ENDLESS FIBRE-REINFORCED COMPOSITE-METAL-IMPELLER: MATERIAL RELATED DESIGN AND DIMENSIONING PROCESS FOR HYBRID RADIAL-FANS

Sebastian SPITZER[1], Martin POHL[1], Richard GROTHE[1],
Albert LANGKAMP[1], Peter HERMERATH[2], Maik GUDE[1]

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

[2] *Piller Blowers & Compressors GmbH, 52, Nienhagener Str. 6, 37186 Moringen, Germany*

SUMMARY

Classical engineering processes according to VDI 2221 in combination with material related failure mode based criteria according to CUNTZE can be used for the efficient and robust design of high loaded hybrid structures. With this approach, composite material in combination with metallic elements can provide new high speed solutions for fan applications. Modular design concepts using single components mounted together by using bonding adhesive enables cost efficient and robust manufacturing processes. This combination of material mix, design concept, manufacturing process and design approach can realise maximum circumference speeds of 400 m/s, without significant damage of the material or the structure. The deformation and first occurring material damages can be determined by using commercial available ANSYS COMPOSITE PREPOST (ACP) Software in combination with data-sheet material properties for composite materials.

INTRODUCTION

Due to their excellent mechanical properties, composite materials are becoming increasingly important for energy-related applications. The combination of endless-fibre-reinforced plastic with metallic components allows new hybrid metal-composite-design (MCD), which provides considerable advantages compared to conventional constructions. Innovative approaches of MCD are almost predestined for highly loaded structures like radial fans, where they show considerable benefits particularly in the optimised use of the materials and the flexible design. Therefore, future concepts can be realised with at least the same functionality but with an increased circumferential speed. In addition to the high efficiency, MCD also enable the possibility of modular concepts which leads to an improvement of the qualification and maintenances processes.

The variety of individual and adjustable material, structural and process parameters result in a complex multi-level design and dimensioning process which impede the practical implementation of radial impellers made of a MCD. The number of parameters is enormously increased, which also leads to numerous possible combinations compared to conventional concepts made of metallic materials. Additional the strong interaction of the disciplines design, dimensioning and manufacturing has to be considered for an efficient design process of hybrid composite structures. Interaction therefore means that the dimensioning process depends on the used manufacturing process. However, the resulting structure of the material yields a related dimensioning and manufacturing process. The manufacturing process also affects the emerging material and influences the possibilities of the structural design, which is classified as an interactive design and manufacturing process. Metal-material specialized companies will be faced by new challenges for the development and manufacturing of metal-fibre-composite radial impellers for high efficiency applications.

An enhanced interaction of the dimensioning process, with the construction and manufacturing methods and the usage of material based dimensioning methods permits a significant shortening of development times and a reduction of development costs for radial impellers as MCD structures. An example of such a linked product development process for a fibre-composite radial impeller for Technology Readiness Level 1 – 3 is the subject of this paper.

STATE OF THE ART AND FUNDAMENTALS

Engineering process and failure mode based design

For the efficient design of technical solutions, methodical development processes are established [1, 5, 6, 8, 10, 14]. These classical design process according to VDI 2221 [14] is running mainly in a serial process with a low interaction in between successive process steps. Based on given material properties, a structural design is developed and transferred to the manufacturing phase.

A composite structure orientated design process considers parallel processes of the structural-, material-, process-, and joining design with a strong interaction in between the disciplines during the development process (Figure 1). [4, 7].

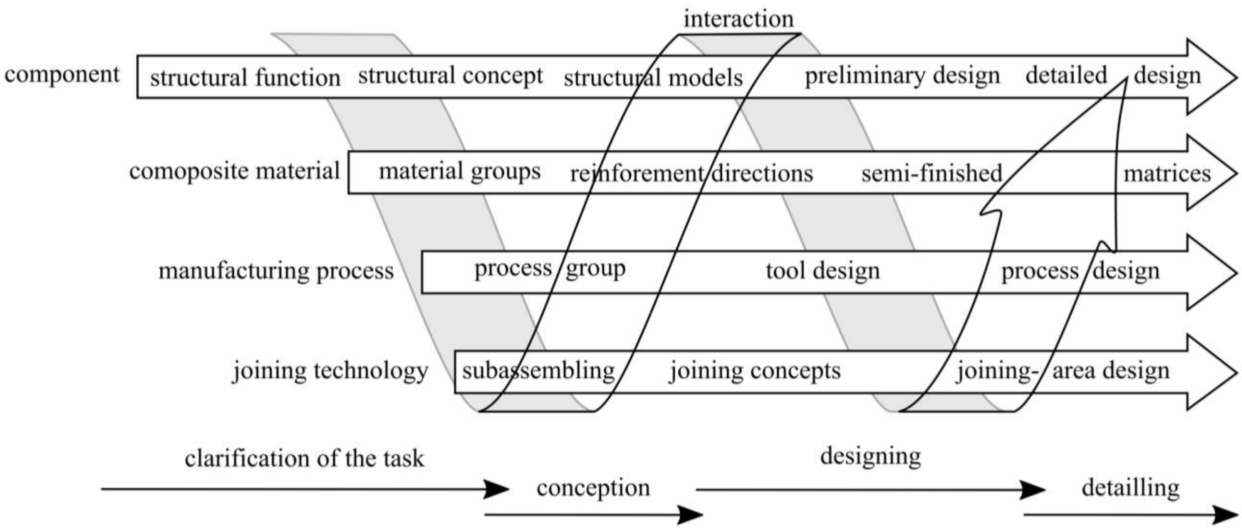


Figure 1: interactive design process for the efficient development of lightweight structures according to [7]

