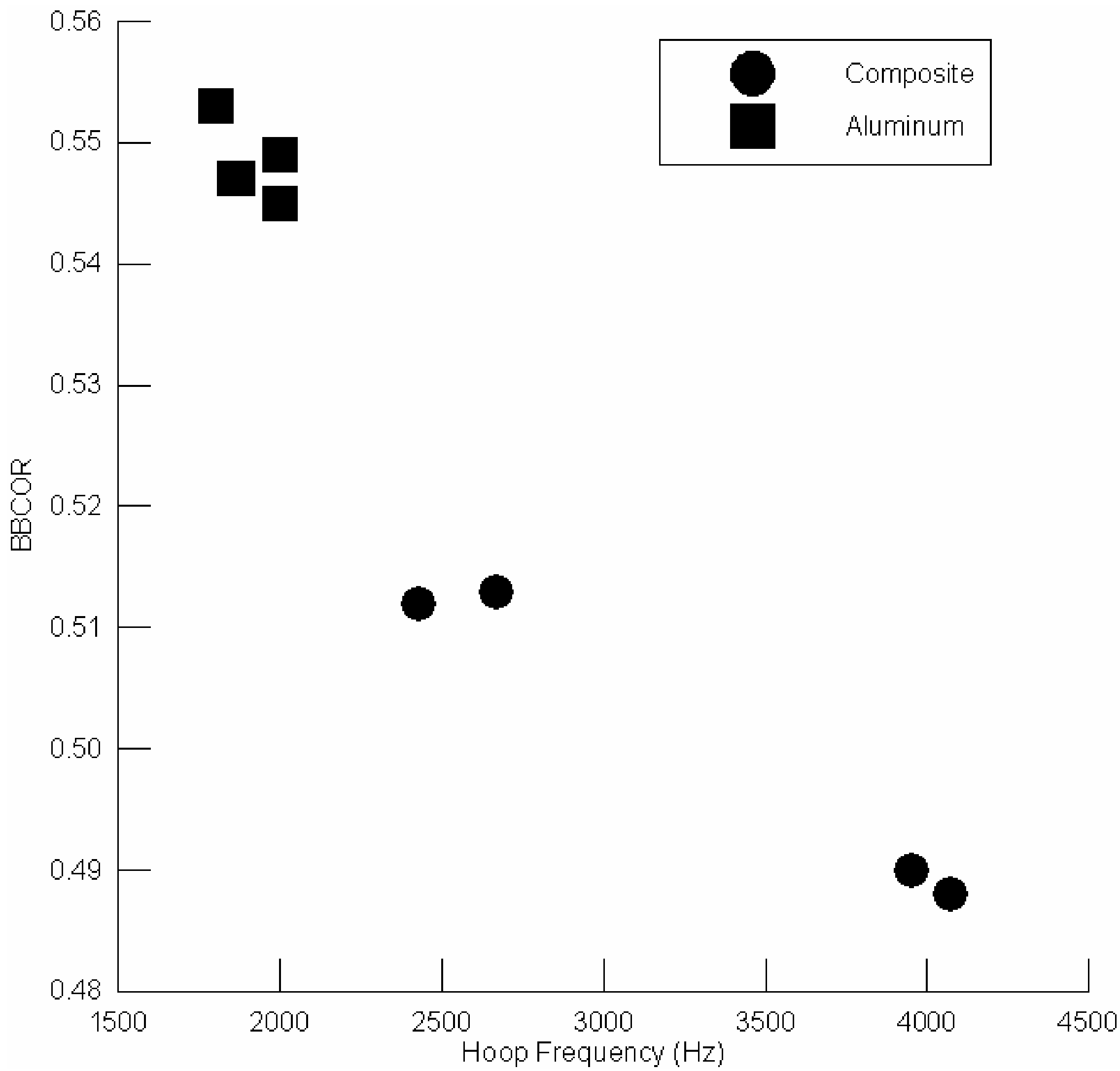

Figure 18 Sweet-spot BBCOR vs. hoop frequency for composite and aluminum bats

The results in Figure 17 correspond with the results from the composite bats. The differences in the aluminum barrel stiffnesses are similar to the differences in barrel stiffnesses between the low- and medium-stiffness composite bats. There was no measurable difference between low- and medium-stiffness composite bats, as there is no measurable difference between any of the aluminum bats.

Figure 18 shows the sweet-spot BBCOR values for each composite and aluminum bat plotted against hoop frequency. For the aluminum bats, the barrel-stiffness values were too close between stiffness classes to discern any significant observations in performance variations due to the barrel-stiffness property. The bats in Figure 18 agree with Russell's hoop-frequency model. However, more data points are needed to better define the BBCOR vs. hoop-frequency curve.

Figure 19 is a plot of BBCOR vs. hoop frequency for all the bats tested in this study. It can be seen that there is a strong correlation between hoop frequency and upper limit of BBCOR.

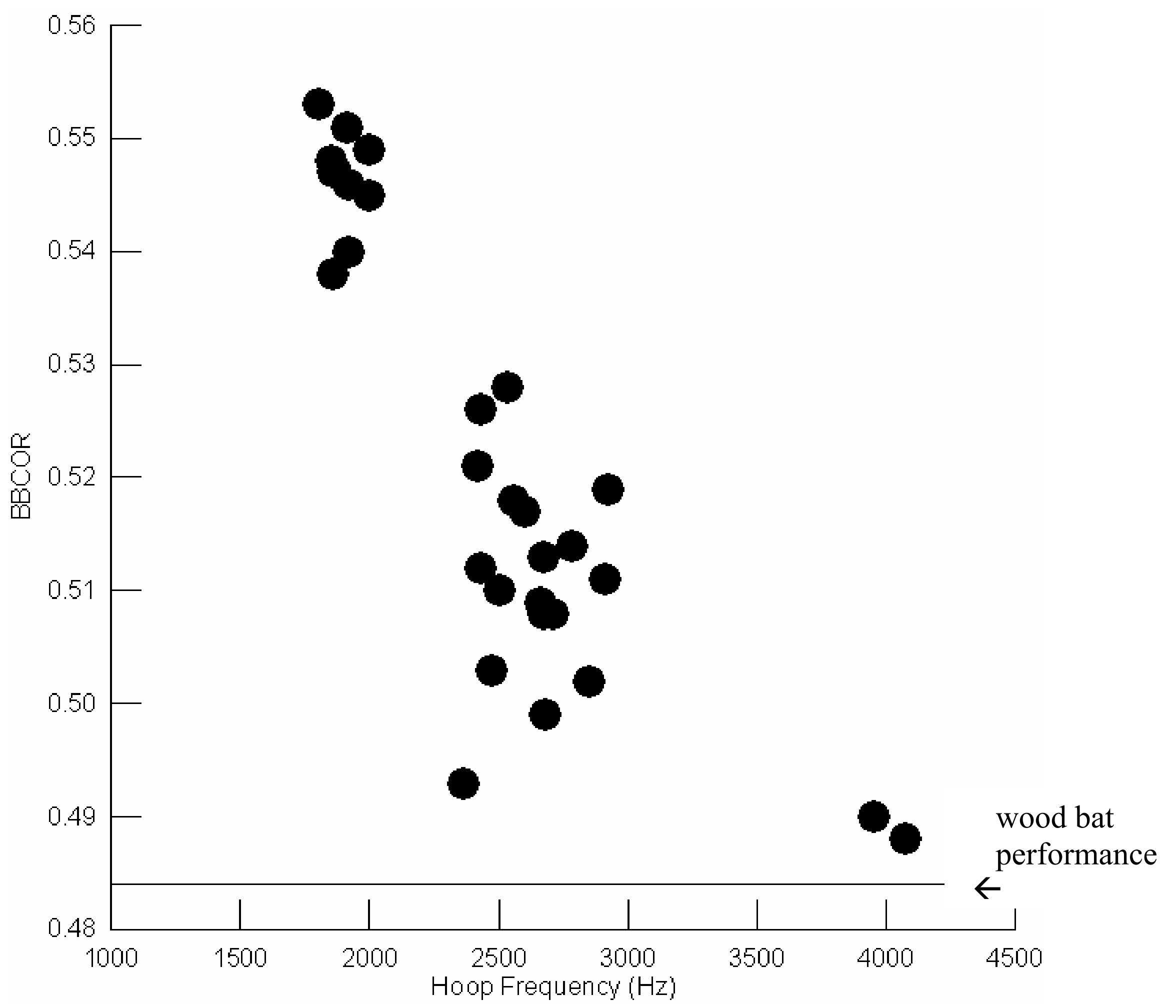

Figure 19 BBCOR vs. hoop frequency for all bats tested

4.3 MOI

The MOI bats consist of bats with the same length and weight, but different weight distributions along the length of the bat.

4.3.1 Composite

The composite bats are constructed of carbon fiber and epoxy resin. The moments of inertia are varied by adding weight to different parts of the bat.

4.3.1.1 Preliminary Results for Composite MOI Bats

The weight and MOI measurements for the composite bats are presented in Table 10. The MOI measurements for this set of six bats show three different MOI classes: low (2-M-H), medium (2-M-B) and high (2-M-E) with nominal MOI values of 9000, 11,000, and 13,000 oz-in^2, respectively. Unlike the barrel-stiffness bats in Sec. 4.2.1, the MOIs of these bats are evenly distributed over a range of discernable values. Using Equations 3 through 6, the effect of MOI on BESR and lab BBS can be calculated, and the results are presented in Table 11. For these calculations, it was assumed that a bat with an MOI of 11,000 oz-in^2 had a BESR of 0.730 (0.730 was the measured value for bat BS026) and that the BBCOR was the same for each bat. All calculations were done at the 6-in. location, a common location for the sweet spot of a bat. These calculations predict a difference in BBS of 11.3 mph between bats with MOIs of 9000 and 13,000 oz-in^2.

