AN EXPERIMENTAL INVESTIGATION OF THE EVOLUTION OF COMPOSITE BASEBALL BAT PERFORMANCE USING ACCELERATED BREAK-IN PROCEDURES

BY

MATTHEW LEO BROE
B.S. UNIVERSITY OF MASSACHUSETTS LOWELL (2008)

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: ______________________________________ Date: _______________________
Matthew Leo Broe

Signature of Thesis
Supervisor: ____
James A. Sherwood, Ph.D.	Department of Mechanical Engineering
University of Massachusetts Lowell

Signatures of Other Thesis Committee Members:

Committee Member Signature: ____
Peter Avitabile, D.Eng.	Department of Mechanical Engineering
University of Massachusetts Lowell

Committee Member Signature: ____
Daniel A. Russell, Ph.D.	Department of Physics
Kettering University

Committee Member Signature: ____
Lloyd V. Smith, Ph.D.	Department of Mechanical Engineering
Washington State University

AN EXPERIMENTAL INVESTIGATION OF THE EVOLUTION OF COMPOSITE BASEBALL BAT PERFORMANCE USING ACCELERATED BREAK-IN PROCEDURES

BY

MATTHEW LEO BROE
B.S. UNIVERSITY OF MASSACHUSETTS LOWELL (2008)

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

Signature of
Matthew Leo Broe Date: December 21, 2010

Signature of Thesis Supervisor:

James A. Sherwood, Ph.D.	Department of Mechanical Engineering University of Massachusetts Lowell

Signatures of Other Thesis Committee Members:

Peter Avitabile, D.Eng.	Department of Mechanical Engineering University of Massachusetts Lowell
Daniel A. Russell, Ph.D.	Department of Physics Kettering University
Lloyd V. Smith, Ph.D.	Department of Mechanical Engineering Washington State University

AN EXPERIMENTAL INVESTIGATION OF THE EVOLUTION OF COMPOSITE BASEBALL BAT PERFORMANCE USING ACCELERATED BREAK-IN PROCEDURES

BY

MATTHEW LEO BROE

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE
DEPARTMENT OF MECHANICAL ENGINEERING
UNIVERSITY OF MASSACHUSETTS LOWELL
2010

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

Abstract

A representative set of baseball bats (comprised of several models and lengths various from several manufacturers,) were tested. The bat properties (hoop frequencies and barrel stiffness) were determined by impact modal and compression testing, respectively. Performance metrics (BESR, BBCOR and BBS) were calculated from high-speed air cannon system test data. Two different accelerated break-in (ABI) rolling procedures were used (displacement- and load-control). The test data were analyzed to track the evolution of each metric over multiple cycles, plotted to explore any trends and correlations between different metrics and evaluated to compare the two ABI methods simulating game use on a bat. It was found that composite baseball bats do breakdown causing an increase in performance in response to a decrease in barrel stiffness and hoop frequency. Correlations showed that as barrel stiffness and/or hoop frequency decrease, there is an increase in batted-ball performance. Game used bats and ABI bats similarly showed higher batted-ball performance during testing than new bats.

Acknowledgements

I would like to thank the following organizations and companies:

- NCAA that allowed me to use bats tested by the lab for my study.
- Anonymous bat companies that donated bats to my study.
- The GRGA and GSA for donating funds to my thesis.

In addition, I would like to thank the following individuals for their support or help with this research:

- Prof. James Sherwood, for taking me on as a graduate student in the Baseball Research Center, allowing me to do this research and helping me along the way.
- Prof. Peter Avitabile, for the lessons over both my undergrad and graduate careers and for serving on my defense committee.
- Profs. Daniel Russell and Lloyd Smith for serving on my defense committee.
- Patrick Drane, for his expert knowledge in the field of baseball sports engineering and testing.
- Glen Bousquet and Gary Howe for allowing the use of the mechanical engineering and civil engineering laboratories and equipment as well as their testing expertise.
- Keith Flynn and Matteo Forgione for machining and assembly of my load-controlled ABI roller setup.
- All of the graduate students in the UMLBRC, ACMTRL and Modal lab for giving me their support: Josh Jones, Andrew Sutton, Tim Connelly, John Fitek, Joe Sargent, Dave Cloutier, Jacqueline Buckley, Konstantine Fetfatsidis, Molly Clay and Chris Warren.
- The rest of the UML ACMTRL for giving me their support: Zeke Radik, Nicole Rondo, Dimitri Soteropoulos, Lisa Dangora, Prof. Julie Chen, Prof. Emmanuelle Reynaud and Dr. Samira Farboodmanesh
- All of the undergraduate students in the UMLBRC for giving me their support and help with my testing: Renzo Colossimo, Evan Gauthier, Steve Natoli, Allison Fidler, Eric Ruggiero, Anthony Fill and Joshua Hills.
- My family for their continued support in my education and in life.
- My roommate Brian Munroe for putting up with me and helping me along the journey of 6+ years of engineering.

Table of Contents

Section Page

List of Tables

Table Page

List of Figures

ACRONYMS

ABI	Accelerated Break-In
ASA	Amateur Softball Association of America
ASTM	American Society for Testing and Materials
BBCOR	Bat-Ball Coefficient of Restitution
BBS	Batted-Ball Speed
BESR	Ball Exit Speed Ratio
BP	Balance Point
COR	Coefficient of Restitution
FRF	Frequency Response Function
GUI	Graphical User Interface
LVS	LV Sports baseball bat performance cannon test system
MLB	Major League Baseball
MOI	Moment of Inertia
NBI	Natural Break-In
NCAA	National Collegiate Athletic Association
UMLBRC	University of Massachusetts Lowell Baseball Research Center

1 Introduction

Baseball originated as a game of hitting a ball with a solid wood bat. In the 1970s hollow aluminum baseball bats surfaced as a cost-effective alternative to the traditional wood bats. The aluminum bats were alleged to perform similar to the wood bats they replaced but had the advantage of being more durable than wood. The NCAA adopted the new hollow aluminum baseball bats, in 1974, as a means of reducing operating costs to teams since at the time aluminum bats cost $40 and were found to be very durable compared to wood [1]. The use of aluminum bats soon propagated to other levels of amateur baseball, e.g. high school and Little League. Despite the allegation that players and coaches felt the early aluminum bats hit comparably to wood [1], Major League Baseball (MLB) did not adopt the same position as the NCAA and continues to use only solid wood baseball bats. MLB defends its position by saying the exclusive use of solid wood bats maintains the tradition of the game.

With the introduction of hollow bats into amateur baseball, manufacturers started to produce higher performing baseball bats as they learned how to take advantage of the new design variables that came with a hollow aluminum bat. In 1986 the NCAA adopted a minimum weight criterion that limited how light an aluminum bat could be [2]. Even with the weight limit, the increase in performance of baseball bats led to an offensive advantage and compromised the balance of the game from that of wood as bat companies took advantage of new technologies and alloys. To restore the integrity of the game in 1999 the NCAA instituted a bat certification process limiting the ball exit speed ratio (BESR) to reign in bat performance and move to a wood-like standard in an effort to restore the balance of the game [2]. As the NCAA's understanding of bat performance evolved, the certification process evolved to accommodate the lessons learned over time.

Nonwood bats that perform significantly better than wood bats will not only hit a ball farther than wood, thereby resulting in more homeruns than wood bats but also hit a ball faster. These faster batted balls can develop a compromising situation for a pitcher who is less than 60 feet from the batter after he completes his throwing motion. The performance limit that was in force at the time this research was started was the Ball Exit Speed Ratio (BESR). The NCAA was reasonably satisfied with how BESR regulated the nonwood baseball bats, and the regulation would stay in place from 1999 until 2011 when the NCAA will switch to Bat-Ball Coefficient of Restitution (BBCOR).

Composite bats first appeared in 1993 in the form of graphite bats intended to be as durable as aluminum but perform similar to wood. However, due to the poor performance they disappeared from the market soon after their release because their low performance relative to the aluminum bats made them unpopular [3]. Composite bats would once again surface in the early 2000s in the form of carbon-fiber based bats. Companies learned how to design and produce very durable and high performing composites that would hit very close to the BESR limit just as aluminum bats could. However, a new concern arose due to the mechanical behaviors that composites exhibit which are significantly different than those of aluminum, this difference would eventually lead to moratoriums on composite bats in 2009 and 2010 by the NCAA [4] and NFHS [5]. A composite bat model was readmitted to the game after it passed an accelerated break-in (ABI) test procedure. This addition of an ABI criterion for the composite baseball bat certification occurred after credible test data became available showing that composite baseball bats do exhibit an improvement in performance with use.

Aluminum baseball bats have two primary modes of damage that can lead to ultimate failure—denting and cracking. Denting is more common than cracking. However, excessive denting can eventually lead to cracking. Cracking in the absence of denting is an indication of a brittle material behavior. In baseball bats, such cracking in the absence of denting may be a consequence of poor material processing. Regardless of whether the bat cracks or dents, such flaws can typically be found visually or by sliding a hand along the length of the bat, and the bat is removed from the game by the player, a coach or an umpire. Performance testing of “seasoned” aluminum bats with small cracks and dents has shown that such bats exhibit batted-ball speeds very similar to those when the bats were new [6].

Composite baseball bats are typically made of fiberglass and/or carbon yarns reinforcing a polymer-based matrix. These bats may be made using filament winding, braiding and/or the adding of layers using woven and/or braided fabrics. As a consequence of the manufacturing process, the composite can sustain damage by matrix and fiber microcracking and/or delamination. Both failure mechanisms can induce damage that is fairly undetectable at initiation and that can effectively soften the barrel of the bat, which can in turn result in an increasing batted-ball speed with increasing damage. As more damage is accumulated, the performance can continue to increase until the microcracks coalesce and propagate through the composite as macrocracks—making the bat unusable. This phenomenon has been documented for softball bats [7]. However, to date, no such comprehensive study has been completed for baseball bats. The objective of this thesis is to fill that void by studying a representative sample of composite baseball bats.

To determine the maximum performance of a composite bat, the useful life of the bat must be considered. The batted-ball performance of a new bat right "out of the wrapper" is not necessarily the same as a used bat. To account for the possible performance increase due to barrel damage, the ASA (Amateur Softball Association) has adopted an accelerated break-in procedure as part of the composite bat-certification process. The objective of an ABI process is to track the performance of bat throughout its useful life based on lab testing.

The scope of this thesis is to use the ABI process to investigate if and how the performance evolves for a representative sample of high school and collegiate composite baseball bats. To break in a composite bat naturally to the maximum performance could take hundreds of impacts on the field and therefore would be very time consuming. Thus, for this research, field-service damage will be induced using a rolling process—similar to what is used for the softball bat ABI process.

Two rolling methods are investigated to break-in the bats for this study. The first is a displacement-control rolling procedure (which is the current method used by the ASA for softball bats), and the second is a load-control rolling procedure. These two rolling methods will be compared and evaluated as a means of simulating game use of a bat to achieve a maximum batted-ball performance.

All rollers currently on the market are displacement-control, and therefore, are very well adapted for use on softball bats, as these bats have a constant-diameter barrel. However, baseball bats have a taper, and thus, using a fixed displacement will result in the pressure varying as a function of length as the bat is rolled. The constant-load rolling method will ensure that all of the rolled area of a baseball bat sees the same force.

2 Background

This chapter will discuss some history of baseball bats as they progressed from wood to today's composite baseball bats. Bat properties relevant to batted-ball performance in composite baseball bats will be discussed including moment of inertia (MOI), drop, modal response, barrel compression and material. To calculate the projected batted-ball speed in the field, the use of a swing-speed model will be required. Three different bat performance metrics will be presented including Ball Exit Speed Ratio (BESR), Bat-Ball Coefficient of Restitution (BBCOR) and Batted-Ball Speed (BBS). Finally, existing research in composite bats including accelerated break-in procedures and existing bat rollers will be discussed.

2.1 History of the Baseball Bat

When baseball was a new game in the 1850s, there was an experimental period where batters could use essentially any length, size or shape of wood bat they wanted. Batters soon learned that round baseball bats hit the best, and in 1859 a rule was passed that the maximum barrel diameter would be 2.5 in. In 1869, a rule was passed limiting the maximum length to 42 in. Up until the 1890s, bats could be flat (for use in bunting). The new rules passed in the 1890s stated all bats were to be cylindrical and have a maximum diameter no greater than 2.75 in. Today’s wood baseball bats do not differ much from the bats in the 1890s aside from being lighter and having thinner handles [3].

In 1924, the first patent for a nonwood bat was awarded. The patent (number 1499128) was issued to William Shroyer Jr. for a metal baseball bat [8]. Despite this patent, metal bats were not used until the 1970s when the first aluminum bats appeared in the game. After the first aluminum bats surfaced, competing companies began producing them as well by the late 1970s. Then, in 1993, titanium bats were beginning to be produced and in 1995 very light, strong aluminum bats were introduced as well [9]. Because of their exceptional batted-ball performance, the titanium bats were quickly banned.

The most recent nonwood addition to the game of baseball is the composite baseball bat. Composite bats are available for use in youth, high school and collegiate play. Composite bats allow for a much greater design freedom than is available with aluminum. Bat manufacturers now produce all-composite bats that are made from carbon fiber and/or fiberglass and a polymer-resin matrix. Composite bats also come in other combinations, e.g. composite handle with an aluminum barrel and composite handle with a wood barrel.

2.2 Baseball Bat Properties

This section will discuss a number of properties of a baseball bat including moment of inertia, drop, modal response, barrel compression and construction material. These properties are important in the performance testing of the composite baseball bats investigated in this study.

2.2.1 Moment of Inertia (MOI)

A baseball bat with a high MOI is what a batter would call a ‘heavy bat’—mmeaning that it is harder to swing than a bat with a lower MOI. Two bats can have the same weight but very different MOIs, i.e. one can have relatively light ‘swing weight’ while the other has a relatively heavy ‘swing weight’. This difference in swing weights for two bats of the same overall weight can occur due to the design freedom that bat manufacturers have to vary the weight distribution in a metal or composite bat. The MOI can be tuned by varying wall thickness and/or weighting the handle and/or tip of the barrel with a polymer (or other weighting material, e.g. steel pellets). Because a wood bat is made from a solid piece of wood, there is no option to add mass anywhere on the bat. Rather the MOI of a wood bat is a consequence of the combination of the density of the wood and the profile of the bat. To limit the design freedom of MOI such that the swing weights of nonwood bats are not significantly lighter than those of comparable-length wood bats, the NCAA and NFHS place limits on a minimum MOI for each length of nonwood bat [10].

2.2.2 Drop

Drop is a property of the bat dependant on the length and weight of the bat. Drop is defined by:

$$Drop = Weight - Length \tag{1}$$

where *Weight* is measured in ounces and *Length* is measured in inches. The maximum drop allowed by the NCAA is -3. The NCAA nonwood bat rule for drop is intended to regulate nonwood bats so bat manufacturers cannot create bats that are significantly lighter than their comparable-length wood counterparts. All of the composite bats used in this study are -3 drop bats.

2.2.3 Modal Response

All structures have natural frequencies. These natural frequencies are dependent on the mass and stiffness distributions across the structure. All baseball bats have bending modes and hollow (metal and composite) baseball bats also have hoop modes. The hoop modes of a hollow metal bat can easily be heard as the ‘ping’ sound that the bat emits right after it makes contact with the ball. Graphical representations of the first two hoop modes are in shown in Figure 1. The frequencies shown in Figure 1 are for a typical bat and show the relative magnitudes of the first and second hoop frequencies.

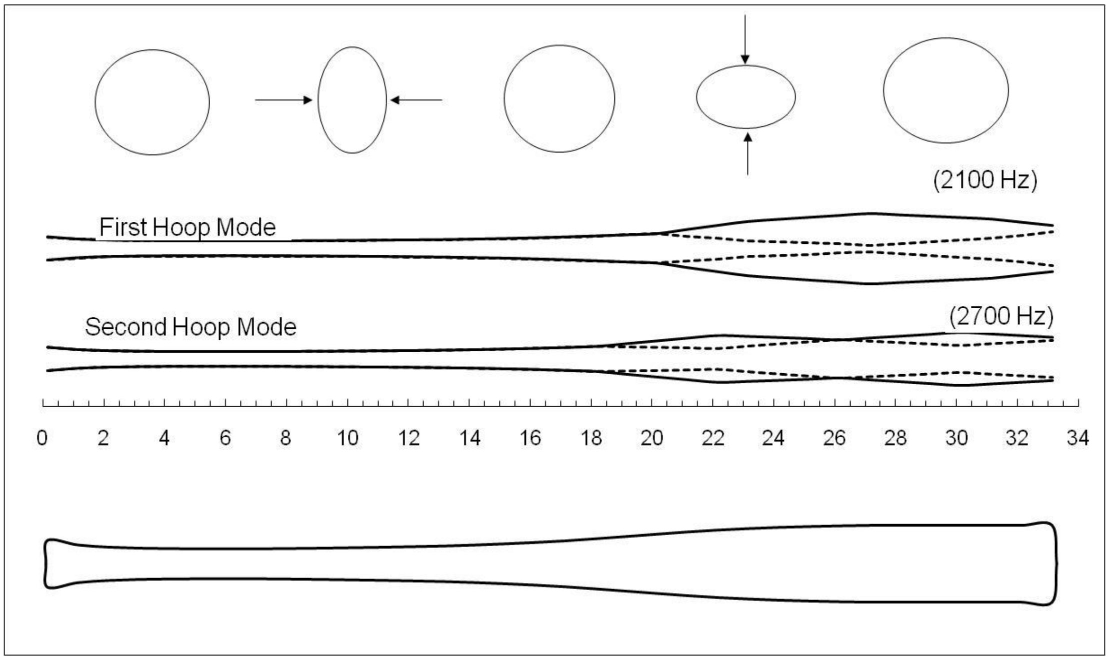

Figure 1. First two hoop modes of a typical 33-in. long hollow baseball bat. [11]

The hoop modes are important in the performance of a hollow baseball bat as shown by Nathan, *et.al.*[12]. Using a nonlinear mass-spring-damper model, Sutton [11] found that a first hoop frequency of around 1250 Hz will result in the optimal bat-ball collision efficiency by adapting the method used by Russell [13] to correlate softball bat performance with hoop frequency when he adapted the mass-spring model that Cochran used to model a golf club and ball interaction [14]. Figure 2 shows the results of the model over a range of hoop frequencies from ~500 to 10K Hz. Because the barrel is acting similar to a trampoline or spring during a collision, the hoop natural frequencies should be proportional to the mass and stiffness of the barrel shown by:

$$f \propto \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (2)$$

where f is the natural frequency in Hz, k is the stiffness in lbs/in and m is the mass in $\mathrm{lb_m}$.

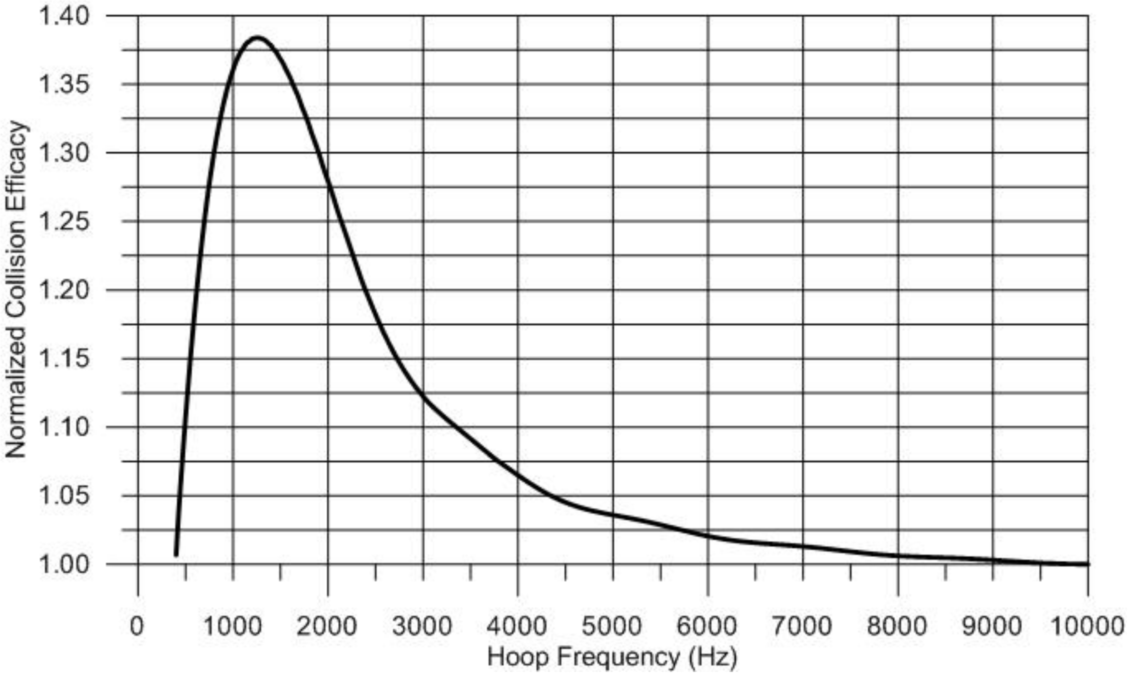

Figure 2. Normalized collision efficiency vs. hoop frequency. [11]

2.2.4 Barrel Stiffness

Linked to the modal response of a baseball bat barrel is the stiffness of the barrel. As stated in Section 2.2.3, the natural frequency should be proportional to the square root of the stiffness divided by the mass. Because the barrel can be modeled by a simple linear spring, the effective stiffness can be determined by Hooke's Law:

$$F = kx \tag{3}$$

where F is the force on the barrel, k is the stiffness of the barrel and x is the displacement of the barrel. Note that use of Equation 3 is dependent on the barrel acting as a linear spring. Composite baseball bat barrels are found to be linear after an initial barrel compression of 0.001 in. as shown in Appendix A.

2.2.5 Composites as a Bat Material

As mentioned in Section 2.1, there are three classifications of baseball bats, i.e. solid wood, hollow metal and composite. The majority of the composite baseball bats are hollow. These hollow composite bats are typically made using filament winding, braiding or layering of woven or braided fabrics made with fibreglass and possibly carbon yarns reinforcing a thermoset or thermoplastic matrix.

All material classifications of bats are subject to damage. Damage in solid wood bats typically occurs as a crack in the wood. After the crack has occurred, the bat is removed from service. Damage in aluminium bats develops in the form of dents or cracks. Once the dents and cracks form, the aluminium bat is likewise removed from service.

Composite bats can exhibit a relatively complex progression of failure. During everyday use, composite bats will develop microdamage in the form of microcracks in the matrix, fiber breakage and localized delaminations between adjacent plies. The microdamage will eventually propagate to gross cracking and delamination of the layers. However, before the bat is removed from service due to ultimate failure or excessive cracking, the damage to the barrel can be beneficial to the performance of the bat. As the microdamage is accumulated, the microcracks, fiber breaks and delaminations reduce the stiffness of the barrel which in turn reduces the hoop frequency and thereby can increase the ‘trampoline effect’ of the composite barrel.

2.3 Swing-Speed Model

The bat swing speed is dependent on the MOI of the bat and the ability of the player. In research to develop an understanding of the relationship between MOI and swing speed, Crisco and Greenwald [15] conducted the most comprehensive swing-speed study to date using high school and collegiate baseball players. The study was conducted at an indoor batting cage. The ball speed, ball trajectory and the bat angular speed were all tracked using a video system and subsequently the video data were analyzed to calculate pitch, swing and batted-ball speeds.

Using the data from this extensive swing-speed study, Nathan [16] developed an empirical swing-speed model. This swing-speed model is used in the current research to calculate a projected swing speed in the field as a function of the MOI of the bat. Fleisig [17], Adair [18] and Bahill [19] have also developed MOI based swing-speed models. However, the Nathan model is assumed to be the most credible at this time. Nathan’s model is based on a ‘standard’ baseball bat with properties as summarized in Table 1 and described by Equation 4.

Table 1. Swing-Speed 'Standard' Bat Properties

v_{bat0}	L_0	exp	MOI_0
66 mph	28 in	0.3	19000 oz-in^2

This linear speed of a given impact ‘band’ or axial location is given by:

$$v_{bat} = v_{bat0}\left(\frac{L-B}{L_0}\right)\left(\frac{MOI_0}{MOI}\right)^{exp} \tag{4}$$

where: v_{bat} is the velocity of the bat at a given band location (mph)
v_{bat0} is a constant: velocity of the 'standard' bat at the 6-in. band location (mph)
L is the length of the bat (in)
L_0 is a constant: effective length of the 'standard' bat
B is the band location of interest for bat speed (in)
MOI_0 is a constant: the moment of inertia of the 'standard' bat (oz-in^2)
MOI is the moment of inertia of the bat (oz-in^2)
exp is a constant: exponent value for the 'standard' bat player swing ability

The standard bat is a 34-in. bat that is pivoted about the location 6 in. from the base of the knob. The bat has a length of 28 inches beyond the 6-in. pivot. The exponent value (*exp*) used in this swing-speed model can be assumed to be the player's ability to swing a bat as explored by Nathan in his swing-speed model [16]. From these properties, the swing-speed model can calculate the linear speed of any impact location along the bat as a function of the MOI of the bat.

2.4 Batted-Ball Performance Metrics

This section will discuss the three performance metrics that will be used in this study. The metrics are Ball Exit Speed Ratio (BESR), Bat-Ball Coefficient of Restitution (BBCOR) and Batted-Ball Speed (BBS). These are three different ways of quantifying the performance of a bat-ball collision. Each of these metrics is currently used in the field of baseball sports engineering. The metrics can be found using a lab test that can be performed in any one of three possible configurations:

- A moving bat hitting a stationary ball, i.e. tee test
- A moving ball and moving bat

- A moving bat and a stationary bat, i.e. air cannon test.

The moving ball and stationary bat is the test configuration used in this thesis.

2.4.1 Ball Exit Speed Ratio (BESR)

BESR is the metric used by the NCAA between 1999 and 2010 to certify nonwood (metal and composite) baseball bats. The BESR test measures the pitched (inbound) and batted (rebound) velocities of the baseball to calculate the BESR of the bat. The BESR is calculated as,

$$BESR = \frac{V_{reb}}{V_{inb}} + 0.5 \qquad (5)$$

where: *BESR* is the Ball Exit Speed Ratio of a tested baseball bat (dimensionless)
V_{reb} is the rebound or 'batted' velocity of the baseball (mph)
V_{inb} is the inbound or 'pitched' velocity of the baseball (mph)

However, because different band locations along the barrel will have different linear velocities during a swing, Equation 5 is modified in the NCAA bat performance standard [10]:

$$NCAA\_BESR = \frac{V_{reb} - \delta V}{V_{inb} + \delta V} + 0.5 \qquad (6)$$

where: *NCAA_BESR* is the NCAA Ball Exit Speed Ratio of a tested baseball bat (dimensionless)
V_{reb} is the rebound or 'batted' velocity of the baseball (mph)
V_{inb} is the inbound or 'pitched' velocity of the baseball (mph)
δV is a correction term to account for linear speed of the bat at contact

The δV term in Equation 6 is required to account for the linear speed of the bat at the point of bat/ball contact and is calculated using.

$$\delta V = 136\, mph - V_{contact} \tag{7}$$

where $V_{contact}$ is defined by

$$V_{contact} = V_{swing}\left(\frac{L-6-z}{L-12}\right) + V_{pitch} \tag{8}$$

and where: $V_{contact}$ is the contact velocity of the baseball bat at the impact location (mph)
V_{swing} is the swing speed of the baseball bat (mph) as measured 6 in. from the tip of the bat
L is the length of the bat (in.)
z is the impact location measured from the tip of the barrel (in.)
V_{pitch} is the velocity of the pitched baseball (mph)

2.4.2 Bat-Ball Coefficient of Restitution (BBCOR)

The BBCOR is a measure of the efficiency of the bat/ball collision and accounts for the MOI of the bat and the mass of the ball. The BBCOR is calculated by

$$BBCOR = (BESR - 0.5)(1 + k) + k \tag{9}$$

where: $BBCOR$ is the Bat-Ball Coefficient of Restitution (dimensionless)
$BESR$ is the Ball Exit Speed Ratio (dimensionless)
k is defined by the equation $k = \frac{m_{ball}x^2}{MOI}$ (10)
where: m_{ball} is the mass of the ball (oz)
x is the distance between the pivot and impact locations (in.)
MOI is the moment of inertia of the bat about pivot (oz-in^2)

2.4.3 Batted-Ball Speed (BBS)

The BBS metric quantifies the projected batted-ball speed on the field. The BBS metric requires the use of a swing-speed model and can be calculated by,

$$BBS = v_{pitch}(BESR - 0.5) + V_{swing}(BESR + 0.5) \tag{11}$$

where: *BBS* is the Batted-Ball Speed of the baseball (mph)
V_{pitch} is the velocity of the pitched baseball (mph)
BESR is the Ball Exit Speed Ratio (dimensionless)
V_{swing} is the linear speed of the baseball bat at the point of contact (mph)

2.5 Relevant Existing Composite Baseball Bat Research

There is relatively little research on composite bats in the open literature. The majority of the research on these bats has been conducted by the bat manufacturers, and thus, the findings are proprietary. The papers that are public knowledge in the field of baseball as well as softball are discussed in this section.

2.5.1 Composite Softball Bat Modification

Cruz [7] and Smith, *et. al.* [20] explored accelerated break-in (ABI) procedures (which included rolling, a process Cruz referred to as ‘vising’ and hammering bats), weighting, shaving, natural break in (NBI) and bat painting. Figure 3 shows examples of bat shaving, bat hammers and ‘vising’.

Cruz demonstrated that all of these bat modifications provided an increase in batted-ball speeds for softball bats. Weighting a bat changes the MOI of a bat causing an increase in performance. Shaving thins the wall of a bat barrel thereby causing a stiffness reduction and a corresponding performance increase due to the increased ‘trampoline effect’. Bat painting does not change the performance of a softball bat, but it does allow for a player to disguise a non-certified bat as a certified bat providing a performance edge for the batter.

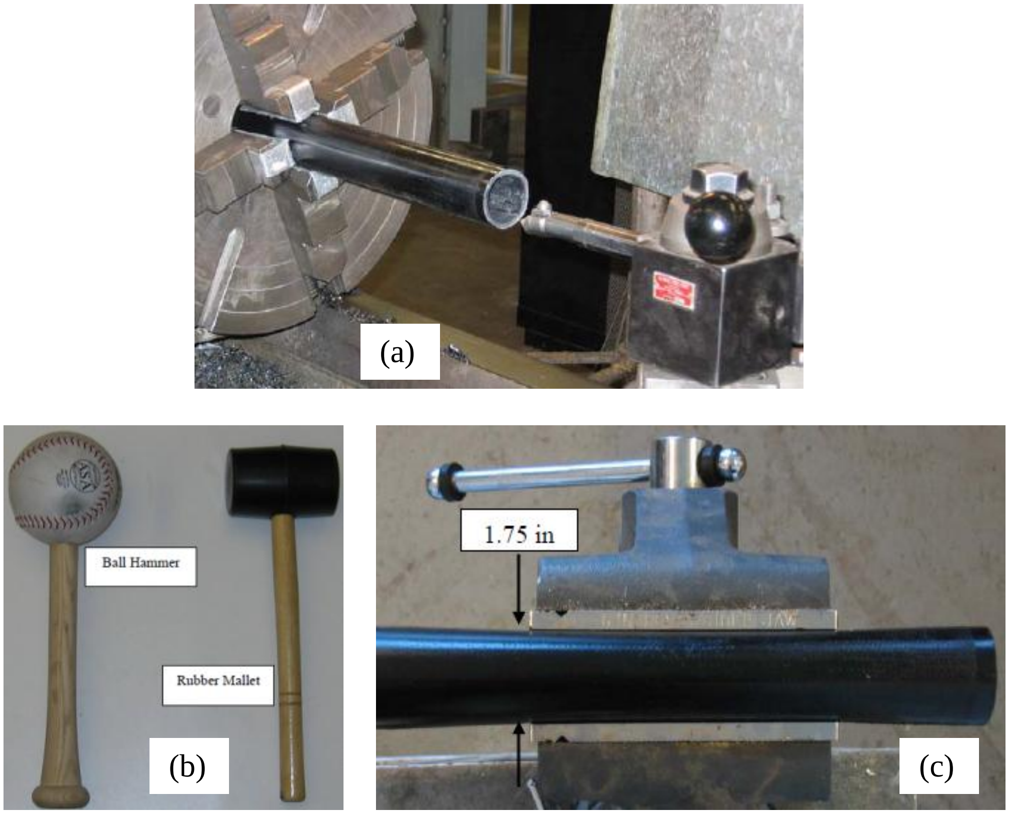

Figure 3. Bat modifications including: (a) bat shaving, (b) bat hammering and (c) bat 'vising'. [7]

The more relevant part of Cruz's study to the current research is the NBI and ABI procedures as the current study is focusing on the performance effects of 'breaking in' a composite baseball bat. Cruz defined an NBI bat as a bat that was broken in by intended use such as hitting pitched balls or hitting balls off tees. The theory behind 'breaking in' a composite bat is generally accepted by the baseball and softball communities that the composite bat will get 'hotter' or perform better once it has had several hundred good hits on it. An NBI procedure is merely a player naturally using their bat in games and practice. However, if the player was so inclined, he could bring his bat to a batting cage and hit balls to get the number of hits on the bat to jump up very quickly and accelerate the NBI.

An ABI procedure hopes to achieve the same result as a NBI procedure but on a much shorter timescale than the NBI process and not necessarily require any use in play before the batter sees the performance effects of breaking in a bat. Cruz defined an ABI technique as one that does not physically alter the bat (as shaving or weighting) but instead induces damage to the barrel of a composite bat, which in turn reduces the barrel stiffness to cause a performance increase due to increased 'trampoline effect'.

Cruz described two forms of ABI that a player could easily perform at home which included hammering or 'vising' a bat. Hammering a bat consisted of a player taking their composite bat and impacting it with a rubber mallet or a specialized 'ball hammer' which was a softball mounted on a handle. Squeezing a bat in a vise—termed 'vising'—was a very extreme means of altering a bat. The process of 'vising' a bat involved compressing it typically from 0.5-0.75 in. or more if the player was not worried about durability issues. What Cruz called 'bat doctoring' was the third form of ABI techniques which has evolved into the process of bat rolling.

Cruz investigated the effects of an ABI process on several metrics including MOI, first flexural or bending frequency, first hoop frequency, barrel stiffness and BBS. Cruz found that MOI and first flexural frequency were unaffected by ABI techniques (shown in Figures 4 and 5, respectively).

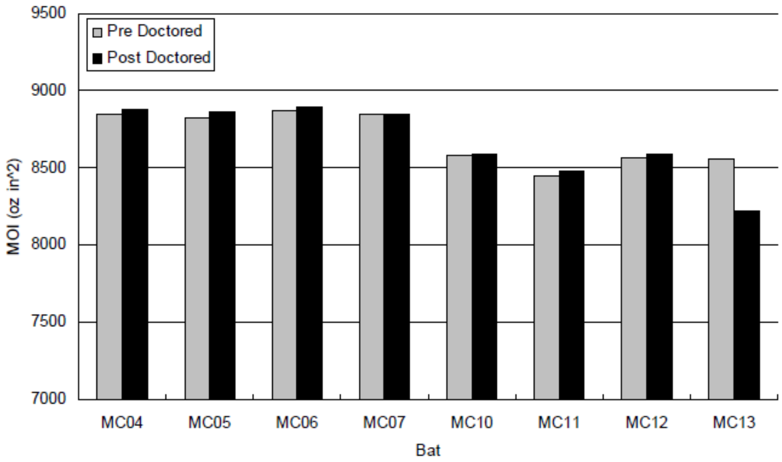

Figure 4. No significant change to MOI as a result of ABI. [7]

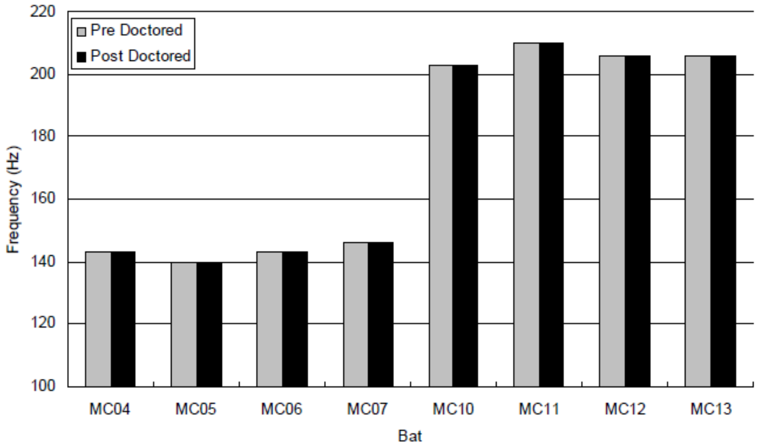

Figure 5. No significant change to first bending frequency as a result of ABI. [7]

Cruz also found that both barrel stiffness (Figure 6) and first hoop frequency (Figure 7) decreased after an ABI technique while the performance (BBS) was increased (Figure 8). Cruz also noticed that the bats with the largest BBS performance increase had the most visible damage to the barrel in the set of ABI bats (Figure 9).

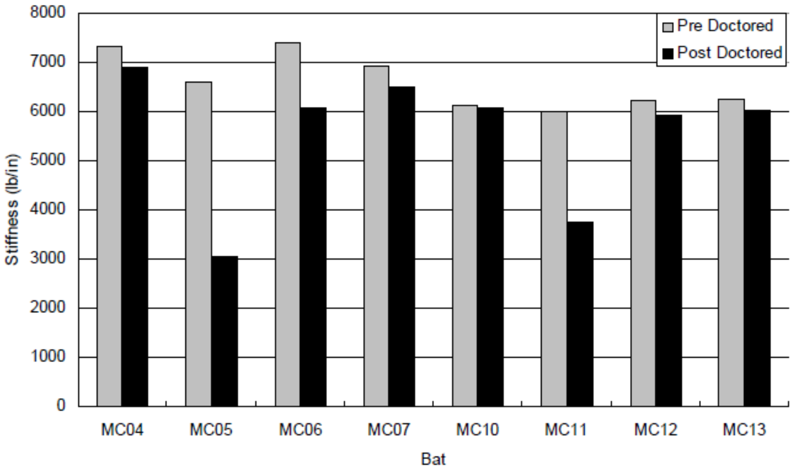

Figure 6. Decrease in barrel stiffness as a result of ABI. [7]

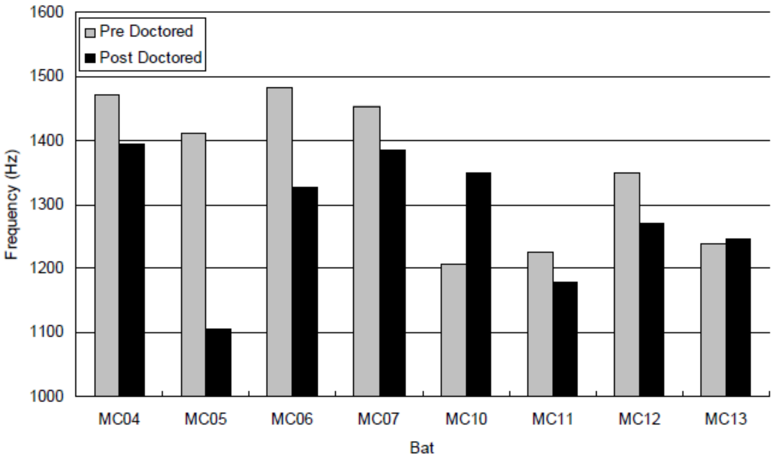

Figure 7. Change in first hoop frequency as a result of ABI. [7]

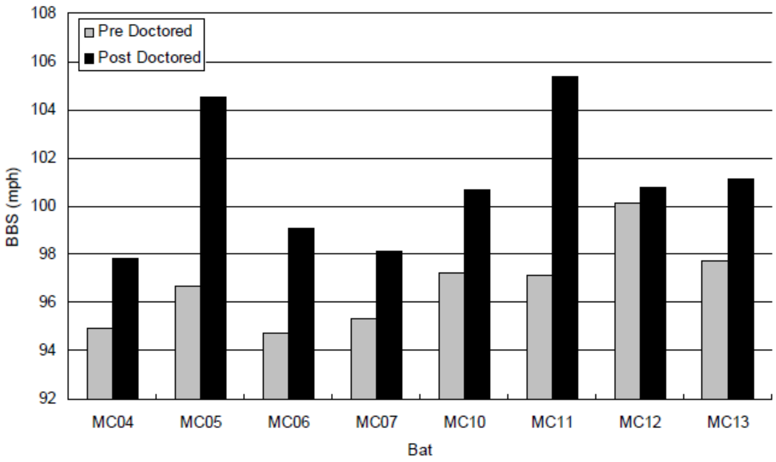

Figure 8. Increase in BBS as a result of ABI. [7]

Figure 9. Damage to ABI bat. [7]

NBI bats that were tested did not exhibit any visible damage while there were also performance increases after rounds of 500 hits were put on the bats (Figure 10). As with the ABI group, the NBI group showed a drop in first hoop frequency (Figure 11) and barrel stiffness (Figure 12). There was no significant change in first flexural frequency (Figure 13) after NBI.

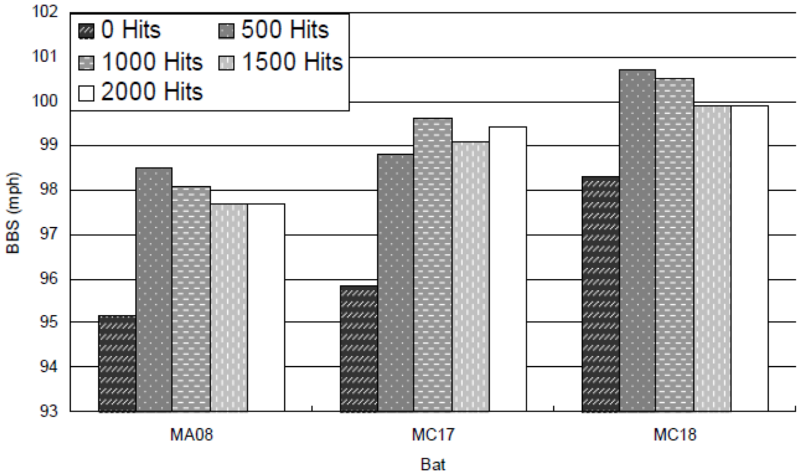

Figure 10. Change in BBS as a result of ABI. [7]

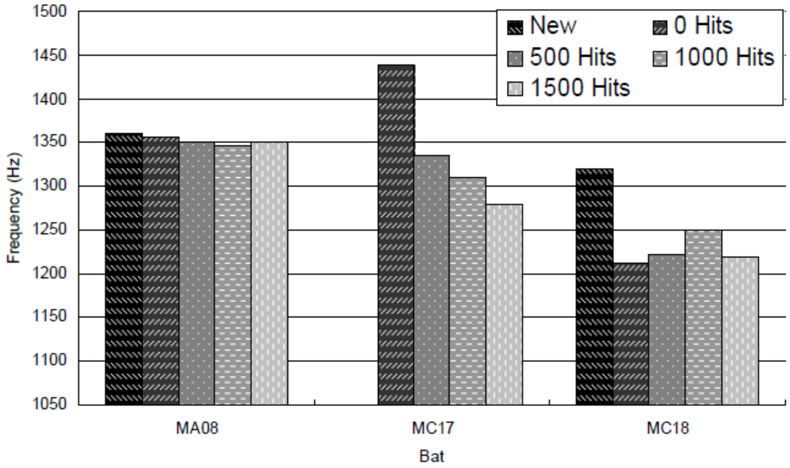

Figure 11. Change in first hoop frequency as a result of NBI. [7]

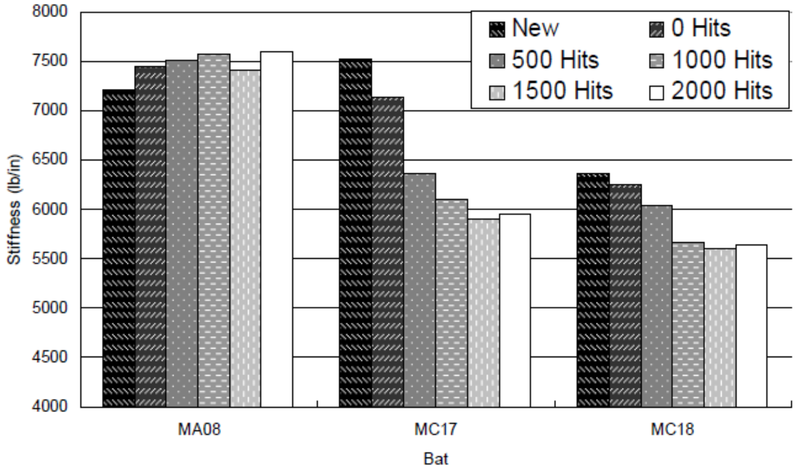

Figure 12. Change in barrel stiffness as a result of NBI. [7]

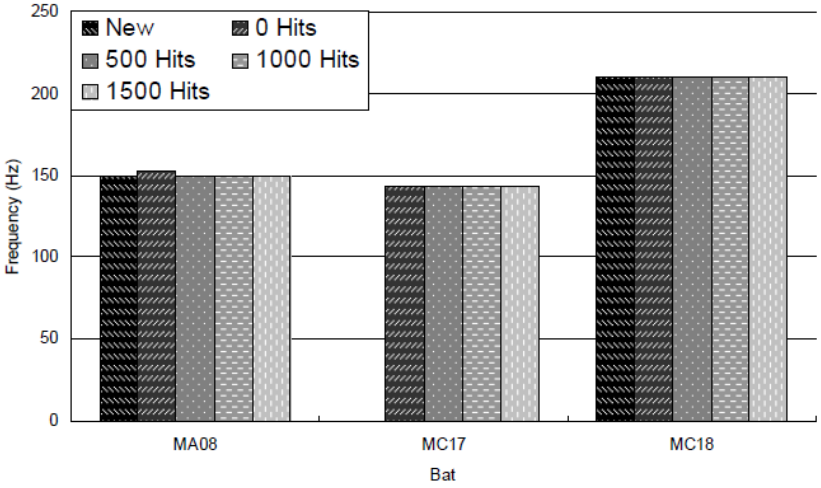

Figure 13. No significant change to first bending frequency as a result of NBI. [7]

It was also apparent that the performance increase due to NBI was roughly the same as the increase displayed by the ABI group. This extensive study was performed on softball bats. There has been significantly less research done on baseball bats before now.

2.5.2 Composite Baseball Bat Durability

Sherwood and Drane [21] conducted a small experimental study to explore the effect of use on the performance of composite baseball bats. This study used six popular composite baseball bats and one aluminum bat as a control for the experiment. The baseball bats were subjected to a performance test followed by rounds of 100 hits in a durability machine before each performance test. The bats were cycled through 100s of hits and performance testing until the bats developed easily noticeable damage. The durability machine is capable of firing baseballs from an air cannon at speeds up to 200 mph and can be programmed to scatter hits along the length of the barrel. The durability machine was programmed to simulate game play (i.e. speeds from a slow knuckleball up to a fastball and scattered along the length of the barrel). The study did not show an increase in performance, but this lack of any increase was likely due to the fact that all but one of the composite bats used in the study failed before 200 hits were put on the bat. Figure 14 shows the change in max BESR during the useful life of the test bats, and Table 2 summarizes the same data. In Figure 14, the legend denotes the aluminum bat as M1 and the composites bats with a C prefix on the Bat ID. The same nomenclature is used in Table 2.

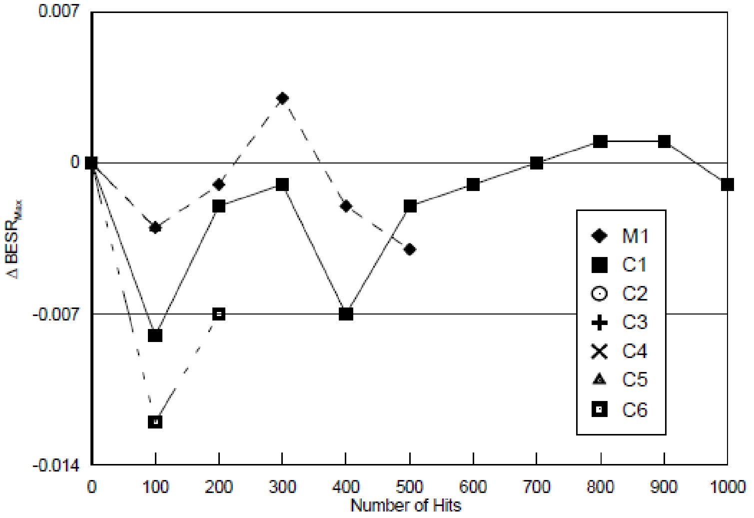

Figure 14. Change in maximum BESR during NBI testing. [21]

Table 2. Change in Maximum BESR during NBI testing. [21]

Bat ID	Number of Hits										
	0	100	200	300	400	500	600	700	800	900	1000
M1	0.000	-0.003	-0.001	+0.003	-0.002	-0.004	--	--	--	--	--
C1	0.000	-0.008	-0.002	-0.001	-0.007	-0.002	-0.001	0.000	0.001	0.001	-0.001
C2	--	--	--	--	--	--	--	--	--	--	--
C3	0.000	--	--	--	--	--	--	--	--	--	--
C4	0.000	--	--	--	--	--	--	--	--	--	--
C5	0.000	-0.003	--	--	--	--	--	--	--	--	--
C6	0.000	-0.012	-0.007	--	--	--	--	--	--	--	--

This study showed that some composite bats had a significant durability issue. Figure 15 shows a bat that broke before getting 100 hits. The one bat (C1) that did last 1000 shots did not show significant change in performance and merely oscillated about its original performance until the bat failed. This bat may or may not have been intentionally designed to exhibit no performance increase with use.

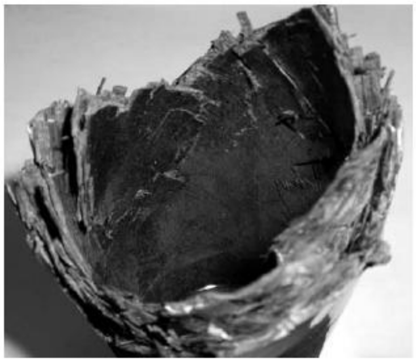

Figure 15. Low durability baseball bat that had barrel separation from a NBI. [21]

2.6 Available Bat Rollers/Performance Claims

There are several websites that pop up when a search is performed on the topic of ‘bat rolling’. There are typically two types of websites: ones that offer bat-rolling services and those that sell bat rollers directly to consumers. There are also sites that will do both (sell rollers and perform rolling on single bats). These online websites make it very easy for a baseball player, parent or even a coach to modify bats by rolling it themselves or by sending it out to be rolled to get a performance increase.

Sites that will accept bats from customers, then roll and ship the bats back cost between $25 and $50 for a single bat. The more expensive sites claim that the cheaper vendors cut corners and that you will not see the correct performance increase or even worse have a broken or visibly damaged bat. The cheaper sites focus on saying that they understand customer satisfaction and can provide the same results for less.

There are a few different bat-roller designs available for purchase. The various designs tout specific design features to consumers. These rollers can cost anywhere from $360 to over $500 depending on the site.

Figure 16 shows a typical perpendicular bat roller, i.e. the bat travels through the rollers perpendicular to the direction of the travel of the rollers. The load is applied to the barrel by cranking the top screw drive down a specified number of turns. The displacement is related to the amount of rotation of the crank by the pitch, i.e. threads per unit length:

$$pitch = \frac{threads}{length} \qquad (12)$$

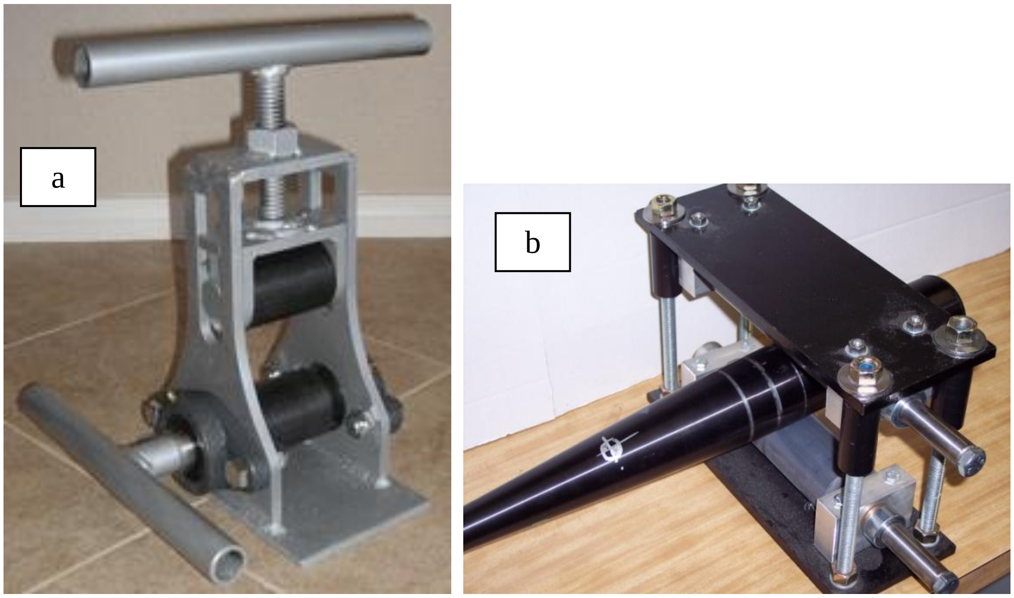

Figure 16. Typical perpendicular bat roller [22] (a) and bat loading (b).

