The BESR
(Ball Exit Speed Ratio)

by

Dr. James Ashton-Miller, Dr. Michael Carroll,
Dr. Kenneth Johnson, Dr. Alan Nathan

NCAA Baseball Research Panel

Todd Petr, Ty Halpin

NCAA

Introduction

The NCAA requires that all nonwood bats be certified so as to limit their "liveliness." The certification process is accomplished by measuring the performance of a bat under controlled conditions and then assigning a number to it; this number is known as the BESR (Ball Exit Speed Ratio). To be certified, the BESR of the bat must fall at or below a predetermined value set by the NCAA. This paper discusses the concept of the BESR.

The Ball-Bat Collision

Figure 1 shows a ball and a bat just before the collision and the ball just after the collision (the position of the ball after the collision has been moved downward for the sake of clarity).

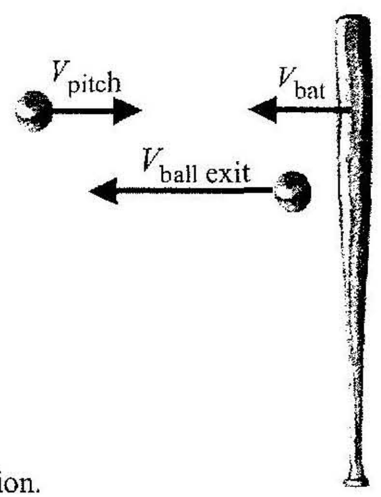


Figure 1 The ball-bat collision.

The speeds involved in the collision are:

V_{pitch} = speed of the pitched ball just before it collides with the bat.
V_{bat} = speed of the bat just before it collides with the ball. This is the bat speed at the point of impact.
$V_{ball\ exit}$ = exit speed of the ball just after it leaves the bat.

What Is the BESR?

The BESR is a number, once known, that allows one to determine the ball exit speed $V_{ball\ exit}$ when the bat speed V_{bat} and the pitch speed V_{pitch} speed are specified. The relationship between the BESR and these speeds is:

$$V_{ball\ exit} = \left(\text{BESR} + \tfrac{1}{2}\right)V_{bat} + \left(\text{BESR} - \tfrac{1}{2}\right)V_{pitch} \qquad (1)$$

As an example, suppose the BESR for a particular ball-bat collision is 0.65, and that the bat and pitch speeds are $V_{bat} = 70$ mph and $V_{pitch} = 75$ mph. The ball exit speed would be

$$V_{ball\ exit} = \left(0.65 + \tfrac{1}{2}\right)(70\text{ mph}) + \left(0.65 - \tfrac{1}{2}\right)(75\text{ mph}) = 92\text{ mph}$$

Conversely, if one measures the bat speed, the pitch speed, and the ball exit speed, then Equation 1 can be used to determine the BESR (see Equation 2).

Note from Equation 1 that greater values of the BESR give rise to greater ball exit speeds. Therefore, the BESR is a measure of the "liveliness" of the ball-bat collision and it includes, for example, any "trampoline" effect that the nonwood bat may display (due to its barrel being temporarily deformed by the ball during the collision).

Where does the BESR get its name?

When one algebraically solves Equation 1 for the BESR the result is

$$\text{BESR} = \frac{V_{\text{ball exit}} + \frac{1}{2}\left(V_{\text{pitch}} - V_{\text{bat}}\right)}{V_{\text{pitch}} + V_{\text{bat}}} \qquad (2)$$

When the speeds of the pitched ball and bat are the same ($V_{\text{pitch}} = V_{\text{bat}}$), Equation 2 becomes

$$\text{BESR} = \frac{V_{\text{ball exit}}}{V_{\text{pitch}} + V_{\text{bat}}}$$

We see in this case that the BESR is equal to the ratio of the ball exit speed $V_{\text{ball exit}}$ to the relative speed ($V_{\text{pitch}} + V_{\text{bat}}$) of the pitched ball and bat before the collision. Hence, the name "Ball Exit Speed Ratio."

How does the BESR Depend on the Properties of the Ball and Bat?

Figure 2 illustrates a ball just before colliding with the bat. The bat is assumed to be clamped in a hitting machine and is free to rotate in the plane of the paper about the pivot point.

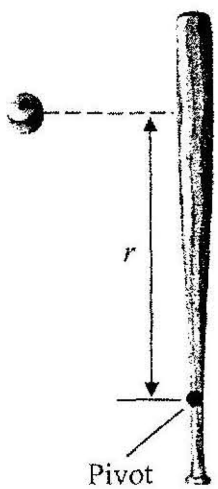


Figure 2 The bat pivot point and the distance r from the pivot point to where the ball collides with the bat.

The physics of the collision is described by applying the law of conservation of angular momentum to the ball-bat interaction. When this law is used, along with the definition of the coefficient of restitution (see below), we arrive at Equation 1, where the BESR is given in terms of the properties of the ball and bat as[1,2,3]

$$\text{BESR} = \frac{e + \frac{1}{2}\left(1 - \frac{mr^2}{I_p}\right)}{1 + \frac{mr^2}{I_p}} \tag{3}$$

where

e = coefficient of restitution of the ball-bat collision. The coefficient of restitution is defined as the ratio of the relative speed of the ball and bat after the collision to that before the collision. Suppose that, before the collision, the ball and bat are moving toward each other with a relative speed of 160 mph. Suppose, further, that after the collision the ball and bat are moving with a relative speed of 80 mph. Then the coefficient of restitution of the ball-bat collision is (80 mph)/(160 mph) = 0.5.

m = mass of the ball.

r = distance from the pivot point to where the ball hits the bat (see Figure 2).

I_p = moment of inertia of the bat about the pivot point. This parameter depends on the mass of the bat as well as how the mass is distributed relative to the pivot point. The more the mass is concentrated away from the pivot point, the larger is the moment of inertia.

Note that the BESR depends on the properties of the ball (m), the bat (I_p), and the ball-bat collision (e and r).

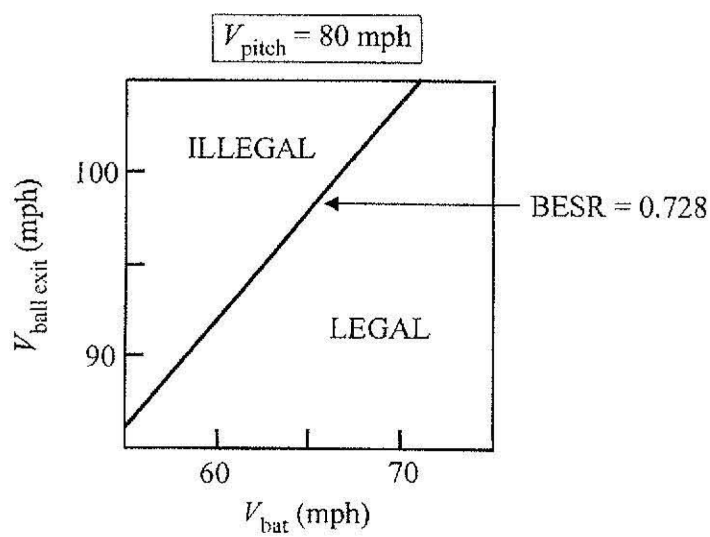
Why Use The BESR Rather Than Specify a Ball Exit Speed?

In general, different bat testing laboratories use different types of hitting machines: (1) the pitched ball is moving and the bat is initially stationary, (2) the ball is stationary and the bat is initially moving, and (3) both the pitched ball and bat are initially moving. Even if each type of hitting machine is set up to have the same relative speed ($V_{pitch} + V_{bat}$) of the pitched ball and bat, the ball exit speeds will be different. However, all types of machines will give the same value for the BESR. This result, while not obvious, is a direct consequence of Equation 1.

What Is The Maximum Allowed Value For The BESR?

When bats were first tested in 1999, an initial lot of baseballs was used. The tests were conducted by using a pitch speed of 70 mph and a bat speed (at a point 6 inches from the end of the barrel) of 66 mph. Under these conditions, the best major league wood bat yielded a BESR of 0.728, which the NCAA then set to be the maximum allowed value.

The graph below shows a plot of ball exit speed ($V_{ball\ exit}$) versus bat speed (V_{bat}) for the case when the pitch speed is V_{pitch} = 80 mph. The straight line represents Equation 1 in which the BESR has been set to the legal limit of 0.728. Any bat that gives rise to a ball exit speed at or below this line is legal. Likewise, any bat that produces a ball exit speed above this line is illegal.



Subsequent tests on nonwood bats used different lots of new baseballs. Because the properties of balls differ from lot to lot, even when they are stored and used in a humidity-controlled room, the BESR is adjusted to account for these differences. Therefore, the maximum allowed value for the BESR changes slightly, depending on the particular lot of baseballs used in testing a given nonwood bat. However, in every case, the BESR of the nonwood bat is always compared with that of major league wood bats tested in the same machine with the same lot of baseballs under standardized ball-bat testing conditions.

