*Proceedings in Applied Mathematics and Mechanics*

SPECIAL ISSUE 95th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM)

RESEARCH ARTICLE OPEN ACCESS

# Approach for Damage-Free Disassembly of Highly Stressed CFRP Structures

Janko Kreikemeier[1] | Hans Helge Schwieger[2] | Frederik Raake[1] | Steffen Opitz[1]

[1]Institute of Lightweight Systems, German Aerospace Center, Braunschweig, Germany | [2]Institute of Transport and Automation Technology, Leibniz University Hannover, Garbsen, Germany

**Correspondence:** Janko Kreikemeier (janko.kreikemeier@dlr.de)

**Received:** 15 July 2025 | **Revised:** 24 November 2025 | **Accepted:** 27 November 2025

## ABSTRACT

In today's pursuit of sustainability, the aviation industry faces challenges in reusing materials and structural components made from carbon fiber-reinforced polymer (CFRP). Conventional downcycling methods degrade CFRP's structural integrity by cutting load-bearing fibers and embedding them in new matrices, reducing performance. The authors propose a nondestructive disassembly concept using a precise wedge-based separation technique that preserves fiber integrity. This enables direct reuse of materials and components in identical or alternative applications, advancing recycling technologies and paving the way for "Structural Life 2.0." Analytical and finite element analyses show the wedge separation mechanism is feasible and effective in shell structures without damaging the base material. Thinner wedges generate lower forces, depend less on panel stiffness, and require shorter crack initiation lengths, minimizing failure risk. Critical parameters should be defined during the design phase since retroactive changes are difficult. Thus, the philosophy of "Design for Disassembly" is proposed to integrate nondestructive separation features into new components. Building on previous analytical and numerical work, this paper extends investigations with experiments on coupon-level specimens and full-scale components using a self-developed test rig. Results confirm controlled separation of bonded elements without damaging fiber-reinforced materials. Key findings demonstrate the wedge-based process's practical applicability, supporting advanced recycling strategies and sustainable reuse. The technique proves highly effective for nondestructive disassembly of stiffening elements and offers a promising solution for future sustainable component reuse.

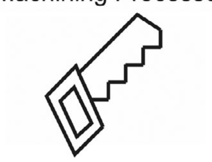
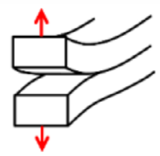
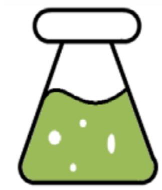
## 1 | Introduction

The separation of carbon fiber-reinforced polymer (CFRP) structural components starts with analyzing possible mechanisms. Based on fundamental principles, the most promising approach is selected, aiming to detach parts without damage. An initial analytical model is used to test feasibility, followed by FEM pre-investigations to reduce development risk.

Mechanical, physical, and chemical methods are considered. Conventional machining, targeted material overload (peeling stresses), thermal activation, and solvent-based methods are compared (see Table 1). While combinations are possible, thermal and chemical methods face major limitations due to the difficulty of accessing the adhesive layer.

Conventionally, as matrix materials, predominantly curable epoxy resins are currently used because they offer good mechanical properties, higher temperature resistance, and comparatively lower material costs, [2]. However, their properties also create challenges during disassembly. CFRP's low laser penetration and the uniform heating produced by induction or resistance methods make selective heating impractical [3], while solvent application risks damaging surrounding parts, and embedded reactive elements would add weight and weaken the joining zone, which is unacceptable for aerospace structures.

**TABLE 1** | Comparison of separation methods, [1].

| **Mechanical Separation** | | **Physical Separation** | **Chemical Separation** |
|---|---|---|---|
| Machining Processes  | Deliberate Material Overload  | Energy Dissipation  | Decomposition  |
| + Low stress on base material | + No loss of material | + Complexly shaped adhesive surfaces are separable | |
| + Well known process | + Simple process | | |
| – Elaborate process technology | – Possible component damage due to process forces | – Only possible with a pre-inserted mechanism | |
| –Cutting losses | – Complex adhesive froms are difficult to separate | –Damage to Surrounding structures due to heating/chemical effects | |
| | | – Lightning protection obstructive to radiant heating | |

