EFFECT OF COMPOSITE REINFORCEMENT ON THE DURABILITY OF WOOD BASEBALL BATS

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ABSTRACT

This study examines the durability of a laminated wood baseball bat reinforced with an e-glass braided sleeve. A novel processing technique, referred to as reverse balloon molding, was developed to apply the reinforcement. Production trials indicate that this technique has a higher production rate, similar consumable material cost, and produces a superior surface finish with less rework and lower operator skill level than current traditional methods. A testing device is described which allows controlled dynamic experimental evaluation of baseball bats. A computational model is also presented which may be used to accurately predict bat stresses and hitting characteristics. The measured and predicted results are in good agreement. Wood lamination was observed to decrease the scatter in bat stiffness and strength that is inherent with wood. Results of this work indicate that significant improvements in bat durability are achievable with minimal reinforcement.

KEY WORDS: Baseball Bat, Durability, Dynamic Finite Element Analysis

INTRODUCTION

The game of baseball enjoys a long history. Until the last 20 years, only solid wood was used to make baseball bats. Over the past few decades, however, numerous amateur leagues have allowed bats made from aluminum and advanced composites. While the initial intent of using non-wood bats was to increase its durability, many bats have been designed to hit the ball further than may be accomplished with a solid wood bat. This increased hitting performance is a cause

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Table 1. Longitudinal properties of common woods used in bats.

Material	E (GPa)	MOR (MPa)	μ
Ash	12	103	0.60
Hickory	14	123	0.62
Maple	13	109	0.63

of concern for some. The increased hit ball speed is believed to increase the risk of injury to players, while the increased hitting ability may provide an advantage to the batter thus changing the traditional balance of defense and offense. These concerns, combined with the upward spiraling costs of some non-wood bats, have led to renewed interest in wood bats. The focus of the present study is to increase the durability of wood bats using advanced composites.

An understanding of the bat response in the bat-ball impact is important to developing an effective reinforcement strategy. An experimental testing device has been developed to simulate a dynamic ball-bat impact. A dynamic finite element model has also been developed to predict the bat response where experimental testing may not be feasible or possible. The measured and predicted bat response are shown to be in good agreement, and begin to explain how the traditional wood bat can be made more durable without changing its hitting performance.

MATERIALS

The Major Baseball League will certify any bat made from a single solid piece of wood [1]. As may be expected, however, some woods have a higher specific strength and modulus (strength and stiffness divided by density, respectively) than others. Early in the history of baseball bat strength was considered more important than weight. Thus most bats were produced from a relatively strong, but heavy wood (Hickory was a common choice). Over the years, however, there has been a shift toward lighter bats. Today most bats are constructed from Northern White Ash. While Maple has also been used to produce bats, this species does not generally have the weight benefits of Ash. Maple is popular among some players, however, for an apparent increase in surface integrity. The elastic modulus (E), modulus of rupture (MOR) and specific gravity (μ) of these woods are compared in **Table 1** [2]. It should be noted that the values listed in **Table 1** are average. The variation of these properties can be large. Grain size and orientation, knots in the wood, and density can all have an effect on bat durability. Wood quality may be controlled to some degree, however, through lumber grading and crop management.

Northern White Ash has been used to produce bats for the current study. The billets from which the bats were turned are made from a three-piece lamination. The wood slats are selected and placed in the billet according to their mechanically graded properties. Static testing of these and one-piece bats indicate that this selective lamination scheme decreases the scatter in the stiffness and strength of the bat, as shown in **Fig. 1**. It has not, however, resulted in a measurable increase in bat durability.

Wood failure is complex and not well understood. In the case of a baseball bat failure it is often observed to occur just beyond the handle. (A region spanning between 150 and 500 mm from the knob end of the bat.) A scheme incorporating advanced composites has been devised to

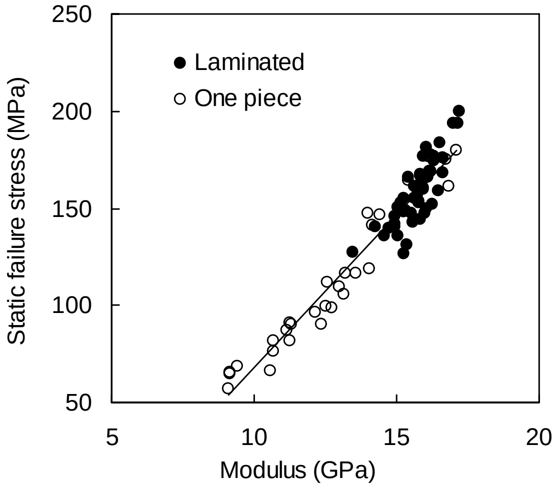

Fig. 1. Static strength of one-piece and laminated bats as a function of bat stiffness.

