Fracture Mechanisms of Composite Baseball Bats: Post-Diagnostic Insights

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ABSTRACT

This study examined degradation in composite baseball bats from game and practice use. Techniques including X-ray diffraction, Raman spectroscopy, optical imaging, SEM, and EDX revealed microstructural changes: repeated impacts caused resin microcracks, fiber breakage, and delamination, progressively reducing performance. Carbon fibers showed amorphous/partially ordered structures, with high-stress regions initiating cracks. Elemental analysis identified carbon, oxygen, and nitrogen as primary components, with silicon/sodium traces from glass fibers. Key durability factors include tensile strength, fiber alignment, interfacial integrity, and laminate architecture. These findings underscore the necessity of optimized material selection and structural design to extend bat service life while maintaining performance.

Keywords: Composite baseball bat, fracture mechanism, analysis, carbon fibers

INTRODUCTION

Composite baseball bats, made from high-tech materials like carbon fiber and fiberglass, offer some real perks over the old-school wood or aluminum versions. Because they're lighter, players can swing them faster and enjoy a more balanced feel in their hands. The way these materials are engineered also lets manufacturers adjust the bat's stiffness just right, which not only helps transfer more energy to the ball but also makes the "sweet spot" bigger and easier to find. Another big plus is how well composite bats absorb vibrations-so when you don't hit the ball perfectly, you feel less sting in your hands. Thanks to these advantages, composite bats have become a go-to choice for players in youth, high school, and college leagues who want both top-notch performance and extra comfort.

The journey of crafting a modern composite baseball bat starts with top-quality carbon fibers and resins, which are woven or knitted into sheets or tubes. These layers are then carefully arranged by hand over a mandrel inside a bat-shaped mold, with each layer oriented just right to create the perfect mix of stiffness and flexibility. To boost strength where it matters most, both carbon fiber and fiberglass are strategically placed in the barrel and handle. Once the layers are set, resin is infused throughout the structure, and the bat is cured under carefully controlled heat and pressure-ensuring the composite materials bond perfectly. The process wraps up with the molding of the knob and end cap. The result: A bat that's not only strong and lightweight, but also offers a larger sweet spot and better vibration damping, giving players a real edge at the plate [1].

Composite baseball bats, though designed for high performance, can still break or wear out over time because of the way they're made, the materials used, and how they're handled on the field. One frequent issue is delamination [2], where tiny gaps or flaws between the composite layers cause them to separate, especially after repeated use. With every swing and hit, the bat also faces material fatigue [3], as small cracks slowly form in the polymer matrix, gradually weakening the bat's structure. On top of that, the flexible barrel-which is meant to help players hit harder-can actually create vibrations that, over time, further stress and weaken the composite material [4]. All these factors highlight why it's so important to keep improving both the materials and manufacturing methods for composite bats, so players can enjoy bats that are not only powerful, but also durable and long-lasting.

Researchers have found that the way voids and resin are distributed inside composite baseball bats has a big impact on how long the bats last and how well they perform. When there are too many voids, dynamic vibration testing shows that the bonds between the layers get weaker, making the bat more likely to experience delamination and ply separation-which can eventually cause serious fiber failure [2]. Other tests that simulate repeated use reveal that each impact encourages tiny cracks to form in the polymer matrix, which slowly makes the bat less stiff [5] over time. These insights really underscore why it's so important to keep improving manufacturing methods to reduce voids and ensure the resin spreads evenly, helping the bat's materials hold together better and last longer.

This study takes a close look at how composite baseball bats break down, using a range of advanced techniques to really get to the heart of the problem. X-ray diffraction (XRD) helped us see that the carbon fibers inside these bats are mostly amorphous, with some turbostratic carbon formed during high-temperature processing. Raman spectroscopy gave us even more detail, letting us spot the differences between the more ordered and disordered parts of the fibers. By photographing the bats, we were able to catch the very start of cracks at the sweet spot-a key area for understanding how damage begins and spreads through the bat's layered structure. Scanning electron microscopy (SEM) let us zoom in on the fractured surfaces, where we found aligned fibers, loose debris, and porous spots-all of which play a role in how the bat eventually fails. Energy-dispersive X-ray spectroscopy (EDS) revealed that these bats are made up of about 89% carbon, 7% oxygen, 3% nitrogen, and tiny traces of sodium and silicon, highlighting carbon's crucial role in making the bats both strong and lightweight. Altogether, these findings show just how important it is to thoroughly analyze a bat's structure if we want to make future designs more durable and high-performing.

