VARIABLE AXIAL COMPOSITES FOR COMPLEXLY LOADED HIGH-SPEED ROTORS

W. Hufenbach , G. Archodoulakis , R. Grothaus , L. Kroll , A. Langkamp

Institut für Leichtbau und Kunststofftechnik (ILK), University of Technology Dresden, 01062 Dresden, Germany

SUMMARY: Variable axial textile reinforced thermoplastics with their excellent lightweight characteristics, good resistance to chemicals and their wide scope of designability offer a new range of performance for advanced high-speed rotors with a load-adapted thermo-mechanical anisotropic property profile. For the design of variable axial composites for those applications, material adapted calculation methods and optimisation tasks with modified physically based failure criteria are developed. The manufacturing of specimens and lightweight rotors made of commingling hybrid yarn with maximum dimensions up to a length of 3.5 m and a diameter of 1.5 m can be realised using the HT-autoclave and HT-press at ILK. Carbon reinforced thermoplastic composites are fabricated and characterised in material adapted and special tests. Experimental investigations using the ILK-spin test unit confirm, that exclusive by applying material adjusted calculation methods the extreme lightweight potential of variable axial anisotropic composites can be exhausted optimally.

KEYWORDS: lightweight rotors, variable axial reinforcement, thermoplastic composites, 3D-stress analysis, failure analysis, high-speed testing, HT-autoclave, commingling hybrid yarn.

INTRODUCTION

Advanced high-speed rotors, which are subjected to centrifugal forces, media and temperatures, can efficiently be realised using variable axial textile reinforced thermoplastics due to the possibility of creating a load-adapted thermo-mechanical property profile and due to the excellent resistance to chemicals. The dominant tangential stresses induced by the centrifugal forces often cause especially for isotropic materials the component failure. Therefore, very high specific tensile strengths in the tangential direction are generally required, whereas for some particular areas, e. g. fan connections and apertures, locally different fibre orientations also into the thickness direction are urgently needed. Consequently, the variable axial composites with their wide scope of designability — especially the possibility to adjust the strength, stiffness and thermal expansion behaviour locally — offer a new range of performance for instance in the process technology for complexly shaped rotors as e. g. impellers and fans.

For the load adapted design of the new generation of variable axial composite rotors modified 3D-calculation methods and new failure criteria are necessarily required, which take into account the effects of the locally variable reinforcement structure. The calculation and optimization of the textile reinforcement is performed using modified analytical and numerical calculation methods, which realistically simulate the mechanically or the hygro-thermally induced material strains for the individual 3D-orientations. The anisotropic mechanical, thermal and medial material data, which is necessary for the calculation, is determined in specific experiments or with the help of extended rules of mixture. The analytical calculation provides the elementary information about the variable axial structure of the 3D-textile reinforcement.

PROCESSING TECHNIQUES

The manufacturing of prototype lightweight rotors made of commingling hybrid yarn consisting of reinforcing carbon fibres and high temperature (HT) thermoplastic matrix as for example polyetheretherketone (PEEK) is performed using a HT-autoclave (Fig. 1) or a HT-press. Thermoplastic composite material components with maximum dimensions up to a length of 3.5 m and a diameter of 1.5 m can be realised with these technologies at the Institut für Leichtbau und Kunststofftechnik (ILK).

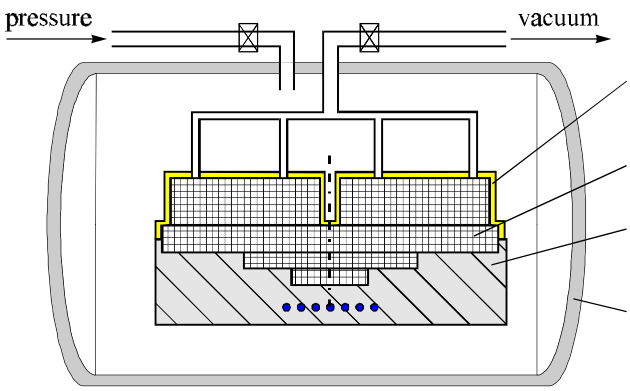

Fig. 1: Principal sketch of ILK high-temperature autoclave with exemplary mould

Uni-directional (UD) and bi-directional (BD) carbon fibre reinforced PEEK composite specimens were fabricated from commingling hybrid yarn with Torayca HTA fibres using the HT-pressing technique. The PEEK-HTA commingling yarn was developed and produced within the DFG-project "Textile Reinforcement for High Performance Rotors in Complex Applications". The determination of the volume fraction of the PEEK-HTA composites by image analysis of optical micrographs gaves values of 60 Vol.-%.

