Sustainable Rotor Blades: Recyclable Resin Systems for Fiber and Matrix Recovery

Heber, Michael – University of Applied Sciences Niederrhein (HSNR), Department for Engineering and Computer Science Krefeld, Germany, michael.heber@hs-niederrhein.de

Shafir, Emma – University of Applied Sciences Niederrhein (HSNR), Department for Engineering and Computer Science, Krefeld, Germany, emma.shafir@hs-niederrhein.de

1. Abstract

The increasing number of end-of-life wind turbine blades presents a significant challenge for sustainable composite material management. Conventional thermoset-based blade structures are difficult to recycle, highlighting the need for alternative material systems that enable circular economy approaches.

This study explores prospects for the implementation of recyclable resin systems in the manufacture of CFRP components for rotor blades, being based on a comparative material-analysis with conventional resin systems and the corresponding recyclates. Firstly, the paper outlines cleavable resin technology. CFRP flat profiles made with Recyclamine® 301, representing rotor blade outer skins, serve as test specimens. Furthermore, the developed device for laminating profiles via wet pressing is described. Additionally, a method was developed that allows gentle separation of the matrix and fibers and is expected to preserve the mechanical properties of the fibers. The core of the paper deals with destructive material testing. The potential of recyclable CFRP laminates and the recyclates obtained from them is discussed in conclusion on the basis of tensile tests results. Samples from conventional, recyclable, and n-times recycled CFRP laminates are compared.

The results demonstrate that both fibers and matrix materials can be successfully recovered and reintegrated into new composite products with only limited reductions in mechanical performance. Even after repeated recycling, the resulting laminates exhibit tensile strength and elongation values within a technically relevant range. The applied recycling approach is based on established processing principles and shows no fundamental limitations regarding scalability to industrial recycling systems.

Overall, the findings indicate that recyclable epoxy systems represent a promising pathway toward closed-loop material concepts for large-scale composite applications, particularly in the wind energy sector.

2. Introduction and Motivation

Fiber-reinforced plastics (FRP) have become established across a wide range of industrial sectors. Their high specific stiffness and strength enable widespread use in engineering applications such as automotive and aerospace structures, wind energy, maritime components, civil infrastructure and sports equipment. However, conventional thermosetting resins remain the dominant matrix materials in structural composites, particularly in wind turbine blades. These include standard epoxy, vinyl ester and polyester systems, which cannot be remelted or reprocessed. While their crosslinked thermoset network provides excellent mechanical and chemical stability, it also makes recycling routes such as pyrolysis or solvolysis difficult. As a result, more than 95% of the approximately 1.5 million tonnes of composite waste generated annually is still landfilled or incinerated, leading to an irreversible loss of valuable fiber and polymer resources as well as significant environmental impacts [1-2]. Same applies to the production residues (scrap, offcuts etc.) which account for up to 30% of total product weight [3].

Increasing regulatory pressure and growing awareness of the environmental impacts associated with composite waste have prompted many industries to reconsider how fiber-reinforced materials are designed and handled at end-of-life [4,5]. As disposal routes become increasingly restricted and long-lasting polymer systems accumulate in waste streams, the development of recyclable resin systems that combine high performance with controlled recoverability has become a central research objective. This shift is reflected in policy frameworks such as the EU End-of-Life Vehicles Directive, which requires 85% of material recovery and reuse, encouraging manufacturers to adopt more circular material strategies [6-7]. Against this backdrop, research efforts have intensified towards developing thermoset resin systems that not only meet demanding mechanical requirements but also enable controlled retrieval and reintegration of their constituents, offering a more sustainable alternative to conventional thermoset-based composite structures. This issue has become increasingly urgent for the wind energy sector in particular, as the first generations of rotor blades are now reaching the end of their service life. Growing restrictions on landfill disposal, together with stringent CO_2-reduction targets, demand sustainable recycling pathways.