For isotropic metallic material the stress level is established to evaluate the condition of the component. For orthotropic material systems like fibre reinforced plastic (FRP), failure mode related methods are known, e.g. PUCK and CUNTZE, to predict the mechanical capability on micro scale level [2, 11]. CUNTZE describes two fibre failure modes (FF1, FF2) and three inter fibre failure modes (IFF1, IFF2, IFF3), (Figure 2). 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.

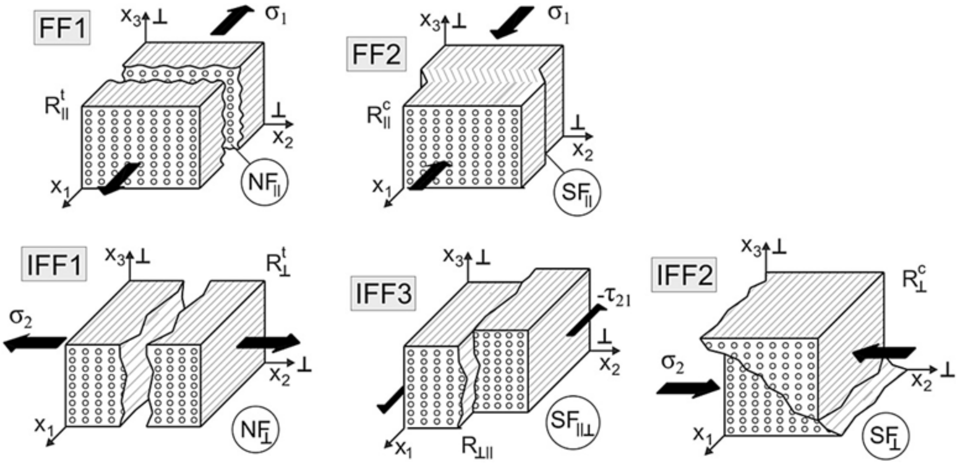


Figure 2: failure modes of composite material according to CUNTZE [2].

For standardised mechanical components, out of FRP, like drive shafts or leaf springs, approaches for mode related design processes can be found [3, 4, 7, 9, 13]. The micromechanical approaches of PUCK or CUNTZE are therefore used to describe the dominating failure modes on material level at specific areas of a construction. This method works well for composite dominated areas of a component, where the interaction between metal and the FRP are low and the number of relevant parameters is small. This approach is used for the design procedure of the composite fan.

Composite fans

Composite radial fans are state of the art and ready to use in chemical highly loaded environments or for high spin speed. Numerous design concepts are known [1, 12, 15, 16, 17, 18]. Figure 3 shows industrially used composite fans and a patented design concept for modular radial fans.

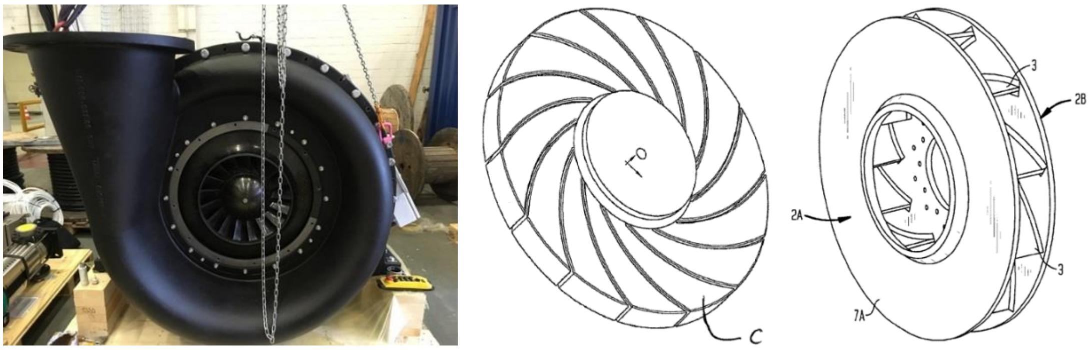


Figure 3: carbon fibre-reinforced plastic fan (left) and patented concepts for composite fan (right), [1, 12]

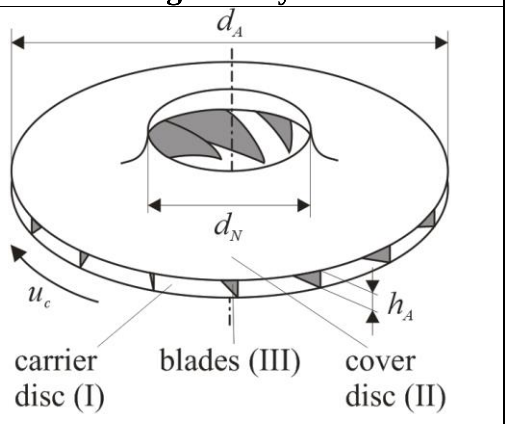
Next to several applications and design concepts, radial fans are used as demonstrators showing the potential of composite related manufacturing processes [12, 17]. Publications describing a holistic development procedure for such components made out of composite material are rare.

