GRADUAL DAMAGE BEHAVIOUR OF POLAR ORTHOTROPIC GLASS-FIBRE REINFORCED EPOXY ROTORS; EXPERIMENTAL AND SIMULATION ANALYSIS

A. Filippatos, A. Langkamp, P. Kostka, I. Koch, R. Böhm and M. Gude

Institute of Lightweight Engineering and Polymer Technology, Faculty of Mechanical Science and Engineering, Technische Universität Dresden, Holbeinstraße 3, 01307 Dresden, Germany
Corresponding author: Email: angelos.filippatos@tu-dresden.de,
Web Page: http://tu-dresden.de/mw/ilk

Keywords: gradual damage behaviour, structural dynamic behaviour, composite rotors, tailored fibre placement

Abstract

The gradual damage behaviour of polar orthotropic glass-fibre reinforced epoxy disc-rotors and the resulting damage-dependent dynamic behaviour is experimentally investigated and described under propagating damage from a combination of out-of-plane and in-plane loads. The damage manifests itself as a spatial increase of inter-fibre failure and growth of delaminations, resulting in local changes of stiffness and damping. A novel observation is reported finding that a monotonic increase of damage results in a significant non-monotonic frequency shift of significant amount at the investigated eigenfrequencies.

Furthermore, a simulation tool is applied, which calculates the damage-dependent dynamic behaviour considering both damage initiation and evolution. Within this model, damage initiation is determined by means of stress-based failure criteria. The gradual damage evolution is then described with a validated continuum damage mechanics model, which captures the degradation processes after considering failure modes and damage coefficients. By comparing the experimental and numerical results, the corresponding damage and vibration response behaviour are analysed and evaluated.
Based on the experimental results, it can be deduced that a monotonic increase of damage can result in a non-monotonic frequency change, which is also observed in the numerical results from the simulation analysis.

1. Introduction

Constantly growing requirements for the efficiency and reliability of modern high-performance rotors demand the increased application of advanced fibre-reinforced composites, as conventional materials are reaching their physical limits. Such composites are advantageous – compared to classical metallic materials – due to the feasibility of producing very complex, load-adapted fibre reinforcements, and as they allow for the development of rotors, which are characterised by gradual damage behaviour [1].

High-performance composite rotors must withstand complex, inhomogeneous and variable stress loads induced by the centrifugal forces, which are mainly characterised by multi-axial tension, as well as regular and unexpected operating loads. Furthermore, their dynamic response is also affected by the apparent stiffening from the applied centrifugal body forces from the complex loading. Consequently, the damage and dynamic behaviour of composite rotors are significantly more complicated than those of stationary structures, and more detailed investigations are required.

1.1. Motivation

Through the gradual damage behaviour, the remaining load capacity of composite rotors is generally not reduced critically, and a sudden structural failure will often be prevented as long as the loads do not further increase. However, as damage influences the stiffness and damping, it results in a change of the modal properties, which can be critical if the modal properties coincide with the operating frequency of the rotors.

The experimental and simulation analysis of the gradual damage and the dynamic behaviour of composite rotors provide therefore the fundamentals for a better understanding and description of partially unknown and complex structural phenomena. Once the phenomena have been described and analysed, different measures can be taken in order to avoid structural failure caused by resonance or other unpredicted effects.

1.2. State-of-the-art

Numerous investigations reveal that the gradual damage behaviour of fibre-reinforced plastic (FRP) is governed by a mixture of various fracture modes e.g. fibre-failure and inter-fibre-failure as well as delamination [1]. The sequence of these modes mainly depends on particular composite architecture and load conditions [2].
Based on these investigations, novel material models combining physically-based failure criteria and continuum damage mechanics have been developed to describe the non-linear stress-strain behaviour of FRP due to the damage progress [3]. These models, characterising the interactions between different failure modes as well as the resulting non-linear deformation process were already applied for diverse fibre- and textile-reinforced plastics and extensively validated in experimental studies for specimens of a simple geometry and homogeneous loading conditions [4, 5]. However, an application of these models for rotor typical loading conditions under consideration of the resulting structural dynamic behaviour has not been reported [6]. For the simulation of composite rotors, a combination of a phenomenological damage mechanics model developed from Cuntze [1] with a simulation model [7] has been introduced for the damage analysis and the corresponding dynamic behaviour and some first qualitative results have been presented [8].

