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Improvements for the Peak Performance Lifespan of a Composite Bat

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Abstract

The push for innovation and enhancement of sports equipment in recent years has led to significant advancements in composite materials. This project aims to propose new design possibilities that will improve the lifespan of a two-piece composite bat. Using finite element analysis (FEA) software, various fiber orientations and materials were modeled and analyzed for their impact response. Two unique quarter-cylinder designs along with a baseline design were modeled with symmetric boundary conditions. The proposed bat designs include a helicoidal model and a CFRP-Aramid hybrid model. Comparative analysis of the elastic responses revealed that both the helicoidal and hybrid models demonstrated higher internal energy when contrasted with the baseline model. This heightened internal energy signifies improved capabilities in mitigating stress, strain, fatigue, and damage accumulation over time. Furthermore, the increased displacement observed in the helicoidal and hybrid models suggests superior flexibility and energy storage during impact, therefore aiding in the distribution of forces across the structure and reducing localized damage. These findings underscore the potential of innovative composite bat designs to further revolutionize sports equipment and provide a competitive edge by maximizing durability within the industry standards.

Keywords: Polymer matrix composites; Finite element analysis; Composite bat; Damage accumulation; Sports Equipment

1. Introduction
Composite materials have revolutionized the landscape of sports equipment, enabling athletes to push the boundaries of performance even further. The unique properties of composites such as high strength-to-weight ratio and tailored flexibility, have facilitated the creation of lighter, more durable, and better performing gear across various sports. From cricket bats [1] to golf clubs, the adoption of composite materials has become imperative to achieving superior athletic performance. In the realm of baseball and softball, composite bats have emerged as game-changers, offering players unparalleled power and control at the plate. This advantage is attributed to a vibrational phenomenon entitled “the trampoline effect” [2,3]. This occurs when the collision energy between the bat and ball is stored within the bat and then efficiently transferred back to the ball resulting in higher batted ball speeds. It has been proven that this effect is amplified in hollow bats as opposed to the traditional solid wood [4,5]. This is due to the compression of the shell and the elastic deformation of the bat returning the potential energy [2,3].

Composite bats can play into this effect very easily due to their increased elasticity and larger center of percussion, or sweet spot [6]. As the barrel walls undergo repeated impact over time, the composite experiences barely visible impact damage. It can manifest as fiber breakage, matrix cracking, delamination, or, in extreme cases, ultimate failure of the bat (Fig. 1a) [7]. As a result, the compressive strength of the bat decreases, thereby increasing the trampoline effect and producing an incredibly high-performing bat [8]. Broe et al. conducted an experimental study using an accelerated break in process to prove that the composite bats exhibited an increased performance as the barrel was broken in. Consequently, it became clear that these discoveries and technological advancements granted the offense a clear competitive edge. In response, governing softball organizations put into effect rules and regulations to limit the performance of composite bats known as the batted ball coefficient of restitution (BBCOR) [9]. Some organizations, such as those that govern Little League,
resorted to putting a moratorium on the use of composite bats due to decreased available pitcher
reaction time [10,11]. Bats must undergo compliance testing to ensure that their performance does
not become both an unfair advantage and a safety risk [12]. Bats that have been approved are listed
on official sites, such as the one for USA Softball, as certified equipment [13]. These new proposed
designs were considered with these safety concerns in mind. Some additional considerations include
cold weather effects. It is recommended that composite bat usage is limited to 60 degree weather and
above due to the likelihood of composites to crack on impact below that threshold [14]. Designs such
as the carbon/aramid hybrid model are possible solutions to this issue.

There is little publicly available research done regarding new design possibilities for the
composite bat. Some have explored the possibility of introducing carbon nanotubes to improve the
performance of carbon reinforced composites. Kostopoulos et al. [15] studied the influence of multi-
wall carbon nanotubes (MWCNTs) on the impact and after impact properties of CFRPs. They found
that at low velocity impact (LVI) there was no significant difference for the delamination area or
absorbed energy. For the composite to reap the full benefits of MWCNTs, they need to be subject to
higher impact energy. There have been attempts made with distributing carbon nanotubes throughout
the resin system, reinforcing the matrix with their enhanced tensile properties [16].

The research gap in this area is relatively large, however what this investigation focuses on is
innovation. To effectively fill this gap, three designs were modeled in Abaqus and evaluated for their
elastic response to a concentrated force. A comparative analysis was conducted on the deformation
and internal energy retrieved from the simulations to determine the success of the two novel designs
with respect to the baseline model.