MECHANICAL CHARACTERISATION

For complexly loaded high-speed rotors, fibre reinforced plastics are applied especially in the form of multi-textile composites, where the single layer is reinforced with uni-directional (UD) rovings or with bi-directional (BD) and even multi-directional fabrics. To fully exhaust the high potential for high-speed rotors of textile reinforced composites, it is essential to arrange the textile reinforcement of the single layers according to the occurring main stresses. Therefore, a deep knowledge of the structural mechanical interconnections and the basic anisotropic material behaviour is required [1-4]. To characterise the property profile of anisotropic textile reinforced composites, the basic hygro-thermo-mechanical material data of the single layers are determined in material adapted test methods. Further failure coefficients, which are needed for the application of novel failure criteria, have to be determined in special testing techniques (e. g. tension/compression-torsion tests on tube specimens). The experimentally measured material data are the basis for the calculation of the so called material specific characteristic functions, which characterise the anisotropic property profile of textile reinforced plastics.

Within the presented investigations, the material behaviour of single-layered carbon fibre (CF) textile reinforced thermoplastics like PEEK and PA (polyamide) were characterised in uni- and multi-axial tests. While the carbon PA composites were fabricated using high temperature winding techniques, the PEEK-CF were produced by hot pressing technique using carbon PEEK commingling yarn, which was developed and produced within a co-operative research project at the University of Technology Dresden [5]. Some basic characteristic values of PEEK-CF and PA-CF at room temperature are compared in Table 1 with the values of carbon fibre reinforced epoxy resin. In Fig. 2 the material specific characteristic functions of UD fibre reinforced PEEK are illustrated in polar diagrams.

Table 1: Experimentally determined characteristic material data

	E_1 [GPa]	E_2 [GPa]	ν_{12}	G_{12} [GPa]	σ_{f1} [MPa]	σ_{f2} [MPa]	τ_{f12} [MPa]	ε_{f1} [%]
PEEK-HTA (UD-layup)	138	11,3	0,24	8,6	1388	87	-	0,98
PEEK-HTA (plain BD-woven fabric)	66	-	0,036	8,0	343	-	-	0,7
PA-HTA (UD-winding)	-	-	-	-	-	10,9	33,9	-
EP-HTA (UD-winding)	135	8,2	0,29	4,5	1620	60	70	1,1
EP-HTA (BD-woven fabric)	72	-	0,033	3,9	812	-	97	-

