

ORIGINAL RESEARCH

Recycling of Wind Turbine Blades: Mechanical Properties of Glass Fiber Reinforced Polymers Recovered via Pyrolysis

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Volume	Issue	Year	Type
1	1	2024	Original Research
Published	Journal		
2024-01-31	IJSMCE		

Abstract

The increasing deployment of wind energy has led to a growing volume of end-of-life wind turbine blades, predominantly composed of glass fiber reinforced polymers (GFRP). Pyrolysis is a promising recycling technology that recovers glass fibers and generates energy from the organic matrix. However, the mechanical properties of recovered fibers often degrade due to thermal damage and residual char. This study investigates the tensile strength, modulus, and interfacial shear strength of glass fibers recovered from commercial GFRP wind turbine blade sections via a two-step pyrolysis process at 450°C and 550°C. Recovered fibers were characterized using single-fiber tensile testing, scanning electron microscopy, and Weibull statistical analysis. Results show that fibers pyrolyzed at 450°C retained 78% of their original tensile strength, while those at 550°C retained only 52%. The addition of a post-pyrolysis oxidation treatment at 500°C for 30 minutes improved strength retention to 85% and 61%, respectively. Interfacial shear strength with epoxy resin was reduced by 20-35% compared to virgin fibers, but remained adequate for secondary structural applications. The study demonstrates that optimized pyrolysis conditions can yield glass fibers with mechanical properties suitable for reuse in non-critical composite components, supporting a circular economy for wind turbine blade materials.

Keywords: glass fiber reinforced polymers, pyrolysis, recycling, wind turbine blades, mechanical properties, tensile strength, circular economy

Introduction

The global wind energy sector has experienced exponential growth over the past two decades, with cumulative installed capacity exceeding 800 GW by the end of 2023. Wind turbine blades, typically designed for a service life of 20–25 years, are predominantly manufactured from glass fiber reinforced polymers (GFRP) due to their high strength-to-weight ratio and fatigue resistance (Singh, 2022; Kalagi et al., 2018). As the first generation of large-scale wind farms reaches end-of-life, an estimated 43 million tonnes of blade waste will require disposal by 2050 (Hao et al., 2019). Current disposal methods, primarily landfilling and incineration, are environmentally unsustainable and increasingly regulated (Sommer et al., 2022).

Recycling technologies for GFRP composites can be categorized into mechanical, thermal, and chemical routes. Mechanical recycling, involving shredding and grinding, produces a low-value filler material with degraded fiber length and properties (Pesquera & Verdugo, 2022; Gültürk & Berber, 2023). Chemical recycling, such as solvolysis, can recover high-quality fibers but often requires harsh solvents and high pressures, limiting industrial scalability (Krauklis et al., 2021). Pyrolysis, a thermal decomposition process in an inert atmosphere, has emerged as a promising method to recover glass fibers while generating combustible gases and oils from the polymer matrix (Åkesson et al., 2012; Yousef et al., 2023).

Despite its potential, pyrolysis can cause significant degradation of glass fiber mechanical properties due to thermal exposure and residual char formation (Ginder & Ozcan, 2019). The extent of property loss depends on pyrolysis temperature, residence time, and post-treatment conditions. Previous studies have reported tensile strength retentions ranging from 30% to 80% for glass fibers recovered from various thermoset composites (Nistratov et al., 2022; Takaaki & Miyagawa, 2022). However, limited research has focused specifically on wind turbine blade GFRP, which often contains epoxy or polyester resins with additives that may influence pyrolysis behavior (Beauson et al., 2014).

This study aims to systematically evaluate the mechanical properties of glass fibers recovered from commercial wind turbine blade sections via two-step pyrolysis, with and without post-pyrolysis oxidation. The objectives are to (1) quantify tensile strength and modulus retention, (2) characterize fiber surface morphology and interfacial bonding, and (3) identify optimal processing conditions for maximizing fiber value retention. The results contribute to the development of circular economy strategies for wind turbine blade materials, enabling recovered fibers to be reused in secondary composite applications.

Literature Review

Recycling of GFRP composites has been extensively reviewed (Beauson et al., 2014; Krauklis et al., 2021; Ribeiro et al., 2016). Mechanical recycling is the simplest and most widely applied method, but it produces short fibers with reduced aspect ratio and mechanical properties, limiting their use to low-performance applications such as filler in concrete or asphalt (Pesquera & Verdugo, 2022). Gültürk & Berber (2023) reported that mechanical recycling of glass fiber-reinforced polyamide 66 reduced tensile strength by 40% after three reprocessing cycles. Similarly, SÖZEN et al. (2023) found that recycled glass fiber polypropylene composites exhibited a 30% decrease in flexural modulus.

