A Study of the Barrel Constructions of Baseball Bats

Lawrence P. Fallon, PE
Graduate Research Engineer
University of Massachusetts, Lowell, Massachusetts, USA

James A. Sherwood, Ph.D., PE
Director, Baseball Research Center
University of Massachusetts, Lowell, Massachusetts, USA

ABSTRACT: The barrel construction of a baseball bat is a critical design feature in its performance. The geometry, mass distribution and material play an important role in the ball exit speed as well as the potential swing speed that a player can achieve. Tubular aluminum barrels have been shown to outperform solid wood bats by as much as 8%. Major League Baseball (MLB) has continued to allow only solid wood bats in its leagues—with ash being the most popular wood. On occasion, players try to "get an edge" by drilling out their wooden barrels and filling them with cork or other materials. In this paper, the relationship between barrel design and its performance is investigated. The study incorporates theoretical, computational and experimental techniques.

The role of diameter and large deformation theory are quantified and the trade-offs between performance and durability due to metal barrel thickness are evaluated. To visualize local deformations, a finite element analysis is overlaid with strain data collected when a MLB player used a new aluminum bat. Pre- and post-impact measurements reveal material yielding on each hit. The possibility of improved performance through workhardening is discussed.

Finally, the question is addressed as to whether a corked wooden bat really out-performs a solid wood bat. Although commonly thought that "corking" a bat provides hitters with better control but no additional power, the results of this study show a slight increase, on the order of 1%, in batted-ball speed with the corked bats in comparison to their solid-wood counterparts.

INTRODUCTION

Some of the factors that influence the design of a baseball bat include manufacturing cost, marketability and game-play legality. However, the two major engineering factors are the resulting bat performance and durability of the product. Ideally, a bat should be designed to match the player's strength and provide just enough durability to optimize the bat's performance. There are three failure modes commonly found in solid-wood bats:

(1) Handle fracture,
(2) Barrel fracture, and
(3) Barrel grain flaking.

Aluminum bats are commonly shelved when a player feels the bat looses its pop. This loss of performance is a result of continuous impacts that fatigue the material and eventually lead to cracks. Where professional and top college players use only their own bat, smaller university teams often have several players using the same bats. In addition, an aluminum bat typically lasts the whole season, whereas a professional player is likely to break a game bat every couple weeks. It is not unlikely that a professional player could break a wood bat after less than a dozen solid contacts. A 2.5-in diameter barrel can have anywhere from 7 to 50 grains. Professional players often have a barrel-grain-density preference of 13 to 20 grains.

There are many factors that influence how far a batted baseball will travel. Among these factors are environmental conditions, pitch speed, bat speed, ball Coefficient of Restitution (COR), impact location and of course, bat design. The main variables of bat design are material and geometry. Two examples of bat barrels are shown in Fig. 1. Bats have been constructed from a variety of woods including ash, hickory and beech. Barry Bonds set the MLB homerun record in 2001 using a maple bat. More recently, some bats have even been constructed of laminated bamboo.

A variety of laminated wood bats are now on the market. They offer patented joining methods, combinations of wood materials and fiberglass, and Kevlar or carbon reinforced handles and barrels. The question arises; does the epoxy in a composite-encased barrel enhance the bat's performance? For that matter, what is the performance effect on a wood barrel if it is "boned", flame tempered or cryogenically frozen? The answers to these questions have not been determined, but it is likely that they have more of an effect on the bat's durability and marketability than its batted-ball performance.