2. Numerical Methodology

2.1 Specimen Geometry and Materials
The baseline model was configured according to the data collected from Figure 1. The barrel has a length of 165.1 mm, an inner diameter of 46.11 mm and an outer diameter of 57.15 mm. The damaged composite bat was cut into smaller sections in order to view the plies under a microscope. Using the microscope program, it was able to be determined that there were 26 plies of thickness 0.21 mm. This gives an overall wall thickness of 5.46 mm. The baseline and helicoidal models use the material properties for the unidirectional M46J/2511 resin system detailed in Table 1. The hybrid model uses both the unidirectional M46J/2511 resin system and the unidirectional Kevlar properties from Table 1.

By studying Figure 1b, it was determined that the baseline model layup is repeating +45 degree, -45 degree with the innermost ply fiber orientation being along the length. They hybrid model uses the same layup as the baseline, with alternating layers of aramid and carbon fiber (Fig. 2b). The layup from the helicoidal model was inspired by research done on LVI resistance behaviors on helicoidal composite laminates [17]. According to Jiang et al. [18], the larger the rotation angle is between each adjacent ply, the better the laminate is able to resist the impact loading. The layup used in this study is [0/6/12/18/24/30/36/42/48/54/60/66/72]s. The symmetric boundary conditions can be seen in Fig. 3 and were used for all three models [18,19].

2.2 Modeling Technique

The analyses of the three designs were conducted in Abaqus/Standard [20]. Many different techniques were tested to accurately model the hollow composite barrel. The chosen method involved creating 26 partitions to represent each ply. Then, sections were created using the material assignment necessary for each design (Fig. 4). Each partitioned ply is then assigned to a region and the appropriate section with the desired material (Fig. 2). The most effective method for creating different fiber orientations for each ply was to assign material orientations rather than using the composite layup tool
(Fig. 5). Using a discrete orientation (Fig. 6), the fiber orientations were able to be inputted into the additional rotation angle box as seen in Figure 5a. It is important to note that the desired fiber angle had to be adjusted by adding 90 degrees. Doing so provides the correct orientation for each ply. The impact was modeled using 8-node quadrilateral continuum shell elements with reduced integration and hourglass control (SC8R). In order to reduce computational time and complexity, a quarter of the barrel of the composite bat was modeled. The impact load was determined by converting kinetic energy into a force.

\[ KE = \frac{1}{2} m v^2 \]  

(1)

Where \( m \) is the mass of a softball, given as 6.5 ounces or 0.184272 kilograms [21] and \( v \) is the velocity of the pitch, approximately 35 mph or 15.6464 m/s [22].

\[ F = \frac{KE}{d} \]  

(2)

Dividing the kinetic energy from Equation 1 by the distance from the pitcher’s mound to home plate, which is 50 ft or 15.24 meters, a force of 1.48 Newtons is obtained. In order to correctly represent this in the simulation, it must be divided by four. This force is then applied to the node shown in Figure 7 in the negative x-direction.

3. Data Analysis

3.1 Impact Application

The durability and performance of composite bats are often tested and refined through various impact applications and after-impact evaluation. Understanding how the bats respond to these impacts is crucial for optimizing their performance and lifespan on the field. In this research, FEA software was used to simulate an impact on a hollow composite tube, thereby replicating the stress and strain generated during real-world bat-ball collisions. By running these simulations, valuable insights into the structural behavior and performance characteristics can be gained. Once the simulation was run
successfully, the stress contours were analyzed (Fig. 8) and data was retrieved from the node on the innermost ply (Fig. 9).

3.2 Elastic Model Evaluation

Two metrics were instrumental in measuring the validity of the two proposed designs. Displacement (Fig. 10) and internal energy (Fig. 11) data were used to interpret the elastic response and performance characteristics of the helicoidal and hybrid designs. Internal energy output serves as a crucial indicator of how energy is distributed and dissipated within the elements of the composite bat models. The energy output variable selected from Abaqus was ALLIE, the total internal energy of the model. This variable is the sum of the stored strain energy, inelastic dissipated energy, energy dissipated by viscoelasticity, and artificial strain energy within the model. By quantifying the amount of energy absorbed by the material due to deformation, it is possible to gain valuable insights into its ability to withstand stress, strain, fatigue, and damage accumulation over time.

Displacement under identical loading conditions provides essential insights into flexibility and energy storage capabilities. The time history of the displacement output illustrates how a structure deforms in response to the applied load over the duration of the analysis. A greater displacement indicated a superior ability to flex and store elastic energy during impact events, such as the dynamics of bat-ball collisions in baseball and softball. Furthermore, increased displacement facilitates more uniform distribution of forces across the structure thereby reducing the risk of localized damage and enhancing the overall structural integrity of the bat.