Table 10 Weight and MOI measurements for composite MOI bats

Bat ID	Model	Length (in.)	Weight (oz)	CG (in.)	MOI (oz-in^2)
BS011	2-M-H	33.875	31.285	14.875	9218
BS012	2-M-H	33.875	31.395	14.813	9259
BS025	2-M-B	33.875	30.955	12.188	11,199
BS026	2-M-B	33.875	30.980	12.625	10,912
BS009	2-M-E	33.875	31.320	10.250	12,722
BS010	2-M-E	33.875	31.525	10.250	12,810

Table 11 MOI performance calculations for the range of the composite MOI bats

MOI Class	MOI (oz-in^2)	Sweet Spot Loc. (in.)	BBCOR	BESR	Lab *BBS* (mph)	Relative Lab *BBS* Diff. (mph)
Low	9000	6.0	0.504	0.682	90.8	-6.5
Med	11,000	6.0	0.504	0.730	97.3	0
High	13,000	6.0	0.504	0.766	102.1	+4.8

The barrel-stiffness and handle-stiffness measurements for this set of bats are shown in Table 12. The barrel-stiffness and handle-stiffness results are very close for all six bats. The only slight differences are in the hoop frequencies of the end-loaded bats and the location of the nodes of the first bending mode. As MOI increases, both the handle and barrel nodes shift out towards the end of the barrel.

Table 12 Barrel stiffness, hoop frequency and handle stiffness measurements for composite MOI bats

Bat ID	Model	Barrel Compression at Axial Location (lbs)			Hoop Freq (Hz)	Handle Flex (lbs)	1st Bend Freq (Hz)	2nd Bend Freq (Hz)	Handle Node (in.)	Barrel Node (in.)
		4 in.	5 in.	6 in.						
BS011	2-M-H	787	821	928	2470	259	193	658	5.3	6.6
BS012	2-M-H	805	843	922	2500	258	193	662	5.4	6.6
BS025	2-M-B	730	762	877	2560	247	188	723	5.6	5.9
BS026	2-M-B	747	808	886	2530	245	186	719	5.3	6.0
BS009	2-M-E	783	800	928	2910	257	202	721	7.0	5.2
BS010	2-M-E	818	827	942	2920	257	203	722	6.9	5.3

4.3.1.2 Performance Results for Composite MOI Bats

The performance results for the composite MOI bats are shown in Table 13 and Figure 20. The performance results show consistency between the two bats of each MOI class. Each of the sets of two samples tested was within a mph of the other bat in its MOI class. There is a large difference in BBS between each MOI class with performance increasing as MOI increases. There is also a difference in sweet-spot location between the MOI classes, the sweet spot moved out towards the end of the barrel with each increase in MOI. Table 14 shows the averaged results for each MOI class.

Table 13 Performance results for composite MOI bats

Bat ID	Model	Sweet Spot Loc. (in.)	MOI ($oz\text{-}in^2$)	BBS (mph)
BS011	2-M-H	5.0	9218	91.9
BS012	2-M-H	5.0	9259	92.8
BS025	2-M-B	4.5	11,199	100.7
BS026	2-M-B	4.5	10,912	100.9
BS009	2-M-E	3.5	12,722	104.7
BS010	2-M-E	4.0	12,810	105.7

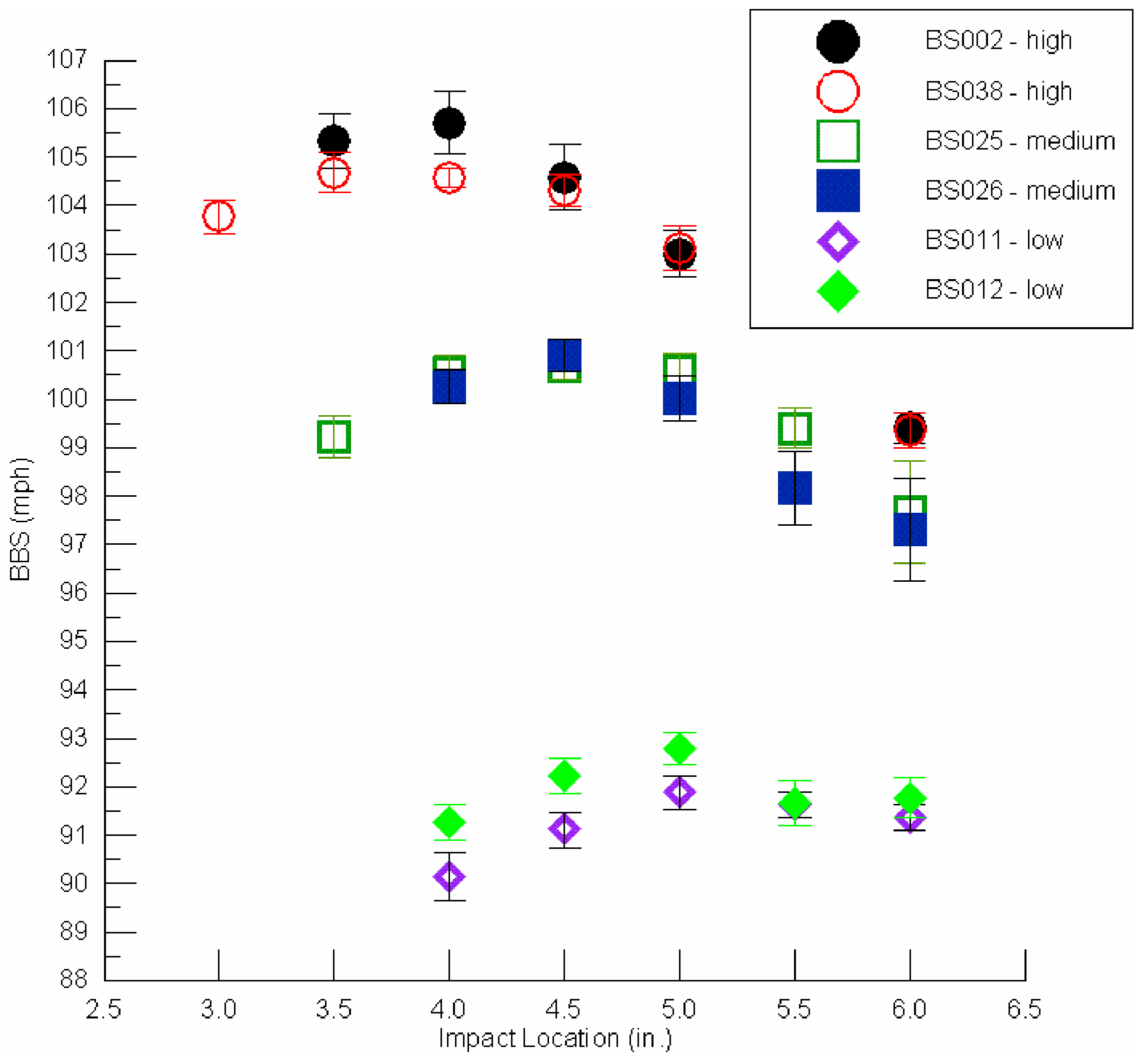

Figure 20 BBS for composite MOI bats

Table 14 Averaged performance results for each composite MOI class

MOI Class	Avg. MOI ($oz\text{-}in^2$)	Sweet Spot Location (in.)	Avg. Lab BBS (mph)	Relative Lab BBS Diff. (mph)
Low	9239	5.0	92.3	-8.5
Med.	11,056	4.5	100.8	0.0
High	12,766	3.5~4.0	105.1	4.3

Table 14 shows that there is a 12.8-mph difference in BBS between the low- and high-MOI bats. This difference is slightly greater than what was calculated using the BESR equation in Sec. 4.3.1.1 and Table 11.

For the bats tested, Table 13 shows the sweet-spot location moved closer to the end of the barrel with each increase in MOI. The theoretical calculations presented in Table 11 for the 6-in. location were repeated using the actual sweet-spot locations for these bats and the actual MOI values. These calculations are shown in Table 15. These calculations assume the sweet-spot BBCOR to be the same for all three bats, i.e. 0.515, which is the average of the sweet-spot BBCORs for the bats. These calculations show a total difference in BBS of 11.8 mph, which is one mph less than what was seen in the tests. These results show that the BESR formula can calculate the change in performance due to MOI for the bats used in this study to within one mph.

Table 15 BBS calculations using MOI and sweet spot data from composite bats

MOI Class	MOI ($oz\text{-}in^2$)	Sweet Spot Loc. (in.)	BBCOR	BESR	Calc. Lab BBS (mph)	Relative Lab BBS Diff. (mph)
Low	9239	5.0	0.515	0.674	93.2	-6.6
Med	11,056	4.5	0.515	0.709	99.9	0.0
High	12,766	4.0	0.515	0.733	105.1	+5.2

4.3.1.3 Field Performance Calculations using a Swing-Speed Model

Projected field BBSs were calculated by adjusting the swing speed in the BBS equation according to Nathan's swing-speed model, as presented in Sec. 2.3. The results are presented in Table 16. The "New V_{bat}" column denotes the swing speed projected for the bat based on Nathan's swing-speed model. The projected field BBS results are averaged for each MOI class. The data are presented in Table 17.

Table 16 BBS calculations for composite bats using experimental data and a swing speed model

Bat ID	MOI (oz-in^2)	Sweet Spot Loc. (in.)	BESR	New V_{bat} @ SS (mph)	New *BBS* (mph)
BS011	9218	5.0	0.665	72.2	95.6
BS012	9259	5.0	0.671	72.2	96.5
BS025	11,199	4.5	0.715	70.1	100.2
BS026	10,912	4.5	0.716	70.6	101.0
BS009	12,722	3.5	0.717	70.7	101.2
BS010	12,810	4.0	0.737	69.1	102.1

Table 17 Averaged BBS calculations for composite bats using experimental data and a swing-speed model

MOI Class	Avg. MOI (oz-in^2)	Sweet Spot Loc. (in.)	Avg. New *BBS* (mph)	Relative New *BBS* Diff. (mph)
Low	9239	5.0	96.1	-4.5
Med	11,056	4.5	100.6	0.0
High	12,766	3.5~4.0	101.6	+1.0

Bats with different moments of inertia will be swung with different swing speeds in the field. The calculations presented in Table 16 and Table 17 show that the swing-speed difference will reduce the performance difference between bats in the field compared to what was observed in the lab values shown in Table 14, where a swing speed of 66 mph was used for all bats. The projected field-performance difference between low- and high-MOI bats is only 5.5 mph (Table 17), compared to 12.8 mph in the laboratory tests (Table 14). Even with the slower swing speed in the field compared to that used in the lab, the high-MOI bat still has the highest BBS. For the three MOI classes investigated in this study, the balanced and end-loaded bats have similar batted-ball speeds, and the handle-loaded bat has a relatively lower batted-ball speed.