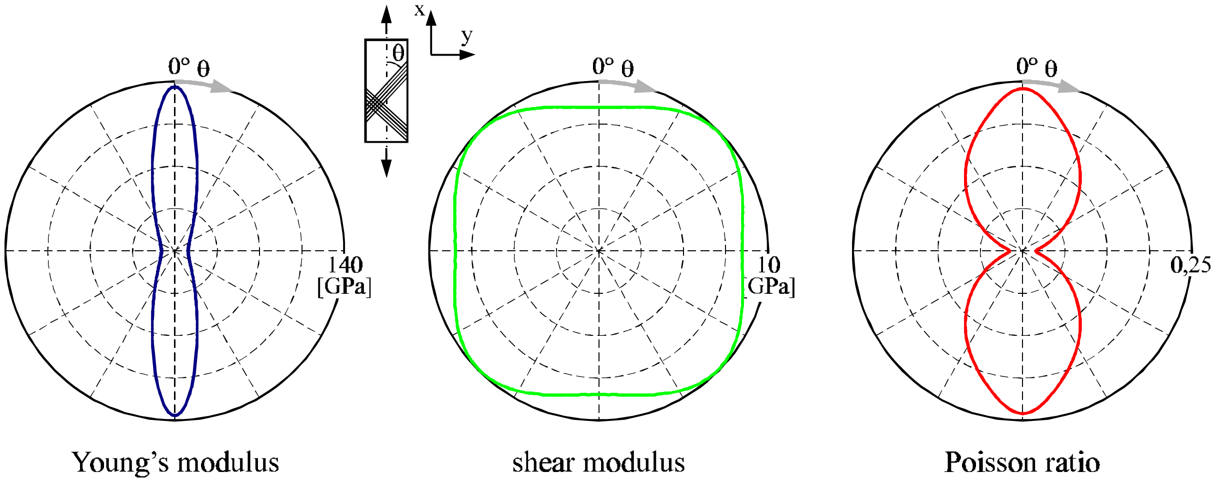

Fig. 2: Directional elastic material data of UD-PEEK-HTA

STRESS ANALYSIS OF COMPLEXLY LOADED COMPOSITE ROTORS

For the load adapted design of this new generation of variable axial rotor structures modified 3D-calculation methods and new physically based failure criteria are necessarily required, which take into account the effects of the locally variable reinforcement structure. The calculation and optimization of the textile reinforcement is performed using extended analytical and numerical calculation methods, which realistically simulate the mechanically or the hygrothermally induced material strains for the individual 3D-reinforcement. The analytical calculation provides the elementary information about the variable axial structure of the 3D-textile reinforcement.

For endless fibre reinforced plastic composite rotors especially two different principal lay-up types are realised, which are principally defined by the existing manufacturing technologies. On the one hand there are for example uni-directionally or bi-and multi-directionally reinforced laminated rotors with a so called orthotropic lay-up. For this special kind of rotors, a non-rotationally symmetrical deformation behaviour even for rotationally symmetrical loading conditions is observed. On the other hand, there are wound composite rotors, which are characterised by a polar orthotropic laminate structure having a rotationally symmetrical stress field [2].

In general, equilibrium conditions, material laws, kinematics, boundary and transitional conditions are necessary for the mechanical description of high-performance structures. Additionally, the principally different mechanical behaviour of laminated and wound composite rotors requires extended calculation methods. For the mathematical description of laminated rotors in cartesian coordinates x, y the method of conformal mapping and complex stress functions are applied here [2, 3]. The resulting stress and displacement fields are dependent on the fibre orientation φ, which can be seen in the following relations:

$$\sigma_i,\ u_j \sim \rho \cdot \omega^2 \cdot (x^2+y^2) \quad (1)$$

$$\sigma_i,\ u_j = f(\varphi,\ \omega,\ ...) \quad (2)$$

with	$\sigma_i = \sigma_x, \sigma_y, \tau_{xy}$	stress components	ρ	density
	$u_j = u_x, v_y$	displacement components	ω	angular velocity.

In the case of wound composite rotors, two uncoupled in-homogeneous EULER differential equations of second order are applied to describe the single layer behaviour, which result in linear equation systems for multi-layered structures by applying the relevant boundary and transitional conditions. The following relations principally characterise the mechanical behaviour of the anisotropic wound rotors:

$$\sigma_r,\ \sigma_\theta,\ u_r \sim \rho \cdot \omega^2 \cdot r^2 \quad (3)$$

$$\tau_{r\theta},\ u_\theta \sim \rho \cdot \dot{\omega}^2 \cdot r^2 \quad (4)$$

with	$\sigma_r, \sigma_\theta, \tau_{r\theta}$	stress components	$\dot{\omega}$	angular acceleration
	u_r, u_θ	displacement components	r	radius.

Exemplary the stress fields of a laminated disc shaped BD-PEEK-HTA-rotor is analysed (rotor geometry: 120 mm outer diameter, 30 mm inner diameter, 2.5 mm thickness). The following

Fig. 3 shows the consistent analytically and numerically calculated tangential stresses in the rotor, which is centrifugally loaded with an angular velocity of 6.000 s^{-1}. Comparable to rotors made of isotropic materials, the maximum stresses occur at the inner radius; additionally high tangential stresses and extreme stress gradients are observed here. In the case of BD reinforced rotors maximum stresses occur for a fibre orientation of 0° and 90°. The influence of the fibre orientation decreases rapidly with an increasing radius, so that the dependence on the ply angle is significant only for the vicinity close to the inner radius.