A second type of roller is a parallel bat roller as is shown in Figure 17. In the parallel roller, the bat is loaded and rolled in a direction parallel to the two rollers. This rolling method allows for the entire bat barrel to be rolled at once in a radial fashion which is designed to produce a very even break in for constant-diameter-barrel bats, e.g. softball and youth bats. This type of roller differs from the perpendicular method where a bat travels in a linear fashion through the rollers which applies a load to a limited section of the barrel as the bat travels back and forth through the roller.

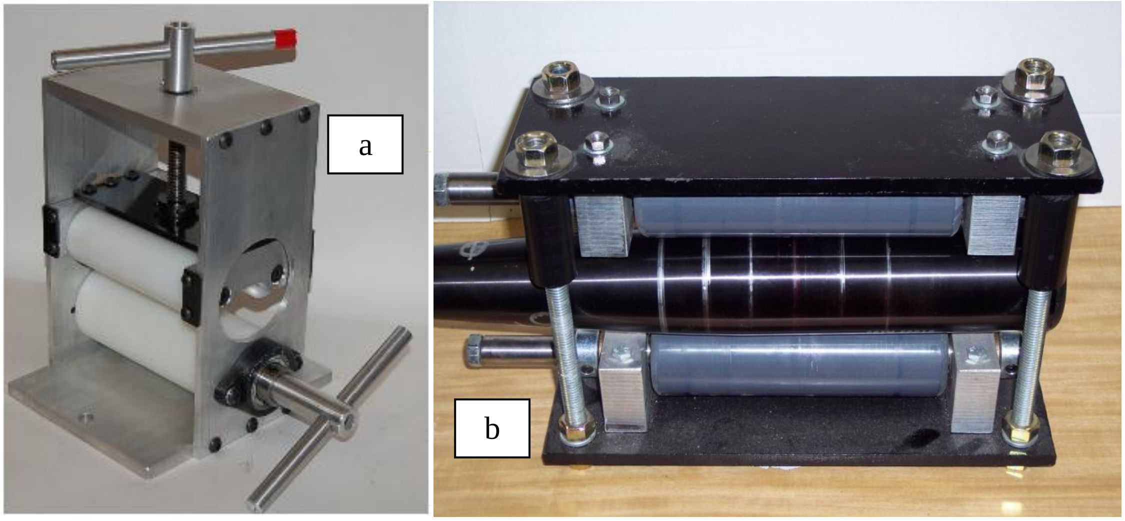

Figure 17. Typical parallel bat roller [23] (a) and parallel loading (b).

The parallel type of roller is much more versatile in the respect that the user can also roll a bat through the parallel bat roller in a perpendicular fashion if desired. In fact there are companies that advertise this versatility of their design [24]. A manufacturer's roller that makes this type of claim can be seen in Figure 18. The particular roller shown in Figure 18 also has the unique design feature that the roller uses a bottle-style jack to apply a load as opposed to the previous two types of rollers that both used the displacement crank method described earlier. A bottle-jack roller allows the user to set load in psi as output on a psi gauge (shown in the bottom of Figure 18). This design feature is interesting because it allows the user to monitor the load on the bat during the rolling process. One drawback is the jack maintains a fixed displacement, so the force on the barrel does change as the diameter of the bat within the roller varies along the length of the bat. One advantage of the using the pressure gauge is that instead of having to calculate the displacement to put on the bat (or trusting the roller manufacturer's directions for how many 'turns' to use when rolling) the user knows the applied load.

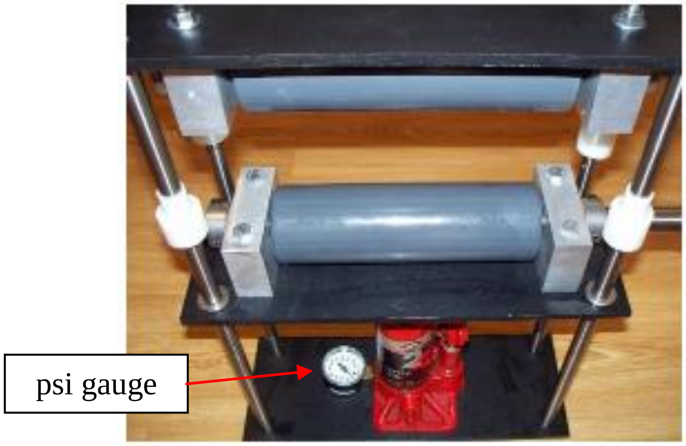

Figure 18. Load monitoring bat roller.[24]

The companies that will perform bat rolling for customers claim that their bat rolling process simulates several hundred hits on the composite bats (usually around 500 hits) and expedite the break-in process of composite bats while not shortening the life of a composite bat. They claim that the customer's bat will have no dead spots and the barrel will be completely broken in. Some of the bat rolling sites claim the process works by breaking fibers and cracking the resin while other sites claim that their process actually stretches the fiber of a composite bat to make it more flexible. Because the fibers are linear elastic and most likely have a strain to failure of ~1%, the stretching feature is more hype than truth and may be a reflection of the limited knowledge of composites by the parties performing such services. The breaking of fibers has the main goal of increasing the trampoline effect through a reduction in the stiffness of the composite material. Some sites also claim that the sweet spot will increase in size as well. All of the sites make a general blanket claim that the batted-ball speed will be greater and the distance of a hit will be farther. Some sites make very specific claims such as 5 mph faster, anywhere from 15-60 ft more distance or an overall percent increase in performance. Some sites even offer graphical performance increase numbers as shown in Figure 19.

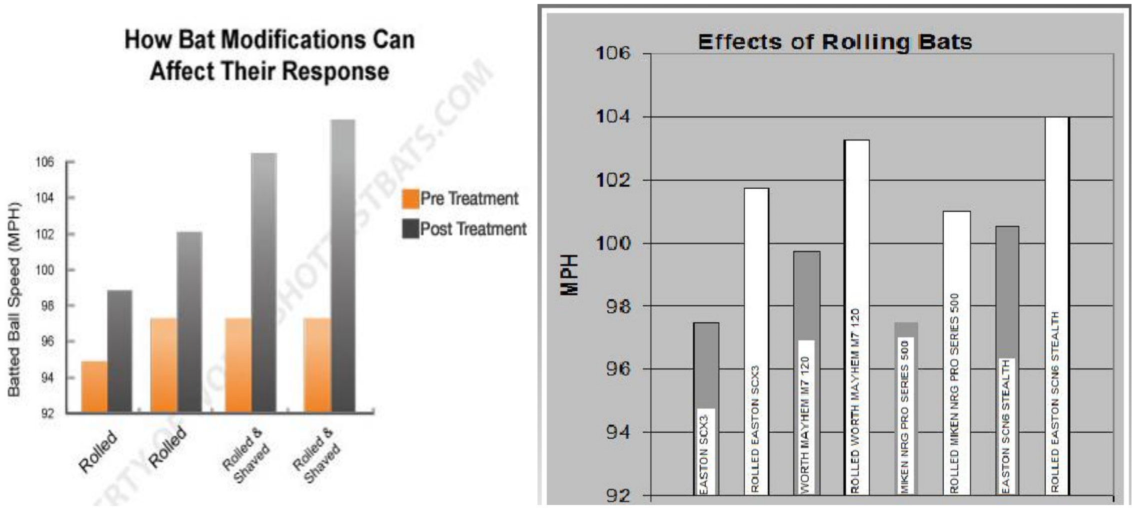

Figure 19. Example of bat roller graphical performance claims. [25, 26]

Companies producing rollers include, but not limited to the following:

1. World Hottest Bats. 27 May 2009 <http://www.worldshottestbats.com/>.
2. Composite Bat Rolling 27 May 2009 <http://compositebatrolling.com/>.
3. Bat Rolling 27 May 2009 <http://batrolling.com/>.
4. Bat Rolling 4U 27 May 2009 <http://batrolling4u.com/>.
5. Dunit Gear 27 May 2009 < http://dunitgear.com/break-in-your-bat-by-rolling-it-use-ppr320+-bat-rolling-machine.html>.
6. Big Dawg Bat Rolling 27 May 2009 http://bigdawgbatrolling.com/
7. Go Deep Batrollers 17 June 2010 http://godeepbatrollers.com/

2.7 Summary

This chapter overviewed the pertinent background information for the current study. The first background information discussed was the evolution of baseball bats from wood to aluminum bats and finally to composite bats.

After the bat as it is known today was described, the different properties of a bat that affect the performance of a bat were discussed. Some of the properties are regulated directly by the NCAA such as the MOI and the drop of the bat. Modal response and barrel stiffness were introduced, and their relevance to the batted-ball performance of hollow bats, especially for composite bats, was discussed.

The batted-ball performance testing background was discussed. Swing-speed models that have been developed from swing-speed studies were discussed. A good swing-speed model is important to accurately determine performance for the three different metrics discussed in this study including BESR, BBCOR and BBS.

Finally the existing composite bat research was discussed. There is relatively limited existing research in the public domain on composite bats. The durability as well as modification of composite bats has been previously explored and presented. The different existing bat rollers on the market today and what they claim they will do for performance increases on a typical bat were presented.

3 Methods

This chapter outlines the testing procedures and methods followed during the testing of each composite baseball bat. These procedures ensured a consistent testing methodology was followed for all bats. All the bats used in this research were new.

3.1 Bat Preparation and Test Method Overview

When a bat was received new, it was assigned an inventory number, an inventory tag was attached, and the grip was removed. A pre-inventory form was used to record the weight and length of the bat, and the inventory number. This information was then entered into the baseball bat inventory database which is used to keep track of all the baseball bats in the lab.

The bat was then profiled. Profiling involves having rings drawn on the barrel at the 3-, 4-, 5-, 6-, 7-, 8- and 9-in. locations measured from the tip of the barrel using a permanent marker. A ring was also drawn around the handle at the pivot point that is used for testing (6 in. from the base of the knob). This pivot point is assumed to imitate a batter swinging the bat around this point when hitting a ball. The diameter of the bat at each of these marked locations was determined by use of vernier calipers and recorded.

After the baseball bat was profiled, the balance point (BP) of the bat and the moment of inertia (MOI) were found. The procedure for finding the BP and the MOI are described in Section 3.2.1.

The next step was a modal test to determine the modal characteristics of the baseball bat. The procedure for determining the modal properties through modal testing and analysis is described in Section 3.2.2. The barrel stiffness was measured by means of a barrel compression test. The procedure for barrel compression testing is discussed in Section 3.2.3. After these properties of the baseball bat were determined, the initial performance test was completed on the new bat.

Performance testing was done using an LVSports bat performance testing system as described in Section 3.2.4. There were three performance metrics that are used in this study, specifically Ball Exit Speed Ratio (BESR), Bat-Ball Coefficient of Restitution (BBCOR) and Batted-Ball Speed (BBS). The balls used for performance testing were prepared using the methods described in Section 3.3. After the initial performance testing was completed, the compression and modal tests were redone prior to an ABI procedure.

ABI was accomplished using one of two different rolling methods, displacement-control or load-control. The ABI procedures used are discussed in Sections 3.4. The ABI procedure was used to simulate the useful life of a bat without the need to put hundreds of hits on the bat which would be both costly and time consuming for one test. After the rolled bat reached the target barrel-stiffness reduction (just over 5% of the starting barrel stiffness), the bat was again performance tested. The process continued until the BESR performance dropped off by a minimum of 0.014. After seeing such a drop, the maximum performance the bat can reach during its life was stated to have been achieved. A graphical version of the process is shown in Figure 20.

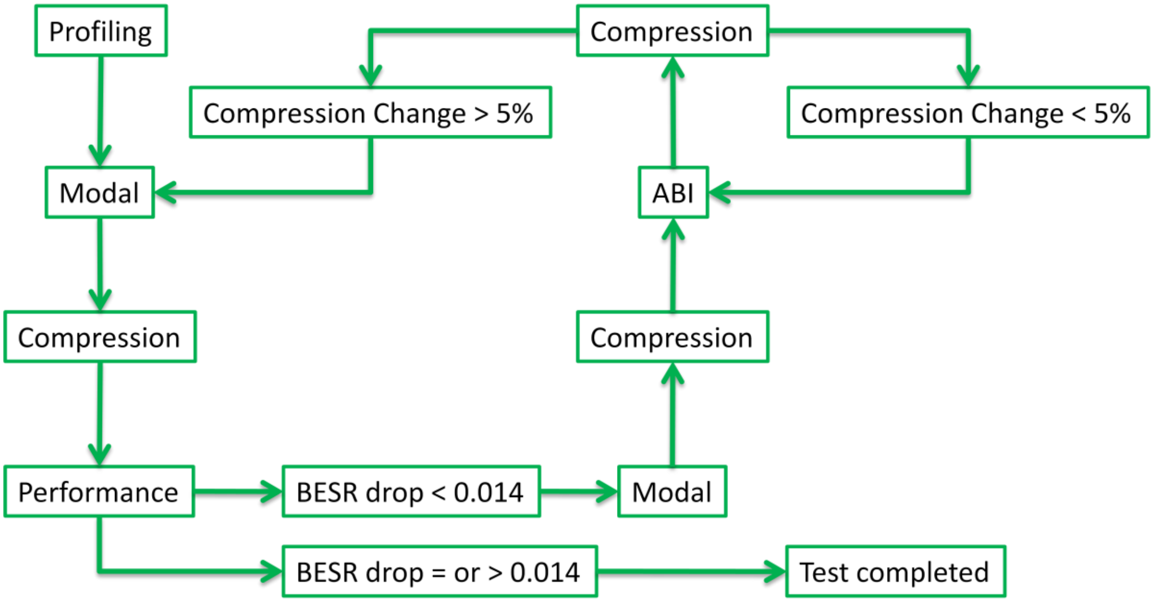

Figure 20. Flow chart of testing procedure.

3.2 Bat Methods

This section will discuss the methods used to test a composite baseball bat for this study. All of these methods are typical to the UMLBRC and follow any available ASTM or NCAA standards relevant to the test.

3.2.1 Bat Balance Point (BP) and Moment of Inertia (MOI)

The BP, also known as the center of mass and the center of gravity, of a bat was determined by following the ASTM Standard F2398-04 for MOI and COP [27]. The BP of a bat was determined by use of two scales. The scales were positioned 18 in. apart, and the bat was placed on the scales so that the knob is 6 in. from the first scale. The schematic of the test setup from the ASTM standard and the actual test setup are shown in Figure 21.

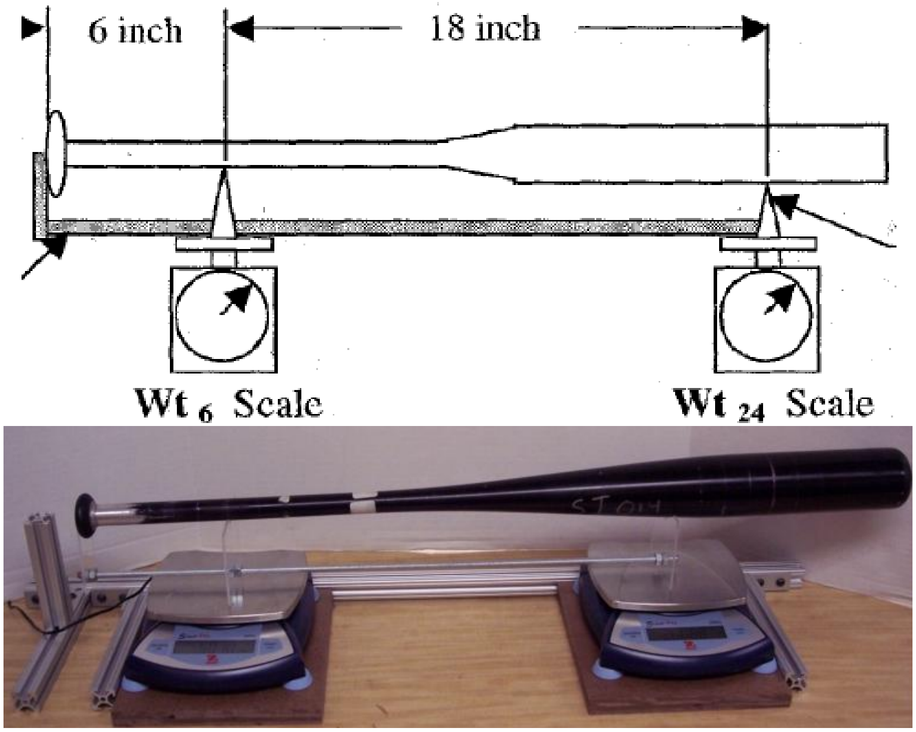

Figure 21. Test fixture to determine the balance point of a baseball bat. [27]

After the bat had been placed in the fixture, as shown in Figure 21, the weights of the two scales were recorded and used to calculate the BP using,

$$BP = \left[\frac{6 * Wt_6 + 24 * Wt_{24}}{Wt_6 + Wt_{24}}\right] \tag{13}$$

where: *BP* is the balance point of the baseball bat as measured from the base of the knob (in.)
Wt_6 is the weight at the location 6 in. from the base of the knob (oz.)
Wt_{24} is the weight at the location 24 in. from the base of the knob (oz.)

The moment of inertia was determined by measuring the period of the bat swinging while pivoted about the 6-in. location when measured from the base of the knob as shown in Figure 22. This test setup and procedure follow the ASTM standard for MOI and COP [27]. The schematic of the MOI test fixture setup is shown in Figure 22.

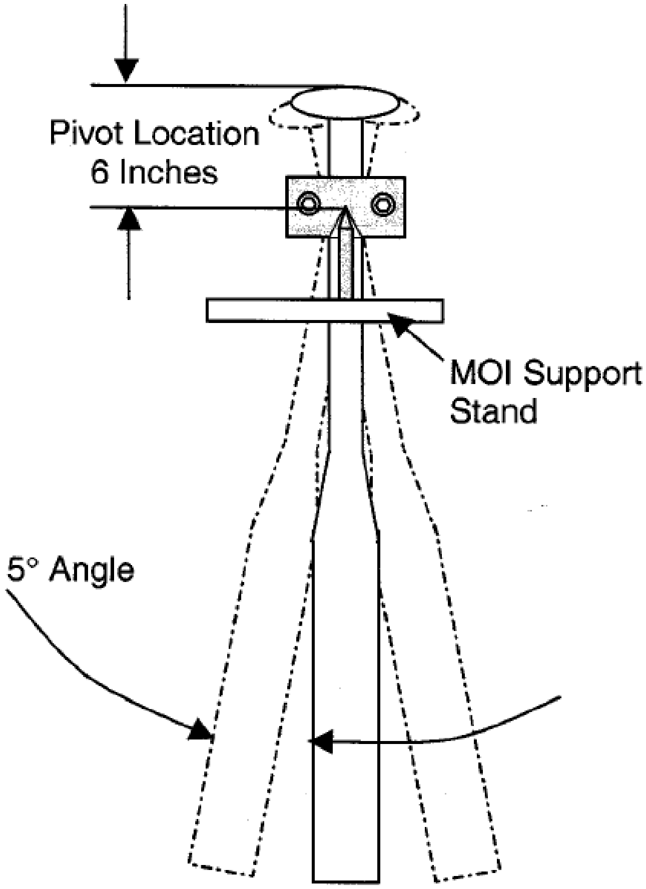

Figure 22. Test fixture to determine the MOI of a baseball bat. [27]

The period of the swinging bat was measured using a light gate. The data were recorded using a data acquisition system powered by a LabVIEW program. The

LabVIEW program also calculated the MOI internally using the equation given in the ASTM standard for MOI and COP [27].

$$I = \left[\frac{{P_{Avg}}^2 * g * W_t * (BP-6)}{4 * \pi^2}\right] \tag{14}$$

where: I is the moment of inertia of the bat (oz-in^2)
P_{Avg} is the average period of the swinging bat (s)
g is acceleration due to gravity (386.1 in/s^2)
W_t is the total weight of the bat (oz.)
BP is the balance point of the baseball bat from knob (in.)

The bat was set into oscillation like a pendulum, and the program was then started by interfacing with the graphical user interface (GUI). The LabVIEW GUI output the MOI that had been calculated using Equation 14. The MOI was recorded, and then this process was repeated four more times. The five test values for the MOI of the bat were averaged to get the effective MOI of the bat.

3.2.1 Modal Analysis

Modal analysis can be performed on any object or structure to determine the natural frequencies or modes of the system. Baseball bats have two different kinds of natural frequencies. The first set are bending modes which have their first two modes at relatively low frequencies (~100-500 Hz), and the second set are comprised of the hoop modes which are only present in hollow bats and at relatively higher frequencies (~1000-3000 Hz) for the first two hoop modes.

These natural frequencies of a baseball bat were determined by an impact modal analysis test. The bat was hung by elastic cords in a simulated free-free boundary condition as shown in Figure 23. Two accelerometers were attached roughly 90^o from each other with wax at the end of the barrel. This method for determining the bending and hoop frequencies using just two accelerometers and one impact location was developed by Sutton [11]. The bat was then struck with a steel tipped force-gage hammer, as shown in Figure 24 on the same side as one of the accelerometers. The accelerometer and the force-gage signals were recorded using a digital data acquisition system and then displayed using a computer as shown in Figure 25.

Figure 23. Simulated free-free impact modal test setup.

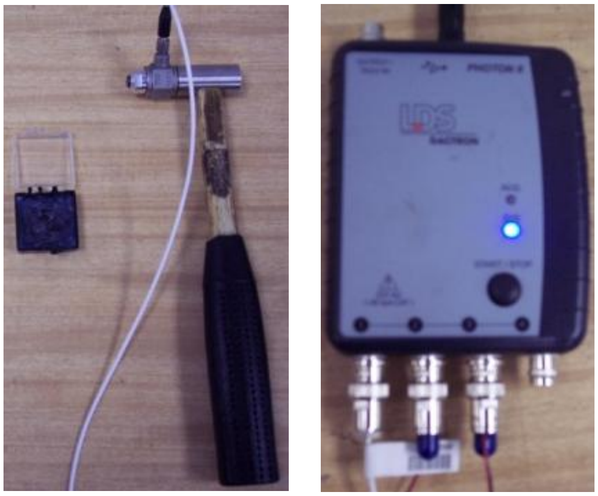

Figure 24. Impact hammer and data acquisition box.

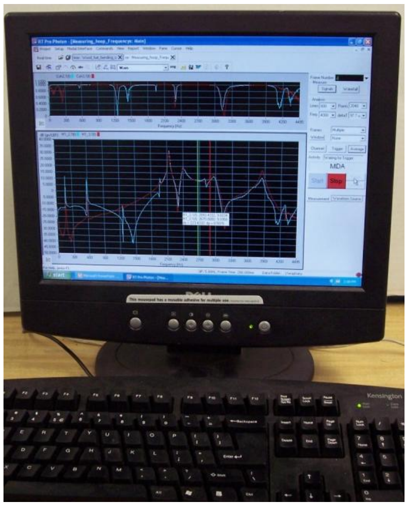

Figure 25. Computer with typical graphical output.

The computer software calculated a frequency response function (FRF) and displayed the result graphically as shown in Figure 25. The FRF was calculated by performing a fast Fourier transform (FFT) from the input (force from hammer impact) and output (vibrations recorded by the accelerometers) of the system. The first two bending frequencies of the bat and the first two hoop frequencies of the bat barrel were recorded. The numerical values of the natural frequencies of the bat were determined by a peak-pick technique from the modal test FRF. There were two FRFs because there were two accelerometer measurements. The two measurements overlaid on peaks of hoop modes and did not overlay on bending modes because the accelerometers were oriented 90° from each other on the barrel as shown in Figure 26 by Sutton [11].

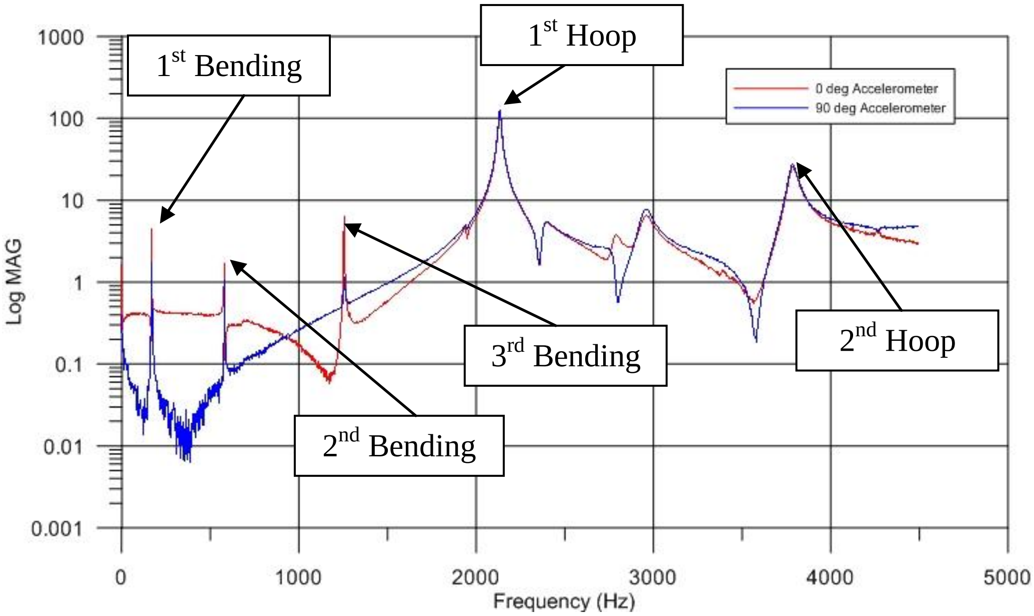

Figure 26. FRF from 90° accelerometers. [11]

3.2.2 Bat Barrel Compression

A barrel compression test was used to quantify the barrel stiffness. This test involved compressing the barrel a known displacement and recording the associated force required to achieve the prescribed displacement. The stiffness was tested by a compression testing device shown in Figures 27 and 28. An initial barrel-compression test was completed on each bat to determine the baseline stiffness before the bat was performance tested. From this baseline value, any change in barrel stiffness as the composite starts to breakdown was tracked.

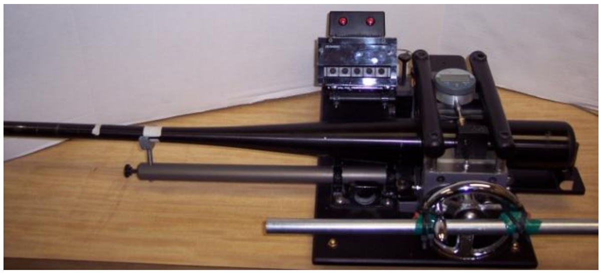

Figure 27. Compression tester with bat loaded.

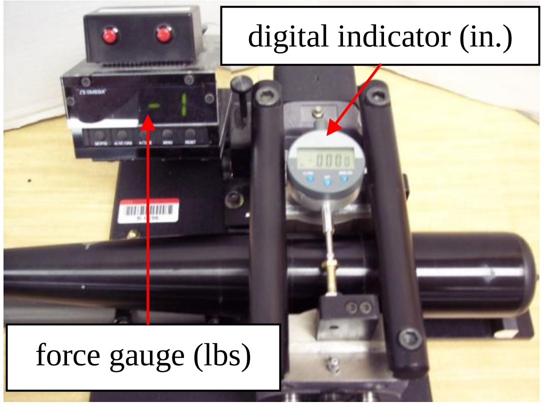

Figure 28. Close up of compression tester instrumentation.

The barrel was compressed by turning the front dial that closes the 3.86-in. diameter cylindrical steel surface on the bat barrel. The digital indicator output the displacement placed on the barrel, and the second output showed force on the bat from the force gage. The bat was given an initial preload of 5 to 15 lbs, and then the two gauges were zeroed to set the zero-displacement reference for the surface of the barrel. The bat was then compressed 0.01 in., and both of the gauges were again zeroed. This step was performed to subtract the nonlinear portion of the barrel response. See Appendix A for experimental validation of this procedure. After the nonlinear portion of the response was zeroed, the bat was compressed an additional 0.03 in., and the exact displacement and load were recorded. The stiffness was then calculated using the force and displacement values,

$$BS = \frac{F_B}{D} \qquad (15)$$

where: BS is the barrel stiffness (lbs/in)
F_B is the force on the barrel (lbs)
D is the displacement on the barrel (in.)

The measurement of force (F_B) and barrel displacement (D) were taken at four different locations (reference location (denoted as 0^o), 90^o and $\pm 45^o$ from that reference location) following the NCAA protocol for Accelerated Break-In Procedure. [28]

Once the barrel stiffness was calculated with Equation 15, the percent change in barrel stiffness was calculated using a percent difference formula.

The barrel stiffness was closely monitored so the bat was broken down to simulate field use but not too fast so that the evolution of the performance profile and peak performance of the bat could not be observed without reasonable resolution. When rolling a bat, a barrel stiffness reduction of just over a 5% was targeted for each rolling/performance test cycle. However, after each performance test, the barrel stiffness was measured, and if the bat had a barrel stiffness reduction from the preceding performance testing of at least 15%, then no rolling was required before the next performance test. This reduction protocol was used to ensure that the bat barrel was not broken down too rapidly so as to miss seeing the maximum performance of the bat. Appendix B summarizes a step-by-step procedure for bat barrel-compression testing from the NCAA protocol for Accelerated Break-In Procedure. [28]

3.2.3 Batted-Ball Performance

As previously mentioned, there are three different configurations that can be used to investigate batted-ball performance experimentally. The three different configurations include: (1) A stationary ball that is hit by a swung bat, (2) a pitched ball hit by a swinging bat and (3) a stationary bat hit by a pitched ball.

The LVS performs the test using Configuration 3. The bat was initially at rest but able to rotate freely about the pivot location (6 in. from the base of the knob), and the ball was then ‘pitched’ at the bat by the air cannon. The linear speed of the impact location (66 mph, which corresponds to a tip speed of 85 mph) was combined with the velocity of a typical pitch of a college pitcher (80 mph that slows down to 70 mph by the time it reaches home plate) to get a total ball speed of 136 mph at the 6-in. band location.

The metrics used to quantify baseball bat performance include the Ball Exit Speed Ratio (BESR), the Bat-Ball Coefficient of Restitution (BBCOR) and the Batted-Ball Speed (BBS). Performance testing follows the ASTM Standard F 2219-07 for Measuring High-Speed Bat Performance [29]. The high-speed air cannon as shown in Figure 29 was used to fire balls at the stationary bat.

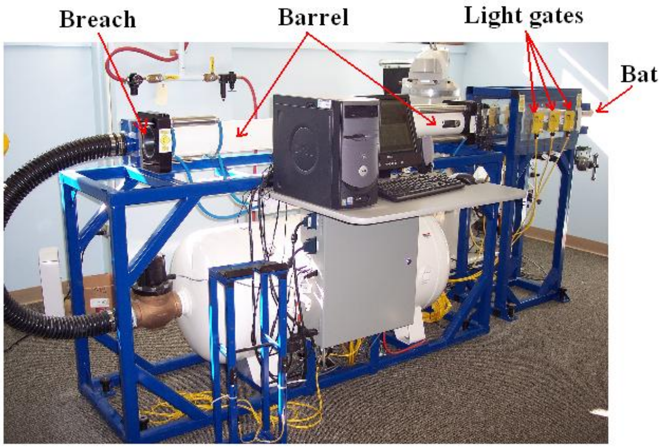

Figure 29. LVSports performance air canon system.

The bat was held in a clamp that is oriented such that the bat rotates freely about the pivot. The ball was carried down the barrel in a sabot (ball carrier) to eliminate any rotation of the ball as it was fired at the bat. The sabot also allows for a precise orientation and consistent speed of the ball for each shot. The sabot collided with the arrestor plate of the cannon, and the ball then traveled through a series of three light gates that are used to calculate the inbound velocity before colliding with the bat. The ball then rebounded through the same three light gates to calculate the rebound velocity of the ball. Figure 30 shows the light-gate box and the position of the bat when loaded.

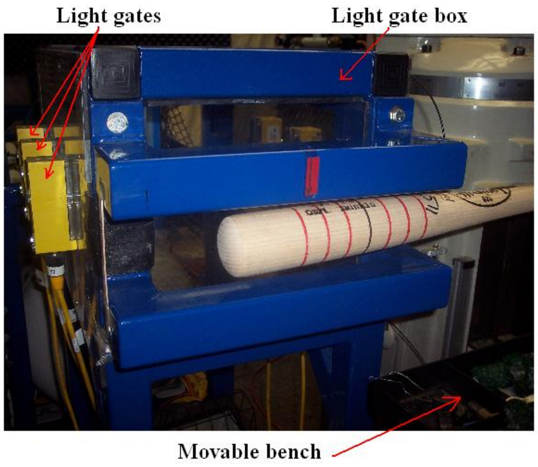

Figure 30. Bat loaded at the end of the light-gate box.

The performance cannon was controlled by a LabVIEW program that is used to interact with the cannon through a GUI and that also performed calculations from the raw data. The light-gate data were used to calculate the inbound and rebound velocities of ball and then the performance of the bat was calculated, such as BESR, BBCOR or BBS, using these velocity data.

3.3 Ball Methods

This section discusses the methods involved to prepare a ball for a batted-ball performance test. This discussion includes the lab conditions required to condition and to maintain a baseball at acceptable properties.

3.3.1 Lab Condition

The UMLBRC is climate controlled in an effort to maintain a consistent test environment and eliminate temperature and humidity related variables from compromising the test results. This climate control is important for achieving repeatability from test to test. The conditions of the lab are 72±4 ^{o}F and 50±5% relative humidity. Baseballs are conditioned a minimum of 14 days in the lab environment prior to being used in testing to ensure they are in equilibrium with the lab environment because ball performance is very sensitive to the moisture content in the ball. Currently, a baseball bat needs only be in the lab environment for two days prior to testing.

3.3.2 Baseball Conditioning

A bat performance test requires a minimum of two dozen baseballs—based on testing four locations along the bat and requirement of six valid impacts per location. All the balls used for bat performance testing in this study were Rawlings model R1NCAA baseballs. As was discussed in Section 3.3.1, a ball must be in the lab for a minimum of 14 days before any testing. The baseballs were grouped into 'ball lots" for use in bat performance testing. A UMLBRC 'ball lot' is comprised of anywhere from 120 to 160 baseballs.

The two weeks allotted for balls to sit in the lab and condition before testing was to allow for both the humidity and the weight of each ball to stabilize. A baseball can absorb moisture from its environment very easily, and therefore its weight can fluctuate slightly until the baseball comes into equilibrium with the controlled environment of the

UMLBRC. All the baseballs selected for the ball lot were required to have a mass of 145.4±1.0 g. All balls received from Rawlings were weighed after the minimum two-week time period and any balls outside of this specific weight range were removed from the ball lot. All balls that met these conditions were marked with the lot number and an individual ball number, e.g. Ball ID R999-010 for Ball Number 10 of Rawlings Ball Lot 999.

After the ball lot was created, the lot was prepared for use in performance testing. Random baseballs were selected from the lot to test on the standard bat. The standard bat was tested at the 6-in. location from the end cap at a target velocity of 136 mph. A set of 30 valid hits on the bat was required for a complete characterization of the lot. The rebound velocity of each baseball was measured by the light gates as described in Section 3.2.3 so that the correction factor, ε, for the ball could be calculated by,

$$\varepsilon = 0.231 - \frac{v}{V} \tag{16}$$

where: ε is the correction factor (dimensionless)
v is the measured rebound velocity of the ball (mph)
V is the inbound test velocity of the baseball (mph)

Equation 16 calculated a correction value for each of the 30 valid shots. The 30 correction factors were averaged to determine the correction value for the entire ball lot, and the ball lot was ready to be used in bat performance testing.

Prior to each bat performance test, the weight of the ball was measured to the nearest 0.1 g to ensure the ball would still fall within the 145.4±1.0 g. The moisture content of the ball was also measured prior to each performance test with a Delmohrst wood moisture meter. The prongs were pushed into the wool winding at the seam of the ball as shown in Figure 31. The date, weight and moisture content of the ball were all recorded on the ball prior to the performance test. Each ball could be used a maximum of eight total times (two impacts on each ear of the ball) before the ball was removed from service.

Figure 31. Measuring the moisture content of a baseball.

3.4 Accelerated Break-In (ABI) Methods

There were two different ABI procedures used to break-in the baseball bats tested in this study, displacement-control ABI and load-control ABI. Each of the break-in methods has pros and cons. The two methods are described in this section.

3.4.1 Displacement-Control Accelerated Break-In (ABI)

The displacement-control rolling ABI method is the most common and commercially available ABI procedure. In this method, a bat was compressed a specified distance between two rollers and then pulled to and fro through the rollers. Displacement of the roller can be determined from the screw pitch on the roller by,

$$pitch = \frac{length}{threads} \tag{17}$$

where: *pitch* is the pitch of the roller's crank screw thread (in./thread)
threads are the number of threads over a given length
length is the length of screw that threads are counted over (in.)

From Equation 17, the pitch can be calculated and once the pitch is known the displacement can be calculated by:

$$displacement = pitch * rotations \tag{18}$$

where: *displacement* is the displacement put on the bat barrel
pitch is the pitch of the rollers crank screw thread as previously calculated (inches/thread)
rotations is the number of times the crank is rotated where one rotation is equal to one thread

Using Equation 18, the displacement for a given screw rotation can be calculated. The rotation-displacement relations for the displacement-control roller used in this research are listed in Table 3. The depth was started at 0.100 in. on the initial rolling. If the rolling had not caused at least a 5% drop in barrel stiffness, then the roller displacement was increased in 1/10th incremental-turns of the displacement-control crank, which corresponds to 0.013 in., and the rolling process was repeated.

Table 3. List of Rolling Depth Steps

Rolling Cycle	Displacement (in.)	Rotations
1	0.100	4/5
2	0.113	9/10
3	0.125	1
4	0.138	1 1/10
5	0.150	1 1/5
6	0.163	1 3/10
7	0.175	1 2/5
8	0.188	1 1/2
9	0.200	1 3/5
10	0.213	1 7/10

The setup used for the displacement-control rolling procedure is shown in Figure 32. Note that there is a grid on the top plate of the roller to determine the starting depth and the net change.

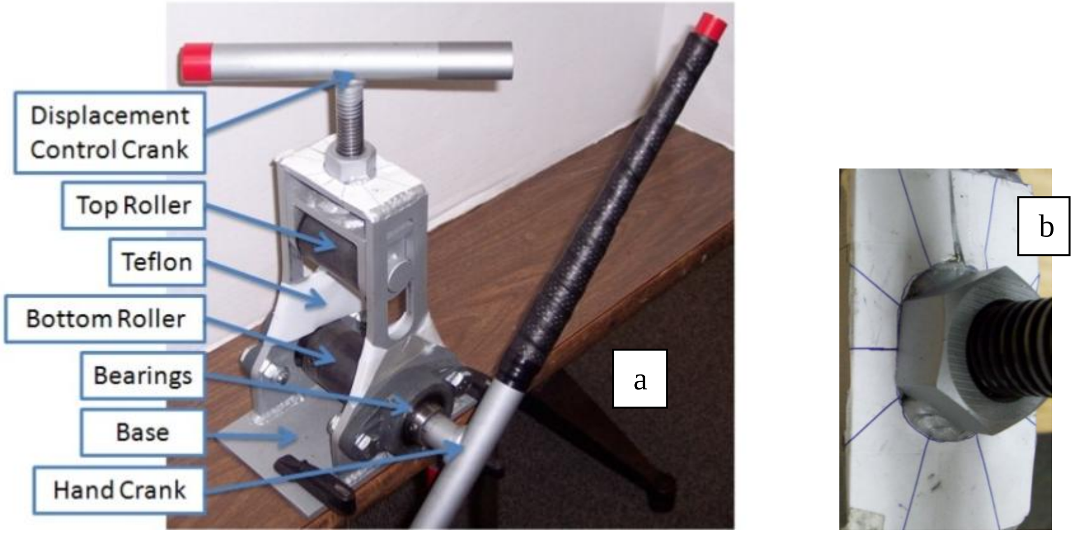

Figure 32. Displacement-control bat roller (a) and grid close up (b).

When using the displacement-control roller, the effective load applied to the bat barrel will vary due to the variation of the diameter along the length of the bat. As the bat moves through the rollers and onto the taper, the load decreases significantly until there is no longer a load being applied to the barrel, which is the limitation of this method. The bat can be moved easily through the rollers using the side hand crank on the device. This method is the one currently used by the UMLBRC in certification testing for the NCAA composite-barrel bats [28]. See Appendix C for a detailed description of the currently used displacement-control procedure.

3.4.2 Load-Control Accelerated Break-In (ABI)

The second method used to break-in bats in this study was a load-control rolling procedure. This process utilized a universal testing machine (Instron). A custom roller setup was designed to take advantage of the testing machine's load-control capabilities. The setup is shown in Figure 33. This design allows for a bat to be loaded into the roller and compressed to a set load on the barrel. The bat is then pulled axially through the roller. As the bat is pulled through the two rollers, the load stays constant as opposed to the displacement-control method. This method of rolling allows for consistent rolling along the entire length of the hitting zone (3- to 9-in. locations) and is a much better method for the rolling of bats that exhibit a taper up into the hitting zone. This roller also features a v-notch top roller that keeps the bat centered on the bottom roller.

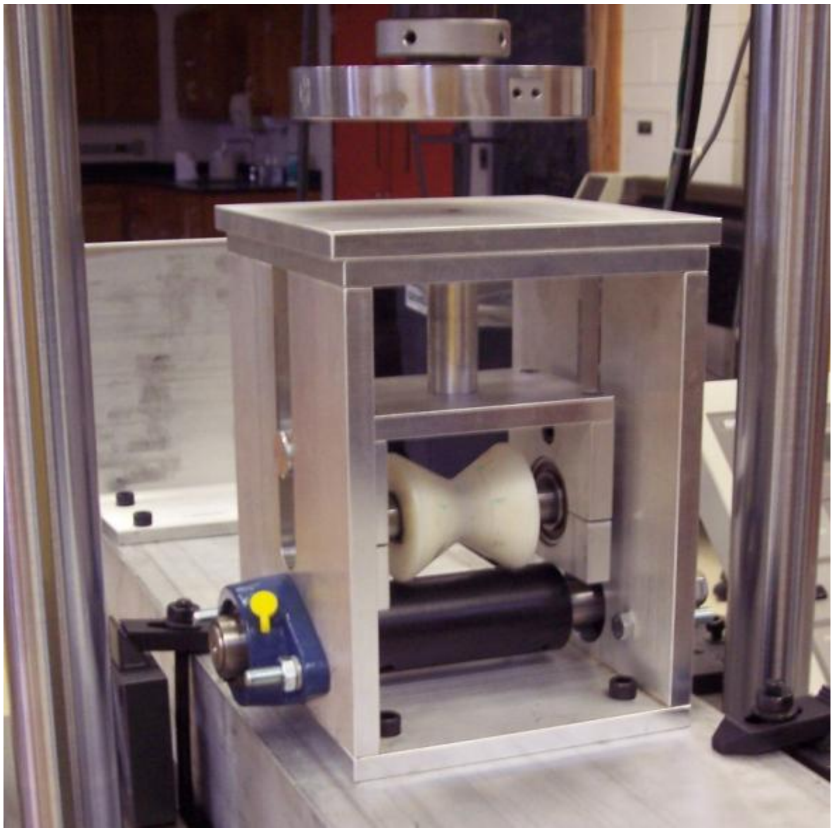

Figure 33. Load-control bat roller.

3.5 Summary

This chapter discussed the methods used during this thesis for testing composite baseball bats. First, the bat preparation and test plan were discussed. Various preliminary bat tests that are conducted on a bat were discussed to determine the following properties: balance point (BP), moment of inertia (MOI), first hoop frequency, barrel stiffness and bat performance (BESR, BBCOR and BBS). The baseball conditioning was discussed including the lab environmental conditions. The displacement- and load-control rolling accelerated break-in (ABI) procedures were presented.

4 Data Analysis/Results

This chapter summarizes the data collected in the course of conducting the research and the subsequent analysis of the data. The data are presented in several ways in an effort to ascertain the most appropriate manner for interpreting the results. The first presentation method will be of the different metrics (batted-ball performance (BESR, BBCOR and BBS), barrel stiffness and hoop frequency) plotted against ABI cycle. The second method will be an analysis plotting batted-ball performance (BESR, BBCOR and BBS) against the bat construction metrics (barrel stiffness, first hoop frequency and second hoop frequency). The final method will be a set of plots that compare data from the two different rolling methods (displacement-control vs. load-control). A comparison of ABI data to data acquired from field used bats will be discussed. There will also be discussion of an uncertainty analysis performed on the data.

4.1 Test Data Analysis Overview

The composite baseball bats were all tested to their respective maximum batted-ball performance (BESR, BBCOR or BBS). To determine the maximum batted-ball performance, several cycles of ABI followed by performance testing were required. When necessary, an ABI procedure was performed to get a measurable change in the barrel compression as required by the NCAA ABI protocol. The test data are first presented as a metric (BESR, BBCOR, BBS, barrel stiffness, first hoop frequency, second hoop frequency) plotted against the cycle number for the bat test. These plots are given is Section 4.2. An example of this style of plot is shown in Figure 34.

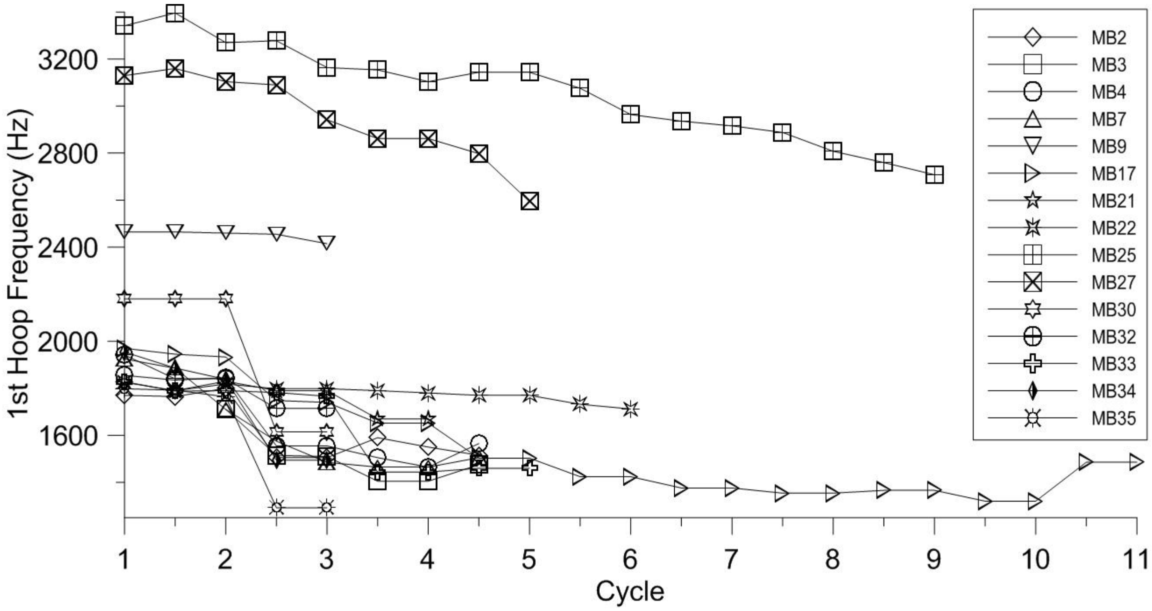

Figure 34. Example of test data plotted against cycle.

Figure 34 shows an example of the metric, in this case first hoop frequency, vs. performance cycle number for a set of bats. Each bat was given a thesis identification tag to blind the data so as to remove any association of a bat with a specific manufacturer and model information. These Bat IDs for this research thesis are in the format of MBxx, where xx was assigned in the order that the composite bat was tested at the UMLBRC. These numbers are not necessarily consecutive, e.g. MB1, MB5, MB6 and MB8 are not shown. These "missing" Bat IDs are due to the fact that not all bats yielded usable data.

Figure 34 also shows that there are measurements taken at each integer cycle (*n*) and half cycle (*n*+½). The need for measurements at cycles *n* and *n*+½ is because metrics including first hoop frequency, second hoop frequency and barrel stiffness were measured before and after each batted-ball performance test. Each test after a batted-ball performance test is considered the *n*+½ cycle test of the metric. All batted-ball performance metrics (BESR, BBCOR and BBS) are only plotted at each cycle and will not have data plotted on *n*+½ cycles.

Bats needed to meet certain minimum criteria to be included in the analysis set of data. Bats were required to have a sufficient number of cycles to see the evolution of the performance of the bat, e.g. the increase in performance, peak performance and then a significant decline in performance or ultimate failure. An example of bats excluded for this requirement were bats tested for ABI that were done in response to a formal bat certification where the test ended if the bat performed over the performance limit, thereby stopping the testing of the bat before it had potentially reached its maximum performance. Clearance had been received from the NCAA to use certification data if it was found that the data were meaningful to the research and the data were properly blinded. It was also required that the bats exhibit sufficient durability so as to reach their maximum performance and give an accurate measure of evolution of the performance profile before ultimate failure occurred. For example, bats that cracked and fragmented on their first or second performance test were not included because they did not meet this requirement. The bats that were selected for the final data set analysis span a representative range of different models, manufacturers and lengths of the composite baseball bats available on the market at the time of the study.

Each bat was assigned a specific symbol to be used when plotted. Each symbol is used consistently throughout the plots for a given bat for ease of tracking by the reader. For example bat MB2 uses a diamond symbol in Figure 34 and is the same throughout this thesis.

Only three of the bats shown in Figure 34 survived greater than five cycles, and as result of this “long” life the rest of the data are “crowded” in the left half of the graph, thereby compromising the ability to view the shorter-life bats. To compensate for this crowding, a close-up view of each set of test data plotted against cycle is given. The close-up view will show only the first four cycles as shown in the example plot of Figure 35.

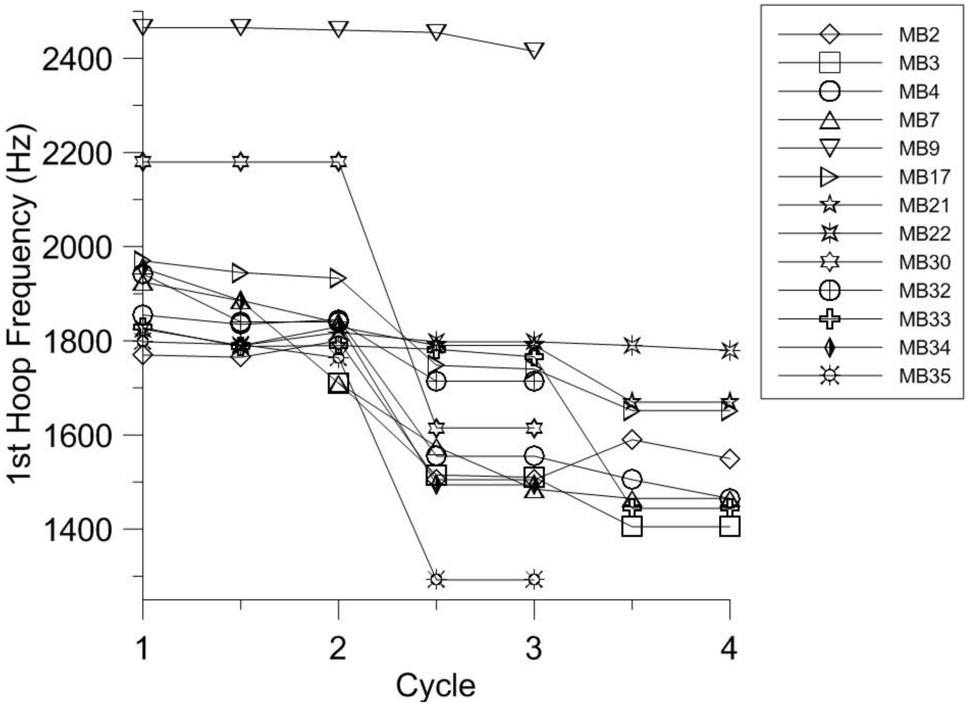

Figure 35. Example of close-up of test data plotted for Cycles 1 through 4.