4.3.2 Aluminum

The bats in this section were all made of C555 aluminum alloy. The moments of inertia were varied by adding weight at different locations along the length of the bat.

4.3.2.1 Preliminary Results for Aluminum MOI Bats

The aluminum bats with varying MOI, which were available for the study, were 33-in. long instead of 34 in. To compare the results of these bats with the 34-in. bats, the aluminum bats were clamped at 5.0 in. in from the knob, instead of 6.0 in., for both performance testing and MOI measurement. Because the part of the bat behind the grip does not affect performance (Koenig 2004), a 33-in. bat clamped at 5 in. instead of 6 in. should have a performance similar to a 34-in. bat with the same barrel construction. The weight and MOI measurements are presented in Table 18.

Table 18 Weight and MOI measurements for aluminum MOI bats

Bat ID	Model	Length (in.)	Weight (oz)	CG (in.)	MOI @ 5.0 in. (oz-in^2)
BS031	2-W-H	32.875	31.42	14.563	9279
BS030	2-W-B	32.875	30.61	12.063	10,758
BS029	2-W-E	32.938	31.13	10.688	12,220

As shown in Table 18, the MOI measurements for these bats are close to those of the high-, med- and low-MOI composite bats. The barrel-stiffness and handle-stiffness measurements are presented in Table 19. The barrel-stiffness and handle-stiffness measurements are very close for all three bats. The barrel node of the first bending mode moves closer to the barrel end of the bat as MOI increases. Movement of the node is a result of the difference in weight distributions. The sweet spot is usually near the nodes of the first and second bending modes (Vedula and Sherwood 2004). Therefore, movement of the node may cause the sweet spot to move out towards the end of the bat for the end-loaded bat.

Table 19 Handle-stiffness measurements for aluminum MOI bats

Bat ID	Model	Handle Flex (lbs)	1^{st} Bend Freq (Hz)	2^{nd} Bend Freq (Hz)	Handle Node (in.)	Barrel Node (in.)	Barrel Compression at Axial Location (lbs)			Hoop Freq (Hz)
							4 in.	5 in.	6 in.	
BS031	2-W-H	187	172	652	4.3	7.0	793	778	782	1850
BS030	2-W-B	191	183	677	5.5	6.3	795	780	774	1860
BS029	2-W-E	181	182	679	6.0	5.7	777	761	770	1860

4.3.2.2 Performance Results for Aluminum MOI Bats

The performance results for the aluminum MOI bats are presented in Table 20 and Figure 21. Table 20 shows a batted-ball speed difference of 8.8 mph between the low- and high-MOI bats. As with the composite bats, the sweet-spot location moved towards the end of the barrel as the MOI increased. Using the BESR equation (Equation 3) and the average sweet-spot value of BBCOR, 0.544, the theoretical performance of the three bats at their actual sweet-spot locations can be calculated. The results are presented in Table 21.

Table 20 Performance results for aluminum MOI bats

Bat ID	Model	MOI @ 5.0 in. (oz-in^2)	Sweet Spot Loc. (in.)	BBS (mph)
BS031	2-W-H	9279	6.5	96.3
BS030	2-W-B	10,758	5.5	101.7
BS029	2-W-E	12,220	5.0	105.1

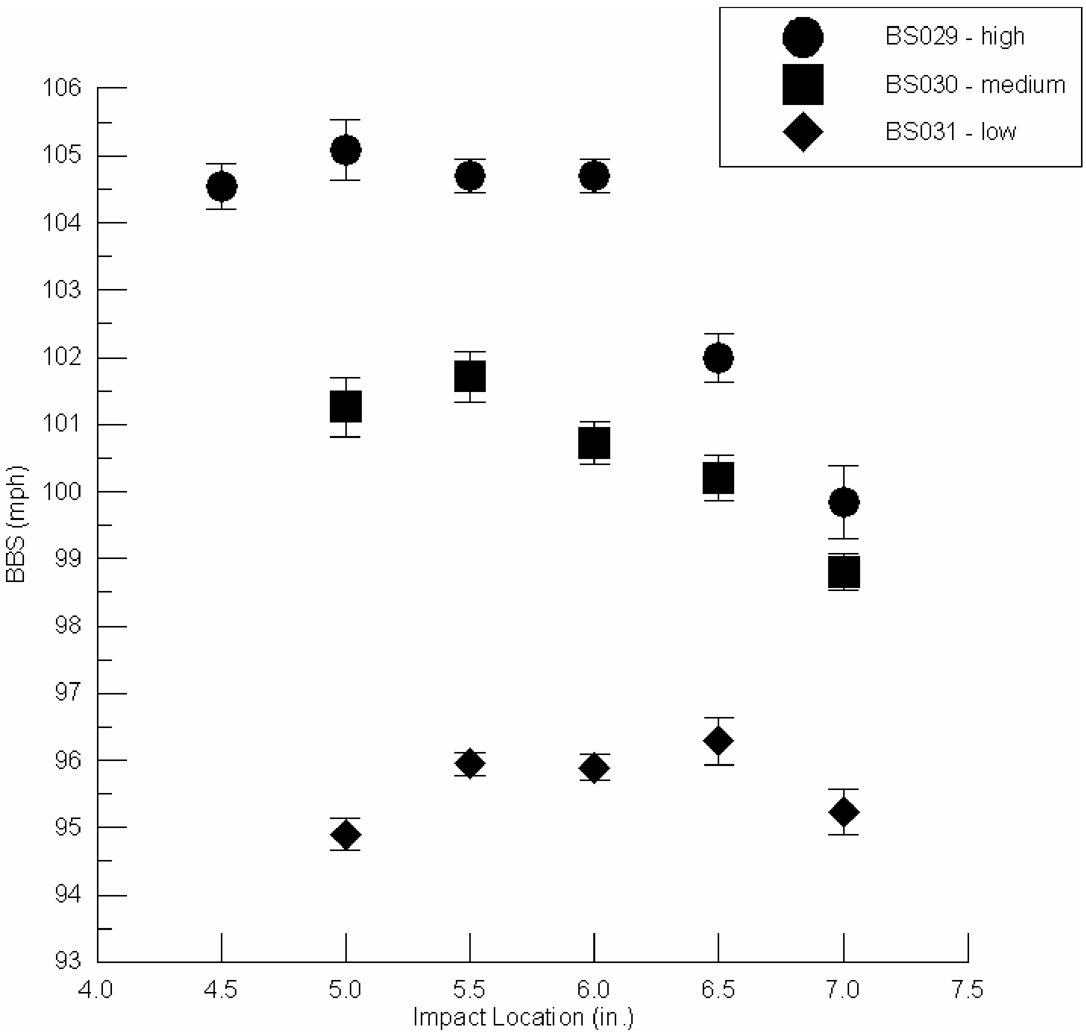

Figure 21 BBS for varying MOI aluminum bats

Table 21 BBS calculations using MOI and sweet-spot data from aluminum bats

MOI Class	MOI	Sweet Spot Loc. (in.)	BBCOR	BESR	Calc. Lab BBS (mph)	Relative Lab BBS Diff. (mph)
Low	9279	6.5	0.544	0.733	95.8	-5.6
Med	10,758	5.5	0.544	0.747	101.4	0.0
High	12,220	5.0	0.544	0.766	106.0	+4.6

The BESR equation calculations, as summarized in Table 21, show a lab batted-ball difference of 10.2 mph between the low- and high-MOI bats. The measured BBS difference as given in Table 20 was 8.8 mph—1.4 mph less than what was calculated. For the composite bats, the BESR equation overpredicted the performance difference by about one mph. For these aluminum bats, the BESR equation underpredicted the performance difference by 1.4 mph. In both cases, there was about a 10% difference between calculated- and measured-performance differences. Some of the difference may be due to experimental variations in the BESR measurements, which result in variations in the calculated BBCOR values.

Figure 22 shows maximum laboratory BBS plotted against MOI for the aluminum and composite bats. Batted-ball speed increases significantly as MOI increases for both aluminum and composite bats.

