Werner Hufenbach[1], Albert Langkamp[2], Paweł Kostka[3], Robert Böhm[4]
Technische Universität Dresden, Institut für Leichtbau und Kunststofftechnik (ILK), 01062 Dresden, Germany

DAMAGE BEHAVIOUR OF HIGH SPEED TEXTILE REINFORCED COMPOSITE ROTORS

Textile reinforced plastics with their excellent light weight characteristics, good resistance to chemicals and their wide scope of design-ability - e.g. possibility of creating a load-adapted thermo-mechanical anisotropic property profile - offer a new range of performance for advanced high-speed rotors. For the load adapted design of variable axial composites for those applications, material adapted calculation methods and optimisation tasks with modified physically based failure criteria and anisotropic, fracture mode specific damage models are developed.

The calculation and optimization of the textile reinforcement for complexly loaded composite rotors is performed using extended analytical and numerical calculation methods, which realistically simulate the mechanically or the hygro-thermally induced material strains for the individual textile reinforcement. A linear elastic approach can be applied for the stress strain analysis until the first fracture occurs. After initiation of the first failure, non linear deformation behaviour caused by different damage phenomena of the textile reinforced composite has to be considered within the calculation.

In the present work a phenomenological plane stress damage mechanics based model for textile reinforced composites is presented. Damage variables are introduced to describe the evolution of the damage state and as a subsequence the degradation of the material stiffness.

Key words: textile reinforced composites, simulation, damage analysis, composite rotors

ANALIZA PĘKANIA SZYBKOOBROTOWYCH WIRNIKÓW WZMOCNIONYCH TEKSTYLNIE

Tworzywa ze wzmocnieniem tekstylnym ze względu na niski ciężar właściwy, odporność na działanie substancji chemicznych oraz możliwość projektowania ich właściwości w szerokim zakresie - na przykład dopasowania anizotropii mechanicznej i termicznej do występujących obciążeń - oferują nowy zakres parametrów eksploatacyjnych nowoczesnych szybkoobrotowych wirników.

Zostały opracowane metody umożliwiające projektowanie wirników wykonanych z wieloosiowo wzmocnionych kompozytów z uwzględnieniem stanu obciążenia. Obejmują one fizykalnie uzasadnione kryteria uszkodzeniowe oraz modele procesu niszczenia uwzględniające anizotropię materiału i rodzaj uszkodzenia. Obliczenia i optymalizacja parametrów wzmocnienia tekstylnego wirników poddanych złożonym stanom obciążenia zostały przeprowadzone z użyciem zaawansowanych metod analitycznych i numerycznych, które pozwalają na realistyczną symulację odkształceń wywołanych obciążeniami mechanicznymi lub higrotermicznymi dla określonych rodzajów wzmocnienia. Teoria liniowo-elastyczna może być zastosowana do analizy naprężeń i odkształceń tylko do momentu, w którym zostaje zapoczątkowana degradacja materiału. Zjawiska składające się na proces niszczenia powodują, że w obliczeniach dotyczących odpowiadającego mu zakresu obciążeń stosowane są zależności nieliniowe.

Artykuł przedstawia fenomenologiczny model mechaniki pękania kompozytu wzmocnionego tekstylnie dla płaskiego stanu naprężenia. Wprowadzono specjalne zmienne opisujące przebieg procesu niszczenia i towarzyszący mu spadek sztywności.

Słowa kluczowe: kompozyty tekstylne, symulacja, mechanizm pękania, wirniki kompozytowe

INTRODUCTION

Advanced high-speed rotors, which are subjected to centrifugal forces, media and temperatures, can efficiently be realised using textile reinforced plastics 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 the component failure especially for isotropic materials. 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 textile reinforced 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 textile reinforced composite rotors modified 3D-calculation methods, material specific failure criteria and new physically based damage models are necessarily required, which take into account the effects of the textile reinforcement structure. The calculation and optimization of the textile reinforcement is performed using

[1] Prof. Dr.-Ing. habil., [2, 3] Dr.-Ing., [4] Dipl.-Ing.