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[1] M. M. Carroll, "Assessment and regulation of baseball bat performance," *Symposium on Trends in the Application of Mathematics to Mechanics*, edited by P. E. O'Donoghue and J. N. Flavin (Elsevier, Amsterdam, 2000), p. 17.

[2] A. M. Nathan, "Dynamics of the baseball-bat collision," Am. J. Phys. **68**, 979–990 (2000).

[3] A. M. Nathan, "Characterizing the performance of baseball bats," Am. J. Phys. **71** (2), 134–143 (February 2003).

A White Paper on

Bat and Ball Test Methods and Performance Characteristics

Presented to the

Amateur Softball Association

By

Lloyd Smith, Ph.D., P.E.

Sports Science Laboratory
School of Mechanical and Materials Engineering
Washington State University, Pullman, WA

www.mme.wsu.edu/~ssl

Summer 2007

1. Introduction

Technology has had a large effect on the game of softball. In general, equipment performs better and is more reliable than it was just a few years ago. To maintain the integrity of the game, test methods have been developed to regulate some of the technologies used in play. The following will consider the characteristics and test methods of balls and bats.

From the invention of the game in 1887 by George Hancock[1] until the 1970's, all softball bats were made of wood. Aluminum bats were introduced to improve durability. It was soon discovered, however, that some hollow bats could hit a ball further than wood. Bat design and material development have continued at a brisk pace. The technology has benefited the offense and done little for defense. This shift in the nature of the game brought into question the benefits of the new bats. In the late 1990's, ASA began to investigate test methods that could be used to regulate bat performance. In 2000 ASA adopted a bat performance test which is described in ASTM F1890. After only a few years the short comings of this test became apparent. An improved method was implemented in 2004 as described in ASTM F2219. While this method was originally drafted for baseball, its development had languished. Field studies and research supported by ASA have helped make this method the state of the art which is being adopted by other major amateur associations.

As occurred with the bat, the ball has also evolved since the inception of the game of softball. The first ball used to play the game was a boxing glove with the laces tied up. Small medicine balls were also used in early versions of the game. The ball has evolved a number of times over the years in size and material, including kapok, rubber and cork. Today most softballs are made from a polyurethane core with a thin leather or synthetic cover. The formulation of the polyurethane is relatively advanced where ball hardness (ASTM F1888) and elasticity (ASTM F1887) are controlled independently. These features interact with the performance of the bat in a complex way. Thus, their accurate control is essential toward reliable performance regulation.

The following will review bat and ball test methods and characteristics relevant to regulating performance.

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[1] Sullivan, G. The Complete Guide to Softball. Fleet Publishing Corporation, New York. 1965.

2. Ball COR

The coefficient of restitution (or COR) is a measure of the energy that is lost during impact. Balls with higher COR will be more lively in play. While it is close to 0.5 for most softballs, it can range from 1 (no energy lost) to 0 (all energy lost).

The ball coefficient of restitution (or *COR*) is a measure of the energy that is dissipated from impact with a rigid surface. It is defined as the ratio of the rebound speed (v_r) to the incoming speed (v_i) as

$$COR = \frac{v_r}{v_i}. \tag{2.1}$$

A ball that lost no energy from an impact (v_r=v_i) would have a *COR* of one, while a ball that lost all of its energy from an impact (v_r=0) would have a *COR* of zero.

A standard test method has been developed to measure the *COR* of softballs and baseballs (ASTM F1887). In this method a ball is pitched at 60 mph toward a steel plate mounted to a massive, rigid wall, as shown in Fig. 2.1. An image showing a ball impacting a flat plate is shown in Fig.2.2. The test is repeated six times, from which the average *COR* value is reported for each ball tested. A softball *COR* of 0.44 is perhaps the most common, but can be as high as 0.47 and as low as 0.40. (For comparison, the *COR* of baseballs is generally higher than softballs, exceeding 0.50.)

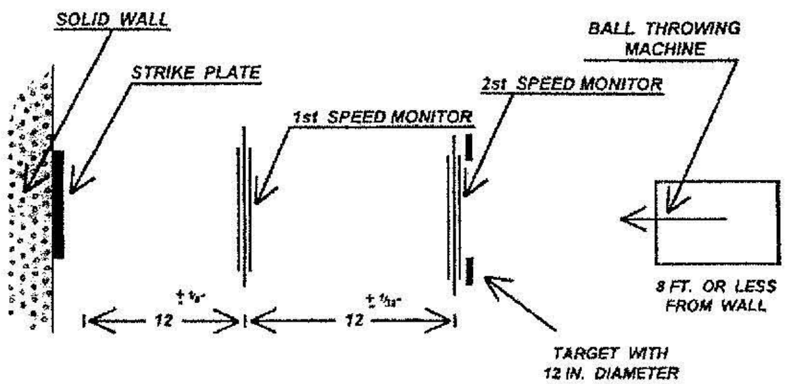

Fig. 2.1. Diagrams of ball COR test apparatus.

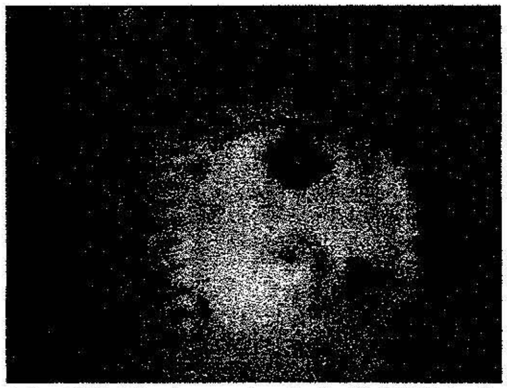

Fig. 2.2. Photograph of a ball COR test.

To describe the energy that is dissipated, consider a ball impacting a massive and rigid wall as described above. The ball *COR* is related to the fraction of dissipated energy, *de*, according to

$$de = 1 - COR^2. \tag{2.2}$$

This means that a typical 0.44 *COR* softball losses 80% of its initial energy upon impact with a rigid wall.

While laboratory tests have been developed to reliably and repeatably measure ball *COR*, it should not be considered constant in the field, outside of laboratory conditions. In general, environments that increase ball deformation will reduce ball *COR*. Softballs become softer with increased temperature and humidity, for instance. These effects would tend to lower the ball *COR*. The same could be said for increased speed (Fig. 2.3) or impacting a cylinder (a bat as apposed to a flat surface). The ball *COR* should, therefore, be viewed as a useful measure to compare the liveliness of balls and not as an absolute measure of energy dissipated in a bat-ball collision.

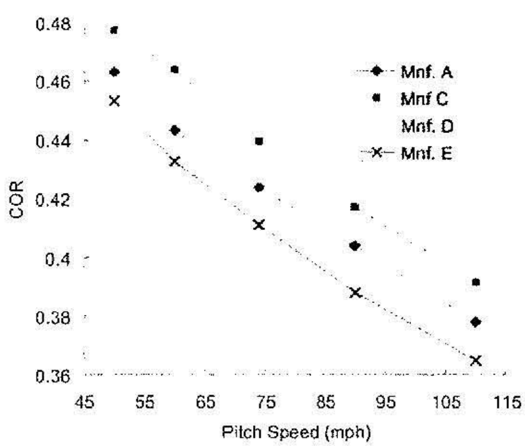

Fig. 2.3. Ball COR as a function of pitch speed.

Ball conditioning has become a topic of interest recently. In standardized tests balls are typically conditioned to 50% relative humidity (RH) at 72°F. Balls will reach ambient temperature relatively quickly, on the order of a few minutes. Reaching ambient humidity can take considerably longer (two weeks), however, as shown in Fig. 2.4.

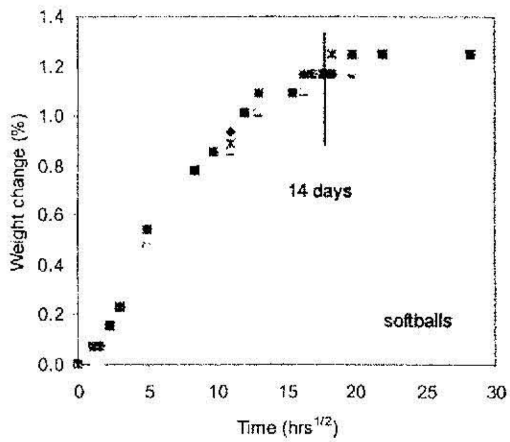

Fig. 2.4. Softball weight change conditioning to 50% RH as a function of time.

3. Ball Compression

Ball compression describes the hardness of the ball. It affects the performance of hollow bats, which increases with compression. The performance of solid wood bats is relatively insensitive to compression.

Ball compression is a measure of a ball's hardness. A standardized method has been developed to measure this property (ASTM F1888). The test apparatus is depicted in Fig. 3.1. The test involves measuring the force to displace a ball 0.25 inches in 15 seconds between two steel flat platens. The ball is compressed twice, once along each "ear" axis. The compression for a ball is reported from the average of these two readings.