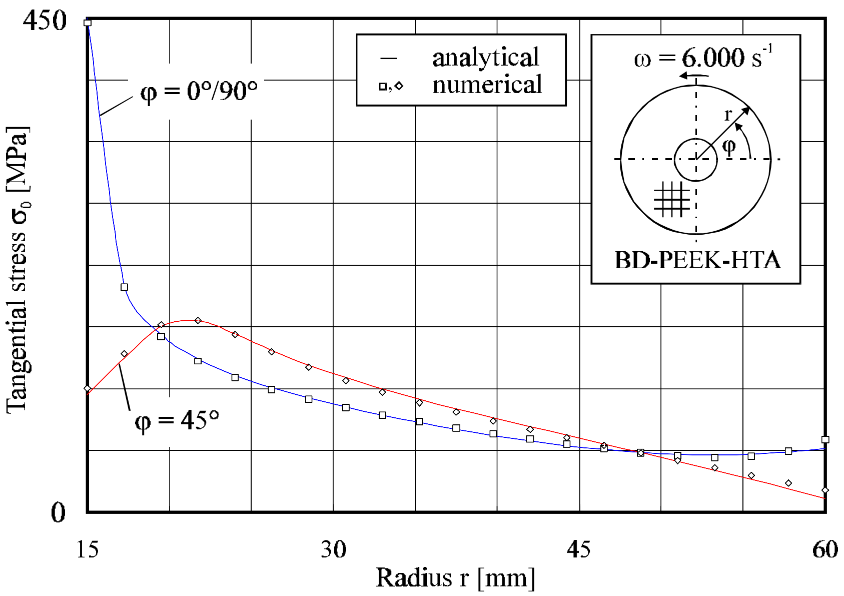

Fig. 3: Tangential stresses in BD-PEEK-HTA-rotor

The extreme dependence on the fibre orientation is demonstrated by the tangential stress polar at the inner radius of the laminated rotor, where the maximum stresses occur in the fibre direction (Fig. 4). Comparing the stress field of UD-PEEK-HTA-rotors with the behaviour of BD-PEEK-HTA-rotors, it can be seen that the fibre strength is better exploited with the bi-directional reinforcement.

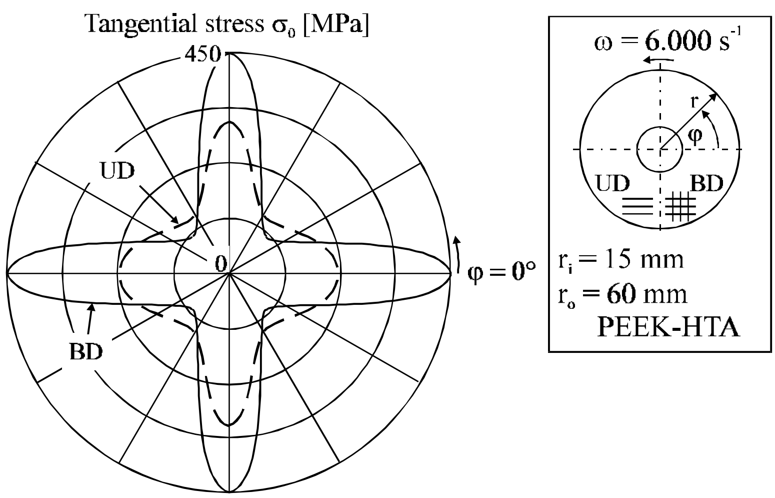

Fig. 4: Tangential stress polar for inner radius of centrifugally loaded laminated rotors

FAILURE ANALYSIS

In praxis different rotor failure mechanisms like delamination, multi-fragmentation, material loss and dynamic response on initial failure have been observed. These mechanisms are dependent on the material, textile structure, shape and loading conditions of the composite rotor [6].

For the theoretical determination of the fracture stresses of textile reinforced thermoplastic composite rotors with complex three dimensional states of stress, the conventional fracture criteria like Tsai/Wu are unsuitable, because these criteria do not take into account 3D-failure effects like fracture modes or angles of fracture [4].

A completely different method for the formulation of realistic 3D-fracture criteria for UD-reinforced composites, taking into consideration the heterogeneous material structure relevant to the fracture, has been adopted by Hashin [7] and Puck [8]. Here, not only the decisive difference between fibre fracture and inter-fibre fracture is considered, but a fracture angle has been introduced as a free parameter which also characterises further fracture types in the plane parallel to the fibres. It is also taken into consideration that, in accordance to mechanical material behaviour and phenomenological observations, compressive stresses perpendicular to the fibres tend to prevent the formation of an fracture, while corresponding tensile stresses tend to promote the composite fracture. Thus, the new fracture type criteria, in contrast to the generalising fracture criteria, are founded on physically based phenomena.

