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An Examination of Cricket Bat Performance

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ABSTRACT: The aims of this study were to experimentally measure and numerically describe the performance of cricket bats and balls. A dynamic finite element model was employed to simulate the bat-ball impact. The ball was modeled as a linear viscoelastic material which provided the mechanism of energy loss during impact. An experimental test apparatus was developed to measure the performance of cricket bats and balls under dynamic impact conditions representative of play. Experiments were conducted to measure the elasticity and hardness of the cricket balls as a function of incoming speed. A bat-performance measure was derived in terms of an ideal batted-ball speed based on play conditions. The model found good agreement with experimental data for a number of impact conditions. A composite skin, applied to the back of some bats, was observed to increase performance experimentally and in the numerical model. While different treatments and designs typical of cricket bats had a measurable effect on performance, they were much smaller than the 10% difference observed between some solid-wood and hollow baseball and softball bats.

Keywords: Cricket bat, Cricket ball, COR, Dynamic stiffness, BBS, Composite skin

1-Introduction

Although, the sport of Cricket is 500 years old [B1] there has been little research studying the bat or the ball. Since the 17th century, the cricket bat has been changed various times, but remains of solid wood [T1]. The aim of the bat is to maximize batted-ball speed, and minimize vibration to the batsman's hands. The blade is made of willow which is strong, lightweight and has good shock resistance. The handle is made of cane which has good shock absorbing properties. The length of the bat cannot exceed 38 inches (96.5 cm), and the width of the blade must be less than 4.25 inches (10.8 cm) [T1].

The performance of cricket bats has been compared using their coefficient of restitution (COR); defined as the ratio of relative speed of the objects after and before the collision. One study found that the COR of the bat decreased as the bat stiffness increased [F1]. Recent advances in technology and materials have motivated a number of changes in cricket bat design. While some studies suggest these advances have not affected performance, more work is needed to quantify their contribution [S4].

Cricket balls are made from a cork nucleus with layers of wound wool and cork and a leather cover. The leather exterior is usually constructed from four sewn pieces. A cricket ball weighs between 5.5 to 5.75 ounces (155.9 to 163 g) and can be no more than 9 in. (22.9 cm) in circumference [T1]. Cricket balls are made in a number of different ways, with varying core design. Some have shown that greater deformation was found for impacts landing on the seam, compared to those landing perpendicular to the seam [C1]. There is little information on the effect of cricket ball properties on bat performance.

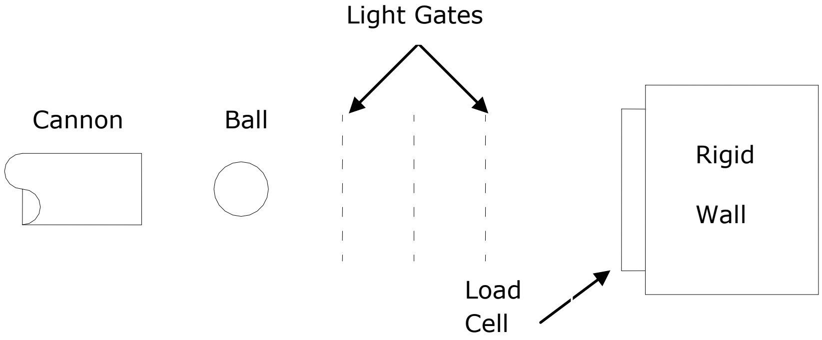

Figure 1: Experimental Setup for COR and Dynamic Compression

2-NUMERICAL MODEL

2.1-BALL

To understand the impact between a bat and ball a finite element model was developed. A viscoelastic model was selected for the cricket ball, defined by the time dependent shear modulus [S1, M1, S3] as,

$$G(t) = G_\infty + (G_o - G_\infty)e^{-\beta t} \tag{1}$$

and a constant bulk modulus, k where G_o is the instantaneous shear modulus G_∞ is the long term shear modulus, and β determines the time sensitivity of the model. An apparatus, Figure 1, was used to characterize the ball at strain rates representative of play. The apparatus and test involved pitching a ball toward a rigidly mounted load cell. Ball speed was measured before and after impact using light gates. The apparatus and ball were modeled using finite elements. By tuning the properties of the ball good, agreement was attained with the load-time curve as shown in Figure 2 for a 60-mph (26.8-m/s) ball speed. The viscoelastic material properties are defined in Table 1.