Experimental

In this study, we utilized two 32-inch, drop 8 composite baseball bats from a popular supplier to investigate their fracture mechanisms with analogous failure mechanism. The findings of this study are not generalized to all vendors or their bats. A comparison of composite baseball bat vendors is beyond the scope of this manuscript, as manufacturers regularly update their compositions

Materials characterizations were performed on fragments of a branded composite baseball bat that was broken during routine training. As the broken fragments were of varying shapes and sizes, pieces were intentionally chosen to be appropriate for the specific materials characterizations (flat and sufficiently large for XRD and Raman spectroscopy, and small enough to be mounted to standard sample stubs for SEM).

XRD was conducted on the carbon fiber fragments with a Ragaku SmartLab X-ray diffractometer with a Cu-Kα X-ray source ($\lambda = 0.15406$ nm) with a scan rate of 1° min^{-1}. Raman spectroscopy was conducted on the fragments using a Thermo Scientific DXR Raman Microscope equipped with a 633 nm laser at 3 mW of power. The fragments were imaged using an FEI Quanta 3D FEG Dual beam SEM equipped with an Everhart Thornley detector (ETD) and an accelerating voltage of 3.0 kV. EDS was performed on the same microscope equipped with an Oxford X-Max 80 detector and operated at a beam voltage of 5.0 kV. The acquired EDS data were analyzed using the Aztec software package (Oxford Instruments).

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RESULTS AND DISCUSSION

The characterization techniques employed in this study provided critical insights into the fracture mechanisms of composite baseball bats, enabling a comprehensive understanding of bat durability and performance under impact conditions. In our former publications, we discussed the selection and performance rationale of wood versus aluminum baseball bats [6], and highlighted the superiority of composite baseball bats in terms of trampoline effect, acoustics, compliance, and safety [7].

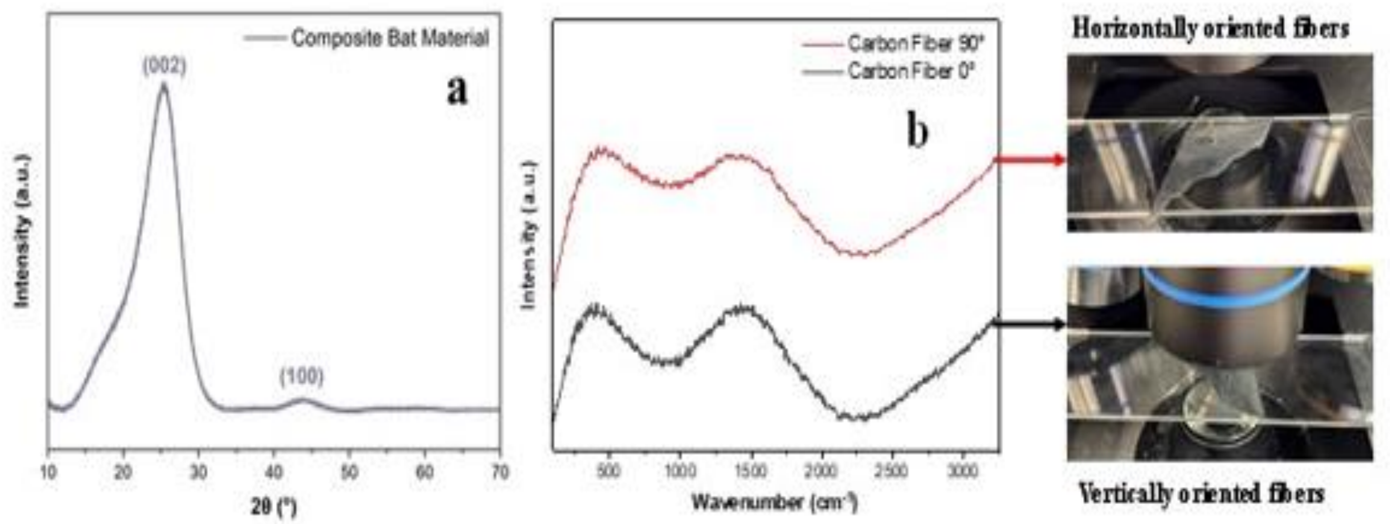

Figure 1. Materials characterization of fractured composite baseball bat fibers: **(a)** Powder X-ray diffraction (XRD) pattern of the composite material; and **(b)** Raman spectra of horizontally and vertically oriented fibers.