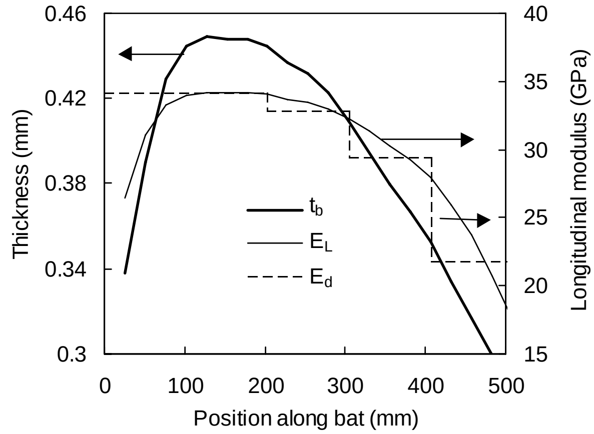

Fig. 2 Variation of a braided reinforcement thickness and modulus as a function of bat position.

strengthen the bat in this area. The geometry of the bat over this region is somewhat hourglassed in its shape. Braided sleeves were therefore selected for reinforcement given their wide availability and good draping characteristics. These desirable draping properties also complicate the determination of the elastic properties of the reinforcing sleeve. The sleeve is able to conform to the changing bat diameter by changing its braid angle. Since the volume of the sleeve is conserved, its wall thickness changes with bat diameter as well. Thus, the reinforcement's orientation and thickness change continuously with the contour of the bat as shown in **Fig. 2**. The properties of the reinforcements were found using established procedures for textile composites. Details of this work and comparison with experiment may be found elsewhere [3].

REVERSE BALLOON MOLDING

The composite reinforcement may be applied to the bat in a number of ways. The configuration of the bat design placed limits on the processing options, however. Heat curing of production parts is often necessary to reduce cure time. Heat has undesirable consequences for wood, however. Wood has limited temperature resistance, and large moisture expansion as it dries in an oven. An ambient curing system was therefore devised, using a wet lay up process with a short pot life epoxy, as described in detail below.

The large number of bat models and lengths make flexible tooling very desirable. Two traditional flexible molding operations were investigated: a tube-clave and consolidation wrapping. The tube-clave was unable to conform to the contour of the bat where diameters ranging from 25 to 60 mm were common. The limited life of the flexible membrane and large number of tube-claves necessary for an ambient cure were also of concern. Wrapping the reinforcement with heat shrink tape or strips of release cloth was also investigated. These methods were better able to conform to the contour of the bat, but required a high level of operator skill and required secondary sanding operations.

Given the inability of traditional processes to produce a satisfactory reinforcement, a novel molding procedure, referred to here as reverse balloon molding, was developed. (A patent application has been filed for this process.) The process may be described in general terms according to the following five steps, as shown graphically in **Fig. 3**.

1. A part to be molded is prepared. (While the case at hand considers a baseball bat, any primarily axisymmetric shape could be conceivably molded using this process.)
2. An elastomeric tube, approximately ½ the minimum diameter of the part, is partially inflated like a balloon.
3. The molded part is pushed into the inflated tube, or balloon, continuing until the inflated tube encloses the molded part.
4. The tube is deflated or otherwise constrained from coming off the part while it cures. If the part is totally enclosed inside the balloon no constraint or deflation is necessary.
5. After the part has cured, the elastomeric tube is inflated, which pushes the cured part out of the tube.

While simple in concept, the reversed balloon molding process has a number of advantages over the wrapping method for this application. Since no rigid tooling is involved capital investment is minimized. The cost of consumable materials is similar. In production trials part time has been nearly cut in half. The improved surface finish eliminated the need for secondary sanding operations and was achieved with greater reliability and at a lower operator skill level.