The tailored fibre placement technology has an increased application in the production of fabrics for high-performance rotors, such as radial fans and centrifuges [9]. It provides fabrics with exceptional design capabilities, and enables an optimal, locally variable arrangement of the fibre reinforcement, as the angle of fibre placement during the lay-up process can be freely adjusted between 0° and 360°. In addition to that, the net-shape manufacturing results in reduced costs and optimal usage of the reinforcement fibres, where the automated deposition ensures high accuracy and repeatability. A local thickness variation in the fibre reinforcement allows for stress-optimised preforms suited for critical high-performance composite rotors [10].

2. Experimental analysis

For the experimental investigation of the damage behaviour of polar orthotropic glass-fibre reinforced epoxy rotors and their resultant dynamic behaviour, a basic rotor is defined as well as their damage-initiating loading conditions. Specifically, an endless fibre-reinforced epoxy rotor is realized with the existing manufacturing capabilities of the tailored fibre placement (TFP) technology.

2.1. Selection of fibre architecture and manufacturing of rotors

The composition of individual layers is selected in such a way that a glass fibre-reinforced epoxy rotor can be generated with a constant thickness and constant polar-orthotropic material properties. The glass-fibre preforms are produced using the TFP method, based on the embroidery technique. The selected fibre orientation, shown in figure (Figure 1), is determined using computer-aided design, then converted into a numerical description of a pattern, which is uploaded into the embroidery machine. In this way, the TFP process ensures that the reinforcement fibres are correctly stitched to the base material.

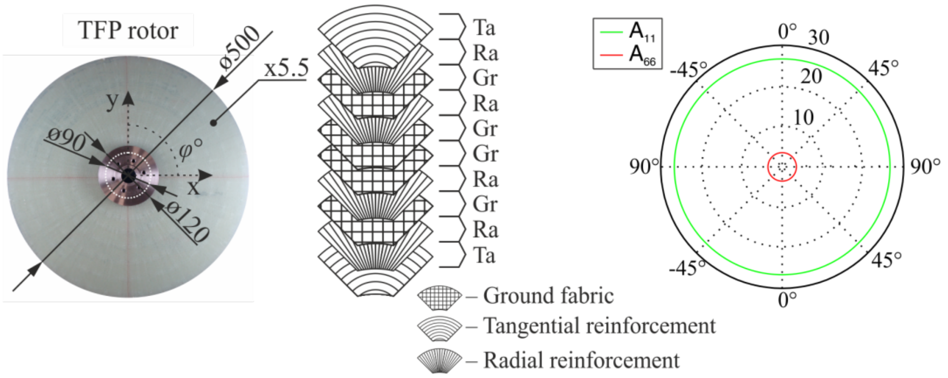

Figure 1. Geometry of a TFP rotor (left) with the lay-up (centre) and the corresponding homogenised directional stiffness properties A_{11} , A_{66} , resulting in a polar-orthotropic behaviour (right).

The composite lay-up consists of 4 fabrics. The first two fabrics constitute a lay-up of one radial (Ra) and one tangential (Ta) layer stitched to the ground fabric (Gr) [Ta/Ra/Gr]. The remaining two fabrics are comprised of a [Ra/Gr] lay-up, as in figure (Figure 1), forming a composite lay-up of $[Ta/Ra/Gr/Ra/Gr]_s$ and a total laminate thickness of 5,5 mm. The inner and outer diameters of the rotor are 100 mm and 500 mm, respectively. The lay-up results in an in-plane polar-orthotropic behaviour.