2.2-BAT

The geometry of the cricket bat was created using CATIA V5 R17. The geometry was imported into LS-DYNA (Livermore Software Technology, Livermore, CA) for finite element analysis. The mesh of the cricket bat consisted of 44544, 8-noded solid elements as shown in Figure 3. The density of the willow and cane were tailored to match the measured weight and mass moment of inertia (*I*) of the bat. Properties of the willow and cane are summarized in Table. 2.

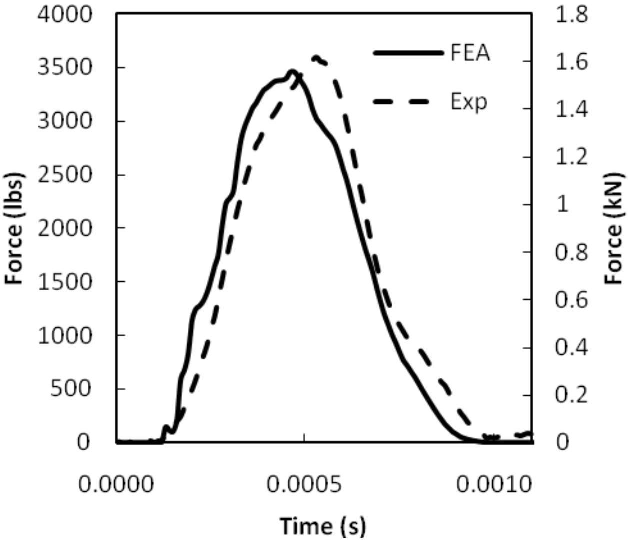

Figure 2: Comparison of finite element and experiment of cricket ball impacting a load cell at v_p = 60 mph (26.8 m/s)

	Density (lb/in^3) / (kg/m^3)	G_o ksi / MPa	G_∞ psi / MPa	K ksi / MPa	B
From Ball Test	0.03075 / 851	6.3 / 43.4	1667 / 11.5	19.5 / 134	10500
Bat Tuned	0.03075 / 851	4.75 / 32.7	1667 / 11.5	19.5 / 134	10500

Table 1: Viscoelastic Material Properties of Ball

	Young's Modulus (Msi) (GPa)			Density(lb/in^3) (kg/m^3)	Shear Modulus (Msi) (GPa)			Poisson's ratio		
	E_x	E_y	E_z	ρ_0	G_{xy}	G_{yz}	G_{zx}	ν_{yx}	ν_{zx}	ν_{zy}
Willow	0.479	0.0319	0.255	0.016	0.0479	0.00479	0.0479	0.015	0.16	0.6
	13.3	0.883	7.06	443	1.33	0.133	1.33			
Cane	0.318	0.318	0.318	0.018	-	-	-	0.3	0.3	0.3
	8.8	8.8	8.8	498						
Composite	11.1	11.1	1.14	0.06	1.04	0.912	0.912	0.037	0.0158	0.26
	307	307	31.6	1661	28.8	25.2	25.2			

Table 2: Elastic Properties of Bat

3-EXPERIMENT

3.1-Ball Testing

Cricket balls were compared by their elasticity and hardness. Elasticity was quantified through their rigid-wall COR. Ball hardness was quantified through a so-called dynamic stiffness [S3], which was defined by equating the ball's initial kinetic energy with its stored energy upon impact with the load cell. The unknown ball displacement was described by the measured force, assuming the ball acted as a linear spring. Accordingly, an expression for the ball's dynamic stiffness, k_d, was found as

$$k_d = \frac{1}{m_b}\left(\frac{F_p}{v_i}\right)^2 \tag{2}$$

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

All balls were conditioned at 72±2˚F (22±1˚C) and 50±5% relative humidity for at least 14 days (or saturation) prior to testing. Figure 4 shows the ball dynamic stiffness as a function of incoming ball speed. The FEA results are also included in Figure 4, which show good agreement with the experimental data over a range of speeds.