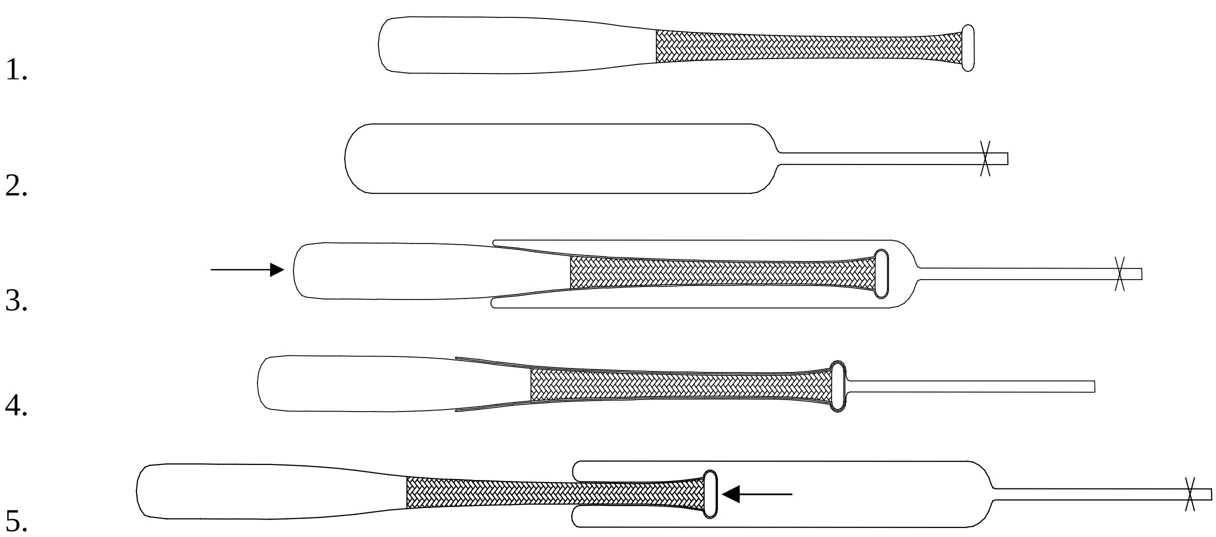

Fig. 3 Five step reverse balloon molding process used to reinforce a wood baseball bat. 1-part preperation, 2-balloon inflation, 3-part insertion, 4-balloon deflation and part cure, 5-balloon inflation and part removal.

Table 2. The effect of reinforcement on bat stiffness.

Bat stiffness	Wood	Reinforced
Analytical (kN/m)	209	253
Experimental (kN/m)	211	252
COV (%)	8.4	8.1

BAT STIFFNESS

The effect of bat reinforcement was experimentally assessed from a static three-point bend test and compared with an analytical model. The experimental test consisted of a 223 N (50 lb) force applied centrally between supports 560 mm (22 in) apart. The support on the handle region was 150 mm (6 in) from the knob end of the bat. The stiffening effect of the composite reinforcement is shown in **Table 2**, where the average bat stiffness from the nine bats tested is observed to increase by 21%. Bat stiffness was computed analytically by numerically fitting the bat profile and integrating along its length using Castigliano's method [4]. The good agreement between the experimental and analytically computed stiffness is an indication of the part quality achieved with the balloon molding process.

The laminating and reinforcing schemes discussed above are intended to improve the durability of a bat. The stiffness and strength of a bat interact in complex ways during the dynamic impact with a baseball. A method of assessing durability that closely simulates its intended service is therefore needed. In the following, two approaches of assessing bat durability will be discussed. The first involves a physical testing device, while the second concerns a predictive numerical model.

BAT TESTING APPARATUS

An experimental apparatus has been developed in which a swinging bat strikes a ball. The speed of both the bat and ball are controlled. The objective of this test is to simulate actual play in a controlled environment. Numerous simplifications concerning ball and bat motion have been made. The balls are pitched using a two wheel, counter rotating pitching machine, such that the ball impacts normal to the length of the bat with minimal rotation. The pitching machine is placed close to the bat to increase pitch accuracy. The bat rotates in a single plane about a fixed but adjustable center of rotation, 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 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. A high-speed video camera (500 frames per second) allow determination of the pitched and hit ball speed as well as verification of the bat swing speed and hit location.