The production of three composite rotors (TFP I.1, I.2, II) was carried out using the state of the art resin transfer moulding (RTM) process, with the epoxy resin MGS™ RIM 135 and process parameters shown in [11]. The prepared layers were infiltrated in a flat steel mould, which was evacuated before and during infiltration process in order to avoid pores and to guarantee the manufacturing of high quality rotors.

2.2. Damage propagation and evaluation

In order to create rotor typical damage from in-plane and out-of-plane loading, two specific damage initiating loads were selected: local compression load of 16 kN and rotor run-up to 12,000 rpm. These damage initiators are selected due to the repeatability of the induced impacts and the ability to model the impact with a sufficient accuracy with the developed simulation models [12].

The first two rotors (TFP I.1, TFP I.2) have been accelerated to different rotational velocities, each time from 8,000 rpm to 12,000 rpm with a step of 1,000 rpm, then decelerated to standstill, where a possible damage initiation and propagation was investigated. The third rotor (TFP II) has been initially damaged with an applied out-of-plane compression load of 16 kN and then followed the same in-plane loading scenario as the rotors TFP I.1 and TFP I.2.

All investigated rotors exhibit the same damage initiation from run-up, especially matrix damage, at similar rotational velocities due to the same fibre architecture and applied epoxy resin, (Figure 2). A fibre failure could not be detected until the total failure of the rotors. The transparency of the investigated composite rotors allows for monitoring both, the crack densities and also the existence of delaminations from the initial impact using the transillumination method with a high-resolution camera as shown in Figure 2. The formation of inter-fibre cracks can only be found in the radial direction for the damaged TFP I.1 rotor from an applied rotational velocity of up to 12,000 rpm.

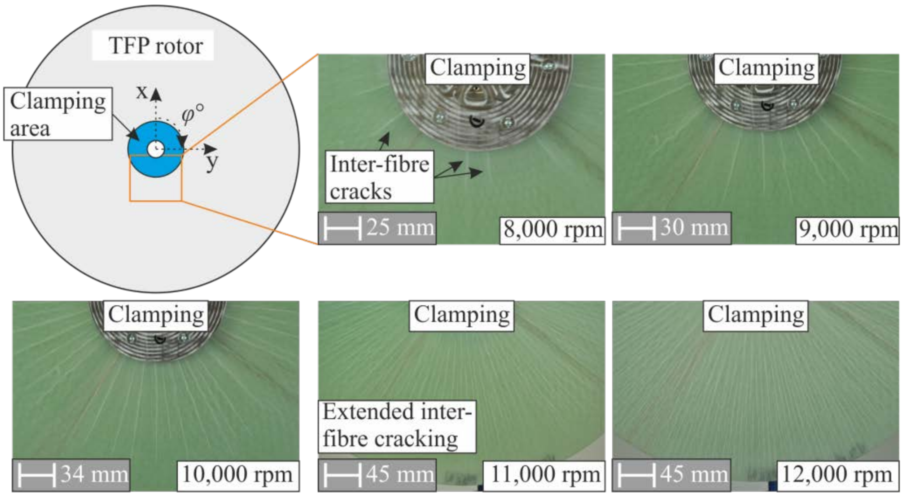

Figure 2. Typical damage due to a run-up of a TFP rotor after different rotational velocities.

There is a similar increasing number of spatial matrix damage of all rotors as shown for the TFP I.1 rotor in Figure 2, starting from 8,000 rpm up to 12,000 rpm. An extended polar symmetric damage evolution can be observed from up to 10,000 rpm.

Furthermore, computer-tomography scan was applied for the identification of single inter-fibre failures, resin-rich areas, and the number of delaminations through the thickness. In the case of damaged TFP rotor II due to a compression load of 16 kN, multiple extended delaminations are evident in the lay-up in Figure 3 and the inter-fibre cracks are distributed among many layers.