Wind turbine blades are complex, heterogeneous composite structures. They often consist of hybrid assemblies combining metallic fixtures, wood, honeycomb cores and foams, all encased in fiber-reinforced polymers based on various matrix systems and fiber types (CF, GF, bio-based, etc.). As a result, effective material recovery requires highly efficient separation of these constituents during the recycling of decommissioned rotor blades [8-9]. Conventional recycling methods for thermosets, such as mechanical shredding, pyrolysis or solvolysis, are not only energy-intensive but also damage the valuable recovered materials, typically yielding only low-value fillers (downcycling) [10]. A controlled, fiber-friendly cleavage process of the composite matrix would not only enable the recovery of intact fiber fabrics, allowing them to be re-impregnated and reused in new components, but also extend the overall material life cycle and significantly reduce its carbon footprint [11].

Recyclable thermosets currently available on the market can be broadly classified into three categories based on their underlying recovery mechanisms. Covalent adaptable networks, such as vitrimers, can be reprocessed through reversible bond-exchange reactions. Cleavable thermosets contain chemically labile linkages that can be selectively broken by acids, bases, or solvents. A third group, thermally reversible thermosets (e.g., Diels-Alder systems), relies on heat-activated reversible reactions to enable reprocessing [12].

Cleavable thermosetting systems represent a particularly promising route for enabling recyclable wind turbine blades. By incorporating labile chemical linkages, such as acetal, ketal, or silyl ether groups, into the epoxy network, these resins allow selective bond cleavage under mild chemical conditions. As a result, the matrix can be gently depolymerized at end-of-life, enabling the recovery of high-quality reinforcement fibers and the generation of polymer recyclates with thermoplastic-like characteristics [13-15]. Commercially available systems such as Recyclamine® and EzCiclo™ have already demonstrated industrial feasibility and compatibility with established composite manufacturing routes, without requiring fundamental changes to process redesign of blade production [16-19].

Despite the clear potential of cleavable thermoset systems, several critical scientific and technical questions remain unresolved. Although fiber recovery from cleavable epoxy laminates has been demonstrated in principle, systematic data on how specific recycling conditions affect fiber integrity and mechanical performance are still scarce. In particular, it remains unclear to what extent recovered fibers retain their tensile strength, stiffness, and surface characteristics, and how the separation process influences fiber alignment, residual sizing, and interfacial adhesion during subsequent reuse. Understanding these aspects is essential, as fiber-dominated properties such as tensile strength, modulus, and failure strain largely determine the performance and value of recycled composite materials.

Equally important is the delamination behavior of the laminate itself. The ability to separate individual fabric layers cleanly, without fiber breakage or cross-contamination, is a key requirement for the recyclability and economic viability of cleavable resin systems in wind turbine applications. A controlled, fiber-preserving cleavage process would not only enable the recovery of intact fiber textiles that can be re-impregnated and used in new components, but also extend the overall material life cycle and substantially reduce the environmental footprint of composite structures.

The present research project aims to explore these relationships experimentally and through statistical experimental design (DoE) and simulation in a systematic and detailed manner. The central research questions are:

1. Can cleavable epoxies match mechanical performance of conventional systems?
2. To what extent do recycled fibers retain their mechanical properties compared to virgin fibers (after one or multiple recycling cycles)?
3. What are the key aspects regarding the reusability of the recycled matrix? (The detailed recovery and reuse of the matrix-recyclate represents a separate investigation and is not within the scope of this work.)
4. How well can individual fiber layers be separated and reprocessed without damaging the textile architecture?
5. What proportion of short fibers is generated during recycling, and how suitable are these fibers for secondary applications?

By correlating fiber integrity and laminate performance with processing parameters, this work seeks to identify the degradation mechanisms responsible for property loss and to quantify the potential of cleavable resin systems for multiple reuse cycles. The overarching goal is to assess the added value of recyclable matrix systems, not only in terms of their recyclability but also regarding their ability to generate high-quality secondary raw materials.

A sub-study within the overall project focuses on carbon-fiber-reinforced laminates based on the recyclable epoxy system Recyclamine®. Among other aspects, it investigates how the recycling process, particularly acid-based matrix cleavage and precipitation, affects the mechanical properties and integrity of the recovered fibers.

This publication presents only a selected part of the overall study, concentrating on a representative excerpt of the experimental work conducted.