Figures 34 and 35 show how one property of each composite baseball bat evolves during the ABI testing process. The trend of each metric can be followed for each bat from new (out of the wrapper) to as the bat begins to break-in through the eventually significant damage that typically results in complete failure of the bat. The test data of each metric will first be presented in this manner before the analysis is performed. In addition to the plots of the test data, a table summarizing the initial and max values of each metric is presented. These values are cited because it may be difficult to discern the net increase and actual maximum value of each metric for a given bat by only viewing the graph.

After the test data are presented, the data will be analyzed. The analyses will be accomplished by plotting one metric vs. another as shown in the example Figure 36.

Such plots allow the exploring of trends in the data as the composite bats break-in. This data analysis is discussed in Section 4.3.

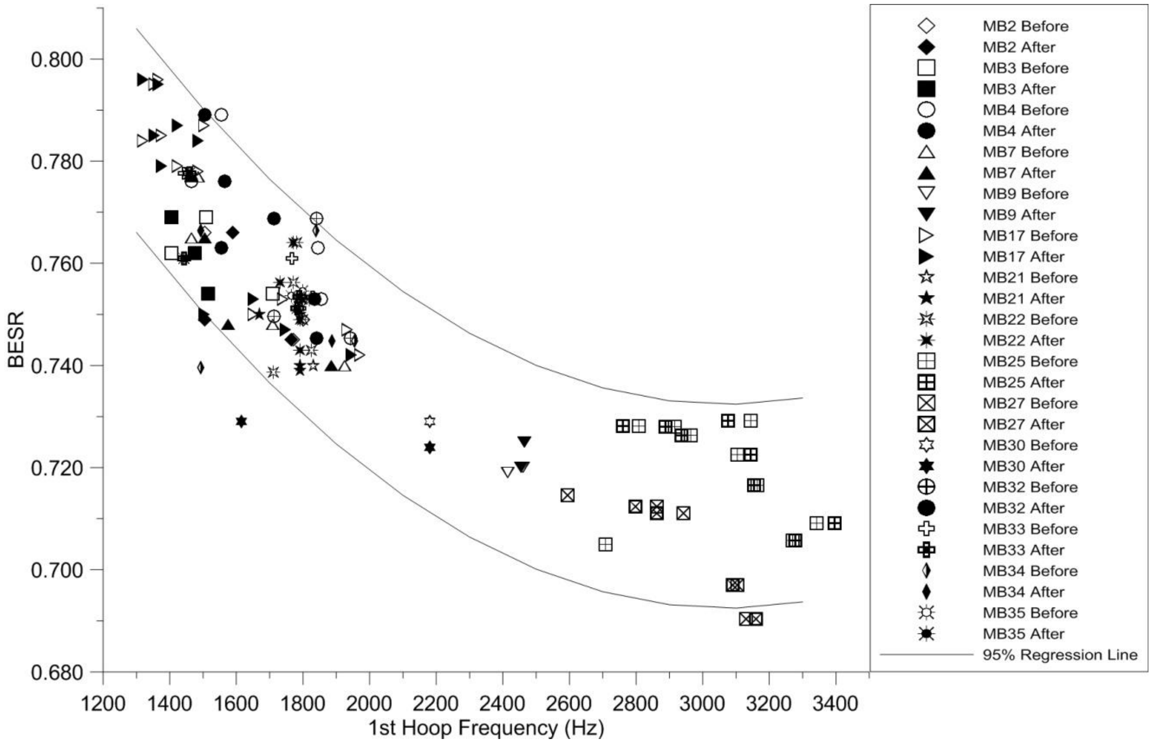

Figure 36. Example of data analysis plot: BESR vs. first hoop frequency.

As can be seen in Figure 36, the symbols are consistent for each bat with those used in Figures 34 and 35. In these comparison plots, each symbol has open and filled forms. An open symbol denotes a measurement (e.g. barrel stiffness, first hoop frequency or second hoop frequency) from a test just prior to the corresponding batted-ball performance test, while a closed symbol denotes a measurement from a test just after the performance test. There will also be three-dimensional plots to explore visually if there are any trends among three different metrics. The plots that show one metric vs. a second metric will also have both a regression analysis and uncertainty analysis performed on the data for each of the batted-ball performance metrics.

After the data are analyzed in this manner, the two different methods of rolling bats as a means of an ABI method will be evaluated, which is done in Section 4.4. The evaluation between rolling methods will be accomplished in part by comparing results of two identical bats (i.e., same model and length) tested utilizing the two different ABI methods (displacement-control and load-control). This data analysis will include a comparison of ABI lab-tested bats to bats that were pulled from service to compare the ABI data to game-used bat data where available.

The uncertainty analysis of the batted-ball performance data will be discussed last. This uncertainty analysis will be discussed in Section 4.5.

4.2 Test Data

This section will present the test data as collected for the following metrics: BESR, BBCOR, BBS, barrel stiffness, first hoop frequency and second hoop frequency. These data are presented to display how bats in a representative group of composite baseball bats change with use. Results are reported at performance cycles as was discussed in Section 4.1.

4.2.1 Batted-Ball Performance Test Data

The batted-ball performance data are presented using the three metrics: BESR, BBCOR and BBS.

4.2.1.1 BESR

Figure 37 shows the BESR of each bat used in this study tracked over the useful life of the bat. Figure 37 shows that all but three of the bats lasted less than five batted-ball performance cycles before the performance dropped off and the bat barrel failed. This plot, however, includes the bats that lasted longer than four cycles, so a secondary plot of the first four cycles of BESR testing on all bats can be seen in Appendix D to allow a close-up view of the first four cycles of the data. Note that this presentation does not include nor discuss which method of ABI was used for each bat. Matched pairs of bats that were tested using the two different ABI methods are later discussed in this chapter.

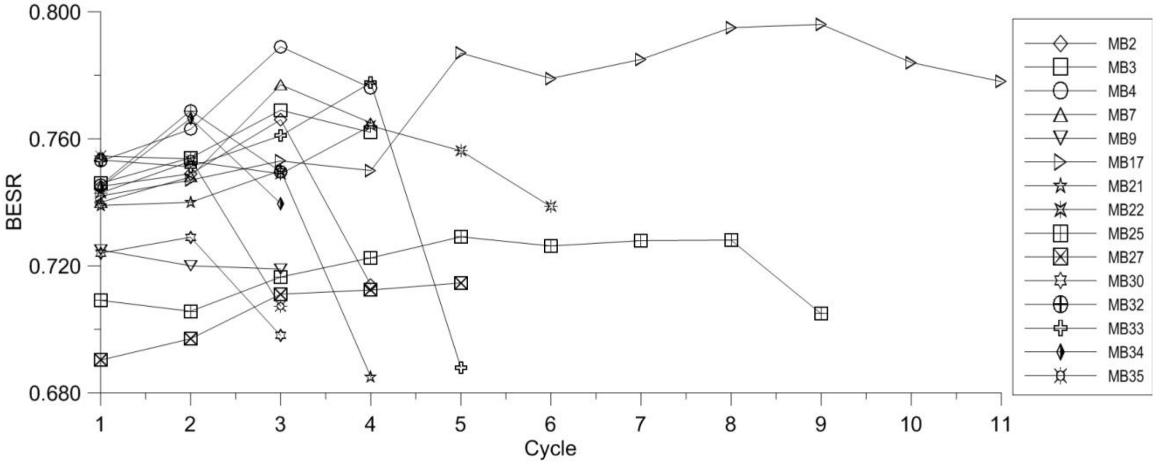

Figure 37. BESR vs. cycle of ABI composite baseball bats.

As can be seen in Figure 37, each bat starts off at an initial BESR performance value which varied between 0.680 and 0.760—dependent on the respective bat manufacturer and the associated properties (such as length, stiffness and MOI). It can be noted that some of these certified bats performed above the BESR limit when new, and this higher than allowed BESR value shows that there is variation in the production of composite baseball bats. Although some of the bats were over-performing when new, this lack of compliance was not a main focus of the study. The increases in overall performance during the ABI process were the main focus. After the first test was completed, the bat was subsequently subjected to the ABI procedure outlined in either Section 3.7.1 (displacement control) or 3.7.2 (load control). As the bat is broken-in using one of the two ABI procedures (displacement- or load-control), the performance was retested and tracked from cycle to cycle as this process was repeated. As can be seen in Figure 37, the majority of the composite baseball bats exhibited an increase in performance before the performance peaked and then dropped off (or the bat became unusable).

Bats MB2, MB3, MB4, MB7 and MB21 all lasted four test cycles before the performance dropped off or the bat barrel failed. Of these five bats, only MB21 did not show a significant performance increase in going from the first to second performance test. All five of these bats had their peak performance at Cycle 3 and then the performance dropped on Cycle 4. It is also noted that bats MB2 and MB21 had a much more significant performance drop on the fourth cycle than the rest of the bats. These large drops can be attributed to extensive cracking in MB2 on the final test and to complete barrel separation from the handle for MB21 during the fourth performance test cycle.

Four bats lasted only three performance cycles, i.e. MB9, MB30, MB34 and MB35. Bat IDs MB30 and MB34 did show a performance increase between Cycles 1 and 2 before the performance dropped off measurably during Cycle 3 due to extensive cracking of the bat barrel on this cycle. Bat IDs MB9 and MB35 did not show any increase in performance and were the only two bats tested in this study that did not show a performance increase over the life of the bat. After the initial test of both MB9 and MB35, the performance dropped slightly between the first and second cycles and then saw large drops in performance when the barrel began to separate on the third cycle. Bat ID MB9 was one of the thickest walled bats that were tested in this study.

Note that no bats were intentionally cut for this study or measured, so only when the barrel of the bat separated from the handle could the wall thickness be viewed. The two bats that did not survive as many performance cycles as the majority of bats are thought to have lower durability and a relatively brittle barrel construction.

There were also bats on the opposite end of the durability spectrum. The longest test in this study was for MB17 which survived eleven performance cycles. Bat ID MB17 did show a small performance increase for the first three cycles of testing. However, a significant increase in performance did not occur until the fourth cycle, which is the cycle where the majority of the other bats had ceased to continue the ABI process due to a drop-off in performance or bat barrel failure. After this large increase in performance on the fourth cycle, there was a small decrease in performance as can be seen in Figure 37. This decrease was small and limited to one cycle of test. On the next performance test cycle, the performance continued to rise until Cycle 9 when the performance then began to decline until the bat barrel separated from the handle on the Cycle-11 performance test.

Bat IDs MB22, MB25, MB27 and MB33 all survived for at least five performance cycles as well (6, 9, 5 and 5 cycles, respectively) showing that there is a range of durability in existing composite baseball bats. Bat IDs MB25 and MB27 also had significantly lower performance when new than the other bats tested. These bats (MB25 and MB27) show that even an out-of-the-wrapper lower-performing composite bat can show performance increase during use.

The BESR data are summarized in Table 4 to show the new-bat and peak BESR values, the total number of cycles and the cycles associated with the peak BESR value, and the absolute change and percent change in BESR. As can be seen in Table 4, MB17 had the largest percent change and the highest peak BESR of all of the tested bats. Most of the bats had between a 3 and 5% increase in BESR performance. Bat IDs MB9 and MB35 were the only two bats that did not show a performance increase. However, MB30 had a relatively small increase when compared to the rest of the bats in the study. Baseball governing bodies should be aware that composite bats do increase in performance, shown in Figure 37 and Table 4. This potential increase has implications for the certification of bats because a bat that is certified just at or below the limit could easily exceed the limit as the bat breaks in. This exceeded limit would create an unfair offensive advantage for the user of a composite bat and a decreased reaction time for a fielder due to higher batted ball speeds—especially the pitcher who is closer than 60 ft away after the pitching motion has been completed.

Table 4. BESR Performance Change during ABI Testing

Bat ID	BESR Performance					
	Start	Total Cycles	Peak	Peak Cycle	Increase	%Increase
MB2	0.745	4	0.766	3	0.021	2.8
MB3	0.746	4	0.769	3	0.023	3.1
MB4	0.753	4	0.789	3	0.036	4.8
MB7	0.740	4	0.777	3	0.037	5.0
MB9	0.725	3	0.725	1	0.000	0.0
MB17	0.742	11	0.796	9	0.054	7.3
MB21	0.739	4	0.750	3	0.011	1.5
MB22	0.743	6	0.764	4	0.021	2.8
MB25	0.709	9	0.729	5	0.020	2.8
MB27	0.690	5	0.712	4	0.022	3.2
MB30	0.724	3	0.729	2	0.005	0.7
MB32	0.745	3	0.769	2	0.024	3.2
MB33	0.753	5	0.778	4	0.025	3.3
MB34	0.745	3	0.766	2	0.021	2.8
MB35	0.755	3	0.755	1	0.000	0.0

4.2.1.2 BBCOR

Figure 38 shows the BBCOR of each bat used in this study tracked over the useful life of the bat. This plot shows the same performance trends as was observed in the BESR plot (Figure 37).

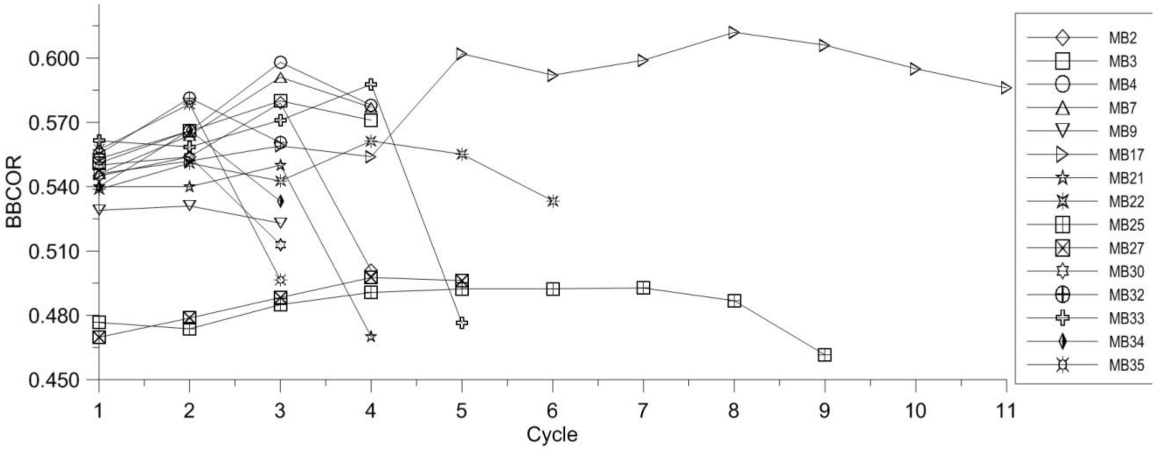

Figure 38. BBCOR vs. cycle of ABI composite baseball bats.

The BBCOR data are summarized in Table 5 to show the new-bat and peak BBCOR values, the total number of cycles and the cycles associated with the peak BBCOR value, and the absolute change and percent change in BBCOR. As can be seen in Table 5, MB17 had the largest percent change and the highest peak BBCOR of all of the tested bats. Most of the bats had between a 5 and 8% increase in BBCOR performance. Bat IDs MB9 and MB30 had relatively small increases when compared to the rest of the bats in the study.

Table 5. BBCOR Performance Change during ABI Testing

Bat ID	BBCOR Performance					
	Start	Total Cycles	Peak	Peak Cycle	Change	%Change
MB2	0.545	4	0.579	3	0.034	6.2
MB3	0.551	4	0.580	3	0.029	5.3
MB4	0.553	4	0.598	3	0.045	8.1
MB7	0.546	4	0.591	3	0.045	8.2
MB9	0.529	3	0.531	2	0.002	0.4
MB17	0.546	11	0.612	8	0.066	12.1
MB21	0.540	4	0.550	3	0.010	1.9
MB22	0.539	6	0.561	4	0.022	4.1
MB25	0.477	9	0.492	6	0.015	3.1
MB27	0.470	5	0.498	4	0.028	6.0
MB30	0.550	3	0.554	1	0.004	0.7
MB32	0.555	3	0.581	2	0.026	4.7
MB33	0.561	5	0.588	4	0.027	4.8
MB34	0.54	3	0.566	2	0.026	4.8
MB35	0.557	3	0.557	1	0.000	0.0

4.2.1.3 BBS

The third batted-ball performance metric calculated was batted-ball speed (BBS) which is calculated by the procedure discussed in Section 2.4.3. Figure 39 shows the BBS of each bat used in this study tracked over the useful life the bat. The trends in this plot are similar to what were previously shown for BESR and BBCOR in Figures 37 and 38, respectively.

The BBS data are summarized in Table 6 to show the new-bat and peak BBS values, the total number of cycles, the cycles associated with the peak BBS value, and the absolute change and percent change in BBS. As can be seen in Table 6, MB17 had the largest percent change and the highest peak BBS of all of the tested bats. Most of the bats had between a 5 and 8% increase in BBS performance. Bat IDs MB9, MB30 and MB35 had relatively small increases when compared to the rest of the bats in the study.

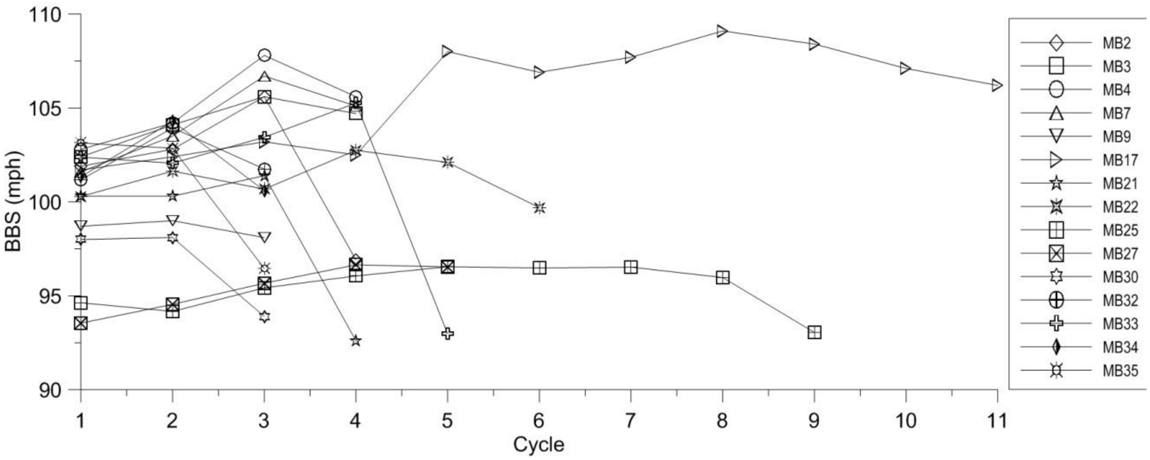

Figure 39. BBS vs. cycle of ABI composite baseball bats.

Table 6. BBS Performance Change during ABI Testing

Bat ID	BBS Performance					
	Start (mph)	Cycles	Peak (mph)	Peak Cycle	Change (mph)	%Change
MB2	101.9	4	105.6	3	3.7	3.6
MB3	102.4	4	105.6	3	3.2	3.1
MB4	102.8	4	107.8	3	5.0	4.9
MB7	101.6	4	106.7	3	5.1	5.0
MB9	98.7	3	99.0	2	0.3	0.3
MB17	101.7	11	109.1	8	7.4	7.3
MB21	100.3	4	101.4	3	1.1	1.1
MB22	100.3	6	102.7	4	2.4	2.4
MB25	94.6	9	96.5	5	1.9	2.0
MB27	93.5	5	96.6	4	3.1	3.3
MB30	98.0	3	98.1	2	0.1	0.1
MB32	101.2	3	103.9	2	2.7	2.7
MB33	102.4	5	105.3	4	2.9	2.8
MB34	101.3	3	104.3	2	3.000	3.0
MB35	103.1	3	103.1	1	0.000	0.0

4.2.2 Barrel Stiffness Test Data

Barrel stiffness is determined by the procedure discussed in Section 3.2.3. Figure 40 shows the barrel stiffness of each bat used in this study tracked over the useful life of the bat. As was likewise for the batted-ball performance data over the lifetime of the bat, the barrel stiffness data for the first four performance cycles can be viewed better in Appendix D on a plot that only shows the first four cycles .

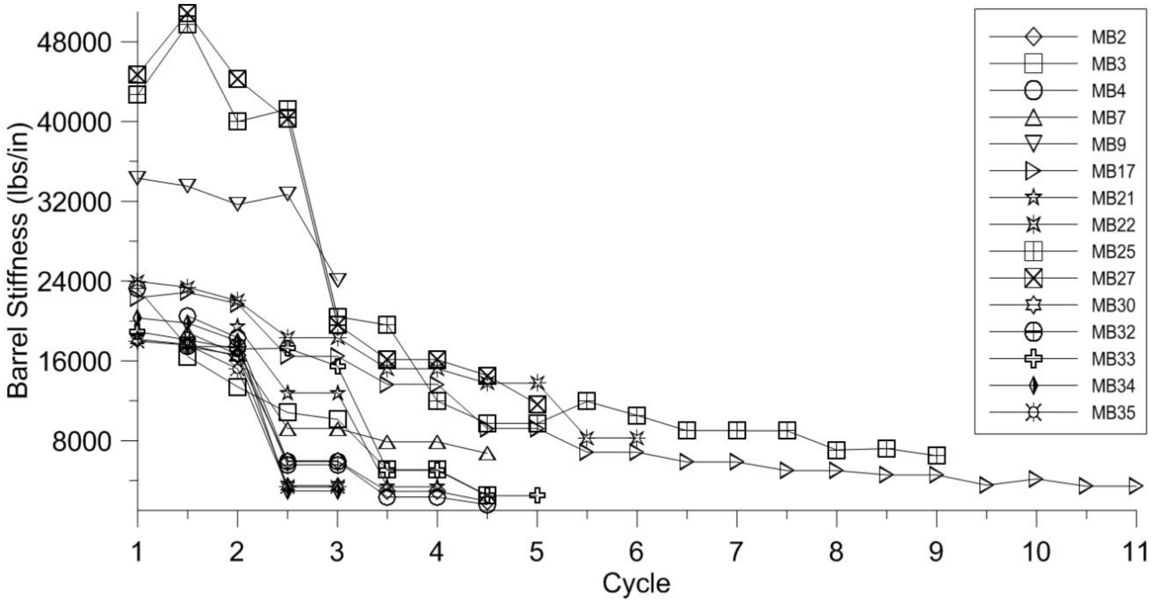

Figure 40. Barrel stiffness vs. cycle of ABI composite baseball bats.

As can be seen in Figure 40, each bat starts off at an initial barrel stiffness value which varies between 16K and 44K lbs/in. All of the bats in the study show that as the bat was broken-in as result of the testing process the stiffness dropped off. This trend was expected due to the assumption that as the bat barrel breaks down it should become less stiff.

There were instances where the barrel stiffness showed a slight increase as can be seen for Bat ID MB17 in Figure 40. This increase in barrel stiffness is likely due to how the barrel is constructed or may be a consequence of the manufacturing process due to air pockets or space between plies that were changed during the hitting and/or rolling actions on the bat. Bat IDs MB9, MB25 and MB27 have very high initial barrel stiffness when compared to the rest of the bats. This relatively high stiffness can be attributed to thick-walled barrel construction in comparison to the other bats.

In addition to plotting the barrel stiffness as a function of the cycle number, the data are presented in Tables 7 and 8 for the stiffness before and after the peak performance cycle, respectively. The data are presented this way to show the new-bat stiffness, stiffness at batted-ball performance peak, absolute change in stiffness and percent change in stiffness.

Table 7. Barrel Stiffness Change before ABI Testing Cycle of Peak Performance.

Bat ID	Barrel Stiffness					
	Start (lbs/in.)	Cycles	Just Before Peak Cycle (lbs/in.)	Peak Cycle	Change (lbs/in.)	%Change
MB2	17417	4	5971	3	-11446	-65.7
MB3	16442	4	10142	3	-6300	-38.3
MB4	20508	4	5917	3	-14591	-71.1
MB7	18855	4	9229	3	-9626	-51.1
MB9	34317	3	34317	1	0	0.0
MB17	22342	11	4567	9	-17775	-79.6
MB21	19417	4	12800	3	-6617	-34.1
MB22	23975	6	15217	4	-8758	-36.5
MB25	42667	9	9737	5	-32930	-77.2
MB27	44700	5	16123	4	-28577	-63.9
MB30	18167	3	16467	2	-1700	-9.4
MB32	23225	3	17425	2	-5800	-25.0
MB33	18925	5	5017	4	-13908	-73.5
MB34	20300	3	18000	2	-2300	-11.3
MB35	17966.7	3	17966.7	1	0	0.0

Table 8. Barrel Stiffness Change after ABI Testing Cycle of Peak Performance.

Bat ID	Barrel Stiffness					
	Start (lbs/in.)	Cycles	Just After Peak Cycle (lbs/in.)	Peak Cycle	Change (lbs/in.)	%Change
MB2	17417	4	2917	3	-14500	-83.3
MB3	16442	4	5088	3	-11354	-69.1
MB4	20508	4	2350	3	-18158	-88.5
MB7	18855	4	7880	3	-10975	-58.2
MB9	34317	3	33517	1	-800	-2.3
MB17	22342	11	3542	9	-18800	-84.1
MB21	19417	4	3377	3	-16040	-82.6
MB22	23383	6	13758	4	-9625	-41.2
MB25	49733	9	11933	5	-37800	-76.0
MB27	50900	5	14533	4	-36367	-71.4
MB30	18167	3	3500	2	-14667	-80.7
MB32	17425	3	5575	2	-11850	-68.0
MB33	18108	5	2492	4	-15616	-86.2
MB34	19791.7	3	2966.67	2	-16825	-85.0
MB35	17591.7	3	17591.7	1	NA	NA

As can be seen in Table 7, the largest percent change for stiffness was MB17. This bat lasted more test cycles than any other bat and had the highest peak batted-ball performance of all bats in the study. This bat is an example that if a bat has a high drop in barrel stiffness before the barrel hits its peak performance then that bat may have a significant increase in performance.

Most of the bats had between a 35 and 80% decrease (as reported in Table 7) in barrel stiffness when their peak batted-ball performance was reached. The two bats that had the smallest performance increase also had very low barrel stiffness reductions at their peak performance. This ‘flat’ or unchanging performance can be attributed to relatively stiff and brittle bat barrels. Once this type of bat barrel starts to breakdown, the cracks in the barrel are critical and easily grow, thereby significantly compromising the integrity of the barrel which results in a drop in batted-ball performance.

4.2.3 Hoop Frequency Raw Data

Modal analysis was used to determine the hoop frequencies of the bat barrel. These hoop frequencies were shown by Sutton [11] to have good correlation with the degree of the 'trampoline effect' in hollow baseball bats. In the current research, the first two hoop modes of the composite bats were tracked before and after each performance cycle. The hoop frequencies were determined by the procedure discussed in Section 3.2.2.

4.2.3.1 First Hoop Frequency

Figure 41 shows the first hoop frequency of each bat used in this study tracked over the useful life of each bat. Similar to the batted-ball performance data, the first hoop frequency data for the first four performance cycles can be viewed better in Appendix D on a plot that only shows the first four cycles.

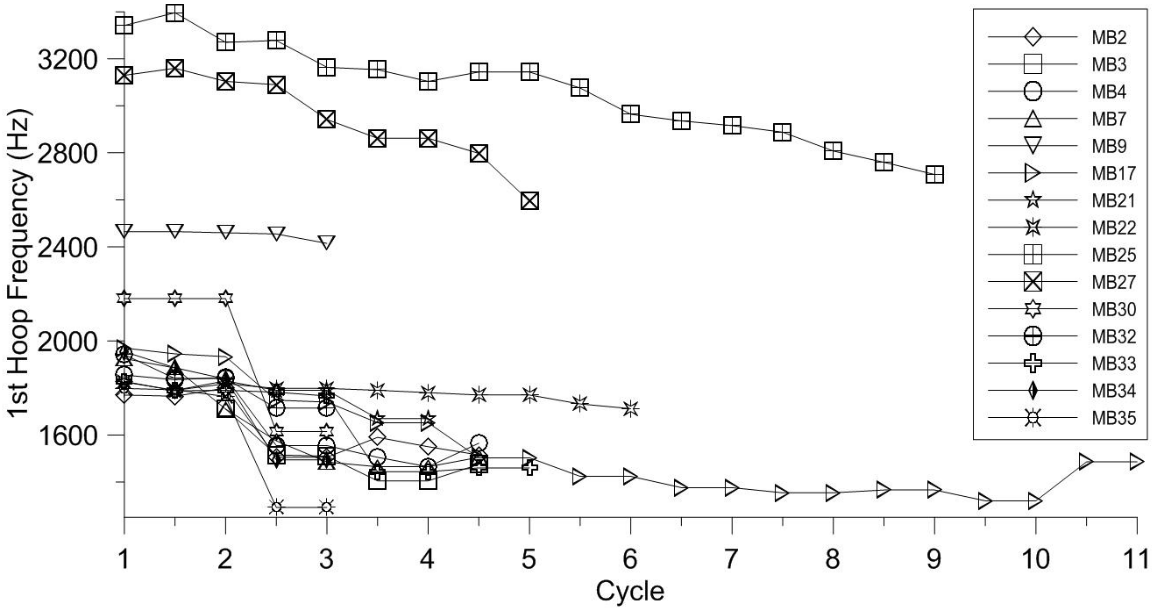

Figure 41. First hoop frequency vs. cycle of ABI for the composite baseball bats.

As can be seen in Figure 41, each bat starts with an initial first hoop frequency value between 1800 and 3400 Hz. The first hoop mode is a breathing mode in and out of the barrel and is related to the ‘trampoline effect’. Due to the potential for this ‘trampoline effect’ in hollow aluminum- and composite-barrel baseball bats, companies typically tune this hoop frequency to be ~2000 Hz to achieve a batted-ball speed that is at or close to the limit set by the governing body, i.e. the NCAA for the bats investigated in this research. The performance limit forces the hoop mode to be much greater than the optimal frequency shown by Sutton [11] of ~1250 Hz. When bats are close to ~1250 Hz, the barrel of a hollow bat is able to ‘breath’ in and out as the ball comes into and leaves the bat/ball collision, thereby causing an optimal collision. An optimal collision will have the maximum amount of energy retained during a collision and result in the maximum batted-ball speed and distance.

While the bats shown in Figure 41 start with a first hoop frequency that yields an acceptable batted-ball performance, the hoop frequency dropped as the bat was tested and broken-in. This drop in hoop frequency is expected after looking at the decreasing barrel stiffness trend, which was shown in Figure 40, because frequency is highly dependent on the mass and the stiffness of the bat. Because the mass is essentially not changing for these bats, the barrel stiffness plays the primary role for the change in the hoop frequency of each bat.

With respect to the mass not changing, there were a few instances where part of the barrel broke off internally or externally. The pieces that did separate from the barrel were typically relatively small pieces when looking at the overall mass of the barrel and were considered to have essentially no effect on the hoop frequency.

There were instances where the first hoop frequency did increase as can be seen in Figure 41 for Bat IDs MB3, MB4 and MB17 near the end of the life for each of these three bats. This increase in barrel stiffness was likely due to how the barrel at this point of these three tests was fragmenting apart and therefore the frequency recorded is no longer the hoop frequency of a continuous barrel, but a portion of the original effective barrel length. A bat with the barrel separated from the handle could have a higher hoop frequency due to the remaining segment being less massive.

Bat IDs MB9, MB25 and MB27 had a very high initial first hoop frequency when compared to the rest of the bats. These high hoop frequencies were due to the thick-walled barrels of these bats in comparison to the other bats and corresponding relatively high barrel stiffness as discussed in Section 4.2.4.

The first hoop frequencies before and after each performance cycle are presented in Tables 9 and 10, respectively. As can be seen in Table 10, the largest percent drop for hoop frequency was Bat ID MB17. This bat exhibited the highest peak batted-ball performance of all of the tested bats and the highest drop in barrel stiffness. Most of the bats had between a 0 and 20% decrease in first hoop frequency between when new and when their peak batted-ball performance was recorded. The bats that had the greatest barrel stiffness reduction before the bat hit its peak performance also had a correspondingly relatively large drop in their first hoop frequency—although this relationship was not directly proportional. Bat ID MB4 had a greater drop in barrel stiffness than it did for first hoop frequency when compared to the other bats tested.

Table 9. First Hoop Frequency Change before ABI Testing Cycle

Bat ID	First Hoop Frequency					
	Start (Hz)	Cycles	Just Before Peak Cycle (Hz)	Peak Cycle	Change (Hz)	%Change
MB2	1770	4	1505	3	-265	-15.0
MB3	1710	4	1510	3	-200	-11.7
MB4	1855	4	1555	3	-300	-16.2
MB7	1925	4	1485	3	-440	-22.9
MB9	2465	3	2465	1	0	0.0
MB17	1970	11	1366	9	-604	-30.7
MB21	1830	4	1790	3	-40	-2.2
MB22	1825	6	1780	4	-45	-2.5
MB25	3342	9	3144	5	-198	-5.9
MB27	3130	5	2862	4	-268	-8.6
MB30	2180	3	2180	2	0	0.0
MB32	1942	3	1840	2	-102	-5.3
MB33	1828	5	1444	4	-384	-21.0
MB34	1954	3	1838	2	-116	-5.9
MB35	1798	3	1798	1	0	0.0

Table 10. First Hoop Frequency Change after ABI Testing Cycle

Bat ID	First Hoop Frequency					
	Start (Hz)	Cycles	Just After Peak Cycle (Hz)	Peak Cycle	Change (Hz)	%Change
MB2	1770	4	1590	3	-180	-10.2
MB3	1710	4	1405	3	-305	-17.8
MB4	1855	4	1505	3	-350	-18.9
MB7	1925	4	1465	3	-460	-23.9
MB9	2465	3	2465	1	0	0.0
MB17	1970	11	1320	9	-650	-33.0
MB21	1830	4	1670	3	-160	-8.7
MB22	1790	6	1770	4	-20	-1.1
MB25	3396	9	3076	5	-320	-9.4
MB27	3160	5	2798	4	-362	-11.5
MB30	2180	3	1615	2	-565	-25.9
MB32	1840	3	1714	2	-126	-6.8
MB33	1788	5	1460	4	-328	-18.3
MB34	1886	3	1494	2	-392	-20.8
MB35	1792	3	1792	1	0	0.0

4.2.3.2 Second Hoop Frequency

Figure 42 shows the second hoop frequency of each bat used in this study tracked over the useful life of each bat. It can be seen in Figure 42 that each bat shows an initial second hoop frequency value which varies between 2400 and 3900 Hz. Because the second hoop frequency is higher than the first hoop frequency, it should have less effect on the performance of the barrel than the first hoop frequency does. This reduced effect is due to the fact that a bat collision that is ~1250 Hz will primarily excite lower frequencies (primarily the lower-order bending modes and first-order hoop mode).

Typically a bat with a higher first hoop frequency will have a higher second hoop frequency with respect to the other bats. As can be seen in Figure 42, the second hoop frequency sows a progressive drop as the useful life of the bat evolves. However, the drop is less than it was for the first hoop frequency when looking at the same bat. This reduced drop is expected by looking at the decreasing barrel stiffness trend because the second hoop frequency is still dependent on both the mass and the stiffness of the bat. The change in first and second hoop frequencies is not necessarily proportional due to the fact that the second hoop mode is not a harmonic of the first.

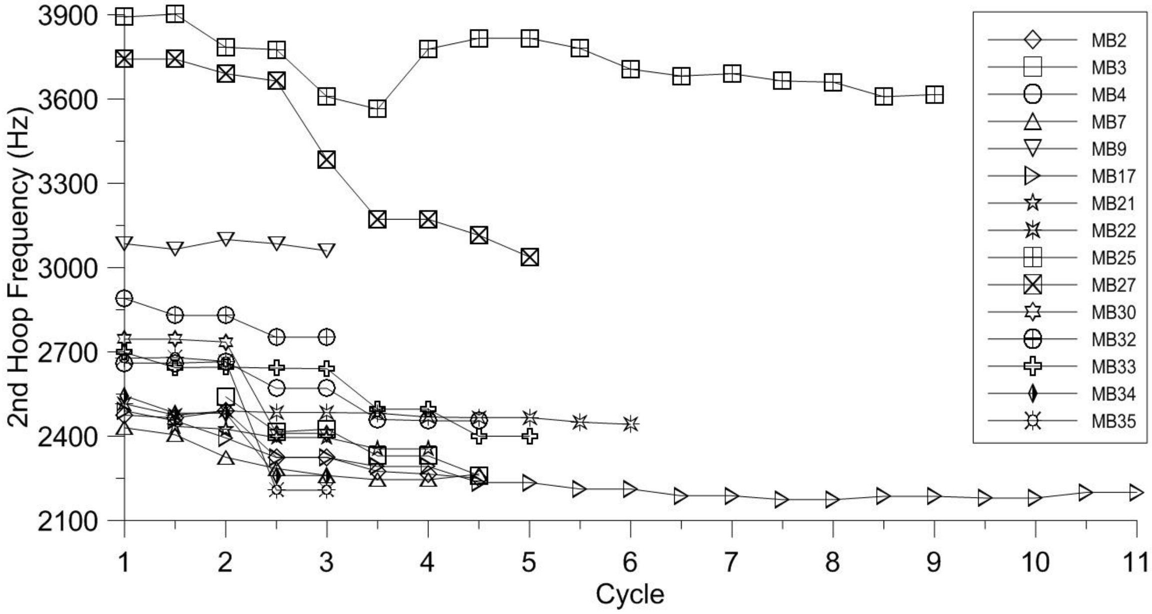

Figure 42. Second hoop frequency vs. cycle of ABI composite baseball bats.

The second hoop frequencies before and after each performance cycle are presented in Tables 11 and 12, respectively. As can be seen in Table 12, the largest percent drop for second hoop frequency was Bat ID MB27 which is not the same bat that had the largest first hoop frequency drop (MB17 in Table 9). Most of the bats had between a 0 and 10% decrease in second hoop frequency between the cycle when the bat was new and the cycle when the bat's peak batted-ball performance was recorded.

The bats that had the greatest barrel-stiffness reduction before the bat hit its peak performance also had a correspondingly relatively large drop in their second hoop frequency—although this relationship was not directly proportional. Bat ID MB4 had a greater drop in barrel stiffness than it did for second hoop frequency when compared to the other bats tested.

Table 11. Second Hoop Frequency Change before ABI Testing Cycle

Bat ID	Second Hoop Frequency					
	Start (Hz)	Cycles	Just Before Peak Cycle (Hz)	Peak Cycle (Hz)	Change (Hz)	%Change
MB2	2475	4	2325	3	-150	-6.1
MB3	2540	4	2425	3	-115	-4.5
MB4	2660	4	2570	3	-90	-3.4
MB7	2430	4	2260	3	-170	-7.0
MB9	3085	3	3085	1	0	0.0
MB17	2490	11	2186	9	-304	-12.2
MB21	2435	4	2395	3	-40	-1.6
MB22	2515	6	2468	4	-47	-1.9
MB25	3892	9	3816	5	-76	-2.0
MB27	3742	5	3172	4	-570	-15.2
MB30	2745	3	2735	2	-10	-0.4
MB32	2890	3	2830	2	-60	-2.1
MB33	2698	5	2496	4	-202	-7.5
MB34	2544	3	2482	2	-62	-2.4
MB35	2678	3	2678	1	0	0.0

Table 12. Second Hoop Frequency Change after ABI Testing Cycle

Bat ID	Second Hoop Frequency					
	Start (Hz)	Cycles	Just After Peak Cycle (Hz)	Peak Cycle (Hz)	Change (Hz)	%Change
MB2	2475	4	2275	3	-200	-8.1
MB3	2540	4	2330	3	-210	-8.3
MB4	2660	4	2460	3	-200	-7.5
MB7	2430	4	2245	3	-185	-7.6
MB9	3085	3	3065	1	-20	-0.6
MB17	2490	11	2180	9	-310	-12.4
MB21	2435	4	2355	3	-80	-3.3
MB22	2475	6	2466	4	-9	-0.4
MB25	3902	9	3780	5	-122	-3.1
MB27	3742	5	3115	4	-627	-16.8
MB30	2745	3	2410	2	-335	-12.2
MB32	2830	3	2752	2	-78	-2.8
MB33	2644	5	2400	4	-244	-9.2
MB34	2482	3	2260	2	-222	-8.9
MB35	2680	3	2680	1	0	0.0

To investigate how the first and second hoop frequencies compare, the frequency data recorded just before each cycle is presented in Table 13. Table 13 shows that no bat that reached its peak performance on a cycle after Cycle 1 had the same percent change in first and second hoop frequencies. The first hoop mode was typically more affected by the ABI process than second hoop mode was. This observation can be concluded from Table 13 where the difference in the percent reduction in the first hoop mode frequency is typically greater than the percent reduction of the second hoop mode frequency.

Table 13. Comparison of First and Second Hoop Frequency Reduction

Bat ID	First Hoop Frequency		Second Hoop Frequency		%Change Difference
	Change (Hz)	%Change	Change (Hz)	%Change	
MB2	-265	-15	-150	-6.1	-8.9
MB3	-200	-11.7	-115	-4.5	-7.2
MB4	-300	-16.2	-90	-3.4	-12.8
MB7	-440	-22.9	-170	-7	-15.9
MB9	0	0	0	0	0
MB17	-604	-30.7	-304	-12.2	-18.5
MB21	-40	-2.2	-40	-1.6	-0.6
MB22	-45	-2.5	-47	-1.9	-0.6
MB25	-198	-5.9	-76	-2	-3.9
MB27	-268	-8.6	-570	-15.2	6.6
MB30	0	0	-10	-0.4	0.4
MB32	-102	-5.3	-60	-2.1	-3.2
MB33	-384	-21	-202	-7.5	-13.5
MB34	-116	-5.9	-62	-2.4	-3.5
MB35	0	0	0	0	0

4.3 Metric Comparison Analysis

This section will discuss the data analysis performed on all of the collected data presented in Section 4.2 including batted-ball performances (BESR, BBCOR and BBS), first and second hoop frequencies and barrel stiffness. The data are presented to explore how the different metrics that were investigated in the current research relate to one another. Results will be presented with one metric plotted against another metric as was discussed in Section 4.1.

4.3.1 Metric Analyses

This section will discuss the comparison of the three batted-ball performance metrics (BESR, BBCOR and BBS) to first hoop frequency, second hoop frequency and barrel stiffness.

4.3.1.1 Batted-Ball Performance Analysis

BESR vs. barrel stiffness is shown in Figure 43. This figure shows that the BESR increases as the barrel stiffness decreases. This trend can be seen as a global trend for all of the bats tested and as a bat is breaking down through ABI. There is increasing scatter in the data as the barrel stiffness decreases. This scatter is likely a consequence of the randomness of the damage evolution, i.e. not all bats necessarily accumulate damage in the same way.

There are a few instances where a lower value of barrel stiffness corresponded to a lower BESR value for a bat such as MB3. This result is a consequence of the bat barrel failing completely on the final test, thereby ending in an incomplete performance test due to the damage being so significant that the bat could no longer be tested to give meaningful results. Figure 43 also shows a 95% regression analysis that was performed.

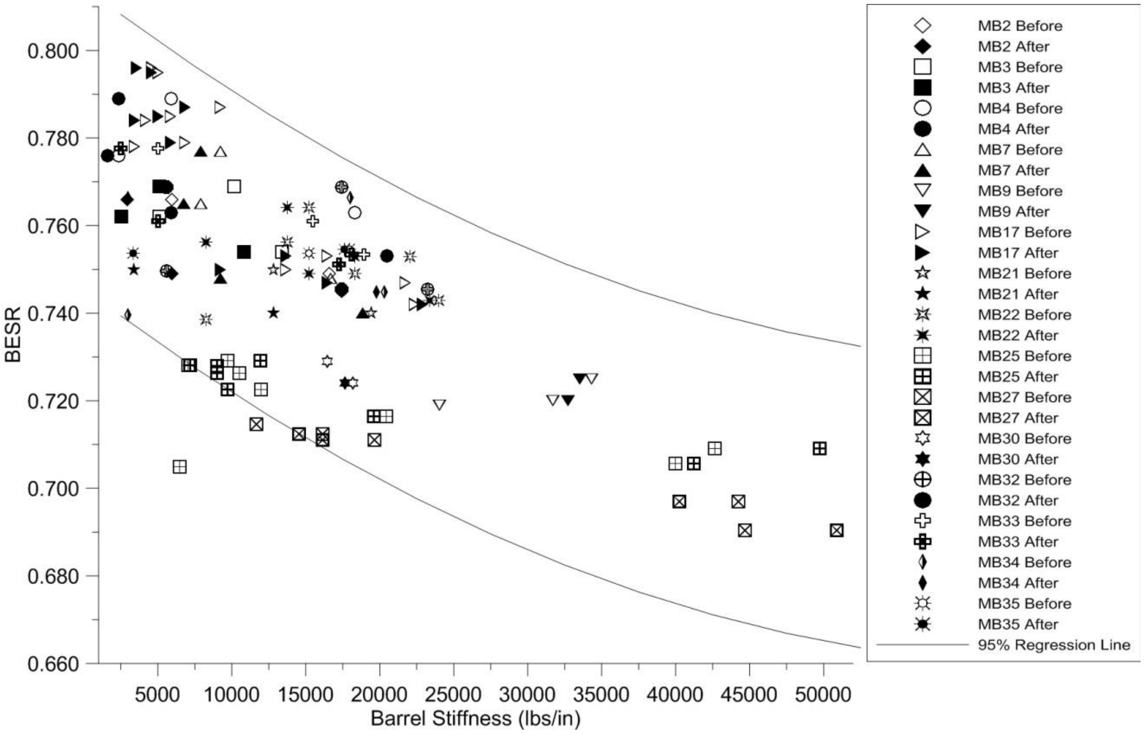

Figure 43. BESR vs. barrel stiffness.

As can be seen in Figure 43, there are two bats that lie outside of the lower bound of the 95% regression line. These two bats that have data points outside the lower regression line are MB25 and MB27. These bats were the two stiffest bats tested in this study. As shown in Figure 43, these two bats had an initial barrel stiffness of over 50K lbs/in. Due to this high barrel stiffness (exceeding the load-cell capacity of the UMLBRC's compression tester) an alternate means of tracking the barrel stiffness during tested was implemented. The alternative method utilized was removing the plates from the compression tester and fixturing them in a universal testing machine (Instron).

The potential reason why these two bats (MB25 and MB27) do not follow the same trend as the rest of the tested bats was hypothesized to be due to the difference in how load was applied to the barrel of a bat from one testing method to the other, i.e. compression tester vs. Instron. To explore this hypothesis, a bat that could be compressed using both methods was tested and compared between the two methods. The results from each method and the difference between the two are summarized in Table 14.

Table 14. Comparison of Compression Methods

Barrel Stiffness (lbs/in)		
Compression Tester	Universal Tester	Difference
21793	14934	6859

As can be seen in Table 14 the barrel stiffness of the two different methods does differ by a significant amount from method to method (6859 lbs/in). The difference also shows that the compression tester shows higher values than the universal tester does when testing the same bat for barrel stiffness. Due to the fact that the two methods had different compression values, the 95% regression analysis was redone without these two bats (MB25 and MB27) included and is shown in Figure 44.

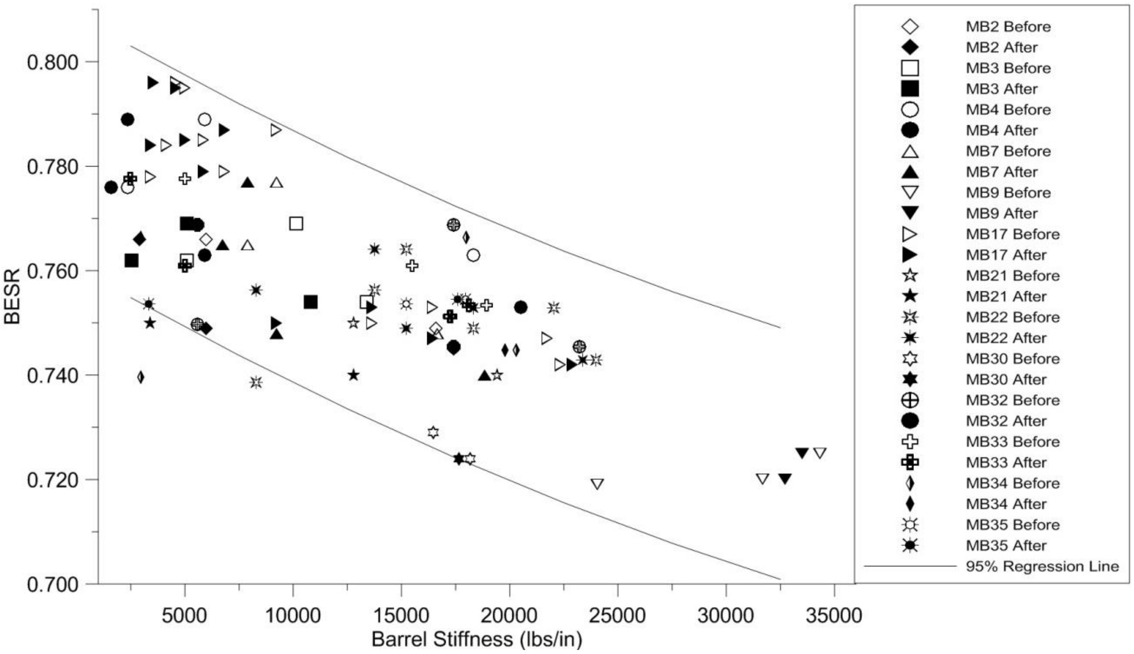

Figure 44. BESR vs. barrel stiffness without MB25 and MB27.

Note that all future stiffness plots will be presented without MB25 and MB27. To view the stiffness plot with MB25 and MB27 see Appendix E. With this new 95% regression analysis performed, the regression lines are much tighter from the top to the bottom of the remaining data. This 95% of bats tested that fall within these two lines exhibit a BESR range of 0.048 points shown in Figure 44 and in Table 15 which is a much tighter 95% regression analysis than was shown in Figure 43, which was a range of ~0.070 BESR points.

Table 15. 95% Regression Analysis Range Comparison

Metric	95% Regression Range			
	Barrel Stiffness	1st hoop	2nd hoop	1st/2nd Hoop
BESR	0.048	0.040	0.057	0.045
BBCOR	0.057	0.047	0.067	0.071
BBS (mph)	7.5	5.0	7.7	7.6

Table 15 shows that first hoop frequency shows the best correlation to performance for all three metrics (BESR, BBCOR and BBS). Barrel stiffness shows better correlation than second hoop frequency does but not quite as good as first hoop frequency. The tighter range of the first hoop frequency makes it the best detector of performance and the best 'field test' to estimate how well a bat will perform.

Figure 45 shows BESR cycle data vs. first hoop frequency cycle data. Similar to Figure 43 which showed that BESR increases with decreasing barrel stiffness, Figure 45 shows that BESR increases with decreasing first hoop frequency. Figure 45 spans the same range of BESR as Figure 43, but the data visually show less scatter than is observed in Figure 43. This reduced scatter implies that the first hoop frequency is a better metric than barrel stiffness for estimating BESR performance. Figure 45 also shows a 95% regression analysis that was performed on the data. The regression analysis shows a range of 0.040 BESR points which is a tighter correlation than barrel stiffness had shown.