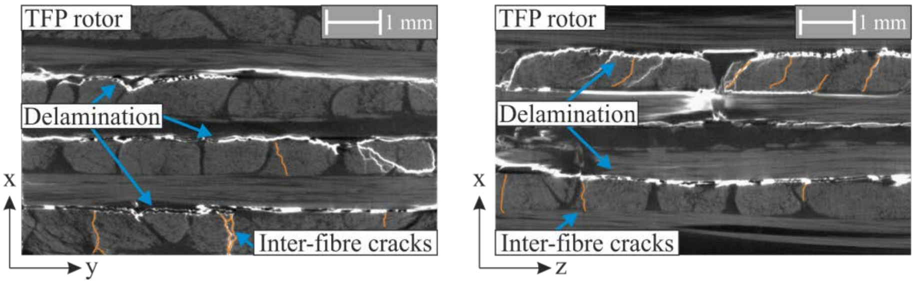

Figure 3. Computer-tomography picture of a TFP rotor, with an initial damage caused by a compression load of 16 kN resulting mainly to delaminations and inter-fibre cracks.

2.3. Investigation of the damage-dependent dynamic behaviour of composite rotors

The damage-dependent dynamic behaviour of the investigated rotors were estimated using an experimental modal analysis and some first results are presented here and evaluated. Specifically, the impact excitation is performed using an electrodynamic shaker with a mounted steel impactor and the vibration response measurement is conducted using with a contactless Laser-Scanning-Vibrometer

(LSV) (Polytec, Type PSV-400). For the experimental modal analysis the vibration response was measured in a total of 128 symmetrically distributed points. The analysis was conducted with a sample frequency of 6.4 kHz, triple magnitude averaging and a FFT in a frequency range from 5 Hz to 1,000 Hz under laboratory conditions with typical ambient temperature of 20° C.

The relation between applied in-plane loads and the corresponding shift of eigenfrequencies due to damage increase was investigated for two different damage sequences, one with damage only from in-plane loading (TFP I.1, I.2) and the second with out-of-plane and in-plane loading (TFP II). For each damage sequence, a total of 16 eigenfrequencies were identified for all three TFP rotors. A normalised in-plane load F_c' was introduced,

$$F_c' = \left(\frac{n_{rpm}}{n_{rpm}^{max}}\right)^2, \tag{1}$$

where each rotational velocity n_{rpm} rpm is divided by the maximum rotational velocity n_{rpm}^{max}. The frequency shift Δf for each eigenfrequency was determined as the difference between the frequency value for each state under a rotational in-plane load and the frequency value of the eigenmode for the undamaged initial state. For the two investigated rotors without initial damage from an out-of-plane load a mean frequency shift was calculated and fitted using a third-degree polynomial.

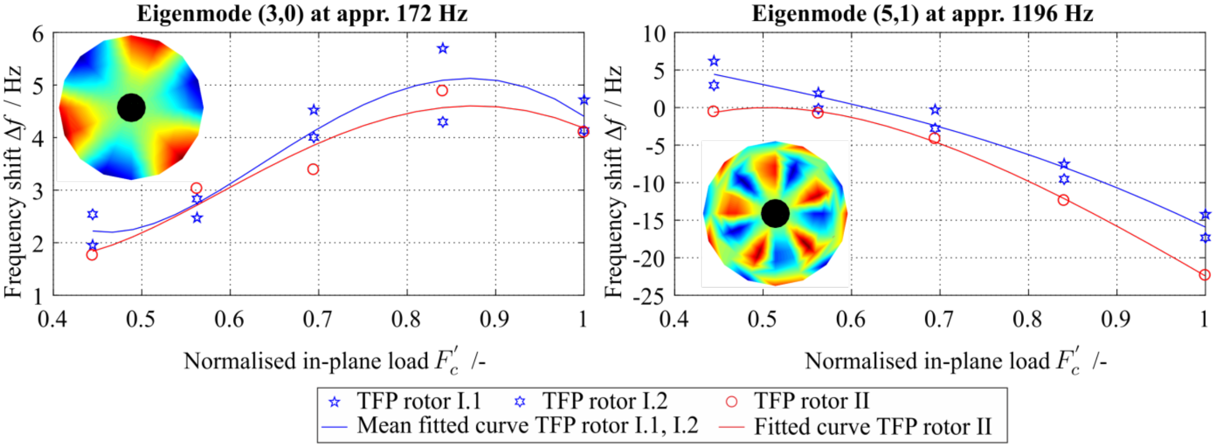

Figure 4. Shift of two eigenfrequencies of all investigated TFP rotors.