modified analytical and numerical calculation methods, which realistically simulate the mechanically or the hygro-thermally induced material strains for the individual 3D-orientations. For the calculation of the non-linear stress and strain behaviour of complexly loaded composites rotors with textile reinforcement special emphasis has to be given to the interaction between fibre failure due to stress in fibre direction and matrix failure due to transverse and shear stress. This demands the formulation of realistic failure criteria taking into account the micro-structural material behaviour as well as different modes of fracture. New failure criteria like fracture mode concepts (FMC) consider these different failure modes as well as further fracture types in the plane of reinforcement. To consider the anisotropic nature of damage under various loading directions, the degradation model generally requires a number of parameters that are very extensive to be determined by experiments. Thus, model parameters may be determined either by experimental measurement or by inverse identification. Additionally, any further modification of the composite material requires the damage parameters to be adapted.

LINEAR STRESS ANALYSIS OF COMPLEXLY LOADED TEXTILE REINFORCED ROTORS

The calculation and optimization of the textile reinforcement for complexly loaded composite rotors is performed using extended analytical and numerical calculation methods, which realistically simulate the mechanically or the hygro-thermally induced material strains for the individual textile reinforcement. The analytical calculation provides the elementary information about the fibre structure of the textile reinforcement.

On the one hand there are for example uni-directional (UD) or bi- and multi-directionally (BD) 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.

In case of endless fibre reinforced plastic composite rotors especially two different principal lay-up types are realised, which are defined by the existing manufacturing technologies. On the one hand there are Cartesian orthotropic rotor structures with bi- and multi-directionally reinforcement. For this kind of rotors, a non-rotationally symmetrical stress strain behaviour even for rotationally symmetrical loading conditions is observed. On the other hand, there are wound composite rotors, which are characterized by a polar orthotropic laminate structure having a rotationally symmetrical stress strain field.

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 individually adapted 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 [1]. The resulting stress and displacement fields are dependent on the fibre orientation φ, which can be seen in the following relations:

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

$$\sigma_i,\, u_j = f(\varphi,\, \omega,\, \ldots) \tag{2}$$

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:

$$\sigma_r,\, \sigma_\theta,\, u_r \sim \rho \cdot \omega^2 \cdot r^2 \tag{3}$$

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

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

It should be noted here that the angular acceleration induces shear stresses in the rotor, which could be critical for composite materials with their typically low shear strength, so that special care has to be taken to include acceleration effects occurring in praxis.

PHENOMENOLOGY OF DAMAGE IN TEXTILE REINFORCED COMPOSITE ROTORS

Characteristics of textile composites

Essential features of textile reinforcements are reinforcing layers, in which the reinforcing fibres can be matched to the actual loads and to the contours of the component. This permits more effective exploitation of the characteristic potential of the reinforcing fibres in the compound component under multi-axial loading conditions. In recent years, novel textile reinforcements, composed of multi-axial reinforcing layers that are held together by systems such as a stitching yarns, have been developed. Reinforcing yarns, e. g. glass fibres, carbon fibres or thermoplastic fibres can be used within all textile yarn systems [2, 3]. The reinforcing yarn systems provide a very high composite strength and stiffness and the textile structure provides a high drapability of the preform as well as a good impact behaviour of the composite material [2].

Due to the complexity of the geometry and the fracture mechanisms of these micro-heterogeneous textile reinforced composites, a convenient structural failure analysis causes extensive difficulties, since the microstructural configuration (e.g. fibre and matrix material, arrangement of reinforcing fibres) is of vital importance for the description of the degradation behaviour. It becomes apparent that a successful damage analysis initially requires a realistical determination of all occurring damage mechanisms.

Physical nature of damage in textile composites

Damage is conventionally defined as the progressive deterioration of materials due to nucleation and growth of micro-cracks. Micro-cracking is one fundamental mechanism of the non-linear behaviour of textile reinforced composites. Besides matrix micro-cracking, failure modes like fibre failure, delamination or compressive failure are observed which are more important in practical cases. The choice of appropriate damage variables significantly depends on well known and separable damage mechanisms. The observed damage at the macroscale is initiated without a large amount of plastic strain, so that brittle damage could be assumed.