4. Results and Discussion

4.1 Effect of Design on Internal Energy and Displacement

For each model the internal energy is plotted versus time (Fig. 10). They all display an exponentially increasing trend with subtle differences in value. When the data for the three models is
graphed on a bar chart, it becomes much easier to compare. There it is evident that the hybrid and helicoidal models both exhibited a higher internal energy (Fig. 10d) in comparison to the baseline model, suggesting an improved capacity to mitigate stress and strain as well as fatigue and damage accumulation over time. The minor differences in peak internal energy are indicative of the new designs’ ability to elongate the peak performance lifespan without exceeding the regulations and standards that dictate the maximum capabilities of composite bats.

The helicoidal design features a unique arrangement of fibers, which enhances energy absorption and dissipation properties. The hybrid design combines the high stiffness and strength of carbon fiber with the impact resistance and toughness of aramid fibers. This hybrid material composition also offers optimal energy absorption and dissipation abilities, making the bat resilient to impact forces while maintaining its structural integrity over time.

4.2 Effect of Design on Displacement

In addition, the hybrid and helicoidal models show an increased displacement in comparison to the baseline model. An increased displacement under the same loading conditions indicates effective stress redistribution as a result of elastic deformation. The gradual change in fiber angle along the plies of the helicoidal model allows for ease of deformation, helping to redirect the matrix cracking which is an effective damage dissipation mechanism [17]. Figure 8 shows the deformation and stress distribution of the three models. The helicoidal and hybrid models show a much larger and widespread stress distribution than the baseline (Fig. 8b, 8c). This shows potential to help limit localized damage that would result from repeated impacts over time. The hybrid configuration enables the complementary properties of carbon fiber and aramid fibers to work together. Carbon fiber excels in efficiently distributing applied loads, while aramid fibers exhibit superior energy absorption and deformation resistance. These materials work in concert to effectively dissipate stress through a
combination of load bearing and energy absorbing mechanisms, minimizing the risk of localized stress concentration and structural failure. In the event of impact or loading-induced damage, such as fiber breakage and delamination, these designs can deflect crack propagation and redistribute stress with ease.

5. Conclusions

In conclusion, the investigation into new design possibilities for composite softball bats has yielded valuable insights into the potential for innovation within the realm of sports equipment. The research conducted aimed to propose designs that enhance the lifespan of two-piece composite bat, leveraging advanced materials, composite layups and finite element analysis simulations to assess their impact response. The helicoidal fiber layup and carbon fiber/aramid hybrid models emerged as promising alternatives to conventional designs, demonstrating superior elastic responses characterized by increase internal energy and displacement. These findings underscore the potential of these innovative composite bat designs to mitigate stress, strain, fatigue, and damage accumulation over time. By offering enhanced flexibility, energy storage, and stress distribution capabilities, these designs show promise to maximize durability and performance within industry standards. Furthermore, there are some critical considerations to address, such as safety concerns, environmental factors, and manufacturing feasibility. The proposed designs take into account regulatory requirements like compliance with BBCOR standards, and offer potential solutions to cold weather consequences, as well as ensuring player safety and equipment reliability.

This project also highlights the importance of continued research and development in sports equipment design. Moving forward, the ease of manufacturing, scalability for mass production, and cost-effectiveness of the proposed designs will be essential considerations for their practical implementation [25]. By pushing the boundaries of design innovation and analysis techniques, it can
be determined that the two proposed designs show potential for real-world application and industry advancement.

Acknowledgements

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References


**Fig. 1.** (a) Composite bat that has experienced ultimate failure due to impact; (b) cross section of bat showing fiber orientation of innermost ply; (c) microscopic image of bat section highlighting wall and ply thickness.
Fig. 2. a) Section assignments for baseline and helicoidal models; b) Section assignments for hybrid model.

Fig. 3. Symmetric boundary conditions.
**Fig. 4.** a) Section for baseline and helicoidal models; b) Sections for hybrid model.

**Fig. 5.** a) Material orientation dialogue; b) fiber orientation from x-y view; c) fiber orientation from x-z view.
Fig. 6. a) Discrete orientation dialogue box for assigning material orientation; b) Normal surface and primary axis selections.

Fig. 7. Meshed part showing node where concentrated force is being applied.

Fig. 8. Mirrored stress contours of a) baseline model; b) helicoidal model; c) and hybrid model.
Fig. 9. Circled node that displacement and internal energy data is collected from.

Fig. 10. Bat design internal energies for a) baseline; b) helicoidal; c) and hybrid models. d) Bat design internal energies comparison.
Fig. 11. Bat design displacements for a) baseline; b) helicoidal; c) and hybrid models. d) Bat design displacement comparison.

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