The Dependence of Bat Performance on Ball Properties

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Nomenclature

BBS	Batted ball speed	e_a	Apparent COR	v_p	Ball pitch speed
MOI	Mass moment of inertia	v_i	Inbound ball speed	v_b	Bat speed at impact point
COR	Coefficient of restitution	v_r	Rebound ball speed	m	Ball mass

Abstract

The performance of baseball and softball bats can depend strongly on the properties of the ball. Standard test methods exist to measure the ball weight, hardness and coefficient of restitution (*COR*). Ball hardness is measured in a quasi-static compression test and the *COR* is measured by impacting the ball against a rigid plate. Little has been done to determine how these properties relate to the measurement of high speed bat-ball impacts. This study considers the rate dependence of ball compression and the normalization of bat performance with ball weight. A dynamic stiffness test, where the ball impacts a rigidly mounted load cell, was used to compare the quasi-static and dynamic ball hardness. A method to determine the appropriate rigid wall impact speed representative of ball-bat impact conditions is presented. Bat performance was shown to more reliably correlate with the dynamic ball stiffness, which was on average 3.8 times greater than the quasi-static value.

Introduction

Advances in the design and manufacture of baseball and softball bats have improved their hitting performance significantly. Regulating agencies have placed limits on the performance of bats in an effort to maintain a balance between the offensive and defensive aspects of the game. Bat performance may be measured and quantified in a number of different ways, all of which are subject to experimental error and manufacturing deviations. Since many bats are designed near their performance limit, small differences in performance can have a large competitive and regulative effect. There is interest on the part of regulating agencies and manufacturers, therefore, to understand factors affecting bat performance and, if possible, to improve the reliability of its measurement. The current study considers the effects of softball properties in measuring bat performance.

Background

The two properties that are most commonly used to describe a baseball or softball are its *COR* and compression [1-2]. The *COR* is a measure of the energy that the ball loses during impact with a rigid wall [3], while compression is a measure of the ball's hardness (denoted as the force in pounds needed to compress the ball by ¼ inch). Both the *COR* and compression are measured against flat surfaces and can affect a bat's hitting performance. Hollow bats exhibit a so-called "trampoline effect" that is enhanced with increasing ball compression [4].

In addition to COR and compression, balls are also regulated by their circumference and weight. Ball circumference has only a negligible effect in controlled laboratory tests which typically involve very short ball flight distances. Circumference becomes more important in game conditions affecting infielder reaction time and ball

Table 1. Ball properties used to measure bat performance

Code	COR	Weight (oz)	Compression (lbs)	DS (lb/in)
w-l	0.462	6.44	452	6545
w-m	0.468	6.79	455	6808
w-h	0.449	7.06	448	7257
c-l	0.436	6.98	341	6198
c-m	0.441	6.97	391	5432
c-h	0.449	6.94	452	7679
e-l	0.411	6.73	466	7342
e-m	0.459	6.73	457	6029
e-h	0.509	6.74	468	5979

flight distance. Ball weight can affect both laboratory and game bat performance. The effect of ball weight is often normalized in laboratory tests. Normalizing relations consider the effect of ball weight on the momentum of the ball-bat impact. There is some concern that ball weight may also contribute to the trampoline effect. Surprisingly neither the weight normalizing relations nor the weight-trampoline effect have been studied experimentally.

Bat performance can be measured and calculated in a number of different ways. In the following bat performance was measured using an air cannon with an initially stationary bat [5]. Bat performance was calculated using the so-called batted ball speed (*BBS*) method [5]. Accordingly, a collision efficiency was defined as

$$e_a = \frac{v_r}{v_i} \quad (1)$$

where v_i and v_r are the inbound and rebound ball speeds, respectively, before and after impacting an initially stationary bat. The *BBS* was found from

$$BBS = e_a v_p + (1 + e_a) v_b \quad (2)$$

where v_p is the nominal pitch speed occurring in play and v_b is the bat speed at the impact location. For the case of slow pitch softball, bat speed was found from player field studies to be proportional to the inverse of its mass moment of inertia (*MOI*) raised to the ¼ power [6].

There is some concern whether the current practices of measuring ball properties adequately describe its response and interaction with a bat. The ball COR, for instance, is measured against a rigid and flat surface at speeds that are nearly two times lower than occurs in play. Ball compression is measured at a displacement rate that is 10,000 times slower than occurs in play. In the following we will show that current measures of ball compression can have unexpected results on bat performance. A test method will be described that improves the description of the effects of ball hardness on bat performance and explains inconsistencies observed using current methods.