Mechanical representation of damage in textile composites

The stress-strain response of textile reinforced composites is known to be non-linear especially for shearing. However, elasticity is assumed to hold if the damage state does not change. All non-linear effects are attributed to damage. In particular, no irreversible deformations are supposed to occur. The microscopic damage phenomena (matrix micro-cracking and crack propagation) are represented by internal damage variables which describe the effects of these microdefects on the macroscopic or mesoscopic scale. The unknown damage variables are treated as phenomenological variables, since they have no direct relation to the micromechanical phenomena. Some of the performed experimental test show that a given stress not only produces a stiffness change in the loading direction, but also creates damage in other directions. This emphasises the general anisotropic nature of damage, even if the initial composite has orthotropic nature on the layer level. Then, the damage analysis must necessarily consider the degra- dation behaviour by including an anisotropic damage tensor as internal damage variable [5].

Another way consists of separating the damage mechanisms. With the additional assumption that the orthotropic nature of the single textile layers, modelled as smeared continua (cp. [4]), is maintained throughout the damage process (similar to [6]), the description of the damage process could be significantly simplified. This assumption is valid as long as micro-cracks have a preferential orientation (either tangential or normal to fibre direction).

The fibre failure of textile composites can be represented by a modified normal stress criterion. The matrix microcracking is then described by a set of internal damage variables (similar to [6]). This separation then allows the calculation of the effective stiffnesses.

DAMAGE MECHANICS MODEL

General aspects and constitutive assumptions

For a practical design of complicated structural components made from textile composites using the finite element method, the description of the material degradation behaviour using continuum damage mechanics (CDM) is very advisable. Hence, the damage behaviour will be described with a CDM based model and adapts the work of Matzenmiller et al. [6] to textile composites. This model is feasible under the aforementioned assumptions:

- The textile composite can be recomposed by i-UD-layers as equivalent single layers.
- All damage modes are experimentally separable, well known and could be considered in a sufficiently accurate manner by using the failure criterion of Puck [7].
- All nonlinear effects of the constitutive behaviour are attributed to damage.
- The orthotropic nature of the mechanical response is maintained at all states of damage.

In this case, plane stress conditions (CLT) are assumed adequate to model the stress-strain behaviour of the textile composite. The analysis described below is conducted layer-wise having regard to the real textile structure by the use of correction factors in the failure criteria. The proposed action plane related criteria act as a set of boundary conditions (damage threshold) for the damage mechanics model.

Non-linear stress-strain-relationship

To transform the nominal stress σ of the orthotropic i-UD-layer to the effective stress $\tilde{\sigma}$ Matzenmiller et al. [6] introduce a rank-four damage operator $\boldsymbol{D}$:

$$\tilde{\sigma} = \boldsymbol{D}\sigma \tag{5}$$

with

$$\boldsymbol{D} = \begin{bmatrix} \frac{1}{1-D_{11}} & 0 & 0 \\ 0 & \frac{1}{1-D_{22}} & 0 \\ 0 & 0 & \frac{1}{1-D_s} \end{bmatrix} \tag{6}$$

The degradation variables D_{11} and D_{12} denote the damage in the two principal axis of the i-UD-layer. An additional degradation variable D_s is introduced to characterize the modification of the shear behaviour. The introduced degradation parameters D_{11} and D_{22} needs to be verified separately for the tension and the compressive domain. All degradation parameters take the value $D_i = 0$ for the undamaged, initial state, and the value $D_i = 1$ for the completely damaged state, respectively. The compliance relationship for the damaged state then results in

$$\varepsilon = S^0\tilde{\sigma} = S^0\boldsymbol{D}\,\sigma = \tilde{\mathrm{S}}\,\sigma \tag{7}$$

where S^0 denotes the compliance matrix at the initial state, with

$$\tilde{\boldsymbol{S}}(\boldsymbol{D}) = \begin{bmatrix} \tilde{S}_{11} & \tilde{S}_{12} & 0 \\ \tilde{S}_{21} & \tilde{S}_{22} & 0 \\ 0 & 0 & \tilde{S}_{66} \end{bmatrix} = \begin{bmatrix} \frac{1}{(1-D_{11})E_{||}} & -\frac{\nu_{21}}{E_{||}} & 0 \\ -\frac{\nu_{12}}{E_\perp} & \frac{1}{(1-D_{22})E_\perp} & 0 \\ 0 & 0 & \frac{1}{(1-D_s)G} \end{bmatrix} \tag{8}$$