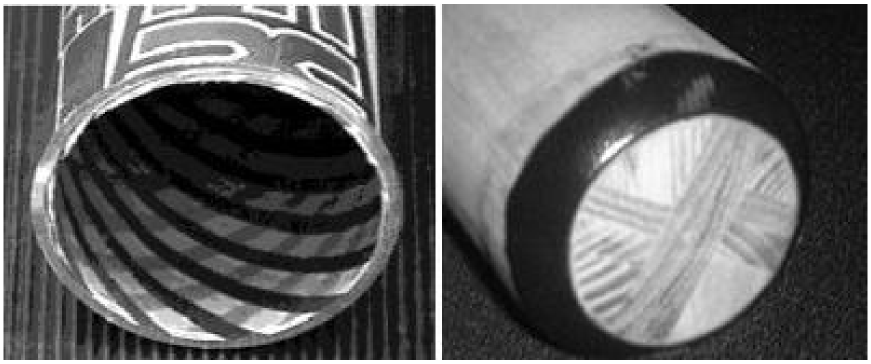

Figure 1. Carbon Reinforced Aluminum Bat and Hickory-Ash Laminated Bat.

The design of the bat handle has a major effect on the bat's overall strength and a lesser effect on its performance (as compared to the barrel design). The handle flexibility will define the amount of "whip" energy that can be transferred to the ball on impact. It also is the driving factor behind the bending modes and the sweetspot nodal point locations. Designers have attempted to overlay the barrel nodal points of the first three modes to decrease the amount of excitation of these modes—thus maximizing the performance of the bats.

The design of the barrel is critical in the bat's performance and to the durability of that barrel. Surface finishes can extend the life of a wooden barrel. For shell-type barrels, geometric features such as wall thickness and barrel diameter, and material characteristics such as strength and elongation, play an important role in its performance. When a player "corks" a bat, he lightens the bat to improve the control of his swing and often attempts to improve the resilience of the barrel and to increase the energy transfer to the ball.

SOLID VS. SHELL

One of the key reasons for variations in bat performance is the amount of energy stored in its barrel and transferred to the ball. According to Adair (1994), the energy stored in the deformation of a solid-wood bat is 2% the deformation energy stored in a ball during the collision. For an aluminum bat, the ratio of energy stored in the bat is more like 10%. Adair also states that the wood bat has poor energy efficiency, similar to that of the ball (if the COR of the ball is 0.500 then its kinetic energy efficiency is the square root of the COR or 71%). The efficiency of the aluminum barrel is closer to 99% if it stays in the elastic range, and the resulting energy exchange has been referred to as a "trampoline effect".

When selecting a material for a solid wood bat, important material characteristics (properties) include strength (Modulus of Rupture), stiffness (Modulus of Elasticity), density (or specific gravity) and hardness (compression). Table 1 contains properties for a variety of woods.

Table 1 Mechanical Properties for Wood

Material	Modulus of Rupture (ksi)	Modulus of Elasticity (10^3 ksi)	Specific Gravity	Compression Parallel to Grain (ksi)	Relative Strength to Weight Ratio
White Ash	15.0	1.74	0.60	7.4	1.00
Hickory	18.1	1.89	0.69	8.0	1.05
Maple	15.8	1.83	0.63	7.8	1.00
Beech	14.9	1.72	0.64	7.3	0.93

Notes: Properties are typical for wood with a moisture content of 12%.
Values are averages and variations of 10-25% are common.
Strength-weight ratio normalized to 1.00 for white ash.

There is much variability within the species. Growth environment (i.e. northeastern USA, southeastern USA, etc), billet preparation (kiln or microwave dried) and storage conditions (moisture content) all affect the strength and performance of the bat. It can be concluded from the strength to weight ratios in

Table 1 why ash and hickory were the most popular choices for bats. It can be concluded from the compression strength why hickory provides excellent barrel integrity, however, as pitching dominance increased, ash became the material of choice because the lower specific gravity resulted in lighter bats, better bat control and increased contact frequency.

There are many materials that could be used to make a shell-type barrel. Aluminum was first introduced at the amateur level for economical reasons because of the high cost of replacing broken wood bats. As the popularity of amateur baseball increased, the driving force for the non-wood bats shifted from economics to performance. The mechanical properties of the aluminum bats continuously improved. Other materials such as ceramics, fiberglass, graphite and titanium also entered the market. The typical mechanical properties of some of these materials are listed in Table 2.

