ENDLESS FIBRE REINFORCED COMPOSITE-METAL-IMPELLER: HIGH SPEED BURST TESTING - DAMAGE AND FAILURE ANALYSIS

Sebastian SPITZER[1], Martin POHL[1], Peter HERMERATH[2],
Jonas KLUGER[1], Richard GROTHE[1], Maik GUDE[1]

[1] Technische Universität Dresden, Institute of Lightweight Engineering and Polymer Technology, Holbeinstrasse 3, 01307 Dresden, Germany

[2] Piller Blowers & Copressors GmbH, Nienhagener Strasse 4 -6, 37186 Moringen, Germany

SUMMARY

Radial impellers made of continuous fibre-reinforced composite material in modular design are spin rig tested until failure up to 538 m/s. Using high-speed recordings during the test and fracture analysis, it is possible to interpret the damage and failure behaviour of the structure and compare it with the results of the numerical simulation. One focus of the discussion is on the chosen joining technique as a relation to the bursting speed. This provides indications for measures to further improve the design and increase the performance and reliability of such structures.

INTRODUCTION

The performance and efficiency of future and existing blowers can be increased by using new types of high-performance radial impellers made of fibre reinforced composite materials [1, 2]. Such materials have outstanding density related mechanical properties, which allow the speed to be increased significantly. As a result of the reduced mass such impellers, in particular the reduced inertia, can react faster to variable speeds and consume less energy. Additionally, composites allow a variable aerodynamically design of the blades e.g. as a NACA-profile. This can lead to flow-optimised cross-sections to additionally increase the efficiency and provide the potential to reduce noise [2–4]. Furthermore, the layered material design of such impellers can be used to integrate sensors as a basis for component monitoring and data generation [5].

Due to the special characteristics of fibre reinforced composite materials with their large amount of adjustable parameters and the necessity of specific know-how in combination with high expenditures and risks for the development and production of integral rotors, they are currently only niche products. Modular composite metal-impeller allow an easier to handle design of the single components. In combination with an understanding of accruing damage and failure behaviour during rotation, engineers in small and medium enterprises should be enabled to implement such modular composite impellers and transfer them to industrial applications.

DESIGN AND MANUFACTURING OF MODULAR RADIAL IMPELLER OUT OF ENDLESS FIBRE REFINFORCED PLASTIC

Turbo radial fans can be made of fibre-reinforced plastic (FRP) in a modular design (acc. Figure 1). The impeller consists of the separate FRP elements: carrier disc, blades and cover disc. The blades are Z-shaped. The resulting flanges are used as an interface to connect the blade-discs via adhesives with excellent bond strength as well as durable properties for structural bonding. Thus to increase the resistance of the bonding against regular stress as well as shock and impact forces. A metal hub connects the impeller to the drive shaft. Compared to integral solutions, the manufacturing effort of this modular design is greatly reduced, which allows a higher availability and variability in production [6].

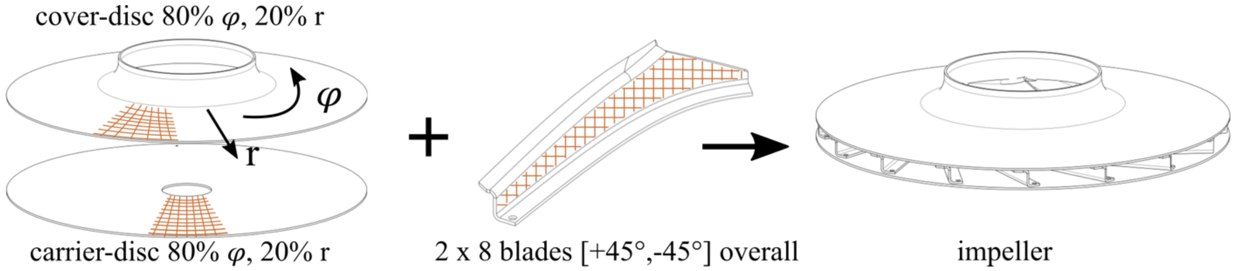


Figure 1: design of the modular composite-metal radial-impeller with material orientations (left) and assembled impeller (right) [6]

Testable radial impellers can be manufactured using prepreg material in combination with an autoclave process (acc. Figure 2). Commercially available prepreg material is cutted (1) into single layers, preformed (2) and vacuumed (3) on forming tools. After consolidation (4) the single components can be demolded (5) and milled (6). The single components can be assembled (7) to a complex radial composite impeller. To join the Z-shaped blades with the discs, a structural bonding is used. Three testable impellers were manufactured: impeller 1, 2 and 3. To realize a necessarily defined thickness of the bonding in-between the blades and the disks, copper wire for impeller 1 and glass pearls for impeller 2 and 3 are used in the interface.