3. Current State of the Technology Industry Uses

The industrial relevance of recyclable epoxy concepts is increasingly reflected in a growing patent landscape. Various methods have been proposed to recover both fibers and polymer fractions from FRPs as secondary raw materials. Early approaches to separate fibers from the matrix, such as those described in EP 0 797 496 B1 [20], used oxidative separation by exposing composites to ozone dispersed in a liquid medium, enabling matrix degradation and fiber release. Similarly, DE 10 2014 114 831 B4 [21] proposed steam-assisted concentration of polymer solutions to obtain granular polymer recyclates, while US 5,567,245 A [22] describes mechanical abrasion in a washing fluid to separate layered polymers such as polypropylene and vinylidene chloride. WO 2024/125740 A1 [23] describes an extraction process using formic acid as a swelling agent to partially break down the thermoset network, enabling recovery of epoxy fragments.

Furthermore, so-called self-healing thermosets, such as the vitrimer systems discussed above, are being developed for wind energy applications. Vitrimers represent an advanced approach in recyclable thermoset research. They retain the mechanical robustness and thermal stability characteristic of conventional thermosets while incorporating dynamic covalent bonds, allowing thermoplastic-like reprocessing without fully compromising the network density. Companies such as Westlake Epoxy and Techstorm are developing vitrimer-based formulations with a focus on wind turbine blade production, where both durability and recyclability are critical [24].

Cleavable resin systems are exemplified by US 2017/0145180 A1 [25]. The described process relies on an amine-based, cleavable hardener in epoxy formulations, enabling controlled dissolution of the cured resin in diluted acetic acid. These hardeners introduce acid-labile bonds, such as acetal, ketal, or silyl ether linkages, which can be selectively cleaved under mild conditions, e.g., diluted acid and low temperature. The fibers can be separated intact, washed, and dried, while a thermoplastic-like resin phase can be recovered from the acidic solution through gradual neutralization and precipitation.

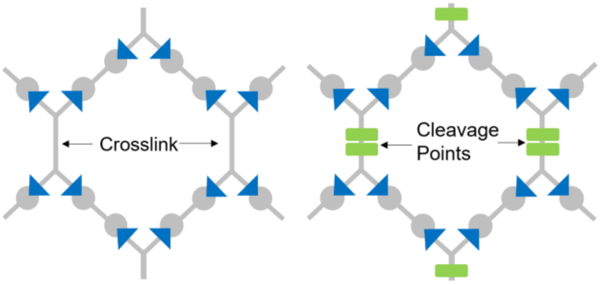

Figure 1: Schematic comparison of conventional epoxy systems (left) and Recyclamine® systems (right)

Commercial activities already reflect this trend: cleavable epoxy formulations such as Recyclamine® from Aditya Birla and EzCiclo™ from Swancor are available as industrial solutions and are designed as direct replacements for existing epoxy systems, allowing implementation without significant process modifications.

4. Technology Approach

In this study, carbon-fiber-reinforced laminates are used as representative model materials for the outer shell of a wind turbine rotor blade. Using a cleavable resin system, flat CFRP profiles were manufactured as test specimens via hot compression molding with a custom-built setup and subjected to mechanical testing before and after recycling. By comparing unrecycled/ virgin (vCFRP), recycled (rCFRP), and repeatedly/ n-times recycled laminates (nrCFRP), the study aims to evaluate the performance retention and reuse potential of cleavable, epoxy-based CFRPs.

To illustrate the technological implications of recyclability discussed above, the performance of these materials is further compared to laminates produced from a conventional, non-cleavable epoxy system. For this purpose, additional laminates using a non-cleavable matrix were manufactured under identical processing conditions. Moreover, all laminates were produced with two different fabric architectures in order to capture potential fabric-dependent effects on processing, recyclability, and fiber recovery. To enable gentle matrix cleavage and fiber recovery while preserving fiber integrity, a specialized low-temperature solvolysis and precipitation process was developed as part of the project. A functional prototype device was constructed and integrated into the process.