Figure 5 compares the force-displacement curve of two representative ball brands with the FEA model. Displacement from the experiment was obtained by dividing the force by the ball mass and integrating twice with respect to time. It was observed that Ball A had 17% more deformation than Ball B. The different ball constructions and materials likely contribute to the characteristic responses of Balls A and B observed in Figure 5. The FEA model was tuned to Ball B, and the FEA model and Ball B show good force-displacement agreement.

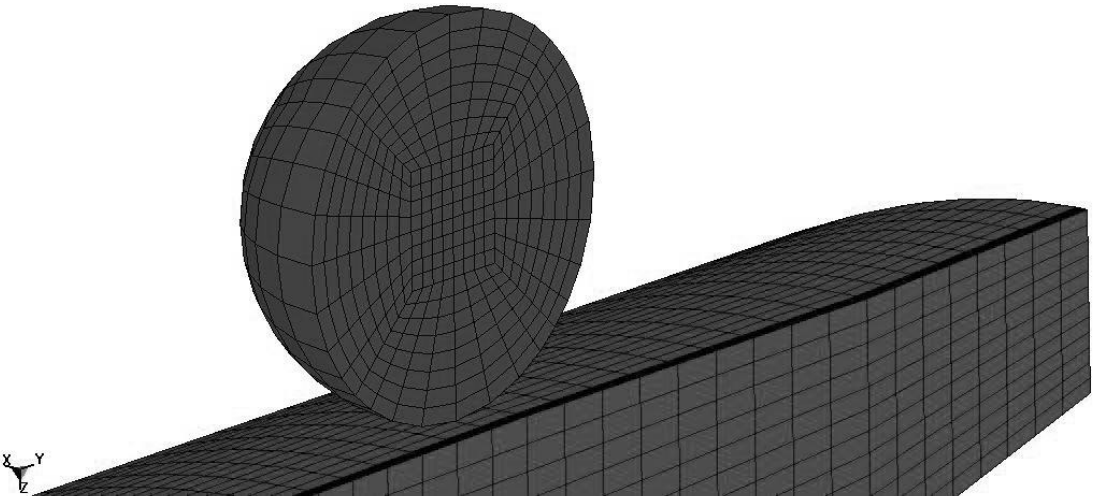

Figure 3: Cricket bat mesh

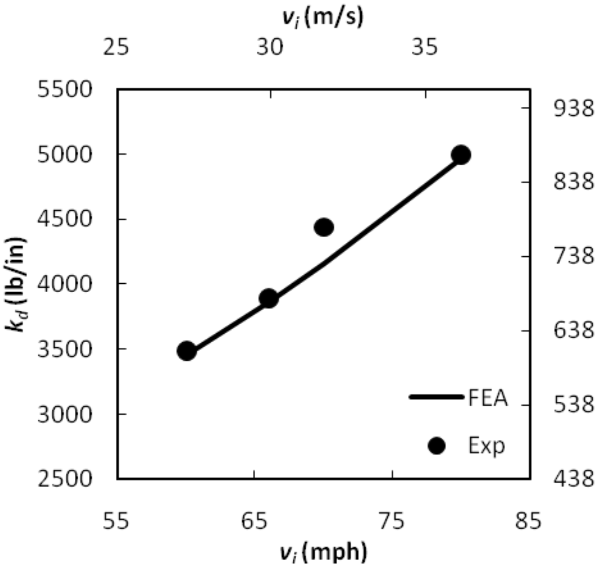

Figure 4: Dynamic stiffness and COR as a function of incoming ball speed

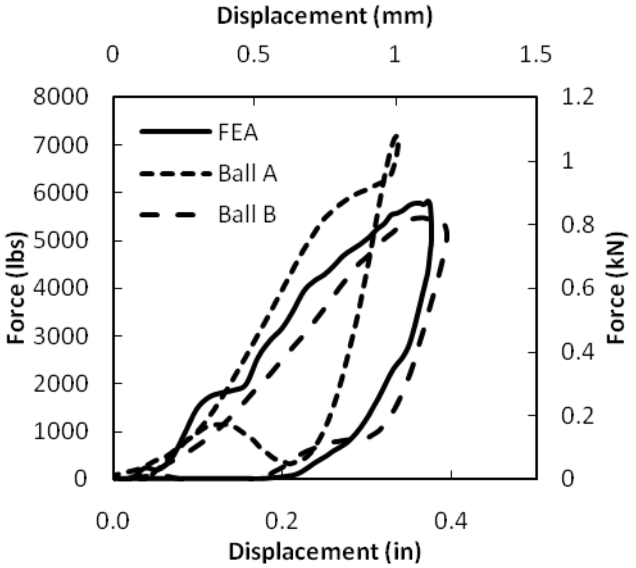

Figure 5: Representative force-displacement curves for two ball models

3.2-Bat Testing Apparatus

The bats were tested using a fixture similar to the ball test as shown in Figure 6. The rigid wall was replaced by a fixed pivot that allowed the bat to recoil after impact and controlled the impact location. In the bat tests, an incoming ball speed of 60 mph (26.8 m/s) was used to prevent accumulated bat damage from influencing the results.

Light gates measured the ball speed before and after the impact. The ratio of the rebound to inbound ball speed is the so-called collision efficiency, e_a [N1]. If the bat, v_b, and ball, v_p, speed in play conditions are known, the collision efficiency may be used to find the batted-ball speed, *BBS*, according to

$$BBS = e_a v_p + (1 + e_a) v_b \tag{3}$$

The bowled-ball speed is relatively easy to measure in play and is usually taken as a constant when comparing bat performance. The release speed of fast bowlers approaches 100 mph (44.7 m/s) at the hand, while the speed at the bat after impacting the pitch is near 80 mph (35.8 m/s) [P1]. In this work, it was taken at 85 mph (38 m/s). The bat speed is more difficult to measure and has a greater effect on the BBS than bowled-ball speed. For this work, a bat speed of 70 mph (31.3 m/s), 21 in. (533 mm) from the knob end was used. This bat speed was found by considering a ball-flight trajectory of 450 yards or 411 m. Bat speed is not constant, but will vary with *I* and impact location, *Q*, [S2], [C2] according to