The XRD data reveal the composite fibers exhibit a turbostratic structure [8], where broad (002) and (100) reflections (Fig. 1a) indicate disordered stacking of graphene-like layers with interlayer spacing (~3.4–3.6 Å) and in-plane crystallite sizes (~1–2 nm), typical of non-graphitic carbons. This disordered arrangement, evidenced by the diffuse maxima, could help maintain mechanical resilience in the baseball bat upon ball impact. Additionally, the absence of extra peaks in the XRD pattern confirms that no other metals or oxides are present, suggesting that the remaining composite materials, such as resin, are likely amorphous. Carbon fiber is a high-strength, lightweight material made by carbonizing polyacrylonitrile (PAN) or rayon fibers, offering exceptional tensile strength, stiffness [9], chemical resistance, and thermal stability, which makes it ideal for advanced applications in aerospace, sports equipment, and engineering.

The Raman spectroscopy of carbon fibers from the composite baseball bat consistently showed two broad bands at approximately 400 cm^{-1} and 1600 cm^{-1} (Fig. 1b), even after accounting for potential beam damage. Both vertically and horizontally oriented carbon fibers exhibited analogous Raman signals, indicating that the material's structural properties remain consistent regardless of fiber orientation. This suggests that orientation has no significant effect on the fundamental structure of the carbon fibers. This observation is consistent with previous studies, such as the NIST investigation [10], which identified prominent D and G bands in composite bat materials, confirming the presence of carbon nanotubes embedded within the polymer resin. These characteristic Raman features are essential for assessing the structural order and nanomaterial content in advanced carbon-based sporting equipment.

Modern composite baseball bats are constructed by layering carbon fiber sheets with resin and molding them under heat and pressure to create a strong, lightweight structure. They outperform metal and wood bats by providing a larger sweet spot, reduced vibration, customizable balance, and greater durability for enhanced power and a more forgiving hitting experience.

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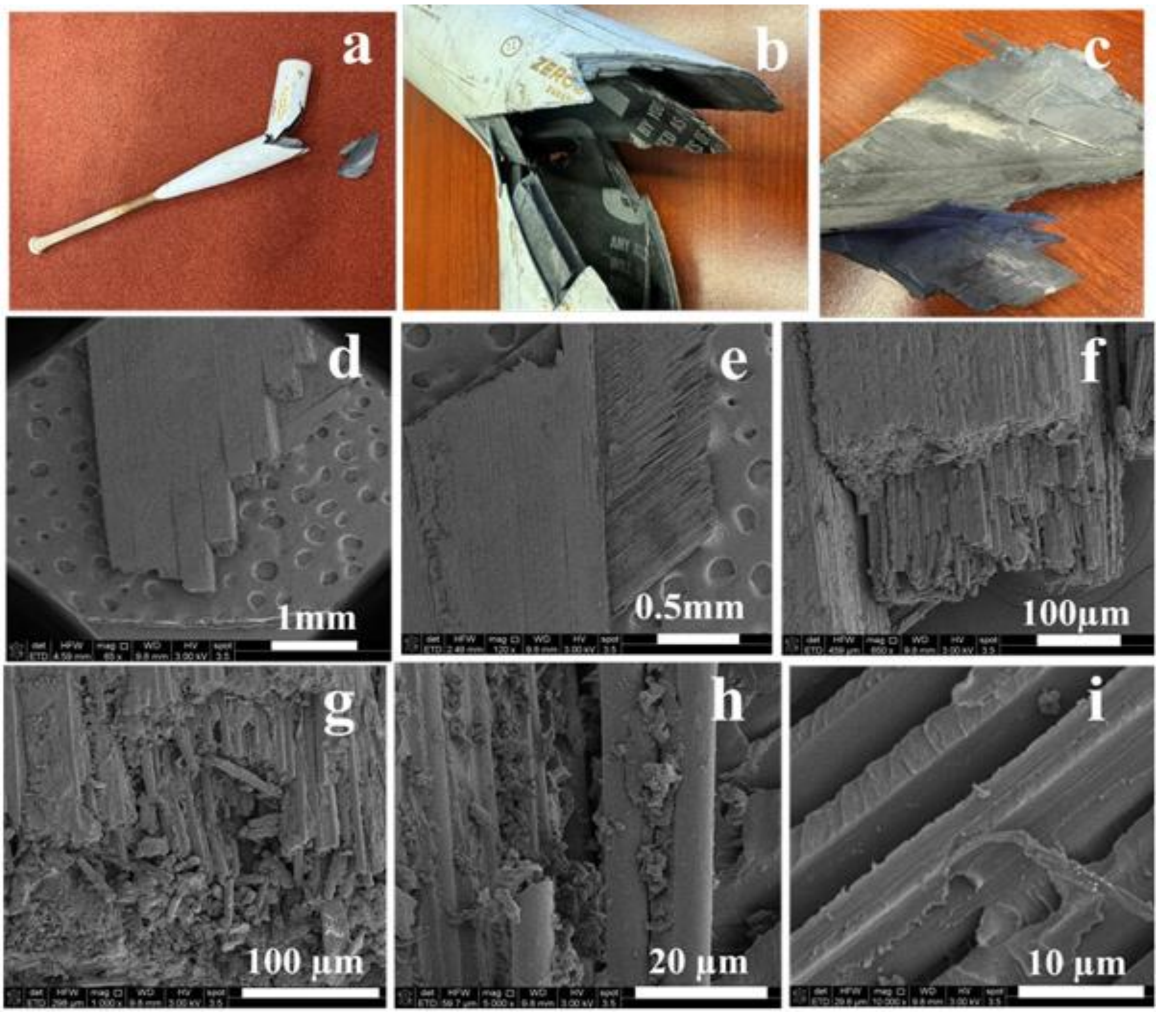