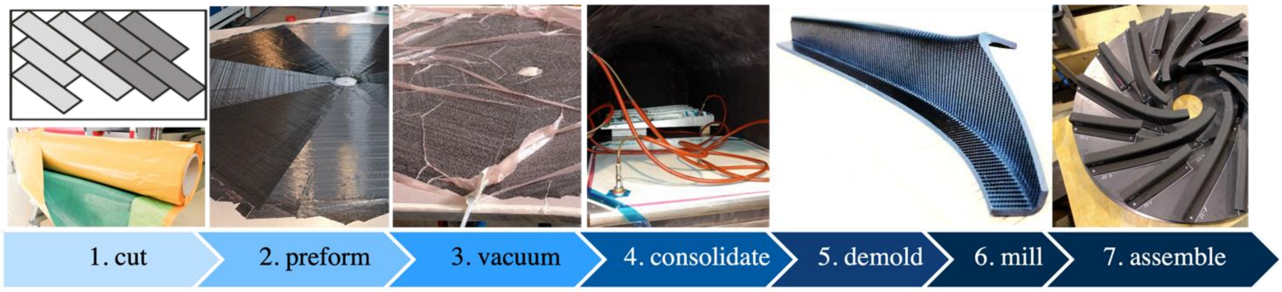


Figure 2: manufacturing process of the composite parts and assembling

This technology enables a cost-efficient impeller manufacturing. Due to the single components of the disks and the blades, the risk during the manufacturing process is quite low. In the case of manufacturing errors, scrubbed components can be replaced easy. The used one-side aluminum tools are cheap, robust and simple to handle. The disadvantage of this process is the plastic deformation of the material in geometrical complex areas like the blade roots. This can influence the mechanical load bearing capacity on the one side. Uncontrolled material deformation also leads to varying mass distributions in the elements and in the assembled fan. Due to this circumstance, balancing of the fan is more difficult.

Impeller 1 was manufactured on one-sided tools, without shaping aids in the transition area from the blade to the blade flange and copper wire to set a defined adhesive layer gap. For impellers 2 and 3, the manufacturing quality, especially in the transition area between blade and blade flange, was successively improved by using 3D-printed inserts and silicone castings. Glass globules were added to the adhesive to achieve a defined bonding slit. The quality was significantly improved during the manufacturing processes. Furthermore, an additional heat treatment was applied to the impeller 2 by six-hour tempering.

DIMENSIONING AND COMPOSITE MATERIAL RELATED FAILURE MODES

The dimensioning and the virtual proof of strength of such a composite impeller can be done using ANSYS Mechanical Composite PrePost (ACP, acc. Figure 3). This commercial software allows the consideration of the material specific characteristics.