Table 2 Mechanical Properties for Non-Wood Potential Bat Materials

Material	Yield Strength (ksi)	Ultimate Strength (ksi)	Modulus of Elasticity, *E* (10^3 ksi)	Pois. Ratio ν	Density (lb/in^3)	Maximum Elongation (%)
Aluminum 7075	73	83	10	0.33	0.10	11.0
Glass-Epoxy	-	120 x-axis 5 y-axis	8.0 x-axis 1.2 y-axis	0.2	0.07	1.5
Carbon-Epoxy	-	210 x-axis 6 y-axis	19.0 x-axis 1.3 y-axis	0.2	0.06	1.1
Thermoplastic PEEK	-	308 x-axis 11.6 y-axis	19.4 x-axis 1.3 y-axis	0.44	0.05	1.8
Ceramic ZrO2	-	80	27	0.33	0.22	0.3
Titanium	131	141	16	0.33	0.16	13.0

Thin wall theory is valid for cylinders whose inner diameter is more than 20 times greater than the wall thickness. This ratio is typically the case for the barrel section of a non-wood bat. To size the wall thickness and to compare the performance of different barrel materials, a generalization can be made using some classical formulas for stress and deformation, along with a formula for ball exit velocity developed from the Conservation of Momentum equation and the definition of Coefficient of Restitution (COR or *e*).

For material comparison purposes, the stress at ball impact on a metal barrel will be similar to that of an open-ended cylinder subject to a uniform radial pressure p. The maximum hoop stress, σ_{Hoop}, can be estimated using Equations (1) and (2) (Roark 1965).

$$l = \sqrt[4]{\frac{12\left(1-n^2\right)}{f^2 t^2}} \qquad (1)$$

$$s_{Hoop} = \frac{-p f l}{4t} \qquad (2)$$

Knowing that aluminum bat barrels often have a minimum barrel thickness, *t*, of 0.090 inch, the pressure, *p*, that would cause the hoop stress, σ_{Hoop}, to be equal to the yield stress can be found using Equations (1) and (2) and the barrel diameter, *f* Using the same pressure, it can be determined that the barrel thickness of a titanium bat would be 0.061 inch at yield for the same load conditions. To compare the barrel deformation and the trampoline effect, Roark's cylinder equation for diametrically opposite concentrated loads, Equation 3, can be used.

$$d = 6.5\frac{F}{Et}\left(\frac{f}{2t}\right)^{1.5}\left(\frac{2L_{Barrel}}{f}\right)^{-0.75} \qquad (3)$$

For comparison purposes, a barrel length, L_{Barrel}, of 12 inches and the impact at 6 inches (near the sweetspot) are assumed. Barrel deformations, *d*, of 0.021 inches are reasonable for aluminum bats. Substituting a *d* of 0.021 inches and an elastic modulus, *E*, of $15\text{x}10^6$ psi into equation 3 results in an equivalent static load, *F*, of 250 lbs. Resolving for a wall thickness, *t*, equal to 0.061 inch, the titanium barrel results in a deformation of 0.035 inch.

The energy efficiencies of the strains in the bat and ball have a direct influence on the bat's performance. Adair attributes the increased performance of the aluminum bat to the barrel's deformation which stores 10% of the strain energy compared to the smaller deformation of the solid wood bat which stores only 2% of the collision energy (with the remaining 98% stored in the ball). The ball has a poor efficiency as a portion of its energy is dissipated through internal friction and not returned as kinetic energy; 68% is assumed for these calculations. The aluminum returns nearly 100% of the energy stored (99% assumed for this study). Using the static load and displacement determined for the titanium barrel, the strain energy stored in the titanium bat can be estimated at 17%. The resulting CORs are 0.506 for the aluminum bat-ball collision and 0.535 for the titanium bat-ball collision.