$$v_b = v_r \left(\frac{Q}{Q_r} \right) \left(\frac{I_r}{I} \right)^{1/4} \tag{4}$$

where v_r (70 mph or 31.3 m/s) is the reference speed, Q_r (21 in or 0.533 m) is the reference location, and I_r (10,000 oz in^2 or 183 g m^2) is the reference bat mass moment of inertia.

Each bat was impacted six times at multiple locations along its length until a maximum BBS location was found within 0.50 in. (13 mm). Representative performance curves for the experimental data and the finite element model are shown in Figure 7. Note the relatively small region which produces a maximum BBS. The algorithms used to manage contact between colliding bodies in explicit dynamic simulations are sensitive to node alignment and mesh density. In spite of the effort used to characterize the ball, its viscoelastic properties required tailoring to achieve the correlation observed in Figure 7**.** These properties are also summarized in Table 1.

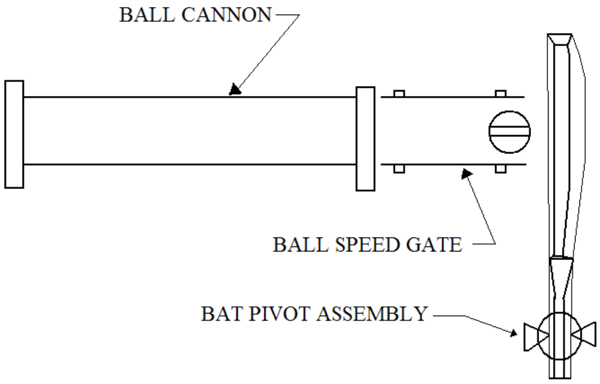

Figure: 6 Schematic of test fixture used to test cricket bats

3.3 Bat Testing Procedure

While cricket rules require the bat to be made of wood, some manufacturers have added a thin composite skin to the back surface. The mass properties of a bat with and without a skin are compared in Table 3. The skin stiffens the blade and is purported to improve durability. The performance of a bat was compared with and without a composite skin. The results are included in Figure 8, which shows the skin increased the BBS by 1.4%. It should be noted that removing the skin reduced the bat's *I* by 4.6%. The effect of *I* on bat performance, independent of the composite skin, may be considered in Eq. (3) and (4) using the bat-ball COR from the bat without the composite and increasing the bat *I*. Accordingly, a 4.5% change in *I* was found to increase bat performance by 0.85%. Thus, roughly half of the performance advantage attributed to a composite reinforced blade is due to its increased *I*.

