Simulated Composite Baseball Bat Impacts Using Numerical and Experimental Techniques

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ABSTRACT
A study has been undertaken to develop techniques for assessing baseball bat durability and performance. Experimental investigations were conducted by constructing a testing device to simulate the ball-bat interaction occurring in play. A sensitivity study of the machine's inertia and forces on the bat were found to have a small effect on hit ball speed, and a much larger effect on bat stress. A dynamic finite element analysis was employed to simulate the ball-bat interaction. The ball was modeled as a linear viscoelastic material. This provided a mechanism of energy loss during impact (coefficient of restitution) and accounted for its observed speed dependence. The model has found favorable correlation with experimental results of bat durability and performance. A bat reinforcement scheme was shown to significantly reduce bat stress with minimal accompanying changes in bat performance.

INTRODUCTION
Non-wood baseball bats were approved for collegiate play over 25 years ago. The primary motivation was to reduce the expense associated with replacing broken wood bats. There is growing concern recently, however, that non-wood bats (designed to hit the ball faster) have changed the historic balance of the game and may increase the risk of injury to players. Recent bat performance limits adopted by the NCAA have helped motivate interest in developing test methodologies and predictive capabilities regarding bat performance. The goal of these regulations is to make the hitting characteristics of non-wood bats similar to wood bats. The current study considers techniques to predict and measure the performance of baseball bats by examining the inverse problem: increasing the durability of wood bats.

MATERIALS
Key to modeling how components of a system, such as a bat and ball, interact is obtaining an understanding of the properties of the materials involved. The current study involves a ball and reinforced wood bat. The static properties of wood (Northern White Ash) and reinforcing composite (fiber reinforced polymer) are well understood and readily obtained from the literature [1,2]. However, the properties of a baseball are not available and are difficult to measure.

In the current study two types of baseballs are considered. The first is a traditional baseball, produced from yarn wound around a cork and rubber pill, and covered with leather. The second baseball type is synthetic, and commonly used in batting cages. It is injection molded from an air filled rubber and designed to simulate the hitting characteristics of a traditional baseball.

Several attempts were made to extract the elastic properties of the balls through quasi-static compression testing. These included compression loading a traditional baseball between flat plattens, and comparing the load displacement curve with a large deflection Hertzian type contact model [3]. For the case of the homogeneous synthetic ball, a uniaxial compression specimen was cut from the ball. The elastic modulus was then found from the compressive stress-strain response of this coupon. In both cases, however, the elastic modulus was apparently too low. This was determined by examination of ball deformation patterns from numerical impact simulations. It was postulated that the disparate strain rates achievable with a load frame and that occurring in an actual ball-bat impact (roughly three orders of magnitude) may be significant. Thus a time dependent material model and high load rate device were needed.

A strategy was developed to determine the properties of the baseball at high strain rates indirectly by modeling an

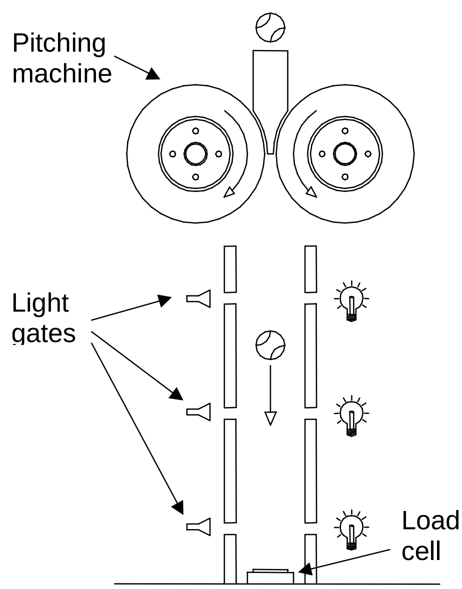

Fig. 1 Experimental set up for measuring the baseball coefficient of restitution.

instrumented ball impact with a dynamic finite element code. In the experimental setup, shown in **Fig. 1**, a ball was pitched toward a load cell. Light gates measured the ball speed before and after impact, and a high speed data acquisition system recorded the load vs. time data. A high speed video camera was also employed to monitor impact location, ball trajectory and ball deformation.

Load cell inertia can have a large effect on dynamic measurements. These inertia effects were minimized in the current study by mounting the load cell to a rigid surface (cement floor) and designing a light weight ball impact plate. The effect of load cell inertia was verified by observing its oscillation after the ball impact.