4.1. Materials

The CFRP constituents used in this study include for the reinforcing materials: virgin carbon fiber woven fabrics, twill weave and plain weave (ECCellent®, C. Cramer & Co. GmbH). Plain-weave and twill fabrics were chosen as the reinforcing fabrics because their distinct interlacing patterns result in different levels of crimp, drapability, and in-plane fiber alignment. Plain weaves typically exhibit higher geometrical stability but stronger fiber waviness, whereas twill fabrics provide improved drape and a smoother load path due to reduced crimp. These structural differences can affect both the degradation behavior during recycling and the mechanical response of the reprocessed fibers. In order to be able to produce laminate profiles with the same number of layers per cross-section using the hot compression molding process, the same base fiber was used for both types of weave.

Table 1: Technical data and mechanical properties of the reinforcing fibers

Weave type	Twill-weave/ Plain-weave
Areal weight (g/m²)	160
Tensile Strenght (MPa)	4200
Tensile modulus (GPa)	240
Fibre density (g/cm^3)	1,78

For the matrix material two types of resin systems are used: a cleavable system using hardener R301 (Recyclamine®, CTP Advanced Materials GmbH, Aditya Birla Group) and a bisphenol-A based epoxy resin YD-127 (Epotec®, CTP Advanced Materials GmbH, Aditya Birla Group). For the representative commercial, non-recyclable resin system constituent were selected as follows: hardener HP-HTE300RI-9 (HP-Textiles GmbH) and bisphenol-A based epoxy resin HP-HE3000RI-30 (HP-Textiles GmbH). Since no dedicated datasheet is available for this specific system, the following material properties were experimentally determined for the Recyclamine®-based formulation.

Table 2: Processing parameters and material properties of cured epoxy resin for cleavable and commercial systems

Resin System	YD-127/ R301	HP-HE3000RI-30/ HP-HTE300RI-9
Mixing ratio (resin:hardener)	100:26	100:30
Curing Conditions (h/ °C/ bar)	24/ 80/ 150	5/ 50 + 6/ 80
Tensile Strenght (MPa)	82-92	72
Elongation at Tensile Strenght (%)	5-8	5-6
Tensile Modulus (GPa)	2.5-3	3

For the recycling process dilute acetic acid (VWR Chemicals BDH®) with a concentration of 25% is used as well as NaOH (VWR Chemicals BDH®) with a concentration of 25% for the precipitation process.

4.2. Experimental Process

4.2.1. Manufacturing of CFRP Laminates

The cleavable composites were prepared according to their datasheet (Table 2). All laminates were produced via hot compression molding using a heated press and a custom aluminum mold (Figure 2) to ensure reproducible processing conditions.

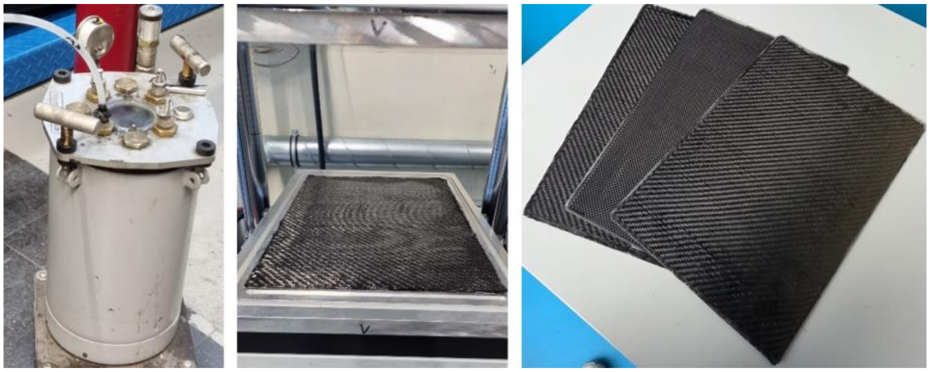

Figure 2: Vacuum chamber (left), heated press with mold (middle), CFRPs (twill and plain) (right)