For the mode shape (3,0) there is an increase of the frequency under damage increase, followed with a typical frequency decrease under extended inter-fibre cracking, (Figure 4, left). The same behaviour is exhibited also for other mode shapes, e.g. (2,0), (3,0), (4,0) and (5,0). However, in the case of the mode shape (5,1), a monotonic decrease is observed under increase of damage, (Figure 4, right). Also on this case, mode shapes exhibit qualitatively the same behaviour, e.g. mode shapes (0,1), (2,1), (3,1), (4,1) and (5,1). From these results, it can be deduced that a monotonic increase of damage can result in a non-monotonic frequency change for a significant amount of eigenmodes.

3. Simulation analysis

For the numerical investigation of the damage-dependent dynamic behaviour a parametric FE-model was created using the finite element software ABAQUS, which considers both the damage initiation and the in-plane damage evolution from a combination of out-of-plane and in-plane loads. Existing subroutines describing the damage behaviour of TFP-reinforced composites were integrated to model the gradual damage behaviour [9]. Specifically, for the material degradation a user-defined field subroutine (USDFLD) is included which captures the degradation processes after considering the failure modes and respective damage coefficients [13]. The considered loads were derived from the experimental procedure. The simulation delivered numerical results both to the local stresses of the structure, the resulting efforts and damage modes as well as to the structural dynamic response.

3.1. Change of eigenfrequencies due to damage increase

For the TFP I.1 rotor, two eigenfrequencies, (1,0) and (4,0), are exemplary presented (Figure 5). A non-monotonic change of the eigenfrequencies is observed also in the numerical results for multiple eigenfrequencies.

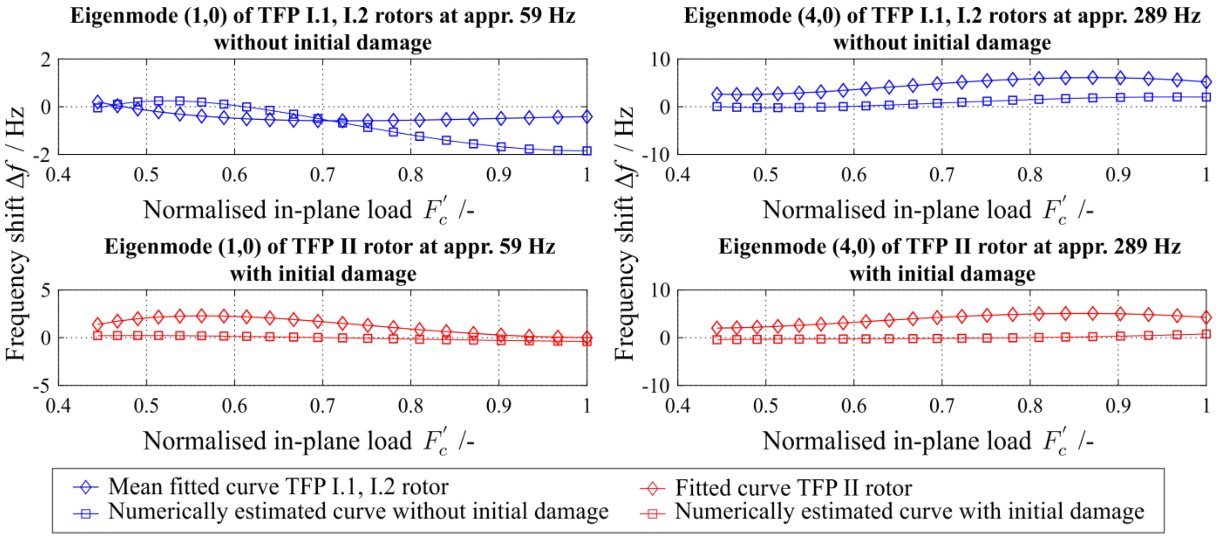

Figure 5. Experimentally and numerically determined change of the eigenfrequency for two mode shapes of a TFP rotor.