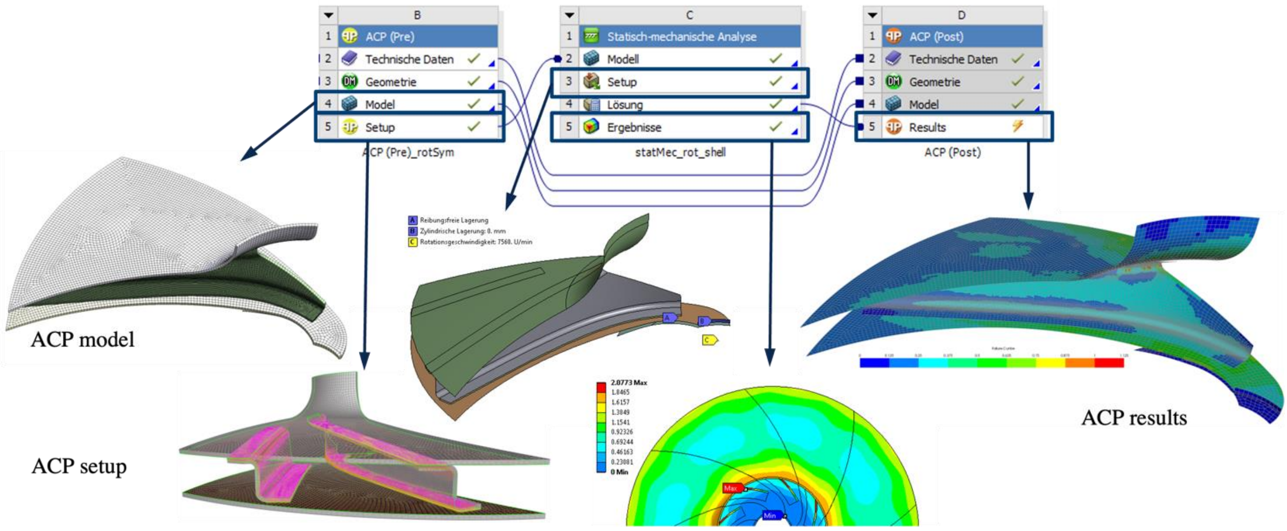


Figure 3: numerical simulation setup using ANSYS Mechanical Composite PrePost (ACP)

Orthotropic FRP material systems can be interpreted using failure mode related methods e.g. PUCK and CUNTZE to predict the mechanical capability on a micro scale level during mechanical loading [7, 8]. CUNTZE describes two fibre failure modes (FF1, FF2) and three inter fibre failure modes (IFF1, IFF2, IFF3). In an impeller with the proposed design and material orientations (acc. Figure 1), these material-related fracture modes can be assigned to different areas of the structure (acc. Figure 4).

In addition to the most probable failure mode, other modes can also occur. In a damage hypothesis the effort of the single failure modes is summarized to a total effort. According to CUNTZE, the term effort will be used to describe the total effort of the composite material depending on the single failure modes. The term "strength" in the context of composite material will be avoided in this paper to demarcate composite failure hypotheses to metal failure hypotheses.

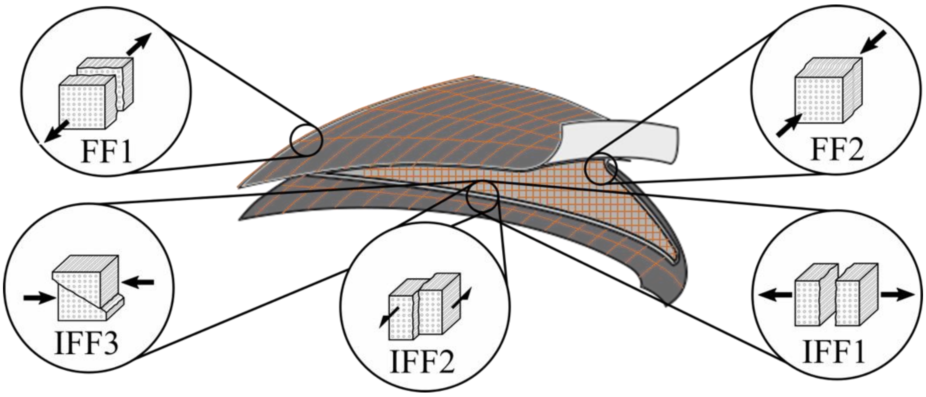


Figure 4: probable material failure modes according to CUNTZE [7] in relation to the structure the modular impeller

For the modular design of the impeller, two aspects are assessed: the structural effort with regards to the CUNTZE failure modes and the stress distribution in the interface in-between the blades and the disks. Figure 5 shows the CUNTZE-effort of an impeller segment (left) with the detail A of the critical area in the radius of the blade (right top) and the stress distribution in the bonding interface (left, right bottom). If damaged or failure accrue, it is expected to be at the radius of the Z-shaped blades or in the joining interface between the discs and blades.

