Measuring the Hardness of Softballs

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Nomenclature:

k	Ball stiffness
n	Ball stiffness exponent
F	Ball impact force
F'	Scaled ball impact force
F_p	Peak ball impact force
m_b	Ball mass
v_i	Inbound ball speed
v_r	Rebound ball speed
v_1	Inbound ball speed for mass 1
v_2	Inbound ball speed for mass 2
r_1	Recoil factor for mass 1
r_2	Recoil factor for mass 2
p	Power relating speeds of mass 1 and 2
b	Distance from the pivot to the impact location of a bat
I	Mass moment of inertia of a bat

Abstract

The following describes a method that may be used to measure the hardness and elasticity of balls with application to softballs. While standardized test methods currently exist to measure these properties, they do not represent the ball deformation rate and magnitude that occurs in play. The method described herein involves impacting a fixed solid cylinder (matched to the diameter of an intended bat) with a ball and measuring the impact force and speed of the ball before and after impact. The ratio of the ball speeds provides a measure of elasticity, while the impact force was used to derive a ball stiffness, akin to a one dimensional ideal spring. The ideal spring model was shown to be non-linear where geometric effects caused non-linear hardening and material effects caused non-linear softening. To relate ball deformation from game conditions to a laboratory setting, a relationship is needed for impacts with objects of different mass. The study considered equating impulse and energy. It was observed that the constant energy model more closely replicated the impact force and elasticity observed between recoiling cylinders of different mass. For an example of the significance of the new ball hardness measure, bat performance showed a much stronger dependence on the proposed ball stiffness than the traditional ball compression measure. The method has application to associations wishing an improved method to regulate the effects of ball performance.

Introduction

To help regulate bat performance, softballs are commonly described by their elasticity and hardness. In relation to bat performance, higher ball hardness increases barrel deformation and gives rise to an increase in the trampoline effect. The ball elasticity measure is denoted *COR* (coefficient of restitution) and is found from a 60 mph (26.8 m/s) impact against a rigid flat surface (ASTM F1887). Ball hardness is denoted *compression* and is the peak force found by compressing a ball 0.25 inches (6.3 mm) over 15 seconds between flat platens (ASTM F1888). The deformation magnitude and rate in these tests are five and 10,000 times lower, respectively, than play conditions. Given the rate dependence of the common polyurethane softball, it is important to know how the quasi-static compression measure compares to a ball's dynamic response.

Impact force has been measured as a function of time by projecting balls toward a rigidly mounted load cell [1-3]. The focus of these studies has been toward human safety and characterizing the dynamic ball response. Comparisons between ball compression and impact force do not always agree. Some have found a linear relationship [4], while others claim there is no correlation [5,6].

As one might expect, the impact force increases with ball speed and compression, while ball deformation decreases with increasing ball compression [7]. Golf balls have been shown to have a high sensitivity to strain rate [8]. The rate sensitivity is likely related to its polymeric constituents, suggesting that softballs may have a similar dependence on strain rate.

In the following a test method is considered to measure the hardness and elasticity of a softball. The aim of this work was to deform the ball to the same magnitude and at the same rate that would occur in play. The proposed method appears to provide an improved correlation with bat performance than the commonly used ball compression.

Measuring Ball Hardness

The impact force was measured by projecting a ball toward a solid cylinder, as depicted in Fig. 1. The cylinder was intended to represent the shape of a softball bat, having a diameter of 2.25 inches (57 mm). The impact force was measured from an array of load cells (PCB model 208C05), placed between the cylinder and a rigid wall. Data from the load cells was collected at 200 kHz, from which an impulse curve, as shown in Fig. 2, was obtained.

The ball was projected at speeds ranging from 60 to 110 mph (26.8 to 49.2 m/s) using an air cannon. The ball traveled in a sabot, which separated from the ball prior to impacting the cylinder. The sabot helped control ball speed and ball orientation. The balls were impacted on their four ears, the locations providing the largest spacing between the stitches. Ball speed before and after impact was measured using infrared light gates, placed as shown in Fig. 1.