ENGINEERING PROCEDURE ACCORDING TO VDI 2221

Clarification of tasks and specification of requirements

The task is to develop a high speed radial fan by using composite material, considering to technical and economical boundary conditions. Table 1 shows the specification of the main requirements for the component and the development process.

Table 1: specification of requirements

feature / characteristic	specification	geometry
outer diameter d_A [mm]	1010	
nozzle diameter d_N [mm]	384	
outer height h_A [mm]	54	
max. circ. speed u_c [m/s]	400 (7500 rpm)	
temperatures T_{max} [°C]	20, 80, 150	
medial loads	dry, wet	
no. of parts [/a]	4	
engineering procedure	Acc. to VDI2221	
proof of concept/design	Num., exp.	

Analysis of reference structure and conceptual design

To get a deep understanding of the mechanical behaviour of the component and the single elements and the induced stresses during the rotation, a numerical model of a metallic reference structure is used (ANSYS Workbench V17.1, cyclic symmetric model, 1/8 segments, element type Tet10 and Hex20). To represent the metallic material, the isotropic linear material model (type: structural steel) is implemented. The solver is working nonlinear, considering big deformations. The maximum and minimum principal stresses of the elements is used to define a first fibre orientation concept for the main elements of impeller (comp. Figure 4).

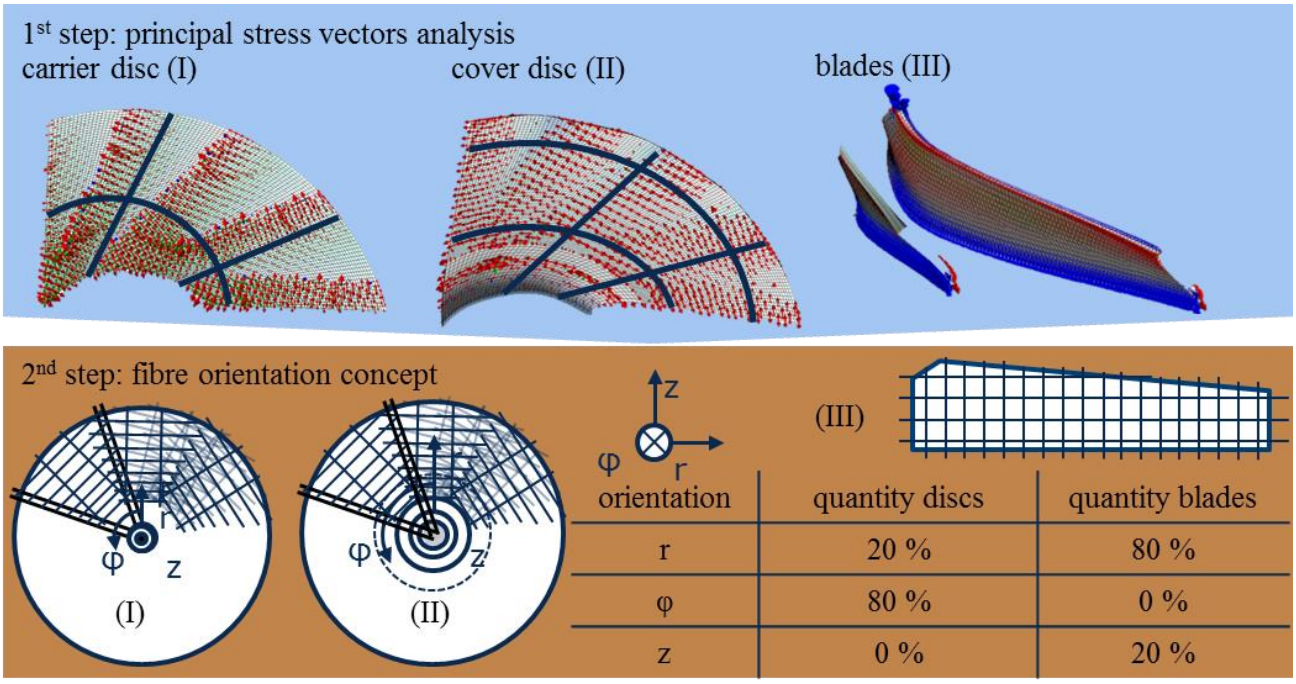


Figure 4: principal stress analysis (top) as base for the fibre orientation concept (below)

The stresses in the discs are mainly orientated in tangential direction, with concentrations at the blade contact area. In the blades, the stresses are mainly orientated in radial direction. The fibre orientation concept is following this indicator. To realize a cost-efficient material concept and manufacturing process, the fibre alignment is assumed as straight, whereby a patched layup results.