Using typical properties (I=3500 oz-in^2, cg=12.5-in with respect to end of the barrel) for a 34-inch, 30-ounce aluminum bat and assuming an 85-mph pitch, 80-mph bat tip speed and 6-inch impact location; the batted-ball velocity can be calculated at 104.4 mph using Equation 4 as documented by Fallon (2000).

$$v_{1a} = \frac{\left[v_{1b}\left(e - \frac{W_1}{W_2} - \frac{W_1\left(x_{cg} - x_i\right)^2}{I_{2cg}}\right) + \left(1 + e\right)\left(v_{2b} + \left(x_{cg} - x_i\right)w_{2b}\right)\right]}{\left(1 + \frac{W_1}{W_2} + \frac{W_1\left(x_{cg} - x_i\right)^2}{I_{2cg}}\right)} \qquad (4)$$

In equation (4), *e* is the Coefficient of Restitution, W_i is the weight, v_i is the velocity, w_{2b} is the bat's angular velocity, x_i is the distance from the end of the barrel and I_{2cg} is the bat's moment of inertia about its center of gravity. The subscript *1* represents the ball, *2* the bat, *a* – after impact and *b* – before impact.

A pivot point of 3.25-in off the knob was used based on a study by Crisco (1997). Assuming the thickness of a titanium bat varies proportionally to the aluminum (i.e. approximately one third that of aluminum across its entire length), the resulting titanium bat would weigh 32.5 ounces and be swung with a tip velocity approximately 2.5 mph slower. The resulting batted-ball velocity for the titanium bat would be 3 mph faster than that of the aluminum bat, which studies have shown can be as much as 8 mph faster than that off solid wood. By repeating the process for an aluminum bat with a reduced diameter of 2.625 inches, the effect of the 1999 NCAA implemented maximum barrel diameter reduction rule can be investigated. Based on the new geometry, the barrel wall thickness could be reduced to 0.0886 inch; the bat weight to 29.5 ounces and the deformation would now be 0.020 inches. The resulting batted-ball exit velocity is 104.1 mph or a reduction of 0.3 %. Incorporating the new NCAA minus 3 rule (i.e. 34-inch bats must weigh 31 ounces), the batted-ball exit velocity is reduced another 0.2%.

The theory presented in this paper provides insight into the elastic deformation of the barrel. However, the results do not incorporate the effects of large deformation and the influence of local plastic deformation in the metal barrels. Titanium, with its greater elongation at break than aluminum, may further outperform the aluminum bat. Large deformation effects can account for a 13% decrease in bat hoop stiffness and an additional 1% of energy stored in the metal barrel.

BARREL DEFORMATION TEST AND ANALYSIS

A new aluminum bat with a 2.75-inch diameter barrel was aligned in an Indy-Ron, Bendix roundness measurement machine. The profile and diameter were measured at four locations along the barrel. The out-of-roundness was between 0.0015 and 0.0030 inches for the four locations. The roundness for one of these locations is plotted in Figure 2.

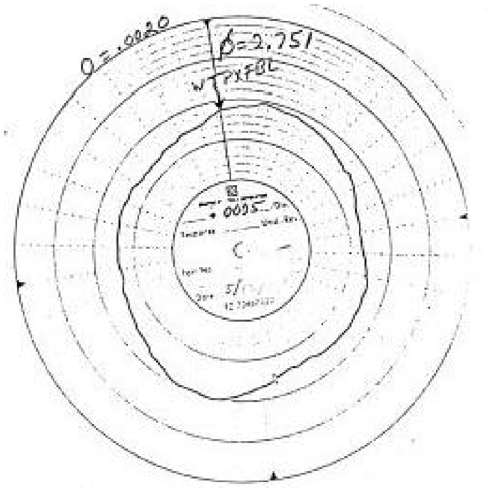

Figure 2. Sample Roundness Plot for a New Aluminum Baseball Bat Barrel.