The center of mass displacement of the ball may be found by dividing the impact force by the ball mass and integrating twice. A representative force-displacement curve for the fixed cylinder impact is shown in Fig. 3. The nearly linear response during the loading phase is surprising, given the non-linear Hertzian contact and non-linear polymeric material response. The oscillations during the loading phase of the curve were observed for two types of fixture constraint (a massive rigid wall and a more flexible table). The oscillations are, therefore, likely related to the vibrational response of the ball rather than the constraint.

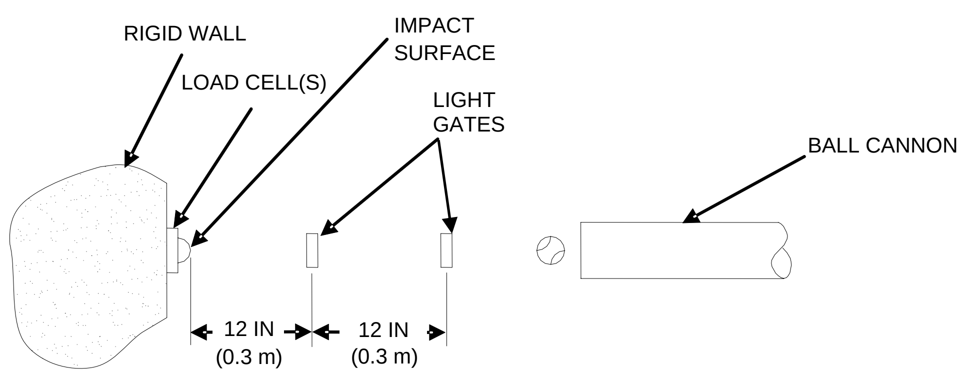

Fig. 1. Schematic of apparatus used to measure the softball impact force.

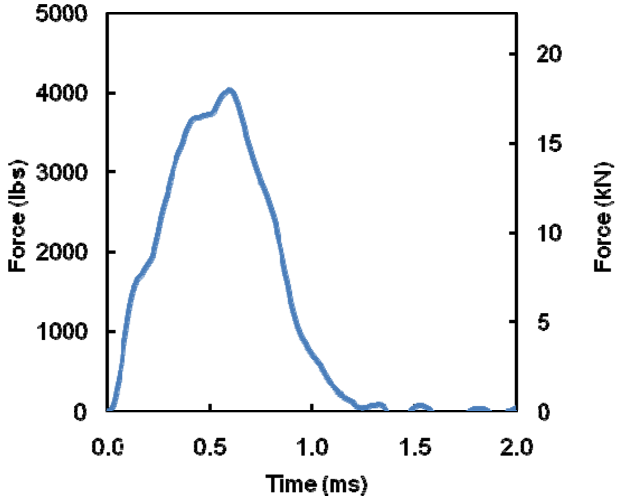

Fig. 2. Representative impulse curve of a softball impacting a fixed cylinder at 95 mph.

Ball hardness should correspond to the peak impact force. The peak impact force will also depend on the ball speed (as shown in Fig. 4) and weight. It is desirable to regulate ball hardness, independent of test and manufacturing variations. In the following we will assume that the ball behaves as a non-linear spring during the loading phase according to $F = kx^n$, where F and x are the force and displacement of the spring, respectively and k and n are unknown spring constants. A linear spring is described with n = 1, while classical Hertzian contact occurs with n = 1.5. An expression for the coefficient, k, may be obtained by equating the kinetic energy before impact with the potential energy at maximum deflection during impact as

$$k = \left[\frac{2}{m_b(n+1)}\right]^n \frac{F_p^{\,n+1}}{v_i^{\,2n}} \tag{1}$$

where m_b is the ball mass, F_p is the peak impact force, and v_i is the incoming ball speed.