Figure 2. Optical and SEM images of the fractured baseball bat: **(a–c)** optical images showing the bat, fracture site, and inner carbon fiber; **(d–f)** low-magnification SEM images highlighting the layered carbon fiber sheets; **(g–i)** high-magnification SEM images at the fracture site.

Fracture is likely to initiate at the sweet spot of a composite baseball bat because this region experiences the highest energy transfer and repeated localized stress during impact, despite minimal vibration being felt by the hitter. In the current study, the bat was struck by the ball over 4,000 times during three months of routine training with a pitching machine and tea ball hitting in a controlled indoor facility, minimizing temperature effects. The repeated force concentration at the sweet spot can exceed the material's fatigue threshold, making it the most susceptible point for crack initiation and failure (Fig 2a).

After breaking a composite baseball bat, various layers typically show signs of delamination (Fig 2b) and fiber failure, where the matrix separates from the fibers and individual plies may peel apart, indicating that delamination is the primary failure mechanism preceding fiber breakage and catastrophic failure [11].

In a composite baseball bat, pre-impregnated carbon fiber sheets are strategically layered (Fig 2c-f) in specific orientations to optimize stiffness and flexibility before being placed into a bat-shaped mold. The application of heat and pressure cures the resin, firmly bonding the layers [12] and creating a strong, lightweight structure with precisely engineered performance properties [13]. Scanning electron microscopy (SEM) of composite baseball bats revealed debris of small particles between the carbon fibers (Fig. 2g-h), which may include resin fragments and aggregates of specialized materials embedded in or protruding from the polymer matrix. These particles originate from the composite materials used in the bat's construction and may also include fragments generated during bat breakage, or other destructive processes. The micrometer-sized gap observed in SEM images of carbon fibers in a composite baseball bat is typically due to delamination or separation (Fig 2i) at the fiber-resin interface, resulting from manufacturing defects, mechanical fatigue, or repeated impacts, and serves as a common indicator of structural degradation within the laminate.