The Dependence of Bat Performance on Ball Properties

A study was conducted where balls were arranged in groups of controlled weight, *COR* and compression. The balls were placed in three groups where only one parameter varied (i.e. *COR*-*e*, weight-*w*, or compression-*c*). For each group, the varied parameter had three values, identified as low-*l*, medium-*m* or high-*h*. The balls are described and identified according to their respective codes in Table 1.

The balls were compared by using them to test four bats of differing performance. The bats are described in Table 2, where *MOI* was found 6 inches from the knob. Bat performance was found using the *BBS* method [5], where performance was normalized with the ball weight, but not its *COR*.

BBS from the four bats is shown for the ball group with varying weight in Fig. 1. While the *BBS* shows a slight decrease with increasing ball weight, the average change is relatively small at 0.6%. If the data were not normalized for ball weight, the average *BBS* decreased 2.6% with increasing ball weight. It is for this reason that ball weight normalization is viewed favorably and has been incorporated into standard test methods [5]. It should

Table 2. Mass properties of bats.

Bat	Material	Weight (oz)	MOI (oz in^2)	Length (in)
A	Wood	32.63	10623	34.19
B	Aluminum	35.69	10401	33.88
C	Composite	26.50	7897	34.06
D	Composite	30.64	9036	34.00

be noted, however, that this normalization process may not be appropriate for large changes in ball weight that contribute measurably to the trampoline effect.

BBS from the four bats is shown for the ball group with varying compression in Fig. 2. The *BBS* is observed to increase with ball compression; a trend that is consistent with the bat trampoline effect. Since energy loss in the ball-ball collision is primarily associated with ball deformation, the performance of hollow bats should increase with ball hardness. Note that the effect of ball hardness is smaller for bats A and B than for bats C and D (1.2% vs. 7.3%). Thus, the ball compression effect increases with barrel compliance (which is generally larger in higher performing bats).

BBS from the four bats is shown for the ball group with varying *COR* in Fig. 3. The performance of bats A and B shows a strong dependence on ball *COR*, increasing 6.4%, while the performance of bats C and D actually decreases 1.4% with increasing *COR*. This apparent violation of the conservation of energy may be explained in terms of the construction of the bat and the response of the ball, and will be investigated further in the next section.

The foregoing showed how balls with large differences in *COR*, compression and weight can affect bat performance. Consider the variation in bat performance from three balls of similar *COR*, compression and weight, varying by 3.4%, 9.8% and 7.7%, respectively. (The *COR* and compression values from this set of balls fell within the relatively tight parameters of standardized bat tests that are intended to minimize the effect of the ball in measuring bat performance [5].)The *BBS* of a bat impacted with these balls varied by 6.8%, which variation was larger than observed from any of the balls shown in Table 1.

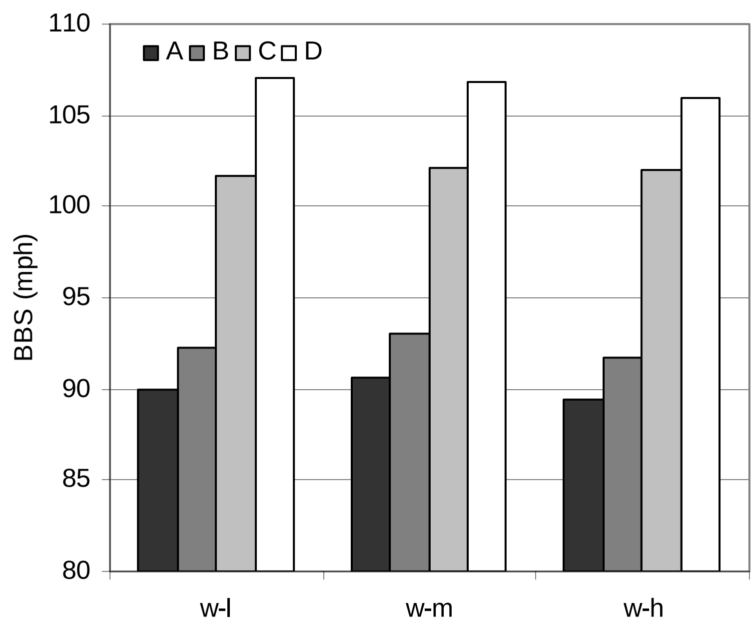

Fig. 1. BBS of four bats of differing performance using test balls of varying weight.