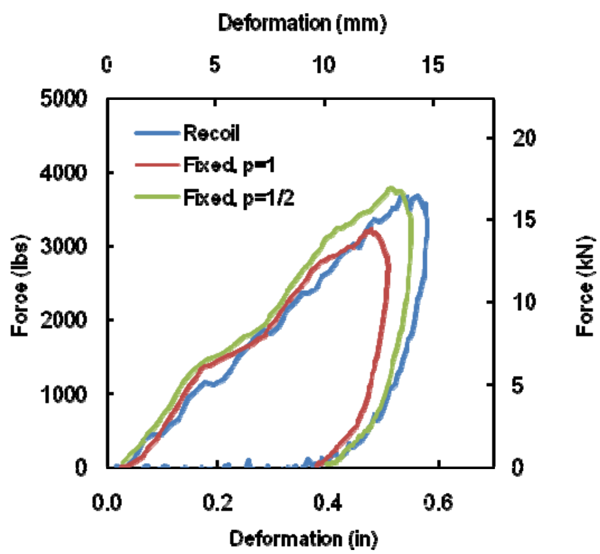

Fig. 3. Representative force-displacement curve of a ball impacting a fixed and free cylinder.

The ball speed and impact force each provide a measure of the impact impulse. Ideally these measures would be equal as

$$m_b(v_i + v_r) = \int F(t)dt \tag{2}$$

where v_r is the rebound ball speed and $F(t)$ is the measured impact force as a function of time. While experimental error prevents the equality, the redundant measures can be used to improve the accuracy of the result. If, for instance, the speed measurements are more accurate than the force measurements, the latter may be corrected according to

$$F'(t) = F(t)\frac{m_b(v_i + v_r)}{\int F(t)dt} \tag{3}$$

where $F'(t)$ is the scaled impact force. To compare how this procedure affected the ball hardness values, 12 balls were tested on two separate fixtures. The average coefficient of restitution of the two fixtures differed by 1%. The average ball stiffness from the two fixtures differed by 3% using the measured force. The average difference in ball stiffness decreased to 1.5% when the scaled force was used.

Ball Hardness Results

The ball coefficient, k, is presented as a function of incoming speed in Fig. 4 for n = 1 and n = 1.25. The response appears non-linear, where with n = 1 the coefficient, k increases with speed (although at a slower rate than the force). With n = 1.25 (less than the n = 1.5 classical Hertzian contact) the spring coefficient is relatively constant with speed. This result is surprising as large deformation effects tend to increase the exponent for Hertzian contact [9].

To separate the non-linear material and geometry effects, the rigid cylinder impacts were simulated using an elastic finite element model [10]. The ball was given a modulus of 6600 psi (45 MPa) and a Poisson's ratio of 0.1. This produced an impact force that was approximately 20% higher than was found experimentally, while the contact duration was comparable (1 ms). The impact speed of the model was varied, for which a power of n = 1.75 achieved a speed independent spring coefficient, k.

The impacts considered here have three components of non-linearity. First, classical small deformation