A professional player hit five baseballs off a tee, and the impacts were recorded using a high-speed motion analysis system with a capture rate of up to 2000 frames per second. The diameter of the contact area between the bat and ball was estimated at 1.4 inches. Figure 3 shows a frame of the baseball during maximum deformation.

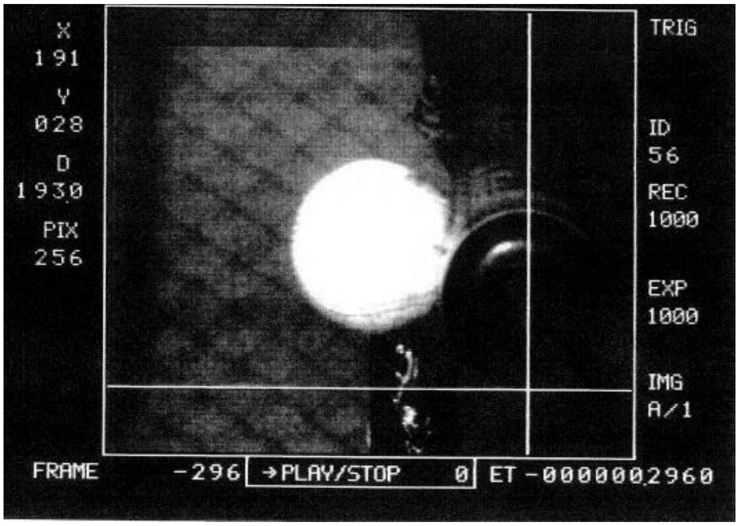

Figure 3. Motion Analysis Capture of a Bat -Ball Impact.

Next, the aluminum bat was instrumented with strain gages on the top and face of the barrel at 3.5 and 6.5 inches from the tip of the barrel. The gages were oriented so that the hoop strain would be read. A pitching machine was set at 75 mph, and the strains were recorded for several good impacts, which were monitored using the high-speed motion analysis system. An impact at 5 inches resulted in a 25,000-psi stress in the 2 face gages. The pulse data are shown in Figure 4.

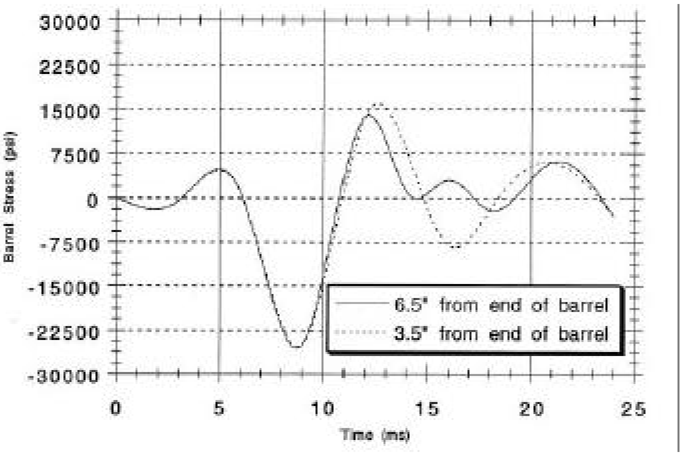

Figure 4. Dynamic Strain Data on an Aluminum Bat during Baseball Impact

After completing approximately 70 impacts on the aluminum bat, measurements were repeated on the Indy-Ron. The out-of-roundness had increased to 0.0025 to 0.0045. It was evident that permanent deformations had occurred in the bat during normal use after a short period of time. The bat performance may be influenced by the workhardening of the material.

The measured results were incorporated into an ANSYS finite element model of the bat. The model was constructed using 8-node quadrilateral shell elements and nonlinear spring elements to represent the boundary conditions of the batter's grip. The load was distributed across the contact area with the greatest concentration near the center of the contact area. With the strain measurements correlated, an area directly beneath the ball contact of approximately 0.5 inch in diameter exceeded the yield strength of the aluminum. Figure 5 plots the von Mises stresses.