A quantitative assessment of the model's performance is performed with regard to the mode shapes and the eigenfrequency change. The Modal assurance Criterion (MAC) and the correlation is selected as a statistical criterion for this assessment. The MAC is calculated between experimentally and numerically estimated mode shapes, (Figure 6, left). The correlation is calculated between the mean fitted curves of the experimental and numerical eigenfrequencies as shown in Figure 5, and the results are shown in Figure 6, right.

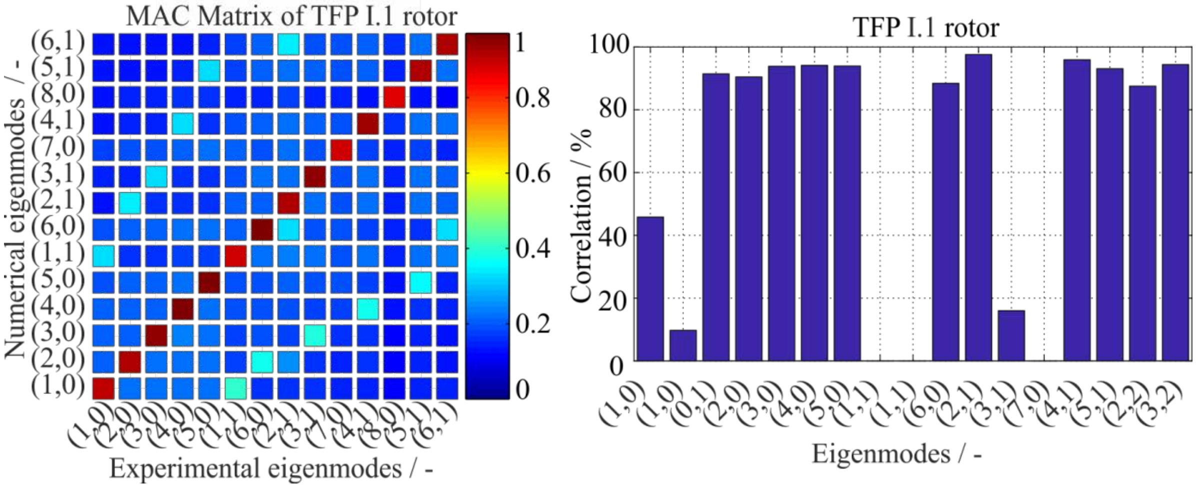

Figure 6. Comparison of measured and calculated mode shapes using MAC for the TFP I.1 rotor (left); statistical comparison between experimentally identified and numerically calculated changes of eigenmodes, using the correlation measure (right).

The majority of the eigenfrequencies (11 out of 17) have a correlation of more than 80 %, showing a promising approach for the simulation of the gradual damage behaviour of composite rotors, (Figure 6, right). The remaining six eigenfrequencies deviate significantly. The first two eigenfrequencies are presumably affected from the modelling of the clamping. The other four eigenfrequencies deviate due to a discrepancy between real and modelled geometry at the nodal diameters and circles of the rotor.

The deviation between experimentally and numerically determined results is due to production-related features, such as the thickness variation of the manufactured rotors, preform thickness variations, small changes to fibre orientation and local resin pockets. A better manufacturing process would result in a higher reliability and therefore in a better accuracy of the models. In the case of a significant deviation between experimentally and numerically determined eigenfrequencies, further work has to be performed for the rotor-specific simulation, in contrast to a homogenised nominal simulation model that has been applied here.

4. Conclusions

A first experimental investigation is performed, in order to assess the gradual damage behaviour of polar orthotropic glass-fibre reinforced epoxy rotors and the relation between damage and vibration behaviour. Consequently, characteristic damage sequences are examined considering in-plane and out-of-plane load conditions. By comparing the experimental and numerical results, the corresponding damage and vibration response behaviour are analysed and evaluated.