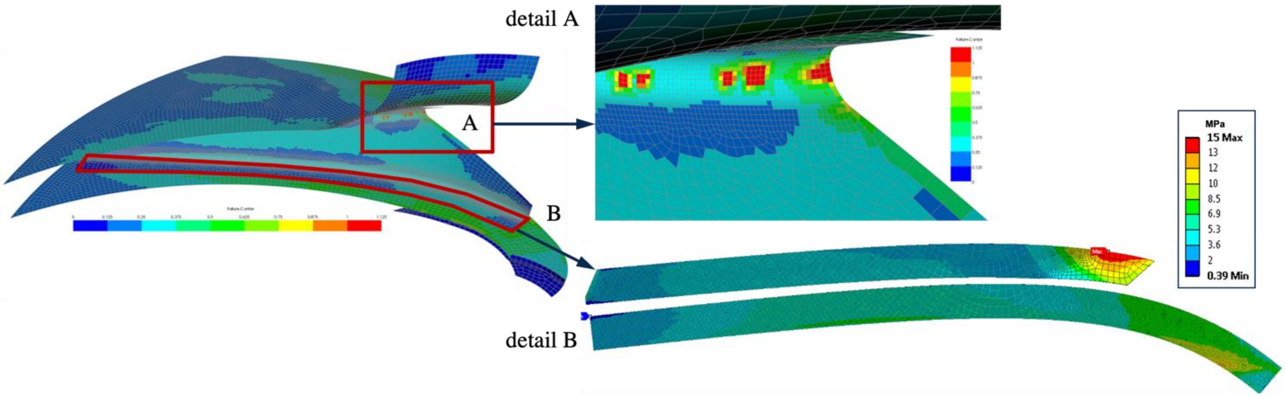


Figure 5: CUNTZE-effort of an impeller segment (left) with the detail A of the critical area in the radius of the blade (right top) and the detail B of the stress distribution in the bonding interface (left, right bottom)

It should be mentioned that the model used predicts the initial failure. It is worth mentioning that the model used predicts the initial failure, which may be e.g. intermediate fibre failure on the material level and thus not critical in terms of structure. Therefore initial damage in the material does not necessarily lead to failure in the component. Further statements can be made with extended damage models or through physical verification.

PHYSICAL DETERMINATION OF DAMAGE AND FAILURE BY SPIN TESTING TO BURSTING

The three manufactured impellers are tested in a Schenk spin rig to evaluate the structural design (acc. Figure 6). Therefore, the fan is mounted at the spin rig gear. High speed cameras are installed at the bottom, observing events during the test.

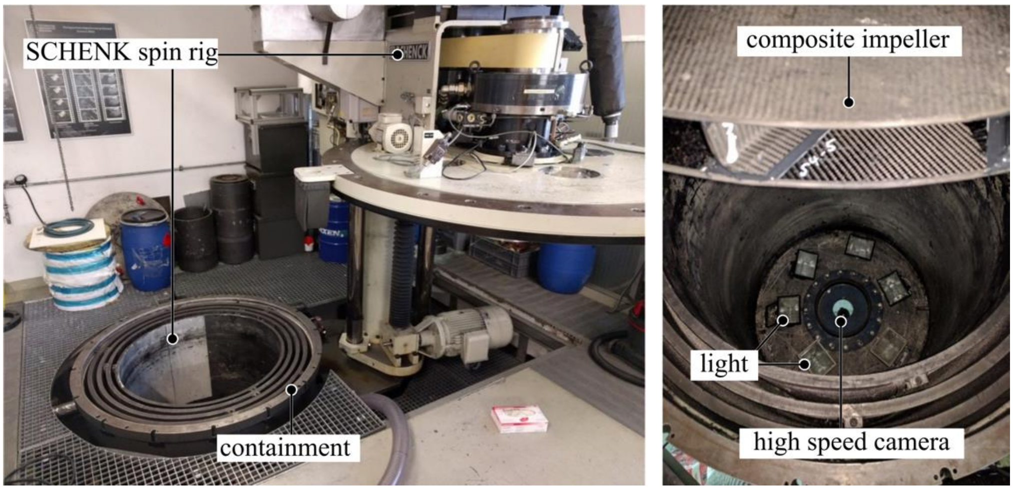


Figure 6: test set-up in the Schenk spin rig (left) and a mounted composite impeller with the position of the high speed camera (right)

To determine the damage behavior of the impellers, a white spray paint is applied evenly to the surface to ensure better visibility for any cracks that may occur by improving the contrast and accompanying shorter exposure times for the camera shots.