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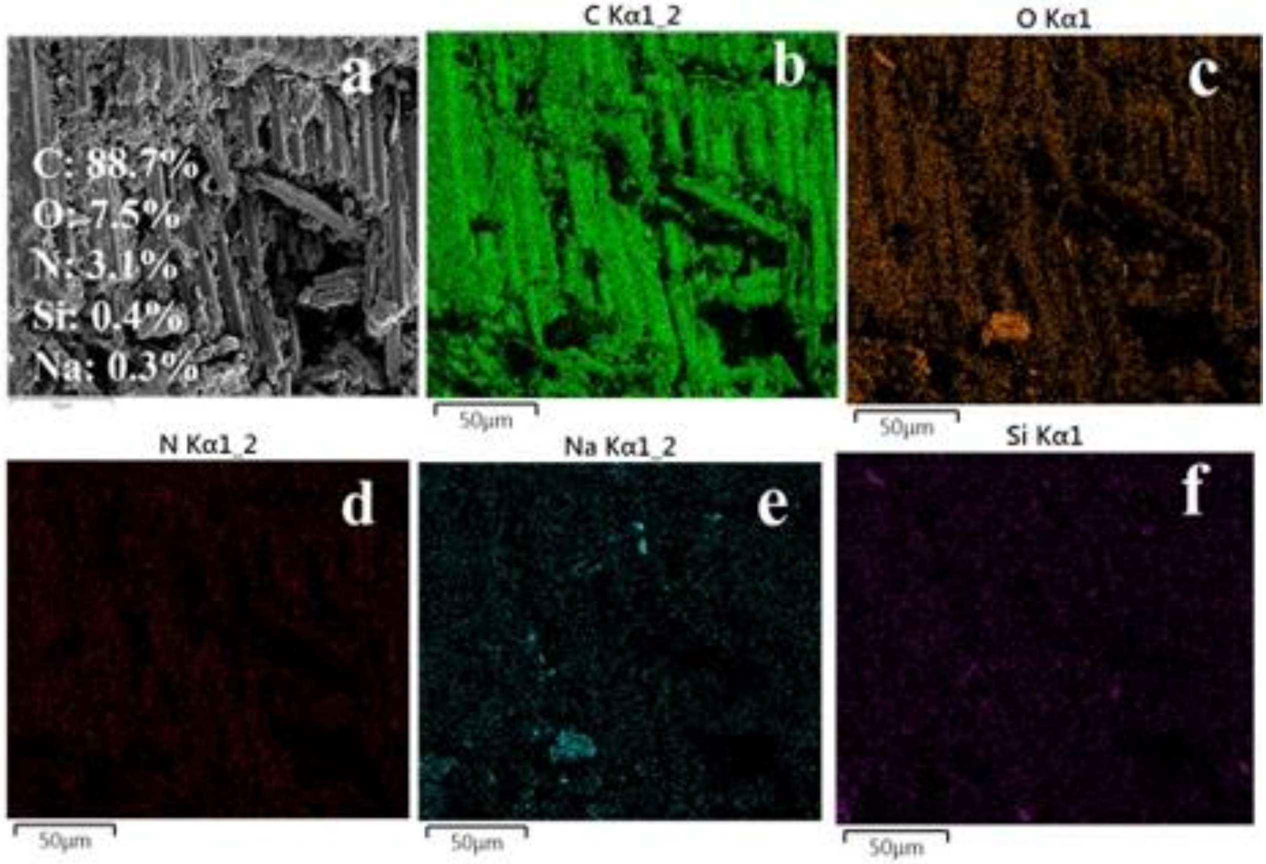

Figure 3. SEM/energy dispersive spectroscopy (EDS) analysis of the carbon fiber material at a fracture location. a) SEM image of the carbon fiber material. and b-f) Overlayed EDS maps for various elements present in the carbon fiber sample.

We analyzed the carbon fiber in a composite baseball bat using EDS and found 88% C, 7.5% O, 3.1% N, 0.4% Si, and traces of sodium (Fig. 3a). The presence of silicon suggests the use of silica fillers by the manufacturer, while the detected nitrogen likely originates from the PAN precursor used in carbon fiber production. The color mapping of the same SEM area depicted a homogeneous distribution of C, O N, Na and Si, respectively (Fig 3b-f). These findings confirm that the broken bat contains additional supporting materials-such as silica/glass fillers-used by manufacturers to enhance the composite baseball bat's properties. Fiberglass is a composite material made from very fine glass fibers embedded in a resin matrix, typically produced by melting raw materials such as silica sand, limestone, soda ash, borax, and alumina at high temperatures to form molten glass that is then drawn into thin fibers confirms the presence of Si and Na elements.

For composite baseball bats, the outer surface coating-typically made of toughened polymers or epoxy-based materials-generally ranges from about 50 microns (0.05 mm) up to 1 mm in thickness (Fig 4a-b and their respective SEM, depicted by 1,2), depending on the manufacturer’s process and the specific protective or aesthetic requirements. This coating layer provides both enhanced durability and a high-quality finish. The carbon fiber layer is located just beneath the surface polymer coating, and the various orientations of the carbon fibers are clearly depicted in the corresponding SEM images (Fig 4c, 3).