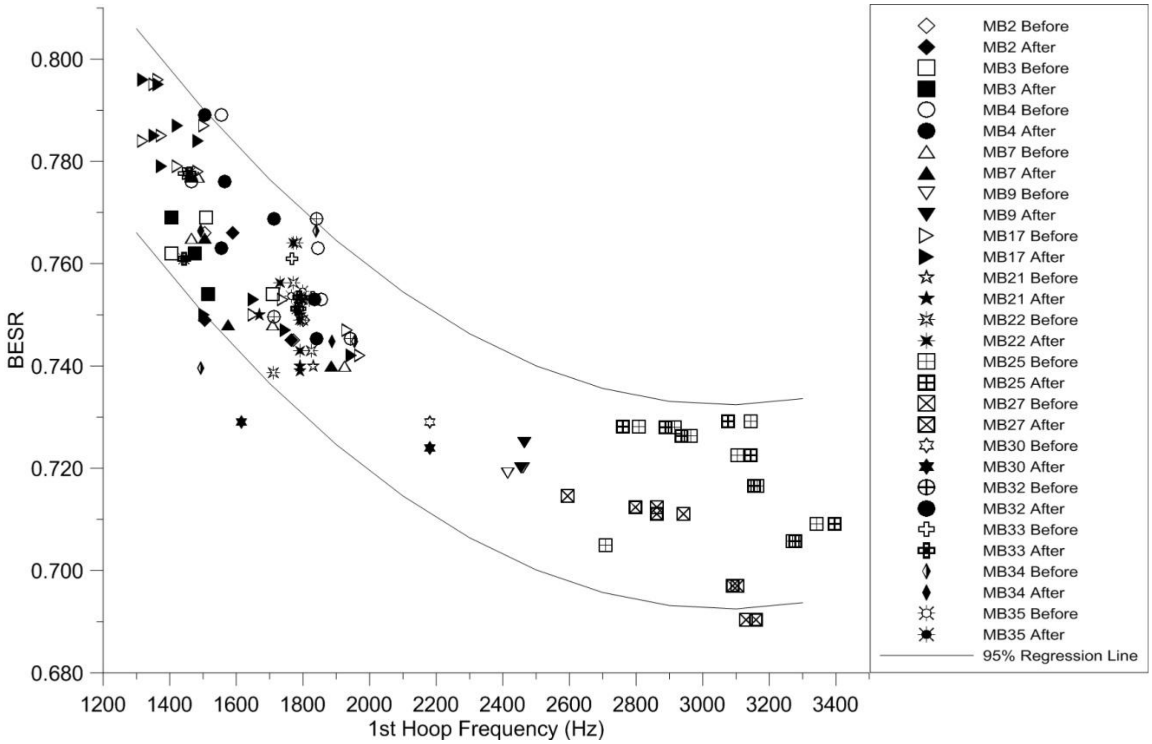

Figure 45. BESR vs. first hoop frequency.

After removing MB25 and MB27 from the barrel stiffness plots, BESR was plotted against first hoop frequency also without MB25 and MB27 to see if their removal improved the BESR vs. first hoop frequency correlation. Figure 46 shows BESR vs. first hoop frequency without MB25 and MB27. As can be seen by the dashed lines in Figure 46, there is not a significant improvement in the 95% regression analysis from the solid lines that were found with the inclusion of MB25 and MB27. Due to this similarity in 95% regression analyses, MB25 and MB27 will be included in all the hoop frequency plots.

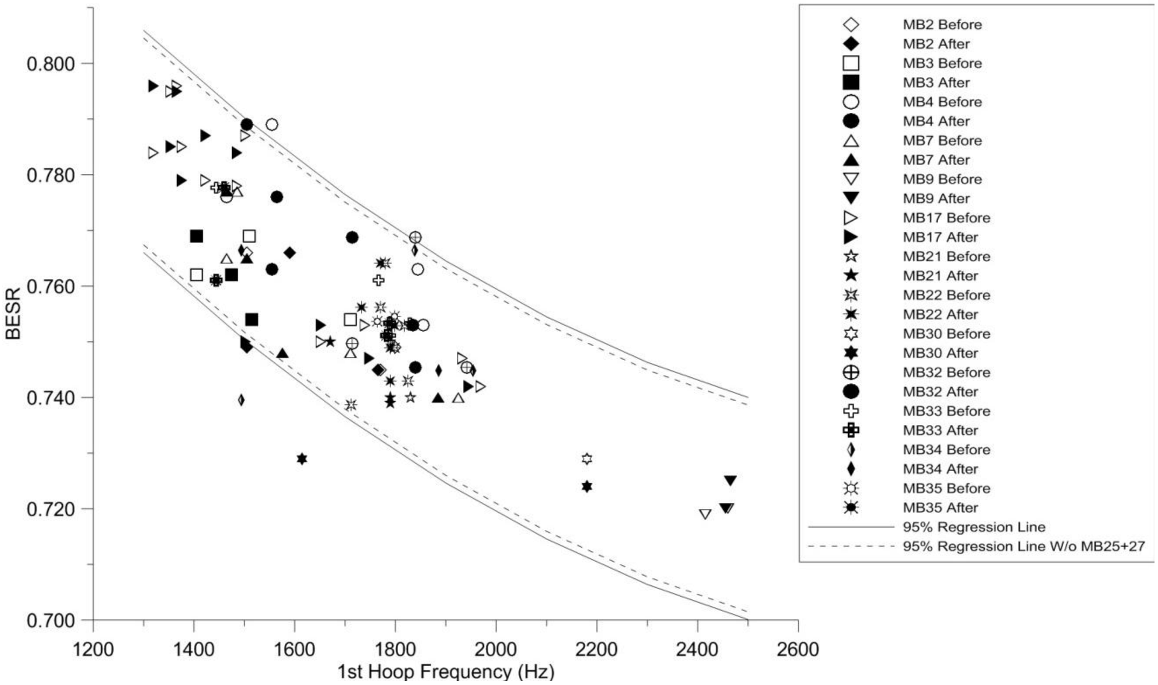

Figure 46. BESR vs. first hoop frequency without MB25 and MB27.

Figure 47 is a plot of BESR vs. second hoop frequency. This figure shows that BESR increases as the second hoop frequency decreases. This trend is similar to BESR vs. first hoop frequency. Because the second hoop frequency is dependent on barrel stiffness, this correlation between BESR and second hoop frequency is expected. The BESR vs. second hoop frequency data are more scattered than in the BESR vs. first hoop frequency data, as can be seen when comparing Figure 47 to Figure 45. This reduced correlation is expected because the higher-order hoop modes of the baseball bat should have less of an effect on batted-ball performance than the primary hoop mode (first hoop mode) because the time of collision is relatively so short that the ball cannot excite the second hoop mode (or higher order modes) as strongly as the first hoop mode. Figure 47 is consistent with this reasoning.

Figure 47 includes lines for a regression analysis of the BESR vs. second hoop frequency. In this figure, the 95% regression line that best fits the BESR vs. second hoop frequency data is a curved line similar to the trend for first hoop frequency shown in Figure 45. This trend line does not show as steep an increase in slope as the first hoop frequency exhibited at the lower end of the hoop frequency range, which may be partially due to the increased scatter for the second hoop frequency data in comparison to the first hoop frequency data. The 95% regression analysis performed in Figure 47 shows a range of 0.057 BESR points which is not as tight of a range as first hoop frequency (0.040 BESR points) and barrel stiffness (0.048 BESR points).

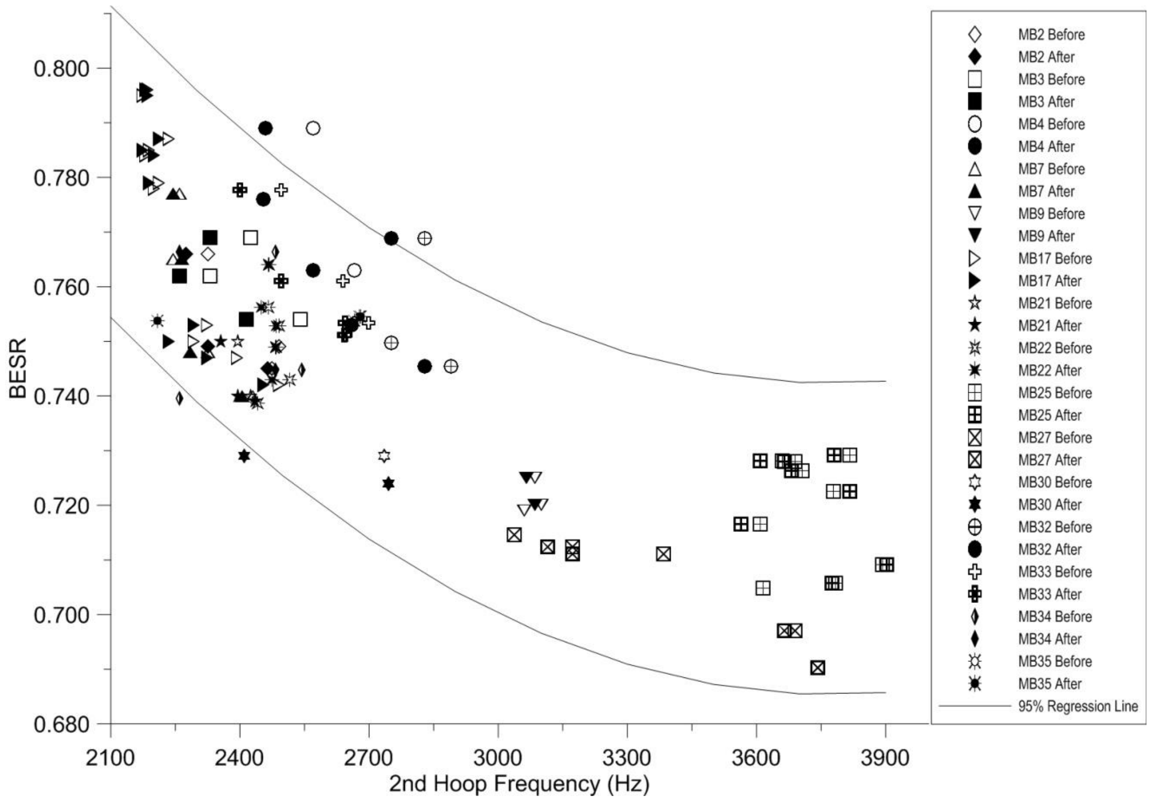

Figure 47. BESR vs. second hoop frequency.

Both the first and the second hoop frequency show a correlation to performance. Due to these two correlations, BESR was plotted against the ratio of second hoop frequency divided by first hoop frequency (Figure 48). As can be seen in Figure 48 and Table 15, this ratio did not show an improved correlation, having a 95% regression analysis range of 0.045 BESR points.

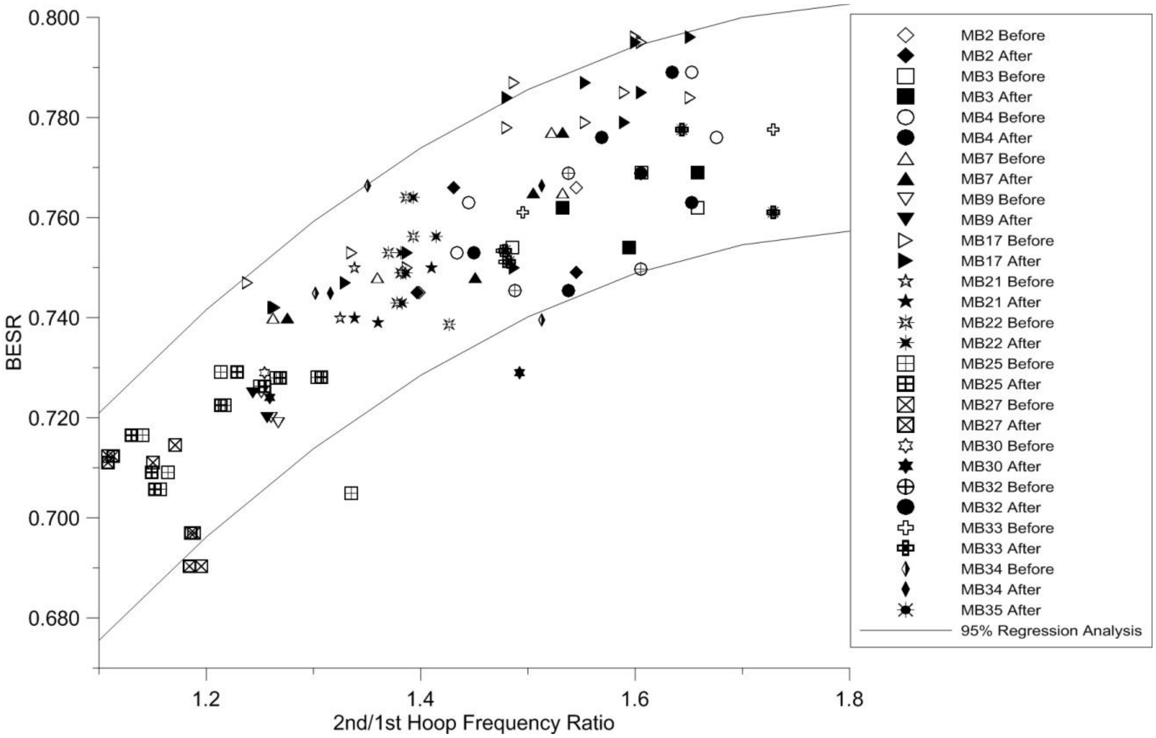

Figure 48. BESR vs. second/first hoop frequency ratio.

Figures 43 through 47 imply that the BESR increases as the first and second hoop frequencies and the barrel stiffness of a composite baseball bat decrease. It is not obvious from these data if and how these three barrel parameters interact to conclude the overall BESR performance. To explore how the hoop frequency, barrel stiffness and performance interact, two three-dimensional plots were generated.

Figure 49 is a plot of BESR vs. first hoop frequency and barrel stiffness. Figure 49 shows the highest BESR values are located in the corner of the plot that corresponds to the lowest barrel stiffness and lowest first hoop frequency values. As the trend moves from the lower to higher barrel stiffness and from the lower to higher first hoop frequencies, there is a clear decreasing BESR trend. Note that MB25 and MB27 are not presented in Figure 49 and can be viewed in Appendix E.

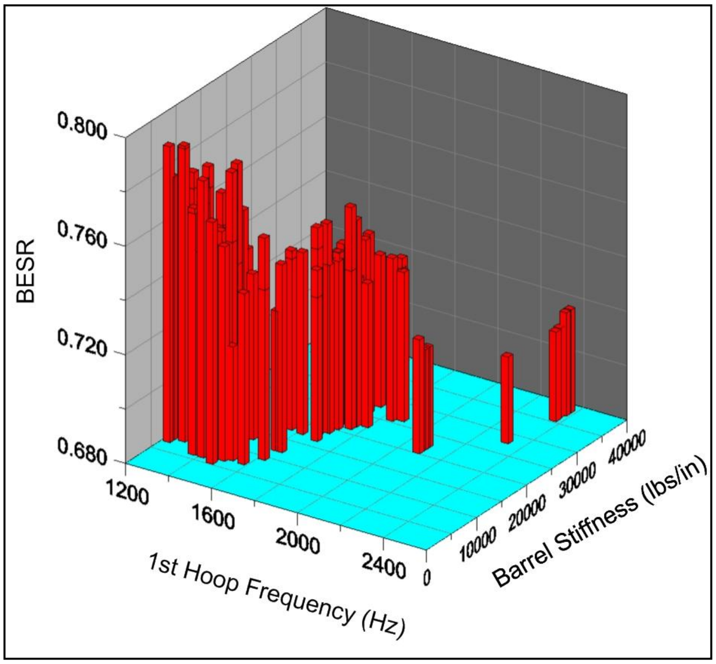

Figure 49. BESR vs. first hoop frequency and barrel stiffness without MB25 and MB27.

Figure 49 implies that composite baseball bats cannot exist that have a low barrel stiffness and high first hoop frequency or conversely a bat with a high barrel stiffness and low first hoop frequency are not on this plot and rightfully so. These two properties are linked as discussed in Section 2.2.3, i.e. first hoop frequency increases as barrel stiffness increases, which is verified in Figure 49 due to the absence of any bats that have high stiffness and low hoop frequency or vice versa. The natural frequency of an object is proportional to the square root of stiffness over mass. Thus, as the stiffness of the barrel is changed up or down, the frequency of the barrel must also change up or down, respectively.

Figure 50 is a plot of BESR vs. second hoop frequency and barrel stiffness. Figure 50 shows a trend very similar to Figure 49. The highest BESR values are in the corner of the plot that corresponds to the lowest second hoop frequencies and lowest barrel stiffness values. Similar to Figure 49 these data were plotted without bats MB25 and MB27 due to the different compression test methods. Bats MB25 and MB27 can be viewed on this plot in Appendix E. As the trend moves to the corner of the plot that corresponds to the highest second hoop frequency and highest barrel stiffness values, the BESR decreases. It is still possible to discern the increased scatter from the second hoop frequency data in Figure 50 when comparing this plot to Figure 49. However, it is less apparent here than in the two-dimensional plots of BESR vs. second hoop frequency.

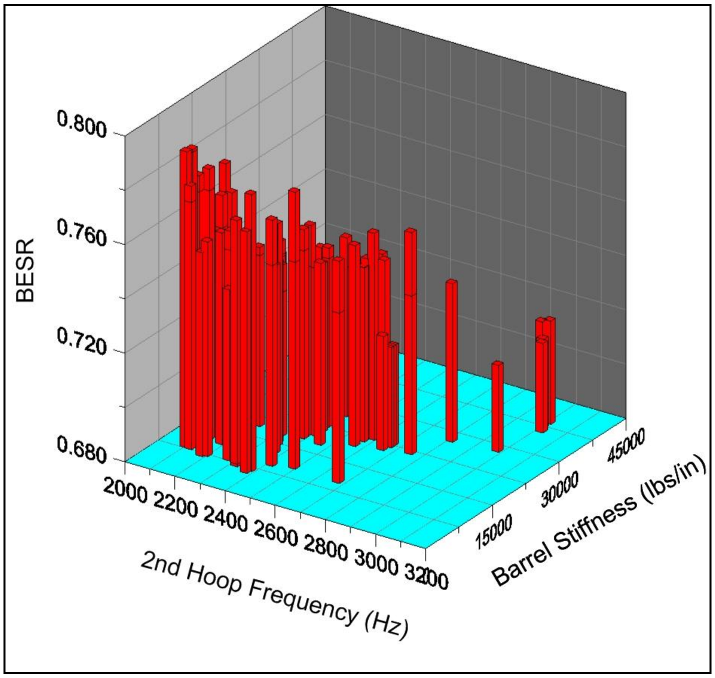

Figure 50. BESR vs. second hoop frequency and barrel stiffness without MB25 and MB27.

Figures 51 and 52 are plots of BBCOR vs. barrel stiffness and BBS vs. barrel stiffness, respectively. Figures 51 and 52 show the same trend as BESR had in Figure 43. The only variation among Figures 43, 51 and 52 comes from the differences in calculations for BESR, BBCOR and BBS, respectively. These two plots (BBCOR vs. barrel stiffness and BBS vs. barrel stiffness) are also plotted with MB25 and MB27 as previously discussed in this section in Appendix E. The 95% regression analyses were performed on the data of Figures 51 and 52. As summarized in Table 15, the 95% regression analysis range for barrel stiffness is 0.057 points for BBCOR and 7.5 mph for BBS.

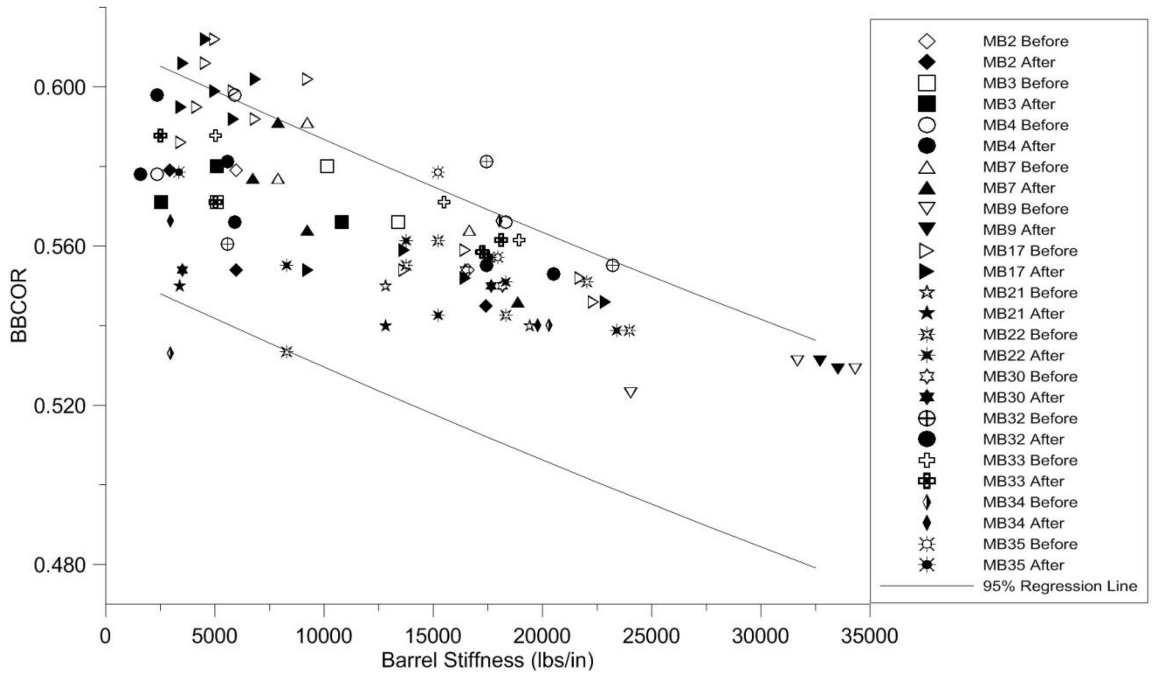

Figure 51. BBCOR vs. barrel stiffness without MB25 and MB27.

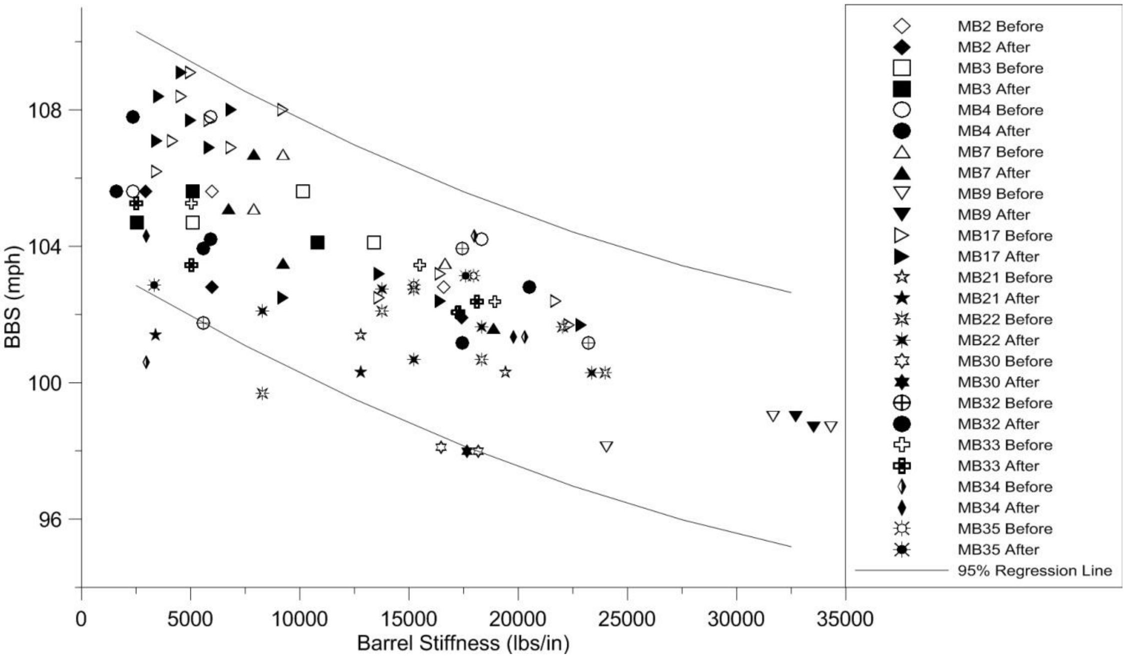

Figure 52. BBS vs. barrel stiffness without MB25 and MB27.

Figure 53 shows BBCOR vs. first hoop frequency, and Figure 54 shows BBS vs. first hoop frequency. Figures 53 and 54 exhibit the same trend for first hoop frequency as BESR does in Figure 45. The only variation among Figures 45, 53 and 54 comes from the differences in calculations for BESR, BBCOR and BBS, respectively. It can be noted from Figures 53 and 54 that the trend of the BBS data displays more curvature than the trend of the BBCOR data. The BBCOR data suggest a linear trend that continues to decrease above 3000 Hz, while the BBS data suggest that the performance may level out at first hoop frequencies above 3000 Hz. The BBS trend may make more sense in the respect that as the hoop frequency goes to a very large value the ball is essentially colliding with a solid wall (solid wood bat) and should not see any performance increase from the hoop frequency. As summarized in Table 15, the 95% regression analysis range for barrel stiffness is 0.047 points for BBCOR and 5.0 mph for BBS.

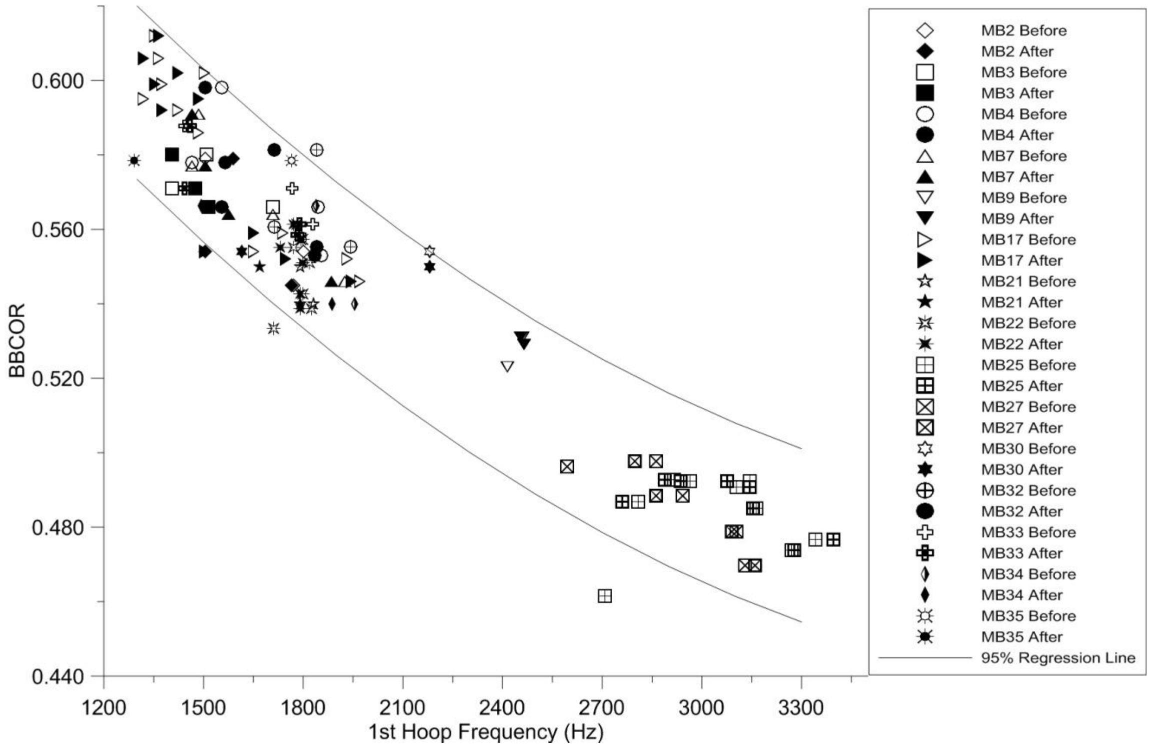

Figure 53. BBCOR vs. first hoop frequency.

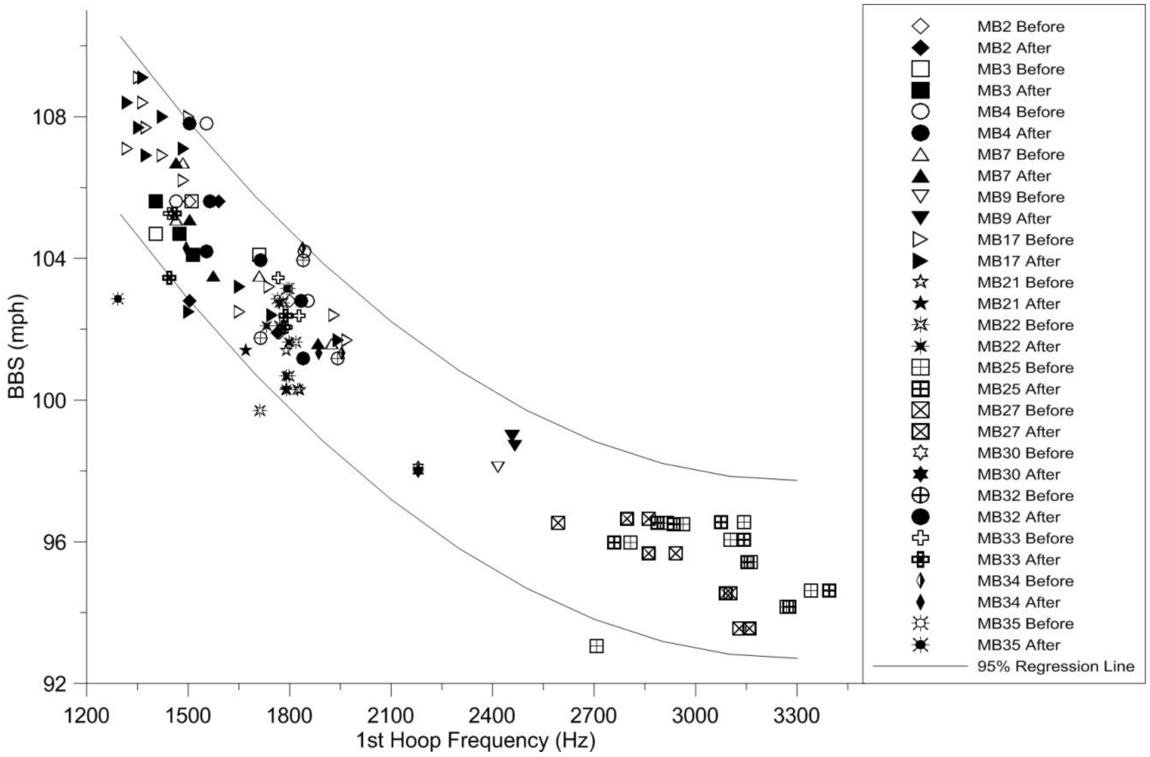

Figure 54. BBS vs. first hoop frequency.

Figures 55 and 56 are plots of BBCOR vs. second hoop frequency and BBS vs. second hoop frequency, respectively. Figures 55 and 56 show the same trend as BESR had in Figure 47. The only variation among Figures 47, 55 and 56 comes from the differences in the calculations for BESR, BBCOR and BBS, respectively. As stated in Table 15, the 95% regression analysis range for barrel stiffness is 0.067 points for BBCOR and 7.7 mph for BBS.

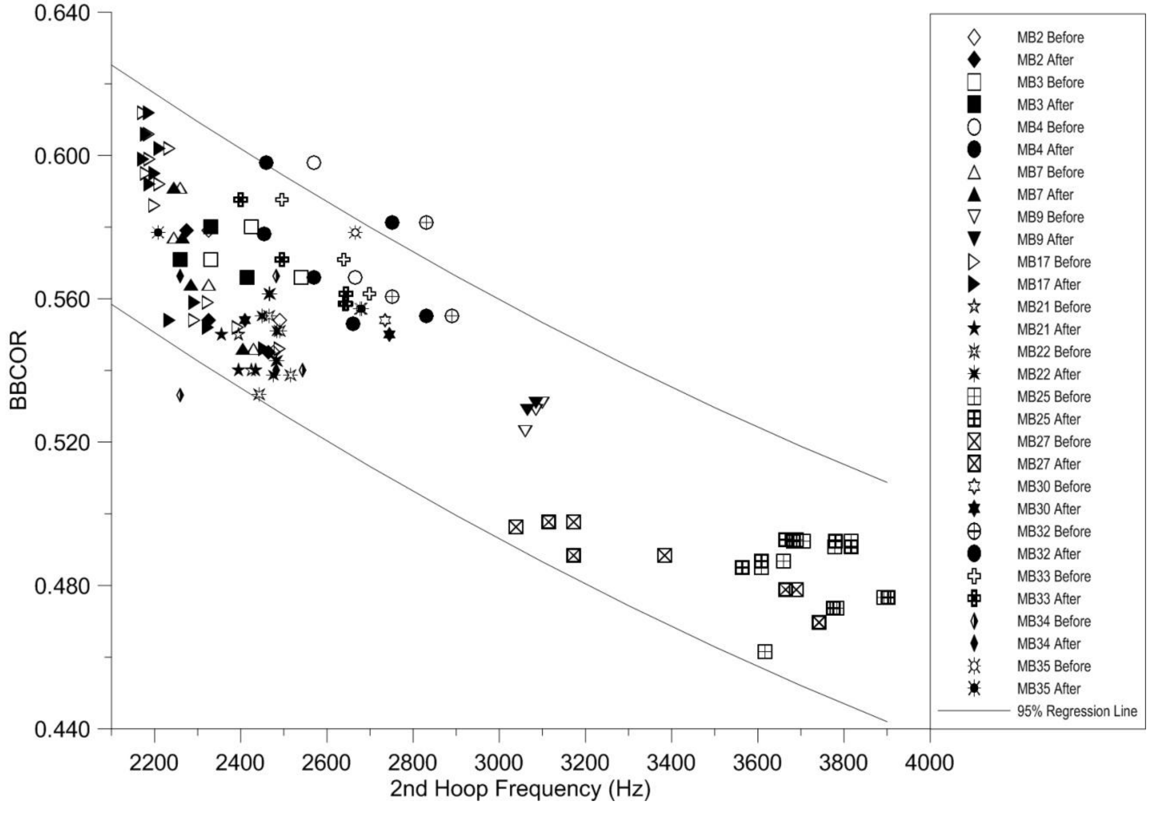

Figure 55. BBCOR vs. second hoop frequency.

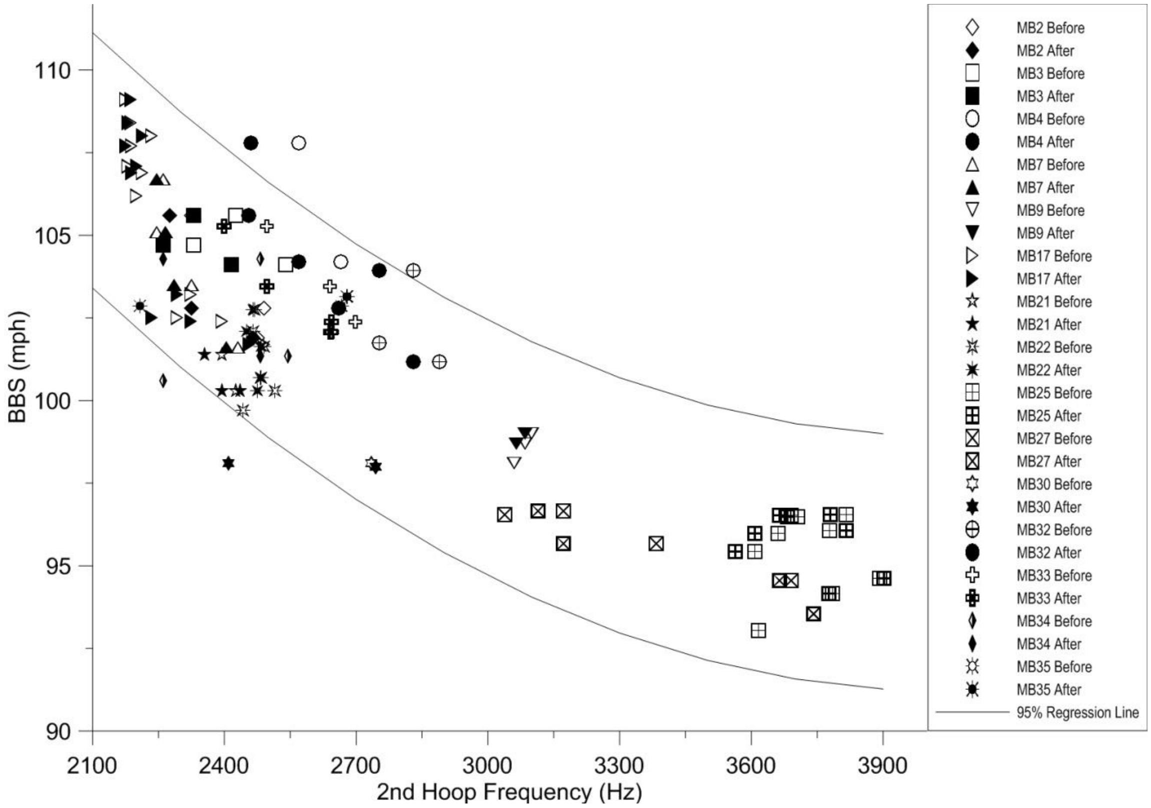

Figure 56. BBS vs. second hoop frequency.

The batted-ball performance metrics (BBCOR and BBS) were plotted against the ratio of second hoop frequency divided by first hoop frequency (Figures 57 and 58). As can be seen in Figure 57, Figure 58 and Table 15, this method for examining the data did not show an improved correlation over first hoop frequency, which had a 95% regression analysis range of 0.071 BBCOR points and 7.6 mph BBS.

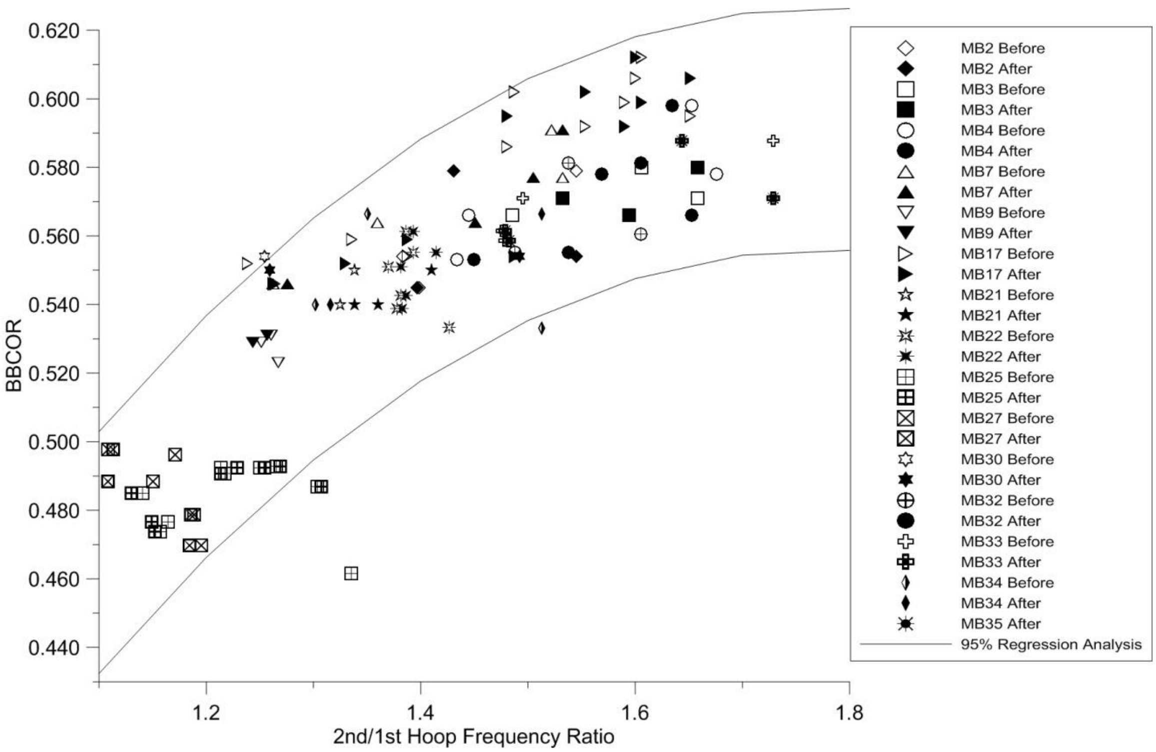

Figure 57. BBCOR vs. second/first hoop frequency ratio.

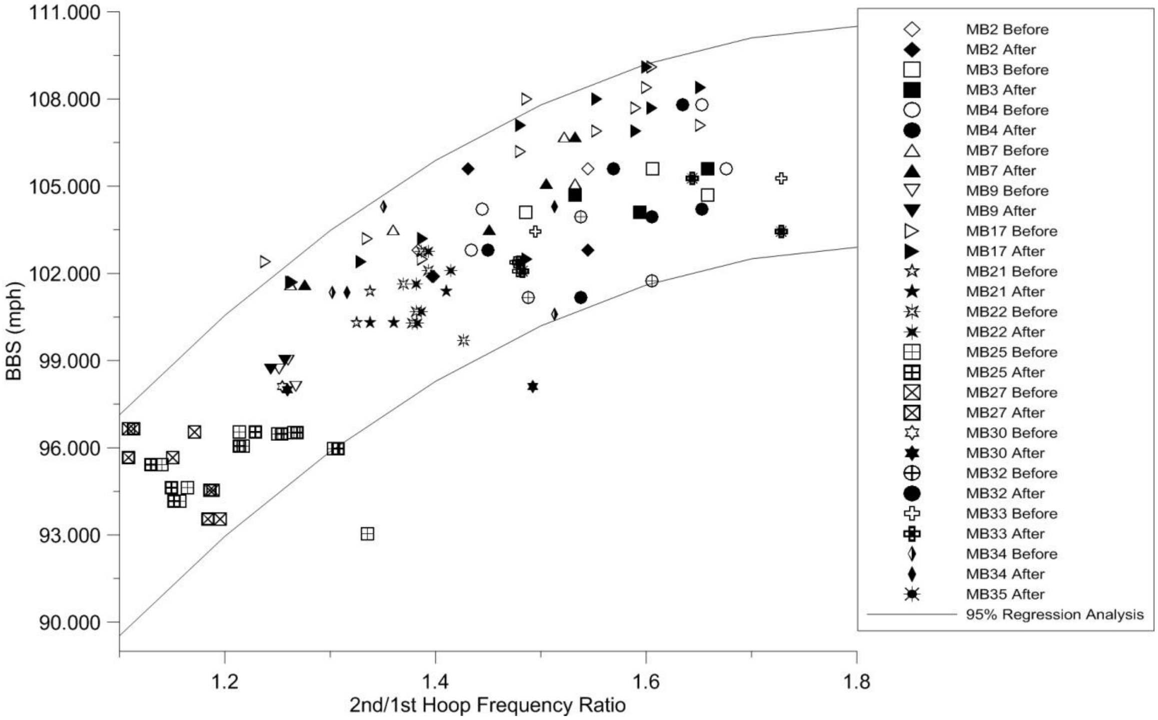

Figure 58. BBS vs. second/first hoop frequency ratio.

Figure 59 shows BBCOR vs. barrel stiffness and first hoop frequency, and Figure 60 shows BBS vs. barrel stiffness and first hoop frequency. Figures 59 and 60 exhibit the same trend as BESR had in Figure 49. As was done for BESR vs. barrel stiffness and first hoop frequency, these data are plotted with MB25 and MB27 in Appendix E.

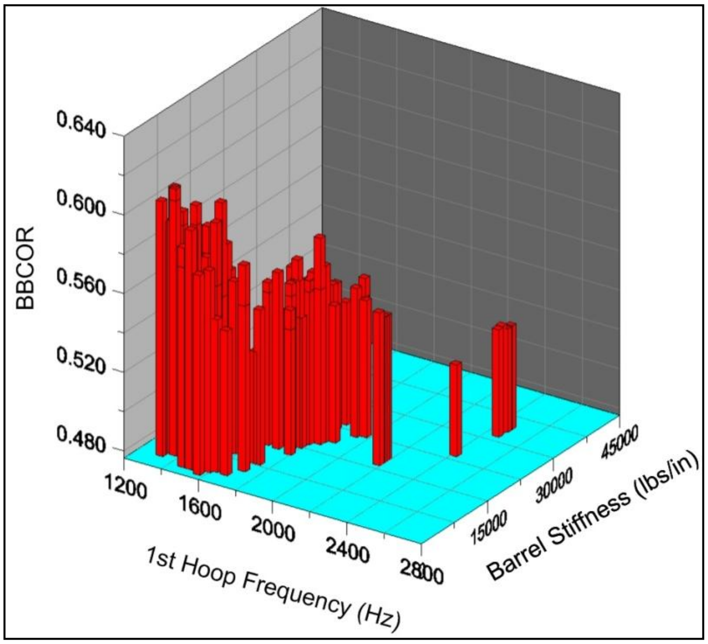

Figure 59. BBCOR vs. first hoop frequency and barrel stiffness without MB25 and MB27.

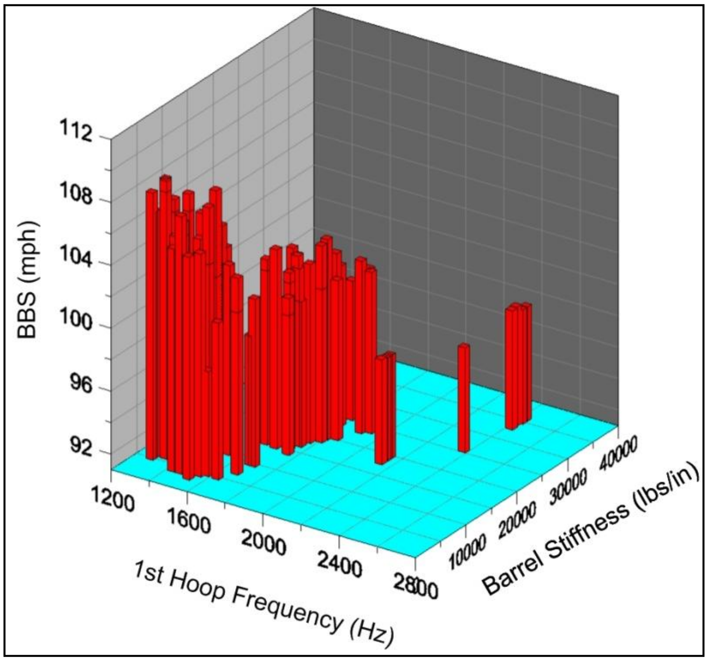

Figure 60. BBS vs. first hoop frequency and barrel stiffness without MB25 and MB27.

Figure 61 shows BBCOR vs. barrel stiffness and first hoop frequency, and Figure 62 shows BBS vs. barrel stiffness and first hoop frequency. Figures 61 and 62 display the same trend as BESR had in Figure 50. As was done in the plot for BESR vs. barrel stiffness and first hoop frequency, these data are plotted with MB25 and MB27 in Appendix E.

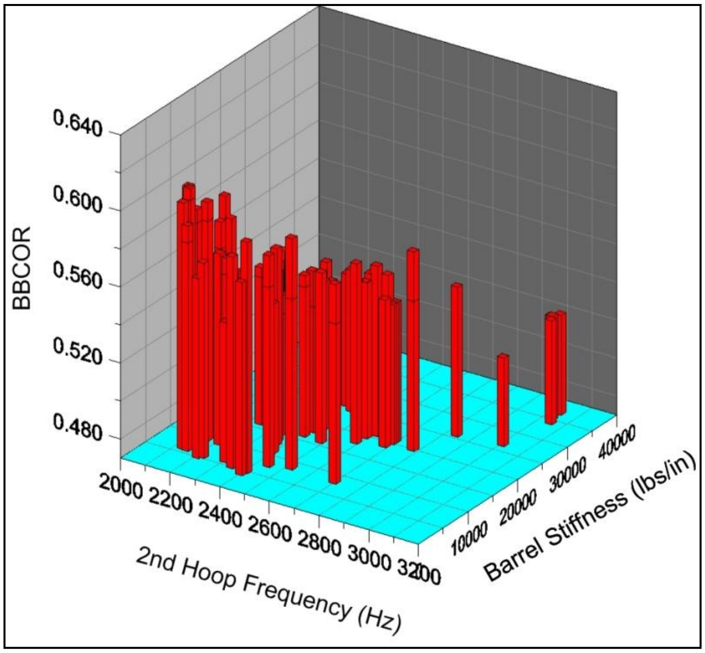

Figure 61. BBCOR vs. second hoop frequency and barrel stiffness without MB25 and MB27.

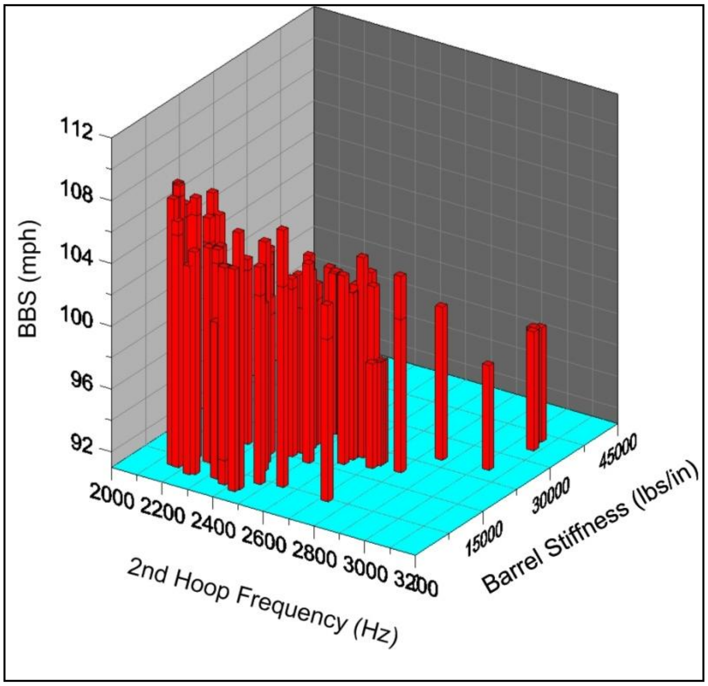

Figure 62. BBS vs. second hoop frequency and barrel stiffness without MB25 and MB27.

Figure 63 is a plot of BBS vs. BBCOR. When BBS is plotted against BBCOR, the data separate into families of straight lines by length. While this plot is for a relatively small subset of the data, it follows the same trend as can be seen when considering a more comprehensive plot of the same quantities using data from the UMBRC certification database (Figure 64). Thus, as the BBS and BBCOR values of the bats in Figure 63 evolved through ABI, the linear relation as a function of length that is observed for bats that are only performance tested for one cycle remained unchanged.

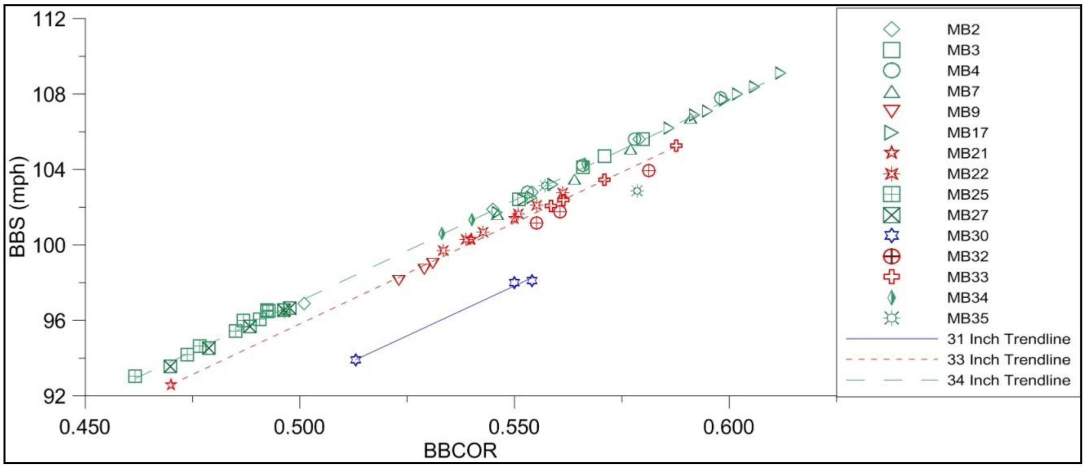

Figure 63. BBS vs. BBCOR for bats used in the current research.

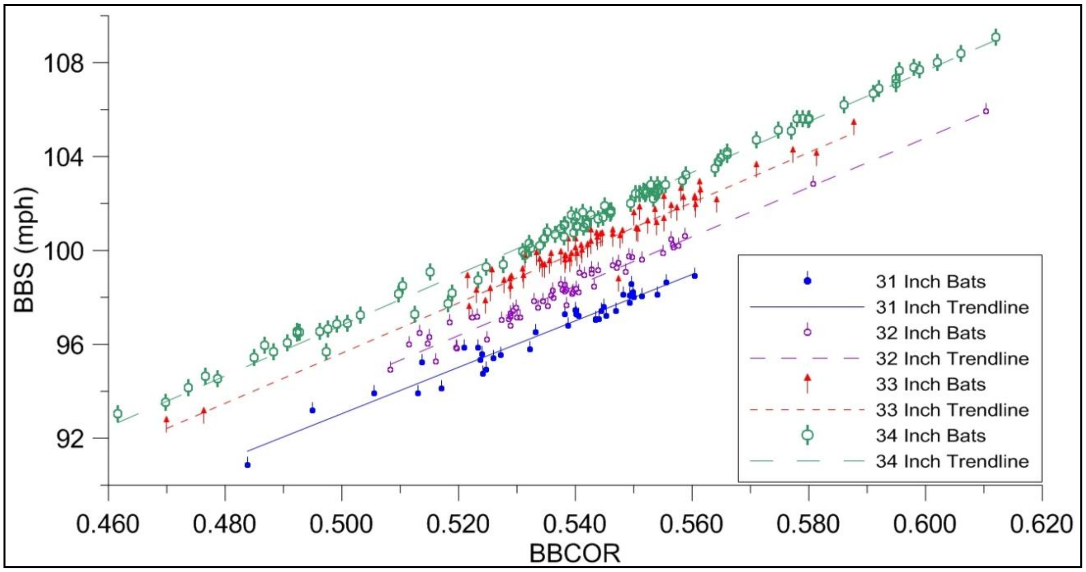

Figure 64. Database of BBS vs. BBCOR currently available.