The laminate dimensions were selected such that approximately twelve tensile test specimens, conforming to DIN EN ISO 527-4, could be obtained from each laminate (Table 3). The mold is prepared prior to lamination by cleaning the surface and applying a release agent, ensuring easy demolding of the finished laminate. The fabrication procedure was as follows: the preform was cut from continuous fiber fabric rolls with a rotary cutting tool to match the mold dimensions; the Recyclamine®-resin component was preheated in an oven for 30 min at 60 °C to reduce viscosity and thereby improve fabric wet-out during impregnation; the two-component resin systems were mixed according to their specified ratios, degassed in a vacuum chamber (Figure 2) for 1 h and applied uniformly to each carbon-fiber layer. For each laminate twelve layers of fabric were used and cured according to their datasheet (Table 2). More resin was mixed than the nominal amount required to ensure complete impregnation of all fiber layers. Any excess resin was expelled during mold closure through special outlet tubes positioned at the front and rear of the tool, ensuring that a consistent resin quantity remained inside the mold for each laminate. The resulting laminates have a fiber volume content of approx. 51.5%.

Table 3: Dimensions of laminates, respective tensile test specimen and tabs.

Laminate Dimension (LxWxT) (mm)	410 x 285 x 2
No. of Fiber Layers	12
Tensile Test Specimen Dimension (LxWxT) (mm)	250 x 25 x 2
Tabs Dimension (LxWxT) (mm)	50 x 25 x 2
No. of Tensile Test Specimen	120-150

4.2.2. Recycling Process of Laminates for Fiber and Matrix Recovery

For the recycling process, in which the cleavable points of the hardener are selectively opened, each laminate was immersed in a 25% acetic-acid bath at 80 °C for 9 h. A dedicated separation unit was developed for this purpose, enabling the simultaneous recycling of multiple laminates. To prevent fraying, and enable complete matrix removal, a rack-based holding system with permeable clamping elements was designed. This setup keeps the laminates under slight tension during cleavage while allowing the acid solution to penetrate uniformly through all layers (Figure 3).

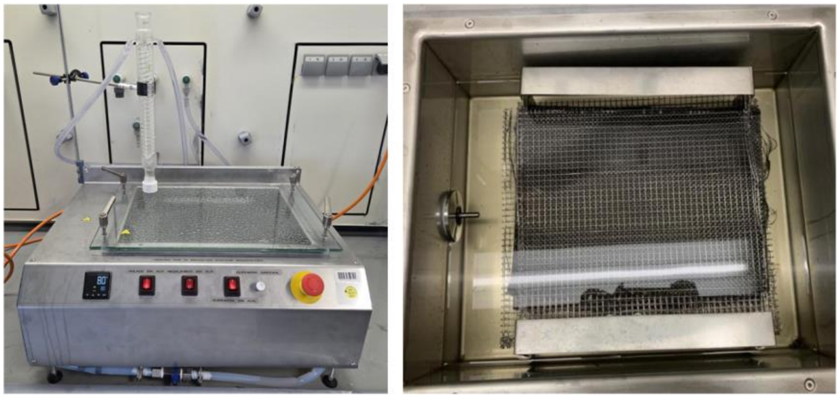

Figure 3: Recycling unit (left), permeable clamping elements (right)

Continuous stirring of the bath further enhances homogeneous mixing and accelerates the diffusion of the solution into the laminate; the clamping system helps maintain positional stability during agitation. To maintain a stable processing temperature, a sensor-controlled heating system was integrated into the bath, while a condenser helps the evaporated acetic acid to recirculate. A process time of 9 h was identified as necessary to fully remove the matrix and exposing all fiber layers.

After cleavage, the fiber preforms are removed from the bath and released from the clamping system. The twelve individual fiber layers are then separated manually using tweezers and washed sequentially in a washing line: first in a dilute alkaline solution to neutralize residual acid, followed by rinsing with deionized water, all while held in the clamping fixture to avoid mechanical damage. The separated preform layers are laid out to dry at room temperature for 24 h. The remaining acetic acid solution that contains the cleaved matrix can subsequently be neutralized with NaOH to precipitate a thermoplastic recyclate of the matrix, enabling material recovery beyond the fibers.