A viscoelastic material was selected for the ball, defined from a time dependent shear modulus as [4]

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

and constant bulk modulus, k. The material constants, G_∞, G_o, and β were found by fitting the experimental load-time curve with that obtained from the finite element analysis, and are presented in **Table 1**. The bulk modulus, k, was found from the instantaneous shear modulus, G_o, and Poisson's ratio. The Poisson's ratio was in turn selected from ball diameter comparisons between the model and experiment. Good agreement was achieved with the load-time curve, as shown in **Fig. 2** for a typical case involving a synthetic baseball.

The coefficient of restitution was found from the pitched and rebound ball speeds from both the model and experimental results. The comparison was conducted at four impact speeds. Good agreement was achieved between the finite element results and experiment, where a speed dependent coefficient of restitution may be observed in **Fig. 3**.

Table 1. Engineering properties of two baseball types.

Ball type	G_o (MPa)	G_∞ (MPa)	β	k (MPa)
Baseball	41	11	9,000	69
Synthetic	2	1	1,250	19

It should be noted that both wood and synthetic composites are known to exhibit time dependent behavior. This response has been neglected in modeling the bat, however, to simplify the analysis and reduce the number of free variables. The mechanisms contributing to a material's coefficient of restitution are numerous and complex. While the success of viscoelasticity in modeling these losses is encouraging, the motivation has been for computational efficiency.

BAT TESTING

An experimental apparatus has been developed in which a swinging bat strikes a pitched ball. The objective of this test is to simulate actual play in a controlled environment. Numerous simplifications concerning ball and bat motion have been made, however. The balls are pitched using a two wheel, counter rotating pitching machine. The pitching machine is placed close to the bat to increase pitch accuracy. The bat center of rotation is fixed but adjustable, and nominally set at 76 mm from the knob and off the bat 70 mm as indicated in **Fig. 4**. This location was found to be the most common center of rotation at impact from an extensive study of amateur and professional players [5]. A pneumatic cylinder, connected to a rack and pinion, drives the bat. The cylinder is used to accelerate and decelerate the bat before and after impact, respectively. The timing of bat deceleration

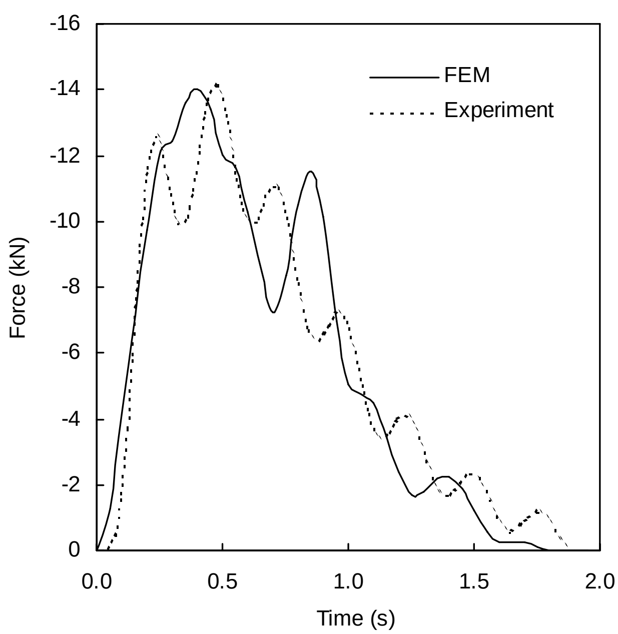

Fig. 2 Comparison of finite element results and experiment of a synthetic baseball impacting a load cell at 49 m/s.

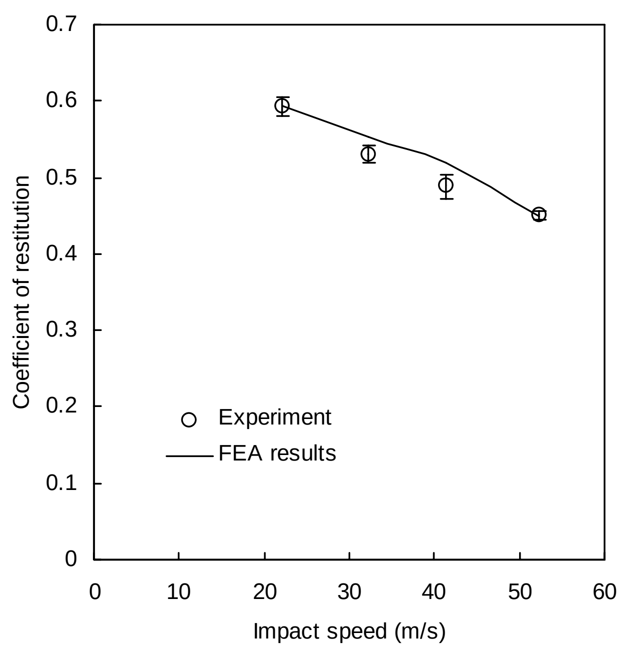

Fig. 3 Comparison of the experimental synthetic baseball coefficient of restitution and that predicted by the finite element model at four different impact speeds.