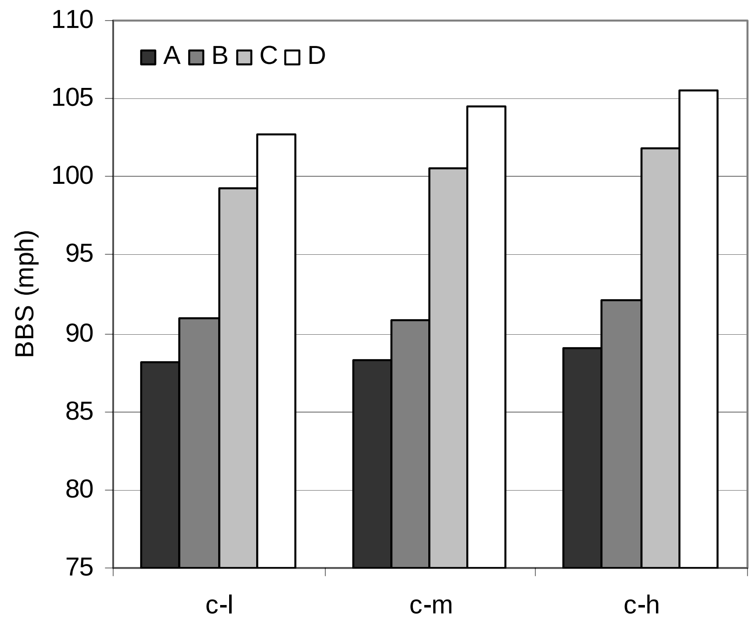

Fig. 2. BBS of four bats of differing performance using test balls of varying compression.

Dynamic Stiffness

From the foregoing it appears that current methods of measuring ball performance may not fully describe its response and performance potential with a bat. A new method is proposed, therefore, that more closely approximates the displacement rate and ball deformation that occurs in a ball-bat impact. The method will also incorporate a measure, termed dynamic stiffness, which may be used to compare and regulate ball hardness.

The effect of ball hardness can be viewed from the perspective of impact force. This has been achieved by firing balls toward a rigidly mounted load cell, as depicted in Fig. 4 [4,7-9]. The focus of past work has been toward

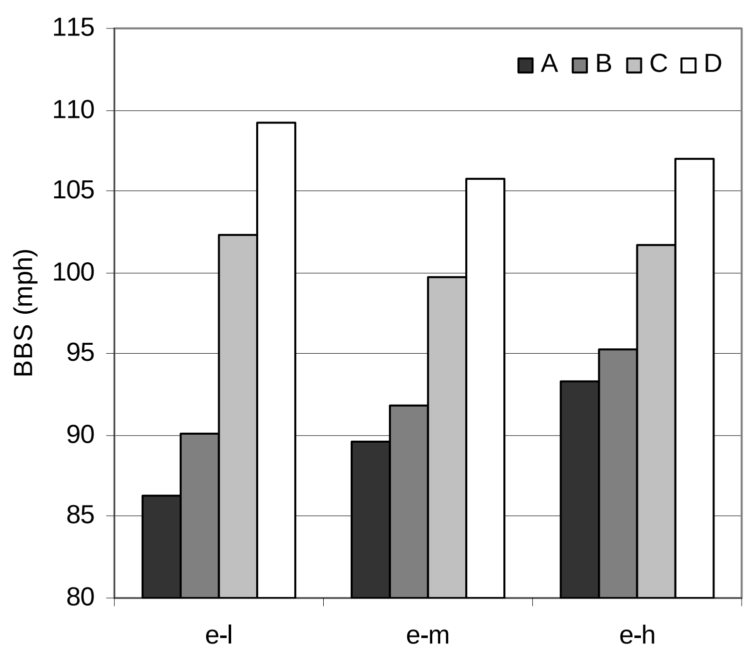

Fig. 3. BBS of four bats of differing performance using test balls of varying COR.

human safety and developing numerical simulation models. A result of this work was an observed linear correlation between the dynamic and static hardness [9].

As shown in Fig. 5, force can be measured as a function of time from a ball impacting the load cell. The area under the curve is the impulse imparted to the ball from the collision. The peak force during contact may be viewed as a measure of the ball's hardness.

The proposed configuration has the desirable characteristics of improved simulation of the deformation rate and magnitude of the ball during the ball-bat impact. The peak force is sensitive to variations in ball mass and speed, however. This dependence may be reduced if the ball is assumed to act as a linear spring. Equating the initial ball kinetic energy $\frac{1}{2}mv^2$ to the ball's potential energy at maximum deformation (and force) $\frac{1}{2}kx^2$, an idealized ball stiffness, k, may be obtained by eliminating the unknown displacement, x, using the measured peak force, F, where $F=kx$, as

$$k = \frac{1}{m}\left(\frac{F}{v_p}\right)^2, \qquad (3)$$

where k is denoted the dynamic ball stiffness, and m, F, and v are the ball mass, peak force, and pitch speeds, respectively.