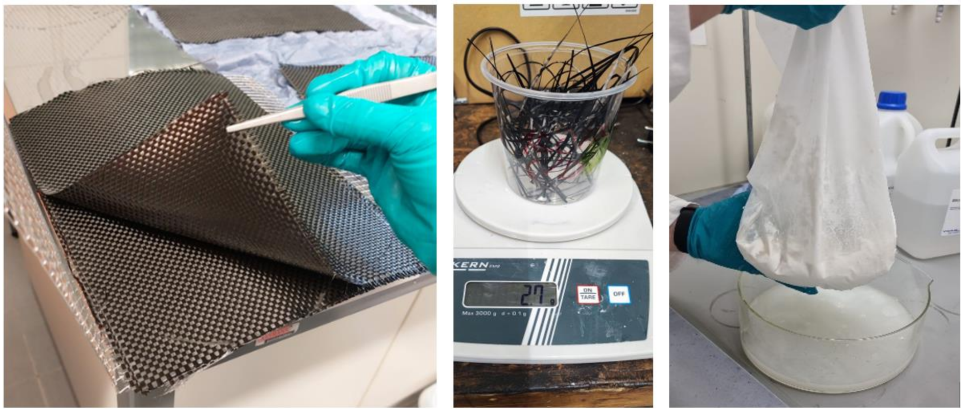

Figure 4: Separation of CFRP layers (left), short fiber (middle) and matrix-recyclate after recycling (right)

Short fibers generated during the recycling process are statistically evaluated to assess fiber damage mechanisms and quantify the gentleness of the method. The detailed recovery and reuse of the matrix-recyclate represents a separate investigation and is not within the scope of this work.

4.2.4. Preparation of Tensile Test Specimen

For the tensile specimens, Type 3 geometry was selected according to DIN EN ISO 527-4, as it is suitable for fabric-reinforced composites and requires the use of load-introduction elements (tabs). Initial tests without tabs resulted in premature failure outside the valid gauge section. According to the standard, tabs must be applied in such cases to ensure proper force transfer into the specimen and to shift potential stress concentrations outside the measurement region. Several tab configurations were evaluated, including CFRP, GFRP, and GFRP with an additional taper. The most consistent and valid failure patterns were obtained using GFRP tabs with a small taper, which helps to gradually transition stiffness between the tab and the specimen and thereby reduce stress concentrations at the tab termination. The tensile specimens were cut using an abrasive waterjet process to ensure accurate geometry and high-quality edges, with the fiber orientation being 0/90°. The GFRP tabs were machined from plates with a fiber orientation of ± 45°, providing lower axial stiffness that reduces termination stresses and allowing the grips to bite into the tab surface effectively. The tab taper angle was set to approximately 20°, based on prior in-house experience, although values in the range of 10–15° are commonly recommended in the literature [26]. For bonding, a high-shear-strength adhesive was required; therefore, Scotch-Weld™ DP490 was selected.

4.2.5. Test Equipment and Tensile Testing

Tensile tests were performed on a Shimadzu AGX-V universal testing machine. Given the expected maximum loads of 35–45 kN for the CFRP specimens, a 50 kN load cell was used. Wedge grips with pyramidal jaws were used for clamping, ensuring careful alignment along the specimen axis. Specimens were preloaded to 50 N at a rate of 0.5 mm/min and subsequently tested at 2 mm/min according to DIN EN ISO 527-4. Strain measurements were controlled using a tactile extensometer. The recorded data included the (fracture) force (kN) and actuator displacement. Based on this data, the tensile stress (σ), strain (ε), and elastic modulus (E) were derived using standard material mechanics principles. The Young’s modulus was evaluated in the strain interval of 0.05–0.25% following the specifications of the standard.

5. Discussion

5.1. Tensile Test Results

The image below shows, as an example, the tensile specimens, labeled according to their groups and their position within the original laminate. Only the specimens that failed within the valid gauge section were considered for evaluation.

Figure 5: Tensile test specimen with tabs after testing

The results were statistically recorded and analyzed. The standard deviations of the measured values across all test series ranged between 0.8% and 7.9%, indicating representative measurement data. The diagram shown in Figure 6 presents the results of the tests performed, where vCFPR is compared with rCFPR obtained after the first recycling cycle and nrCFPR obtained after the fifth recycling cycle.