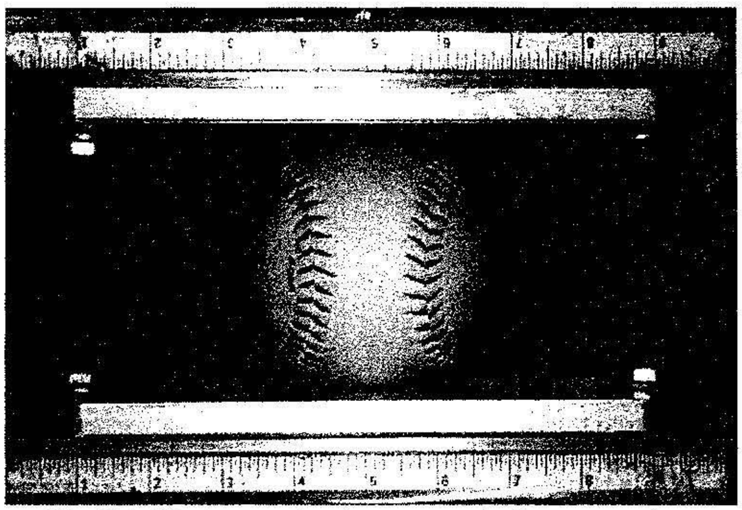

Fig. 3.1. Test apparatus to measure ball compression.

Ball compression decreases with increasing humidity and temperature. Laboratory tests are, therefore, conducted at 72°F on balls that have been conditioned at 50% RH.

The interest in ball compression is related to the so-called "trampoline effect" observed in thin-walled hollow bats[2]. The barrel of a hollow bat will deform during impact with a ball on the order of 0.125 inches. The barrel deformation is nearly elastic, returning most of its energy to the rebound speed of the ball. Recall that ball *COR* is measured from an impact with a rigid surface, and that energy loss increases with ball deformation. Now consider two balls of the same *COR* but made in a way that they have different hardness (or compression). Next allow these two balls to impact the same hollow bat. Upon impact the harder ball will produce more barrel deformation and consequently less ball deformation than the softer ball. Essentially the harder ball exchanges some of its ball deformation (which dissipates energy) with barrel deformation (which does not dissipate energy). It is for this reason that the batted ball speed generally increases with increased ball hardness and decreased barrel hardness. Note that the trampoline effect is negligible

[2] 1 athan, A. M., 5ussell, D. A., 6P ith, L., 2004, "The Physics of the Trampoline Effect in Baseball and Softball Bats," The Engineering of 6Sort 5th fnternational Conference, s ol 2, pp. P8-44, a avis, CA.

for bats with very stiff barrels. These may include hollow bats with thick walls or solid wood bats.

Because of the simple nature of this test, ball compression is used to compare the hardness of many types of balls. Some have noted that since the compression of a softball is larger than that of a baseball, softballs are not "soft." Comparing the compression of balls of different diameter suggests a misunderstanding of the method and an incorrect application of the result.

To illustrate the effect of diameter on ball compression, consider an 11 and a 12 inch circumference softball ball made from the same material. Now consider their contact area with the loading platen after 0.25 inches of displacement. The contact areas would be approximately 1.33 and 1.45 in^2 for the 11 and 12 inch ball, respectively (a larger ball produces a larger contact area). The spherical shape of the ball means that most of the deformation will be concentrated near the platen (increasing ball diameter away from the platen results in less deformation toward the ball center). This means that the pressure over the contact areas for the two balls will be similar. The ball compression is the product of the pressure and the contact area. For this idealized case, one would expect the compression of the 12 inch ball to be 9% higher than the 11 inch ball, even though they are made of the same material. For the 12 inch ball to be truly harder than the 11 inch ball, its compression would need to be more than 9% higher than the 11 inch ball. (This comparison was actually done, and the average compression from 60 balls was 11% higher for the 12 inch ball.)

4. Dynamic Stiffness

Dynamic stiffness is a measure of ball hardness, similar to compression. It is done against a cylindrical surface at a high rate of speed to simulate a bat impact. Test results show it correlates better with bat performance than compression.

In the compression test discussed above, one may observe that the 0.25 inches of displacement is applied diametrically, and produces only 0.125 inches of radial displacement. The ball can displace radially nearly one inch in a bat-ball collision, as shown in Fig. 4.1. The rate of deformation in the compression test is also much slower than occurs in a bat-ball collision (four orders of magnitude, or 10,000 times slower). This difference in the rate and magnitude of ball deformation limit the ability of ball compression to describe ball response in a bat-ball impact.

A test, depicted in Fig. 4.2, has been developed to better approximate the rate and magnitude of ball deformation occurring in a bat impact[3]. The test configuration is similar to that used to measure ball *COR* (Fig. 2.1). The displacement of the ball is comparable to the bat as shown in Fig. 4.3. An essential difference is that the impact surface is cylindrical (intended to approximate the bat) and load cells are used to measure the impact force. Ball *COR* can be obtained from this test, but it is lower than the standard ball *COR*. The lower *COR* value is due to the higher impact speed and the cylindrical impact surface. These tend to increase ball deformation which reduce ball *COR*. It is designated as *CCOR* to distinguish it from the standard measure of ball *COR*.

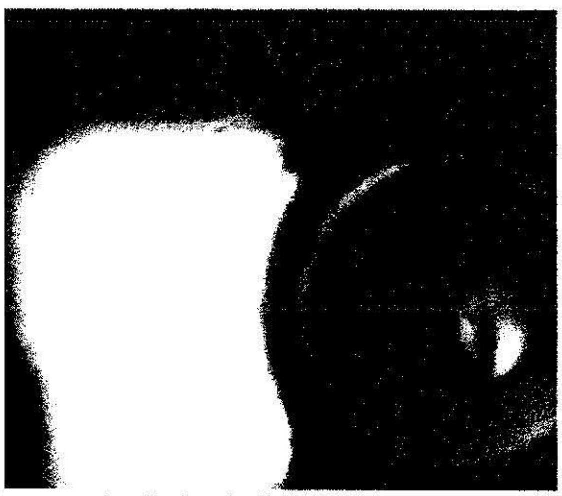

Fig. 4.1. Photograph of a bat-ball impact at maximum displacement

[3] Duris, J., Smith, L. V., 2004, "Evaluating Test Methods Used to Characterize Softballs," The Engineering of Sport 5th International Conference, Vol. 2, pp. 80-86, Davis, CA.

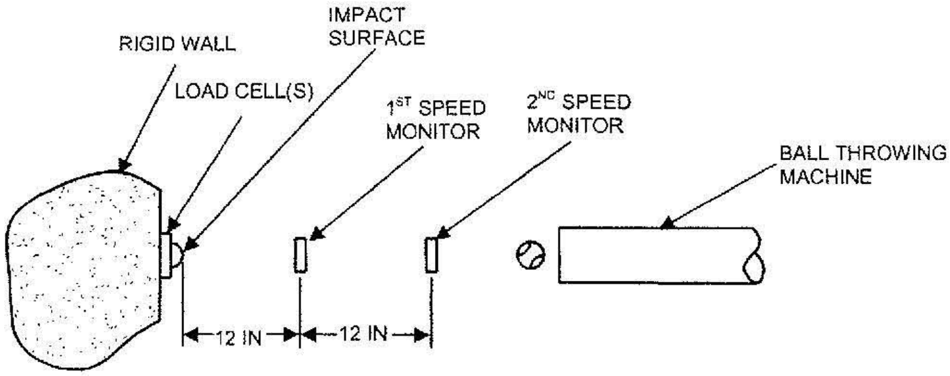

Fig. 4.2. Schematic of dynamic stiffness test apparatus.

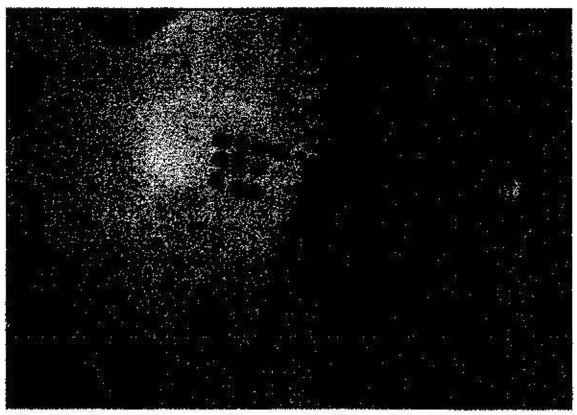

Fig. 4.3. Photograph of a ball impacting a rigid cylinder in a dynamic stiffness test.

Upon impact of the ball with the rigid cylinder, the load cells record the impact force as a function of time, Fig. 4.4. Knowing the incident ball speed, v_i, and weight, m, the stiffness of the ball, k, may found from the peak impact force, F as

$$k = \frac{1}{m}\left(\frac{F}{v_i}\right)^2. \tag{4.1}$$

The expression is obtained by equating the known kinetic energy of the incoming ball ($\frac{1}{2}mv^2$) with its stored potential energy at maximum displacement ($\frac{1}{2}kx^2$). The unknown ball displacement, x, is obtained from the peak impact force assuming the ball behaves as a linear spring ($F=kx$). This leaves only one unknown, k, representing the ball stiffness, Eq. (4.1).