4.3.2 Barrel Stiffness Analysis

This section of the metric analyses focuses on the indirect performance metrics of barrel stiffness, first hoop frequency and second hoop frequency. These metrics are referred to as indirect measures of performance because while they do not measure batted-ball performance directly, as seen in Sec. 4.2, they do infer a level of batted-ball performance.

Figures 65 and 66 are plots of barrel stiffness vs. first and second hoop frequencies, respectively. The data in these figures show that these hoop frequencies decrease as the barrel stiffness decreases. This correlation is expected as was previously discussed in Section 2.2.3 due to the relationship between stiffness and natural frequency, i.e. the hoop frequency of the barrel is directly proportional to the square root of stiffness over mass. The graphs of first and second hoop frequencies were plotted without bats MB25 and MB27 due to the difference in compression method previously discussed in this chapter. Plots with MB25 and MB27 are in Appendix E.

The correlation between barrel stiffness and the second hoop frequency is not as strong as it is for first hoop frequency. This correlation is shown by the range of the 95% regression performed on each set of data. Figure 65 shows that first hoop frequency exhibits a range of ~450 Hz, while Figure 66 shows that second hoop frequency displays a range of ~650 Hz.

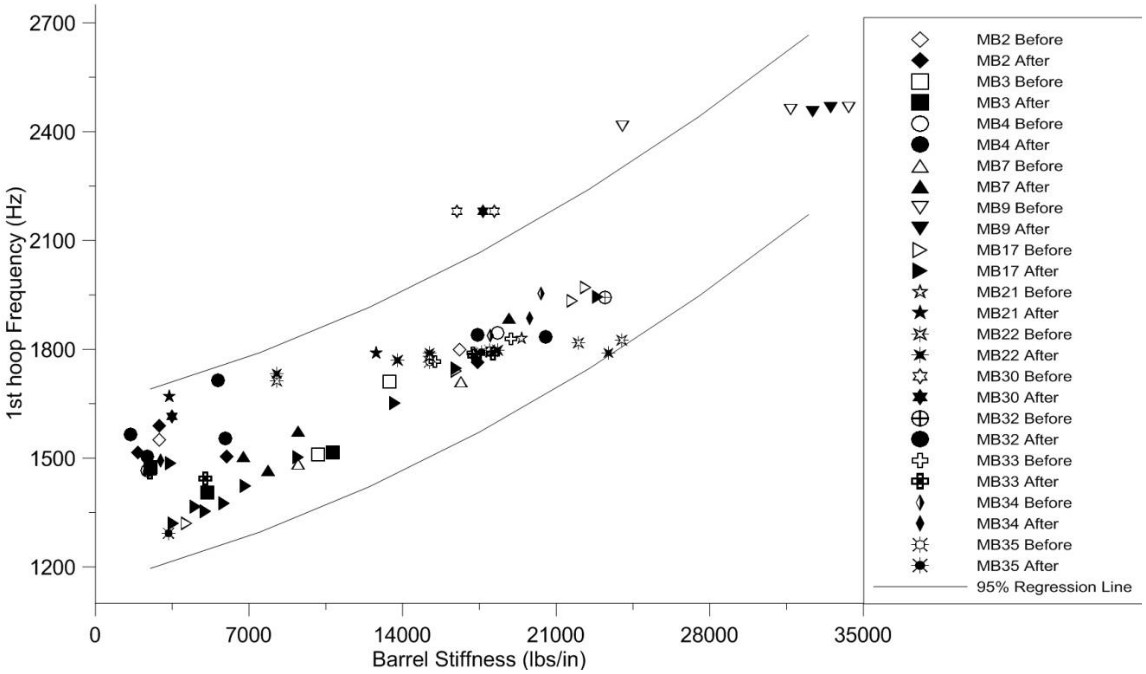

Figure 65. First hoop frequency vs. barrel stiffness without MB25 and MB27.

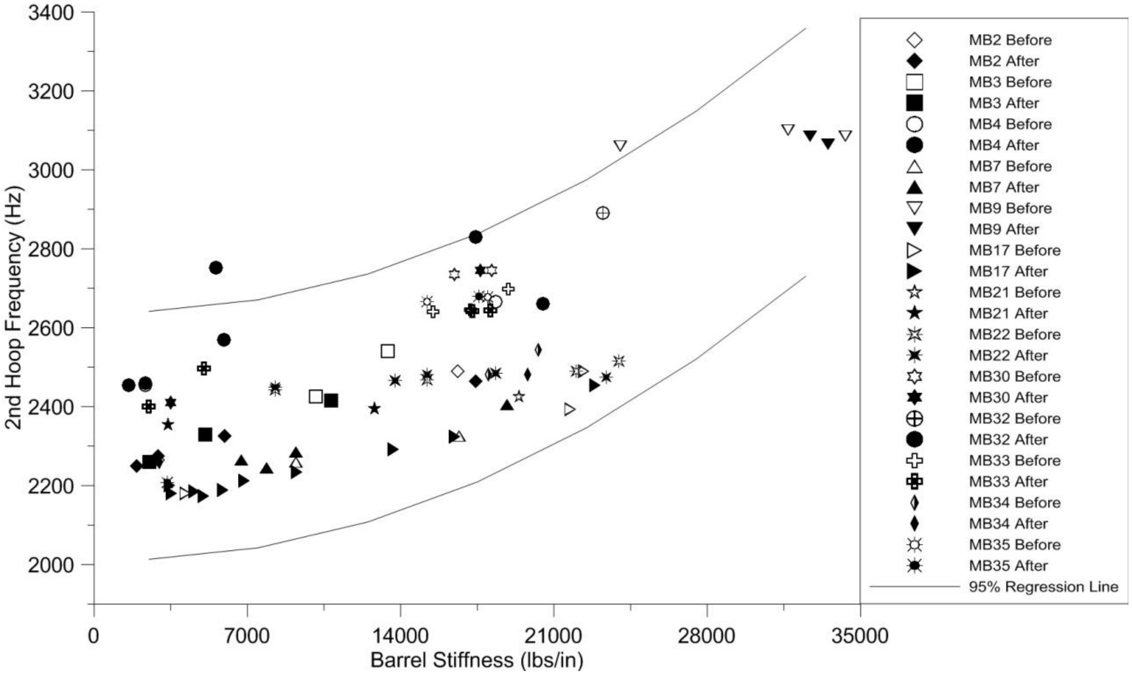

Figure 66. Second hoop frequency vs. barrel stiffness without MB25 and MB27.

To explore how different barrel constructions breakdown, first hoop frequency vs. barrel stiffness is plotted in Figure 67 with symbols denoting barrel material construction. There are three different classifications used: fiberglass, carbon fiber and a mixture of fiberglass and carbon fiber. Only one of the bats in this study was a fiberglass-only reinforced bat. As can be seen in Figure 67, this one fiberglass-only bat showed a first hoop frequency above the 95% regression line for its given barrel stiffness values. These few data points and further study of different barrel constructions should be investigated to see if this trend is specific to fiberglass-only bats or these data are outliers. The majority of the carbon-fiber and mixed-fiberglass-and-carbon-fiber constructions fell within the 95% regression analysis.

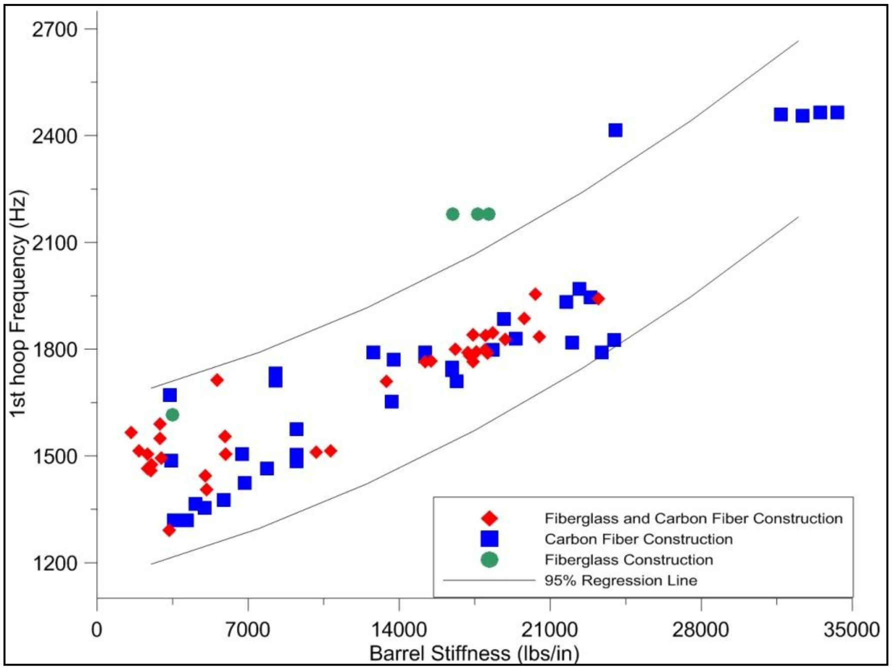

Figure 67. First hoop frequency vs. barrel stiffness barrel construction.

4.4 ABI Data Comparison Analysis

This section presents pairs of data for each of the six metrics of BESR, BBCOR, BBS, barrel stiffness, and first and second hoop frequencies plotted against cycle number. A cycle includes modal testing, compression testing, ABI if needed to reach the prescribed stiffness reduction and a performance test. These pairs of data will be for matched pairs of bats, i.e. the same bat manufacturer, same model and same length. The bats were subjected to two different ABI procedures, i.e. displacement- or load-control rolling methods as were discussed in Sections 3.4.1 and 3.4.2, respectively. In certain cases, these matched pairs of bats will also be compared to data from a bat that was pulled from the field of play of the same make, model and length when available. This type of comparison will allow for a comparison between the two rolling methods as to the positive and negative aspects of each method, comparison of the broken-in bat data to field-use bats and for an evaluation of the rolling methods to simulate the change in bat performance resulting from game use.

4.4.1 Batted-Ball Performance ABI Comparison: Ball Exit Speed Ratio (BESR)

Figure 68 shows the comparison of the two rolling methods for BESR cycle data of Pair 1. Bat ID MB7 was rolled using displacement-control, and Bat ID MB17 was subjected to load-control rolling. The most obvious observation is that MB17 lasted seven more performance cycles than MB7. This difference in life cycles may or may not be a consequence of the rolling method. Many more data points are needed before such a general conclusion can be made as to this aspect of the two ABI methods. It should be noted that MB17 was tested until the barrel separated from the handle while MB7 had a significant drop in BESR and the test was ended by the ABI protocol shown in Appendix C. Bat ID MB7 was a bat included from certification so testing could not be continued to verify if performance would continue to decrease or would show a second increase as MB17 had once it reached Cycle 4.

Both of the bats started at essentially the same BESR values. The bat that underwent displacement-control (MB7) rolling initially showed a similar BESR increase to the load-control bat (MB17). However, on the third cycle, MB7 spiked much higher than MB17, which only saw a small increase on the third cycle. After the third cycle, the displacement-control bat dropped significantly and the test was terminated (per the NCAA ABI test protocol). On the fourth cycle, the load-control bat showed a small decrease in performance, however not enough of a drop (0.014 BESR points) to discontinue the test per the NCAA ABI protocol.   However, on the fifth cycle the bat exhibited a significant increase in BESR—above the peak performance of the displacement-control bat. On the sixth cycle, the bat showed another decrease in performance and then rose as the bat went through the next three cycles. The BESR performance degraded as the bat went through the eighth and ninth cycles and eventually cracked during the ninth cycle. The bat barrel separated from the handle on Cycle 11.

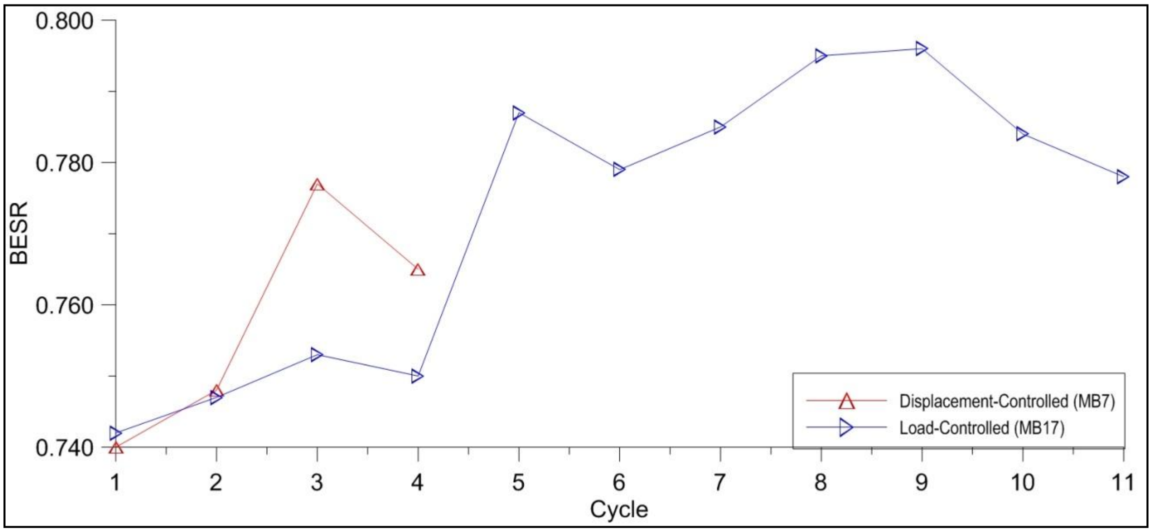

Figure 68. Displacement- and load-control BESR comparison (Pair 1).

Figure 69 shows the comparison of the two rolling methods for BESR cycle data of Pair 2. Bat ID MB21 was rolled using displacement-control, and MB22 was subjected to load-control rolling. The most obvious observation is that MB22 lasted two more performance cycles than MB21. This difference in life cycles may or may not be a consequence of the rolling method but shows the same result as Figure 68 did. The bat that underwent load-control ABI (MB22) reached a higher peak BESR than the displacement-control sample (MB21) in addition to longer life. The bat that underwent displacement-control ABI (MB21) reached its peak BESR at an earlier cycle than the load-control sample (MB22) did which suggests for this pair of bats that the load-control ABI method is not as harsh of an ABI procedure as displacement-control ABI.

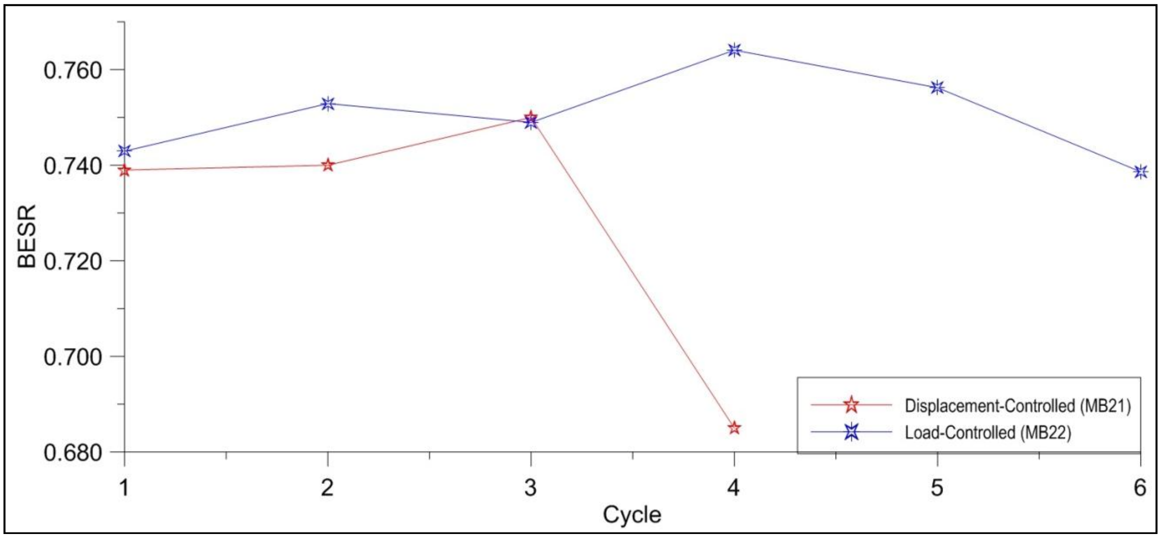

Figure 69. Displacement- and load-control BESR comparison (Pair 2).

Figure 70 shows the comparison of the two rolling methods for BESR cycle data of Pair 3. Bat ID MB32 was rolled using displacement-control, and Bat ID MB33 was subjected to load-control rolling. The most obvious observation is that MB33 lasted two more performance cycles than MB32. This difference in life cycles may or may not be a consequence of the rolling method but shows the same result as Figures 68 and 69 did. The bat that underwent load-control ABI (MB33) reached a higher peak BESR than the displacement-control sample (MB32) in addition to longer life. The bat that underwent displacement-control ABI (MB32) reached its peak BESR at an earlier cycle than the load-control sample (MB33) did which again suggests that the load-control ABI method is not as harsh of an ABI procedure as displacement-control ABI.

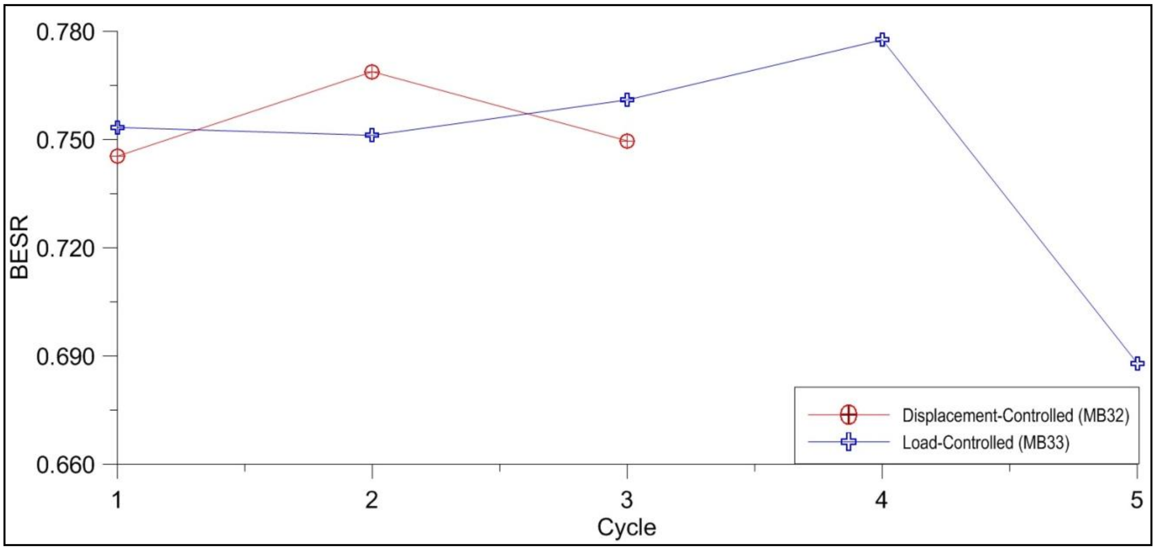

Figure 70. Displacement- and load-control BESR comparison (Pair 3).

Figure 71 shows the comparison of the two rolling methods for BESR cycle data of Pair 4. Bat ID MB3 was rolled using displacement-control, and Bat ID MB34 was subjected to load-control rolling. The most obvious observation is that MB3 lasted one more performance cycle than MB34. This difference in life cycles may or may not be a consequence of the rolling method and shows the opposite result as Figures 68, 69 and 70 did. This result may also be due to the different construction of this bat from the previous three bat pairs. The bat that underwent displacement-control ABI (MB3) reached a higher peak BESR than the load-control sample (MB34) in addition to longer life. The bat that underwent load-control ABI (MB34) reached its peak BESR at an earlier cycle than the displacement-control sample (MB3) did which suggests that the displacement-control ABI method is not as harsh of an ABI procedure as load-control ABI method in this case.

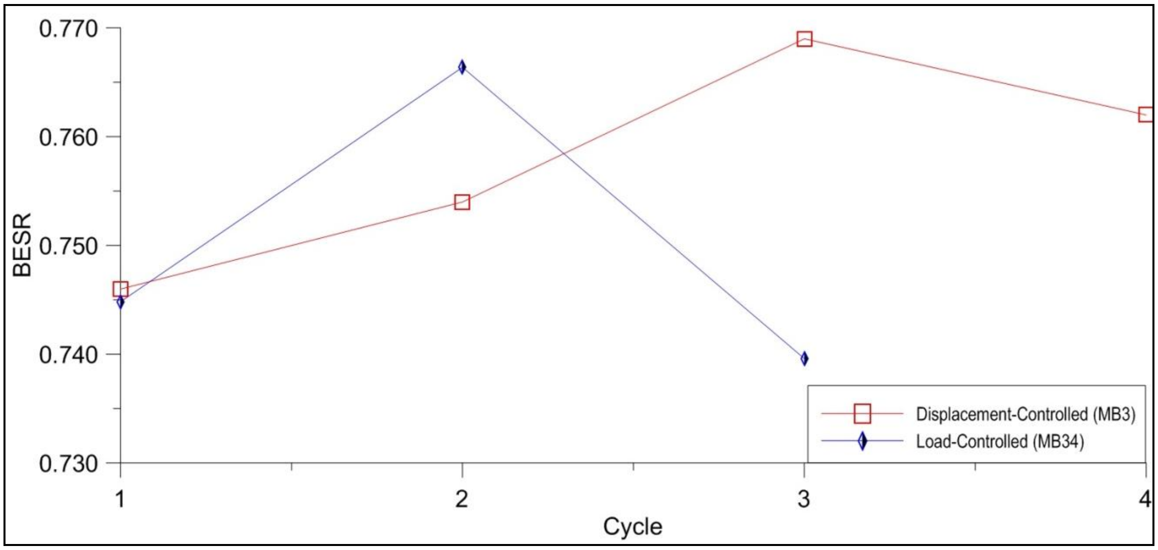

Figure 71. Displacement- and load-control BESR comparison (Pair 4).

Figure 72 shows the comparison of the two rolling methods for BESR cycle data of Pair 5. Bat ID MB4 was rolled using displacement-control, and Bat ID MB35 was subjected to load-control rolling. The most obvious observation is that MB4 lasted one more performance cycle than MB35. This difference in life cycles may or may not be a consequence of the rolling method and shows the opposite result of Figures 68, 69 and 70 did. This result may also be due to the different construction of this bat from the first three bat pairs. The bat that underwent displacement-control ABI (MB4) reached a higher peak BESR than the load-control sample (MB35) in addition to longer life. The bat that underwent load-control ABI (MB35) had no net increase in BESR compared to the displacement-control sample (MB4). This result suggests that the displacement-control ABI method is not as harsh of an ABI procedure as load-control ABI method in this case.

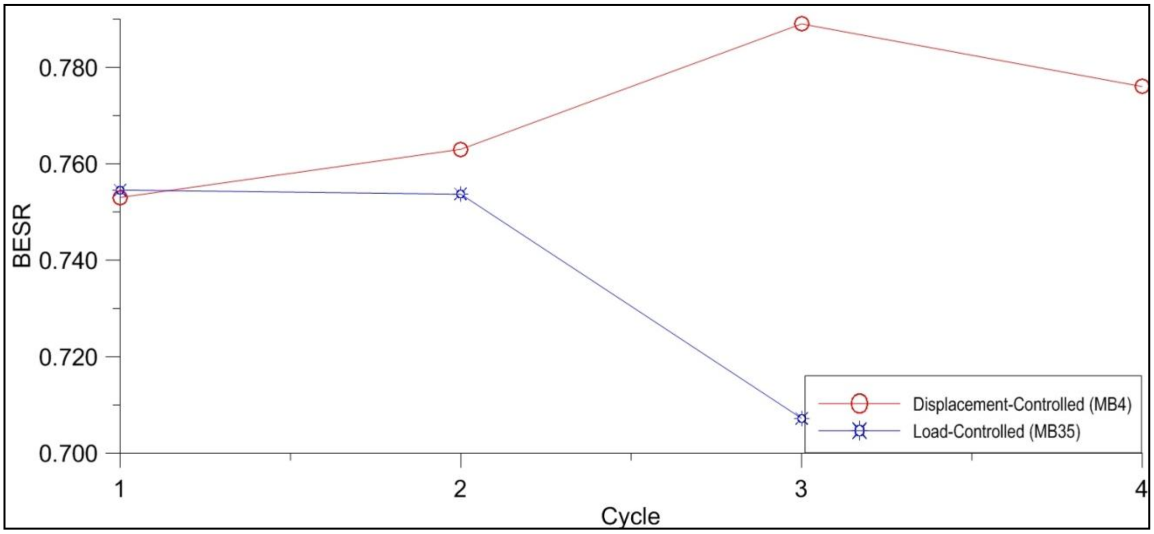

Figure 72. Displacement- and load-control BESR comparison (Pair 5).

Only the BESR data were presented in this section. As was observed previously in this thesis, BBCOR and BBS follow the same trends as BESR, so comparing the pairs of bats using the BBCOR and BBS methods would not show any difference in the trends. However, for completeness, plots for BBS and BBCOR comparing the same pairs of bats are shown in Appendix F.

4.4.2 Barrel Stiffness ABI Comparison

Figure 73 shows the comparison of the two rolling methods for the evolution of the barrel stiffness as a function of performance cycle for Pair 1. Bat ID MB7 was broken-in using the displacement-control method of rolling. Due to an oversight, the barrel stiffness test was not done on the displacement-control bat (MB7) before the first performance test. However, based on the essential equivalent BESR values for this matched pair, it is assumed that the stiffness of MB7 should was essentially the same as MB17. It can be seen in Figure 73 that the load-control bat (MB17) has a higher stiffness than the MB7 bat for the second cycle and all subsequent cycles. This stiffness difference between the two bats may or may not have contributed to the better durability of the load-control bat (MB17).

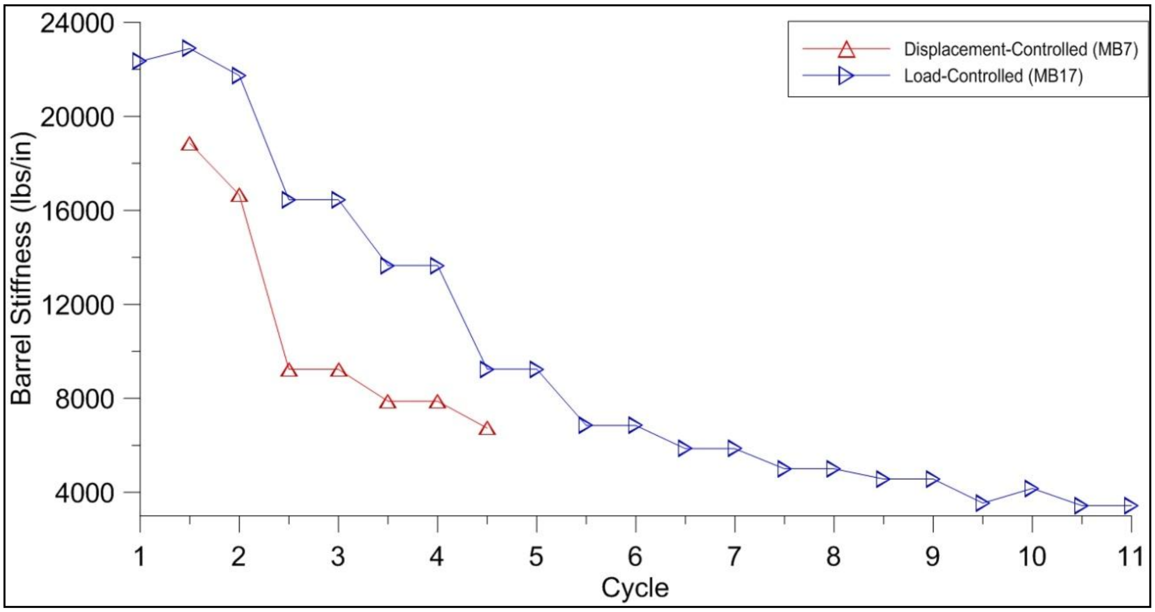

Figure 73. Displacement- and load-control barrel stiffness comparison (Pair 1).

Figure 74 shows the comparison of the two rolling methods for the evolution of the barrel stiffness as a function of performance cycle for Pair 2. Bat ID MB21 was broken-in using the displacement-control method of rolling. Due to an oversight, the barrel stiffness test was not done on the displacement-control bat (MB21) before the first performance test. However, based on the essential equivalent BESR values for this matched pair, it is assumed that the stiffness of MB21 was essentially the same as MB22. It can be seen in Figure 74 that the load-control bat (MB22) has a higher stiffness than the MB21 bat for the second cycle and all subsequent cycles. This stiffness difference between the two bats may or may not have contributed to the better durability of the load-control bat but shows the same result that Figure 73 did.

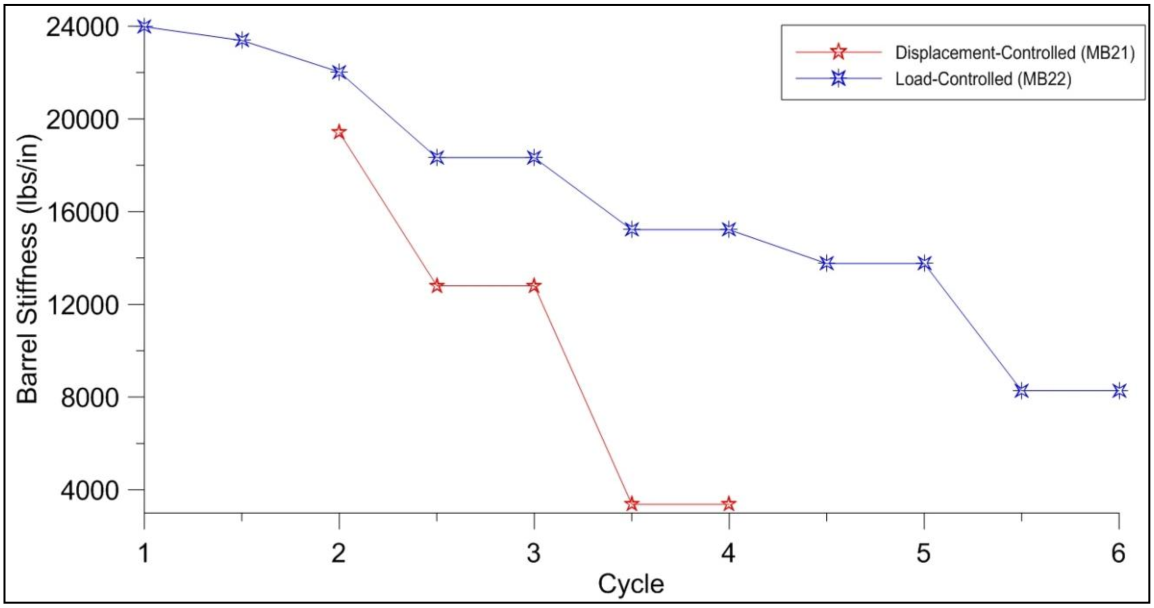

Figure 74. Displacement- and load-control barrel stiffness comparison (Pair 2).

Figure 75 shows the comparison of the two rolling methods for the evolution of the barrel stiffness as a function of performance cycle for Pair 3. Bat ID MB32 was broken-in using the displacement-control method of rolling. Figure 75 shows that the displacement-control bat (MB32) started with higher initial barrel stiffness than the load-control bat (MB33) did. However, it can be seen in Figure 75 that the load-control bat (MB33) has a higher stiffness than the MB32 bat for the second cycle and all subsequent cycles. This more rapid breakdown of the displacement-control bat (MB32) is in line with the results shown by Pairs 1 and 2 in Figures 73 and 74, respectively. These data suggest that the load-control ABI as applied to these bats is a milder break-in procedure and allows bats to have greater durability during testing as well as retaining a higher stiffness over the life of the bat. One possible reason for this phenomenon is a more uniform rolling across the length of the hitting zone using the load-control method as opposed to the displacement-control process, thereby creating less damage to reduce stiffness by 5% or greater in between performance tests.

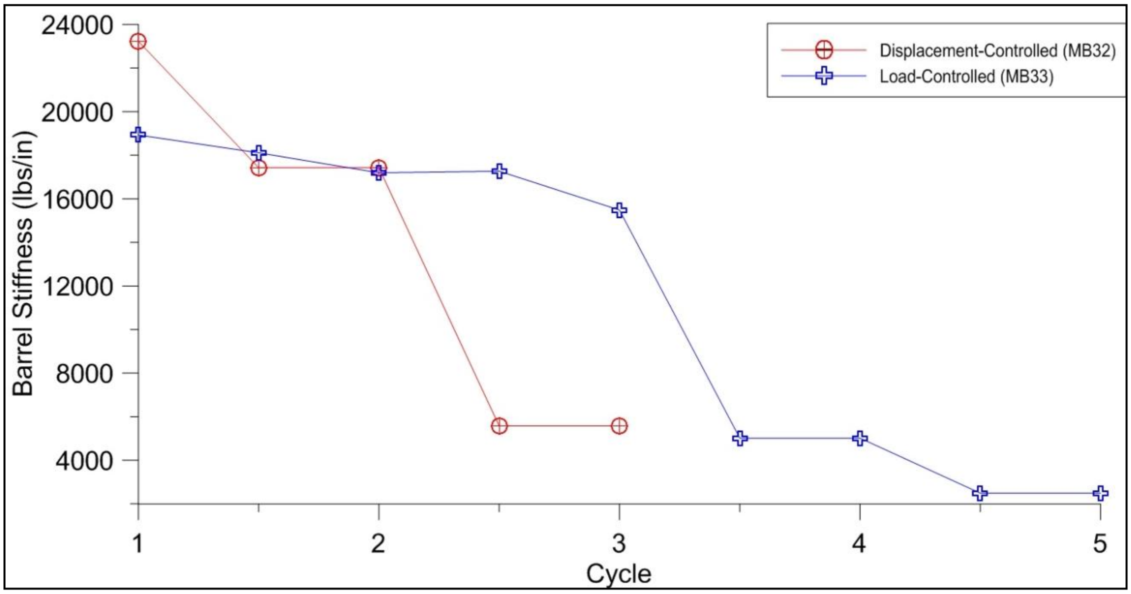

Figure 75. Displacement- and load-control barrel stiffness comparison (Pair 3).

Figure 76 shows the comparison of the two rolling methods for the evolution of the barrel stiffness as a function of performance cycle for Pair 4. Bat ID MB3 was broken-in using the displacement-control method of rolling and did not have any data recorded on Cycle 1 due to an oversight. However, it can be seen in Figure 76 that the load-control bat (MB34) has a higher stiffness than the MB3 bat for the second cycle before dropping below the displacement-control bat in between Cycles 2 and 3. This more rapid breakdown of the load-control bat (MB34) is the opposite of the results shown by Pairs 1, 2 and 3 in Figures 73, 74 and 75, respectively. These data suggest that the displacement-control ABI is a milder break in procedure for this type of bat and allows bats to have greater durability during testing as well as retaining a higher stiffness over the life of the bat. This type of bat construction may be sufficiently different from Pairs 1, 2 and 3 as a reason for having an opposing result.

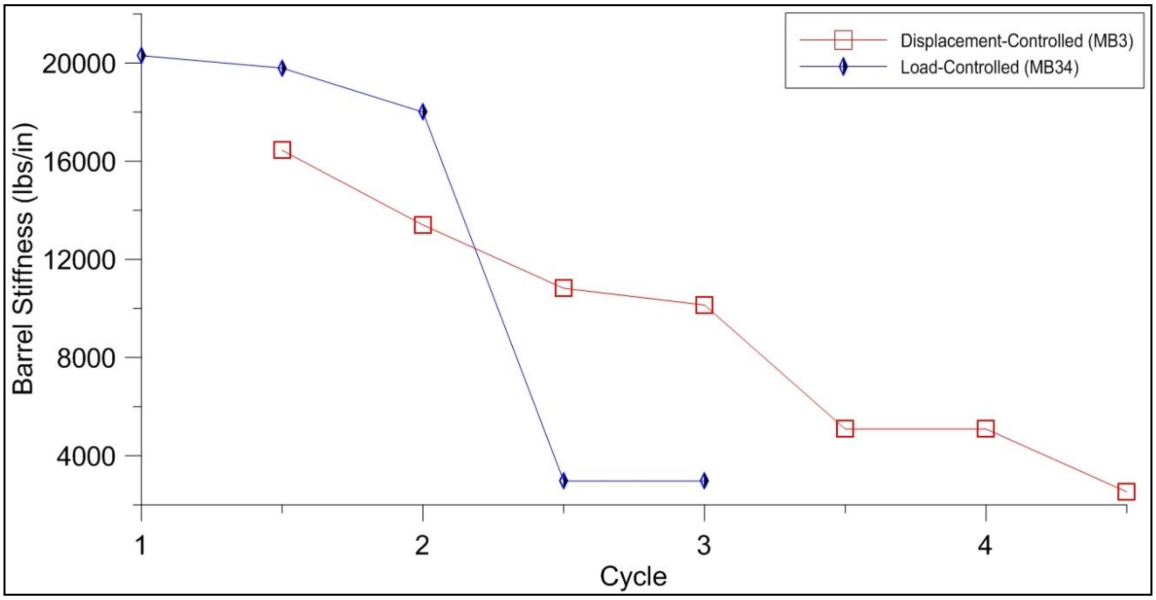

Figure 76. Displacement- and load-control barrel stiffness comparison (Pair 4).

Figure 77 shows the comparison of the two different rolling methods for the evolution of the barrel stiffness as a function of performance cycle for Pair 5. MB4 was broken-in using the displacement-control method of rolling and did not have any data recorded on Cycle 1 due to an oversight. However, it can be seen in Figure 77 that the load-control bat (MB35) has a lower stiffness than the MB4 bat for the second cycle and all subsequent cycles. This result shows a similar breakdown trend in barrel stiffness for the different two methods with a higher initial value in the displacement-control bat case (MB4).

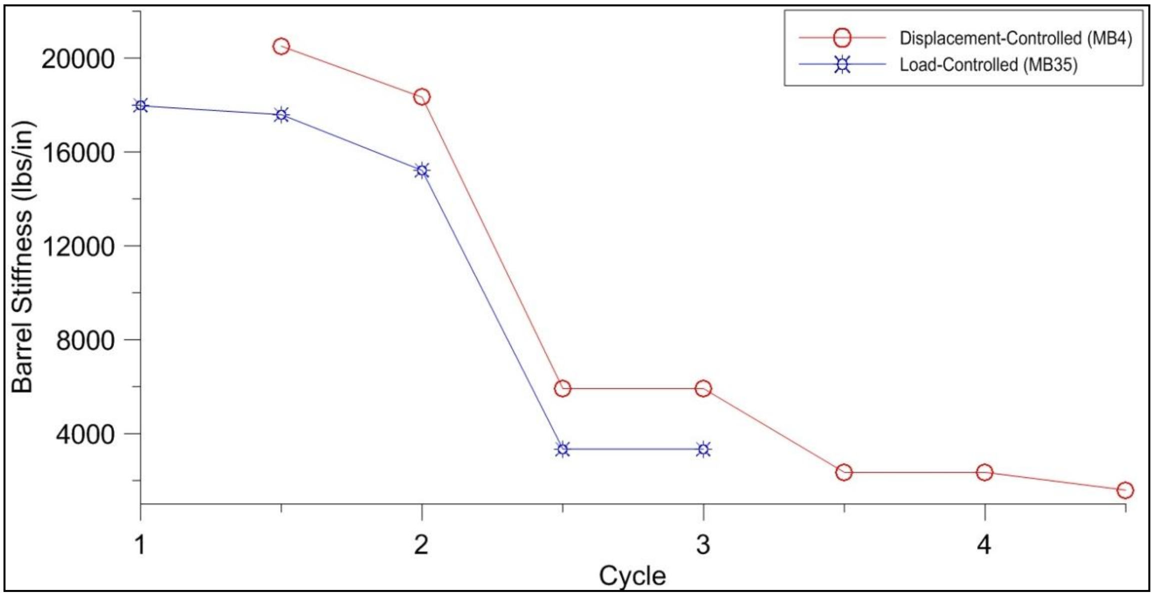

Figure 77. Displacement- and load-control barrel stiffness comparison (Pair 5).

4.4.3 Hoop Frequency ABI Comparison

Figure 78 shows the comparison of the two rolling methods for the first hoop frequency data as a function of performance cycle for the matched pair of MB7 (displacement control) and MB17 (load control). Bat ID MB17 had the higher first hoop frequency up through the fourth cycle. The two bats had essentially the same first hoop frequency when this quantity was measured between the fourth and fifth performance test cycles. The load-control bat (MB17) reached a lower overall first hoop frequency than the displacement-control bat (MB7) did during testing. However, MB17 had a higher first hoop frequency for the first five cycles. Figure 79 shows the comparison of the two different rolling methods for the second hoop frequency cycle data. Bat ID MB17 had a higher barrel stiffness and first hoop mode than MB7. Bat ID MB17 also had a higher second hoop mode which stayed higher than MB7 until after the fourth cycle when MB17 dropped below MB7. The second hoop frequencies stay closer over the entire range than did the first hoop mode frequencies.

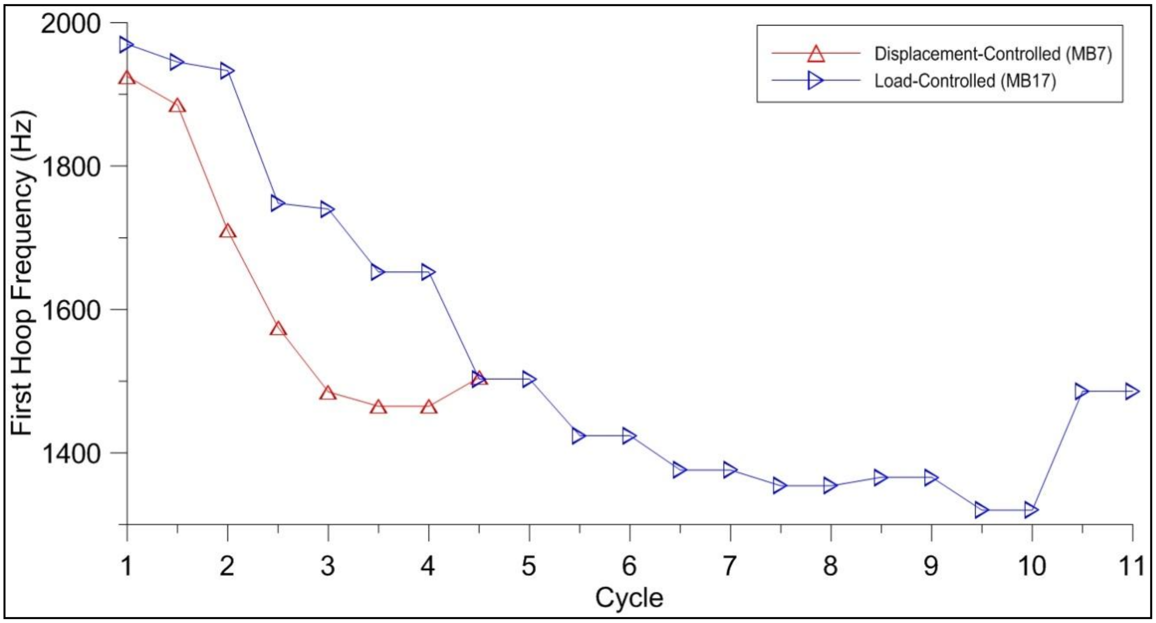

Figure 78. Displacement- and load-control first hoop frequency comparison (Pair 1).

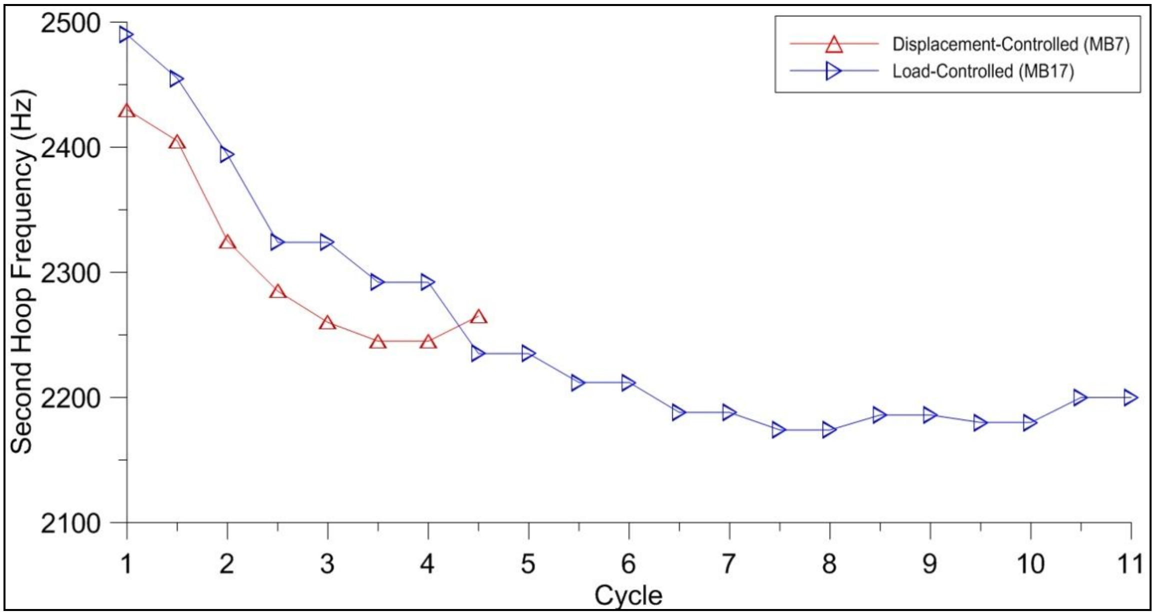

Figure 79. Displacement- and load-control second hoop frequency comparison (Pair 1).

Figure 80 shows the comparison of the two different rolling methods for the first hoop frequency data as a function of performance cycle for the matched pair of MB21 (displacement control) and MB22 (load control). The two bats had essentially the same first hoop frequency up through the fourth performance test cycle where the first hoop frequency of the displacement-control bat (MB21) dropped significantly and the load-control bat (MB22) dropped gradually over the next two cycles. The displacement-control bat (MB21) reached a lower overall first hoop frequency than the load-control bat (MB22) did during testing. Figure 81 shows the comparison of the two different rolling methods for the second hoop frequency as a function of cycle number. Bat ID MB22 had a higher barrel stiffness and slower breaking down of the first hoop mode than MB21. Bat ID MB22 had a higher second hoop mode which stayed higher than MB21 over the entire testing cycle range. The second hoop frequencies are much farther apart over the entire range than are the first hoop frequencies for this second pair of bats.

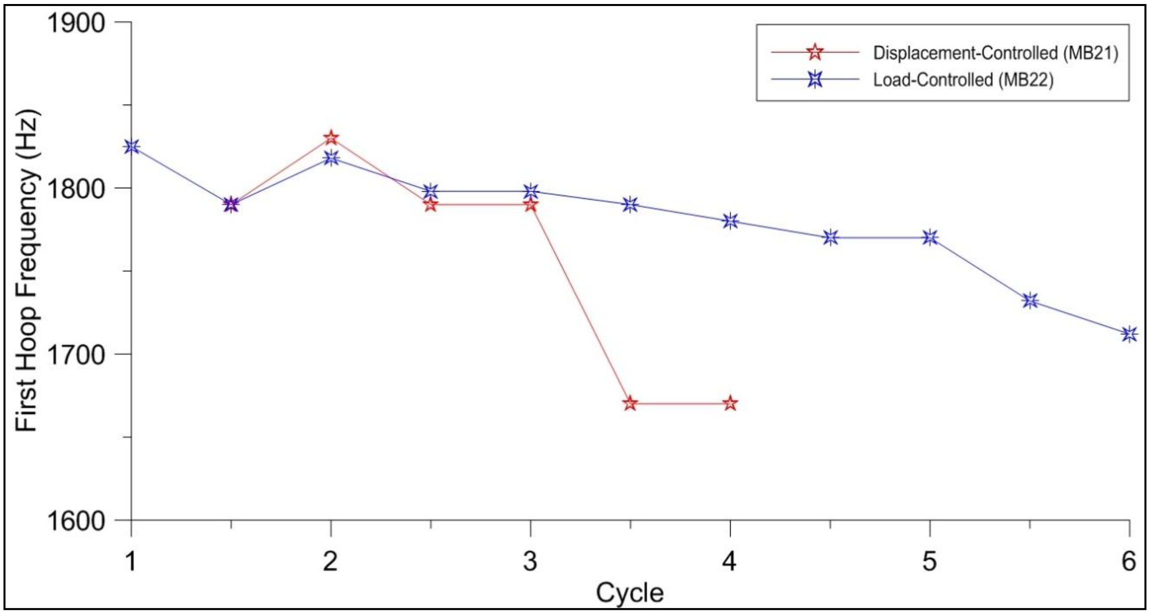

Figure 80. Displacement- and load-control first hoop frequency comparison (Pair 2).

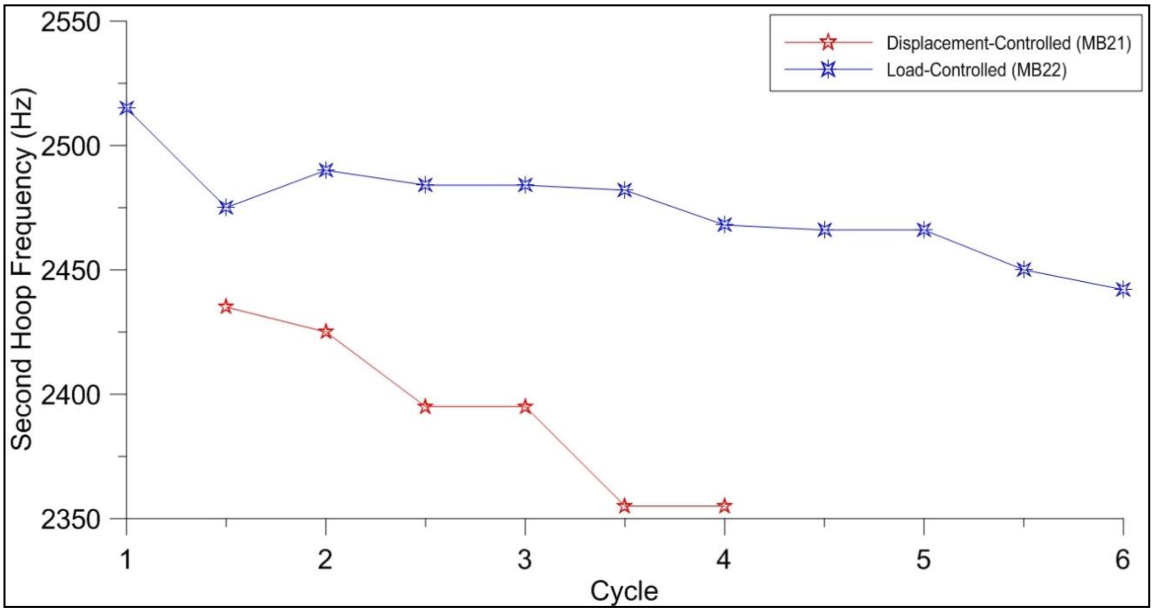

Figure 81. Displacement- and load-control second hoop frequency comparison (Pair 2).

Figure 82 shows the comparison of the two rolling methods for the first hoop frequency data as a function of performance cycle for the matched pair of MB32 (displacement control) and MB33 (load control). The displacement-control bat (MB32) started at a higher first hoop frequency and remained higher until just before Cycle 3 when it dropped below the load-control bat (MB33). However, the load-control bat (MB33) dropped lower than the displacement-control bat (MB32) again after Cycle 3 when the displacement-control bat testing ceased. The load-control bat (MB33) reached a lower overall first hoop frequency than the displacement-control bat (MB32) did during testing. Figure 83 shows the comparison of the two rolling methods for the second hoop frequency vs. cycle data. MB32 had a higher barrel stiffness and first hoop mode than MB33. Bat ID MB32 had a higher second hoop mode which was higher overall than MB33 at the end of testing. The second hoop frequencies are much farther apart over the entire range than are the first hoop frequencies.