During the spin test, the impeller is inspected after defined load steps, to identify initial damage and failure of the material. Figure 7 shows the numerical model of a segment (left - top) with the area of initial damage of the impeller (detail A, right) and initial failure of the material (detail B, left). However, this initial damage does not lead to any impairment of the general functioning of the component. The initial damage occurs differently from the numerically predicted place. At the predicted point of initial failure there is no structural change or initial damage visible.

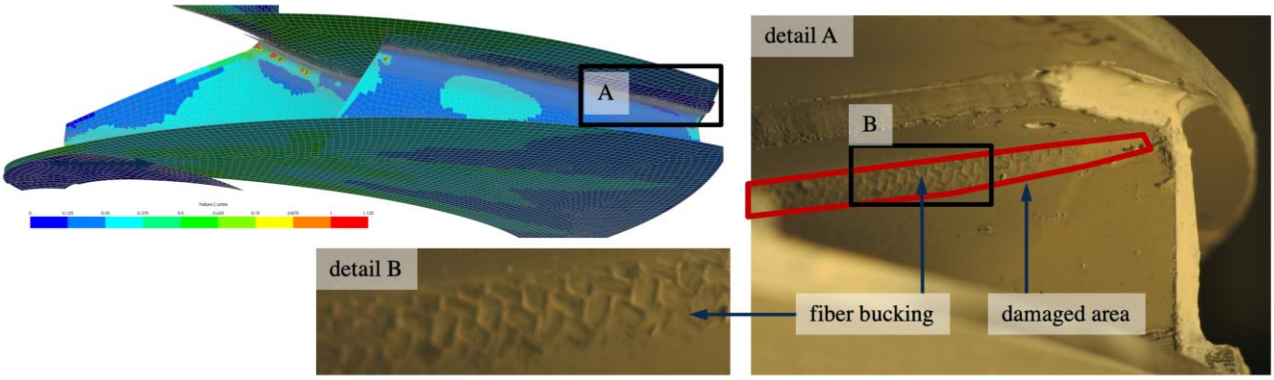


Figure 7: numerical model of a segment (left - top) with the area of initial damaged of the impeller (detail A, right) and initial failure of the material (detail B, left)

Figure 8 on the left shows the impeller during rotation. The footage shows that blade no. 08 is the first to detach from the disc. In the process, the blade itself delaminates (red line in pictures 1-4) and thus loses its load-bearing effect. After this initial failure, other blades shear off and the cover disk wobbles and fails by hitting the containment.

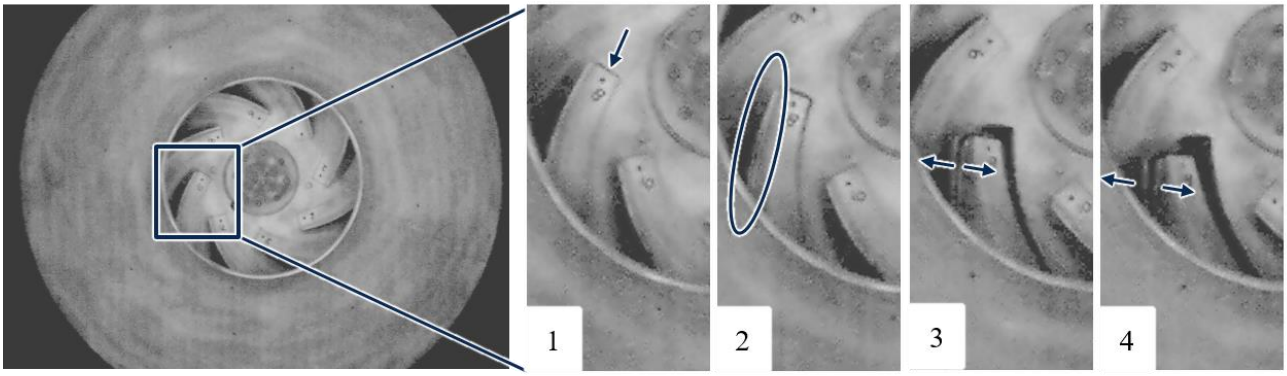


Figure 8: images from the high speed recordings of the impeller failure with the presumed initial failure at blade no. 08

The failure procedure is the same for all three impellers, but they reach different bursting speeds, which can be explained by the different details in the manufacturing process, e.g. copper wires or glass pearls in the bonding interface. Impellers 1-3 burst at 5,920, 6,652 and 10,266 rpm, which correspond to circumferential speeds of 310, 349 and 538 m/s for a diameter of 1050 mm.