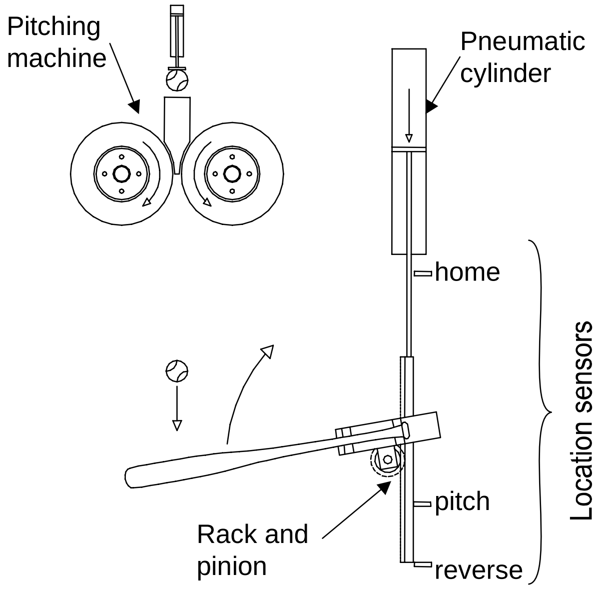

Fig. 4 Diagram of bat testing machine.

and ball pitch is accomplished through a series of non-contact electronic switches (labeled home, pitch and reverse in the figure) and a programmable logic controller. A torque cell and potentiometer in the load train allow bat torque, position and speed to be recorded for each test.

The durability of a bat can be quantified by measuring the number of hits before failure at a given speed or the maximum relative speed required to break a bat. In the name of expediency the latter approach has been the metric used in testing to date. There is a significant difference between the inertia and gripping stiffness of the bat machine and a player. This typically results in bat failure occurring at lower speeds in the bat machine than occurs in actual play. Reduced inertia and gripping forces are desirable to improve the comparison with player data. This has proven difficult to achieve experimentally, however.

To assess the effect of constraint on the bat performance and durability, four types of boundary conditions have been modeled, as shown in **Table 2**. The first three conditions have a fixed center of rotation, while in the forth, the bat is allowed to move freely after receiving the same initial rotational velocity as in the other conditions. In comparison to the bat inertia of 0.439 kg·m^2, the grip inertia varies from 0 to 0.090 kg·m^2. Fixture inertia appears to have a larger effect on bat durability (stress) than bat performance (hit ball speed). The larger effect of inertia on bat stress is likely due to its maximum occurring after impact and is related to bat

Table 2. Effect of bat constraint on stress and performance.

Constraint	Grip inertia (kg·m^2)	Max bat stress (MPa)	Hit ball speed (m/s)
Pinned	0.090	69	34.7
Pinned*	0.046	59	34.7
Pinned	0.018	50	34.7
Free	0	34	34.5

*Nominal valued used in the analysis.

vibration in the gripping fixture. It is unclear which condition most accurately represents a player's motion. Thus it may be expected that durability studies performed on testing machines of this nature should be conducted on a relative scale.

When a player swings a bat, a significant portion of the bat's motion is translation. There is concern that the torque required to accelerate a bat in a testing machine (rotating about a fixed center) may induce large bending stresses. While a bat machine may be designed to release the torque during the ball impact, timing inconsistencies do not always allow this to occur. The effect of applied torque during ball impact was considered in the numerical model, results of which are presented in **Table 3**. A torque of 56 N·m was applied to the gripping fixture, and represents a typical value if zero impact torque was not specified. The torque resulted in a slight increase in bat speed, but apparently not sufficient to affect the hit ball speed. The applied torque is observed to increase the maximum bat stress by 10%.

COMPOSITE REINFORCEMENT

With a metric in place to assess bat durability, mechanisms improving bat strength can be investigated. The most common region of bat failure occurs in the handle of the bat. A composite sleeve was placed over the handle to strengthen this region. The effect of handle reinforcement on the bat static stress and deflection may be obtained using a number of closed form analytical techniques. Assessing the influence of reinforcement on dynamic impact is not trivial, however. The impulse of a compliant bat must equal that of a stiff bat, under similar impact speeds. A stiff bat will have a shorter relative contact duration with the ball, however, and therefore a larger impact force. To increase durability, the reinforcing medium must, therefore, impart a greater increase in strength than stiffness to the bat. To this end, composite sleeves in unidirectional and biaxial orientations made from carbon, glass and aramid fibers have been investigated.