Experimental difficulties arise in the verification of the new failure criteria, because complicated experiments with many different stress combinations have to be carried out. For example, tension/compression-torsion tests with tangentially wound tubes enable predicting the behaviour of the fracture angel dependent on the stress combination and considering the effect of the inner material friction on the shear failure, which is of special importance for textile composites.

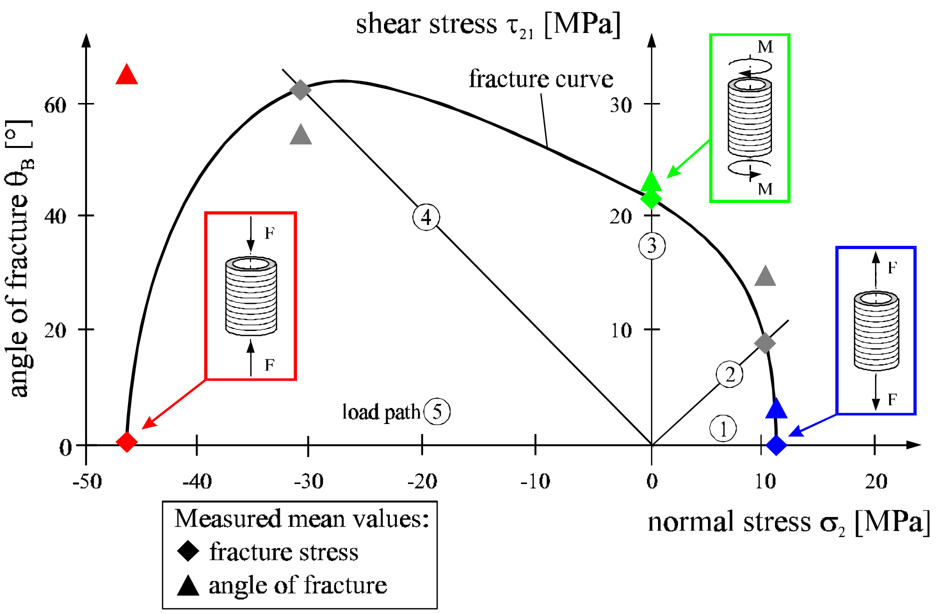

Fig 5: Fracture body of wound PA-HTA composite for σ_2-τ_{21}-in-plane loading

The application of the physically based failure criterion is principally demonstrated for tangentially wound carbon-polyamide (PA-HTA) tube specimens for different states of stress σ_2-τ_{21} in Fig. 5. Applying a modified form of this hypothesis, the complex 3D-state of stress of advanced textile reinforced rotors – also around cut-outs and near to rotor attachments – can be evaluated in a realistic manner. For a material adapted failure analysis of textile reinforced composites extended degradation models have to be developed on the basis of the a. m. fracture criteria and under consideration of structural mechanical interconnections [5]. Having the local failure assessment of the textile structure, the safety factor of the whole rotor structure can be estimated.

Experiments

Experimental investigations using high-speed rotor testing units (Fig. 6) support the verification of the developed design methods for new lightweight rotors under extreme centrifugal, media and thermal loading conditions. Maximum rotor speeds of 250,000 rpm in combination with maximum temperatures of 700 °C for rotor dimensions up to one meter can be achieved with the ILK spin pits. Special telemetric-based on-line measurements of strain, temperature, etc. are used to verify the calculated structural behaviour of the variable axial reinforced components. Additionally, adapted burst tests are used to investigate the specific failure mechanism of composite rotors and to verify the new failure criterion. The extended 3D-stress analysis in combination with the physically based failure assessment enables developing a new generation of variable axial composite rotors having a damage tolerant and high-temperature, media resistant characteristic [4].