The loads introduced into the bat from the testing machine are obviously different from what might occur in actual play. A study was conducted to examine the effects of the testing machine on the bat stresses and hitting characteristics [6]. It was observed that the machine inertia and torque have a minimal effect on the bat hitting performance, yet a significant effect on the magnitude of the bat stress. This may be explained by consideration of the bat-ball contact duration, which is typically on the order of 1 ms (and less than the period of oscillation of the bat). During this short interval the flexible grip supporting the bat is unable to introduce significant load into the bat. The system inertia or applied torque, therefore, do not affect the impulsive force delivered to the ball. The peak stress occurs within about 5 ms after the initial impact, as the bat passes the point of maximum bending displacement. (The exact time depends upon the frequency of the bat vibration.) It is at this point that the grip forces become significant and the system inertia is transferred to the bat. This often results in bat failure in the testing machine at lower relative velocities than is observed in play.

An ideal bat durability study would employ a testing device with minimal system inertia. Matching the machine inertia to an actual player does not appear to be currently possible. Useful information concerning bat durability may still be garnered by conducting tests on a relative scale, however. Using a testing machine in this way to assess bat durability provides increased repeatability and controllability, both of which are difficult to achieve in field-testing.

DYNAMIC FINITE ELEMENT MODEL

The interactions of the bat and ball were modeled using a commercial dynamic finite element code, LS–Dyna 3D version 950 (Livermore Software Technology Corp., Livermore, CA). All the analyses were performed on a 600MHz Pentium III processor. The model consisted of 2048 and 9696, 8–noded solid elements for the ball and wooden bat, respectively, as shown in **Fig. 5.** The reinforced sleeve was meshed using 4–noded Hughes Liu shell elements which provide

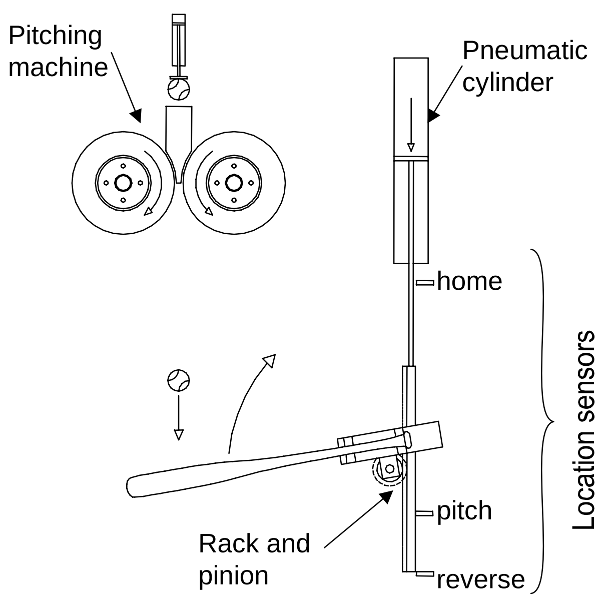

Fig. 4 Diagram of the bat testing machine.

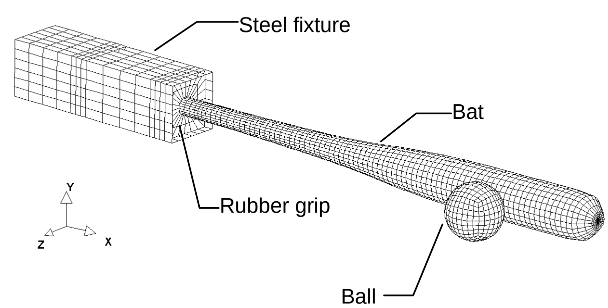

Fig. 5. Dynamic finite element mesh.

improved compatibility with solid elements [7]. While these elements can accommodate shell thickness changes, the preprocessor used to generate the model, did not. The sleeve was, therefore, discretized into 4 regions, where mean values for the thickness and modulus of each region were used. The discretized longitudinal modulus, E_d, used for the braided sleeve is shown in **Fig. 2**. The computational model used a time dependent material model to describe the response of the ball. This allowed surface contact energy losses between the bat and ball to be accommodated.

BASEBALLS

Strict rules govern the manufacture and performance of baseballs in professional and amateur play [1]. The objective of these rules is to maintain a consistent competitive balance between the pitcher and hitter. Traditional leather covered balls degrade readily, however. Commercial batting cages reduce the expense of ball replacement by using a more durable synthetic ball. Synthetic balls are desirable to use in durability studies because their deformation response is more repeatable than a traditional ball. While comparisons between ball types generally focus on their hitting performance, the effect of ball type on bat durability has received less attention. The impact behavior of the two types of balls has been shown to be quite different [5]. The effect on strain response for the two ball types is examined below.