Using composite material, the impeller can be made out of single elements which have to be assembled afterwards (differential design, d) or manufactured as one component (integral design, i) (comp. Figure 5). The single elements of the differential design can be manufactured with a lower tool invest and lower risk, which is according to the low number of pieces (comp. Table 1), an efficient solution for the composite impeller. To reduce the complexity of the geometry and manufacturing process, design concept d1 with flat cover and carrier discs is chosen.

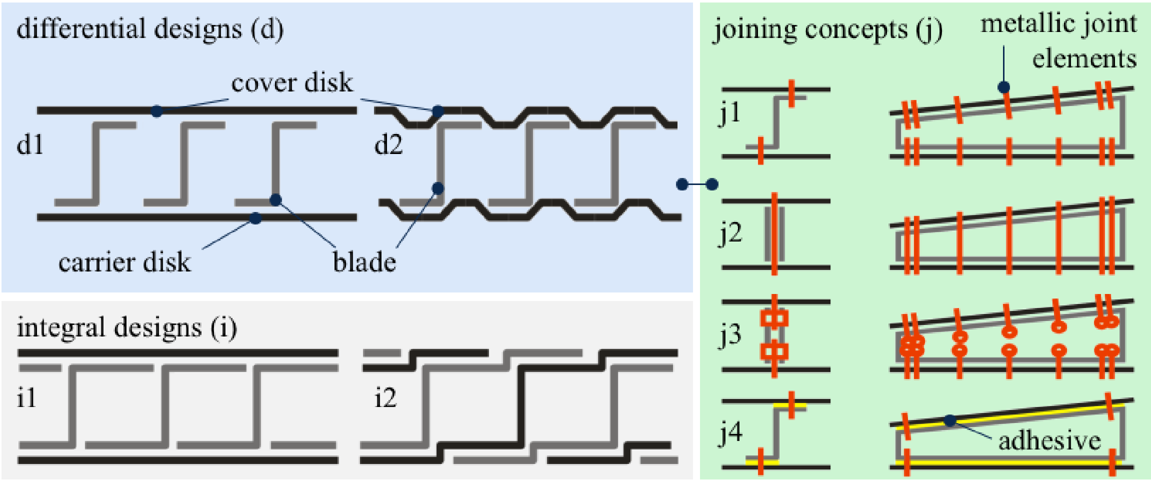


Figure 5: global and local design (left) and joining concepts (right)

To join the single elements, several concepts are available (comp. Table 1; j). Concept j4 uses metallic joining elements in combination with adhesive. Shear loads can be taken by the adhesive zone, peel loads at the bounders are taken by metallic elements. Based on those concepts, the design of the radial fan is generated.

Figure 6 shows the fan assembly. Cover disc, carrier disc and the blades are made of composite material and joint by metallic elements and adhesive. To mount the fan to the drive, a metallically hub is used to provide a common interface. Metallic edges protect the blades and avoid erosion. Due to the simple geometry, the components can be manufactured by using simple tools and prepreg material.