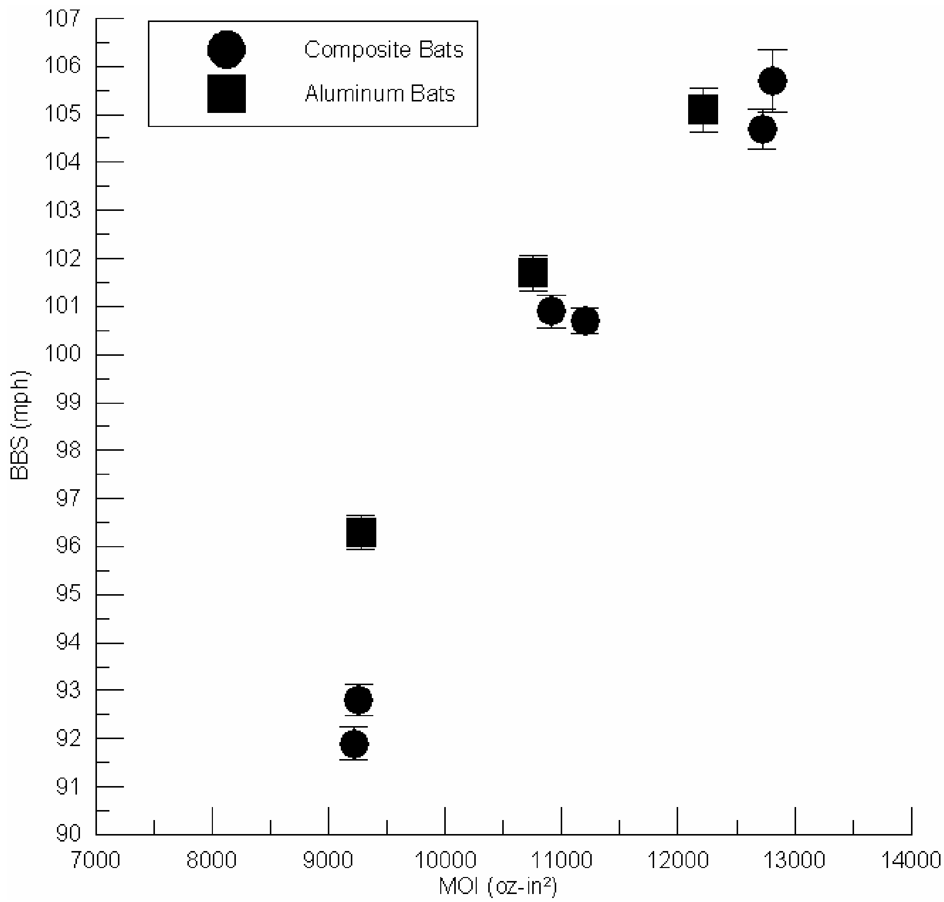

Figure 22 Maximum BBS vs. MOI for composite and aluminum bats

4.3.2.3 Swing-Speed Calculations

Using Nathan's swing-speed model, the projected field performance can be calculated for the three aluminum bats. The field-performance calculation results are shown in Table 22. As with the composite bats, use of this swing-speed model indicates that the end-loaded bat will be the highest performing, followed by the balanced bat and then the handle-loaded bat. The total projected field-performance difference between the low- and high-MOI bats is 2.5 mph, compared to 8.8 mph for the laboratory testing method.

Table 22 BBS calculations for aluminum bats using experimental data and a swing speed model

Bat ID	MOI ($oz\text{-}in^2$)	Sweet Spot Location (in.)	BESR	New V_{bat} @ SS (mph)	New *BBS* (mph)	Relative Field BBS (mph)
BS031	9279	6.5	0.736	67.3	99.7	-2.1
BS030	10,758	5.5	0.749	67.6	101.8	0.0
BS029	12,220	5.0	0.760	66.7	102.2	+0.4

4.3.3 Field Tests

Field tests were performed using three composite bats from the MOI set: BS011 (handle-loaded), BS025 (balanced) and BS009 (end-loaded). Seven players from the UMass Lowell baseball team (NCAA Division II) were used. The players were asked to hit with each of the three bats in random order. The players hit until five solid, deep-outfield or home run trajectory hits were obtained, then the next batter hit. After each solid hit, the distance was marked by a person in the outfield, and a Nikon Laser 800 Rangefinder was used to measure the distance to the spot where the ball landed. The rangefinder had an accuracy of ±1 yard. The players continued to hit until each player had five solid hits with each bat, for a total of 15 hits per player (105 total hits, 35 with each bat). A pitching machine was used to keep the pitch speed consistent. The machine was set to pitch at 55-60 mph. Some of the hits either hit or went over the outfield wall. For these hits, it was recorded either where on the wall the ball hit (low-, mid-, or high-wall) or approximately how far over the wall the balls were hit (just over, over, or well over). For these hits, the distance to the wall was measured and additional distance was added as given in Table 23.

Table 23 Additional distance added to hits that did not land in the field of play

Hit Description	Distance Added (ft)
Low Wall	0
Mid Wall	6
High Wall	12
Just Over Wall	15
Over Wall	30
Well Over Wall	60
Over Trees Beyond Wall	90

The data from the field tests were analyzed in two ways. First, the distances of all 35 hits with each bat were averaged to give an average hit distance for each bat. These results are shown in Table 24.

Table 24 Average hit distance for each composite bat tested in the field

Bat ID	Model	Avg. Hit Distance (ft)	Standard Deviation of the Mean (ft)
BS011	2-M-H	358.5	5.4
BS025	2-M-B	369.6	6.3
BS009	2-M-E	364.2	6.9

From the data in Table 24, bat BS025, the balanced bat, hit the farthest, followed by bat BS009 (end-loaded) and then bat BS011 (handle-loaded). From the swing-speed model calculations presented in Table 17, it was expected that the end-loaded bat and balanced bats would hit similarly, and the handle-loaded bat would hit significantly shorter distances. The data in Table 24 show all three bats to be very close in performance.

In field testing, the players hit over a range of axial locations along the barrel. Therefore, to compare the lab data with the field testing data, the field-projected BBS values for each bat were averaged over the 4- to 6-in. region of the barrel. Table 25 shows the projected field performances for these bats based on the lab testing averaged over the "hitting" area of the bat.

Table 25 BBS data for three composite bats used for field testing incorporating the swing-speed model with *n* = 0.3

Bat ID	Model	BBS (mph) Avg. over 4 to 6 in. locations
BS011	2-M-H	94.9
BS025	2-M-B	99.0
BS009	2-M-E	99.9

The value of n in the swing speed formula (Equation 9) was assumed to be 0.3 for all of the swing-speed calculations up to this point. The field data suggests that the dependence of swing speed on MOI may actually be greater than what is predicted using $n = 0.3$. Table 26 and Table 27 show the projected field performance results for the three bats using values of $n = 0.4$ and $n = 0.5$, respectively. In each case, the performance of the three bats are very close, however, the maximum performance shifts from the end-loaded bat for $n = 0.3$ to the balanced bat for $n = 0.5$. To predict which MOI will be the highest performing for a particular player, the dependence of swing speed on MOI must be known for that player.

Table 26 BBS data for three composite bats used for field testing incorporating the swing-speed model with *n* = 0.4

Bat ID	Model	BBS (mph) Avg. over 4 to 6 in. locations
BS011	2-M-H	96.2
BS025	2-M-B	98.7
BS009	2-M-E	98.7

Table 27 BBS data for three composite bats used for field testing incorporating the swing-speed model with *n* = 0.5

Bat ID	Model	BBS (mph) Avg. over 4 to 6 in. locations
BS011	2-M-H	97.5
BS025	2-M-B	98.5
BS009	2-M-E	97.5

A second way to analyze the data was to look at each player individually and to rank the bats as to which hit farthest (#1 rank), second farthest (#2 rank), and shortest (#3 rank) for each player. These data are presented in Table 28. This analysis approach shows that three players hit the farthest with each of bats BS025 and BS009, whereas only one player hit the farthest with bat BS011. These data correspond with what would be expected from the swing-speed model calculations using n =0.3 or n = 0.4 – the end-loaded and balanced bats hit similarly and the handle-loaded bat was lower performing. The most important conclusion from these data is that the significant difference in performance observed in the lab test is not reflected in the field performance. In his swing-speed study, Bahill (2004) found that swing speed can vary significantly among players, and there is no ideal MOI for all players. Bahill's observation is supported by the limited field testing done in the current study.

Table 28 Field test bats ranked for each player

Bat ID	Model	#1 Ranks	#2 Ranks	#3 Ranks
BS011	2-M-H	1	3	3
BS025	2-M-B	3	2	2
BS009	2-M-E	3	2	2

4.4 Handle Stiffness

The bats discussed in this section are composite bats with different handle flexes. All measurements should be equal except for handle flex, and consequently the bending frequencies and the location of the nodes of the first bending mode.

4.4.1 Composite

The handle-stiffness bats are constructed of carbon fiber and epoxy resin, the handle stiffness can be varied by altering the fiber angle in the handle region of the bat. The positioning of the fibers along the length of the bat can influence the handle stiffness.

4.4.1.1 Preliminary Results for Composite Handle-Stiffness Bats

The handle-stiffness measurements are presented in Table 29. The two bats used in the study are low (3-M-L) and high (3-M-H) stiffness. The handle flexes show a 2:1 ratio.

Table 29 Handle-stiffness measurements for composite handle-stiffness bats

Bat ID	Model	Handle Flex (lbs)	1st Bend Freq (Hz)	2nd Bend Freq (Hz)	Handle Node (in.)	Barrel Node (in.)
BS035	3-M-L	123	139	493	4.8	6.3
BS014	3-M-H	258	189	698	5.2	6.3

It should be noted that the bats used in the previous sections (Sec. 4.2 barrel stiffness and Sec. 4.3 MOI) had handle-flex values close to those of the high-flex bat in this section. The low handle-stiffness bat in this section has significantly lower handle-flex and bending-frequency values. The remaining preliminary measurements are shown in Table 30. Both bats are 33.875 in. in length.

Table 30 Barrel stiffness measurements for handle-stiffness bats

Bat ID	Model	Weight (oz)	CG (in.)	MOI (oz-in^2)	Barrel Compression at Axial Location (lbs)			Hoop Freq (Hz)
					4 in.	5 in.	6 in.	
BS035	3-M-L	31.03	13.813	10,995	684	730	814	2360
BS014	3-M-H	31.25	13.938	9899	804	853	955	2710

Of the properties that are supposed to be equal, there are several differences between the bats. The MOIs of the two bats are different by about 1000 oz-in^2. Because the effect of handle stiffness on BBS is expected to be relatively small for impacts near the sweet spot, this large difference in MOI may make it difficult to discern if differences in performance between the two bats are due to handle-flex or due to MOI. The barrel stiffness values also differ slightly. The low handle-stiffness bat has a lower barrel stiffness, which can be seen in the barrel-compression and hoop-frequency values. Both of these differences in properties would cause the low handle-stiffness bat to be higher performing. These differences in MOI and barrel stiffness will result in the low-stiffness bat having a higher BBS than the high handle-stiffness bat. It is expected when normalized to an MOI of 10,000 oz-in^2 that the high handle-stiffness bat will have a slightly higher BBS than the low handle-stiffness bat due to a decrease in bending vibrations. It is expected that the performance difference will be small for impacts close to the nodes of the first two bending modes because bending vibrations will be minimized.