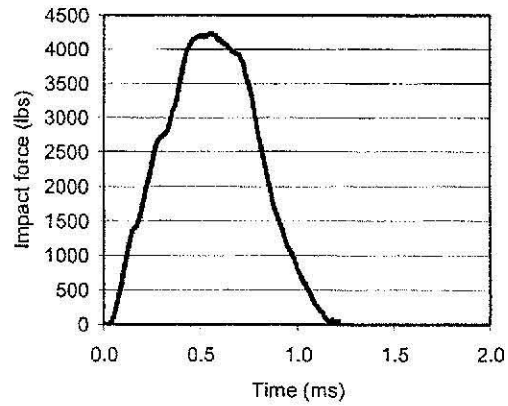

Fig. 4.4. Representative impact force reading during dynamic stiffness test.

A potential shortcoming of this approach is the assumption that the ball deforms as a linear spring. The accuracy of this assumption may be tested by examining a plot of the ball force-displacement during impact. Unfortunately the nature of the ball impact is unsuitable for a direct measure of ball displacement. An indirect measure of ball displacement can be obtained by integrating its acceleration twice. The acceleration, in turn, is found by dividing the impact force by the ball mass. A representative example of the ball force-displacement curve is presented in Fig. 4.5, which shows a relatively linear response during the loading phase. (Hysteresis and non-linearity during the unloading phase determine the energy loss and *CCOR*, but do not affect the linear spring assumption associated with the loading phase.)

The dynamic stiffness from a large group (12 dozen) of ASA 44/375 balls ranged between 6000 and 8000 lb/in while the *CCOR* ranged from 0.35 to 0.38.

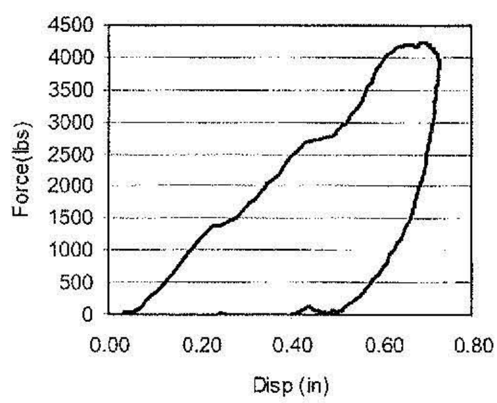

Fig. 4.5. Representative ball force-displacement curve during a dynamic stiffness test.

The dynamic stiffness test was developed to describe both the deformation rate and magnitude of a bat-ball impact. A relatively wide range of impact speeds would approximate the deformation rate reasonably well. To capture the deformation magnitude, however, the impact speed must be chosen more carefully. One might ask: at what speed should a rigid cylinder be impacted to simulate an impact with a recoiling bat? One plausible answer would be the speed where the impulse is the same for the two cases. Impulse is the area under the curve in Fig. 4.4, and is the momentum change at impact producing the rebound ball speed. Another plausible answer would be the speed where the ball deformation is the same for the two cases. A relation between the recoiling, v_r, and fixed, v_f, cases can be found as

$$\frac{v_r}{v_f} = (1+k)^n \tag{4.2}$$

where $k=mQ^2/I$, and the exponent, n, is unity for constant impulse and ½ for constant deformation. (The other terms will be discussed in more detail later. For completeness, Q is the distance from the bat pivot to the impact location and I is the mass moment of inertia of the bat about the pivot point or *MOI*.) The constant deformation case correlates better with experimental measurements.

The test speed will depend on the impact location, Q, and bat *MOI*. For a recoiling bat speed of 110 mph, this produces a test speed of 90 mph (light bat with an outside impact) to 100 mph (heavy bat with an inside impact). The test speed was selected as 95 mph to average between these extreme cases. In the test, the cylinder is impacted 6 times, from which the average dynamic stiffness is reported.

5. Balance Point

The balance point is the location on a bat where it may be supported and balance. It is needed to find the mass moment of inertia of the bat (MOI).

The balance point, center of gravity, or center of mass are terms used to describe a location on the bat where all of the mass would be concentrated if the bat had no volume. While it is often close to the geometric center of the bat, it does not have to be. The bat would lie horizontally balanced if it were supported only at its balance point. The location is reported in reference to either the knob end of the bat or the pivot point. The pivot point is 6 inches from the knob and will be described in more detail below.

The balance point can be readily found by balancing the bat on your finger. In this way one can observe the effect of knob or end loaded bats. A laboratory test, depicted in Fig. 5.1, provides a more accurate and repeatable measure of the balance point. The method is described in detail in ASTM F2398. The bat is placed in a fixture with supports that are 6 inches and 24 inches from the knob. The supports are placed on two scales. The weight from these scales (minus the weight of the fixture) W_6, and W_{24}, are used to find the balance point, BP, according to

$$BP = \frac{6W_6 + 24W_{24}}{W_6 + W_{24}}, \tag{5.1}$$

where BP is with respect to the knob end of the bat. The balance point of a 34 inch long bat will typically be between 24 and 28 inches from the knob.

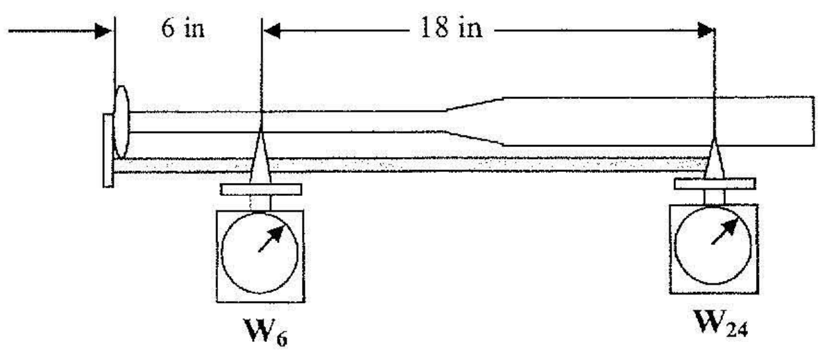

Fig. 5.1. Schematic of laboratory fixture to measure balance point of a bat.

6. Center of Percussion

The center of percussion is the impact location which produces no reaction force at the pivot. It is only by coincidence that the COP is often located near the so-called "sweet spot" of the bat. While early bat performance tests prescribed impacts at the COP, modern methods do not use the COP.

The center of percussion (or *COP*) of a bat is the impact location that produces no reaction force at the pivot point. It may be distinguished from the balance point with a simple test (a kick). If a bat placed on the floor is kicked at its balance point, it will move forward, but not rotate in the plane of the floor (although it may roll about its long axis). If the same bat (still on the floor) is kicked at its *COP*, it will tend to rotate about the pivot point conjugate to the impact location. In bat testing, the pivot point from which the *COP* is defined, is usually 6 inches from the knob. (The pivot point, however, may be defined at any location of interest along the length of the bat.)

A bat impact is often cited as an example to explain the *COP*. It is argued that when a ball strikes the *COP*, the hands feel no reaction force, providing the so called "sweet spot." The sting a player feels in the hands from a poorly hit ball is due to bat vibration, not a reaction force, however. It is only a coincidence that the *COP* of a bat is often close to the location that minimizes bat vibration. In spite of experimental and theoretical evidence supporting the independence of the *COP* and sweet spot, some maintain its significance. ASTM F1890, for instance, measures bat performance at the *COP* which is reported as *BPF* (described below). The *COP*, relative to the pivot point, is found from

$$COP = g\left(\frac{t}{2\pi}\right)^2 \tag{6.1}$$

where t is the average period (in seconds) of the bat swinging freely about its pivot point (Fig. 6.1), and g is the gravitational constant (386 in/s^2). A detailed method describing how the *COP* is measured can be found in ASTM F2398. The *COP* will typically lie between 21 and 22 inches from the pivot point of a 34 inch long bat.

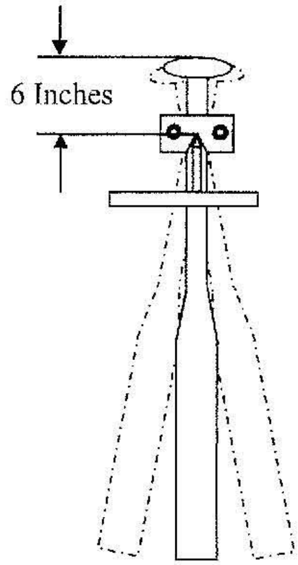

Fig. 6.1 Schematic of bat swinging freely about its pivot point.

7. Mass Moment of Inertia

The mass moment of inertia (MOI) is a measure of the distribution of mass in the bat. A knob and end loaded bat may weigh the same, for instance, but the end loaded bat will have a higher MOI. Bat speed depends on MOI, and is an important component of the ASA performance test.