The primary fracture mechanisms in composite baseball bats arise from the progressive development of microdamage-specifically microcracks in the resin matrix, fiber breakage, and ply delamination-caused by repeated impacts during use. While some players may opt to “break in” their new bats with a number of practice swings to develop their preferred feeling as a function of initial microcrack formation, over time, these microcracks propagate into macrocracks and significant delamination, ultimately leading to structural failure, with contributing factors including the brittleness of composites, repeated flexing, vibrations, wear and tear, improper use, and extreme temperatures, all of which decrease barrel stiffness and increase the risk of catastrophic failure.

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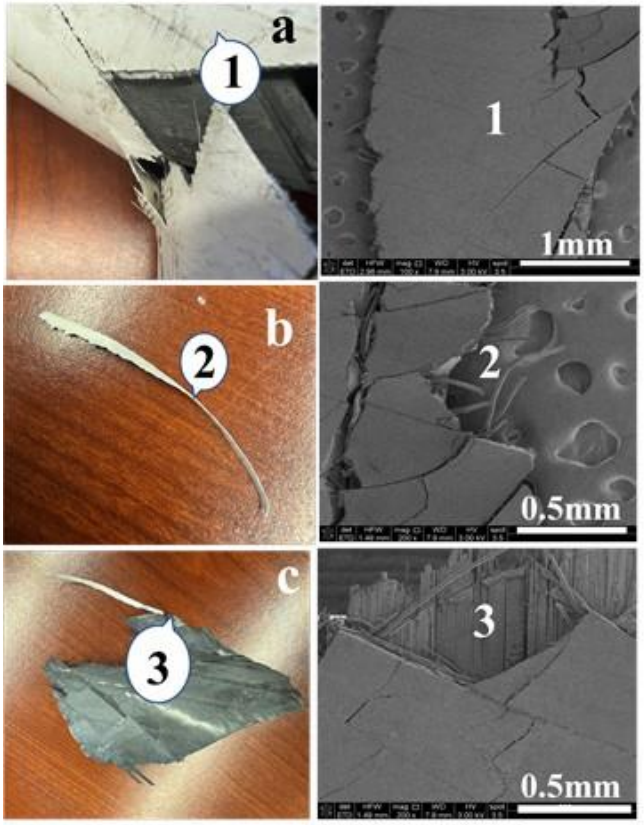

Figure 4. Optical and SEM images of the bat's outermost layer: (a) painted surface, (b) higher magnification showing paint and underlying carbon fibers, and (c) layered structure with carbon fiber beneath the paint.

Based on the study "Research on Tensile Properties of Carbon Fiber Composite Laminates"[14], carbon fiber composite laminates exhibit high tensile strength and modulus, with mechanical performance significantly influenced by fiber orientation and stacking sequence. Laminates with fibers aligned parallel to the loading direction show superior tensile properties compared to off-axis or cross-ply configurations. The research also found that increasing laminate thickness and optimizing ply design enhance fracture strength and resistance to delamination under tensile loading. These results really drive home just how important it is to get the laminate design right when working with carbon fiber composites, especially if you want to make the most of their strength and durability in engineering projects.

For baseball bats, in particular, the tensile strength of the composite material plays a huge role in how well the bat holds up over time. When a bat has high tensile strength, it can handle the powerful forces from repeated hits because the carbon fibers are able to resist stretching and breaking. This means the bat stays strong, keeps its shape, and performs well, even after lots of hard swings and contact with the ball. On the flip side, if the tensile strength [15] isn't up to par, the bat is much more likely to develop cracks, experience delamination, or even fail completely during play.

CONCLUSIONS

In this study, we took a close look at how and why composite baseball bats break down over time. We found that tiny cracks start to form in the resin, the fibers themselves can snap, and the layers inside the bat can separate- all of which get worse the more the bat is used. Everyday factors like the natural brittleness of composites, constant flexing, vibrations, regular wear and tear, leaving the bat in a hot car, or exposing it to extreme temperatures can make things even worse by reducing the barrel's stiffness and making the bat more likely to fail. To really understand what's happening inside these bats, we used a range of advanced techniques, including X-ray diffraction, Raman spectroscopy, SEM, and EDS. These methods helped us confirm that the carbon fibers are mostly amorphous and packed with carbon. We also discovered that how the fibers are arranged, the way the layers are stacked, and the overall laminate design all have a big impact on the bat's strength and its ability to resist breaking. All of this points to the importance of thoughtful engineering and careful design when it comes to making composite baseball bats that are not only high-performing but also safe and long-lasting.

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