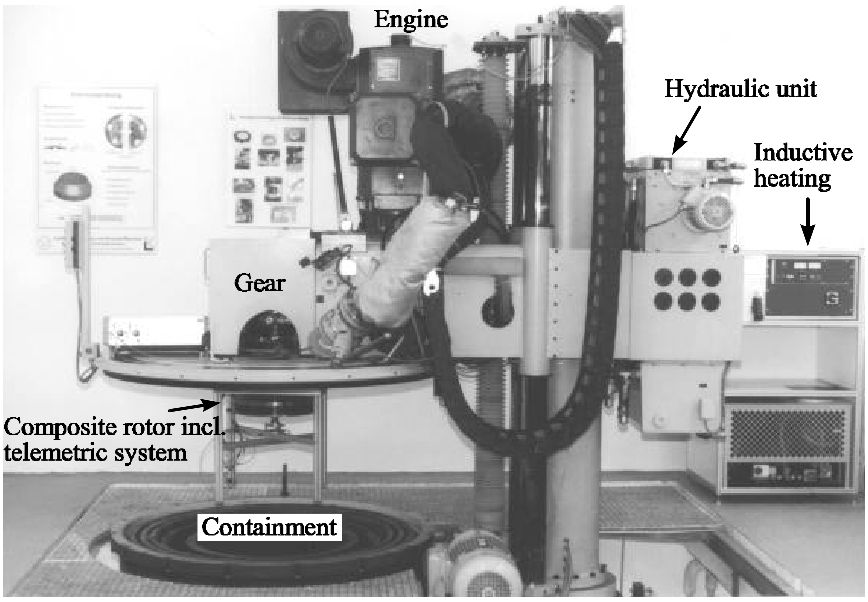

Fig. 6: Vacuum high-speed rotor testing unit incl. telemetric strain measurement system at ILK

CONCLUSION

Textile reinforced composites offer the potential for a load adapted lightweight design of high performance rotors in complex applications as for example for fans and blades. Therefore, modified calculation methods and material adapted failure analyses have been applied to optimally exhaust the material anisotropy and tailorability of the rotor structure to fulfil the individual technical demands. The developed and experimentally verified calculation methods are an efficient tool for purposeful parameter studies within the design and optimisation process of enhanced 3D-textile reinforced composite rotors. Using these tool, especially laminated and wound carbon fibre reinforced rotors have been analysed, where important differences in the mechanical behaviour have been found. These different behaviours and their consequences with respect to failure prediction, failure mode and fracture angle can be evaluated with the help of new realistic physically plausible failure criteria, so that a new generation of advanced high-speed composite rotors with damage tolerant characteristic are designed and prototyped.

Acknowledgements

The authors gratefully acknowledge the financial support given by the Deutsche Forschungsgemeinschaft (DFG), Bonn.

REFERENCES

/1/ Hufenbach, W., Kroll, L., “Design and Construction of Hygro-thermally Stable Shells”, *Mechanics of Composite Materials*, Vol. 31, No. 5, 1995, pp. 677-683.

/2/ Hufenbach, W., Kroll, L., Grothaus, R., Gude, M., “Ceramic Composite Rotors under Extreme Thermal and Centrifugal Loads “ *Ceramics*, (in press)

/3/ Hufenbach, W., Kroll, L., “Stress Analysis of Notched Anisotropic Finite Plates under Mechanical and Hygro-Thermal Loads“ *Archive of Applied Mechanics*, (in press)

/4/ Hufenbach, W., Kroll, L., Grothaus, R., “New Design Methods for Complexly Loaded High-Speed Composite Rotors”, *Proceedings of the Eighth European Conference on composite Materials*, Neaples, Italy, 3.-6. June 1998, Vol. 1, , pp. 511-518.

/5/ Hufenbach, W., Offermann, P. et al., “Textile Verstärkungen für Hochleistungsrotoren in komplexen Anwendungen – Beanspruchungsgerechte und versagenstolerante Hybridstrukturen”, DFG-Forschergruppe (Hu 403/13-1), Dresden since 1997.

/6/ Grothaus, R., “Composite Rotor Failure Analysis and Adapted Lightweight Containment Design”, *Proceedings of the International Flywheel-Safety-Workshop “FLYSAFE“*, Dresden, Germany, 3.-5. February 1999.

/7/ Hashin, Z., “Failure Criteria for Uni-directional Fibre Composites”, *Journal of Applied Mechanics*, Vol. 47, 1980, pp. 329-334.

/8/ Puck, A, *Festigkeitsanalyse von Faser-Matrix-Laminaten - Modelle für die Praxis*, Carl Hanser Verlag, München, 1995