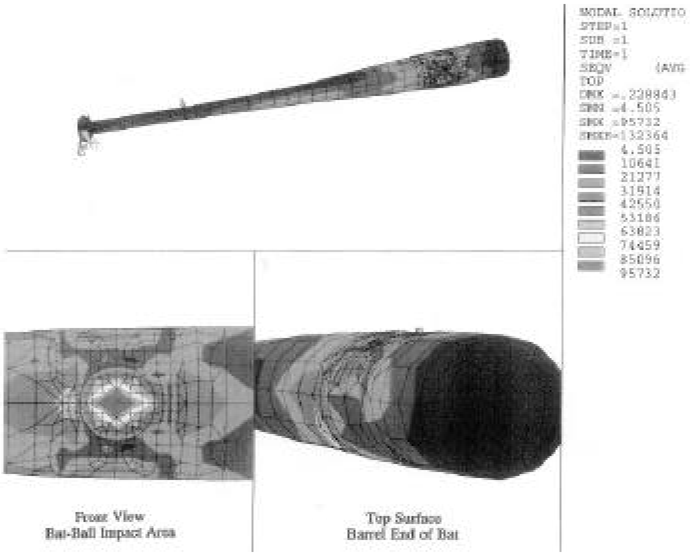

Figure 5. Von Mises Stresses on an Aluminum Bat during Ball Impact

The barrel diameter compressed 0.054 inch in the direction of impact and increased 0.043 inch in the vertical direction. A magnified barrel distortion is plotted in Figure 6.

CORKED BAT PERFORMANCE TEST

Four wood bats, two of which were corked (Figure 7), were submitted to the UMass-Lowell Baseball Research Center and performance tested on its hitting machine. The input speeds for the tests were set to approximately 66 mph for the bat (as measured 6 inches from the tip of the barrel) and 70 mph for the ball. The exit velocities for each impact were measured and the results normalized to account for the variances in bat-to-bat inertial properties. After 3 to 8 impacts, the corked bats began to develop a crack along the barrel grains.