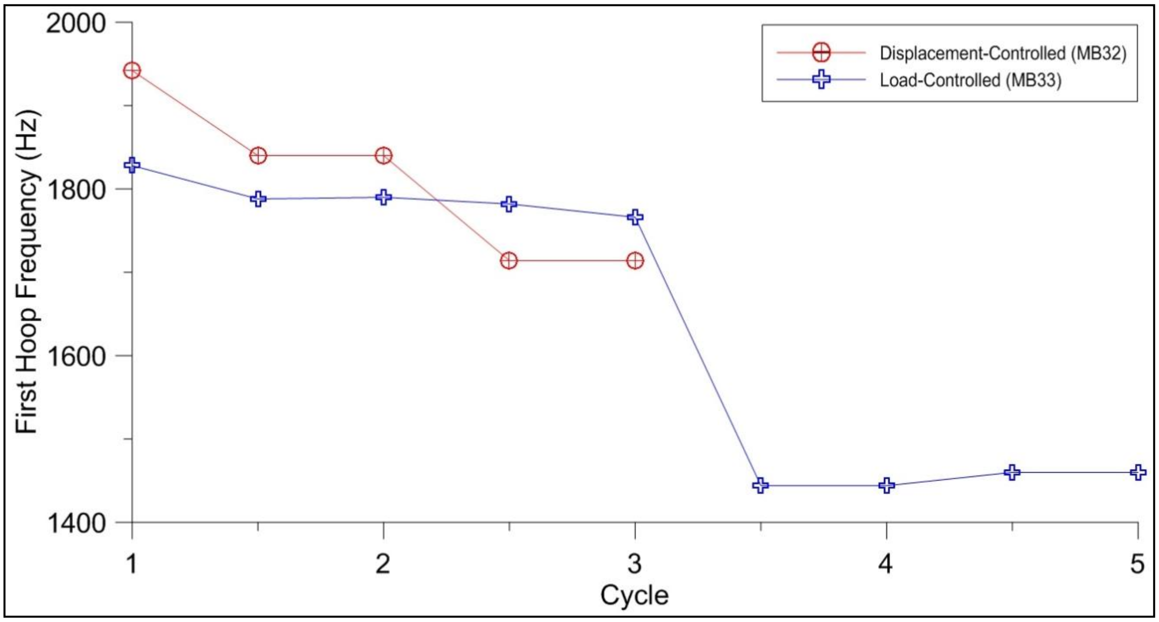

Figure 82. Displacement- and load-control first hoop frequency comparison (Pair 3).

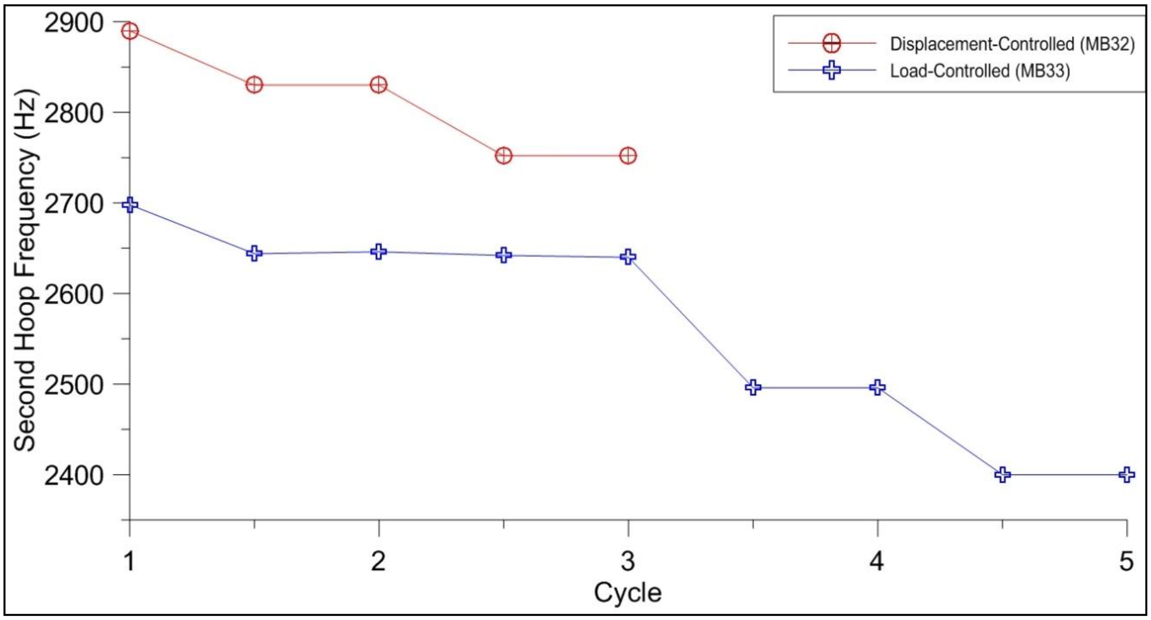

Figure 83. Displacement- and load-control second hoop frequency comparison (Pair 3).

Figure 84 shows the comparison of the two rolling methods for the first hoop frequency data as a function of performance cycle for the matched pair of MB3 (displacement control) and MB34 (load control). No frequency data were recorded for the displacement-control bat (MB3) until Cycle 2. At this point in the ABI process, the first hoop frequency for the displacement-control bat was lower than that of the load-control bat (MB34). However, the load-control bat (MB34) dropped to roughly the same first hoop frequency as the displacement-control bat (MB32) after Cycle 2. The displacement-control bat (MB3) reached a lower overall first hoop frequency than the load-control bat (MB34) did during testing. Figure 85 shows the comparison of the two different rolling methods for the second hoop frequency data vs. cycle. The displacement-control bat (MB3) exhibited a higher second hoop frequency than MB34 at each cycle. However, the displacement-control bat did go two more cycles than the load-control bat, and the second hoop frequencies on the respective last cycle for each bat were essentially the same. The cycle-to-cycle second hoop frequencies are much farther apart than the first hoop frequencies are.

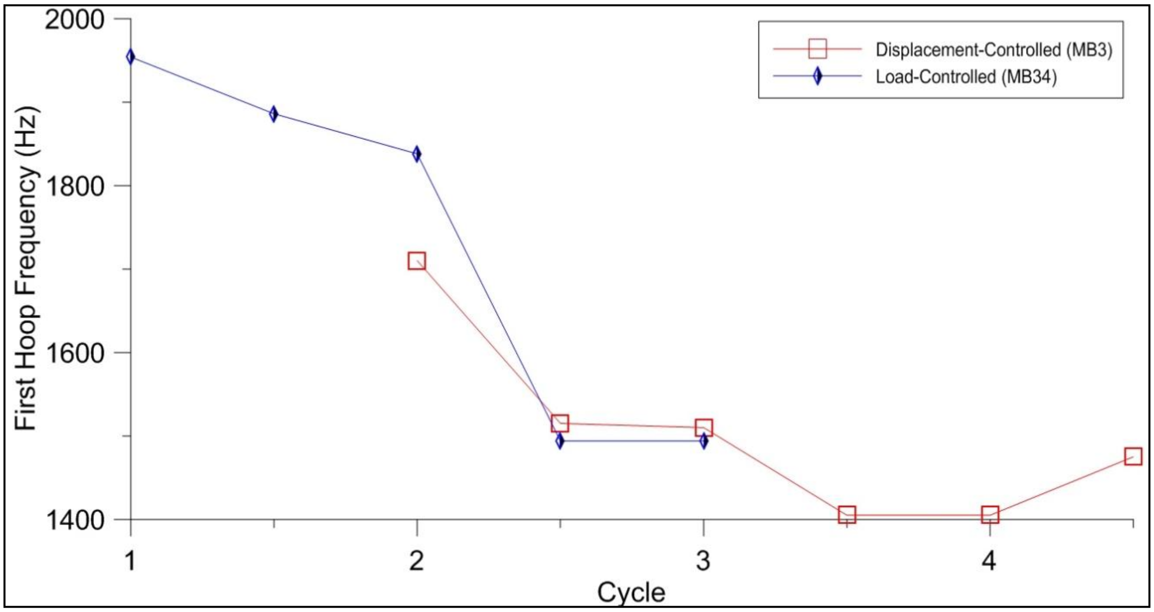

Figure 84. Displacement- and load-control first hoop frequency comparison (Pair 4).

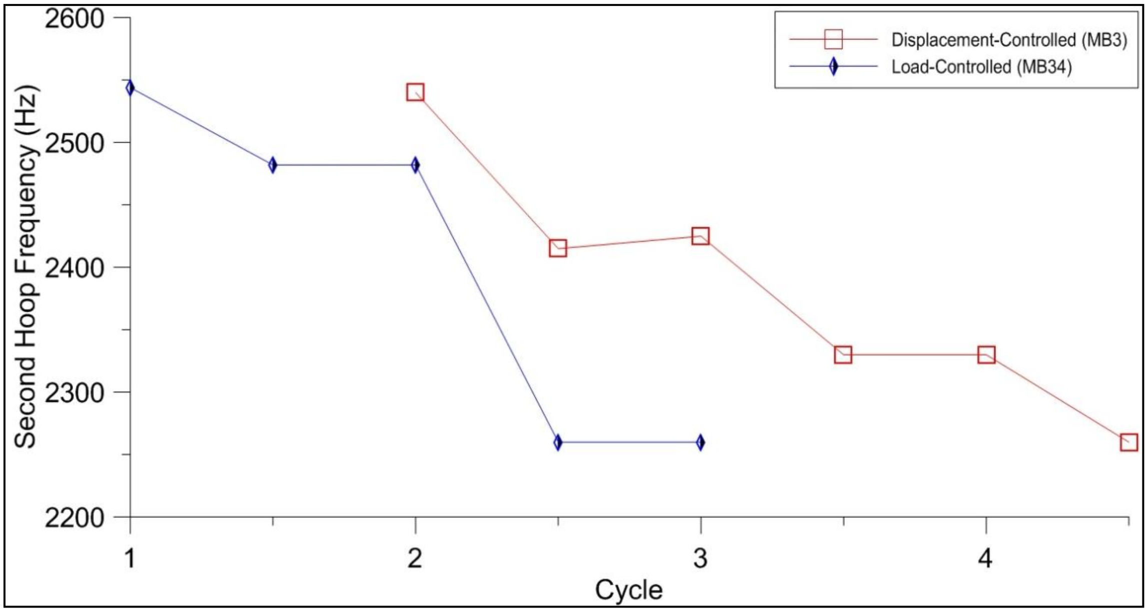

Figure 85. Displacement- and load-control second hoop frequency comparison (Pair 4).

Figure 86 shows the comparison of the two rolling methods for the first hoop frequency data as a function of performance cycle for the matched pair of MB4 (displacement control) and MB35 (load control). The displacement-control bat (MB4) has a higher first hoop frequency than the load-control bat (MB35) for all of cycles. The load-control bat (MB35) reached a lower overall first hoop frequency than the displacement-control bat (MB3) did during testing. Figure 87 shows the comparison of the two rolling methods for second hoop frequency data vs. cycle. Bat ID MB4 had a similar second hoop mode to MB35 until Cycle 2.5 where MB35 (load-control bat) dropped very radically.

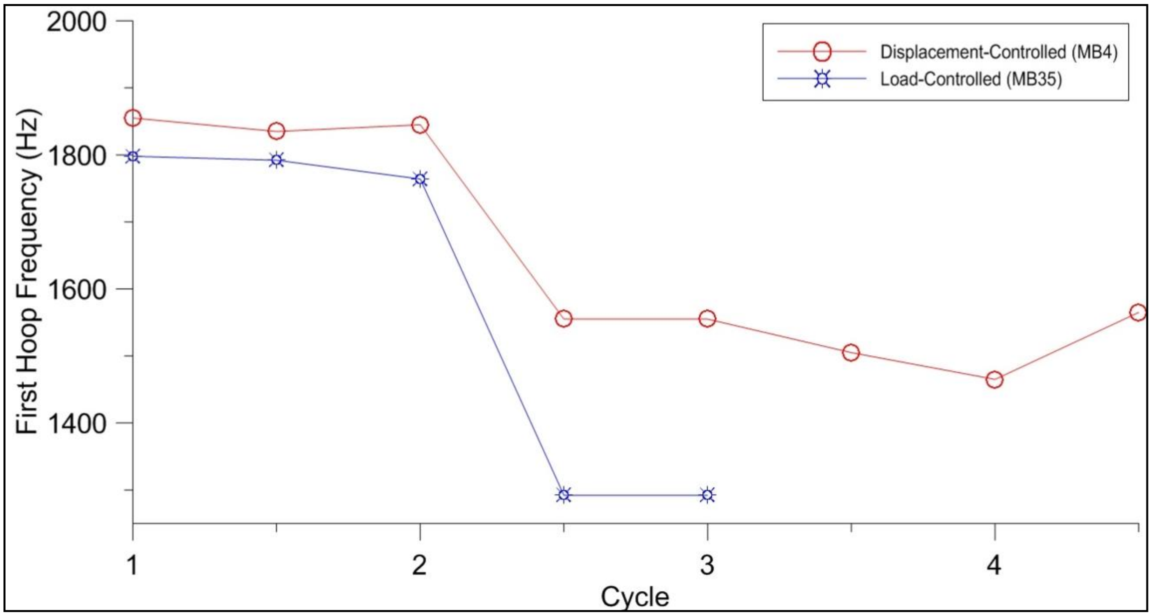

Figure 86. Displacement- and load-control first hoop frequency comparison (Pair 5).

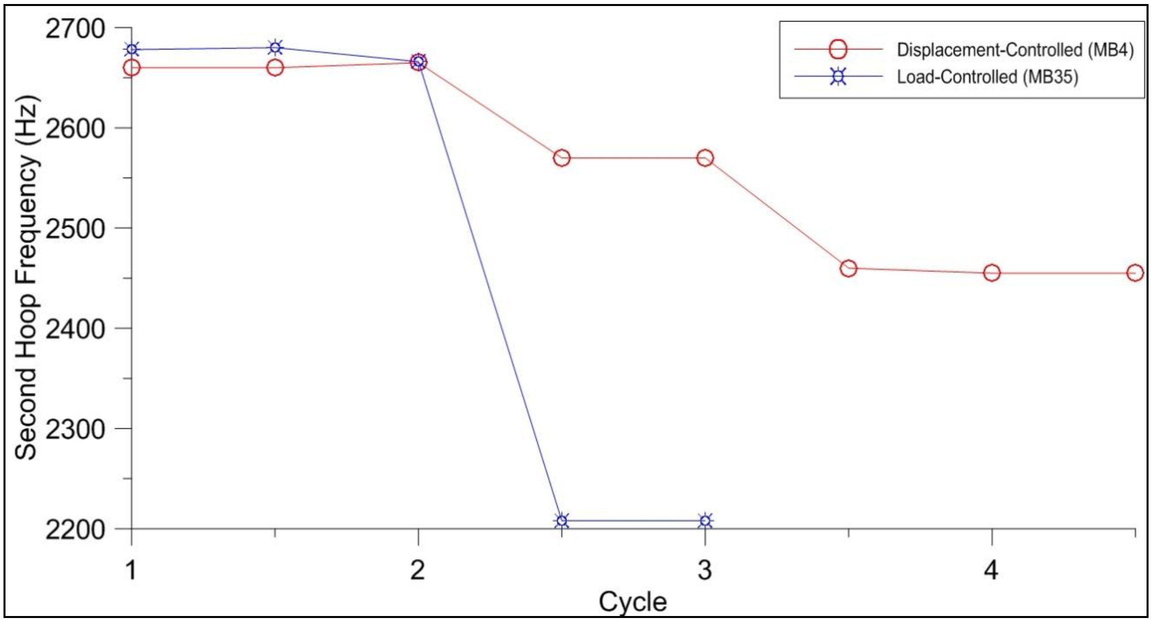

Figure 87. Displacement- and load-control second hoop frequency comparison (Pair 5).

4.5 Comparison of Field-Used to ABI Bats

The two ABI procedures used in this study are meant to simulate the evolution of the bat through game use. Up to this point in the thesis, no analysis comparing the ABI procedure to field data has been performed. A very limited analysis will be performed here. This analysis is limited due to the small amount of field data currently available. There were three existing NCAA compliance bats which had been pulled from various college teams that matched the ABI bats used in this study. No bats were field tested for this study, so there is only one performance test for each of the field bats.

The first field bat (Field 1) matches MB7 and MB17. The properties of each bat (MB7 and MB17) at peak performance are compared to the current properties of Field 1in Table 16. Table 16 shows that MB7 and MB17 exhibit higher peak performance (BESR, BBCOR and BBS) than the field bat. Both MB7 and MB17 have higher first hoop and second hoop frequencies than Field 1at their peak performance. However, MB17 has lower barrel stiffness at its peak performance than Field 1 while MB7 is stiffer. These data imply that the field bat may have likely degraded past its peak performance prior to testing in the lab. Assuming that the theoretical peak performance occurs for the first hoop frequency at 1250 Hz, then the field-service bat may be to the left of the peak on the BBS vs. first hoop frequency plot (Figure 52), and the lab ABI bats may be to the right of this peak. Recall that Figure 52 shows a steep decline in performance with a small change in hoop frequency when a point is to the left of the peak performance frequency.

Table 16. Comparison of Field-Used to ABI Bats (Set 1)

Bat ID	Field 1	MB7	MB17
Break-In Procedure	Field	Displacement-Controlled	Load-Controlled
MAX BESR	0.765	0.777	0.796
MAX BBCOR	0.570	0.591	0.606
MAX BBS	104.6	106.7	108.4
1st Hoop at Max	1185	1465	1320
2nd Hoop at Max	1970	2245	2180
Barrel Stiffness at Max	6108	7880	3542

The performance as a function of location along the barrel is shown in Figure 88 for the set of bats (MB7, MB17 and Field 1). This plot shows that both MB7 and MB17 have similar performance when new. When the displacement-control bat (MB7) and the load-control bat (MB17) break-in, they show a spike in performance at the 6.5-in. location and show similar shaped trends in their curves for performance vs. axial location. These trends look different from the field bat which has a relatively smoother performance curve, i.e. no radical spikes. This difference between the shapes of the performance profiles suggests that the ABI procedures may not imitate the natural break-in for the entire barrel. However, the rolling methods can work a bat to its peak performance. Keep in mind that the field bat (Field 1) may have been past its peak performance due to its very low first hoop frequency.

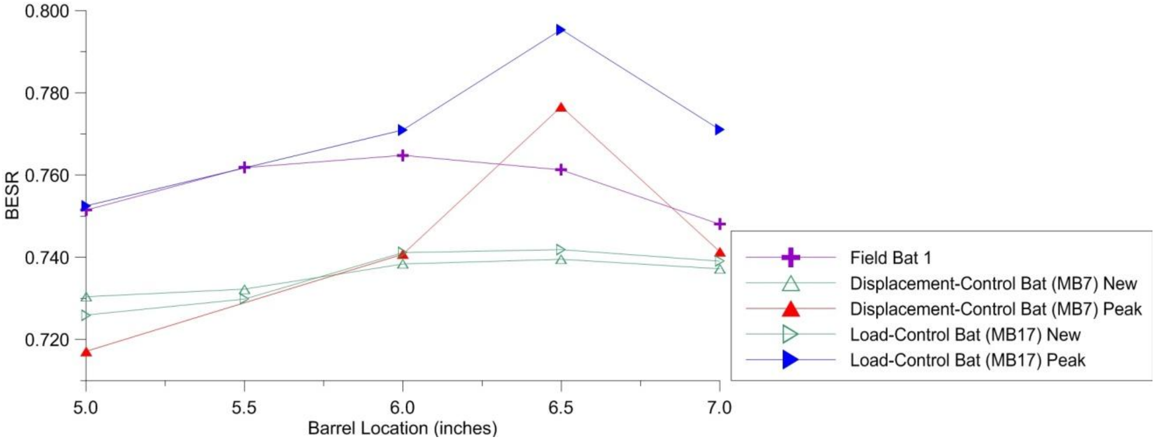

Figure 88. Performance vs. barrel location for field used bat comparison (Set 1).

The second field bat (Field 2) matches MB3 and MB34. The properties of each bat (MB3 and MB34) at peak performance are compared to the current properties of the field bat in Table 17. Table 17 shows that MB3 and MB34 show lower peak performance (BESR, BBCOR and BBS) than Field 2. Both MB3 and MB34 have higher second hoop frequencies at their peak performance than Field 2. Bat ID MB34 also has a higher first hoop frequency. However, it has lower barrel stiffness at its peak performance than Field 2. Bat ID MB3 also has lower barrel stiffness than Field 2. These data imply that the field bat has reached a higher overall performance than the ABI bats and that the two ABI methods may be too harsh to see the true potential for this style of bat.

Table 17. Comparison of Field-Used to ABI Bats (Set 2)

Bat ID	Field 2	MB3	MB34
Break-In Procedure	Field	Displacement-Controlled	Load-Controlled
MAX BESR	0.793	0.769	0.766
MAX BBCOR	0.596	0.580	0.566
MAX BBS	107.7	105.6	104.3
1st Hoop at Max	1455	1405	1494
2nd Hoop at Max	2140	2330	2260
Barrel Stiffness at Max	5192	5088	2967

The performance for each bat as a function of location along the barrel is shown in Figure 89 for this second set of bats (MB3, MB34 and Field 2. This plot shows that MB3 and MB34 have similar performances when new. When the load-control bat (MB34) breaks in, it shows a spike in performance at the 6.0-in. location. The displacement-control bat did not show a performance increase at the 5.0-in. location but did show a much smoother curve between the 6.0- and 7.0-in. locations suggesting a more even break-in than the load-control bat and similar style trend to the field bat (Field 2). These results suggest that the ABI procedures may not fully imitate the natural break-in for the entire barrel and did not allow for the peak performance seen in Field 2. However, it must also be kept in mind that it is essentially impossible to make all composite bats exactly the same. Thus, these differences in performance between the field-use bat and the lab ABI bats may be a consequence of the manufacturing process. A larger sample of bats should be studied using the two ABI processes on new bats and a number of bats collected from field service, such that statistically significant conclusions can be made to compare the two ABI methods to the evolution of bat performance in field service.

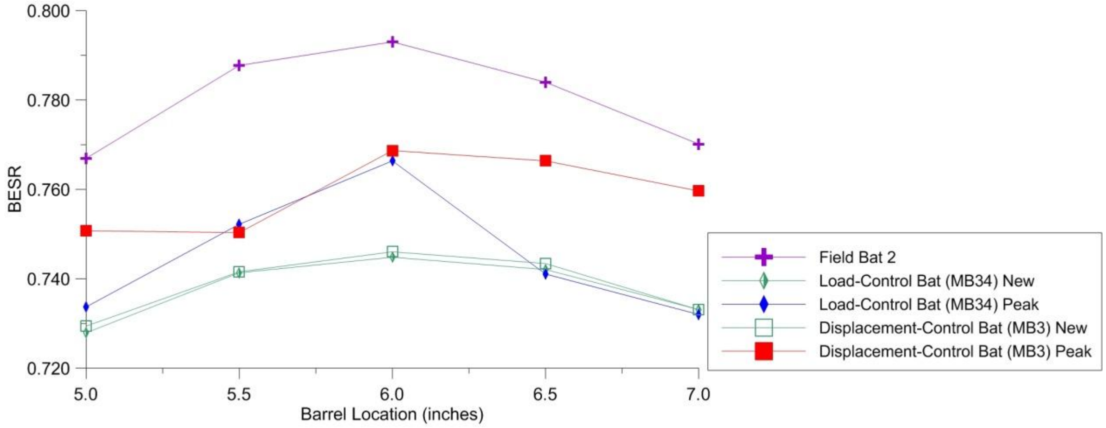

Figure 89. Performance vs. barrel location for field used bat comparison (Set 2).

The third field bat (Field 3) matches MB4 and MB35. The properties of each bat (MB4 and MB35) at peak performance are compared to the current properties of the field bat (Field 3) in Table 18. Table 18 shows that MB4 (displacement control) shows slightly higher peak performance (BESR, BBCOR and BBS) than Field 3, while MB35 (load control) shows lower peak performance than Field 3. Bat ID MB35 has a higher first hoop frequency, second hoop frequency and barrel stiffness at peak performance than this field bat, while MB4 only had a higher first hoop frequency than the field bat. These data imply that the field bat has reached a higher overall performance than the load-control ABI method but slightly lower performance than (or maybe essentially the same as) the displacement-control method.

Table 18. Comparison of Field-Used to ABI Bats (Set 3)

Bat ID	Field 3	MB4	MB35
Break-In Procedure	Field	Displacement-Controlled	Load-Controlled
MAX BESR	0.781	0.789	0.755
MAX BBCOR	0.595	0.598	0.557
MAX BBS	107.3	107.8	103.1
1st Hoop at Max	1420	1505	1792
2nd Hoop at Max	2515	2460	2680
Barrel Stiffness at Max	4567	2350	17592

The performance as a function of location along the barrel is shown in Figure 90 for this third set of bats (MB4, MB35 and Field 3). This plot shows that MB4 and MB35 have similar performance when new. The load-control bat (MB35) shows its peak performance when new. The ABI process looked to induce a relatively rapid breakdown of the bat barrel. As a result, the peak performance of the bat may have been missed. The displacement-control bat shows a large spike at the 6.5-in. location which has a very similar performance profile to the field used bat (Field 3). More data points are required to be certain, but this similarity suggests that this particular bat pulled from the field may have been rolled at some point in its life. This plot also shows performance spikes at the 6.5-in. location which is very similar to the trend shown in Figure 89. More data points are needed to determine whether or not this shift in the sweet spot of the bat is a result of rolling for ABI. Also note that for the bat MB35 the new and peak performance were the same in this case for the load control method indicating that this bat was broken in much to quickly by this methods in this specific case.

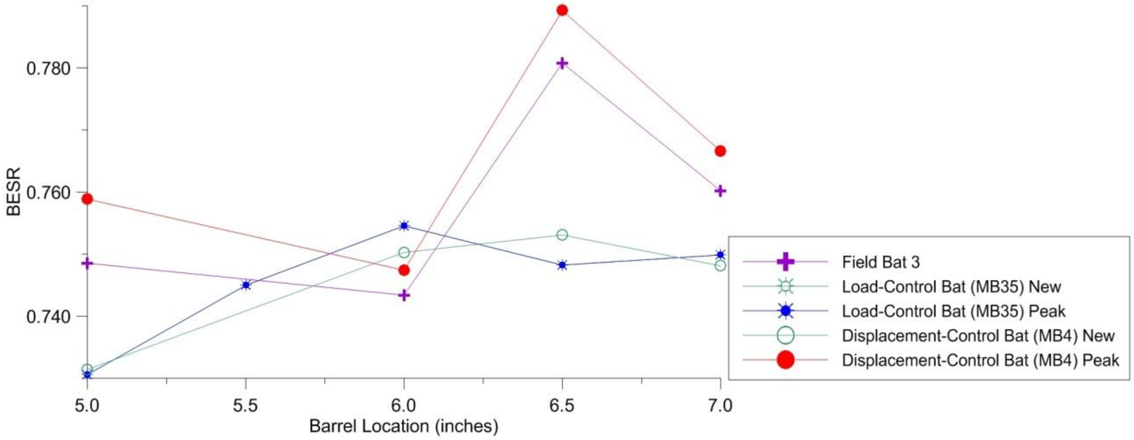

Figure 90. Performance vs. barrel location for field used bat comparison (Set 3).

4.6 Comparison of ABI loading

The two methods of ABI procedure (displacement- and load-control) apply a load to a barrel in very different ways. The displacement-control method works by setting a known displacement on the barrel at the 6-in. location and then rolling through the resulting load. Using this method the load will vary with the change in diameter of the bat. The load along the length of a barrel under constant displacement (0.100 in.) is plotted in Figure 91. Figure 91 shows that at the 9-in. location there is no load on the barrel. The load then ramps up to ~850 lbs between the 9- and the 7-in. locations. Between the 7- and 3-in. locations where the barrel diameter does not change drastically the load varies much less. The variation seen here is due partially to the variation in diameter and partially due to variation in the stiffness of the material as a function of length.

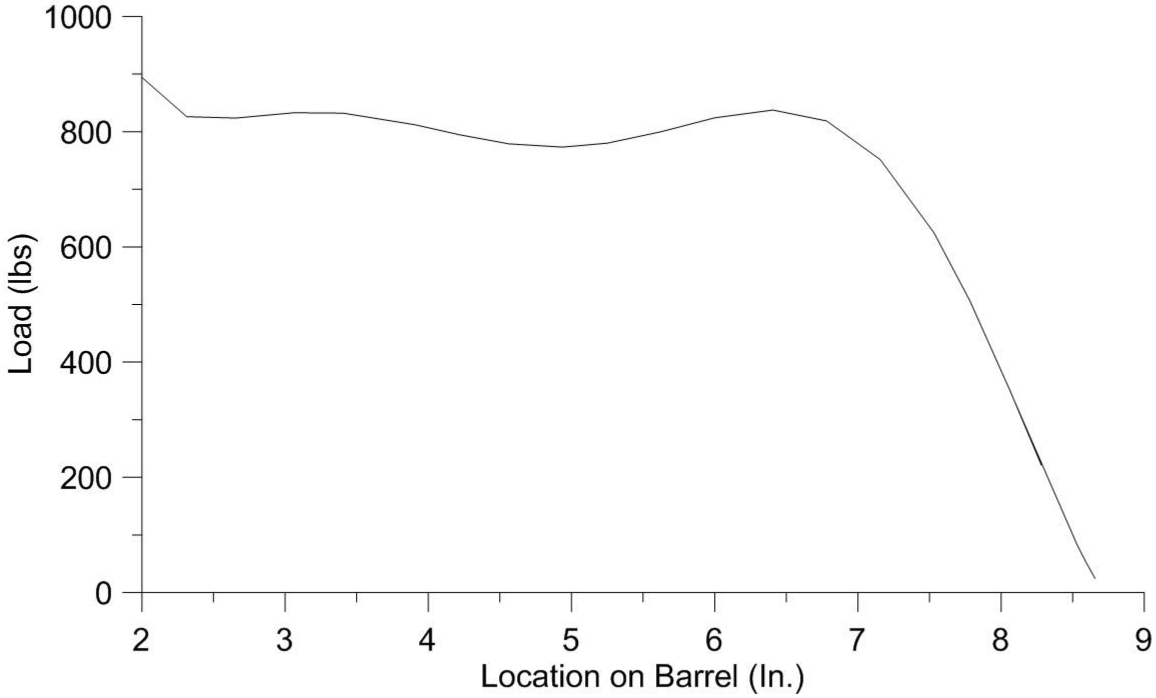

Figure 91. Load profile along the length of a barrel under displacement-control ABI (0.100 inches).

The second ABI procedure is load control. The load-control method works by setting a known load on the barrel and then rolling through the constant load. Using this method, the displacement will vary depending on the localized barrel stiffness. The displacement along the length of a barrel under constant load (500 lbs) is plotted in Figure 92. Figure 92 shows that the least stiff location is between the 5- and 6-in. locations and the barrel gets stiffer and therefore shows less of a displacement on the taper (towards the 9-in. location) and near the end cap (toward the 3-in. location)

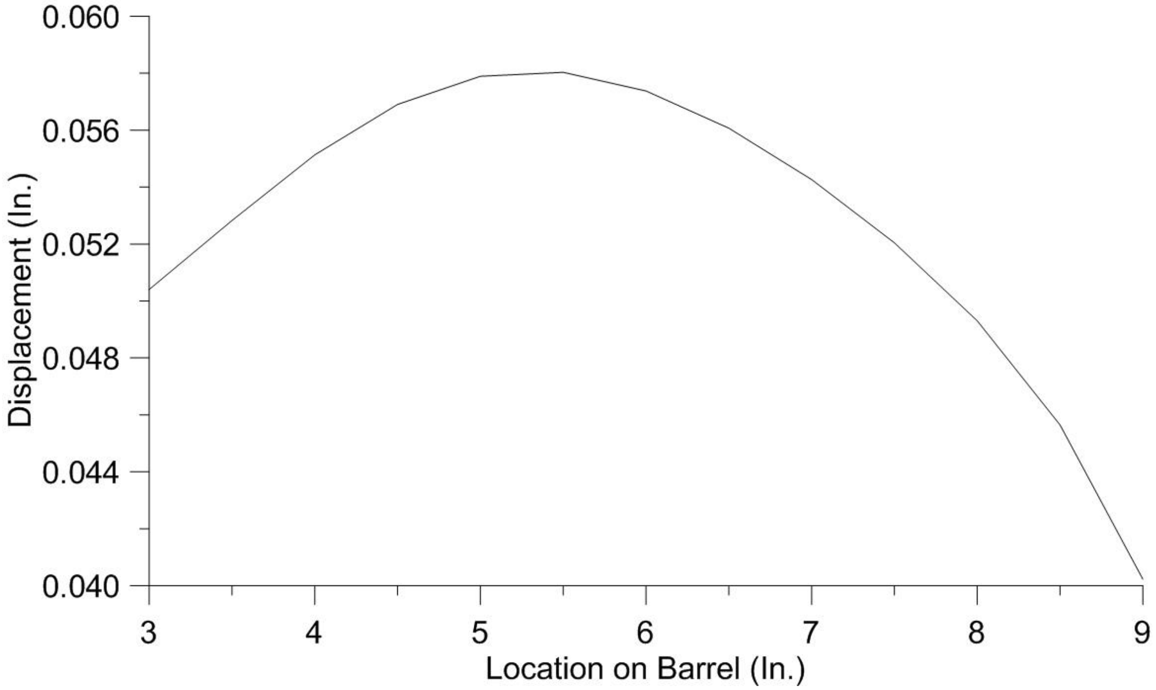

Figure 92. Displacement profile along the length of a barrel under load-control ABI (500 lbs).

4.7 Standard Deviation of Mean Uncertainty Analysis

A standard deviation of the mean uncertainty analysis was performed on the three performance metrics (BESR, BBCOR and BBS). This standard deviation of the mean uncertainty analysis used the data from the six valid shots on the highest performing band location for each test cycle because only the maximum batted performance (BESR, BBCOR and BBS) was presented for each metric in this thesis. Per the performance test protocol, every impact location required six valid hits, and these six data points were averaged to calculate the performance of the bat at an impact location. The average value is used to ensure that an accurate representation of the barrel performance is determined and not biased by anomalous measurements. The bat was arbitrarily rotated before each impact to simulate the randomness of impact locations that can occur during field use. These random rotations also serve to ensure no bias in the bat measurement due to potential differences in performance from one circumferential location to another. Thus, six shots were acquired from random points around the circumference of the baseball bat barrel per the NCAA protocol (unless the bat has a grip that does not allow a batter to rotate the bat or the bat has a type of wood that should only be hit in one direction) [10]. However, none of the bats investigated in this these fell into this special category. Thus, all of the bats were randomly rotated after each impact.

The standard deviation of the six valid shots was calculated, and then the standard deviation of mean uncertainty of the performance value (BESR, BBCOR or BBS) was calculated by,

$$std\ of\ mean = \frac{std_1}{\sqrt{n-1}} \tag{19}$$

where: *std of the mean* is the uncertainty in the measurement (dimensionless for BESR, BBCOR and mph for BBS)
std_1 is one standard deviation of a population of six valid shots (dimensionless for BESR and BBCOR and mph for BBS)
n is the population size of six valid shots at one location of one test

After the standard deviation of the mean uncertainty was calculated by Equation 19, an uncertainty bar was added to the plot of batted-ball performance metrics (BESR, BBCOR and BBS). Figure 93 shows BBCOR vs. first hoop frequency with uncertainty bars. Figure 93 is an example of the standard deviation of mean uncertainty analysis plots. Appendix G summarizes a complete set of standard deviation of the mean uncertainty-bar analysis plots for the current research.

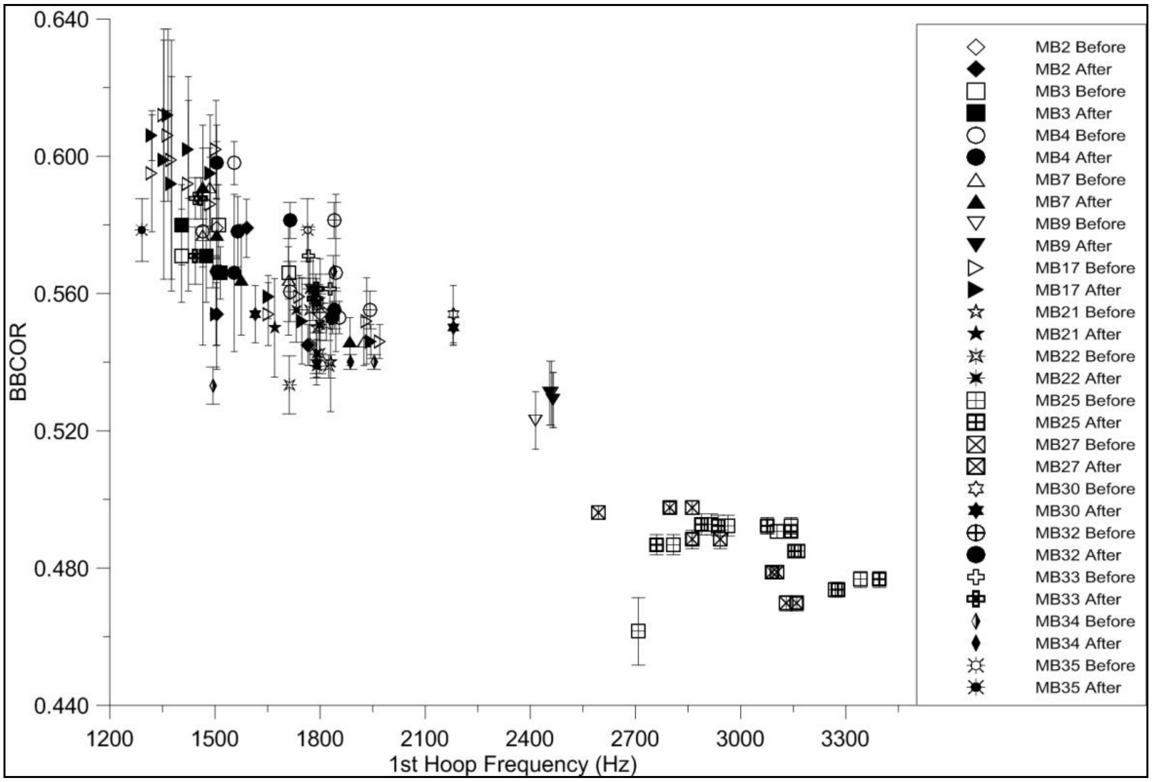

Figure 93. BBCOR vs. first hoop frequency uncertainty analysis.

Figure 93 shows, in general, that the size of the uncertainty bars increases as the hoop frequency of a bat decreases. This relationship between first hoop frequency and uncertainty-bar size is most likely a consequence of the level of damage in the bats. Because damage is not necessarily accumulated uniformly around or along the length of the barrel (due to ball impacts and rolling in the case of an ABI process), the effective stiffness of the barrel may vary around the circumference of the barrel. Thus, these variations in the effective hoop stiffness around the circumference of the bat will have the consequence of variations in the resulting batted-ball speed as a function of the circumferential location on the bat. As more and more damage is accumulated in the composite, the range of ball rebound speeds measured in the test can potentially expand.

Thus, a composite baseball bat that is broken-in will hit more inconsistently than a new bat.

This explanation may be more clearly appreciated by viewing Figure 94, which shows the data for MB17. By looking at a less busy plot than Figure 93, it can easily be seen that the uncertainty bars are much wider as the frequency drops due to the accumulation of damage as a consequence of rolling.

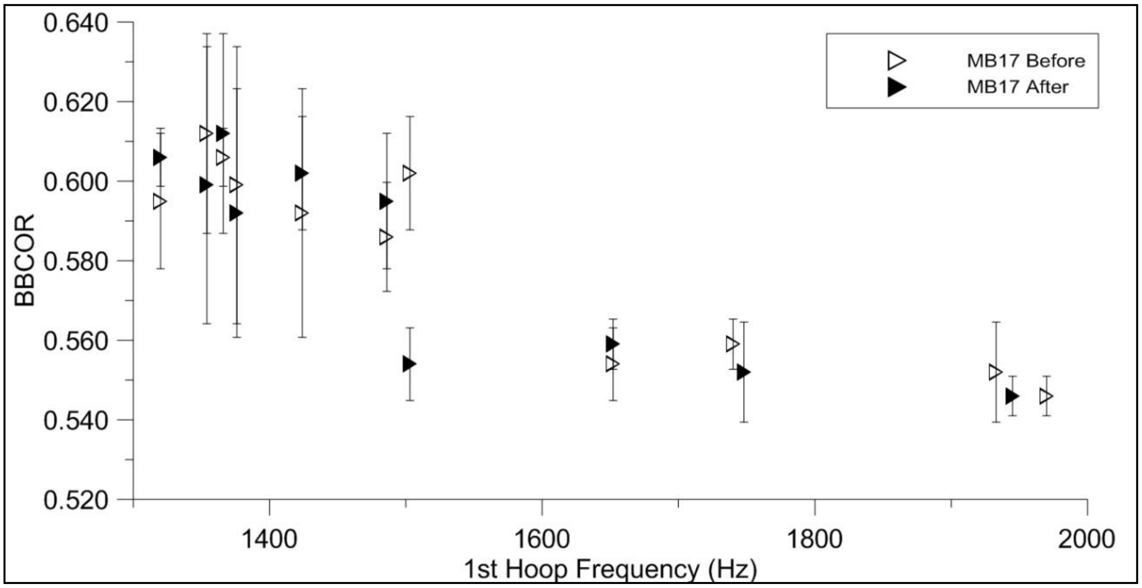

Figure 94. BBCOR vs. first hoop frequency uncertainty analysis of MB17.

4.8 Summary

This chapter discussed the data collected in the course of conducting the research and the subsequent analysis of the data. The data were presented in several different ways. The first presentation method was of the different metrics (batted-ball performance (BESR, BBCOR and BBS), barrel stiffness and hoop frequency) plotted against ABI cycle. The second method was an analysis plotting batted-ball performance (BESR, BBCOR and BBS) against the bat construction metrics (barrel stiffness, first hoop frequency and second hoop frequency). The final method was a set of plots that compare data from the two different rolling methods (displacement control vs. load control). There was also a discussion of the uncertainty analysis that was performed on the data.

5 Conclusions

A representative group of composite baseball bats of various manufacturers, models and lengths were tested to investigate the relationships between batted-ball performance and bat properties. These properties and performance values were tracked over the useful life of each bat. Bats were artificially broken in using one of two different ABI procedures (displacement- or load-control rolling) to simulate game use in a laboratory setting. The data were then plotted in different ways and presented in tables to explore how the properties and performance of composite baseball bats change with use and to discern any relationships among the parameters investigated. There are several conclusions that can be made from this study:

- Of all the correlations preformed, batted-ball performance showed the best correlation to first hoop frequency. Thus, if only one metric or test was to be used to evaluate performance in the field, then a modal test should be performed. As the first hoop frequency decreased for a given bat, the batted-ball performance increased.

- All of the composite baseball bats considered in this study showed performance (BESR, BBCOR and BBS) increases after undergoing the ABI process. These increases have implications for the governing bodies of baseball. These governing bodies should be aware that composite bats will show a performance increase when the barrel begins to breakdown and prior to ultimate failure. Thus, if a performance ceiling is in place by the governing body, then a thorough certification should be used to evaluate the performance of the bat throughout its useful life.
- All of the composite baseball bats showed a decrease in barrel stiffness due to breaking down during testing, i.e. fiber breakage, matrix cracking and delamination. As the barrel became less stiff, the batted-ball performance (BESR, BBCOR and BBS) increased in almost all cases.
- All of the composite baseball bats showed a decrease in first and second hoop frequencies during testing which is expected due to hoop frequency being physically and mathematically linked to barrel stiffness which decreases during break-in.
- Batted-ball performance showed a strong correlation to barrel stiffness. The trend is almost linear over the range of data acquired. As the barrel stiffness decreased for a given bat, the batted-ball performance increased.
- Batted-ball performance showed less of a correlation to second hoop frequency than it did to first hoop frequency and barrel stiffness. The trend is again a

nonlinear curve over the range of data acquired in the current study. As the second hoop frequency decreased for a given bat, the batted-ball performance increased.

- The ratio of second hoop frequency divided by first hoop frequency did not show an improved correlation to batted-ball performance compared to first hoop frequency alone.
- BBS vs. BBCOR showed a linear correlation for each length classification of bats even as the BBS increased as the bat went through the ABI test cycles of its useful life. This trend matches the data collected from both aluminum and composite bats that are currently available in the UMLBRC database and that had not been subjected to an ABI process.
- First hoop frequency showed correlation to barrel stiffness. Bats with higher first hoop frequencies have higher barrel stiffness which is expected due to the physical and mathematical relationship between the two properties.
- Second hoop frequency showed less of a correlation to barrel stiffness than first hoop frequency did. Bats with higher second hoop frequencies have higher barrel stiffness which is expected due to the physical and mathematical relationship between the two properties.
- The results comparing the two ABI rolling methods (displacement- and load-control rolling) were inconclusive. For certain bats the load-control method took longer to work the bat up to max performance. However, for other bats, the displacement-control method had a slower break in that reached higher

performance. These differences are thought to be due to different barrel constructions.

- Both ABI rolling procedures showed that they created a spike in performance at the sweet spot of the barrel while other locations along the barrel did not see as much of a performance increase compared to a field used bat which typically had a smooth performance curve along the barrel.
- Uncertainty analysis showed that stiffer bats with lower batted-ball performance typically had less scatter associated with their measurement.
- Uncertainty analysis also showed that as a single bat breaks down the uncertainty associated with the measurement increased, which is likely due to different sides of the barrel breaking in differently.

6 Recommendations

This thesis gives a good understanding of the performance of composites as a baseball bat material and how field use or ABI affects the properties and performance of a bat. However, there is still further research to be examined with respect to composite baseball bats and their performance can change through use or an ABI process. Recommendations include the following:

- An extensive study of composite youth baseball bats to determine the effects of use on this classification of bats. Youth baseball bats are radically different than NCAA baseball bats in that they can have drops up to -11.5 and the barrel is relatively straight (i.e., no taper) and such a study would allow youth baseball leagues to determine if more stringent testing criteria should be adopted as has been put in place by the NCAA and the NFHS in baseball.
- Study of different roller configurations (i.e. flat rollers compared to a v-notch style roller or another style) as well as different roller diameters under the same

load manner (displacement or load) to determine the most realistic method for simulating game use. The current study focused on flat rollers in the displacement-control method of rolling and one flat and one v-notch roller in the load-control method.

- Further investigation of both the load- and displacement-control methods of rolling specifically to determine which method is preferred for different types of composites (i.e., fiberglass, carbon fiber, a mixture of both fiberglass and carbon fiber and even bats utilizing a more exotic construction than just yarns and a polymer matrix to comprise the composite bats). Such an investigation will also require a study of what different manufacturers are using in composite baseball bat construction and construction methods (i.e., braiding vs. woven fabric layups). Some aluminum barrel bats are now using composite inner rings and inner sleeves, and these new constructions may introduce a new set of ABI phenomena and thereby require new criteria.
- Further study of the first hoop mode to determine if there is an ideal performance at ~1250 Hz. This study will likely require finite element modeling dependent on a very realistic and reliable ball model to determine performance values at low frequencies (lower than 1400 Hz). Finite element modeling is likely needed because bats are not designed to have such low hoop frequencies and even bats that have broken down typically begin separating from their handle around 1400 Hz making reliable data at these low frequencies very hard to determine experimentally. An alternate means to obtain this low hoop frequency performance data would be to have very thin walled bats produced purely for

research purposes or by shaving the inside barrel of a bat until the hoop frequency has dropped below 1400 Hz. This study would also be able to determine if the 95% regression analysis performed in this thesis is reliable in predicting performance.

- Mode contribution should be investigated to determine what percent of bending and hoop modes are excited in a bat under use (hitting a ball). To accomplish this contribution analysis, a full modal test would need to be performed for each bat as well as data acquired during testing. This modal contribution could be tracked over the useful life of a composite bat to determine if the same modes are excited as a bat breaks down and the hoop modes shift to lower frequencies as the barrel stiffness decreases.
- A study could be performed to determine how well an ABI procedure simulates game use. Such a study would require determining the peak performance of several bats as they are used in game play and bats that are tested using an ABI rolling procedure to determine if game play and ABI produce the same performance results. A sufficient number of bats should be investigated to make the outcomes of the study statistically significant.
- A study of performance along the length of a barrel as the bat is broken in should be pursued to find out how the ABI procedures compare to performance along a naturally broken in bat as a means of trying to imitate game use as closely as possible.

7 Literature Cited

[1] Shakin, A., Lemberg, S., Pollitzer, P.M., 2001, "Petition CP 00-1 requesting performance requirements for non-wood baseball bats." http://www.cpsc.gov/library/foia/foia02/brief/baseball1.pdf (last checked 11/30/10)

[2] Russell, D.A., 2007, "How have Aluminum Bats Changed Baseball: Statistics for NCAA Division 1 College Baseball 1970-2010," http://paws.kettering.edu/~drussell/bats-new/NCAA-stats.html (last checked 11/30/10)

[3] Russell, D.A., 2005, "How Are Composite Bats Better than Aluminum Bats?," http://paws.kettering.edu/~drussell/bats-new/compalum.html (last checked 11/30/10)

[4] Brontsema, B., 2009, "Composite Bat Moratorium," http://fs.ncaa.org/Docs/rules/baseball/bats/7-17-09CompositeBatMemo.pdf (last checked 11/30/10)

[5] Herron, A., 2010, "Baseball Rules Change Puts Moratorium on Composite Bats," http://www.nfhs.org/content.aspx?id=4052 (last checked 11/30/10)

[6] Drane, P.J., 2000, "Characterization of the Effects of Use and Moisture Content on Baseball Bat Performance Using Experimental Methods," MS Thesis, University of Massachusetts Lowell.

[7] Cruz, C.M., 2005, “Characterizing Softball Bat Modifications and Their Resulting Performance Affects,” M.S. Thesis in Mechanical Engineering, Washington State University

[8] Shroyer Jr., William A., 1924, Baseball Bat United States Patent 1499128

[9] Mussill, B., 2000, “The Evolution of the Baseball Bat,” http://www.stevetheump.com/Bat_History.htm (last checked 7/30/10)

[10] NCAA, 2009, National Collegiate Athletic Association Standard for Testing Baseball Bat Performance, http://www.ncaa.org/wps/wcm/connect/10e4ff004e0b9c15a2f5f21ad6fc8b25/2006_certification_protocol.pdf?MOD=AJPERES&CACHEID=10e4ff004e0b9c15a2f5f21ad6fc8b25 (last checked 7/30/10)

[11] Sutton, A.D., 2010, “Using Modal Analysis to Investigate Bat-Ball Performance of Baseball Bats,” MS Thesis, University of Massachusetts Lowell.

[12] Nathan, A.M., Russell, D.A. and Smith, L.V., 2004, "The physics of the trampoline effect in baseball and softball bats," Engineering of Sport 5, Vol. 2, pp. 38-44, *Proceedings of the International Sports Engineering Association*, Davis, CA, September 13-16.

[13] Russell, D.A., 2004, “Hoop frequency as a predictor of performance for softball bats,” Engineering of Sport 5, Vol. 2, pp. 641-647, *Proceedings of the International Sports Engineering Association*, Davis, CA, September 13-16.

[14] Cochran, A.J., 2002, “Development and use of one-dimensional models of a golf ball,” *J. Sports Sciences*, Vol. 20, pp. 635-641.

[15] Greenwald, R.M., Crisco, J.J., and Penna, L.H., 2001, “Differences in batted ball speed with wood and aluminum baseball bats: a batting cage study,”. *J. Appl. Biomech*. 17: pp.241-252.

[16] Nathan, A.M., 2003, “Characterizing the Performance of Baseball Bats,” *American Journal of Physics*, Vol. 71, No.2, pp.134-143.

[17] Fleisig, G.S., Zheng, N., and Stodden, D.F. and Andrews, J.R., 2002 “Relationship between bat mass properties and bat velocity,” *Sports Engineering* Vol. 5 pp.1-14.

[18] Adair, R.K., 2002, *The Physics of Baseball, 3rd* Ed. HarperCollins, New York.

[19] Bahill, A. Terry, 2004, “The Ideal Moment of Inertia for a Baseball or Softball Bat,” *IEEE Transactions on systems, Man, and Cybernetics—Part A: Systems and Humans*, Vol.34, No.2, pp.197-204.

[20] Smith, L.V., Cruz, C.M., Nathan, A. and Russell, D., 2005, "How Bat Modifications Can Affect Their Response," in *Proceedings of the APCST2005 International Congress on Sports Technology*, Tokyo Institute of Technology, Tokyo, Japan.