The effect of the 0.005-in. (0.13-mm) thick composite skin was considered in the numeric model using the properties of Table 2. The results are included in Figure 8, where the skin increased the BBS by 1.3% The FEA results of Figure 8 considered a bat model with a different weight distribution than was tested experimentally. This different weight distribution is likely the cause of the 1% lower BBS obtained from the FEA.

4-Summary

This study considered the performance of cricket bats and balls. A finite element model has been used to investigate the performance of a bat numerically. A test apparatus to measure bat and ball properties at impact speeds representative of play conditions was shown to have utility in comparing bat and ball response. The FE models showed good agreement with the experimental data for bat and ball performance. Mass distribution and composite reinforcement were shown to have a measurable effect on bat performance. In comparison with hollow baseball and softball bats, however, the effect was relatively small.

	Material	Length (in / mm)	Weight (oz / g)	I (oz in^2 / g m^2)
Experiment	Willow, Cane	33.8 / 858	38.3 / 1088	10703 / 196
	Willow, Cane, Composite	33.8 / 858	36.8 / 1045	10216 / 187
FEA	Willow, Cane	34.3 / 871	41.9 / 1190	11711 / 214
	Willow, Cane, Composite	34.3 / 871	39.5 / 1122	12542 / 229

Table 3: Properties of Cricket bat and FEA used in the performance comparison

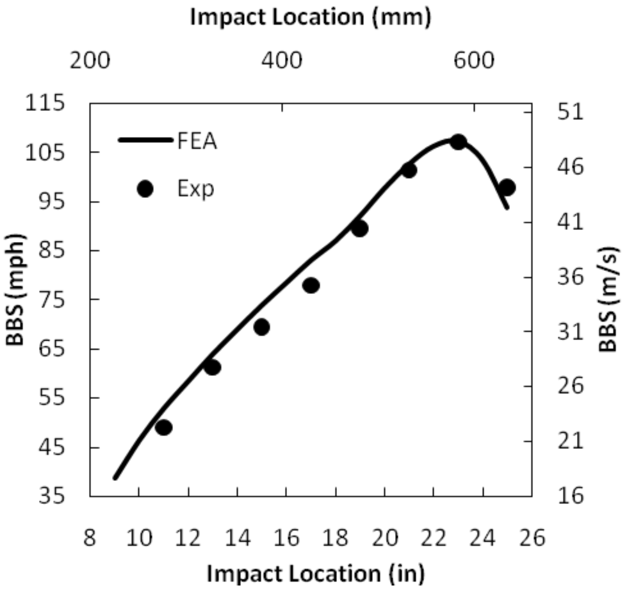

Figure 7: Representative performance curves for bat and model. (Impact location measured from the pivot, 6 in or 152 mm from the knob.)

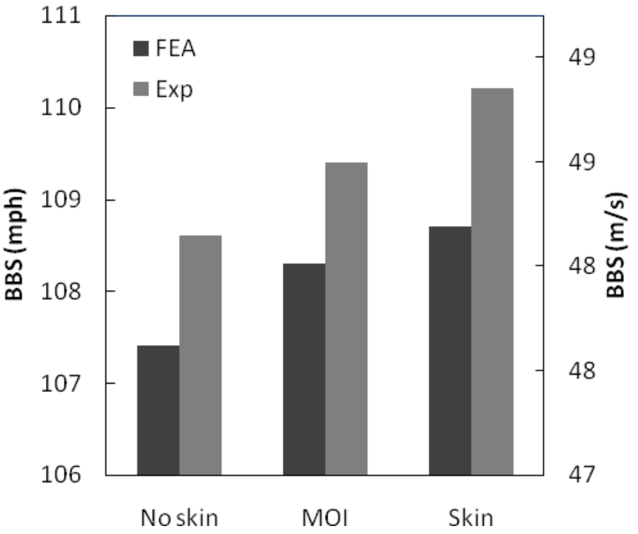

Figure 8: Comparison of finite element model and cricket bat with and without composite skin.

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