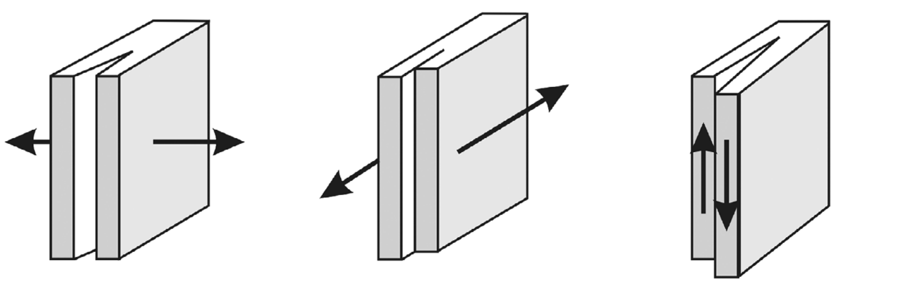



**FIGURE 1** | Load modes of deliberate adhesive overload include tension mode, planar shear as well as non-planar shear [1, 5]. Mechanical overload referring to tension mode (left) offers the greatest potential for damage-free disassembly. The stress intensity factors $K_I$, $K_{II}$, and $K_{III}$ correspond to the modes that must be considered in the mathematical description of failure behavior.

Moreover, metallic lightning protection layers absorb radiation [4], limiting external heating. Mechanical separation avoids these issues and can be applied post-manufacture. However, it demands access and introduces high forces, which can damage components. After evaluating pros and cons, mechanical overload offers the most potential (Figure 1).

Mode 1 (wedge induced peeling) is compact and effective, especially, for example, CFRP-based fuselage structures. In [1], it was correctly mentioned that removing the last stiffening element causes the structure's stiffness to drop and the skin deformation to increase. This can lead to a higher risk of structural failure.

## 2 | Mathematical Description of Wedge Forces

There exist different methods to describe the failure of composite structures that could also be used for wedge element-based disassembly. Progressive damage simulation is preferred for predicting the damage behavior of composite laminates [6]. If low-velocity impact damage is present, both analytical and numerical models can be applied. The complexity ranges from simple approaches with a single degree of freedom up to finite element-based models on the microscale [7]. In [8], an analytical scaling approach is presented that allows the analysis of structural impact scenarios on a small reference coupon. The benefit of this approach is the possibility of numerically predicting impact damage on large structures through high-fidelity methods. The impact scenario itself is constructed by using a much smaller reference coupon representing the damage-prone area. Validation of the low-velocity impact damage prediction through application of the scaling approach is provided in [9]. For this purpose, numerous experimental impact scenarios were used as the basis for assessing the scaling approach. As a result, it was found that the geometry of the impact configurations may lead to damage mode shifts.

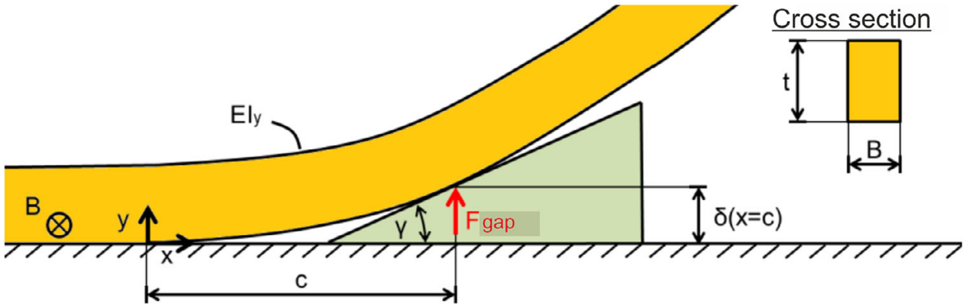



**FIGURE 2** | Wedge model with rigid plate behavior, [1].

All the methods mentioned above could, in principle, also be used to describe wedge element-based disassembly. Nevertheless, in this work, a much simpler analytical approach based on the double cantilever beam (DCB) model is employed. Therefore, a simple mathematical model of wedge element-based disassembly is shown in Figure 2. The wedge element-based disassembly process analysis focuses on the contact between the outer skin and stiffeners. Initially, the outer skin is nearly rigidly fixed by stringers and frames. Analogous to the DCB test, a simple crack model arises: energy release comes solely from detaching the stiffener, modeled as an Euler bending beam with a fixed support at the crack tip. Crack propagation occurs once the critical energy release rate is reached, as given by Equation (1), where $G$ defines the energy release rate of the beam, $U$ the internally stored energy, $B$ describes the bonded beam width, and $c$ is the length up to the bonded area, which corresponds to the crack length in the model (Figure 2).