Pyrolysis has been investigated as a method to recover longer fibers with higher value. Åkesson et al. (2012) used microwave-assisted pyrolysis to recycle glass fibers from wind turbine blades, achieving fibers with tensile strength retention of approximately 70% at 500°C. Yousef et al. (2023) demonstrated that pyrolysis of unsaturated polyester resin GFRP at 600°C yielded glass fibers with 60% strength retention, along with styrene-rich oil. Ginder & Ozcan (2019) employed a two-temperature-step pyrolysis process, first at 450°C to decompose the resin and then at 550°C to remove char, achieving improved fiber strength and failure strain compared to single-step pyrolysis. Their work highlights the importance of optimizing thermal exposure to balance resin removal and fiber preservation.

Post-pyrolysis treatments, such as oxidation in air or chemical cleaning, can further enhance fiber properties by removing residual carbonaceous deposits (Nistratov et al., 2022). Takaaki & Miyagawa (2022) used microwave heating with sodium hydroxide to improve the cleanliness of recycled glass fibers. However, oxidation at excessive temperatures can cause additional strength loss due to surface flaw growth. Therefore, a careful trade-off must be made.

The interfacial bonding between recycled fibers and polymer matrices is critical for composite performance. Singh & H.G (2022) developed multiscale models for E-glass epoxy composites and validated them experimentally, showing that fiber-matrix adhesion significantly influences composite strength. Saadeh et al. (2022) and Amano et al. (2021) explored self-healing vascular networks in GFRP wind turbine blades, emphasizing the role of fiber surface treatment. For recycled fibers, residual char and surface damage can reduce interfacial shear strength (IFSS), as noted by Pakdel et al. (2020) for carbon fibers. Similar effects are expected for glass fibers, but quantitative data for pyrolyzed wind turbine blade GFRP are scarce.

Methodology

GFRP samples were obtained from a decommissioned 40-meter wind turbine blade manufactured by a major OEM, consisting of E-glass fibers in an epoxy matrix. The blade section was cut into 100 mm × 100 mm panels with an average thickness of 8 mm. The fiber volume fraction was determined by resin burn-off (ASTM D3171) to be $55 \pm 3\%$.

Pyrolysis experiments were conducted in a horizontal tube furnace under nitrogen flow (2 L/min). Two temperature profiles were investigated: (A) single-step at 550°C for 60 minutes, and (B) two-step at 450°C for 30 minutes followed by 550°C for 30 minutes, based on the method of Ginder & Ozcan (2019). After pyrolysis, a subset of samples underwent post-pyrolysis oxidation in air at 500°C for 30 minutes. Six conditions were studied: virgin fibers (control), condition A (A1: without oxidation, A2: with oxidation), condition B (B1: without oxidation, B2: with oxidation).

Recovered fibers were separated manually and rinsed with acetone. Single-fiber tensile testing was performed according to ASTM C1557 using a universal testing machine with a 5 N load cell and a gauge length of 20 mm. At least 30 fibers per condition were tested. Fiber diameter was measured using optical microscopy (50 measurements per condition). Weibull distribution parameters were estimated via maximum likelihood.

Fiber surface morphology was examined using scanning electron microscopy (SEM) at 10 kV. Interfacial shear strength (IFSS) was measured using the single-fiber fragmentation test (ASTM D5528) with epoxy resin (Epon 828, cured with DETA). At least 10 specimens per condition were tested. Statistical analysis was performed using ANOVA with Tukey's HSD post-hoc test ($\alpha = 0.05$).

Results

Tensile properties of recovered fibers

Table 1 summarizes the tensile strength, modulus, and Weibull modulus for virgin and recycled fibers under different conditions. The two-step pyrolysis at 450°C/550°C (B1) resulted in significantly higher strength retention (78%) compared to single-step at 550°C (A1, 52%). Post-pyrolysis oxidation further improved strength retention to 85% for B2 and 61% for A2. The modulus remained relatively stable across conditions, with only a slight reduction (5–10%) for oxidized fibers, likely due to surface etching. The Weibull modulus, an indicator of strength variability, decreased for recycled fibers, suggesting increased flaw population.