STRAIN MEASUREMENT

The response of the bat to baseball impacts may be monitored by bonding strain gages to its surface. Strains obtained in this manner can be used not only to consider the effect of various impact scenarios, but also to validate the predictions of the computational model. Many of the results considered here involve a swinging bat impacting a stationary ball. This was done to increase the accuracy of ball placement, and in many cases provides a more meaningful comparison.

Resistance type strain gages with a 6 mm (0.25 in) gage section and 350 ohm nominal resistance were bonded to a reinforced bat at x_s = 230, 300, and 380 mm (9, 12, and 15 inches) from the knob end of the bat. These gages were bonded to the composite reinforcement. This provided a more homogenous surface than wood to monitor strain. The strain gages were conditioned using a Vishay 2120A signal conditioner from the Measurements Group. Computer data acquisition was accomplished using a National Instruments PCI-MIO-16XE-10 analogue to digital data acquisition board. The board had a maximum scan rate of 100 kHz. Typically four channels of data were acquired, resulting in a data capture rate of 25 kHz. LabView software was used to configure and record the data from the a/d board running on a 400 MHz Pentium computer with Windows NT.

EXPERIMENTAL STRAINS

The strain response from a typical bat-ball impact is presented in **Fig. 6**. The strain is from a bat swinging at V_b = 30 m/s (70 mph) (measured 150 mm (6 in.) from the end of the barrel) and impacting a stationary ball at x_i = 500 mm (20 in.) from the knob (inside hit). The strain is recorded from a gage placed x_s = 300 mm (12 in.) from the knob. Bat oscillations are apparent even before impact ($t < 0.28$ s) with the ball, although at a relatively low frequency and magnitude. These oscillations are apparently unique to the hitting machine, and are a result of the large torque that must be quickly applied to accelerate the bat in less than one revolution. The inside hit initially induces compressive stresses on the pitcher side of the bat. Since the bat-ball contact is on the order of 1 ms, the maximum compressive strain is observed to occur after the ball has left the bat. The impact induces a vibration of higher frequency and magnitude than existed before the impact. This vibration would be described as "stinging" the hands from a batter. These high frequency vibrations dampen out relatively quickly, however, and appear to be superimposed over the initial bat vibration that was apparent before the bat-ball impact.

To assess the effects of ball type on the bat response, the strain response of a bat impacted with a traditional and synthetic ball are compared in **Fig. 7**. In this case a bat swinging at V_b = 20 m/s (50 mph) is impacting a stationary ball at x_i = 800 mm (32 in.) from the knob. Surprisingly, the initial strains induced in the bat are compressive. This result is repeatable and also predicted by the computational model. The magnitude of the compressive strains are small, however, and are soon dwarfed by the large tensile strains on the pitchers side for an outside hit, which were expected. The trends of the strain response from the two balls are similar. The traditional ball, however, appears to induce larger peak strains and vibrations after impact. This is consistent with the mechanical response observed in the traditional ball, which is roughly one order of magnitude stiffer than the synthetic ball. It is interesting, that increasing the stiffness of the ball by a factor of ten only increases the strains in the bat by 20%.

Bat durability may be assessed at various impact locations along its length. It is helpful to understand the effect of impact location on the magnitude of the induced strains. To this end a bat was impacted at Δx_i = 50 mm intervals along its length. Strains were recorded on the pitcher

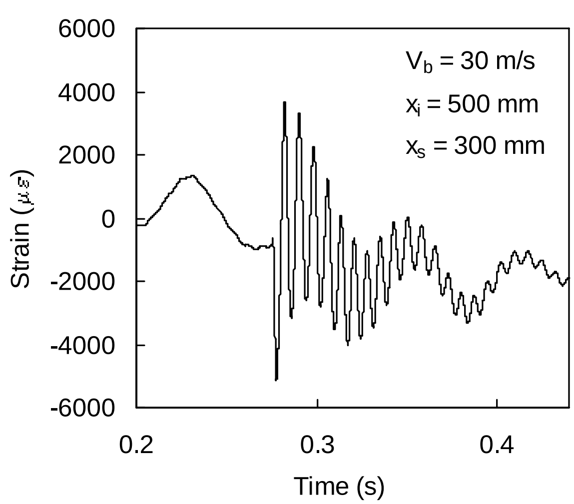

Fig. 6. Representative strain response of a swinging bat impacting a stationary ball.