$$G = -\frac{1}{B}\frac{\partial U}{\partial c} = -\frac{1}{B}\frac{\partial}{\partial c}\left(\frac{1}{2}F_{\text{gap}}\delta(x=c)\right) = \frac{1}{2B}\frac{F_{gap}^2 c^2}{EI_y} > G_{\text{Ic}}. \quad (1)$$

The mathematical evaluation of this relationship, along with the consideration of the maximum bending stress acting in the outer fibers of the stiffening element, ultimately yields the safety factor $S_{\text{F}}$, which can be used to analyze the deformation behavior

$$S_{\text{F}} = \sqrt{\frac{t\sigma^2_{\text{b,max}}}{6G_{\text{Ic}}E}}. \quad (2)$$

It is noteworthy that this equation is independent of both the bonded beam width $B$ and the crack length $c$.

## 3 | Finite Element Modeling of Wedge Disassembly

For verification reasons, an ANSYS-based finite element model of a stringer-frame stiffened curved CFRP structure was investigated. A cohesive zone model was used to analyze the separation of a stringer from the outer shell (Figure 3). All components have the same material thickness of 2.196 mm. The stacking sequence defined is $[45°, -45°, 90°, 0°, -45°, 45°]s$ starting from the bottom layer. The material parameters and the failure parameters were taken from [10] and [11], respectively.

For stabilization reasons, a damping coefficient was used to ensure a convergence of the solution within the implicitly formulated finite element model during the crack propagation. Implicitly formulated finite element models may lack convergence in cases of stiffness loss. At the onset of damage, commonly caused by microcracks and/or microvoids, a concentration of deformation in small finite-sized regions is observed, accompanied by elastic unloading in the surrounding areas. This phenomenon can be macroscopically characterized by strain softening behavior of the constitutive response, as well as by a so-called mesh dependency of the finite element solution, [5]. The main reason for this is the absence of an internal length scale that would ensure the localization zone remains finite.

From a mathematical point of view, the pathological mesh dependency changes the type of underlying system of partial differential equations describing the boundary value problem from elliptic to hyperbolic in quasi-static case. Therefore, the boundary value problem is called ill-posed. To ensure the strong ellipticity of the boundary value problem and, consequently, positive definiteness of the material's stiffness tetrad, the LEGENDRE-HADAMARD condition[1] has to be fulfilled. Additionally, [12] established the notion of strong polyconvexity, which implicitly includes the requirement of strong ellipticity, [5].

In Figure 4, results of the simulation on the 3 mm wedge at the position 120 mm in front of the frame are shown. The area most prone to fracture in the numerical model can be identified at the crack tip. Underneath the stringer web, larger crack lengths exist compared to other regions near the free edge. Compared to the analytical investigations, these results are consistent with each other. Furthermore, the supporting property of the stringer web decreases from the inner to the outer side. The normalized fracture stresses reached in the stringer and the skin are within the same order of magnitude. Adjacent to the wedge, the normalized fracture stress between the wedge an the skin is negligible.

## 4 | Experimental Test Stand

To validate the analytical and numerical findings, an experimental test rig was developed for the damage-free disassembly of structural components. Based on analytical preliminary considerations for the wedge separation process, the test stand was designed for a required wedge force of 3000 $N$. Force transmission from the low-voltage DC motor to the wedge is achieved via a lead screw mechanism. A CAD sketch of the final test stand is shown in Figure 5.