FRACTURE AND FRAGMENT ANALYSIS

The modular impellers fail mainly in the joining areas, resulting in fragments in the form of the individual components or characteristic elements (acc. *Figure 9*).

Next to the individual blades, the discs can be clearly seen, with the flat carrier disc as a disc. The cover disc has disintegrated into smaller fragments. The nozzle is recognizable as a closed ring. All individual parts show strong delamination, especially near the impact areas.

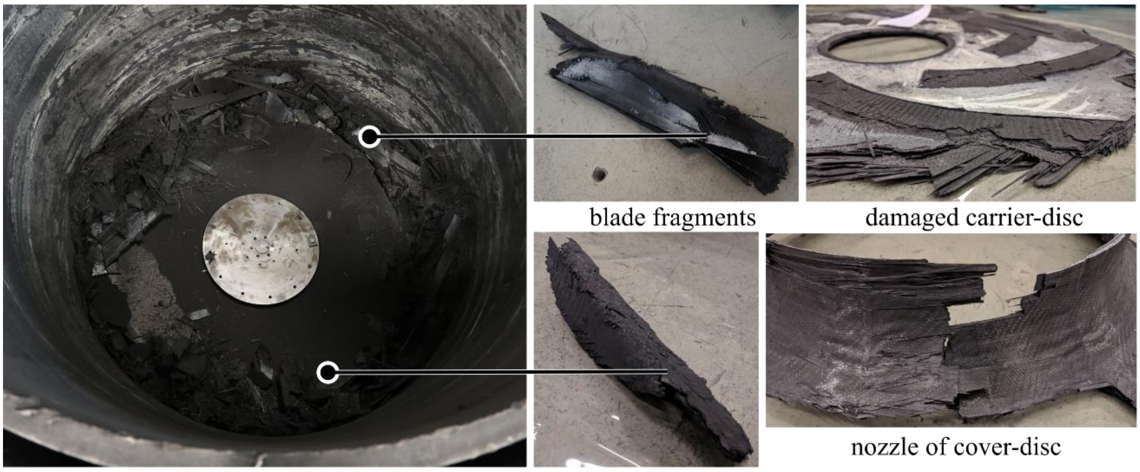


Figure 9: burst impeller (left) and fragments of the bursted impeller (right)

Remarkable are the fracture surfaces between the blades and discs (acc. Figure 9, right top). It can be seen from the fragments that interlaminar failure has occurred in the joint area between the blade and the discs, with the fracture shape alternating between failure in the laminate of the blade and failure in the adhesive layer (acc. Figure 10, left top). Minimally noticeable fragments of the discs can also be found on the vanes (acc. Figure 10, right top). This fracture pattern is characteristic of a mixed fracture and indicates that the interlaminar strengths of the fibre composite and the strength of the adhesive are at similar levels, which under the given test conditions (dry and ambient temperature) can be interpreted as a suitable choice of material.