4.4.1.2 Performance Results for Composite Handle-Stiffness Bats

The performance test results for the two handle-stiffness bats are presented in Table 31 and Figure 23. The low handle-stiffness bat is higher performing, but it also has the higher MOI. Therefore, the data must be analyzed to see how much of this higher performance is due to its higher MOI and if any of the performance difference is due to handle-stiffness differences. Using Equations 3 through 6, the MOI can be normalized to 10,000 oz-in^2 for both bats, and the new BESR and BBS values can be calculated. The results of these calculations are shown in Table 32 and Figure 24.

Table 31 Performance test results for handle-stiffness bats

Bat ID	Model	MOI ($oz\text{-}in^2$)	Hoop Freq (Hz)	Sweet Spot Loc. (in.)	BBS (mph)
BS035	3-M-L	10995	2360	5.0	96.9
BS014	3-M-H	9899	2710	5.0	95.0

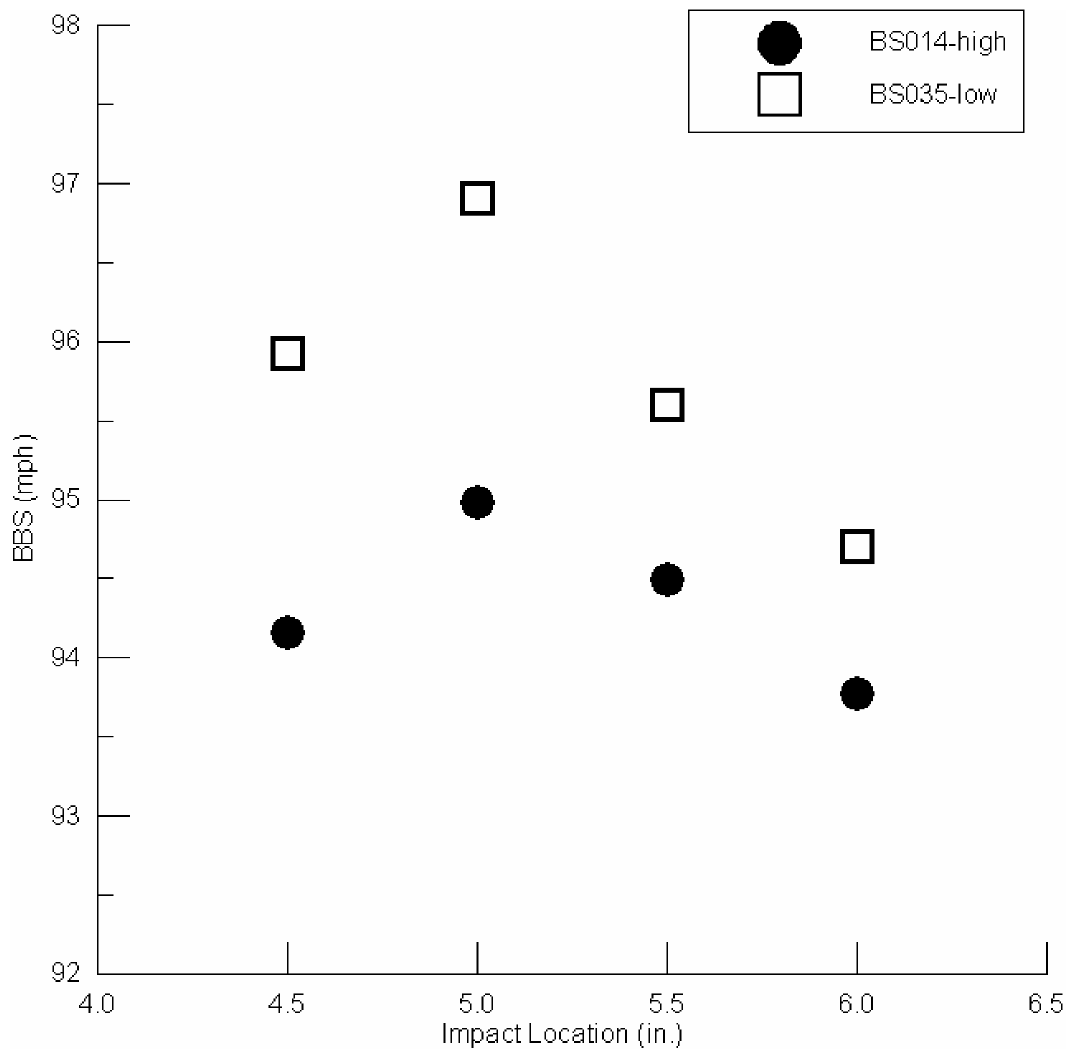

Figure 23 BBS for composite handle-stiffness bats

Table 32 Performance test results normalized to MOI of 10,000 oz-in^2

Bat ID	Model	MOI (oz-in^2)	Hoop Freq (Hz)	Sweet Spot Loc. (in.)	BBS (mph)
BS035	3-M-L	10,000	2360	5.0	93.7
BS014	3-M-H	10,000	2710	5.0	95.3

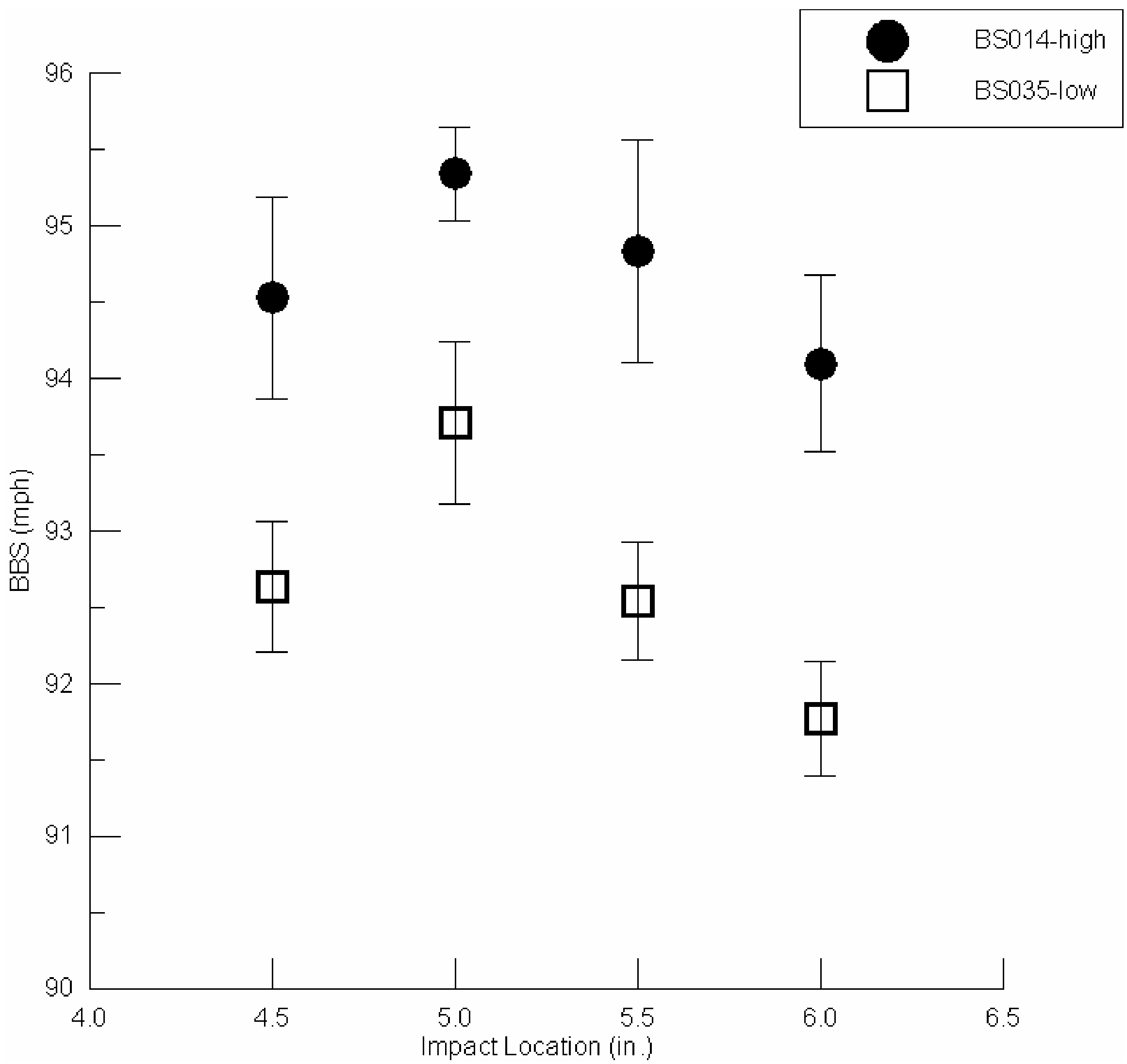

Figure 24 BBS for composite handle-stiffness bats adjusted for differences in MOI

Figure 24 shows that when adjusted for differences in MOI, the high handle-stiffness bat has a higher BBS than the low handle-stiffness bat, as was expected. The barrel stiffness, and hence the hoop frequency, of the low handle-stiffness bat is slightly lower than that of the high handle-stiffness bat. Lower barrel stiffness results in higher performance, so the difference in performance due to handle stiffness may be slightly greater than what is shown in Figure 24.

The amount of energy that goes into bending vibrations depends on the flexibility of the bat. A rigid bat will not lose any energy to bending vibrations, whereas a flexible bat will. Any energy that goes into bending vibrations is energy that cannot potentially be transferred to the ball, and therefore, decreases the potential batted-ball speed. The effect of flexibility on batted-ball speed will be significant for impacts away from the nodes of the first and second bending modes and will be minimal for impacts close to both nodes. Because the sweet spot of a bat is usually close to the nodes of both the first and second bending modes (Vedula and Sherwood 2004), the effects of handle stiffness on maximum batted-ball speed will be small (Nathan 2000). Therefore, it is expected that the difference in performance between these two bats would increase significantly for impacts away from the sweet spot.