Since the dynamic stiffness test involves impacting a rigid surface, a speed must be determined that represents a recoiling bat impact condition. To determine this speed experimentally a recoiling cylinder was needed that did not exhibit a trampoline effect. A 4 inch long solid aluminum cylinder of the same diameter as the rigidly mounted cylinder (2.25 in.) was used. The cylinder had a mass comparable to a bat (25 oz) and was unconstrained during the ball-cylinder impact.

Two approaches were considered to relate a rigid wall impact speed to a recoiling mass speed. The first assumed that the impulse of a rigid wall impact equals the impulse of a recoiling mass impact. The second approach assumed that the deformation of the ball must be the same for two impact conditions. The relationship between the incoming ball speeds for the recoiling, v_r, and fixed, v_f, impact conditions is

$$v_r = v_f\left(1 + \frac{m_b}{m_c}\right)^n, \qquad (4)$$

where m_b and m_c are the mass of the ball and recoiling cylinders, respectively. The exponent, n, is unity for constant impulse and ½ for constant deformation.

Using v_r = 110 mph (typical of a bat-softball relative impact speed), the corresponding ideal fixed cylinder speed is 86 and 97 mph for the constant impulse and deformation conditions, respectively.

The impact force of the recoiling and rigid cylinders were compared to determine which idealization represented a better approximation. The impact force of the recoiling cylinder was obtained from its mass and acceleration by mounting an accelerometer to its back side as shown in Fig. 6. Impacting the recoiling mass at 110 mph produced a peak force of 4468 lbs (average of 3 balls). Impacting the rigid wall at a speed of 95 mph (2 mph slower than the idealized constant deformation speed) produced a force of 4737 lbs. The constant deformation approach appeared to represent a better model to correlate impact force between recoiling and rigid cylinders. It should be noted that the comparison is not perfect (a higher force was observed, even though the test speed was 2 mph slow). The result is nevertheless within the 10% correlation expected between load measurements using accelerometers and load cells [10].

This recoiling mass example can be readily applied to a pivoted bat by replacing the mass ratio m_b/m_c with m_br^2/I, where r is the distance from the pivot to the impact location and I is the bat *MOI* about its pivot point [11]. Taking v_r = 110 mph, an equivalent rigid wall speed may be found as 90 mph for a relatively light bat with an outside impact and 100 mph for a relatively heavy bat with an inside impact. These speeds were averaged to 95 mph for the rigid wall impacts to represent an average bat.

With a method and speed for measuring dynamic stiffness established, the balls in Table 1 can be examined further. The dynamic stiffness for each ball is presented in Table 1 under the column labeled "DS." Note that the

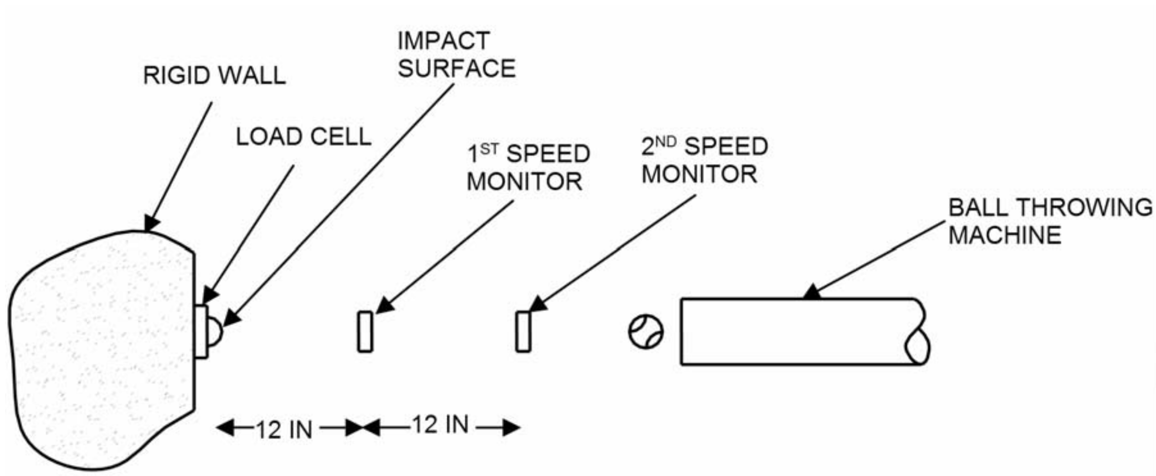

Fig. 4. A schematic depiction showing how dynamic stiffness is measured.

average dynamic stiffness is 3.8 times greater than the quasi-static stiffness. Returning to the *COR* group of balls, the dynamic stiffness of the low *COR* ball “e-l” is 22% higher than the other balls in the *COR* group. Thus, the higher performance of the *e-l* ball is likely related to a difference in its rate effects, relative to the other balls in the *COR* group. Dynamic stiffness was also shown to have a strong affect on the bat tested with balls of similar compression and *COR*. The dynamic stiffness of each ball was measured and compared to the *BBS* as shown in Fig. 7. These two examples suggest that deformation rate and magnitude can play an important roll in describing ball response and in particular the corresponding bat performance.