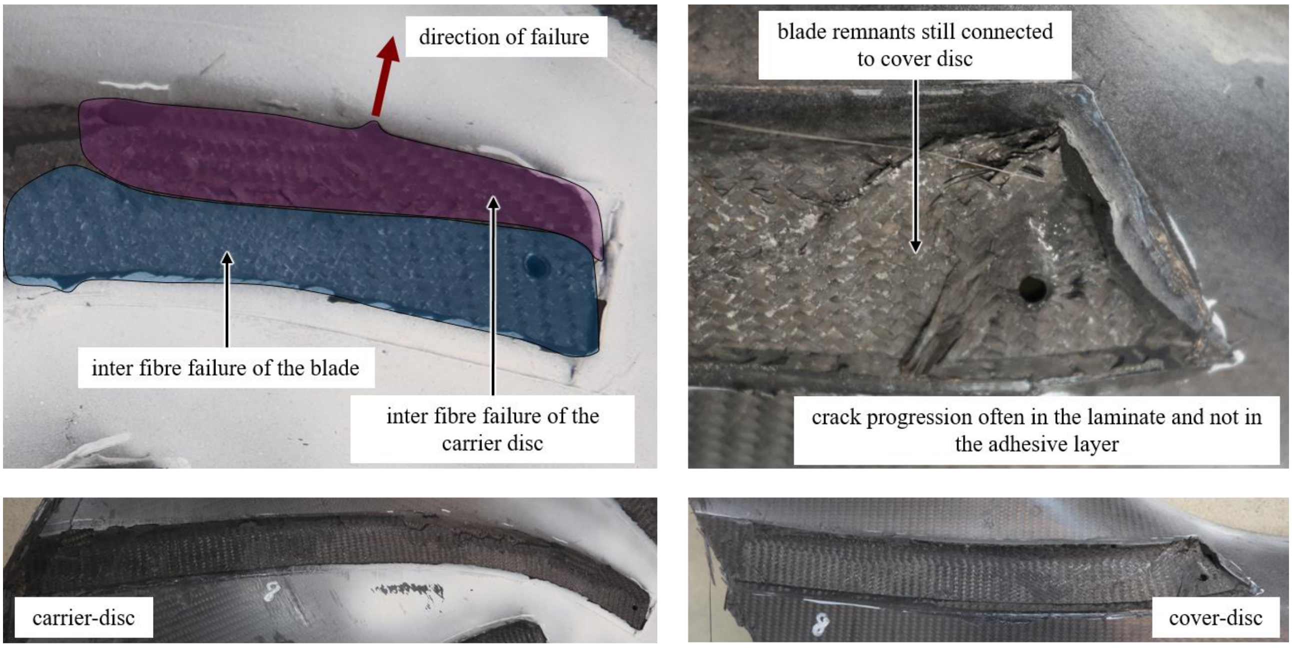
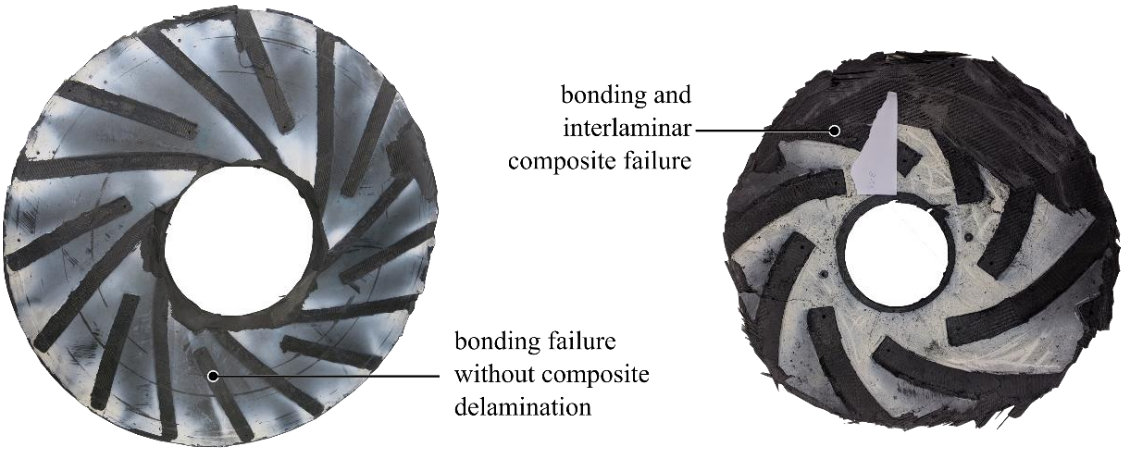


Figure 10: fracture surfaces of the fragments with interlaminar failure in the components of the blade, the disks and the adhesive

In the fragments of impeller 1, the cause of the initial failure can be deduced (acc. Figure 11, left). The copper wire inserted to adjust the slit is located in the fracture surface. The wire in combination with the still relatively undefined geometry of the transition areas from blade to disc and the comparatively low manufacturing quality may be the cause of the lowest circumferential speed of 310 m/s (acc. Figure 11, right).