4.5 Barrel Construction

This set of bats consists of single-wall (5-M-S) and double-wall (5-M-D) composite bats. Each bat should have all measurable properties equal – with the only difference being the barrel construction.

4.5.1 Composite

The barrel-construction bats are made of carbon fiber and epoxy resin. The single-wall bats consist of a single barrel wall. The double-wall bat has two barrel walls that can potentially move relative to one another.

4.5.1.1 Preliminary Results for Barrel-Construction Bats

The preliminary test results are presented in Table 33 and Table 34. The barrel-compression and hoop-frequency measurements show the double-wall bat to be slightly stiffer than the single-wall bats. Based on the results of the barrel-stiffness bats, this stiffness difference would result in the single-wall bats slightly outperforming the double-wall bat. However, the MOI of the double-wall bat is about 200-300 oz-in^2 higher than the single-wall bats, which would contribute to a performance advantage for the double-wall bat with regard to the MOI design parameter. For the hoop frequency range of these bats, it is expected that the differences in MOI will be a more significant influence on performance than the difference in barrel stiffnesses. However, as shown previously, the experimental data can be normalized to a uniform MOI. The handle-flex and bending-frequency measurements are very close for all three bats. There should be no difference in performance due to handle flex.

Table 33 Weight, MOI and barrel stiffness measurements for barrel construction bats

Bat ID	Model	Length (in,)	Weight (oz)	CG (in.)	MOI (oz-in^2)	Barrel Compression for Axial Location (lbs)			Hoop Freq (Hz)
						4 in.	5 in.	6 in.	
BS034	5-M-D	33.750	31.35	14.250	10,279	907	910	921	2850
BS020	5-M-S	33.875	31.27	14.000	9960	794	835	901	2660
BS051	5-M-S	33.813	31.34	13.813	10,089	811	839	955	2780

Table 34 Handle-stiffness measurements for barrel-construction bats

Bat ID	Model	Handle Flex (lbs)	1st Bend Freq (Hz)	2nd Bend Freq (Hz)	Handle Node (in.)	Barrel Node (in.)
BS034	5-M-D	262	194	691	5.1	6.7
BS020	5-M-S	258	189	697	5.2	6.3
BS051	5-M-S	246	191	698	5.3	6.2

4.5.1.2 Performance Results for Barrel-Construction Bats

The performance results for the barrel-construction bats are presented in Table 35. One of the single-wall bats and the double-wall bat had essentially the same BBS. The other single-wall bat had a BBS about 1.5 mph higher than the other two bats. The single-wall bat with the higher BBS also had a sweet spot closer to the end of the barrel than the other two bats, 4.5 in. compared to 5.5 and 6 in. It does not appear that the results were dominated by the differences in MOI.

Table 35 Performance test results for barrel-construction bats

Bat ID	Model	Sweet Spot Loc. (in.)	BBS (mph)
BS034	5-M-D	6.0	95.3
BS020	5-M-S	5.5	95.0
BS051	5-M-S	4.5	96.7

As in previous sections, the performance data were adjusted to account for differences in MOI. These normalized results are presented in Table 36 and Figure 25. To assist in seeing the data, the points in Figure 25 were moved slightly left and right of the actual impact locations. Normalizing to an MOI of 10,000 oz-in^2 results in the double-wall bat having the lowest BBS of the three bats. The results for the two single-wall bats do not agree. There is a 1.3 mph difference in BBS between the single-wall bats and a 1-in. difference between their respective sweet-spot locations. Figure 25 shows that there is no clear trend in performance among these three bats. More bats need to be tested to determine if there is a relationship between barrel construction and performance.

Table 36 Performance results for barrel-construction bats adjusted for differences in MOI

Bat ID	Model	Sweet Spot Loc. (in.)	BBCOR	BBS (mph)
BS034	5-M-D	6.0	0.502	94.4
BS020	5-M-S	5.5	0.509	95.1
BS051	5-M-S	4.5	0.514	96.4

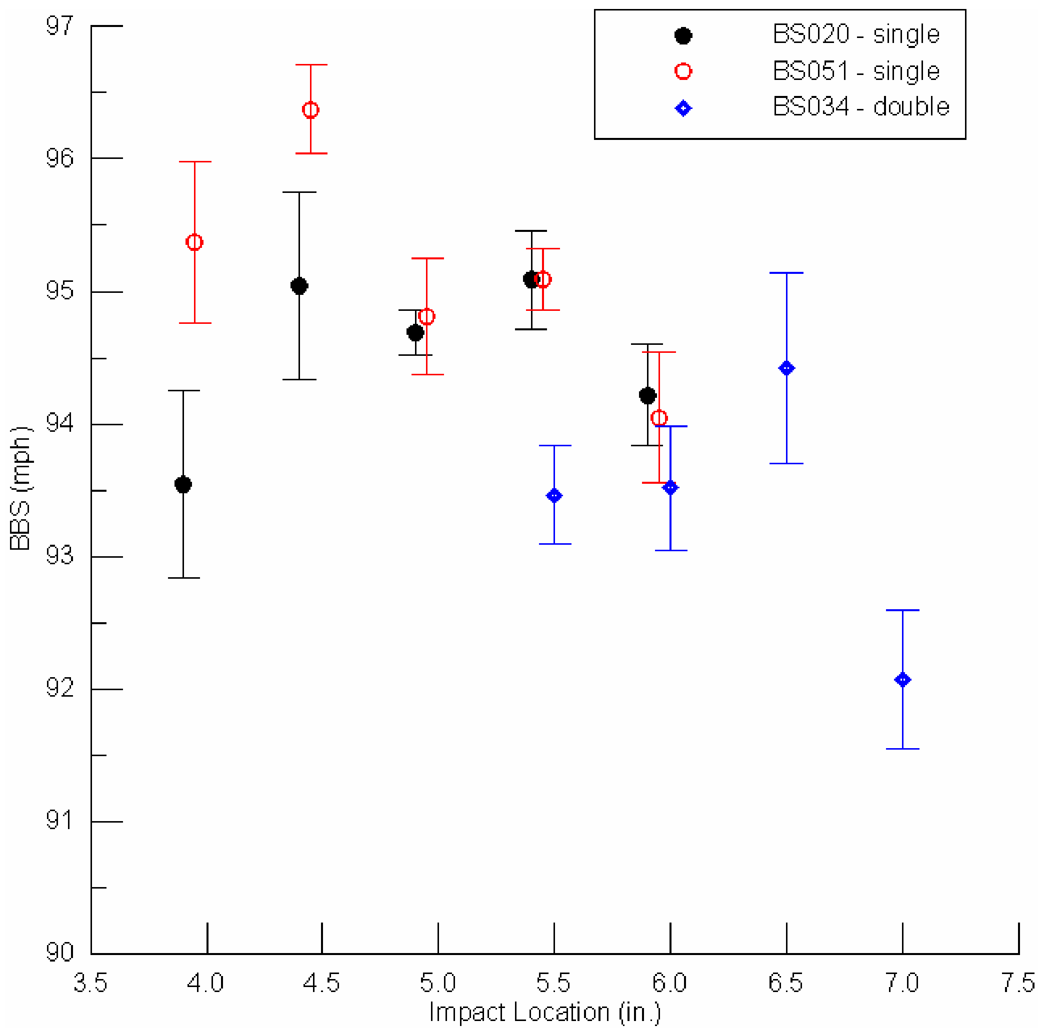

Figure 25 BBS for barrel-construction composite bats adjusted for differences in MOI

4.6 Weight

The weight set of bats consisted of bats of the same length and MOI, but different weights. This set of bats, combined with the set of varying MOI bats, will show how significant the overall weight of a bat is to its performance. For this set of bats, both composite and aluminum bats were tested.

4.6.1 Composite

The composite weight bats consist of carbon fiber and epoxy resin. Weights of different sizes were added at different locations along the bat to achieve the desired properties.

4.6.1.1 Preliminary Results for the Composite Weight Bats

Bats BS022, BS021 and BS023 are end loaded (6-M-E), balanced (6-M-B), and handle loaded (6-M-H), respectively. Each bat has an MOI close to 10,000 oz-in^2, and consequently, the end-loaded bat is the lightest and the handle-loaded bat is the heaviest with respect to overall weight. The basic measurements, including weight and MOI, are shown in Table 37.

Table 37 Weight and MOI measurements for composite weight bats

Bat ID	Model	Length (in.)	Weight (oz)	CG (in.)	MOI (oz-in^2)
BS022	6-M-E	33.875	31.37	13.875	10,408
BS021	6-M-B	33.813	32.47	14.250	10,101
BS023	6-M-H	33.875	33.21	15.500	9867

Due to the differences in MOI, it is expected that the end-loaded bat will hit the fastest followed by the balanced bat and finally the handle loaded bat. The barrel-stiffness and handle-flex measurements are shown in Table 38. All three bats have essentially the same respective barrel-stiffness and handle-stiffness measurements. The barrel stiffness of the balanced bat, BS021, is slightly higher than the other two.

Table 38 Barrel- and handle-stiffness measurements for composite weight bats

Bat ID	Model	Barrel Compression for Axial Location (lbs)			Hoop Freq (Hz)	Handle Flex (lbs)	1st Bend Freq (Hz)	2nd Bend Freq (Hz)	Handle Node (in.)	Barrel Node (in.)
		4 in.	5 in.	6 in.						
BS022	6-M-E	780	815	936	2680	258	189	700	5.3	6.3
BS021	6-M-B	814	868	959	2670	269	191	678	5.3	6.3
BS023	6-M-H	785	806	944	2600	261	190	634	5.4	6.3

4.6.1.2 Performance Results for the Composite Weight Bats

The performance test results are shown in Table 39 and Figure 26. The respective sweet-spot BBS values for each of the three bats were essentially the same. At the 4.5-in. location the end-loaded bat slightly outperformed the other two. The higher performance may be due to the higher MOI of the end-loaded bat. The BBS data are not normalized for MOI because weight and MOI are not independent properties. Adjusting the BESR for MOI would alter the weight distribution which is the property under investigation. To assist in seeing the data, the points in Figure 26 were moved slightly left and right of the actual impact locations.