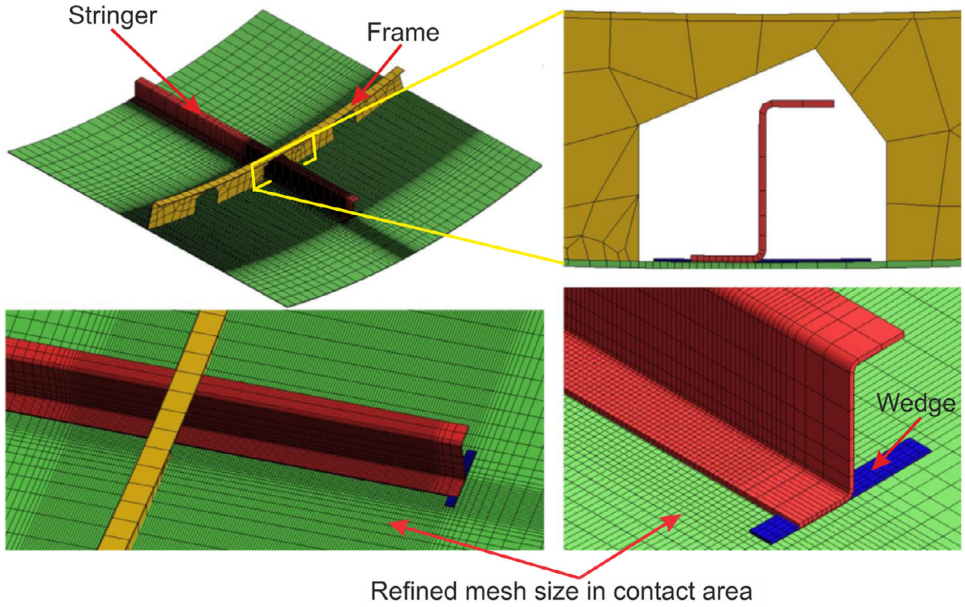



**FIGURE 3** | Finite element model of a stringer-frame stiffened curved CFRP structure, [1].

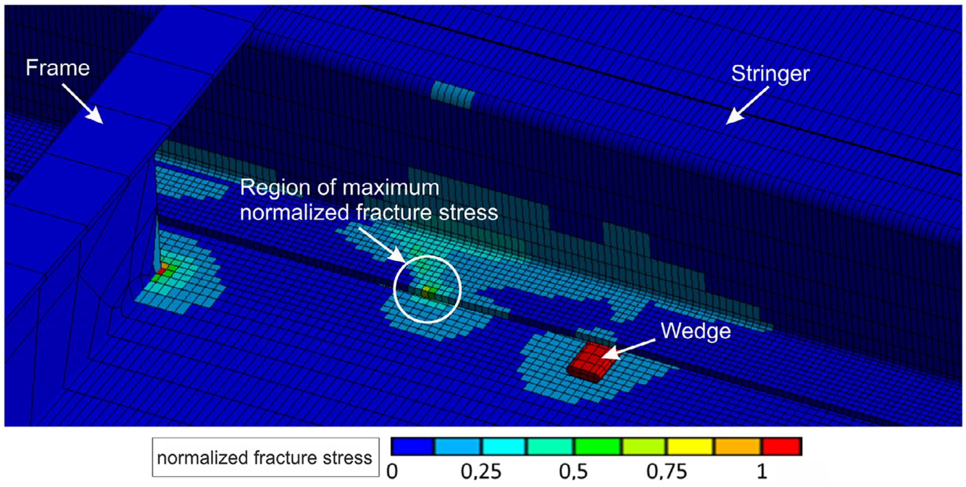



**FIGURE 4** | Normalized fracture stresses of the finite element model.

Following successful preliminary tests on coupon specimens, the test rig was applied to a full-scale CFRP fuselage structure (Figure 6). In this context, an omega stringer element was successfully detached from the skin. Subsequent nondestructive testing (NDT) revealed that the stringer was partially disassembled without damage. A large area at the stringer feet showed near-complete, damage-free separation. However, the specimen also exhibited a significant region of delamination, which was attributed to the manually introduced notch used for wedge insertion (Figure 7).

## 5 | Conclusion and Outlook

To enable an analytical description of the wedge-based separation process, a simplified analytical formula was derived, analogous to the fracture mechanics approach of the DCB test. This formulation allows investigation of the influence of key parameters on the fracture resistance of thin CFRP structures.

A damage-mechanics-based finite element analysis using cohesive zone modeling reveals that the highest normalized fracture stresses occur at the unstiffened, thin edge of a separated stringer.