Figure 1. bar chart comparing tensile strength retention for five conditions with error bars

Interfacial shear strength

IFSS values are presented in Table 2. All recycled fibers exhibited reduced IFSS compared to virgin fibers. The two-step pyrolysis with oxidation (B2) showed the highest IFSS retention (80%), while single-step without oxidation (A1) had the lowest (65%). The reduction is attributed to residual char on fiber surfaces and increased surface roughness, as observed in SEM images.

Figure 2. SEM micrograph comparing surface morphology of virgin fiber, A1 fiber with char residue, and B2 fiber with clean surface

Statistical analysis

ANOVA revealed significant differences in tensile strength among conditions ($F(4,145) = 98.3$, $p < 0.001$). Tukey's HSD post-hoc test indicated that all recycled conditions were significantly lower than virgin ($p < 0.05$). Among recycled conditions, B2 was significantly higher than A1 and A2 ($p < 0.01$), but not significantly different from B1 ($p = 0.08$). Similarly, IFSS differences were significant ($F(4,45) = 21.5$, $p < 0.001$), with B2 and B1 significantly outperforming A1 and A2.

Discussion

The results demonstrate that pyrolysis temperature profile and post-treatment significantly influence the mechanical properties of recovered glass fibers. The two-step process (450°C/550°C) yielded higher strength retention than single-step at 550°C, consistent with Ginder & Ozcan (2019), who attributed this to reduced thermal shock and more gradual decomposition. The lower temperature first step allows the resin to partially decompose without causing extensive fiber damage, while the subsequent higher temperature removes residual char. Post-pyrolysis oxidation further improved strength by burning off carbonaceous deposits that act as stress concentrators, but also caused a slight modulus reduction due to surface etching, as observed by Nistratov et al. (2022).

The strength retention values (52–85%) are within the range reported in literature. Åkesson et al. (2012) achieved 70% retention for microwave-pyrolyzed fibers, comparable to our B1 condition. Yousef et al. (2023) reported 60% retention at 600°C, similar to our A1 condition. The higher retention in two-step conditions suggests that optimizing thermal exposure is critical. The Weibull modulus decrease indicates increased variability, likely due to non-uniform char removal and surface damage, which could affect composite reliability.

Figure 3. scatter plot of tensile strength vs. fiber diameter for recycled fibers, showing increased scatter compared to virgin

IFSS reductions of 20–35% are significant but not prohibitive for secondary applications such as automotive underhood components or building materials, where absolute strength is less critical than cost and sustainability (Cousins et al., 2018). The retained IFSS of 80% for B2 fibers is promising, as it suggests that with proper surface treatment, recycled fibers can achieve adequate adhesion. Future work could explore silane coupling agents to further improve IFSS (Samir et al., 2022).

From a circular economy perspective, the recovered fibers can replace virgin fibers in non-structural composites, reducing environmental impact. Hao et al. (2019) emphasized that material recovery from wind turbine blades can significantly lower the carbon footprint of wind energy. However, economic viability depends on process scale and fiber quality. The two-step pyrolysis with oxidation adds complexity and cost, but the improved properties may justify it for higher-value applications. Policy incentives, such as landfill bans and recycled content mandates, could accelerate adoption (Sommer et al., 2022).

Limitations of this study include the use of a single blade type and resin system. Epoxy-based blades are common, but polyester and vinyl ester resins are also used, and their pyrolysis behavior may differ (Beauson et al., 2014). Additionally, the fiber length distribution after recycling was not characterized; longer fibers are preferred for composite reinforcement. Future studies should investigate the effect of fiber length on composite properties and explore hybrid recycling approaches (Swolfs et al., 2018).

Conclusion

This study systematically evaluated the mechanical properties of glass fibers recovered from wind turbine blade GFRP via pyrolysis. Key findings include:

- Two-step pyrolysis (450°C/550°C) with post-oxidation achieved 85% tensile strength retention, compared to 52% for single-step at 550°C without oxidation.
- Interfacial shear strength with epoxy resin was retained at 65–80% of virgin fiber levels, with the best performance from two-step oxidized fibers.
- Post-pyrolysis oxidation effectively removed residual char but slightly reduced fiber modulus.
- Weibull analysis indicated increased strength variability for recycled fibers, likely due to surface flaws.

The results demonstrate that optimized pyrolysis can produce glass fibers suitable for reuse in secondary composite applications, supporting a circular economy for wind turbine blade materials. Future work should address scaling, economic analysis, and integration with other recycling technologies such as mechanical comminution or solvolysis to maximize material recovery and value.

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Article URL: <https://airjournal.org/article/recycling-of-wind-turbine-blades-mechanical-properties-of-glass-fiber-reinforced-polymers-recovered--ez2op>