[21] Sherwood, J., and Drane, P., 2008, "An Experimental Investigation of the Effect of Use on the Performance of Composite Baseball Bats," *Proceedings of the 7th International Conference on the Engineering of Sport,* July, Biarritz, France.

[22] Cranked Sports LLC Company, TheBatRoller.com, http://www.thebatroller.com/index.htm (last checked 7/30/10)

[23] GoDeep Bat Roller Company, GoDeepBatroller.com, http://www.godeepbatrollers.com/our-bat-rollers (last checked 7/30/10)

[24] Dunit Gear Company, DunitGear.com, http://www.batrollingmachine.dunitgear.com/ (last checked 7/30/10)

[25] World's Hottest Bats, LLC, 2008, WorldsHottestBats.com, http://www.worldshottestbats.com/index.php (last checked 7/30/10)

[26] Big Dawg Bat Rolling, 2006, BigDawgBatRolling.com, http://www.bigdawgbatrolling.com/index.html (last checked 7/30/10)

[27] ASTM Standard F2398-04, 2004, Standard Test Method for Measuring Moment of Inertia and Center of Percussion of a Baseball or Softball Bat.

[28] NCAA, 2009, Accelerated Break-In Procedure, http://web1.ncaa.org/web_files/rules/baseball/bats/NCAAABIProcedure.pdf (last checked 8/6/10)

[29] ASTM Standard F2219-07, 2005, Standard Test Method for Measuring High-Speed Bat Performance.

Appendix A – Effective Barrel Stiffness

This appendix explains the process used to calculate the effective stiffness of the barrel and over what range of barrel compression data the compression behavior of the baseball bat is assumed to be linear. The process allows for the nonlinear portion of the measurement to be removed from the stiffness calculation and allows for the most consistent and repeatable measurements possible using the current test methodology.

The procedure for this linearity test was placing a bat in the compression tester at the 6-in. location as described and shown in Section 3.2.3. The bat was then compressed in increments of ~0.005 in. from no displacement to 0.070 in. The results of a typical test are displayed in Figure A1.

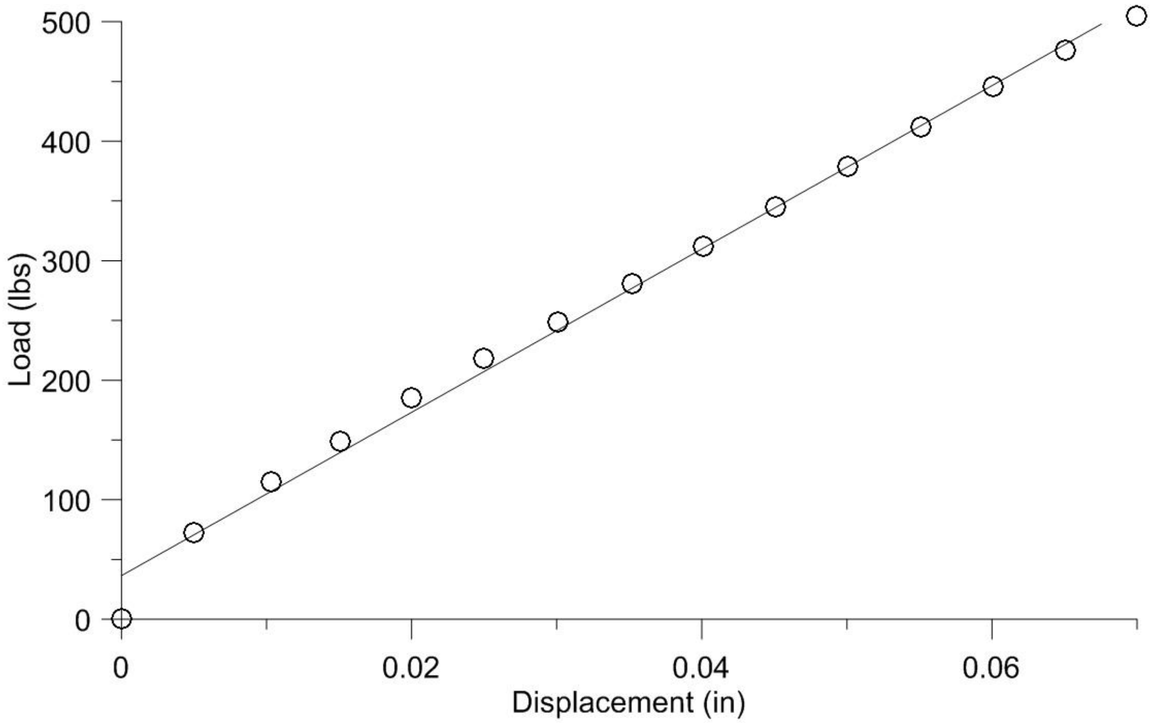

Figure A1. Linearity of composite baseball bat. (R^2=0.994121)

As can be seen in Figure A1, the portion of the graph that does not look linear is for displacements below 0.01 in. The trend line plotted on Figure A1 has an r^2 value of 0.994121. The data below 0.01 in. were then removed from the data set used to make the plot in Figure A2 in an attempt to remove the bias introduced into the linear fit by the nonlinear region of the data, and a new trend line was found. By removing the first 0.01 in. of data, the r^2 value is increased to 0.999712. This first 0.01 in. of data points were removed from all compression test data sets for the calculation of the effective load-deflection curve.

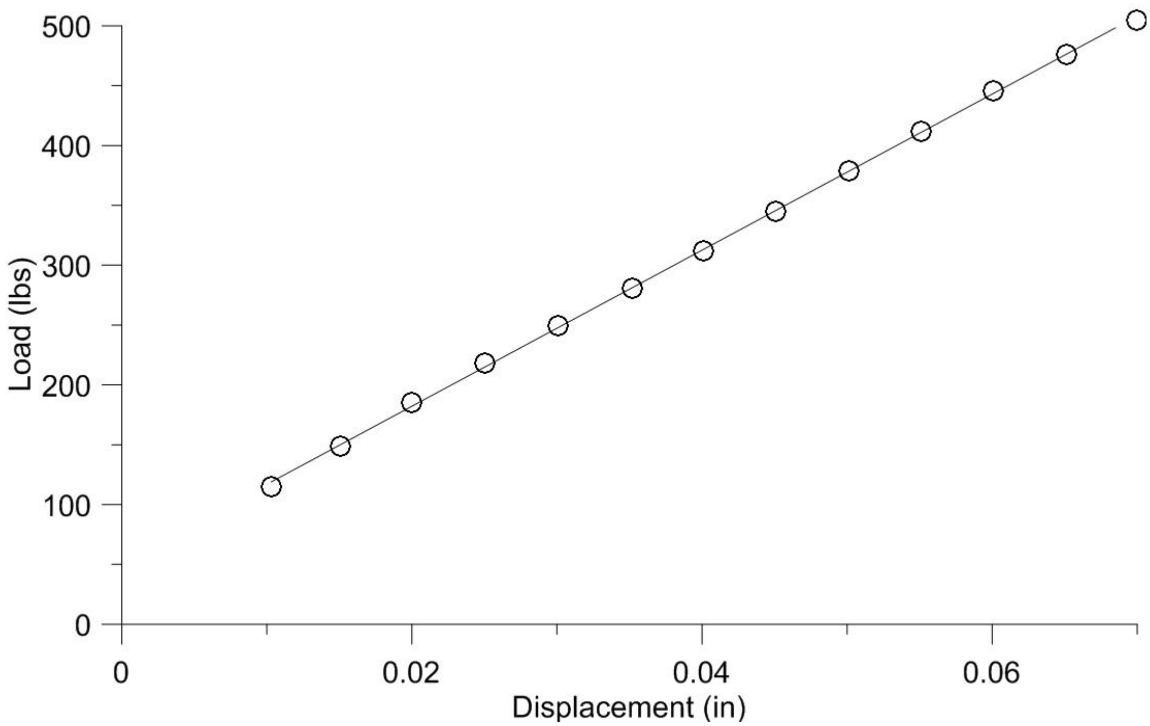

Figure A2. Linear portion of test. (R^2=0.999712)

Appendix B – Compression Procedure

This appendix outlines the NCAA protocol for the compression test associated with the accelerated break-in procedure [29]. The compression tester used for ABI is shown in Figure B1, and the procedure is described on the following pages.

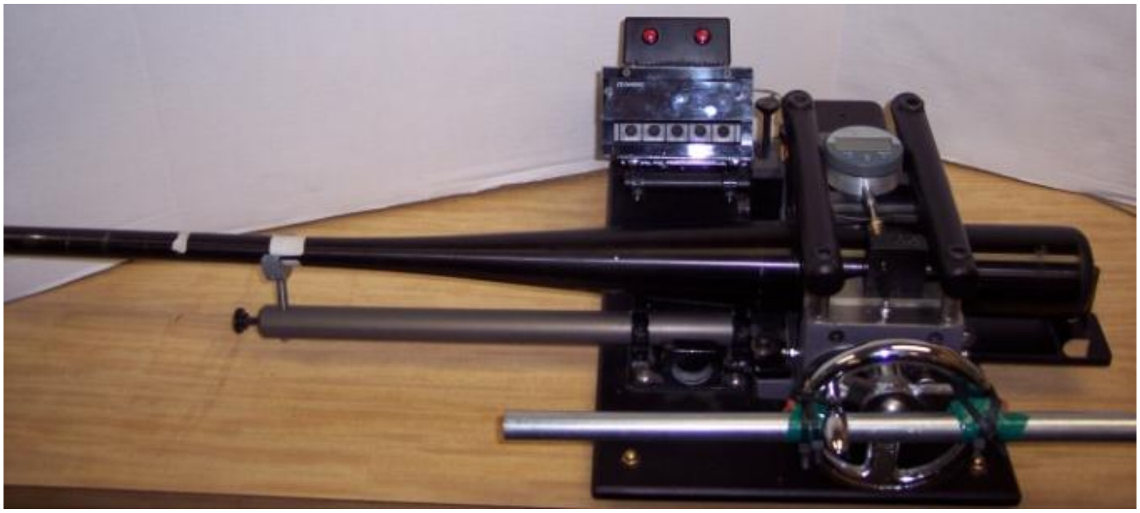

Figure B1. Compression tester used during ABI procedure.

NCAA Accelerated Break-In Procedure

30-September-09

The accelerated break-in procedure is meant to demonstrate how a composite bat will perform during it potential useful life in the field. This test procedure may be used with the NCAA BESR or BBCOR test to quantify the effect that bat usage has on performance and may be used in the certification and compliance testing of composite barrel bats. The procedure is subject to change at anytime.

Procedure:

1. **Measure preliminary properties of the bat per the NCAA BESR or BBCOR Certification Test Protocol and measure an initial barrel compression (BC_0).**

   Follow the attached barrel compression procedure.

2. **Measure bat performance (i.e. *BESR-i or BBCOR-i, where* (*i*=1 to denote the first BESR test cycle).**

   Follow the NCAA BESR or BBCOR test protocol.

   Define BESR_{max} or BBCOR_{max} as the average of the six valid hits at the sweet spot.

   If visible damage is observed or the performance limit is exceeded during the first performance test cycle, then stop the test and go to step 8.

3. **Measure barrel compression (BC_{i-j}), where (j=0)**

   Follow the attached barrel compression procedure and calculate the percent change in barrel compression, $\Delta BC_{0,}$ using,

   $$\Delta BC_0 = \left(\frac{BC_0 - BC_{1,0}}{BC_0}\right)\times 100\% \tag{B1}$$

   If the barrel compression change (ΔBC_0) is greater than 15%, then proceed directly to step 7.

4. **Roll the barrel**

   Follow the attached (given on Page B4) rolling procedure.

   Increment subscript notation: (j=j+1, where j is used to keep track of the roll process)

5. **Measure barrel compression ($BC_{i,j}$)**

   Follow the attached barrel compression procedure.

   Compute the percent change in barrel compression, $\Delta BC_{i,i}$, according to

   $$\Delta BC_{i,j} = \left(\frac{BC_{i,0} - BC_{i,j}}{BC_{i,0}}\right)\times 100\% \tag{B2}$$

6. **Repeat steps 4 and 5** (Increase rolling depth by increments of ~0.0125 in.) **until a barrel compression ($\Delta BC_{i,j}$), reduction of at least 5% is achieved.** The target barrel compression reduction should be as close to 5% as possible.

7. **Measure bat performance (i.e. *BESR-i or BBCOR-i*), where (*i*=*i*+1, i.e. set value of *i* to denote performance test cycle)**

   Follow the NCAA BESR or BBCOR test protocol.

   Order of testing axial impact locations may be adjusted by test operator, if necessary.

   Define BESR_{max} or BBCOR_{max} as the average of the six valid hits at the highest performing location from this test cycle or keep as-is from a previous performance test cycle, whichever is greater.

   Check compliance as specified in step 8.

8. **Compliance check**

   The bat fails if:

   - During the performance test, the bat exceeds the performance limit or does not make it through a complete test without visible damage (damage criterion only applies to first performance-test cycle).

   The bat passes if:

   - During a performance test subsequent to the first performance-test cycle, the bat exhibits a sweet spot performance reduction of at least 0.014 in BESR or 0.018 in BBCOR from the maximum bat performance BESR_{max} or $\text{BBCOR}_{max.}$

   If the bat has neither passed nor failed, then proceed to step 9.

9. **Measure barrel compression ($BC_{i,0}$)**

   Follow the attached (given on Page B4) barrel compression procedure and calculate the percent change in barrel compression, $\Delta BC_{i,}$ using,

   $$\Delta BC_i = \left(\frac{BC_{i,0} - BC_{(i-1),j}}{BC_{i,0}} \right) \times 100\% \qquad \text{(B3)}$$

   If barrel compression change (ΔBC_i) is greater than 15%, then proceed directly to step 7, otherwise proceed to step 4 and reset j=0.

Notes:

1. This procedure is not necessarily all inclusive and is subject to change at anytime.
2. For purposes of this method, a composite bat uses a fiber reinforced polymer (or similar material whose properties may change with impact) in the barrel portion of the bat.
3. A bat is determined to be broken, during the first performance test only, when a visible crack appears (excluding cracks in the paint or clear coat) or the bat fails the NCAA ring test (as defined in the NCAA BESR or BBCOR bat performance protocol). For subsequent performance test cycles (second, third and so on), damage in the bat is not quantified by the test operator and the bat is tested with respect to the damage criterion until the bat is damaged such that further testing cannot reasonably be accomplished.
4. At the discretion of the test sponsor, the test sponsor may request the test to be continued after failure due to exceeding the performance limit but the bat is still in usable condition. The cost of the continued testing is at the expense of the test sponsor.

Barrel Compression Procedure

Purpose: To measure the barrel compression.

Apparatus:

- Load frame capable of 1000 lbf
- Cylindrical steel loading noses with 3.86 in. diameter curvature and long enough to maintain proper contact throughout the test
- Means of measuring load and displacement

Procedure:

1. Mark a side on the barrel of the bat that will be the 0º orientation.
2. Set the force gage to zero.
3. Place the bat in the fixture to make contact at 6 in. from the tip of the endcap as shown in Fig. 2 and with the 0º orientation facing up.
4. Activate the fixture until both cylindrical surfaces are in contact with the barrel of the bat.
5. Compress the bat with 5 to 15 pounds of force.
6. Zero the displacement gage.
7. Compress the barrel 0.01 in. at a rate of about 0.15 in/min.
8. Zero the force and displacement gages.
9. Compress the barrel (an additional) 0.03 in.[1] at a rate of about 0.15 in/min.
10. Record the force (*F*).
11. Release the force.

12. Rotate the bat 90º from the initial rotation. Repeat steps 2 through 11
13. Rotate the bat 45º from the initial rotation. Repeat steps 2 through 11
14. Rotate the bat -45º from the initial rotation. Repeat steps 2 through 11.
15. Compute the barrel compression, *BC*, from the average of each axis by:

$$BC = \frac{1}{4}\left\{(F)_0 + (F)_{90} + (F)_{45} + (F)_{-45}\right\} \tag{B4}$$

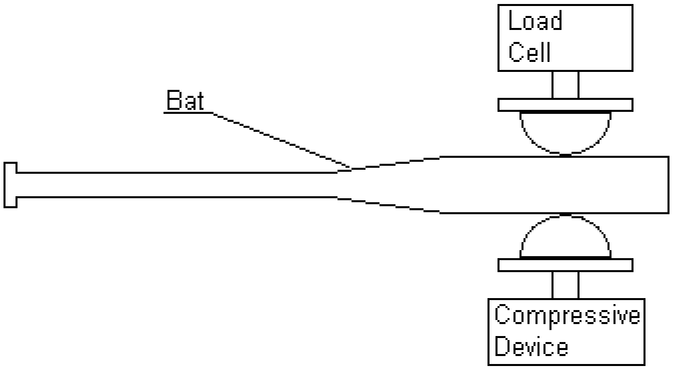

Figure B2. Compression testing.

Note 1: If Force exceeds the load-cell capacity, then the operator may choose to use less displacement (e.g. 0.025 in.). This new displacement must then be used throughout the entire ABI test when measuring barrel compression and be identified in any reports of the tests.

Appendix C – ABI Procedure

This appendix will outline the NCAA protocol for accelerated break-in of a composite baseball bat [29]. The roller used for ABI is shown in Figure C1, and the procedure is presented on the following pages.

Figure C1. Roller used during ABI procedure.

Barrel Rolling Procedure

Purpose: To accelerate break-in of composite bats.

Apparatus (as described here or similar such device)

- Two nylon wheels – 1.5 to 3.0 in. in diameter
- Fixture to press wheels into barrel in ~0.0125-in. increments
- Device to roll the barrel

Procedure:

1. Place the barrel of the bat in the fixture with the rollers contacting the bat at 6 in. from the endcap and the 0º orientation (as identified during the Barrel Compression Procedure) facing up.
2. Bring roller in contact with the barrel. Displace the rollers ~0.10 in. for initial rolling or ~0.0125 in. greater than the previous time through the Barrel Rolling Procedure.
3. Roll the barrel to within 2.0 to 2.5 in. of endcap and past the taper (no contact between rollers and bat) as shown in Fig. 1. Roll the bat 10 times in each

direction. Popping and cracking sounds during this process are normal. (A different number of rolls can be used at the operator's discretion.)

4. Uncompress the bat.
5. Rotate the bat 90º from initial location and repeat steps 1-4.
6. Rotate the bat 45º from initial location and repeat steps 1-4.
7. Rotate the bat -45º from initial location and repeat steps 1-4.
8. For rolling beyond 0.1 in., increase displacement by increments of about 0.0125 in.

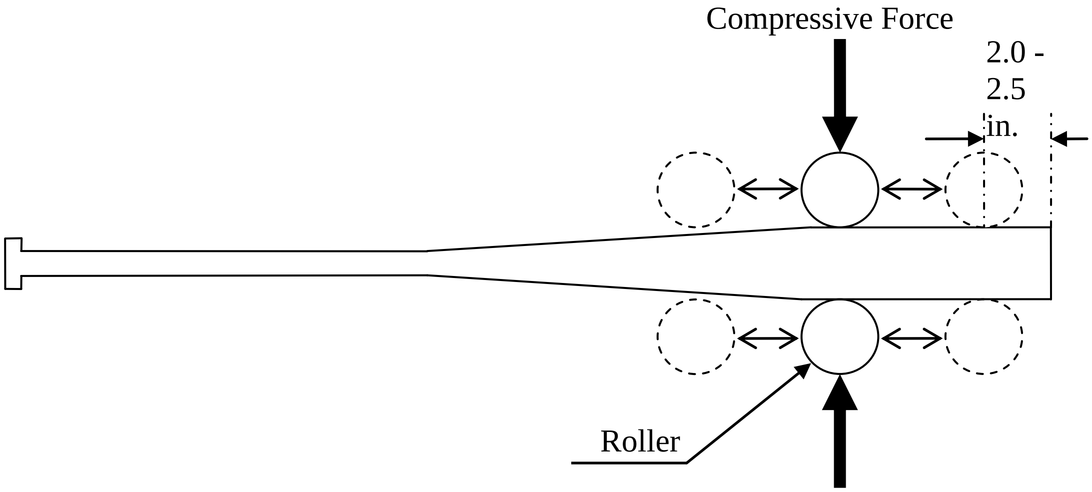

Figure C2. Rolling Parameters.

Appendix D – Close-up Cycle Data Plots

This appendix will display close-ups of data plot as a function of cycle including BESR, BBCOR, BBS, first hoop and second hoop frequencies and barrel stiffness as discussed in Chapter 4.

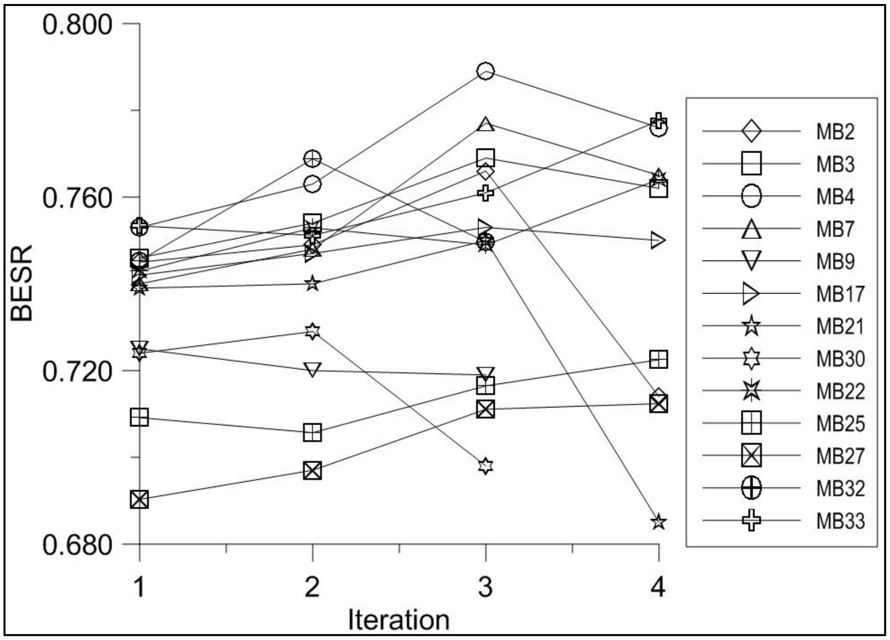

Figure D1. Close-up of BESR vs. cycle.

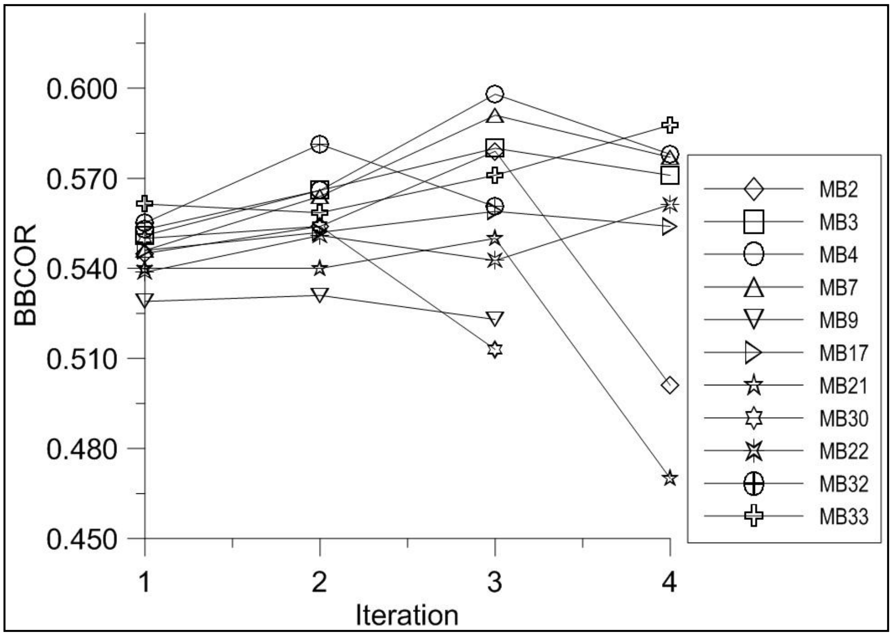

Figure D2. Close-up of BBCOR vs. cycle.

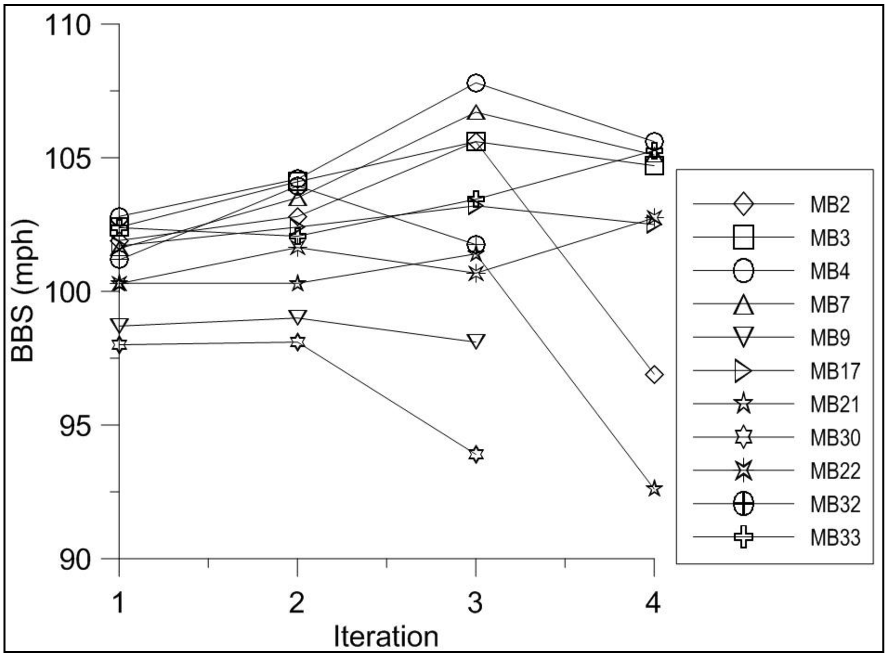

Figure D3. Close-up of BBS vs. cycle.

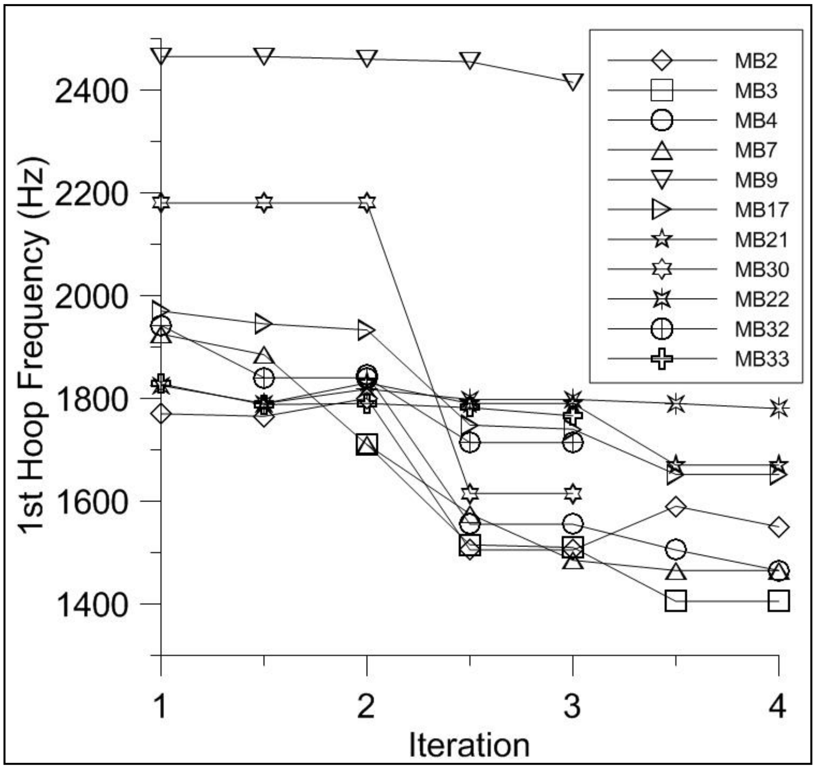

Figure D4. Close-up of first hoop frequency vs. cycle.

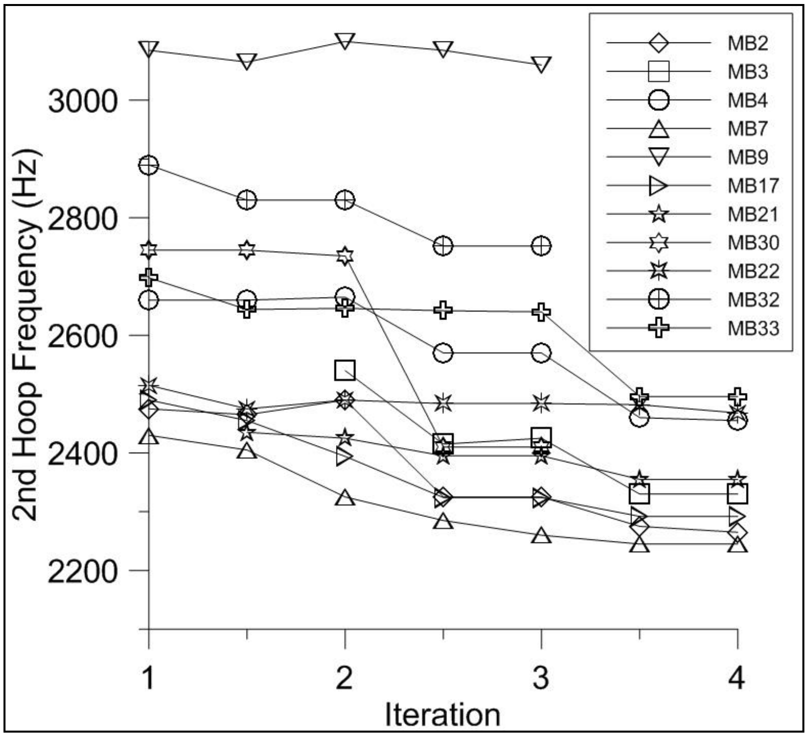

Figure D5. Close-up of second hoop frequency vs. cycle.

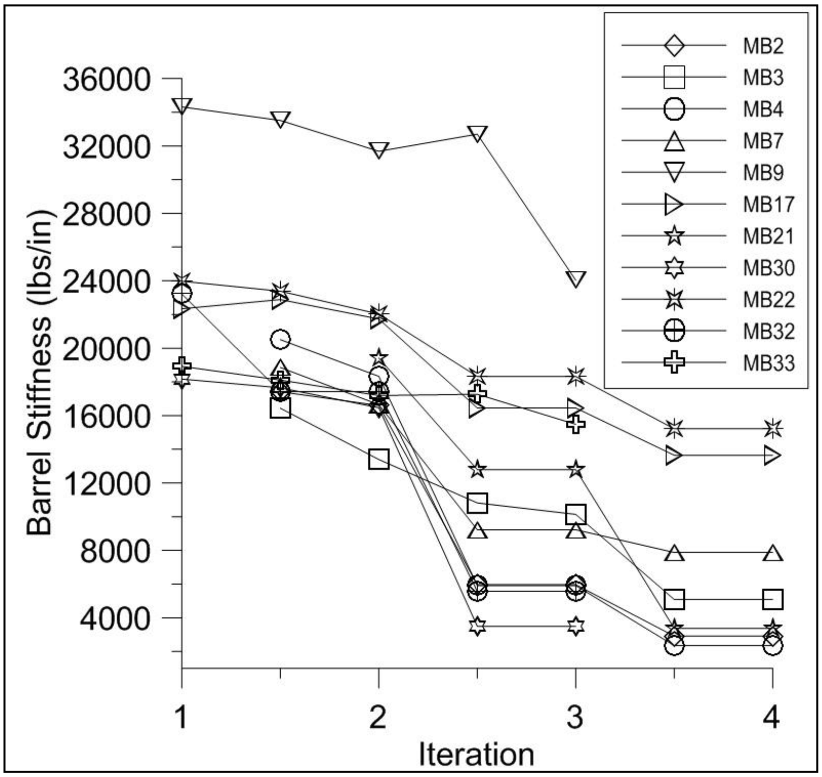

Figure D6. Close-up of barrel stiffness vs. cycle.

Appendix E – Stiffness Data Plots with MB25 and MB27

This appendix will display barrel stiffness comparison data along with Bat IDs MB25 and MB27 as was discussed in Chapter 4. Recall that the construction of these two bats was radically different from the other composite bats investigated in this research.

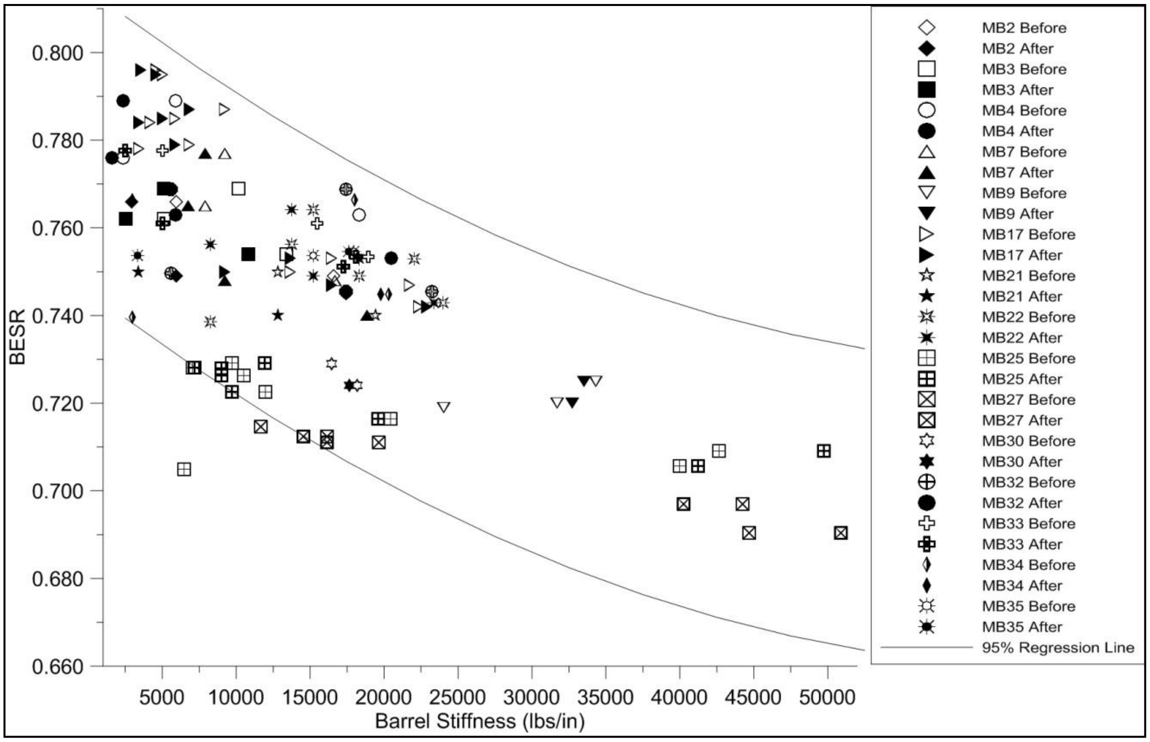

Figure E1. BESR vs. barrel stiffness with MB25 and MB27.

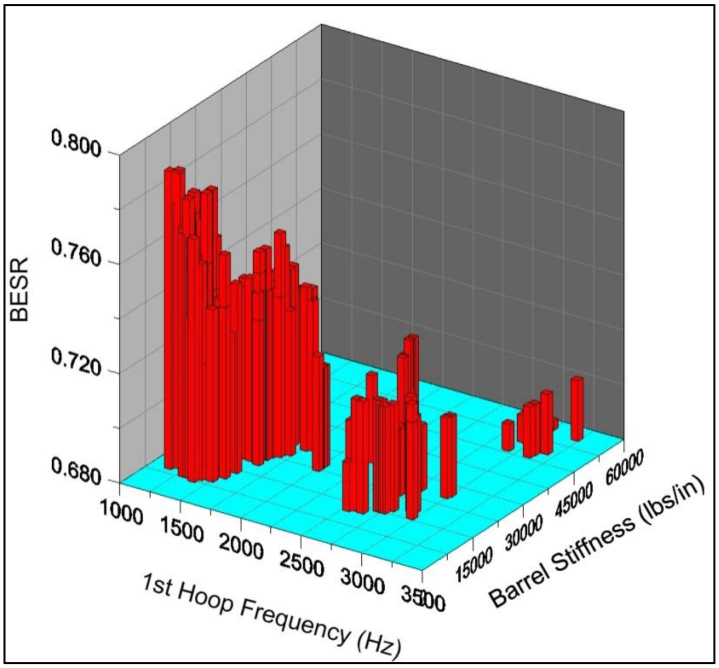

Figure E2. BESR vs. first hoop frequency and barrel stiffness with MB25 and MB27.

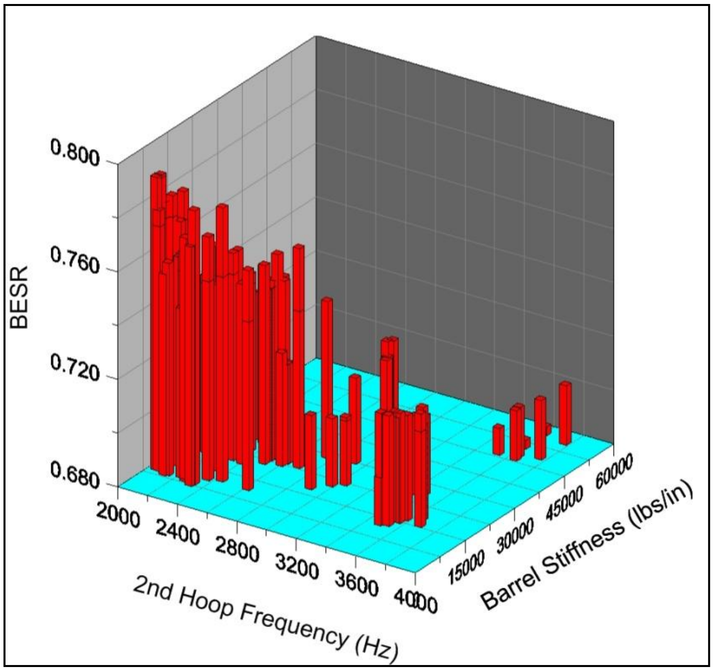

Figure E3. BESR vs. second hoop frequency and barrel stiffness with MB25 and MB27.

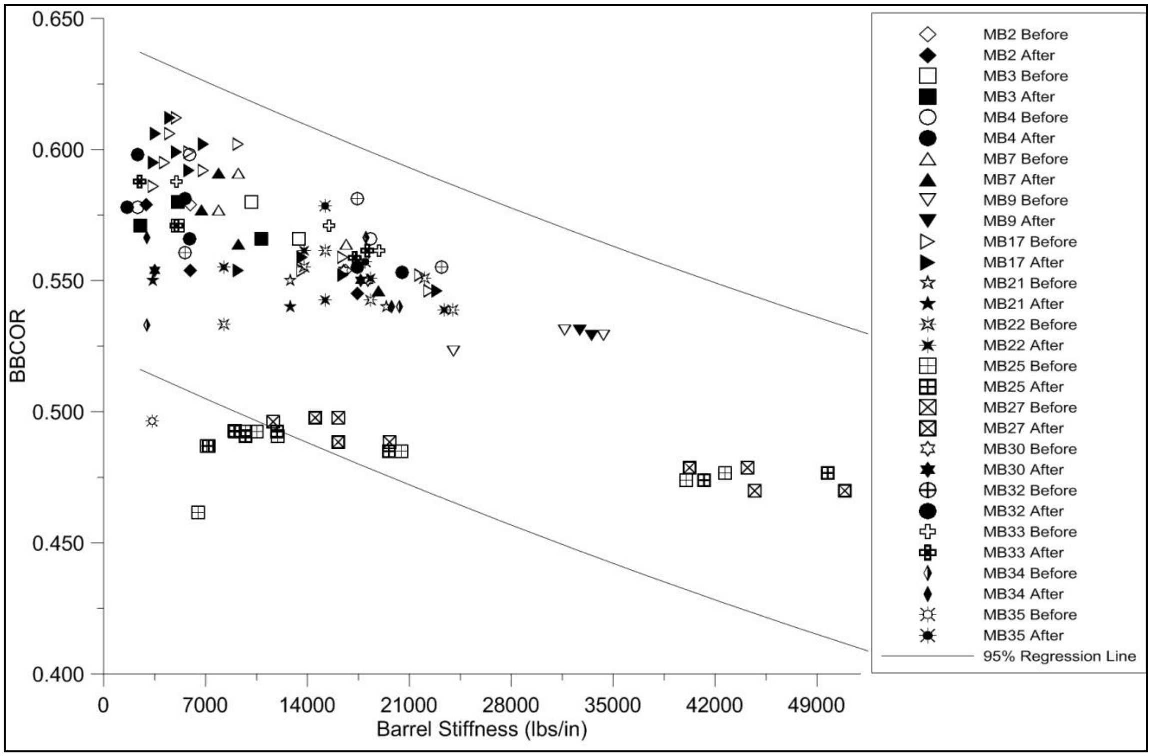

Figure E4. BBCOR vs. barrel stiffness with MB25 and MB27.

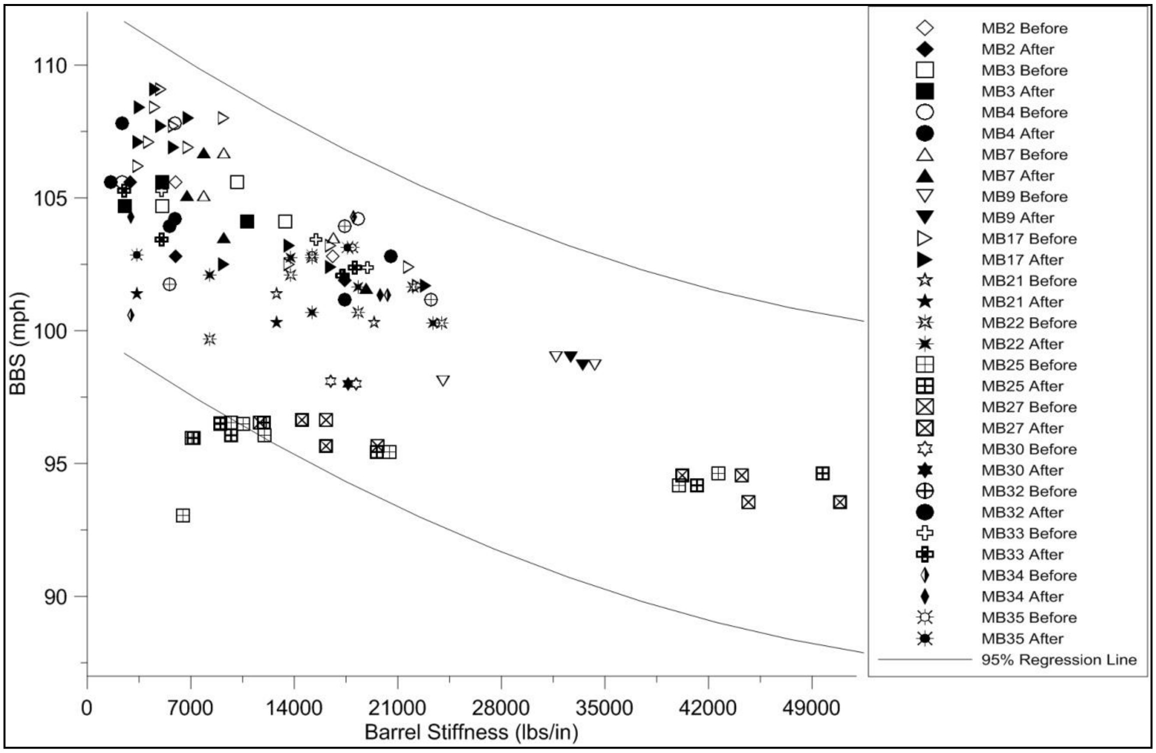

Figure E5 BBS vs. barrel stiffness with MB25 and MB27.

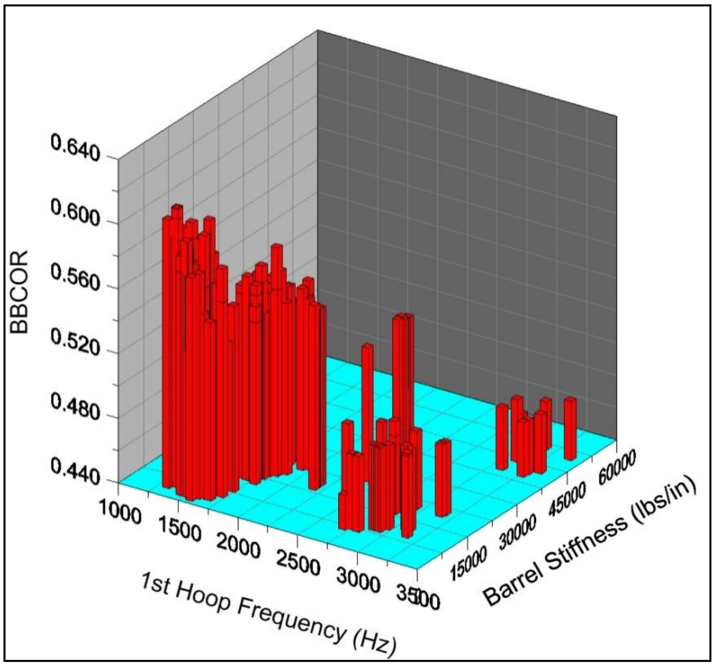

Figure E6. BBCOR vs. first hoop frequency and barrel stiffness with MB25 and MB27.

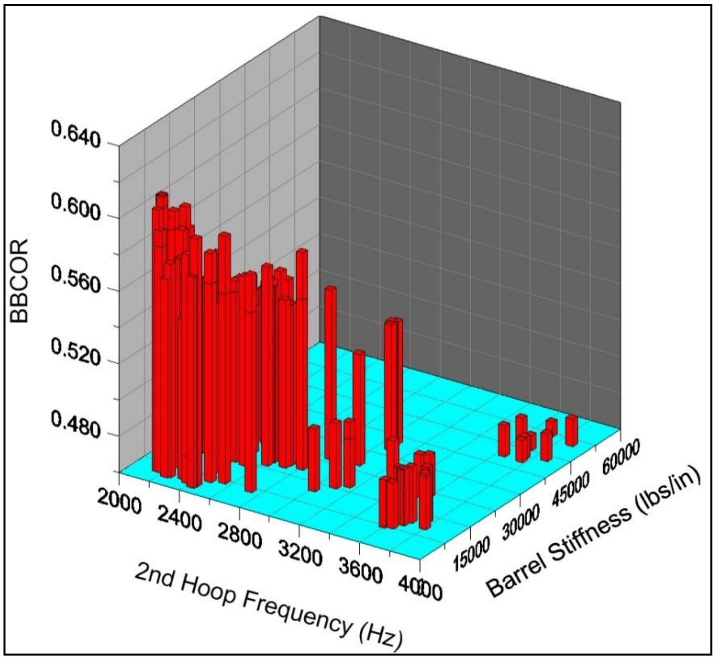

Figure E7. BBCOR vs. second hoop frequency and barrel stiffness with MB25 and MB27.

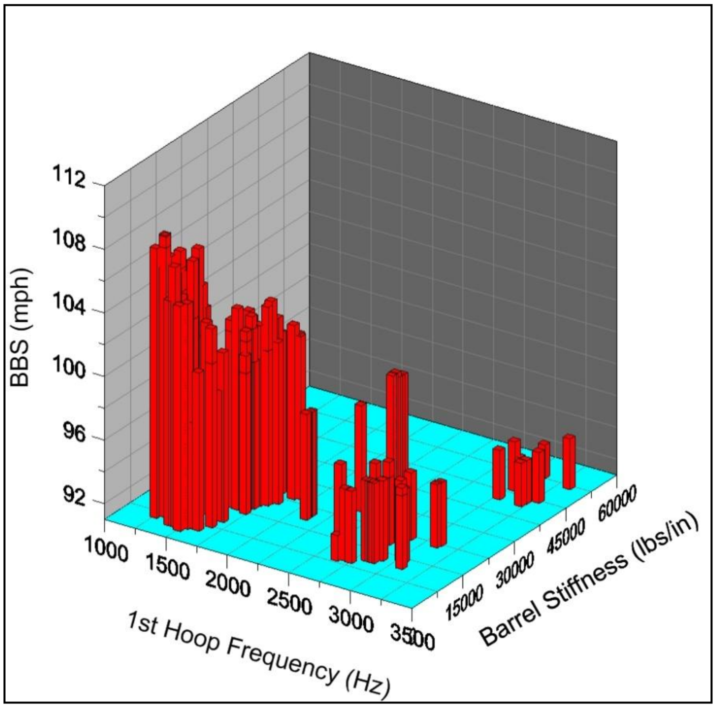

Figure E8. BBS vs. first hoop frequency and barrel stiffness with MB25 and MB27.

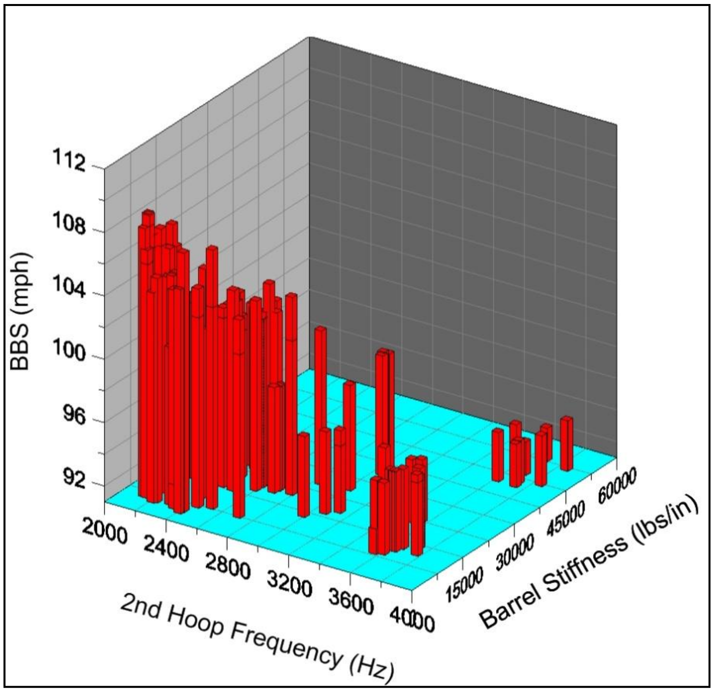

Figure E9. BBS vs. second hoop frequency and barrel stiffness with MB25 and MB27.

Appendix F –BBCOR and BBS ABI Comparison Data Plots

This appendix will display batted-ball performance (BBCOR and BBS) data plotted for matched pair of bats as discussed in Chapter 4. Only BESR was presented in Chapter 4. As noted in Chapter 4, the BBCOR and BBS curves show the same trends as were observed for the BESR vs. Cycle plots. Thus, no additional discussion is given here for these plots.

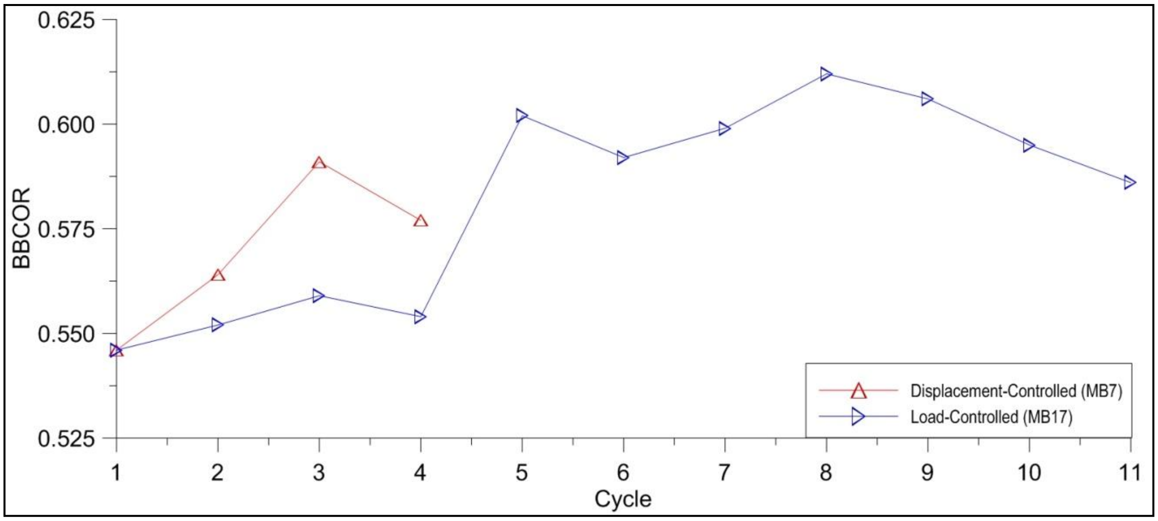

Figure F1. Displacement- and load-controlled BBCOR comparison (Pair 1).