Table 39 Performance test results for composite weight bats

Bat ID	Model	Sweet Spot Loc. (in.)	MOI ($oz\text{-}in^2$)	BBS (mph)
BS022	6-M-E	4.5	10,408	96.0
BS021	6-M-B	5.0	10,101	95.8
BS023	6-M-H	5.0	9867	95.9

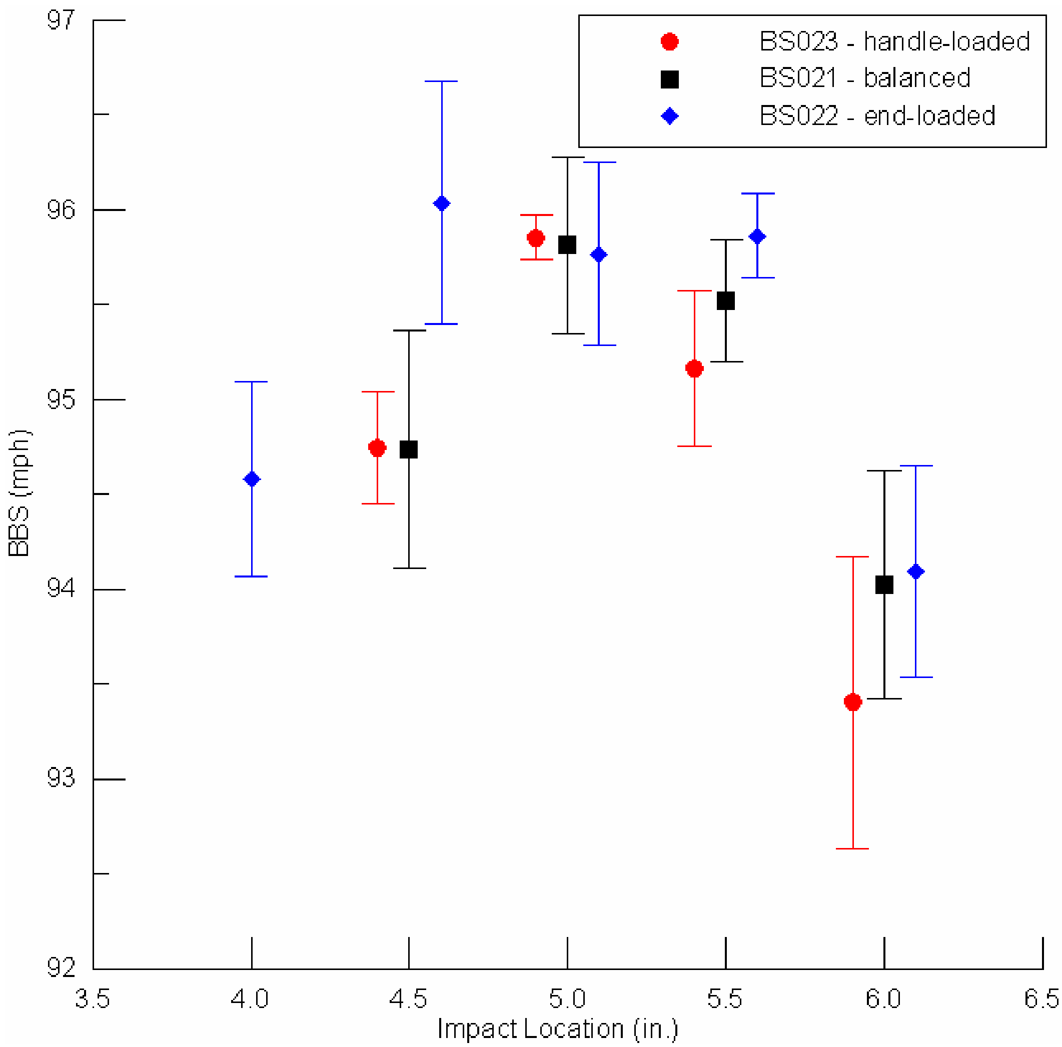

Figure 26 BBS for composite weight bats

4.6.2 Aluminum

The bats in this section were all made of C555 aluminum alloy. Weights of different sizes were added at different locations along the bat to achieve the desired properties.

4.6.2.1 Preliminary Results for the Aluminum Weight Bats

The weight measurements for the aluminum bats are presented in Table 40. These data show the three different weight classes to be approximately 31, 32 and 33 oz. The bats were intended to have the same MOIs, and as a consequence the CGs are different. The MOI values for the end-loaded and handle-loaded bats are very close, within 50 oz-in^2 of each other, but the balanced bat has an MOI about 200 oz-in^2 less than the other two. This MOI difference may result in the performance of the balanced bat being lower than the handle-loaded and end-loaded bats. The measurements for barrel-stiffness and handle-stiffness, shown in Table 41, are all very close.

Table 40 Weight measurements for the aluminum weight bats

Bat ID	Model	Length (in.)	Weight (oz)	CG (in.)	MOI (oz-in^2)
BS044	6-W-E	34.063	31.08	12.125	9724
BS043	6-W-B	34.000	32.26	14.875	9503
BS042	6-W-H	34.000	33.12	15.188	9677

Table 41 Barrel-stiffness and handle-stiffness measurements for aluminum weight bats

Bat ID	Model	Barrel Compression for Axial Location (lbs)			Hoop Freq (Hz)	Handle Flex (lbs)	1st Bend Freq (Hz)	2nd Bend Freq (Hz)	Handle Node (in.)	Barrel Node (in.)
		4 in.	5 in.	6 in.						
BS044	6-W-E	840	828	831	1920	162	156	595	5.8	7.3
BS043	6-W-B	842	829	832	1910	166	158	592	4.9	7.1
BS042	6-W-H	842	833	837	1920	164	152	581	4.4	7.2

4.6.2.2 Performance Results for the Aluminum Weight Bats

The performance results for the aluminum bats are presented in Table 42 and Figure 27. The performance results for these three bats are very close. There is a maximum BBS difference of less than a mph between the handle-loaded and end-loaded bats. The plot of the complete data in Figure 27 shows no real difference among the bats.

Table 42 Performance tests for aluminum weight bats

Bat ID	Model	Sweet Spot Loc. (in.)	BBS (mph)
BS044	6-W-E	6.0	96.7
BS043	6-W-B	6.5	97.0
BS042	6-W-H	6.0	97.4

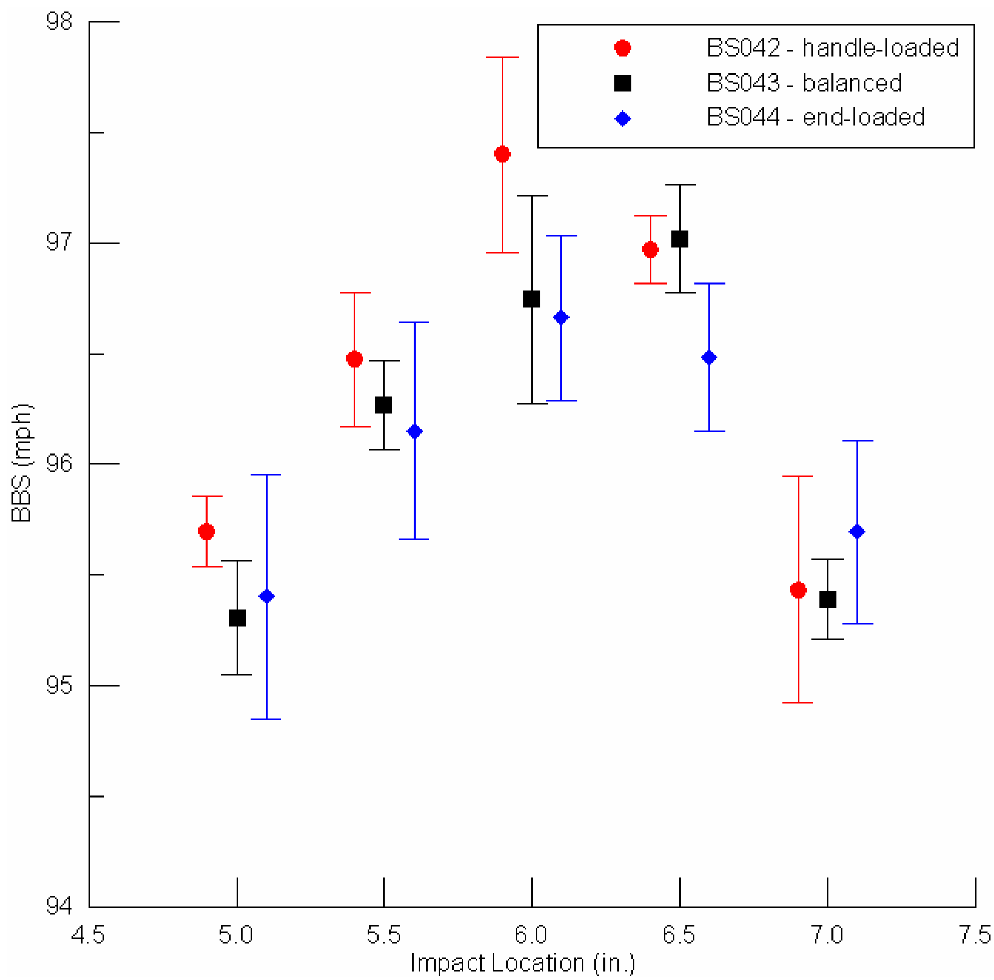

Figure 27 BBS for aluminum weight bats

4.6.3 Weight Summary

For both composite and aluminum bats, there is no significant difference in performance due to weight over the range of weights considered in this study. MOI has a much larger effect on performance than overall weight. Because the ball only "sees" a portion of the bat's mass during the collision, it makes sense that weight distribution, measured by MOI, has a larger effect on performance than the overall weight. A bat's weight can be easily changed by adding weight in the handle of the bat, but that mass will not affect either performance or swing weight if it is added near the axis of rotation.