Another (and important) mass property of a bat is denoted the mass moment of inertia (or *MOI*). It describes the distribution of the mass of a bat. Consider, for instance, a knob and end loaded bat of the same total mass. The end loaded bat will feel heavier when rotated about its pivot point or when swung. As with the *COP*, the *MOI* is found from its average period, t, obtained while swinging freely about a pivot point 6 inches from the knob, as

$$MOI = gW(BP - 6)\left(\frac{t}{2\pi}\right)^2 \qquad (7.1)$$

where W is the total weight of the bat (ounces), g is again the acceleration of gravity (386 in/s^2) and BP is the balance point described above, measured with respect to the knob. The units of *MOI* are unusual (oz in^2), and are indicative of its description of the distribution of mass. The *MOI* described above is taken about a location 6 inches from the knob[4]. The *MOI* of 34 inch slowpitch bats will typically range between 7,000 and 10,000 oz in^2. Fastpitch bats are usually lighter and shorter which lowers their *MOI*, in some cases approaching 5,000 oz in^2.

[4] Sometimes MOI is reported with respect to the knob. Thus when comparing bat MOI, it is important to note the reference location. Bat MOI can change dramatically with the reference location due to its dependence on distance squared. Bat MOI at the knob, for instance, will be approximately 50% larger than MOI 6 inches from the knob.

8. Swing Speed

Swing speed refers to the effect that bat weight (or MOI) has on the speed a bat may be swung in play. It plays an important role in determining bat performance and must be found empirically.

It is readily understood that increasing a bat's weight will lower its swing speed. It is not obvious, however, how much a given change in bat weight will change the swing speed. First one must determine which measure(s) of weight affect swing speed. There appears to be three schools of thought: bat weight, bat *MOI*, or a combination of the weight and *MOI*[5-8]. Bat performance, as measured by the ASA, is influenced by the swing speed. For this reason ASA has conducted four field studies to better understand swing speed in the slowpitch (SP) and fastpitch (FP) game. The results of two of these studies (15 men and 36 women) will be reviewed below[9].

The swing speed field studies were designed using single-walled aluminum bats that were carefully weighted. Modern multi-wall and composite bats were not included in these studies. Modern bats provide enhanced performance and feel, but do not appreciably depart from the weight properties and swing speeds of single-walled aluminum bats. (The performance of modern bat design was observed in separate field studies.) Two groups of bats (SP and FP) had constant *MOI*, but varied in weight. Two other groups of bats had constant weight, but varied in *MOI*. A comparison of the bats used in the field studies is shown in Fig. 8.1.

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[5] S. Plagenhoef, Patterns of Human Motion, Prentice-Hall, New Jersey (1971).

[6] G. S. Fleisig, N. Zheng, D. Stodden, and J. R. Andrews. Sports Engineering, 5:1-8 (2002).

[7] J. J. Crisco, R. M. Greenwald, L. H. Penna, and K.R. Saul, The Engineering of Sport, Blackwell Science, A. J. Subic and S. J. Haake, eds. 193-200 (2000).

[8] K. Koenig, T. Hannigan, N. Davis, M. Hillhouse, L, Spencer, NCAA Research Program on Bat and Ball Performance, Final Report, Providence, RI, 88-100 (1997).

[9] Smith, L. V., Broker, J., Nathan, A., 2003. "A Study of Softball Player Swing Speed," Sports Dynamics Discovery and Application, Subic, Trivailo, Alam, eds., pp. 12-17, Melbourne, Australia.

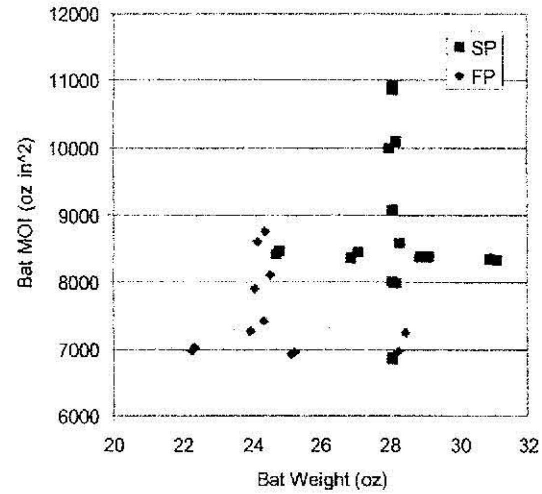

Fig. 8.1. A comparison of bat weight and *MOI* of the swing speed field study bats.

Measuring swing speed is a challenging experimental task. A number of approaches have been employed and were considered including tethered sensors, radar, and light gates. A measurement was desired that would be minimally intrusive to the batter, yet accurately describe the swing speed. The studies were to be conducted in daylight on an outdoor playing field with a live pitch. This ruled out infrared cameras which are routinely used in batting cages with controlled artificial lighting. It also made light gates unsuitable as the bat-ball impact location varied widely with the batter and pitch. Optical high speed video cameras were found to have a sufficient field of view and resolution to track the swing speed, and were selected (Fig.8.2). They were placed above the batter so the batter's natural swing was not impeded. Fiducial marks were placed on the bats which were subsequently tracked (frame by frame) in the video (Fig. 8.3). The bat's center of rotation and rotational speed were extrapolated from the marker velocity vectors[10].

[10] It should be noted that the motion of any object that has translational and rotational components of motion can be described by an instantaneous center of rotation. An object in pure rotation will rotate about its center. An object that is mostly in translation with have a center of rotation located far from it. The location of the instantaneous center of rotation will move as the magnitudes of rotation and translation change to describe the object's motion in space.

Fig. 8.2. Women's fast pitch field study. Note two high speed cameras mounted on scissor jack above batter.

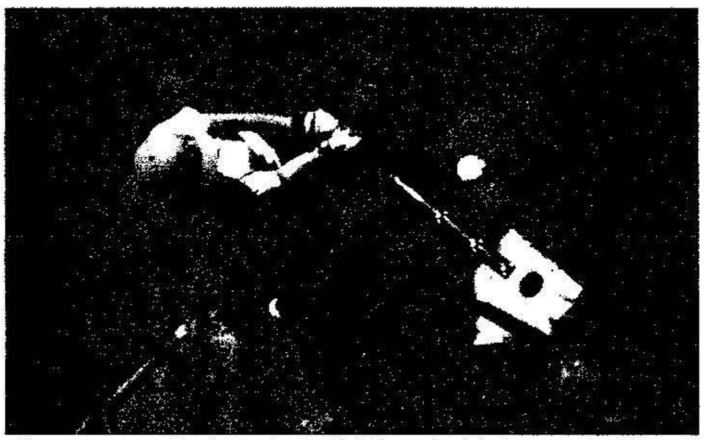

Fig. 8.3. Image from women's fast pitch field study high speed video showing fiducial marks that were tracked to find swing speed.

The center of rotation of the bat during impact was found to lie close to the center of the batter's wrists. In the men's slow pitch study the bat was often gripped at the knob. This resulted in a center of rotation a few inches off of the bat, away from the knob. In the fast pitch study, the women tended to grip the bat on its handle. Accordingly, the center of rotation was a few inches in from the knob. The average centers of rotation are depicted graphically in Fig. 8.4.

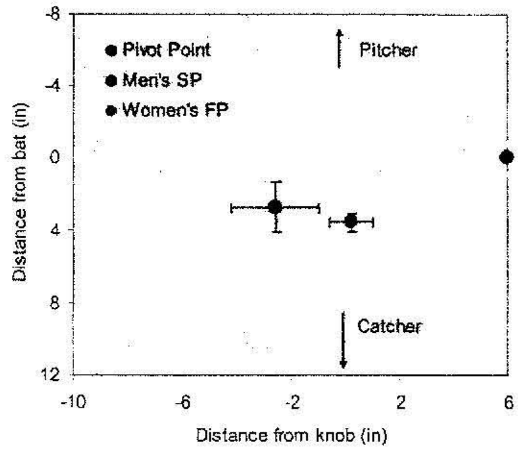

Fig. 8.4. Average instantaneous center of rotation from fastpitch and slowpitch field studies.

To compare the effect of weight and *MOI*, the ratio of swing speed to the average swing speed of each player was used, allowing the data of all batters to be averaged, independent of the batter's ability. (The effect of player ability on swing speed, independent of bat weight, was considered separately.) Swing speed is shown as a function of bat *MOI* and bat weight in Figs. 8.5 and 8.6, respectively. The effect of bat *MOI* was dramatic, while the effect of bat weight was clearly less.