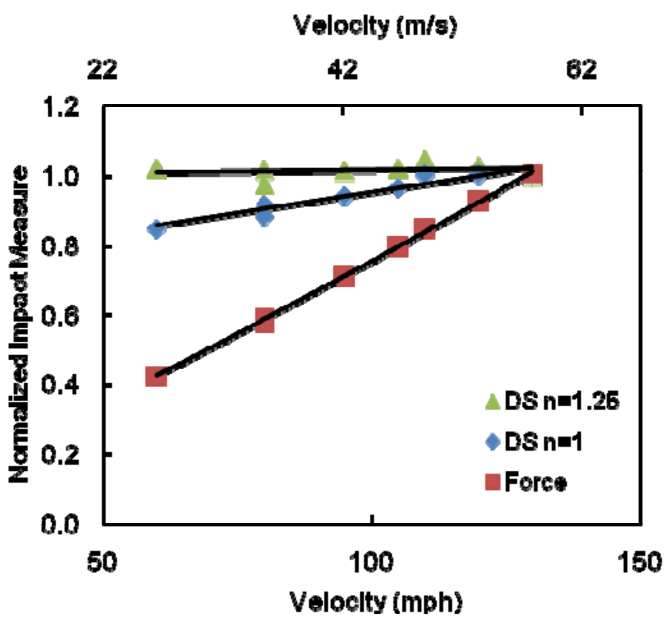

Fig. 4. Impact force and ball stiffness (DS) as a function of incoming ball speed. (Values are normalized with respect to the 130 mph (58 m/s) case.)

Hertzian contact is non-linear. Second, the geometric effects of large deformation Hertzian contact are non-linear. Third, the core of the softball is made from polyurethane which undergoes non-linear softening with large deformation. While the small and large geometric components of non-linearity tend to increase the exponent, *n*, the material softening tends to lower *n*. The results indicate that the effect of material softening is greater than the geometric non-linearities.

The compression and stiffness of 150 softballs comprising 18 models from 5 manufactures are compared in Fig. 5. The procedure for measuring ball hardness was similar to that used for ball *COR*. The ball was impacted 6 times, from which the average stiffness was reported. To be consistent with a proposed ball stiffness test standard and provide *k* with convenient units (force/distance), it was computed with n = 1. (The effect of the exponent in this case is negligible given the relatively small variation in laboratory ball speed.) While there is substantial scatter in the comparison, the data generally fall in three groups, identified as “a”, “b”, and “c” in the figure. The balls in groups “a” and “b” are of similar construction and are likely produced from different urethane formulations. (A relatively small number of overseas facilities produce balls for a large number of domestic companies.) The balls in group “c” have a unique construction having a core that is made of a relatively soft outer shell and a harder interior.

Given the effect of impact force on bat performance, regulating associations are interested in discriminating among the groups of balls in Fig. 5. Some have suggested that this could be done by increasing the displacement of the compression test. This approach may have limited value. Quasi-static loading is more severe than impact loading. Increasing the deformation magnitude of the quasi-static compression test could induce ball damage. Even without this limitation, it is unlikely that a compression test with increased displacement could discriminate between the similar ball designs of groups “a” and “b” in Fig. 5.

Test Speed

An aim of this work was to produce a ball deformation that would correspond to play conditions. Accordingly, an impact speed with the rigid cylinder (i.e. test stand) was needed that corresponded to an impact with a recoiling cylinder (i.e. a bat). Toward this end, an expression may be obtained relating the impact speed of two cylinders of mass m_1 and m_2 as

$$v_1 = v_2 \left(\frac{1 + r_1}{1 + r_2} \right)^p \tag{5}$$

where v_1 and v_2 are the respective incoming ball speeds and r_1 and r_2 are the so-called recoil factors [11]. For the