Figure 11: fragments of impeller 1 with the potential crack initiator in the form of the inserted adhesive layer wire

Due to the relatively low circumferential speed (310 m/s) of impeller 1 (acc. Figure 12, left) at the time of failure and the almost exclusive failure of the bonding interfaces, the carrier disc remains largely intact. The carrier disc of the impeller 2 (acc. Figure 12, right), on the other hand, is more severely damaged due to greater centrifugal forces caused by an increased circumferential speed (538 m/s) at the time of failure. In addition, fibre composite delaminations contribute to damage of the structure due to the increased joint strength.



carrier-disc impeller 1 carrier-disc impeller 2

Figure 12: fragment of the carrier-disc of impeller 1 (left) and impeller 2 (right)

CONCLUSION

In the Forschungsvereinigung für Luft- und Trocknungstechnik own-resources project "Lightweight Radial Impeller" (LeRala), a simplified modular metal-fibre composite (MFB) construction method for a radial impeller was conceived, designed and dimensioned, manufactured and tested. A cost-effective manufacturing process was developed for the numerically designed preferred variant and three testable functional samples were manufactured. Due to numerical analysis of the possible failure modes according to CUNTZE a prediction of the initial composite impeller failure was made. During the subsequent load tests in the centrifugal test rig, information was obtained about the structural and failure behaviour under maximum rotational loads. Comparisons between the actual initial failure and virtual predictions showed discrepancies. Maximum speeds of 5.920, 6.652 and 10.266 rpm were achieved, whereby with an outer diameter of 1010 mm, a maximum circumferential speed of 538 m/s could be realised.

It can be seen that the manufacturing process in its entirety has so far probably been the decisive factor in determining the failure behaviour and performance of the assembly.

The function of the three impellers as a technology demonstrator could be well implemented and possible problems and risks for further development defined. The real performance spectrum of radial impellers made of fibre reinforced polymers could only be touched, due to the high speed desired in the course of manual production and the problems encountered in the manufacturing processes.

The results of this simplified feasibility study show a clear potential for increasing the speed for high-performance centrifugal fans in metal-fibre composite design compared to metal impellers. Such FRP impellers can be manufactured in a modular design with a manageable manufacturing investment, effort and risk and therefore are feasible for small and medium-sized companies in the future.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of this research within the project "Leichtbau-Radiallaufrad (LeRala)" by the Forschungsvereinigung für Luft- und Trocknungstechnik (FLT) e.V. under the grant agreement no. 66570.

BIBLIOGRAPHY

[1] M. M. N. Frojk, N. F. H. Bjergmark, R. L. Bjerg, R. Gomila und P. Valero, *„Metal to composite: Redesign of centrifugal pump impeller"*, The 8th student symposium on mechanical and manufacturing engineering, Jg. 8, **2021**.

[2] R. Mihalache *et al.*, *„Novel Carbon Fibre Composite Centrifugal Impeller Design, Numerical Analysis, Manufacturing and Experimental Evaluations"* (eng), Polymers, Jg. 13, Nr. 19, **2021**.

[3] M. Patil und N. Müller, *„Structural analysis of continuous fiber wound composite impellers of a multistage high-speed counter rotating axial compressor for compressing water vapor (R-718) as refrigerant using Finite Element Analysis"*, Materials & Design, Jg. 50, S. 683–693, **2013**.

[4] D. Devsingh und S. Babu, *„Static and Dynamic Analysis of Centrifugal Blower Using Composite Material"*, Jg. 2, **2018**.

[5] H. Montazerian, A. Rashidi, A. Milani und M. Hoorfar, *„Integrated Sensors in Advanced Composites: A Critical Review"*, Critical Reviews in Solid State and Material Sciences, Jg. 45, S. 1–52, **2019**.

[6] S. Spitzer, M. Pohl, R. Grothe, A. Langkamp, P. Hermerath und M. Gude, „Endless fibre-reinforced composite-metal-impeller: material related design and dimensioning process for hybrid radial-fans" in Fan 2018, Darmstadt (Germany), April 18-20, **2018**.

[7] R. G. Cuntze und A. Freund, „The predictive capability of failure mode concept-based strength criteria for multidirectional laminates", Composites Science and Technology, Jg. 64, 3-4, S. 343–377, **2004**.

[8] A. Puck, *Festigkeitsanalyse von Faser-Matrix-Laminaten: Modelle für die Praxis*. München, Wien: Hanser, **1996**.