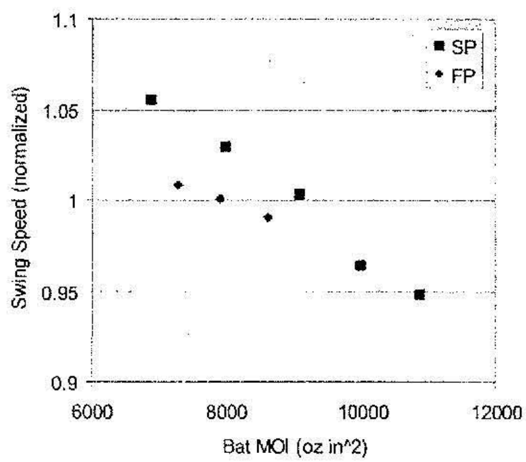

Fig. 8.5. Normalized swing speed as a function of bat MOI.

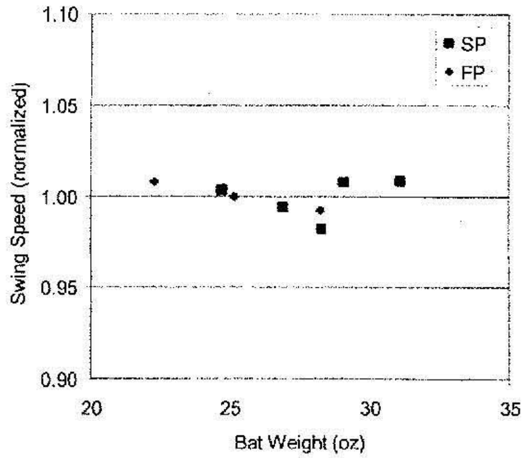

Fig. 8.6. Normalized swing speed as a function of bat weight.

To provide some insight of the effect of *MOI* on swing speed, an idealized model comparing the rotational swing speeds of two bats, ω_1 and ω_2, having different *MOI*, I_1 and I_2, can be found as

$$\omega_2 = \omega_1 \left(\frac{I_1}{I_2} \right)^n \tag{8.1}$$

The exponent, n, represents different assumptions allowing the idealized comparison. According to the various models, the exponent can vary from 0 to 1. An exponent of 0 indicates that speed is constant and not affected by *MOI*. An exponent of 1/3 assumes the batter has a constant power output. An exponent of ½ assumes the batter generates the same bat kinetic energy as *MOI* varies. An exponent of 1 assumes the angular momentum of the bat does not change as its *MOI* varies. Unfortunately our understanding of the human body does not direct us toward any of these assumptions. It is for this reason that the field studies were conducted. One might expect, however, that an exponent of 0 would be too small, while an exponent of 1 would be too large. Not surprisingly, results from the field studies showed that the exponent varied widely between batters. A consistent trend was not observed, however, between the exponent and player strength or size. It is possible that it was related to technique, but this was not considered. The average exponent was found to be 0.25 and 0.20 for the men's slowpitch and women's fastpitch field studies, respectively. The exponent from the men's slow pitch study was incorporated into the ASA bat performance test which is described below.

The field studies were also used to compare the magnitude of the swing speed. The men's slow pitch considered A and D batters from the 2002 National Championship, while the women's fast pitch study considered NCAA Division 1, 2, 3, high school, and Olympic players from the 2004 National Championship. Both studies involved 34 inch long bats. Results of these groups are presented in Figs. 8.7 and 8.8, where the swing speed was reported at 6 inches from the end of the bat.

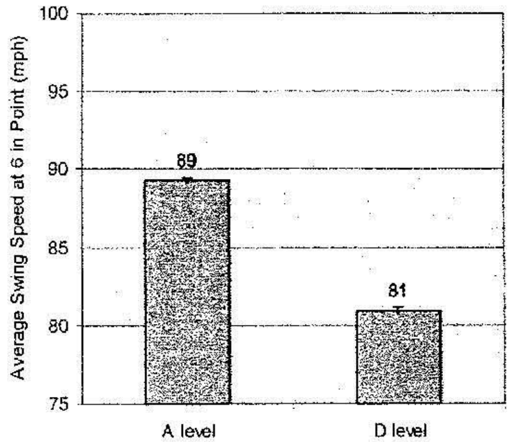

Fig. 8.7. Average men's A and D level slow pitch swing speed.

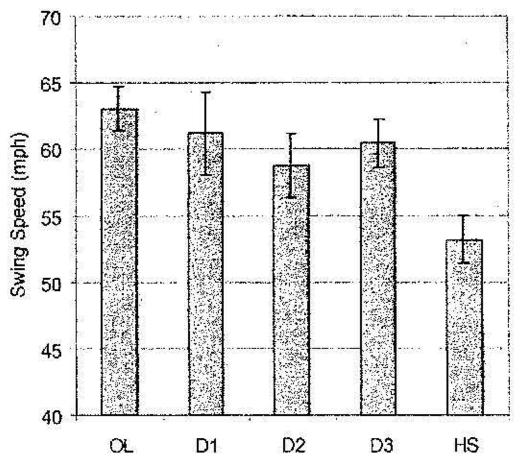

Fig. 8.8. Average women's Olympic, College, and high school swing speed.

9. Bat Performance Test

The bat performance test measures the bat and ball speeds before and after impact in a controlled laboratory setting. The test may be configured in a variety of ways, although two similar methods involving an initially stationary bat are the most common. (The speeds measured in the test can be used in a variety of ways to quantify bat performance as described in the following section.)

A number of devices have been implemented over the years to measure the performance of a bat. Nearly all involve a bat that pivots about a fixed point. While the motion of a bat in play involves translation and rotation, the laboratory fixed pivot point turns out to be a very good approximation to the field situation. To accurately describe the field performance of a bat in the laboratory, one needs to approximate the motion of the bat only during the instant it is in contact with the ball (approximately 0.001 seconds). Two consequences of this short duration greatly simply the experimental requirements. First, the motion of any object at any instant can be described by an instantaneous center of rotation. The location of the center, as well as the speed, may change over time. During the 0.001 second bat-ball contact, it is essentially stationary. Second, the bat-ball contact is sufficiently short that the pivot conditions do not affect the bat at the impact location. In other words, during the 1 ms bat-ball contact, the bat deformation is sufficiently small (the barrel moves less than ½ inch) that the impact location is unaffected by the constraint at the pivot.

The most complex machines used to test bats involve a swinging bat and a pitched ball[11]. This type of device must not only accurately position the bat and ball, it must also time the delivery of both to achieve the desired trajectory. The NCAA used this type of machine to test bats until 2005[12].

A simpler and more common approach to bat testing involves an initially stationary bat or ball. To the lay observer these tests do not appear to describe the motion they were intended to simulate. A simple example can show otherwise. Imagine you are in the belly of a World War II bomber looking at the ground through the bomber's site glass. Imagine further that you are traveling over a ball field in a direction from the pitcher to the catcher. Now imagine what you would see (from the bomber's perspective) if you were directly over the pitcher at the instant the ball was thrown and traveling at the ball pitch speed. From the plane's perspective it would appear as if the ball were stationary before it hit the bat. The speed of the bat and ball (before and after impact) can be correlated in this way with an observer in the plane. In the laboratory the reverse must also be true. That is, an initially stationary bat or ball can be correlated with field conditionings by knowing the respective bat or pitch speed.

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[11] Smith, L. V., Axtell, J. T., 2003. "Mechanical Testing of Baseball Bats," *Journal of Testing and Evaluation*, 31.3:210-214.

[12] Sherwood, J.A., Mustone, T.J., and Fallon, L.P., 2000, "Characterizing the Performance of Baseball Bats using Experimental and Finite Element Methods," Proceedings of the 3rd International Conference on the Engineering of Sport, June, Sydney, Australia

While it is possible to construct a machine involving a swinging bat and an initially stationary ball, they are generally more complex than a machine involving an initially stationary bat. As shown in the preceding example, the bat must travel at the relative bat-ball speed. For softball this is 110 to 120 mph, while for baseball it is over 140 mph. Many bats will break if they are accelerated from 0 to 140 mph in one revolution. Some devices use multiple revolutions to accelerate the bat. If this is done, the delivery of the ball must be timed as it is brought into the path of the bat. The speed of the batted ball also poses challenges for initially stationary ball machines. The batted ball speed will approach 200 mph, which complicates ball containment, speed measurement, and promotes ball damage.

Currently all certified bat performance tests involve an initially stationary bat, as depicted in Fig. 9.1. (Unfortunately, this is the only aspect that is common among the various associations regulating bat performance.) The balls are accelerated using an air cannon, and travel inside a "sabot." The sabot is sized to the cannon barrel which improves speed control, position accuracy, and prevents ball rotation. (The sabot remains inside the cannon and does not travel with the ball toward the bat.) After the ball exits the cannon, it passes through light gates which measure its incoming speed. After impact the speed of either the rebounding ball ("ball out" or ASTM F2219) or the recoiling bat ("bat out" or ASTM F1890) is measured. Angular momentum about the pivot is conserved during the bat-ball impact. It is easier and more accurate to measure two speeds and use angular momentum to find the third speed. The angular momentum balance of a bat-ball impact of a pivoted bat is

$$-mv_iQ + \frac{IV_i}{Q} = mv_rQ + \frac{IV_r}{Q}, \tag{9.1}$$

where m and v are the mass and speeds of the ball, respectively, I and V are the MOI and speeds of the bat, respectively, Q is the impact location relative to the pivot point, and the subscripts i and r refer to the inbound and rebound speeds, respectively. All speeds are taken as numerically positive. For the case of an initially stationary bat, V_i=0, so Eq. (9.1) may be readily solved for the unknown rebound ball or bat speed according to ASTM F1890 or ASTM F2219, respectively.