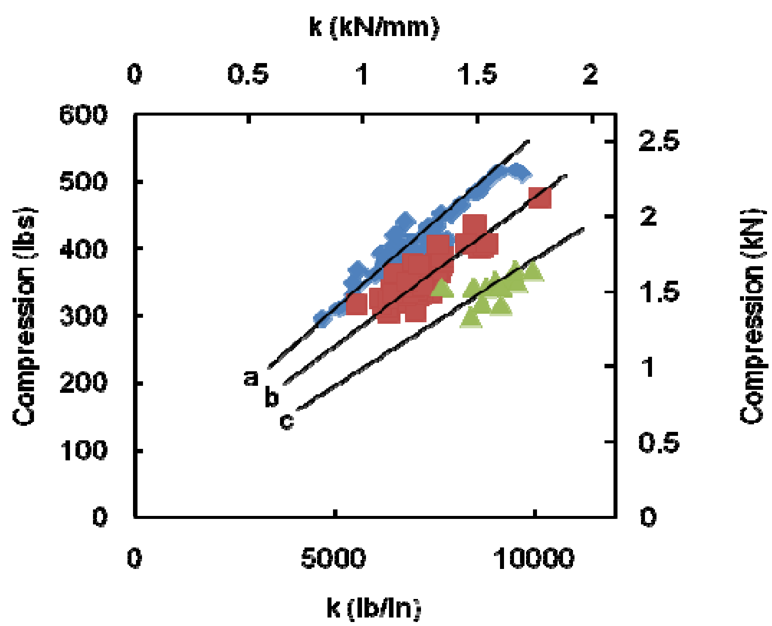

Fig. 5. Comparison of ball compression and stiffness of 150 softballs.

impulse to be equivalent for the two cases, p = 1, while for the ball deformation to be equivalent, p = ½ . The former is found by equating the impulse for the two cases, while the latter is obtained by equating the center of mass energies. For a point-mass system the recoil factor is

$$r_i = \frac{m_b}{m_i} \tag{6}$$

where m_b and m_i are the mass of the ball and recoiling cylinder (1 or 2), respectively. For a pivoted bat system the recoil factor is

$$r_i = \frac{m_b b^2}{I_i} \tag{7}$$

where b is the distance from the pivot to the center of mass of the bat and I_i is the mass moment of inertia of the bat with respect to the pivot point. For a rigid mass, m_i or I_i become large and r_i goes to zero.

Free or recoiling cylinders made from aluminum (25.2 oz or 716 g) and steel (71.9 oz or 2043 g) were impacted to establish the correct relation between impacts with objects of different masses. The cylinders measured 2.25 inches (57 mm) in diameter and were 4 inches (102 mm) long, while the softballs weighed nominally 7 oz (200 g). An accelerometer was attached to the back of the cylinder at its center. Only those impacts whose inbound and rebound trajectories were within 5 degrees were considered.

A set of 12 softballs was impacted against the aluminum cylinder at 80 mph (35.8 m/s). The *COR* and peak impact force for each ball were taken from the average of 6 valid impacts. The steel cylinder was impacted with the same balls at 74.1 mph (33.1 m/s) (p = ½) and 68.7 mph (30.1 m/s) (p = 1). The impact force and *COR* between the steel and aluminum cylinder agreed within 1% for p = ½. For the case of p = 1, the impact force from the steel cylinder was 10% lower than aluminum, while the *COR* was 2% higher. These results are consistent with a low impact speed where force decreases and *COR* increases.

Representative force-displacement curves from impacts with fixed and free cylinders are compared in Fig. 3. In this case a free aluminum cylinder was impacted at 91.0 mph (40.7 m/s), while the fixed cylinder was impacted at 80.6 mph (36.0 m/s) (p = ½) and 71.5 mph (32.0 m/s) (p = 1). The constant deformation case again appears to provide the best comparison. The shape and form of the force-displacement curves are remarkably similar for the three cases.

Effect of Ball Hardness on Bat Performance

The preceding has considered a method to dynamically measure the hardness of a softball. The effort to develop this method was motivated by a concern that the current ball compression test does not reliably describe the effect of ball hardness on bat performance. To compare the effect of the two measures of ball hardness on bat performance, four bats were tested according to ASTM F2219. The bats included a solid wood bat, an aluminum bat and two composite bats. Softballs were selected with similar *COR* and varying hardness (found with n = 1). Bat performance was measured using the batted ball speed (*BBS*) scale as described in ASTM F2219. The *BBS* is shown as a function of ball compression in Fig. 6, and as a function of ball stiffness in Fig. 7.