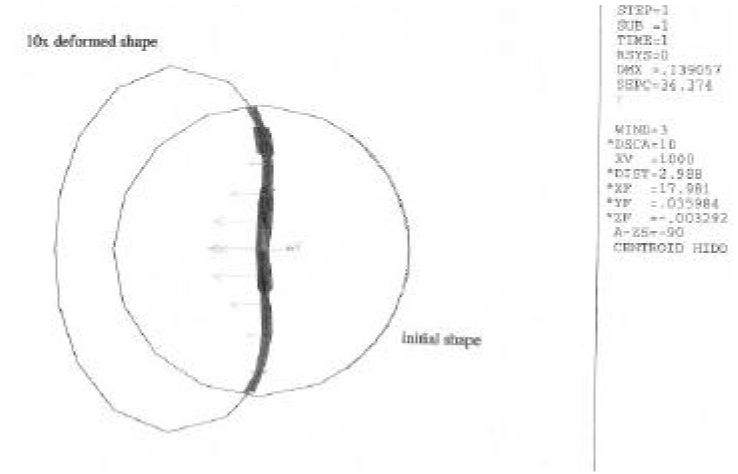

Figure 6. Barrel Deformation with a 10x Displacement Magnification

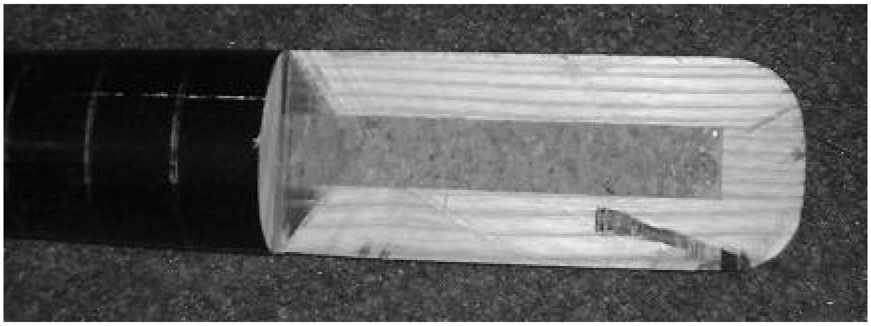

Figure 7. Cross-Sectioned Corked Wooden Baseball Bat

Although only limited data were obtained before the barrels were damaged, the results indicated a slight increase in performance for the corked bats. The relative bat velocity was 1.1 mph faster for the corked bat in comparison to the same bat model uncorked. The fact that the barrel split indicates that some hoop-like deformation must have occurred. These results contradict those reported by Adair who theorized that all of the deformation was on the local surface.

To support these results, another finite element analysis was performed. A two-dimensional plane stress model was generated to represent an ash bat that was either solid wood or drilled with a 1-inch diameter hole. A 250-lb static load was applied to the contact area to represent the ball impact. The deformation was shown to extend into the area where the cork would have been inserted. The surface displacement on the corked bat was 82% greater than that in the solid wood. The maximum principal stress for this static load was 712 psi for the corked bat and the reference tensile strength was 940 psi for white ash.

In order to relate this additional strain energy to performance, the assumption was made that the local surface compression in the wood had an efficiency similar to that of the baseball (as stated by Adair). However, it was assumed that the thick-cylinder hoop related strains had the same efficiency as the thin walled aluminum barrel hoop deformations. Solving in a similar manner, the corked bat produces a batted-ball velocity 0.9 mph greater than the solid-wood bat.

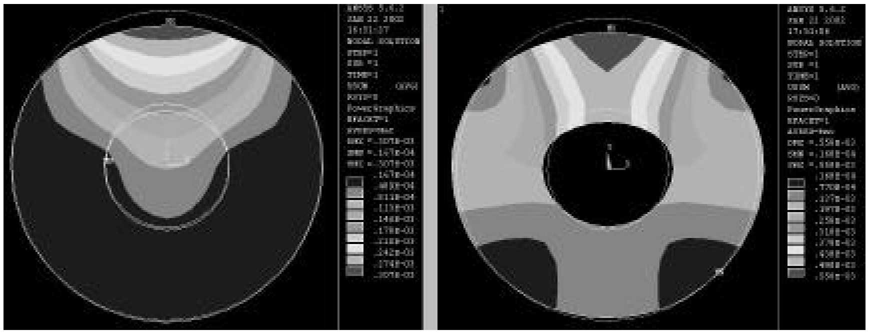

Figure 8. FEA Bat Deformations with Static Load on the Top Surface;
Solid Wood (Left), Corked Wood (Right)

CONCLUSION

A study was performed to investigate the relationship between baseball bat barrel design and performance. Theoretical, computational and experimental techniques were used. The key findings included:

(1) Today's metal bats yield under impact,
(2) Titanium bats outperform aluminum bats by more than 3%,
(3) A reduction of the allowable barrel diameter to 2.625 from 2.75 inches, decreases the batted-ball exit velocities by roughly 0.3 mph,
(4) The "minus 3" rule implemented by the NCAA effectively reduced the batted-ball exit velocity by 0.2 mph.
(5) A corked bat can outperform a solid wood bat by approximately 1%,

REFERENCES

Adair, R. (1994) *The Physics of Baseball*, Harper and Row

CRC Materials Science and Engineering Handbook

Crisco, J.J. (1997) NCAA *Research Program on Bat and Ball Performance*

Fallon, L. (2000) Determining *baseball bat performance using a conservation equations model with field test validation*

Forest Products Laboratory (1999) *Wood Handbook – Wood as an Engineering Material*, U.S. Department of Agriculture, Forest Services

Roark, R. (1965) *Formulas for Stress and Strain - Fourth Edition*, McGraw -Hill Book Company