4.7 Summary

Twenty-nine bats were tested to investigate the relationship between performance and:

- Barrel stiffness
- MOI
- Handle Stiffness
- Barrel Construction
- Weight

Each bat was manufactured to isolate a particular property. The results from the performance testing have been presented. The following sections summarize the results from each set of bats.

4.7.1 Barrel Stiffness

Batted-ball performance increases as barrel stiffness decreases for the range of stiffnesses tested. For the bats tested, a change in barrel compression of approximately 500 lbs resulted in a change in hoop frequency of 1500 Hz and a 3-mph difference in batted-ball speed.

4.7.2 Moment of Inertia

In the laboratory tests, performance increases as MOI increases. To calculate the effect of MOI on field performance, a swing-speed model must be used with the lab data.

For the composite bats tested, a difference of 3500 oz-in^2 resulted in a 12.8-mph increase in lab BBS. Using a swing-speed model, the projected difference in field performance for a 3500 oz-in^2 change in MOI was only 5.5 mph. For the aluminum bats tested, a difference of 3000 oz-in^2 resulted in an 8.8-mph increase in performance. The projected field performance difference for the aluminum bats was 2.5 mph. A limited amount of field testing was done, and the results showed no measurable difference between the different MOI bats. The field test results indicate that a swing-speed model must be used to predict field performance from lab test data.

4.7.3 Handle Stiffness

Two composite bats with different handle stiffnesses were tested in the lab. The high-stiffness bat hit about 1.6 mph faster than the low-stiffness bat after correcting for differences in MOI. Due to the limited amount of data and differences in barrel stiffnesses between bats, the performance difference due to handle stiffness could not be conclusively quantified.

4.7.4 Barrel Construction

One double-wall and two single-wall composite bats were tested in the lab. The limited data were inconclusive as to how barrel construction affects performance.

4.7.5 Weight

There was no measurable difference in performance due to weight when MOI was held constant.

5 Conclusions

Five baseball bat properties were studied through experimental methods: barrel stiffness, moment of inertia, handle stiffness, barrel construction and weight. The relationship between each property and batted-ball speed was experimentally investigated and critically analyzed using bats designed to isolate a particular bat property. The properties of each bat were quantified through a series of preliminary tests. Performance testing was done using an air cannon capable of projecting a baseball at a stationary bat at collision speeds typically seen in the game of baseball. The most significant properties were found to be moment of inertia and barrel stiffness. In the laboratory testing, using the same swing speed for all bats, batted-ball speed increased as the moment of inertia increased. A swing-speed model was used to project the effect of MOI from lab tests to field performance. For the bats used in this study, the range of batted-ball speeds decreased when using a swing-speed model versus a “one swing speed fits all” approach as was used in the laboratory testing. Field testing corroborated this observation. For the range of barrel stiffnesses studied, there was about a 3-mph change in batted-ball speed. Batted-ball speed increases as barrel stiffness decreases for the range of barrel stiffnesses studied. The effect of handle stiffness on maximum batted-ball speed was found to be small, approximately 1.5 mph for the range of handle stiffnesses studied in this thesis. Batted-ball performance was found to increase as handle stiffness increased due to less energy loss from bending vibrations. It is expected that the handle-stiffness effect would be larger for impact points farther from the sweet spot than were tested in this study. The barrel-construction data were inconclusive for the three bats tested. There was no measurable performance difference due to weight. The weight distribution (MOI) is much more significant than the overall weight.

6 Recommendations

Based on the results from the various parameters investigated in this thesis, several recommendations can be made for future investigations:

- A larger-scale field test than was conducted in this study is needed to determine the effect of MOI in the field.
- The lab experimental data on barrel construction from this study was inconclusive. It is recommended that more tests be run with single- and double-wall bats.
- It also recommended that more tests be run to better quantify the affect of handle stiffness on performance, including impacts away from the sweet spot.
- It would be beneficial to run field tests with different handle stiffness bats. Some players may be able to take advantage of a “whip effect” with flexible handle bats.

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APPENDIX A: NCAA BESR EQUATIONS

The definition of BESR used for NCAA certification is shown in Equation A1. The *NCAA_BESR* adjusts the inbound speed to be the speed at the 6-in. position, so each axial location on the bat is tested for the same angular swing speed.

$$NCAA\_BESR = \frac{V_{\mathrm{R}} - \delta v}{V_{\mathrm{I}} + \delta v} + 0.5 + < \varepsilon > \qquad \text{(A1)}$$

where V_{I} and V_{R} are the ball inbound and rebound speeds (in mph) for a test with a moving ball and stationary bat, $< \varepsilon >$ considers liveliness variations among ball lots, and

$$\delta v = 136 \text{ mph} - V_{\text{Contact}} \qquad \text{(A2)}$$

where 136 mph represents the relative speeds between the incoming pitch (70 mph) and the swung bat (66 mph as measured 6 in. from the end of the barrel) and $V_{Contact}$ is adjusted to account for bat-speed variation along the length of the bat:

$$V_{\text{Contact}} = (66 \text{ mph})\left(\frac{L-6-z}{L-12}\right) + 70 \text{ mph} \qquad \text{(A3)}$$

where L is the length of the bat (in inches) and z is the impact location measured in inches from the end of the barrel.

APPENDIX B: BARREL COMPRESSION PROTOCOL

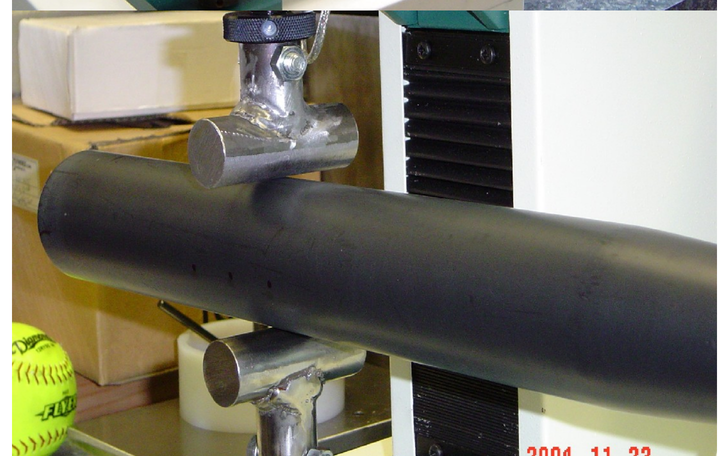
Barrel Compression Test Procedure

• Place the bat in the fixture, make sure the bat stays perpendicular to the axis of the loading fixtures.

• Apply 5 lbs pre-load to the bat between two cylindrical contact shapes (1.0” in diameter).

• Zero out both load and deflection gage and apply load on to the bat until it deflects 0.02”.

• Zero out both load and deflection gage again and deflect the bat 0.07”, note down the load (lbs). Use a load rate of 1”/ min.



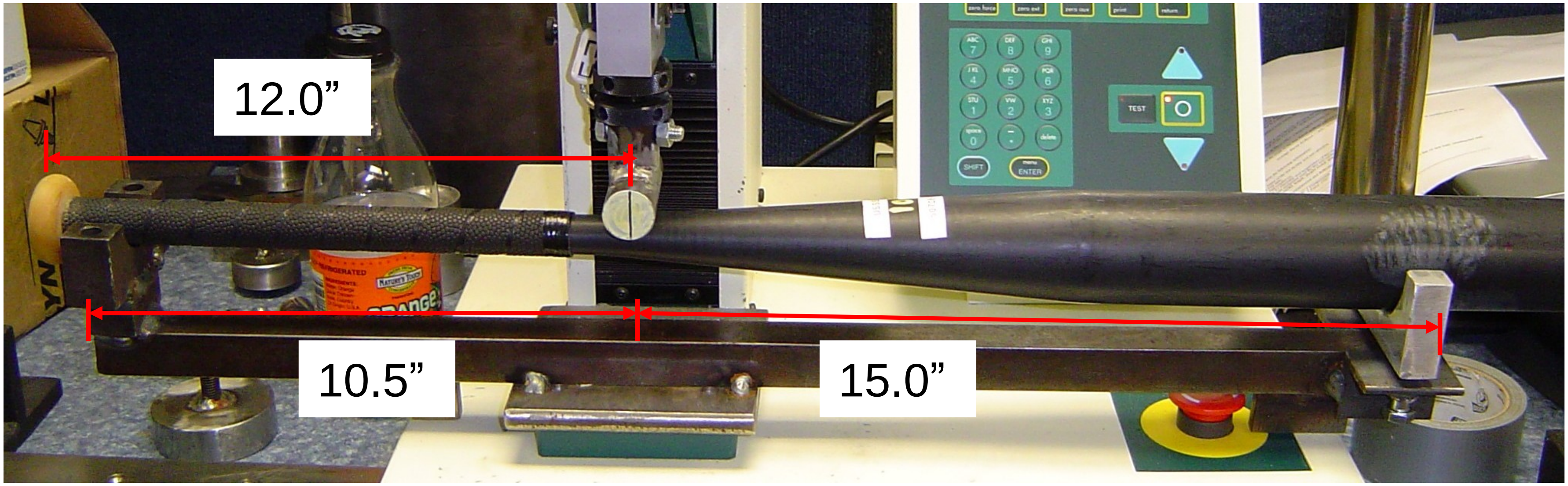
Note:

• Flex the bat at 4”, 5” & 6” away from the barrel end at 0°, 120° & 240° around the periphery for baseball bats.

• Flex the bat at 5”, 6” & 7” away from the barrel end at 0°, 120° & 240° around the periphery for softball bats.

APPENDIX C: HANDLE FLEX PROTOCOL

3 – Point Bend Tests – To Measure Handle Flex/Stiffness



- Place the bat in the fixture.
- Apply a pre-load of 5 lbs on the bat.
- Zero out load and deflection readings.
- Apply load on to the bat until the handle deflects 0.25”, a load rate of 1 in/min is sufficient.
- Note down the load values (lbs).