To investigate the delamination process under realistic conditions, a test rig was developed. It uses a motor-driven, redirected cable system to pull a test wedge through pre-notched specimens. The setup allows clamping of specimens with varying widths and curvatures. In addition, the force required to advance the wedge can be recorded using a calibrated sensor.

An initial validation of the test rig was carried out on a full-scale CFRP fuselage shell. In this test, a stringer element was partially separated from the skin without damage using the

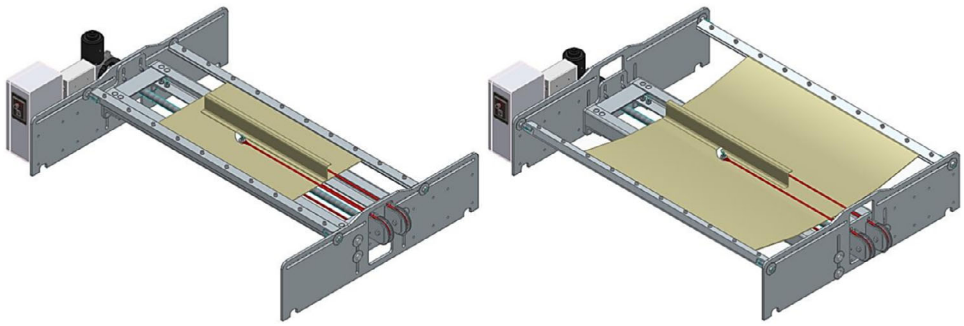


**FIGURE 5** | CAD sketch of the realized disassembly test stand.

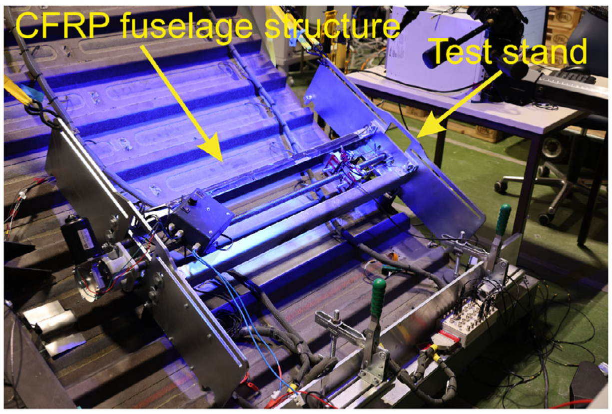



**FIGURE 6** | Application of test stand to full scale CFRP structure.

test stand. The experimental results are consistent with both the analytical and numerical pre-assessments, indicating the potential of this method for future damage-free disassembly of stiffening elements. Thus, this damage-free wedge element-based disassembly methodology could be an enabler for Structural Life 2.0 approach.

Future work should focus on further automation of the disassembly process, particularly on developing an appropriate pre-cracking method to insert the wedge without damaging the structure.

**Acknowledgments**

For carrying out the accompanying ARAMIS measurements, we would like to thank Mr. Ary Zipfel. We also extend our gratitude to M.Sc. Ahmed Bayoumi for conducting the accompanying SHM measurements, and to Dipl.-Ing. (FH) Bernd Friedrichs for performing the accompanying ultrasonic inspections.

Open access funding enabled and organized by Projekt DEAL.

**Endnotes**

[1] $(\boldsymbol{a} \otimes \boldsymbol{b}) \cdot\cdot\, \mathbb{C} \cdot\cdot\, (\boldsymbol{a} \otimes \boldsymbol{b}) > 0$, for all vectors $\boldsymbol{a} \neq \boldsymbol{0}$ and $\boldsymbol{b} \neq \boldsymbol{0}$, which ensures the positive definiteness of the stiffness tetrad $\mathbb{C}$, [5].

**References**

1. J. Kreikemeier and H. H. Schwieger, "Mathematical Insights Into Disassembly and Separation of Highly Stressed CFRP Structures," *CEAS Aeronautical Journal* 16, no. 2 (2025): 557–569, https://doi.org/10.1007/s13272-025-00813-6.

2. N. Mazlan, S. M. Sapuan, and R. A. Ilyas, *Advanced Composites in Aerospace Engineering Applications* (Springer International Publishing, 2022).