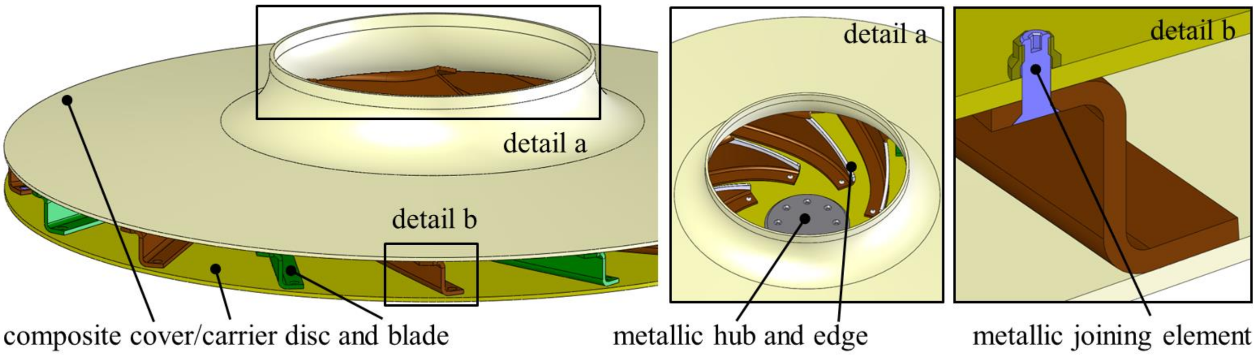


Figure 6: design of the hybrid composite-metal radial-fan

DETAILLING AND NUMERICAL PROOF OF STRENGTH

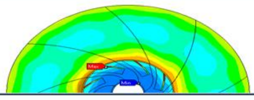
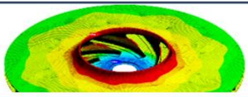
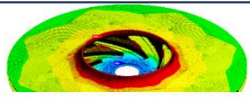
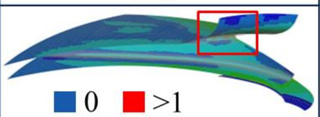
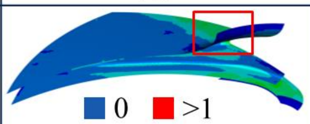
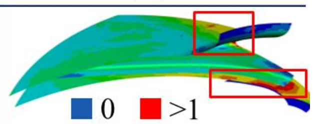
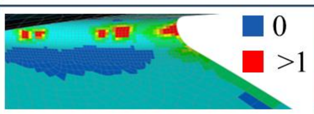
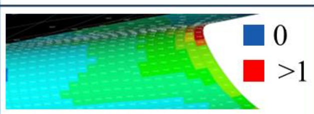
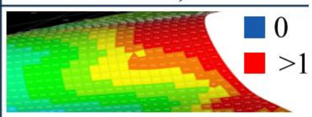
Material system

Considering the requirements regarding a temperature up to 150 °C and a wet environment, the commercial prepreg material TENAX HTA 5131 based on the HTA40 fibre is defined as material systems due to the good availability on one side and good mechanical properties at the other side. The complex behaviour of composite materials is considered by using linear orthotropic material properties. A decreasing due to initial material failure is not considered.

Numerical investigation

To enable a direct transfer of the engineering procedure to the industrial application, the commercial ANSYS COMPOSITE PREPOST (ACP) tool of ANSYS WORKBENCH is used to predict the deformation and failure behaviour of the composite elements. According to the analysis process of the reference structure, the model is built up using cyclic symmetric boundary conditions and shell elements (type Quad4). Out of plane deformation and stresses are expected, and the chosen element type may not reflect those effects well. Due to the limited availability of element types, which does not include any solid elements in the ACP tool, this approach is chosen, accepting this systematic error. Table 2 shows the numerical results of the rotating fan at the speed of 7000 rpm for the defined thermo-medial load cases.

Table 2: post processing matrix with numerical results

thermal and medial condition	20 °C, dry	150 °C, dry	150 °C, wet
deformation			
max. def. [mm]	2.1	2.5	5.5
effort acc. to CUNTZE			
area of damage	blade root	blade root	blade root, discs
critical area			
failure mode	matrix compression		

The largest deformation occurs at the nozzle and increases more than twice at hot and wet conditions. At the upper flange and the root of the blades the highest material effort can be observed. Bending of this curved blade area induces this effort concentration. There the stresses reach the limit of the matrix compression strength. If this is a local effect or a global failure shell be determined by experimental investigations.

Due to the reduction of the material properties, the effort increases at hot/wet conditions. 150 °C and dry conditions seems to be acceptable for the chosen material. 150 °C in combination with moisture lead to high efforts. A change of the material system for this case is recommended.

Next to the composite parts, the stresses in the bonding area are investigated. Here the average shear stresses of 5 MPa at the borders of the blade flange are induced. With shear strength of 30 MPa for the commercial adhesive material 3M® DP490, the bonding area seems to be uncritical, even without the support of metallic joining elements. The experimental investigations will be done without additional metallic joints.

MANUFACTURING, TESTING AND VALIDATION OF DESIGN APPROACH

Manufacturing

For experimental verification, testable radial fans are manufactured using prepreg material in combination with an autoclave process (acc. Figure 7).