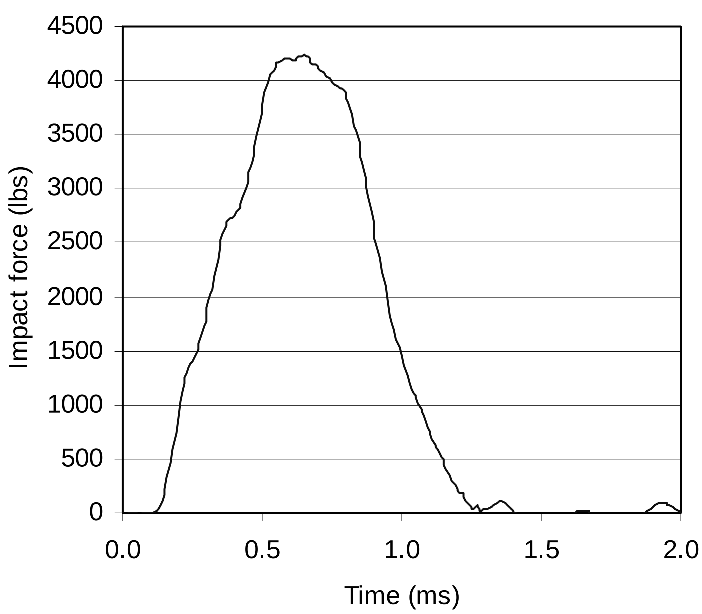

Fig. 5. Impact force of a softball against a rigid cylinder at 95 mph.

Fig. 6. Picture of recoiling solid cylinder with accelerometer on the back side.

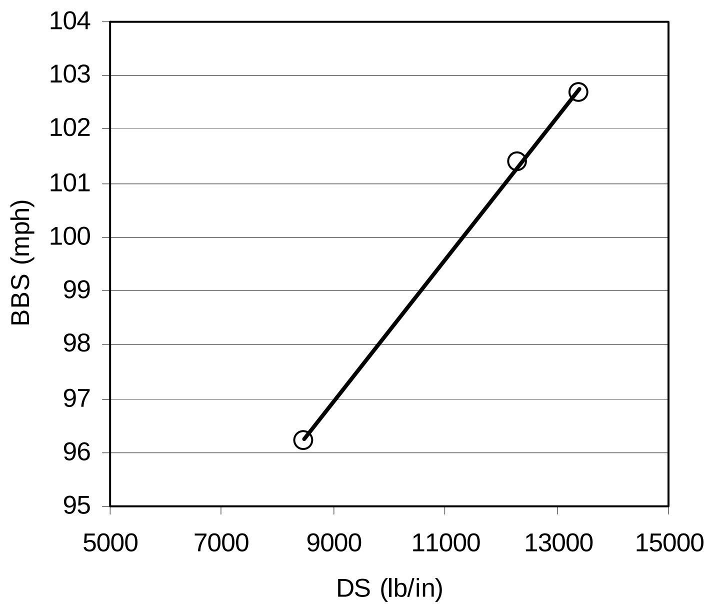

Fig. 7. A comparison of BBS and dynamic stiffness for a bat tested with balls of similar COR and compression.

SUMMARY

This study has considered independently the effects of ball weight, compression and *COR* on bat performance. Variations in ball weight appear to have a relatively small effect on bat performance that can be minimized further using well established momentum considerations. The variations in ball weight considered in this study did not have a measurable effect on the bat's trampoline effect. Bat performance was observed to increase measurably with ball compression. The effect of ball compression increased with the relative bat performance. The ball compression effect may be attributed to the trampoline effect occurring in bats of hollow construction. Bat performance was observed to increase with ball *COR* when the dynamic hardness of the ball was used. Standard measures of ball *COR* and compression were not always able to explain the measured bat performance. A dynamic measure of ball hardness, termed dynamic stiffness, was shown to provide a better correlation with bat performance than the more common ball compression measure.

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