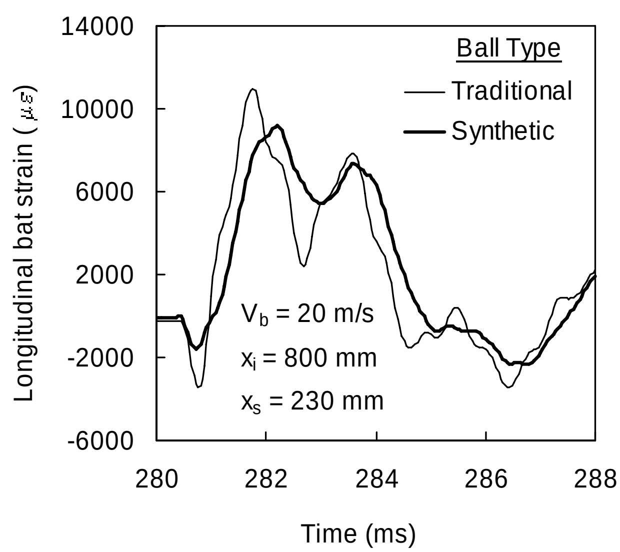

Fig. 7. Comparison of strain response between a traditional and synthetic ball impacting a bat.

and catcher side of the bat, peak values of which are presented in **Fig. 8** as a function of impact location, x_i. The compressive strains appear consistently larger than the tensile strains, which appears to be related to the deceleration of the bat after impact. This illustrates another difficulty in relating the laboratory bat durability predictions with field conditions. The laboratory durability measure is nevertheless useful, as bat durability is typically measured on a relative scale. Qualitatively, the trends of **Fig. 8** are consistent with the expected bat response. The strains are minimum for impacts near the bat's center of percussion, for instance, and outside hits produce large strains near the grip, while inside hits produce peak strains further outside of the grip.

COMPARISON OF MEASURED AND PREDICTED STRAINS

The finite element model of the bat-ball collision can offer insight when assessing the durability of a bat. Past work has focused on the bat's hitting performance, where the model has found excellent agreement [3]. The current work provides an opportunity to verify the predicted strain response with experiment. **Fig. 9** compares the strain of a bat swinging at V_b = 30 m/s (70 mph) and impacting a stationary ball at x_i = 500 mm (20 in.) from the knob (inside hit). Strains are measured at x_s = 300 mm (12 in.) from the knob of the bat. The strains obtained from the model and experiments are in good agreement. This agreement was observed for many bat and ball speeds and impact locations.

It should be noted that the low frequency oscillations observed experimentally from the applied torque do not occur in the model. Also, the energy dissipation after impact is different in the model than that observed experimentally. The good agreement between the model and experiment is typically only observed for the first few oscillations after impact. This is nevertheless the most relevant period, when bat failure often occurs.

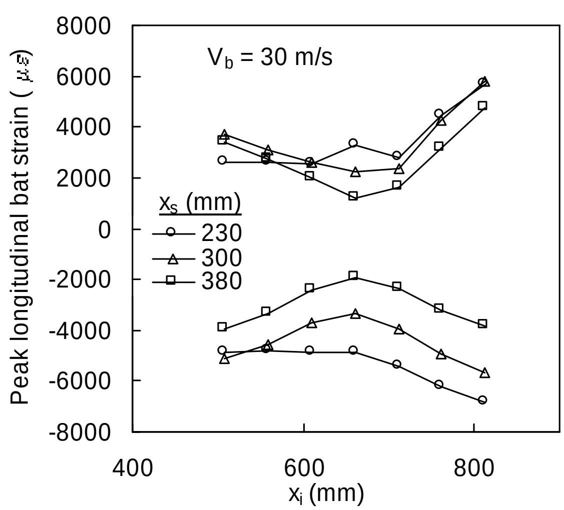

Fig. 8. Peak longitudinal bat strains as a function of impact location along bat.

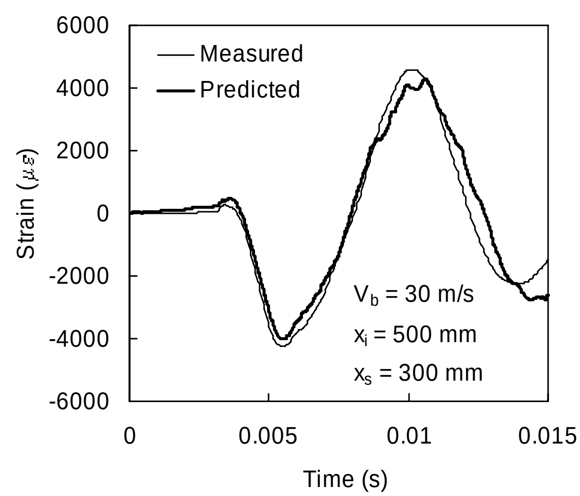

Fig. 9. Comparison of measured and predicted strain response of a bat impacting a stationary ball.