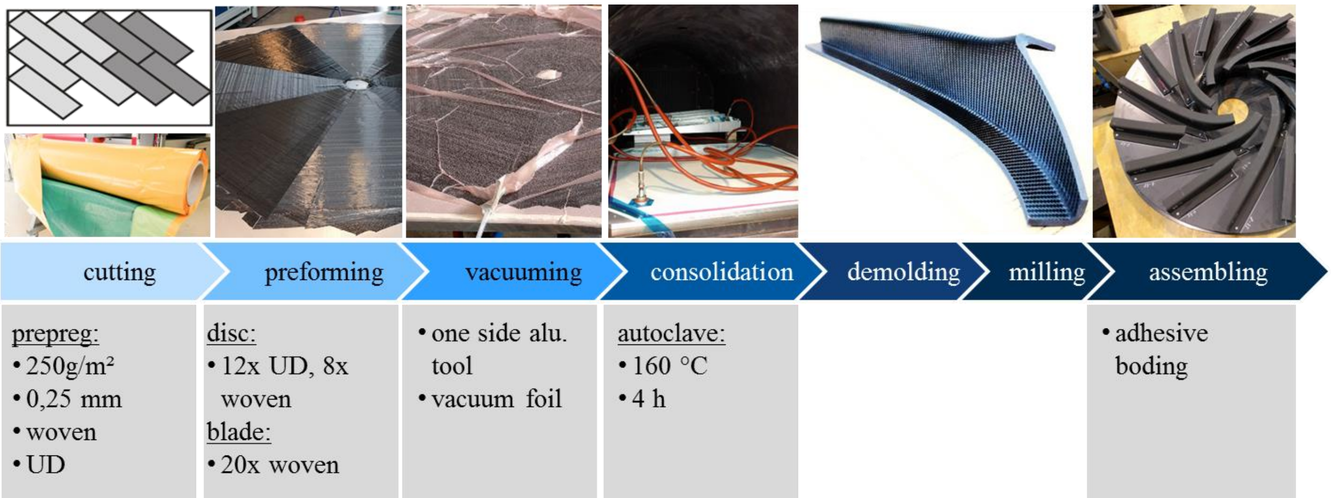


Figure 7: manufacturing process of the composite parts

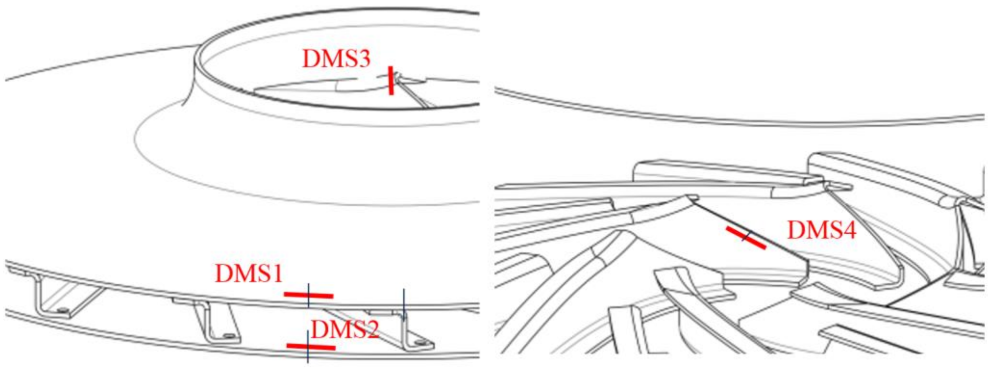
This process enables a cost-efficient fan manufacturing. Due to the single components, the risk during the manufacturing process is quite low. In the case of manufacturing error, scrubbed components can be replaced easy. The one side aluminium tools are cheap, robust and simple to handle. The preformed component is covered by a vacuum foil fixing the material. 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 varying mass distributions in the elements and in the assembled fan. Balancing of the fan is more difficult.

Testing

According to Figure 8, a Schenk spin rig is used to evaluate the structural design of the composite fan. Therefore, the fan is mounted at the spin rig gear. High speed cameras are installed at the bottom, observing events during the test. The rig measures the rotation speed and the rotational vibration amplitude of the fan shaft.

Figure 8: test set-up –
SCHENK spin rig (left) and mounted composite fan (right)

Additional to the spin rig sensors and the camera, the deformation of the fan is measured, using strain gauges (DMS) at preselected positions of the specimen according to Figure 9.



DMS1 – outer diameter cover disc
DMS2 – outer diameter carriere disc
DMS3 – top flange inner diameter blade
DMS4 – middle inner diameter blade

Figure 9: DMS location on the composite fan

The composite fan is tested stepwise (acc. Figure 10). The DMS test is done at 2800 rpm to protect the measurement equipment. Afterwards testing speed is increased stepwise by 1000 rpm until failure. The acceleration is 48 rpm² and the test speed is set constant for 1 min. After each test run, a visual inspection identifying failure is done.