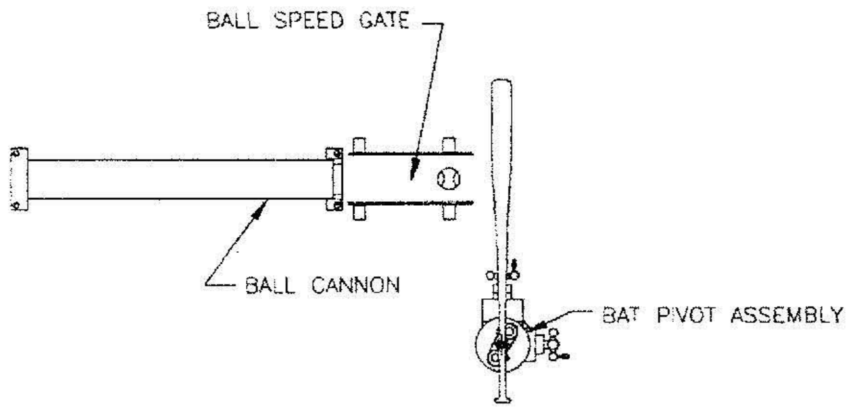

Fig. 9.1. Schematic of a bat test fixture involving an initially stationary bat.

While in principle the "ball out" and "bat out" methods described above appear identical, the following will show three reasons why the "ball out" measure is usually preferred. First, after impact the bat will vibrate as it rotates. The magnitude of the vibrations increase with impacts away from the sweet spot. The vibrations reduce the accuracy of the bat speed measurement. Second, "ball out" measurements tend to be self calibrating. Consider, for instance, light gates that are supposed to be 12 inches apart but are actually 11 inches apart. These gates will report a lower inbound and rebound speed, but their ratio will be correct. As will be shown below, the ratio of the ball speeds is used to determine bat performance, so error in the light gate spacing would cancel. Third, the constants in the angular momentum balance (Eq. 9.1) tend to amplify the "bat out" experimental error. To solve Eq. 9.1 for v_r, the measured quantity, V_r, is multiplied by I/mQ^2 which is approximately three. Conversely, to solve Eq. 9.1 for V_r, the measured quantity v_r is multiplied by mQ^2/I which is approximately 1/3. Given the same variation in measured v_r or V_r (all other factors equal), for a typical bat-ball impact, a "bat out" test would have approximately 4 times the variation as the "ball out" test.

In fairness, the "ball out" method has a distinct disadvantage. Light weight bats with low performance can have slow rebound ball speeds. In some cases it is not possible to get the ball to rebound through the light gates. Without a rebound ball speed, it is not possible to measure bat performance using "ball out." Fortunately these bats represent a relatively small portion of the market. They are also typically not close to the performance limit, so an accurate measure of bat performance is often not needed for this group of bats.

10. Bat Performance Measures

The following describes the common measures of bat performance: BPF, BESR and BBS. The ASA batted ball speed scale appears to be the most accurate and correlates well with field measurements.

Once a bat has been tested, the data may be used to measure performance in a variety of ways. While some measures have been shown to correlate with field performance better than others, the best measure ultimately depends on the objectives of the association regulating performance.

The Bat Performance Factor (or *BPF*) involves the bat-ball coefficient of restitution or *BBCOR*. Its definition is similar to that used for the ball (Eq. 2.1). We take the ratio of the relative speed after to before impact. For an initially stationary bat, V_i=0, this is

$$BBCOR = \frac{v_r + V_r}{v_i}. \tag{10.1}$$

We know that the *BBCOR* is influenced by the ball. Balls with a higher *COR*, for instance, should produce a higher *BBCOR*. This influence is limited by prescribing the type of ball used in the test. Variation in *COR* within a ball model can still affect the result, however. It is desirable to remove the effect of ball variation from the performance result. The *BPF* assumes a linear dependence of the *BBCOR* on the ball *COR* and is defined as

$$BPF = \frac{BBCOR}{COR}. \tag{10.2}$$

Recent experiments and models indicate that the dependence of *BBCOR* on ball *COR* is non-linear. Results show that the *BPF* over-corrects for ball *COR* in many cases. The *BBCOR* and *BPF* are compared in Fig. 10.1 for four bats as a function of test ball *COR*. The *BBCOR* is observed to increase with test ball *COR*. The *BPF* appears to adequately compensate for ball *COR* effects of the lower performing bats (A and B) and over-correct for ball *COR* for the higher performing bats (C and D). The different effect of *BPF* on high and low performing bats (as well as the high *BBCOR* of bats C and D with the 0.41 *COR* ball) is due to a dependence of *BBCOR* on the ball hardness. This interesting interplay is currently being studied. Little League, USSSA, and NSA use *BPF* to regulate bat performance.

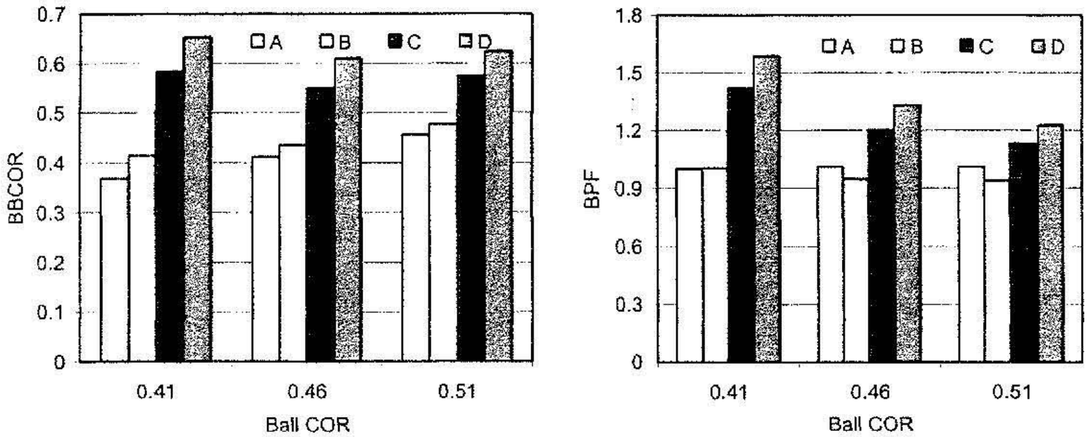

Fig. 10.1. Comparison of BBCOR and BPF from four bats as a function of test ball COR.

The Ball Exit Speed Ratio (or *BESR*) involves what has been called the collision efficiency, e_a. For an initially stationary bat it is defined as the ratio of the outgoing to incoming ball speeds as

$$e_a = \frac{v_r}{v_i}. \tag{10.3}$$

The collision efficiency is between 0.1 and 0.2 for many bats. The *BESR* is obtained by adding ½ to the collision efficiency. The NCAA and High School Federation use a modified *BESR* to regulate performance.

The batted ball speed (or *BBS*) is intended to represent the speed a ball would be hit in field conditions and is found according to

$$BBS = e_a v_p + (1 + e_a)V_b, \tag{10.4}$$

where v_p is the pitch speed, e_a is the collision efficiency and V_b is the bat speed (e_a and V_b are taken at the impact location). The ASA regulates the performance of its bats using the *BBS* based on nominal game conditions found from the slow pitch field study, where v_p=25 mph and V_b is found from

$$V_b = 85\left(\frac{Q+8.5}{30.5}\right)\left(\frac{9000}{I}\right)^{1/4}. \tag{10.5}$$

Equation 10.5 describes the linear speed of the bat at the impact location (in mph), while the analogous Eq. 8.1 describes the rotational speed of the bat (in rpm or rad/s). The nominal speed of 85 mph in Eq. 10.5 is the average of the A and D level players from the slow pitch field study (Fig. 8.7).[13] The additional terms in Eq. 10.5 account for the change in speed with impact location. The nominal 9000 oz in^2 was the average bat MOI in the slow pitch field study. The speed should be referenced to the bat's center of rotation in play. The impact location, Q, is taken at the test pivot point, 6 inches in from the knob. The field study found that the center of rotation is on average 2.5 inches out

[13] While this nominal bat speed has a large effect on the BBS, its primary significance is relative to the allowable BBS limit. If the nominal bat speed were 8Mmph, for instance, the BBS limit becomes 92.4 mph. Similarly, if the nominal bat speed was 9Mmph, the BBS limit becomes 1M.6 mph. In both cases the allowable field bat performance has not changed. We have only adjusted the scale used to compare performance.

from the knob. Thus, the speed is scaled by adding 8.5 to *Q* and dividing it by 22 + 8.5. Any bat certified for ASA play must have a *BBS* less than 98 mph. The ISF adopted this method in 2006, but uses a 100 mph *BBS* limit.