Table 3. Predicted longitudinal and transverse stresses of a wood and reinforced bat.

	x_i = 500 mm (inside)		x_i = 800 mm (outside)	
Stress	Wood	Reinforced	Wood	Reinforced
σ_L(MPa)	55	50	92	80
σ_T (MPa)	15	13	21	16

It is difficult to experimentally assess the effect of the reinforcement on the bat's strain response given the challenges in bonding strain gages to wood surfaces. The finite element model offers an obvious remedy to this dilemma. **Table 3** provides a comparison of the maximum stresses between a wood and reinforced bat in the longitudinal and transverse (pitcher) directions for inside and outside hits. While stress in the transverse direction is nearly an order of magnitude lower than the longitudinal direction, so is its strength. At failure, both the longitudinal and transverse stresses are near their critical values. The reinforcement is observed to decrease stresses from inside hits by approximately 10%, while stresses from outside hits may be reduced by over 20%.

DURABILITY ASSESSMENT

In the absence of a rigorous failure criterion for wood, durability predictions based on either measured or predicted strains are difficult to defend. The effect of the composite reinforcement on the bat's durability was, therefore, compared on a relative basis. The durability of a bat can be quantified at a constant relative impact speed by counting the number of hits to failure or by impacting the bat at increasing levels of relative speed and recording the maximum speed required to break a bat. The latter approach has been adopted for the current study.

A group of 20 bats of the same profile, and of similar weight and static stiffness were selected. Ten of these bats were reinforced and 10 were left unreinforced. Half of each group were tested at an impact location of x_i = 500 mm (20 in.) and the remaining were tested at x_i = 800 mm (32 in.) from the knob. In the durability testing, the bat speed ranged from V_b = 20 to 30 m/s (50 to 70 mph), while the pitch speed ranged from V_p = 30 to 50 m/s (70 to 120 mph). In some cases the bat did not break. The maximum relative test speed and energy was used in these instances.

Table 4. Effect of reinforcement on the average durability of a wood bat.

	x_i = 500 mm (inside)		x_i = 800 mm (outside)	
	Wood	Reinforced	Wood	Reinforced
Energy (N·m)	307	582	328	495
Relative speed (m/s)	58	78	66	86

The average relative speed before impact and energy at impact required to break each group of bats is shown in **Table 4**. The improved bat durability is substantial, where the energy required to break a bat increases from 50% to 90% for outside and inside impacts, respectively. The greater improvement in durability observed for inside hits may be due to the location of maximum stress. It occurs further from the grips than an outside hit, where the bat diameter and hence the inertia of the reinforcement are larger.

Relative speed is a common measure of bat durability, and is easier to compute than energy. As shown in **Table 4**, however, it underestimates the magnitude of the durability increase for inside and outside hits.

SUMMARY

Two methods of improving the durability of a wood bat have been evaluated. The effect of producing wood billets from graded laminated slats appears to reduce the variability inherent in wood, but does not exceed what might be achieved with an ideal piece of lumber. The effect of reinforcing the exterior of the handle region of the bat with an advanced composite appears to have a significant effect on its durability. The increase in static stiffness afforded by the composite reinforcement was accurately predicted by taking into account the curvature of the bat, and changing orientation and thickness of the reinforcement. The increased durability of the bat was assessed through dynamic testing and computational modeling. The experimental testing showed increasing longitudinal strains in the bat with distance of the impact location from the bat's center of percussion. Higher strains were also observed for impacts with traditional leather balls than with synthetic balls commonly used in batting cages. Dynamic testing indicates that reinforcing a wood bat increases its energy absorption capabilities significantly. For the case at hand the energy increased 90% for inside hits and 50% for outside hits over a similar unreinforced bat. The computational model suggests that both the longitudinal stresses and transverse stresses are near their ultimate values when the bat is exposed to a maximum dynamic load. Stresses in both directions should be considered when bat durability is at issue.

ACKNOWLEDGEMENTS

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