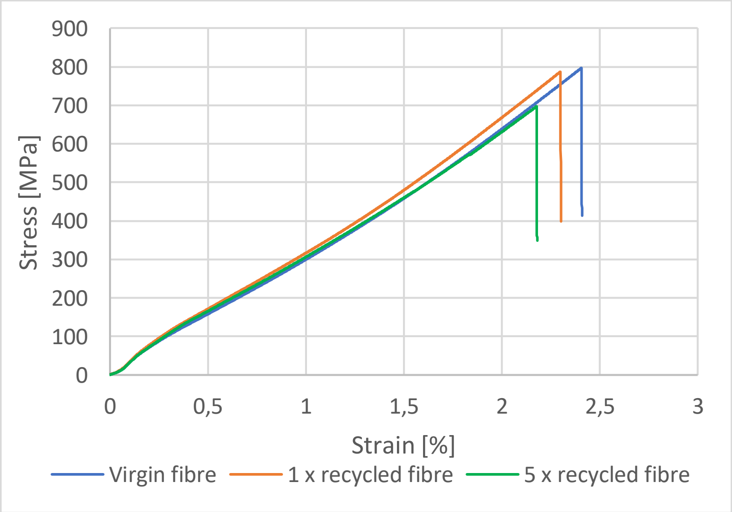

Figure 6: Comparison of vCFRP, rCFRP, and nrCFRP for plain-weave laminates

As expected, the vCFRP exhibits a higher tensile strength of 793.7 ± 36.9 MPa compared to the rCFRP, which shows a strength of 783.2 ± 12.5 MPa. However, the difference of 1.34% is so minimal that it falls within the standard deviation (see also above) and can therefore be considered negligible. The vCFRP specimens show a higher elongation at break of approximately 2.4 ± 0.02% compared to 2.3 ± 0.1% for the rCFRP, corresponding to a difference of 4.35%, which indicates a slightly higher ductility of the vCFRP. The Young's modulus of the vCFRP is 39463 MPa, whereas the rCFRP reaches 42658 MPa, indicating an 8.1% higher stiffness for the rCFRP.

The nrCFRP shows a significant reduction in tensile strength, with a value of 689.5 ± 5.34 MPa, corresponding to decreases of 15.1% and 13.6% compared to vCFRP and rCFRP, respectively. The elongation at break of the nrCFRP, with a value of 2.16 ± 0.08%, also shows a reduction of 11.1% compared to vCFRP and 6.5% compared to rCFRP. The Young's modulus is 40699 MPa, which represents a decrease of 4.8% compared to rCFRP and an increase of 3% compared to vCFRP.

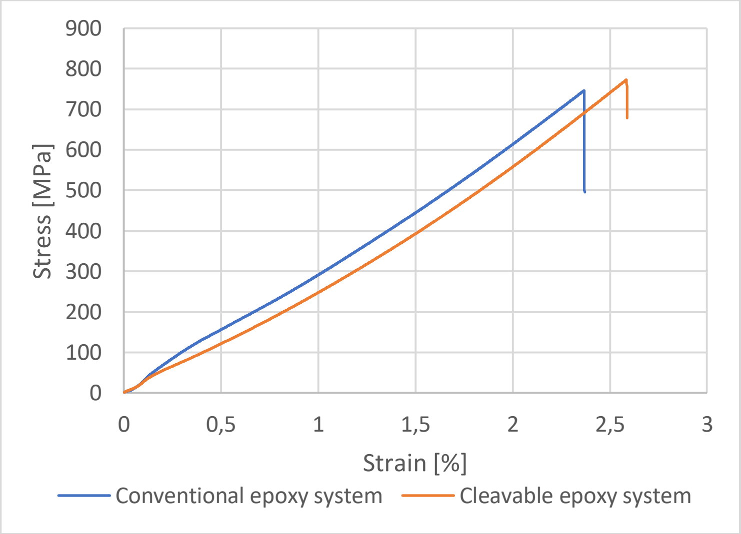

Figure 7: Comparison of conventional and cleavable CFRP for twill-weave laminates

The comparative analysis of the strength of the conventional CFRP, with 734.24 ± 9.4 MPa, and the cleavable CFRP, with 769.3 ± 14.2 MPa, revealed a difference of 4.8% in favor of the cleavable CFRP. The values for the elongation at break were approximately 2.59 ± 0.15% for the cleavable system and 2.37 ± 0.2% for the conventional system, corresponding to a difference of 9.3%. This indicates improved ductility of the cleavable resin systems.