The barrel of the solid wood bat is sufficiently stiff that it does not exhibit a trampoline effect and is expected to be insensitive to either measure of ball hardness. As shown in Figs. 6 and 7, the performance of the wood bat is relatively constant. The performance of the hollow bats appears to be nearly independent of ball compression, as shown in Fig. 6. The contribution of ball hardness becomes clear, however, when bat performance is shown as a function of ball stiffness, Fig. 7. The comparison illustrates the improved correlation that may be obtained by characterizing the ball using a deformation rate and magnitude representative of play conditions. It should be noted that a dependence of bat performance on ball compression would likely become evident if a larger range in ball compression were considered. The range in ball compression used here is, nevertheless, representative of balls used in most leagues.

Summary

The foregoing described a method to measure the hardness of a ball under conditions representative of play. A ball stiffness was derived from the peak impact force, ball mass and incoming ball speed. For the softball impacts considered here, the ball stiffness was shown to increase with incident speed. The speed dependence was attributed to geometric and material non-linearities. A procedure was also presented relating the fixed cylinder impact speed to play conditions. The reproducibility of the method, involving a relatively small set of balls, was shown to improve if the impulse of the measured load was scaled to the impulse from the measured ball speeds. Finally, bat performance was shown to depend strongly on ball stiffness. A similar correlation involving ball compression was only apparent for a solid bat, insensitive to ball hardness.

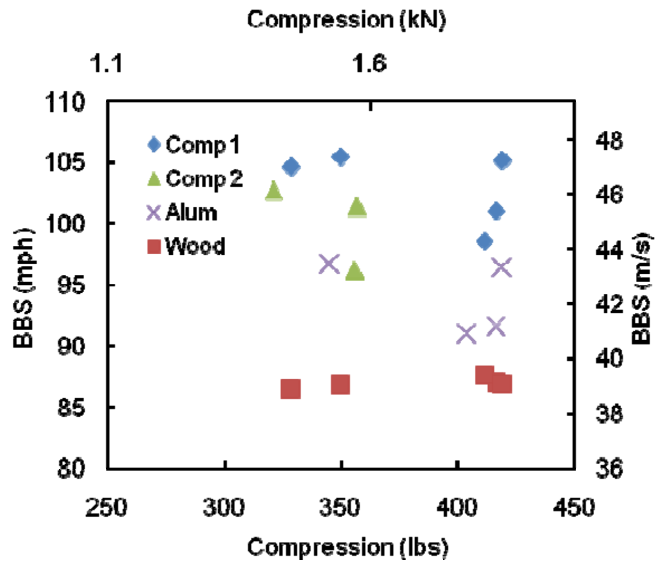

Fig. 6. Bat performance as a function of ball compression.

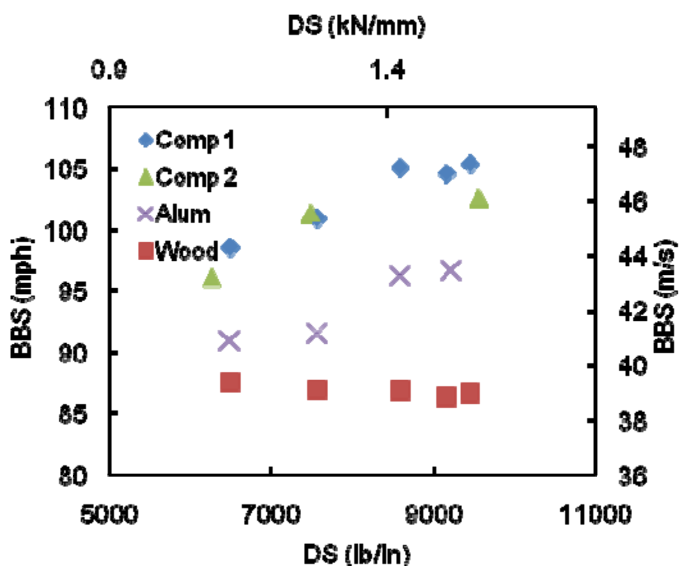

Fig. 7. Bat performance as a function of ball stiffness.

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