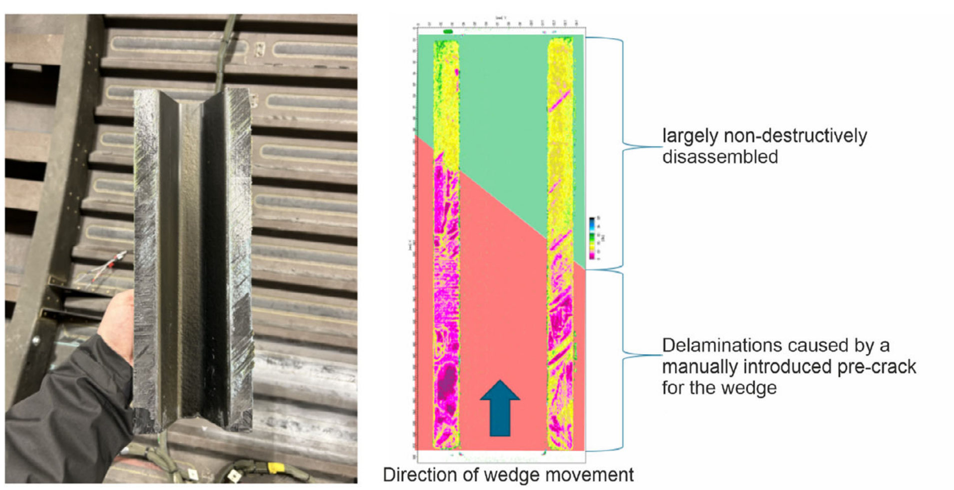



**FIGURE 7** | Disassembled stringer element (left) and corresponding backwall echo. One notices a largely nondestructively disassembled region on the upper side and delaminations, which were caused by a manually introduced pre-crack for the wedge in the lower stringer region, respectively.

3. W. Hintze, *CFRP Processing: Separation Technologies for Composite Materials and Hybrid Lightweight Construction* (Springer, 2021).

4. C. Karch and C. Metzner, "Lightning Protection of Carbon Fibre Reinforced Plastics – An Overview," in *33rd International Conference on Lightning Protection* (ICLP, 2016), https://www.researchgate.net/publication/309231103_Lightning_Protection_of_Carbon_Fibre_Reinforced_Plastics_-_An_Overview_-.

5. J. Kreikemeier, "A Two Scale Finite-Element-Approach to Analyse the Damage State of Composite Structures," German Aerospace Center (DLR), 2011.

6. R. M. Bogenfeld and J. Kreikemeier, "A Tensorial Based Progressive Damage Model for Fiber Reinforced Polymers," *Composite Structructure* 168 (2017): 608–618, https://doi.org/10.1016/j.compstruct.2017.02.006.

7. R. M. Bogenfeld, J. Kreikemeier, and T. Wille, "Review and Benchmark Study on the Analysis of Low-Velocity Impact on Composite Laminates," *Engineering Failure Analysis* 86 (2018): 72–99, https://doi.org/10.1016/j.engfailanal.2017.12.019.

8. R. M. Bogenfeld, J. Kreikemeier, and T. Wille, "An Analytical Scaling Approach for Low-Velocity Impact on Composite Structures," *Composite Structures* 187 (2018): 71–84, https://doi.org/10.1016/j.compstruct.2017.12.012.

9. R. M. Bogenfeld, J. Kreikemeier, and T. Wille, "Validation of the Low-Velocity Impact Damage Prediction Through Analytical Scaling," *Composite Structures* 209 (2018): 715–726, https://doi.org/10.1016/j.compstruct.2018.11.011.

10. M. Juntti, L. E. Asp, and R. Olsson, "Assessment of Evaluation Methods for the Mixed-Mode Bending Test," *Journal of Composites Technology and Research* 21, no. 1 (1999): 37–48, https://doi.org/10.1520/CTR10611J.

11. H. Schürmann, *Designing With Fiber-Reinforced Composites. With 39 Tables. 2nd Revised and Expanded Edition* (Springer, 2007).

12. J. M. Ball, "Convexity Conditions and Existence Theorems in Nonlinear Elasticity," *Archive for Rational Mechanics and Analysis* 63, no. 4 (1976): 337–403, https://doi.org/10.1007/BF00279992.