NUMERICAL RESULTS

With a testing machine and numerical model in place, comparisons between experimental and predicted bat performance may be conducted. Comparisons of hit ball speed vs. impact location are presented in **Fig. 5** for an unreinforced and reinforced bat. The reinforcement selected for comparison employs a unidirectional glass sleeve. The experimental and numerical results are found to be in good agreement over a wide range of impact locations and speeds. The numerical results show that the reinforcement may increase the bat performance slightly; this finding appears to be supported by the experimental results.

The effect of reinforcement on bat stress is shown in **Fig. 6**

Table 3. Effect of applied torque on bat stress.

Torque (N·m)	Grip speed (rad/s)	Max bat stress (MPa)	Hit ball speed (m/s)
0	35	118	29.2
56	37	130	29.2

for the same conditions shown in **Fig. 5**. The reinforcement appears to have a large positive effect on bat stress. Surprisingly, the reinforcement considered here reduces the bat stress more than that achieved by reducing the swing speed by 40%.

SUMMARY

A study has been undertaken to develop experimental and predictive techniques for assessing baseball bat durability and performance. A sensitivity study of the machine's inertia and forces on the bat have been shown to have a negligible effect on hit ball speed, and a measurable effect on bat stress. Accordingly, the device has been used on a relative scale to measure bat durability.

A dynamic finite element analysis was employed to simulate the ball-bat interaction. Modeling the baseball as a linear viscoelastic material provided a mechanism of energy loss during impact (coefficient of restitution) and accounted for its observed speed dependence. The model has found favorable correlation with experimental results of ball-bat impacts. Reinforcing the bat was found to provide a large decrease in bat stress with minimal change in its hitting performance.

ACKNOWLEDGMENTS

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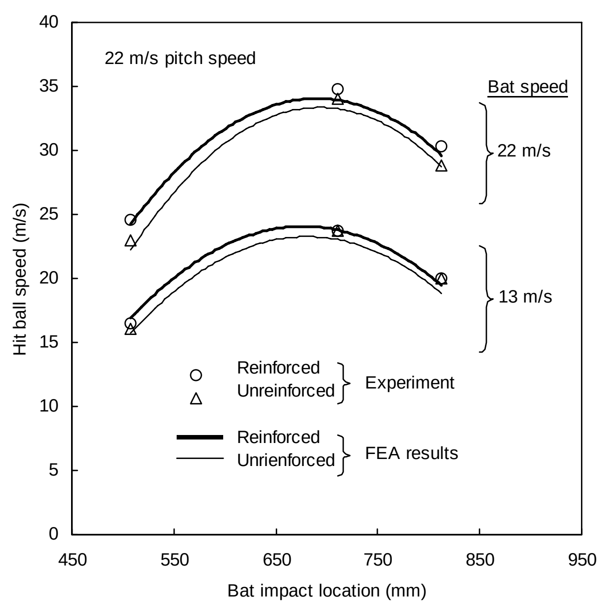

Fig. 5 Comparison of simulated hit ball speeds from finite element results and experiment for an unreinforced and reinforced wood baseball bat.

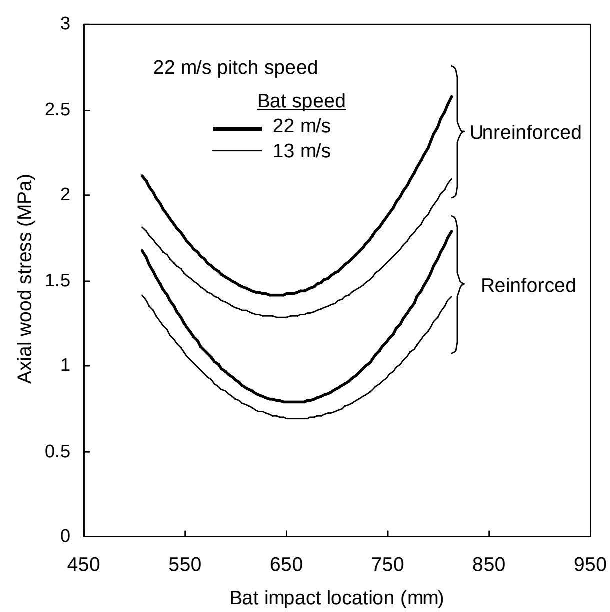

Fig. 6 Comparison of bat stress reduction imparted from composite reinforcement.