One may ask how ASA's approach to regulating bat performance (taken from the slow pitch game) applies to fast pitch softball. A 9,000 oz in^2 bat that just meets the 98 mph *BBS* limit at Q=22 inches will have e_a=0.12. In a fast pitch game where $v_p = V_b = 60$ mph, the *BBS* would be 74 mph. Said another way, a fast pitch bat that just meets the ASA *BBS* 98 mph limit, would actually produce a *BBS* closer to 74 mph in a typical fast pitch game.

11. Normalizing Bat Performance

Normalizing relations are used to minimize error in measuring bat performance. The experimental error can be due to variation in ball properties and test speeds. While they complicate the formulas used to calculate performance, they improve the experimental repeatability.

It is desirable to make the laboratory measures of performance as accurate and repeatable as possible. Small variations in ball weight, hardness, and elasticity can have a measurable effect on bat performance. Consider, for instance, a bat-ball impact with two balls that differ only in their weight. Experiments have shown that the *BBCOR* will be the same for the two impacts. The collision efficiency (and *BBS*) will not be the same, however. The collision efficiency and *BBS* are related according to[14]

$$e_a = \frac{BBCOR - r}{1 + r}, \tag{11.1}$$

where, for a pivoted bat,

$$r = \frac{mQ^2}{I}. \tag{11.2}$$

Thus, the collision efficiency may be normalized to a nominal ball weight from Eq. (11.1) if a nominal ball weight (m) is used in Eq. (11.2). While this is a more complicated path than Eq. (10.3), it reduces the effect of small variations in the weight of test balls on bat performance. An example of weight normalizing is presented in Fig. 11.1 for four bats tested with balls of three weights. Without normalizing, the performance of each bat decreases with increasing ball weight. With normalizing, the performance of each bat is nearly unchanged with test ball weight. (The variation in test ball weight was larger for this illustrative example than occurs in certified bat performance tests.)

[14] Alan M. Nathan, Am. J. Phys. 71, 134 (2003)

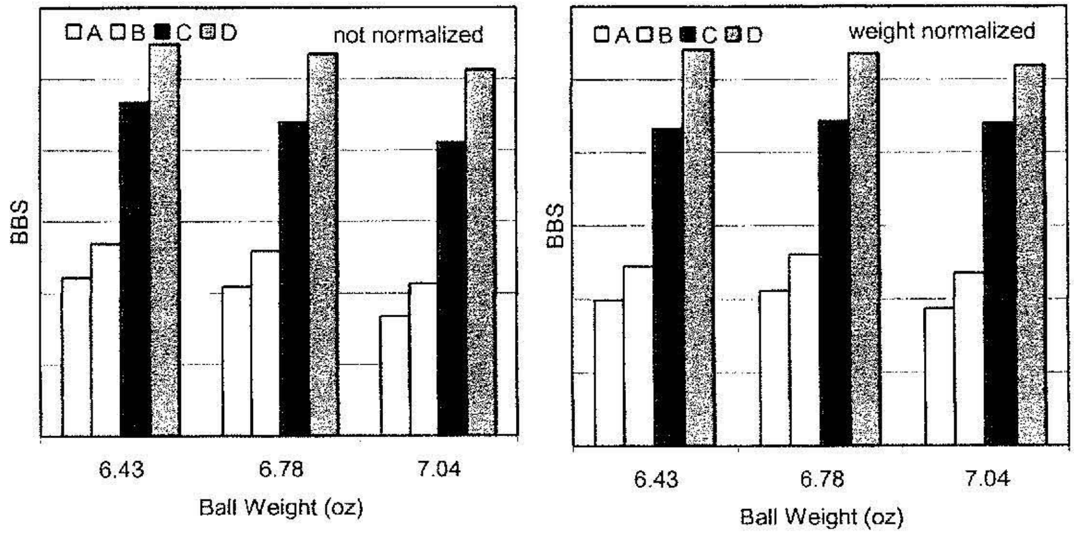

Fig. 11.1. Comparison of normalizing on the performance of four bats as a function of test ball weight.

12. Barrel Effects (Bat evolution: single, multi, composite)

Bats with a hollow barrel have a trampoline effect which can improve bat performance. The following explains some of the technologies used to improve this effect, and a test method used to compare barrel hardness.

The response of hollow and solid bats is similar in many respects. A notable exception involves the deformation of the barrel in the vicinity of the ball impact. This is often referred to as the trampoline effect and was discussed above in Ball Compression. The contribution of the trampoline effect is limited by the strength of the barrel. It is for this reason that many high performing bats have relatively low durability and why bat manufactures are keenly interested in stronger materials.

Multi-wall bats were introduced in the 1990's to increase both performance and durability. To illustrate how this occurs, consider two simply supported plates impacted by a ball at their center as depicted on Fig. 12.1. The plate on the left is solid, while the plate on the right has the same total thickness, but is made up of two un-bonded plates, each of thickness t/2. It is clear that the solid plate is stiffer than the layered plate (4 times) and would produce a slower rebound ball speed. Interestingly, the maximum stress would be the same in the solid and layered plates. If the total thickness of a multi-wall bat is slightly higher than a single wall, both durability and performance can increase.

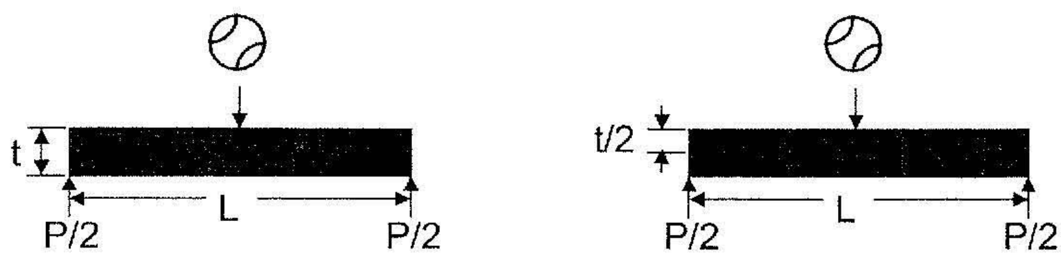

Fig. 12.1. Schematic of an ideal simply support solid plate (left) and layered plate (right) impacted by a ball.

Because of the large effect that the barrel has on bat performance, simplified tests have been considered to describe its contribution. One method, termed barrel compression, has received interest and is described in Fig. 12.2. Steel cylinders of approximately 2 inches in diameter are brought in contact with the barrel. The barrel compression is the force required to radially displace the barrel 0.05 inches in this configuration.

While bat performance is strongly affected by barrel compression, it is only one component of many. It is not clear, for instance, where along the length of the barrel it should be measured. Handle flex, *MOI*, and rate effects can also distort the comparison. For this reason barrel compression is typically used with a relatively large tolerance. It is nevertheless useful for quality control when comparing bats of the same model. It has also been used to identify doctored bats as will be described below.

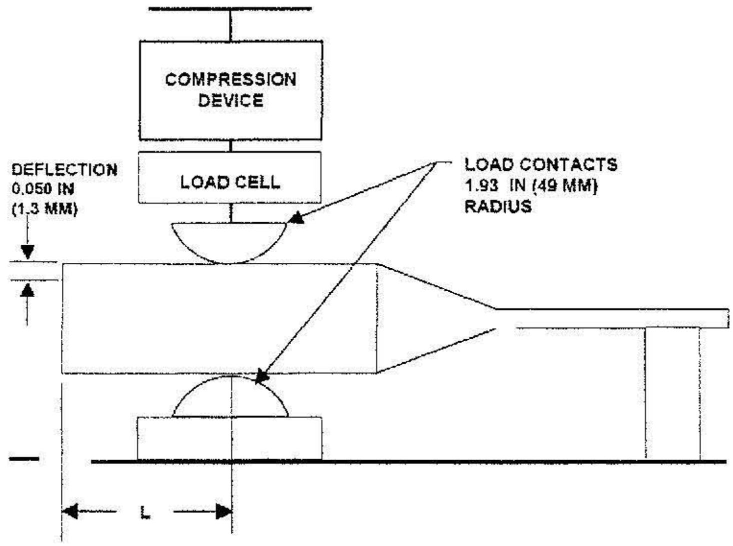

Fig. 12.2. Schematic of proposed bat barrel compression test.

13. Summary

The foregoing has reviewed the major achievements in bat and ball regulation over the past decade. While the game of softball enjoys a long and rich history, much of the science surrounding bat and ball performance has largely been overlooked. The research supported by ASA has made significant contributions that have increased our understanding of the science behind the game. This has lead to improved test measures with increased reliability.

Advances in technology have made the game of softball more exciting and enjoyable, giving the player more options and greater flexibility. Improved equipment has presented challenges in regulation, requiring the adoption of new test methods to accommodate technological advances. Test methods will continue to be studied and developed that help ensure fun and fair competition, while maintaining the integrity of the game.