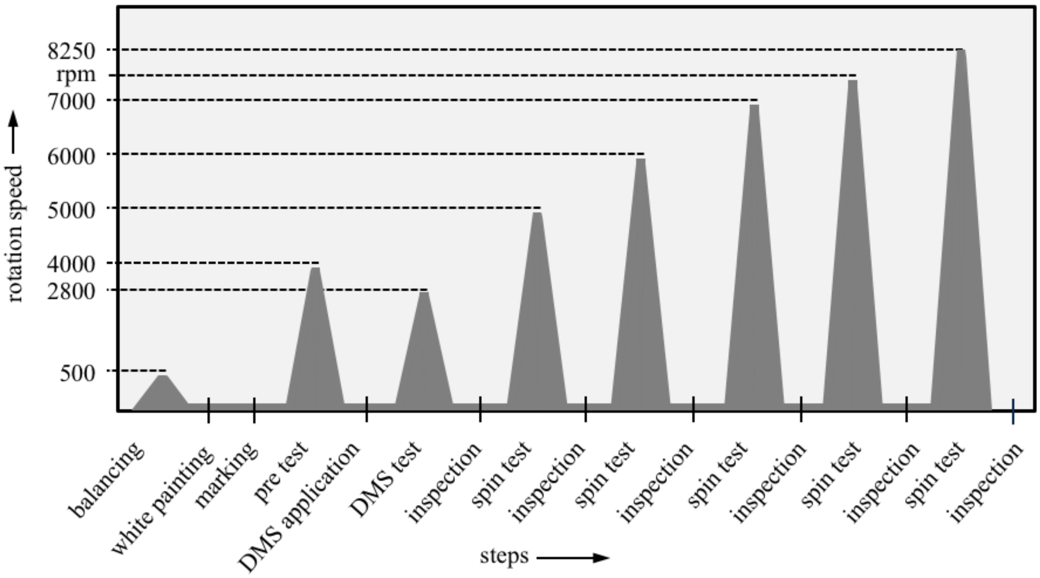


Figure 10: test procedure with testing and inspection steps

Post processing and validation

During speed up and slow down, the rotor runs through its eigenfrequency which causes the first and last peak of the rotational vibration amplitude of the fan shaft (acc. Figure 11, left). Figure 11, right shows the calculated and measured elongation at a speed of 2800 rpm. Except DMS1 the deviation is in a range of 10 % and the modelling approach with shell elements seems to be suitable for a practice-orientated design approach.

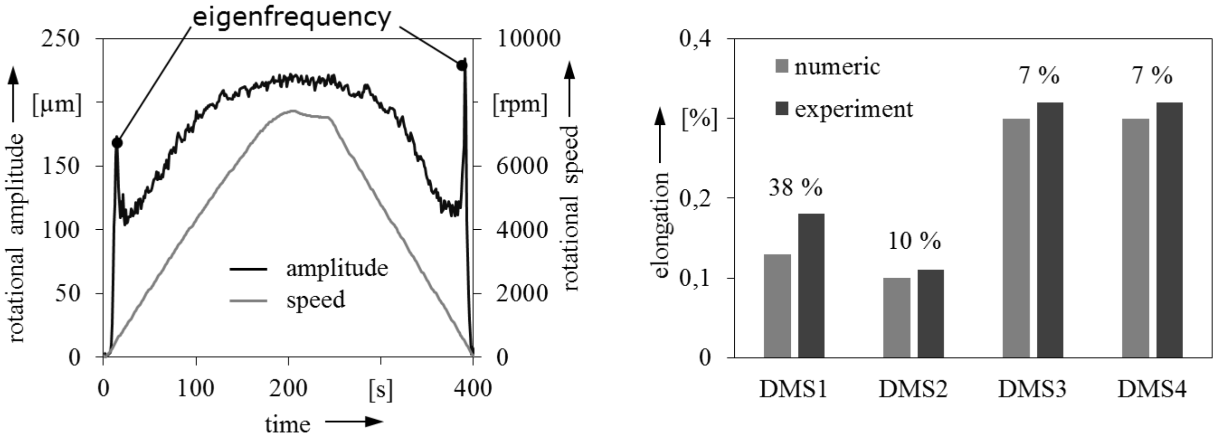


Figure 11: rotational vibration amplitude and rational speed during the test run (left) and numerical and experimental determined elongation at the composite fan acc.to Figure 9 (right)

During the testing procedure, pictures are taken of the critical areas identified by numerical investigations according to Table 2. After 4000 rpm first fibre buckling in the curved area of the blade nearby the root can be observed according to the numerical results. Figure 12 shows the level of damage for all blades on the left side and the damage effect at the blade root of S4-3 depending on the test speed. This damage seems to be an inter fibre failure, predicted by the CUNTZE failure criteria. The measured rotational vibration amplitude is not changing significant by during the stepwise testing procedure. The effect of this local material failure seems to be small. This local damage can only be observed at the blade series S4-1 to S4-8 manufactured in the same autoclave procedure. The second blade series S3-1 to S3-8 is not damaged. Parameters of the manufacturing processes may influence the load bearing capacity of the blades. Possibly, the vibrations could also strengthen this initial damages.