A novel observation is reported finding that a monotonic increase of damage results in a significant non-monotonic frequency shift of multiple investigated eigenfrequencies. It is experimentally identified that the investigated composite rotors are damaged by the applied forces, but that they are still operational after a substantial extent of inter-fibre failure. Based on these results it can be deduced, that a monotonic increase of damage can result in a non-monotonic frequency change of 8 out of 18 eigenfrequencies, a percentage of 45 % of all investigated eigenmodes, for rotors with an in-plane polar-orthotropic behaviour.

This effect is observed for all investigated sequences of all three rotors. Numerical investigations show that the reasons for the non-monotonic behaviour can be coupling effects, a combination of pre-stress effects from the curing process, the occurring type of damage propagation combined with the geometry and specific mode shapes.

Acknowledgments

The authors would like to express their gratitude for the financial support from the German Research Foundation, Deutsche Forschungsgemeinschaft DFG (funding code GU 614/14-1).

References

[1] R. Cuntze and A. Freund. The predictive capability of failure mode concept-based strength criteria for multidirectional laminates. *Composites Science and Technology*, 64:343–377, 2004.
[2] H. Schürmann. *Konstruieren mit Faser-Kunststoff-Verbunden*, Springer Berlin Heidelberg, 2007.
[3] R. Böhm, M. Gude and W. Hufenbach. A phenomenologically based damage model for 2D and 3D-textile composites with non-crimp reinforcement. *Materials & Design*, 32:2532–2544, 2011.
[4] M. Gude, W. Hufenbach and I. Koch. Damage evolution of novel 3D textile-reinforced composites under fatigue loading conditions. *Composites Science and Technology*, 70:186–192, 2010.
[5] R. Böhm, M. Gude and W. Hufenbach. A phenomenologically based damage model for textile composites with crimped reinforcement. *Composites Science and Technology*, 70:81–87, 2010.
[6] A. Filippatos. *A damage identification method for composite rotors under consideration of their gradual damage behaviour*, Dissertation, Technische Universität Dresden, 2017.
[7] W. Hufenbach, M. Gude and A. Freund. Realitätsnahe Simulation des Schädigungsverhaltens von Blindnietverbindungen in CFK/Al-Strukturen infolge thermomechanischer Beanspruchung. *Proceedings Simulation von Verbunden: Material und Strukturen NAFEMS*, Bad Kissingen, 2007.
[8] R. Kuschmierz, A. Filippatos, P. Günther, A. Langkamp, W. Hufenbach, J. Czarske and A. Fischer. In-process, non-destructive, dynamic testing of high-speed polymer composite rotors. *Mechanical Systems and Signal Processing*, 254-55:325–335, 2015.
[9] P. Bártolo. Innovative developments in virtual and physical prototyping. *Proceedings of the 5th International Conference on Advanced Research and Rapid Prototyping*, Leiria, Portugal, September 28th – October 1st, 2011.
[10] P. Mattheij, K. Gliesche and D. Feltin. Tailored fiber placement-mechanical properties and applications. *Journal of reinforced plastics and composites*, 17:774-786, 1998.
[11] W. Hufenbach and K. Köhler. *Textile Verbundbauweisen und Fertigungstechnologien für Leichtbaustrukturen des Maschinen- und Fahrzeugbaus*. Technische Universität Dresden, 2008.
[12] M. Gude, A. Filippatos, A. Langkamp, W. Hufenbach, R. Kuschmierz, A. Fischer and J. Czarske. Model assessment of a composite mock-up bladed rotor based on its vibration response and radial expansion. *Composite Structures*, 124:394–401, 2015.
[13] W. Hufenbach, A. Langkamp, P. Kostka and R. Böhm. Damage behaviour of high speed textile reinforced composite rotors. *Kompozyty-Composites*, 2:23–28, 2005.