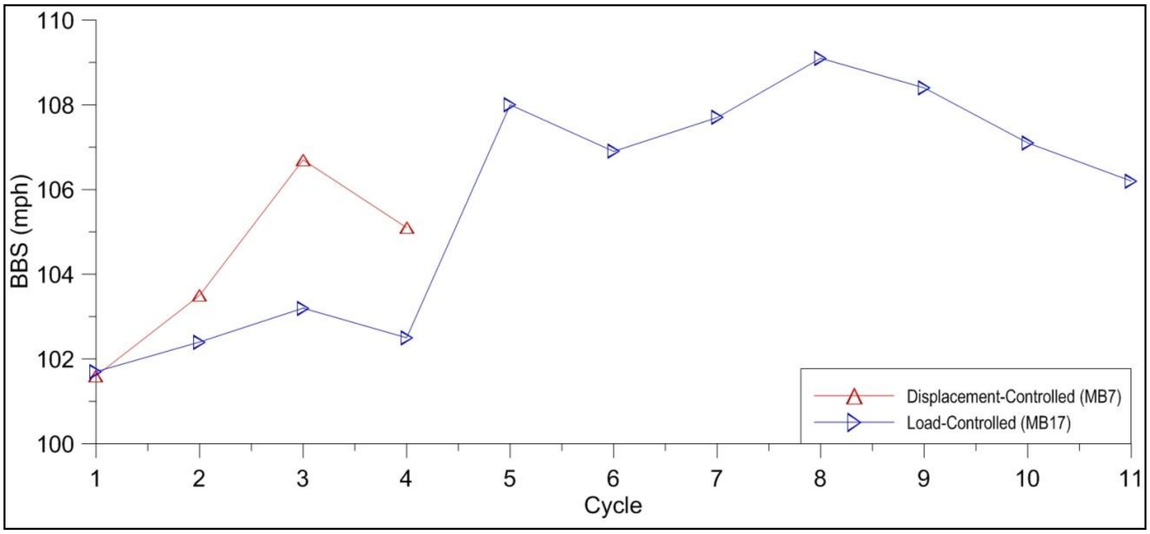

Figure F2. Displacement- and load-controlled BBS comparison (Pair 1).

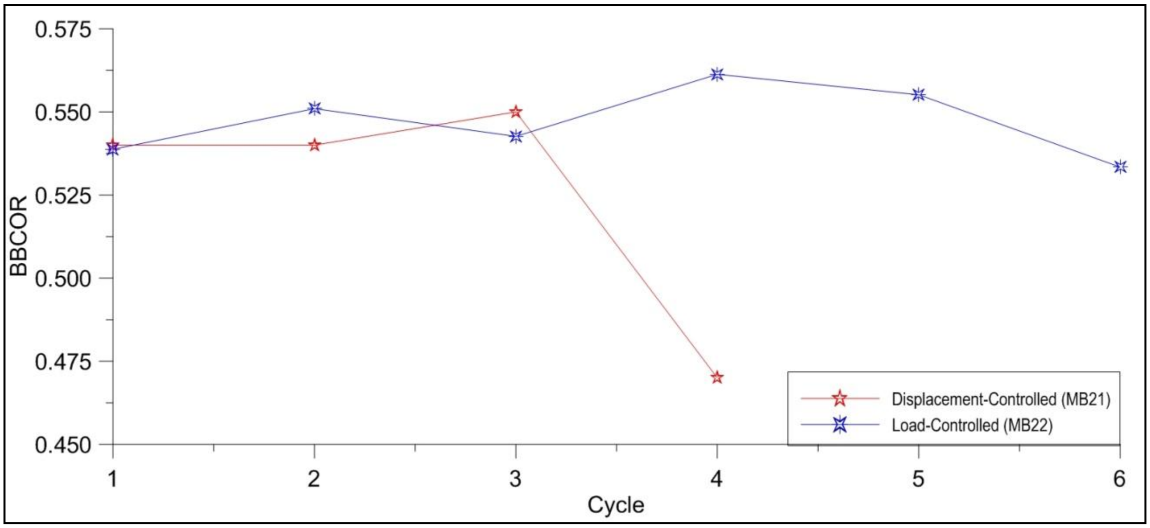

Figure F3. Displacement- and load-controlled BBCOR comparison (Pair 2).

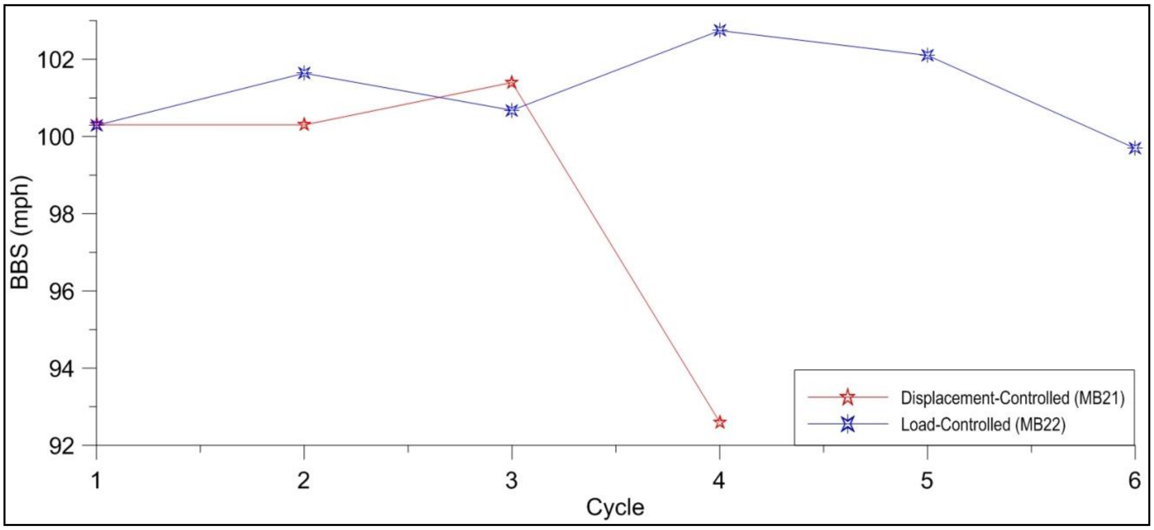

Figure F4. Displacement- and load-controlled BBS comparison (Pair 2).

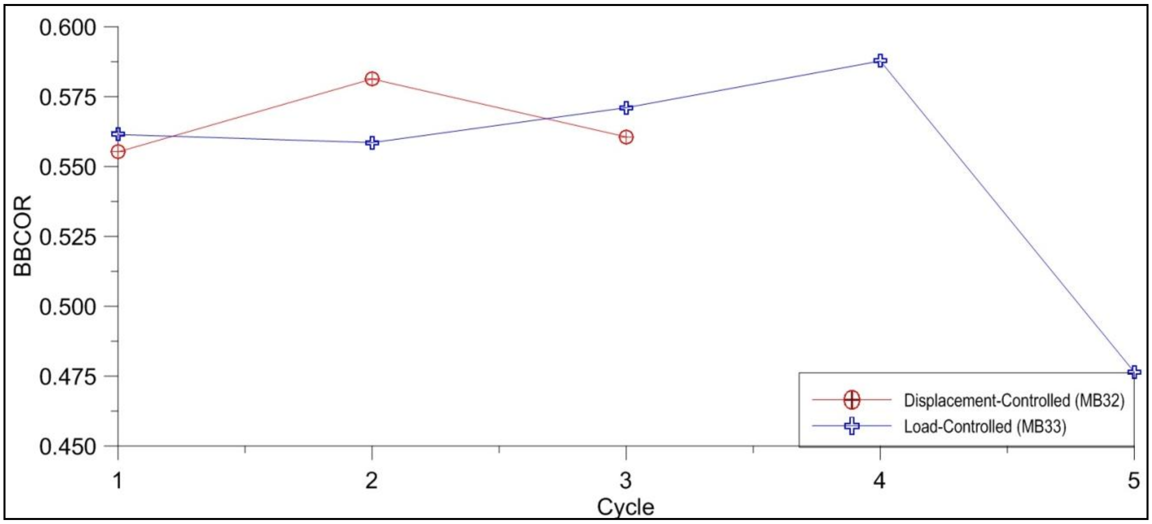

Figure F5. Displacement- and load-controlled BBCOR comparison (Pair 3).

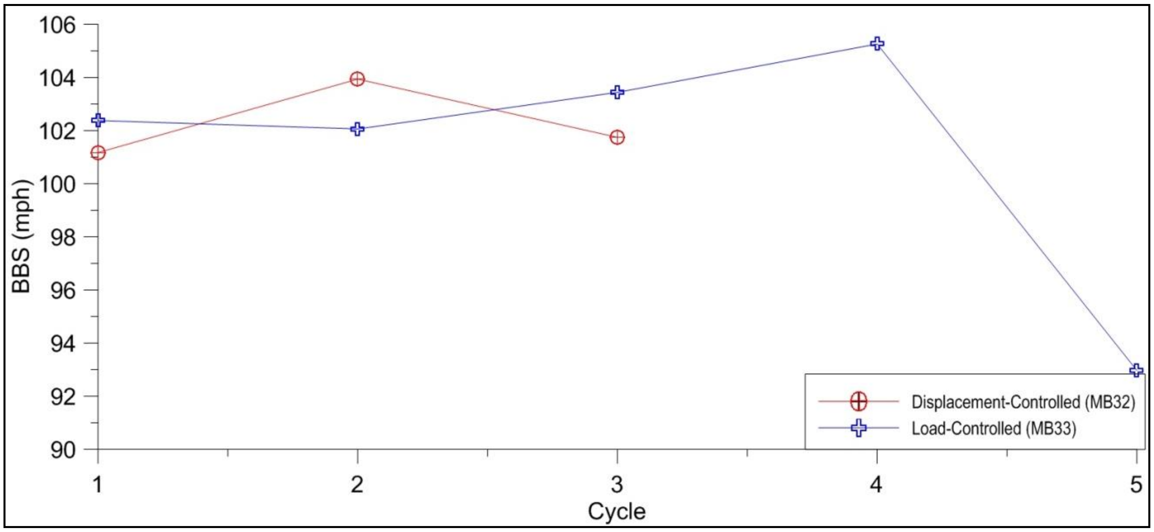

Figure F6. Displacement- and load-controlled BBS comparison (Pair 3).

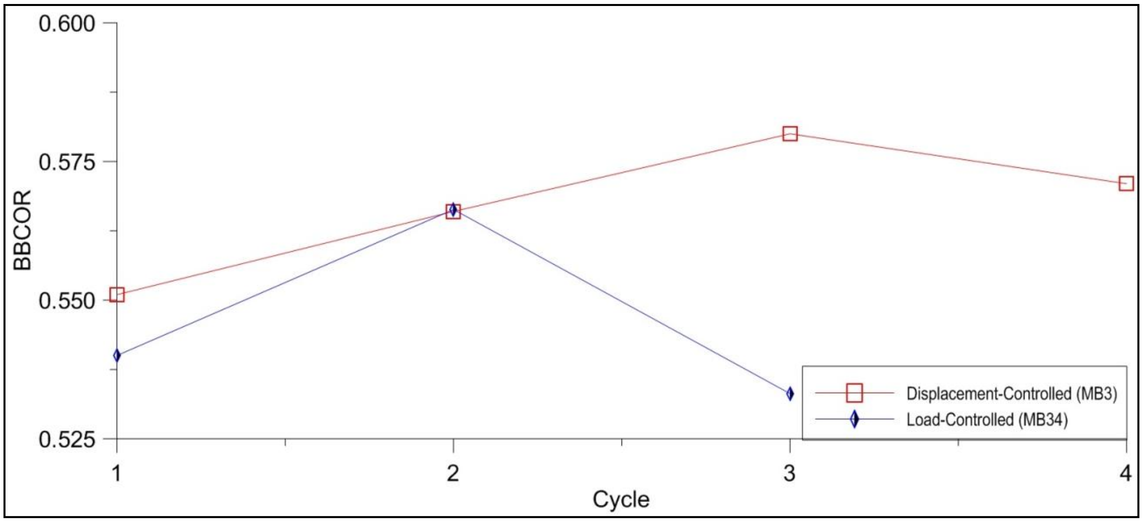

Figure F7. Displacement- and load-controlled BBCOR comparison (Pair 4).

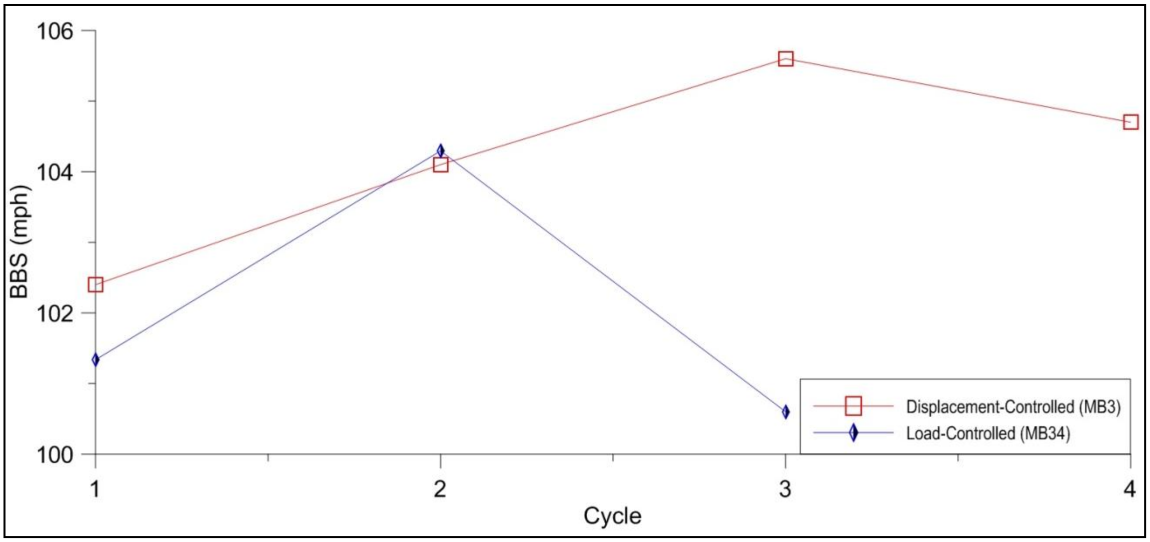

Figure F8. Displacement- and load-controlled BBS comparison (Pair 4).

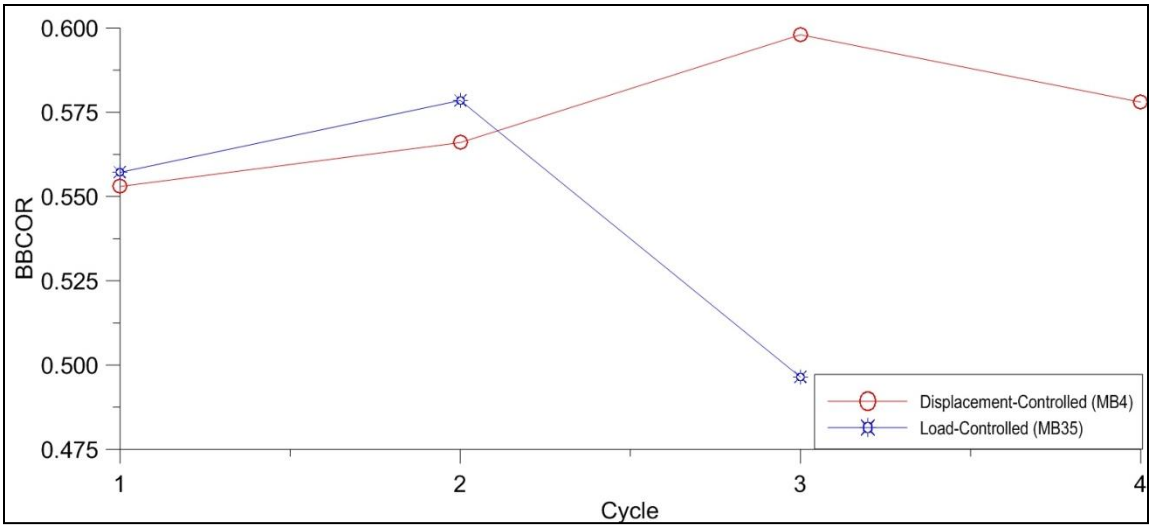

Figure F9. Displacement- and load-controlled BBCOR comparison (Pair 5).

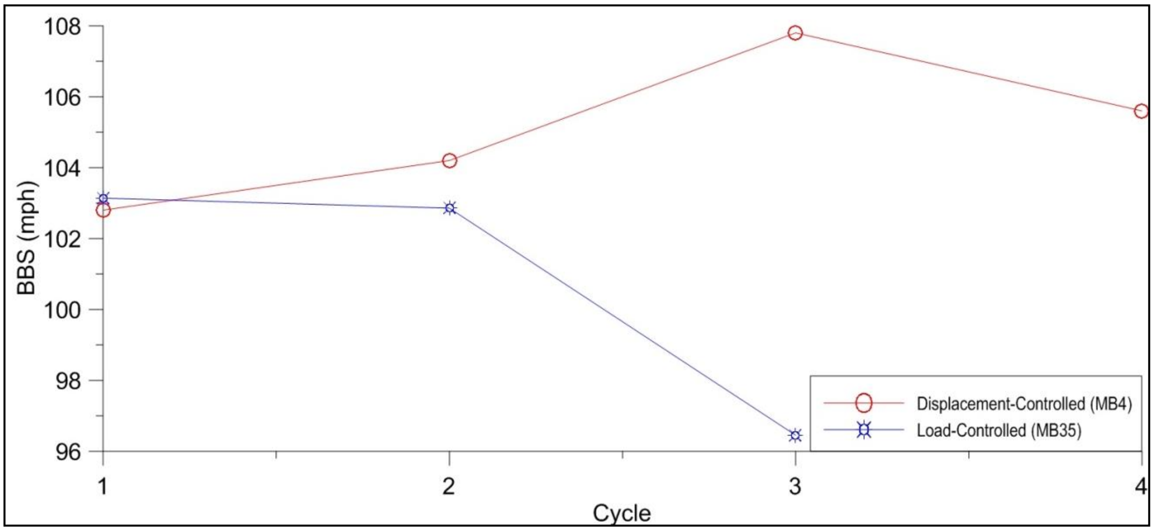

Figure F10. Displacement- and load-controlled BBS comparison (Pair 5).

Appendix G –Uncertainty Analysis Data Plots

This appendix will display batted-ball performance (BESR, BBCOR, BBS) data plotted against non-performance metrics (first hoop frequency, second hoop frequency and barrel stiffness) with uncertainty bars from the uncertainty analysis discussed in Chapter 4.

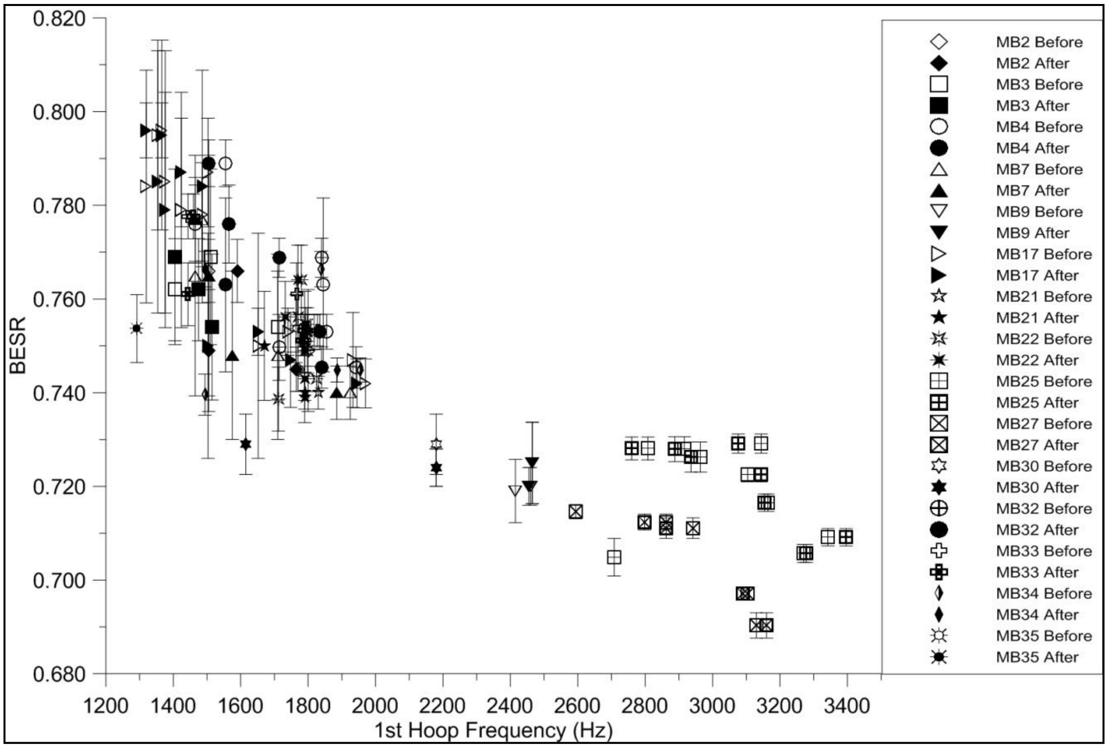

Figure G1. BESR vs. first hoop frequency uncertainty analysis.

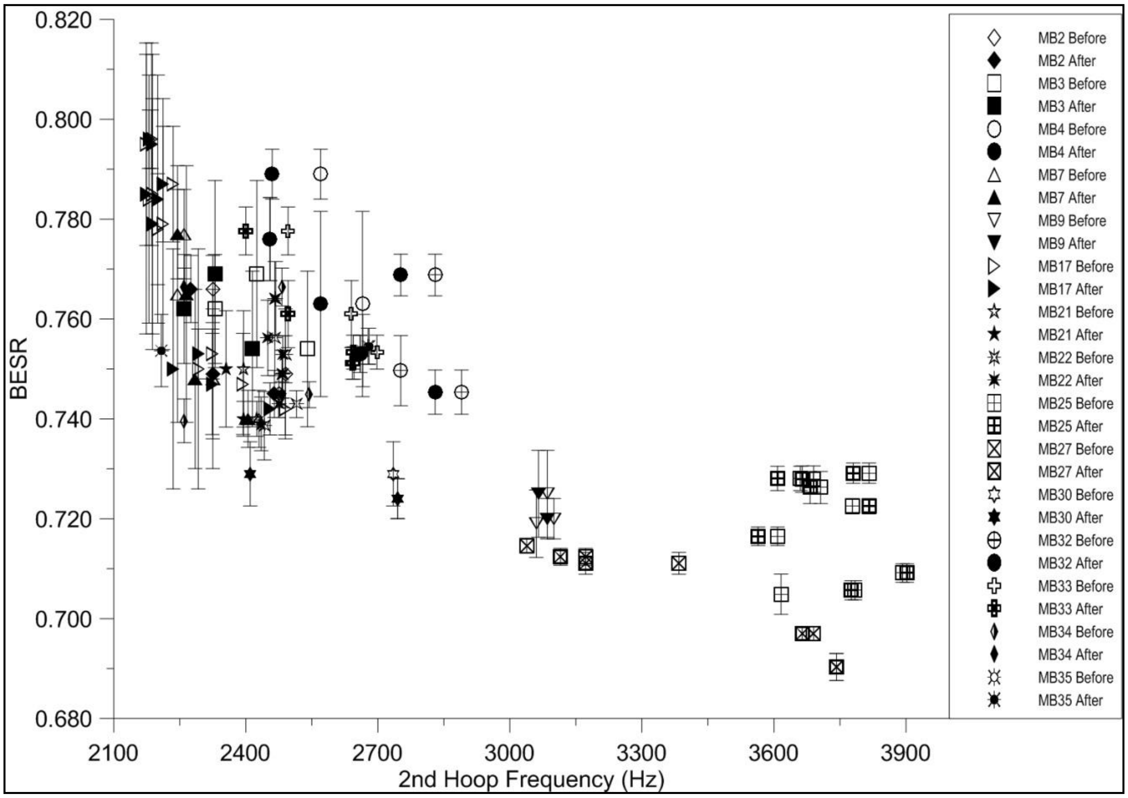

Figure G2. BESR vs. second hoop frequency uncertainty analysis.

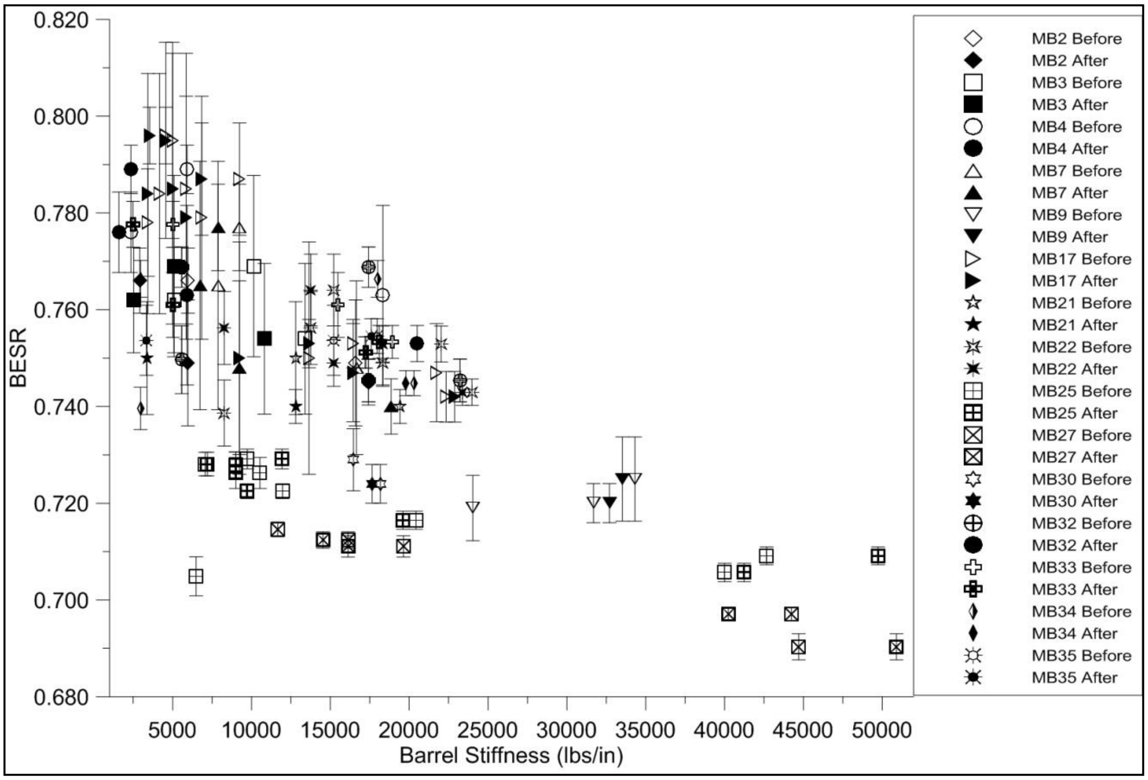

Figure G3. BESR vs. barrel stiffness uncertainty analysis.

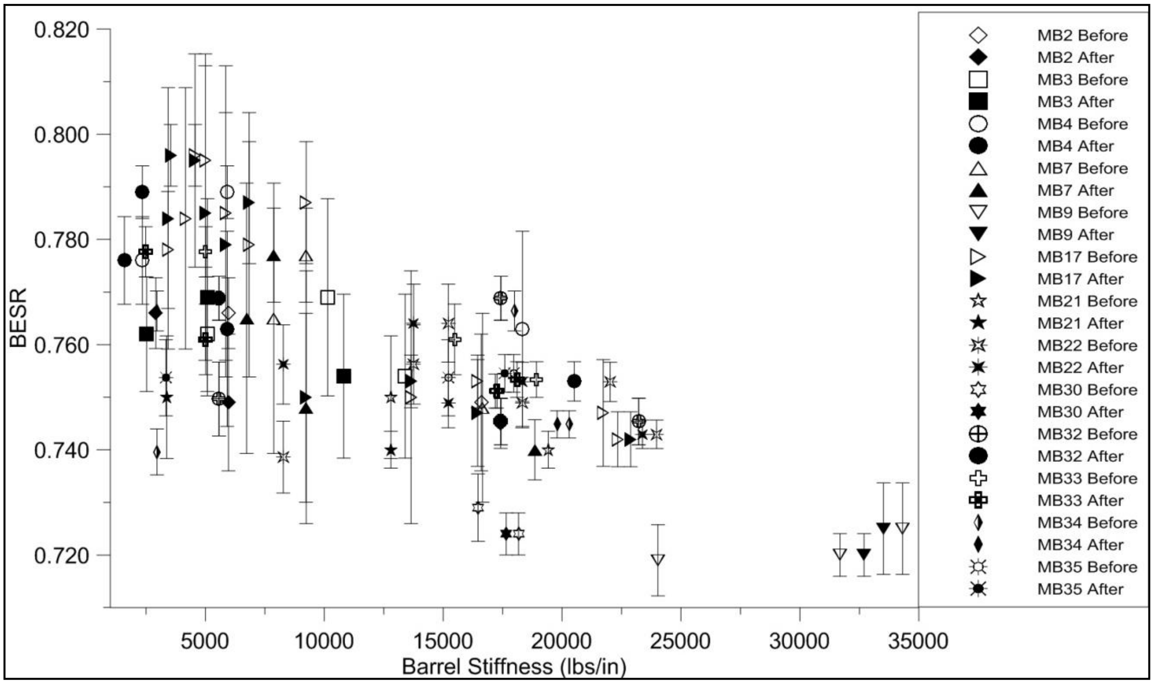

Figure G4. BESR vs. barrel stiffness uncertainty analysis without MB25 and MB27

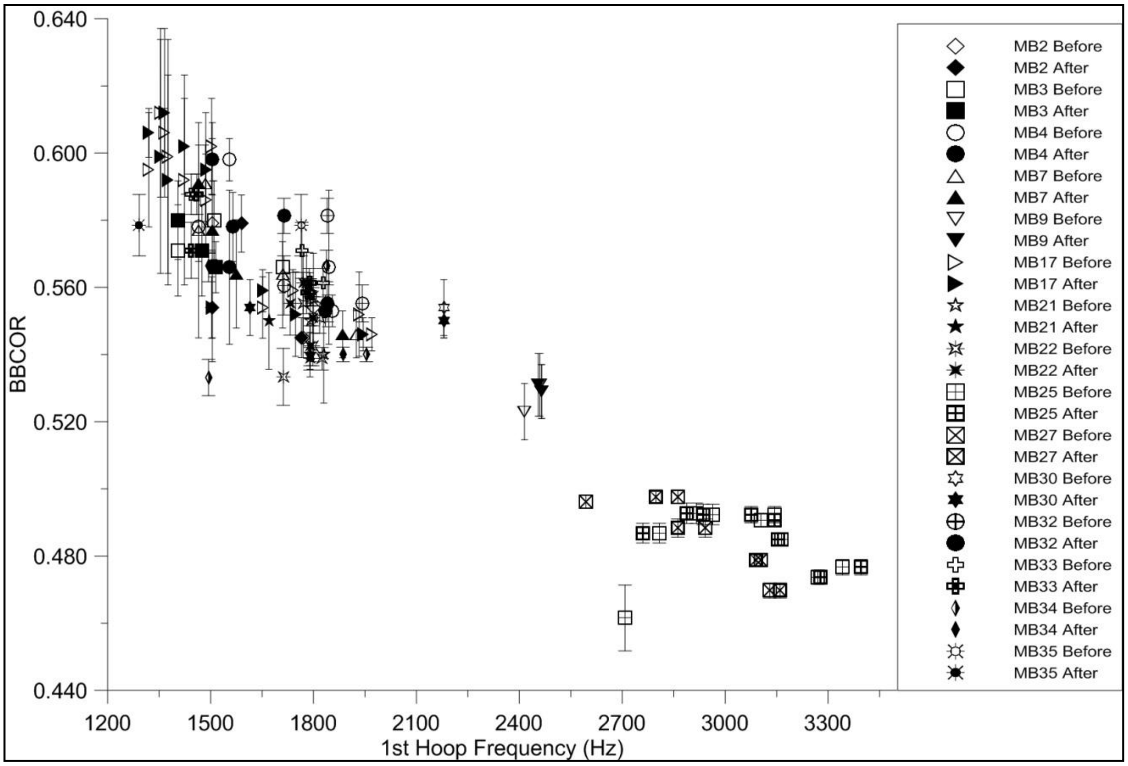

Figure G5. BBCOR vs. first hoop frequency uncertainty analysis.

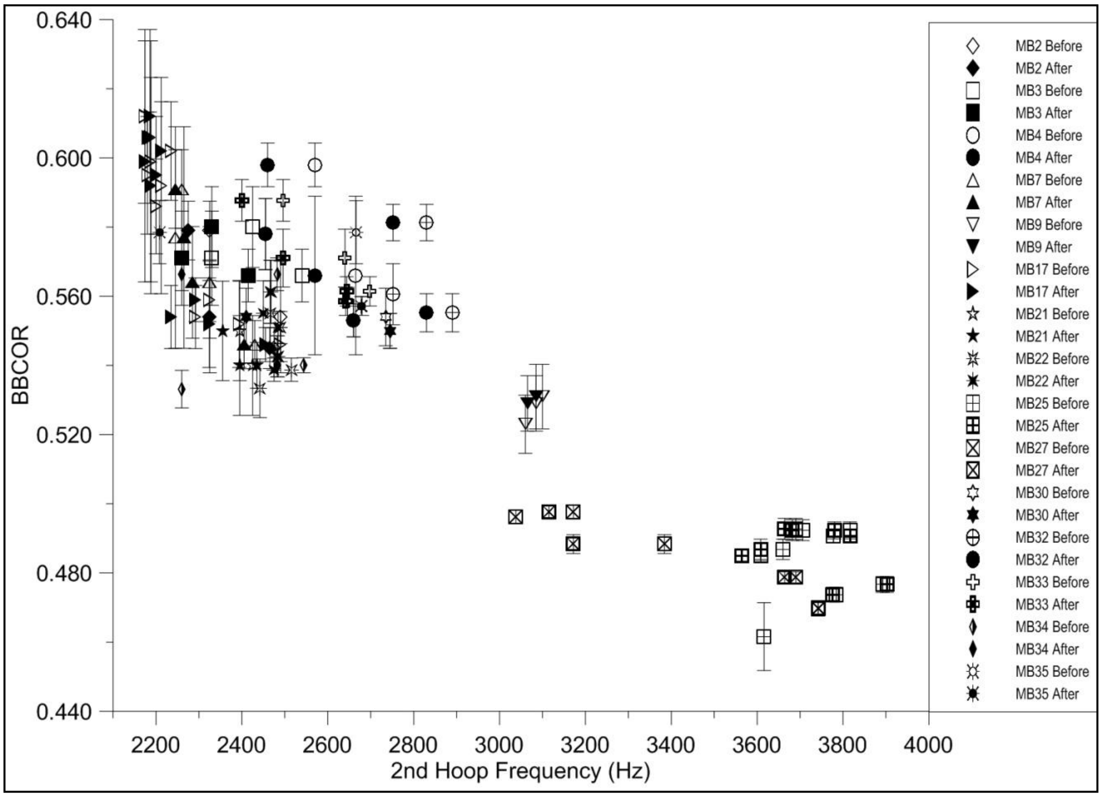

Figure G6. BBCOR vs. second hoop frequency uncertainty analysis.

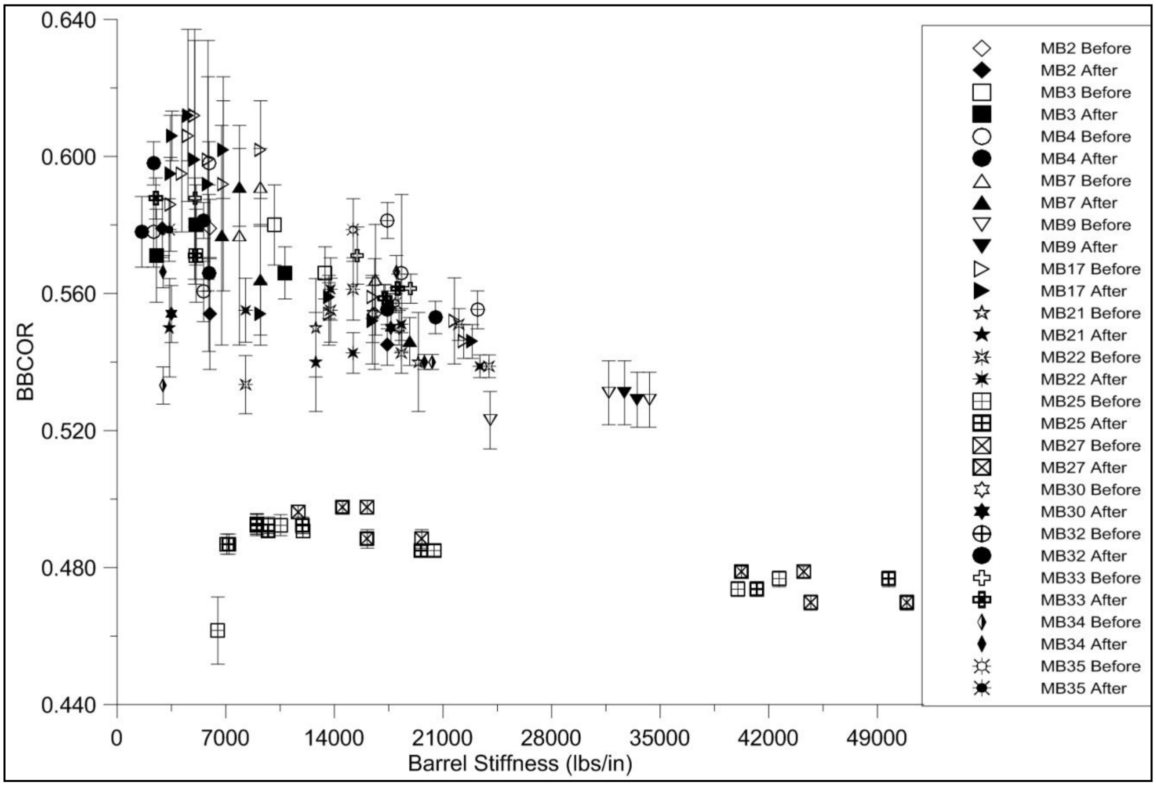

Figure G7. BBCOR vs. barrel stiffness uncertainty analysis.

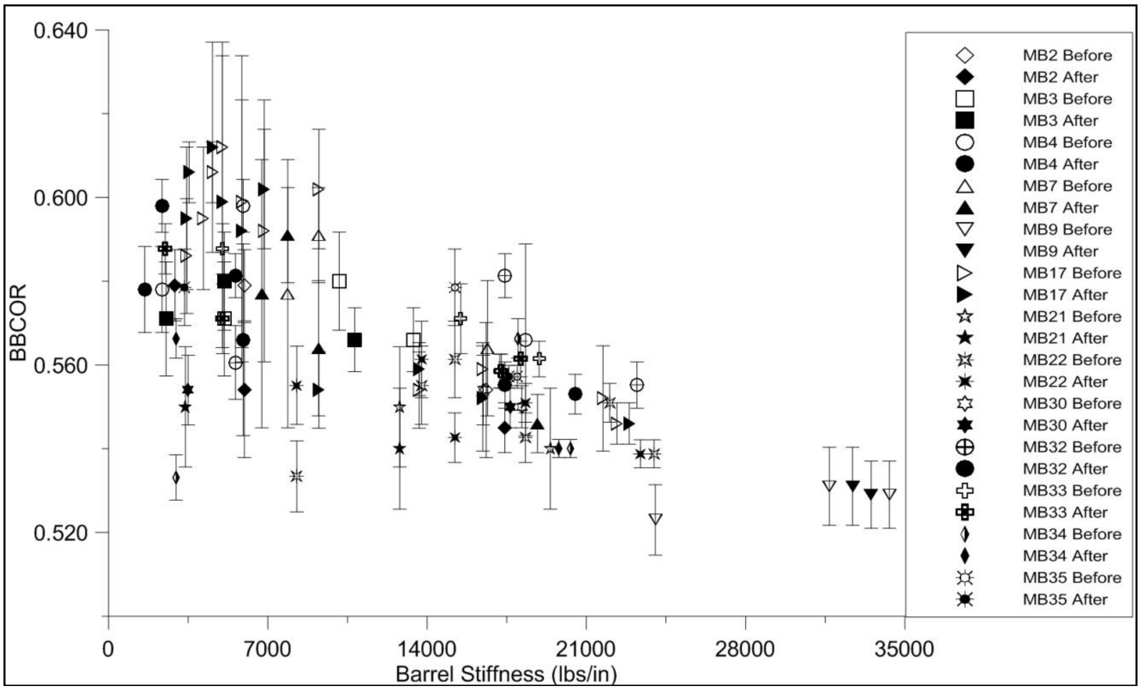

Figure G8. BBCOR vs. barrel stiffness uncertainty analysis without MB25 and MB27.

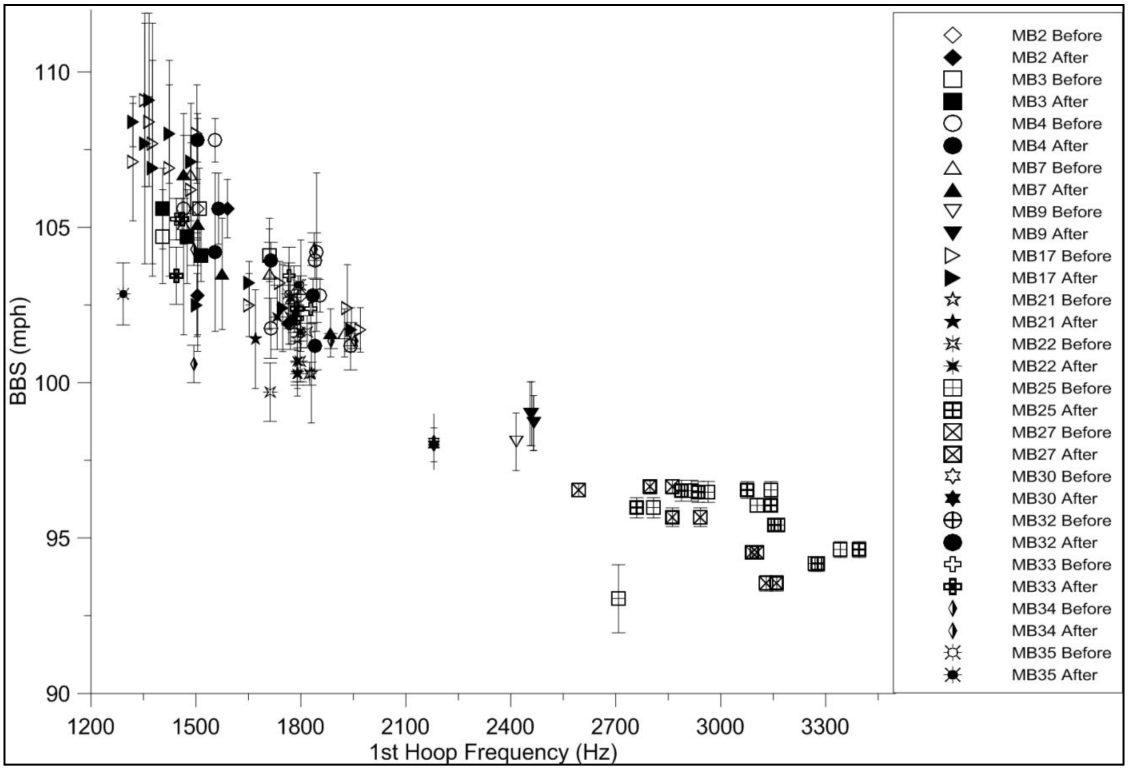

Figure G9. BBS vs. first hoop frequency uncertainty analysis.

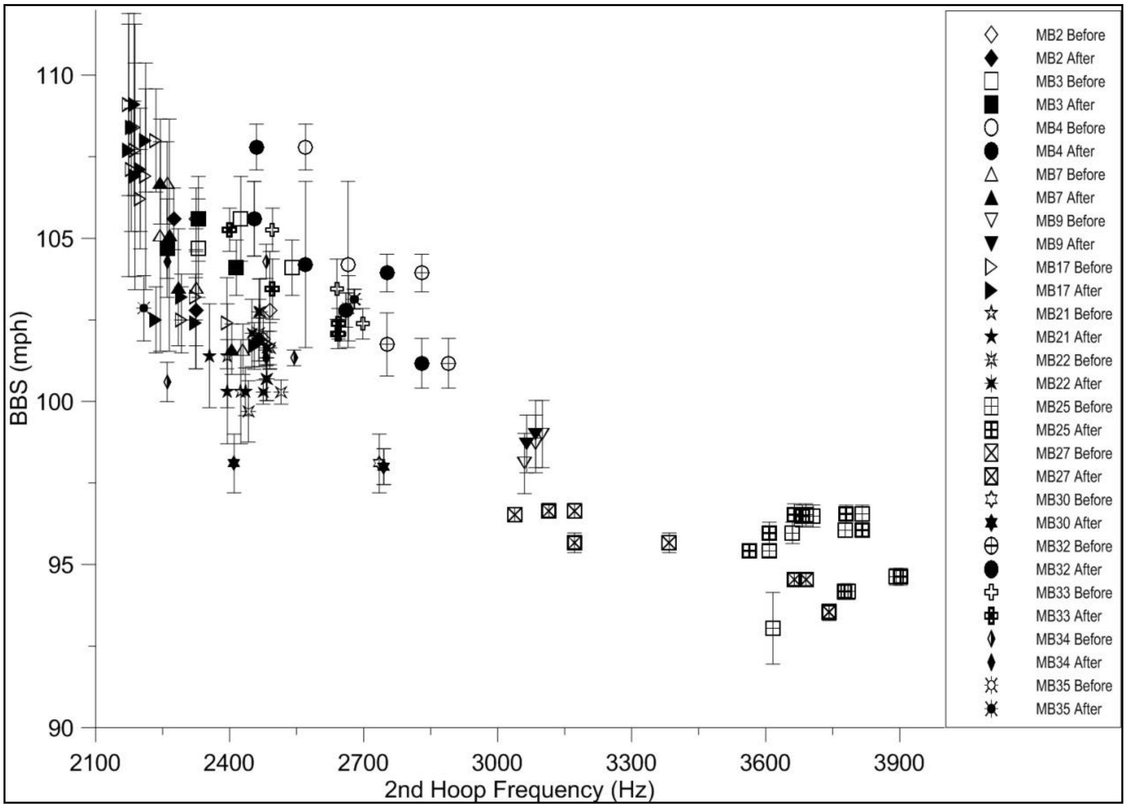

Figure G10. BBS vs. second hoop frequency uncertainty analysis.

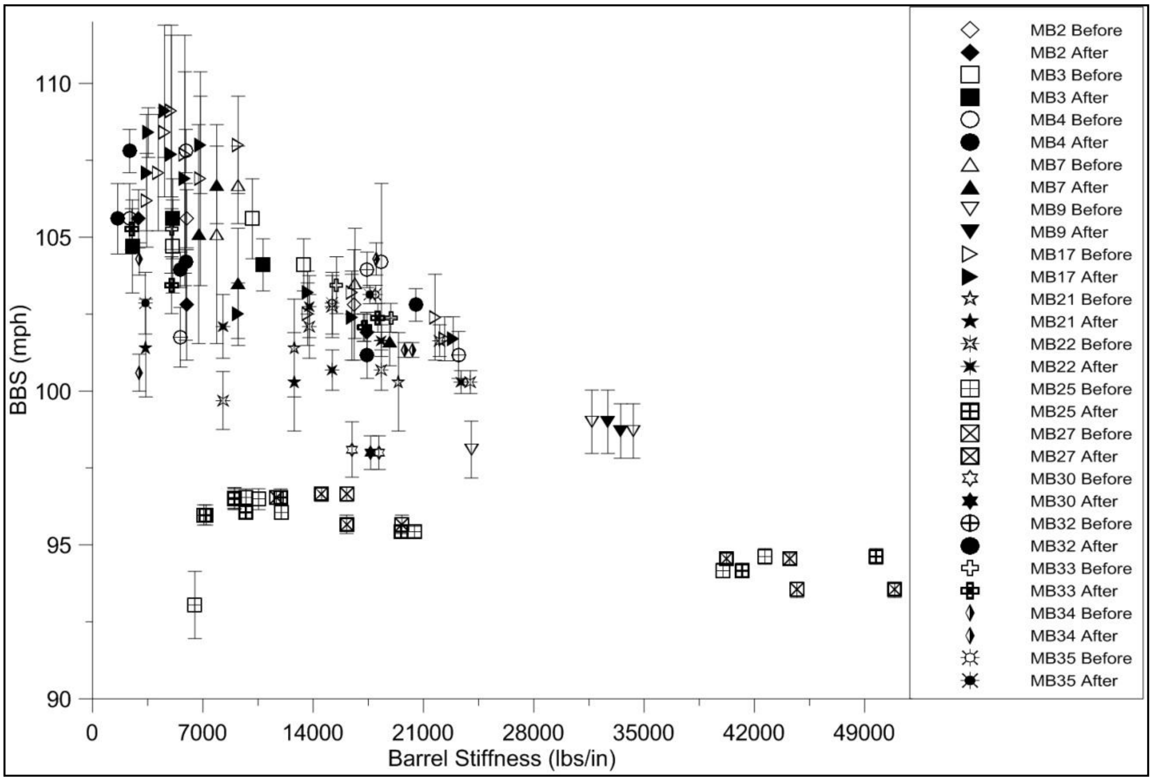

Figure G11. BBS vs. barrel stiffness uncertainty analysis.

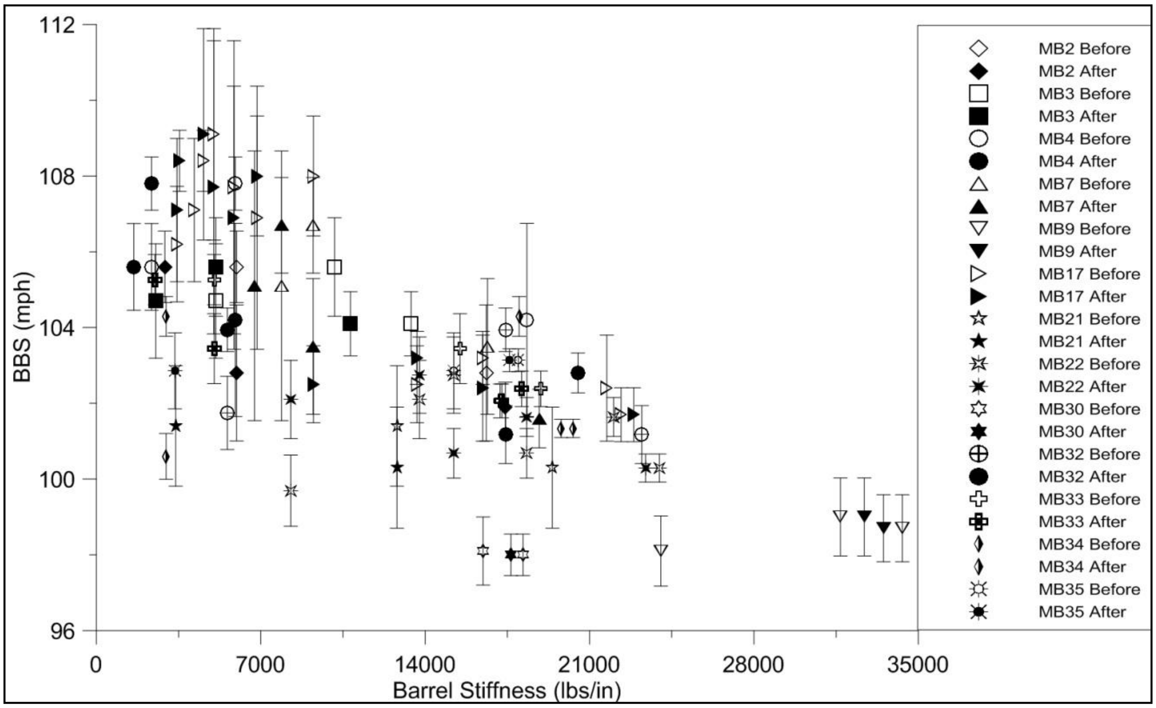

Figure G12. BBS vs. barrel stiffness uncertainty analysis without MB25 and MB27.