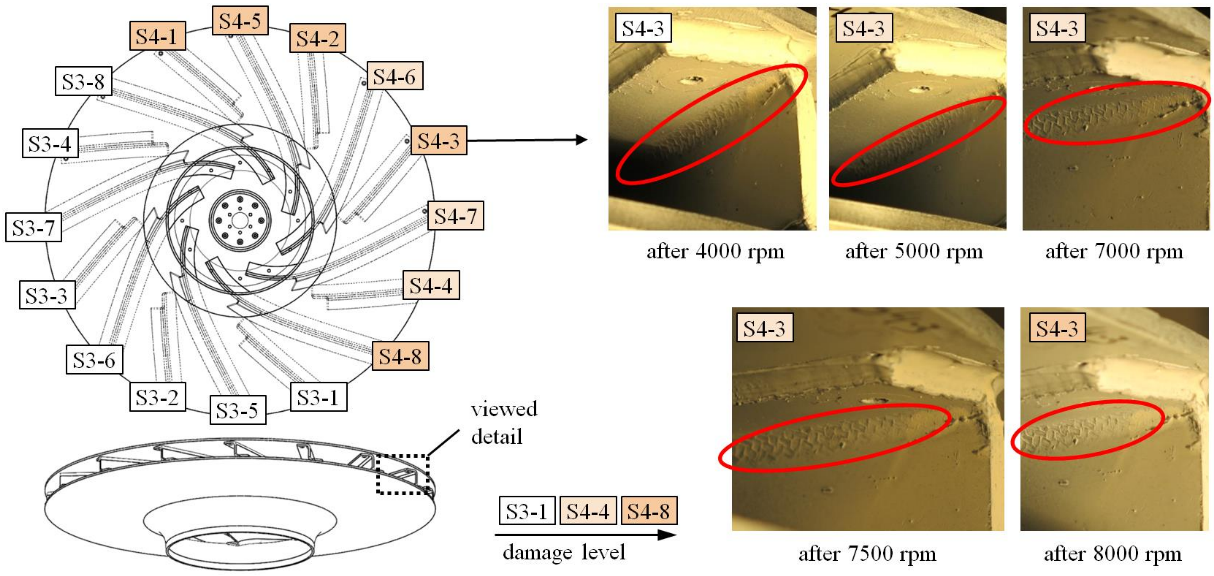


Figure 12: damage level of the blades (left) and place of damage and damage level of the blade S4-3 depending on the test speed (right)

Figure 13 compares the numerical and experimental determined effort or damage of the structure at a simulated rotational speed of 7500 rpm. The numerical models in combination with the CUNTZE failure criteria and data sheet material properties are able to predict the place of failure and the beginning of the first initial damage. After reaching the critical effort, the occurring degradation of material is not considered in the numerical approach. The experimental data shows a robust part design, which allows to increase of speed after initial damage, without significant loss of mechanical performance.

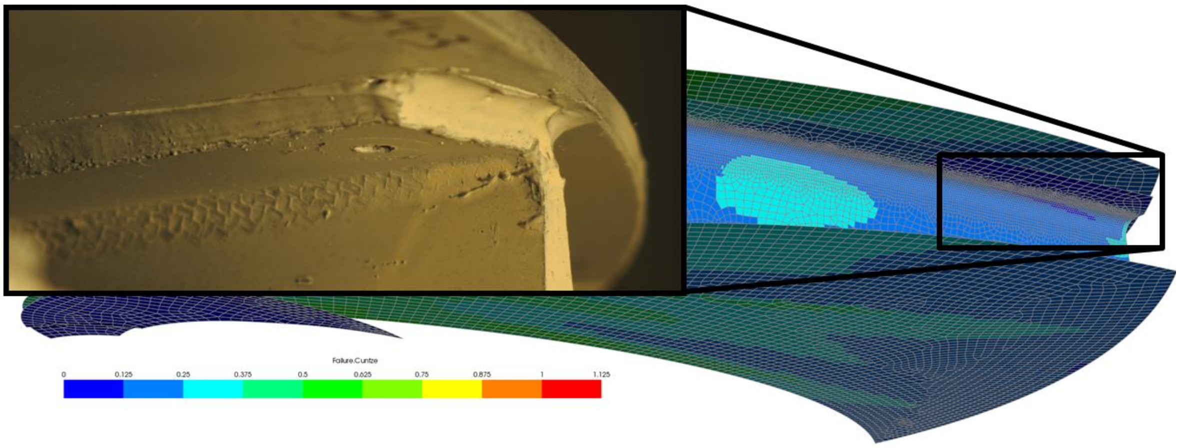


Figure 13: comparison of numerical and experimental results:
numerical prediction of the effort according to CUNTZE and the structure after testing

SUMMARY

Due to their excellent mechanical properties, composite materials are becoming increasingly important for energy-related applications. The combination of endless-fibre-reinforced plastic with metallic components allows new hybrid metal-composite-design (MCD), which provides considerable advantages compared to conventional constructions. Innovative approaches of MCD are almost predestined for highly loaded structures like radial impellers, where they show considerable benefits particularly in the optimised use of the materials and the flexible design. Therefore, future concepts can be realised with at least the same functionality but with an increased circumferential speed. In addition to the high efficiency, MCD also enable the possibility of modular concepts which leads to an improvement of the qualification and maintenances processes.

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An enhanced interaction of the dimensioning process, with the construction and manufacturing methods and the usage of material based dimensioning methods permits a significant shortening of development times and a reduction of development costs for radial impellers as MCD structures. An example of such a linked product development process for a fibre-composite radial impeller for

Technology Readiness Level 1 - 3 is presented in this paper. Therefore the classical engineering processes according to VDI 2221 in combination with material related failure mode based criteria according to CUNTZE in used for the efficient and robust design of high loaded hybrid structures. With this approach, composite material in combination with metallic elements can provide new high speed solutions for fan applications. Modular design concepts using single components mounted together by using bonding adhesive enables cost efficient and robust manufacturing processes. This combination of material mix, design concept, manufacturing process and design approach can realise maximum circumference speeds of 400 m/s, without significant damage of the material or the structure. The deformation and first occurring material damages can be determined by using commercial available ANSYS COMPOSITE PREPOST (ACP) Software in combination with data-sheet material properties for composite materials.

An optimization of the manufacturing process can increase the load bearing capacity of the blades as critical components to reach higher first damage speeds. A further spin rig test up to the final failure of the structure to determine the maximum speed is planned.

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