The Young's modulus of the conventional CFRP, with a value of 38408 MPa, compared to the cleavable CFRP with 28127 MPa, shows a decrease in stiffness of 36.6%. Strength and stiffness values for identical fiber reinforcements with different matrix materials would be expected to fall within a similar range. The unusually large differences observed here were verified by means of a control measurement, which produced the same results.

5.2. Importance of a Fiber-Friendly System in the Recycling Process

It was found that gentle treatment of the fiber layers during the dissolution process is essential for maintaining their structural integrity. Recycling tests without a special holding device led to reduced layer cohesion and a significant loss of up to 10% of the fabric due to fiber damage and the development of short fibers through fraying at the edges. With the help of the above-mentioned device, the research team succeeded in reducing the proportion of short fibers produced in the recycling process to approximately 1%.

6. Conclusions & Recommendations

The results of this partial study make a positive contribution to the current state of the art, highlighting the growing recognition of recyclable resin systems for applications in key technological sectors such as wind energy. Their use in large-scale composite components could represent a turning point for circular economy practices within the wind energy industry. The samples recycled five times show a reduction in both elongation at break and tensile strength; however, with values of 689.5 MPa and an elongation of 2,16%, they still remain within a technically relevant and highly demanded performance range. Since the recycled laminates were not subjected to any in-service loading and were solely recycled one or multiple times after manufacturing, the observed reduction previously described in the mechanical properties may be attributed to the degradation of the sizing on the fiber fabric. It can be assumed that, following significant degradation of the sizing layer, the fiber surface exhibits more hydrophobic characteristics, which in turn affects resin impregnation during the lamination process. While the recycling process investigated in this work was carried out at laboratory scale, the applied processing steps are based on established chemical and thermal treatments that are, in principle, compatible with industrial-scale recycling concepts. No fundamental limitations were identified that would prevent the transfer of the process to larger-scale systems. Furthermore, the recovered fibers exhibit properties that indicate their suitability for reuse in secondary composite applications.

Although some variability in fiber length distribution and surface condition can be expected during scale-up, such effects are common in industrial recycling operations of e.g. obsolete rotorblades and can be managed through process optimization and appropriate material selection. In the case of end-of-life wind turbine blades manufactured with the investigated recyclable matrix system, no additional process-related limitations are expected compared to conventional composite blade recycling routes. In addition, the proposed processing setup is based on a comparatively simple device configuration, which further facilitates scalability to an industrial scale.

Overall, this study demonstrates that recycled fibers and matrix materials can be integrated into new products with minimal loss of performance, marking an important step toward establishing sustainable, closed-loop systems for next-generation composite materials.

7. Acknowledgements

The authors gratefully acknowledge the financial support provided by the Interreg Europe X-Lives project (grant number 22015). The collaboration with CTP Advanced Materials GmbH (Aditya Birla Group) is sincerely appreciated.

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9. About the Author(s)

Prof. Dr.-Ing. Michael Heber: Professor of Design Engineering and Polymer Technology at HSNR, Chair of the Polymer Laboratory, with extensive R&D experience in polymers and automotive applications, including leadership roles at Bericap, Bauknecht/ Whirlpool, Faurecia and Collins & Aikman.

Emma Shafir, M. Sc.: PhD candidate at the University of Duisburg-Essen with a master's in mechanical engineering focused on foam modelling and cutting simulations. Experienced in R&D projects, CAD lecturer, active board member of the Association of German Engineers (VDI). Ms. Shafir will serve as the presenter at the conference.