The effective compliance $\tilde{S}_{11}$ is only affected by the damage parameter D_{11}, and will only be reduced if the fibre failure criterion is fulfilled. Consequently, D_{11} could be interpreted as the damage variable for fibre damage. The transverse elastic compliance $\tilde{S}_{22}$ is only governed by the damage parameter D_{22}, which should be accordingly interpreted as a crack density parameter. The relationship between the crack density and the stress-strain behaviour of the composite could be determined either experimentally or by means of micromechanical models. For an orthotropic layer, the shear compliance $\tilde{S}_{66}$ is independent of the residual compliances. Thus, the determination of shear damage by the damage parameter D_s is a direct consequence of the definition of the constitutive equation. The inversion of the damaged compliance matrix $\tilde{\boldsymbol{S}} = \boldsymbol{S}^{\boldsymbol{0}}\boldsymbol{D}$ leads with $\tilde{\boldsymbol{C}}(\boldsymbol{D}) = \tilde{\boldsymbol{S}}(\boldsymbol{D})^{-1}$ to the effective material stiffness matrix for the damaged state

$$\tilde{\boldsymbol{C}}(\boldsymbol{D}) = \begin{bmatrix} \tilde{C}_{11} & \tilde{C}_{12} & 0 \\ \tilde{C}_{21} & \tilde{C}_{22} & 0 \\ 0 & 0 & \tilde{C}_{66} \end{bmatrix} = \frac{1}{d}\begin{bmatrix} (1-D_{11})E_{||} & (1-D_{11})(1-D_{22})\nu_{21}E_\perp & 0 \\ (1-D_{11})(1-D_{22})\nu_{12}E_{||} & (1-D_{22})E_\perp & 0 \\ 0 & 0 & d(1-D_s)G \end{bmatrix} \tag{9}$$

with $d = 1-(1-D_{11})(1-D_{22})\nu_{12}\nu_{21}$. It becomes apparent that the elastic stiffnesses $\tilde{C}_{12}$ and $\tilde{C}_{21}$ are also affected by damage, which could be attributed to the change of the Poisson's ratio due to matrix cracking or fibre failure.

Damage threshold

Within the framework of a continuum damage mechanics, the physically based failure criteria act as threshold functions; similar to the yield surface in plasticity theory. The elastic region is bounded by the fracture surfaces associated with the different composite failure modes. The threshold functions r, defining the elastic region during the damage process, become a function of the effective stress $\tilde{\sigma}$ and consequently of the damage operator $\boldsymbol{D}$). In detail, the surface f_{ff} represent the fibre failure mode, and on the other hand $f_{iff,t}$ and $f_{iff,c}$ typify the IFF modes in the tension and the compressive domain, respectively:

$$f_{ff} = \left(\frac{\tilde{\sigma}_1}{g_{||}^{(\pm)}R_{||}^{(\pm)}}\right)^2 - r_{ff1} = 0 \tag{10}$$

$$f_{iff,t} = \left(\frac{\tilde{\sigma}_n}{g_\perp^{(+)}R_\perp^{(+)}}\right)^2 + \left(\frac{\tilde{\tau}_{nt}}{g_{\perp\perp}^{(A)}R_{\perp\perp}^{(A)} - p_{\perp\perp}^{(+)}\tilde{\sigma}_n}\right)^2 + \left(\frac{\tilde{\tau}_{n1}}{g_{\perp||}R_{\perp||} - p_{\perp||}\tilde{\sigma}_n}\right)^2 - r_{iff1,t} = 0 \tag{11}$$

$$f_{iff,c} = \left(\frac{\tilde{\tau}_{nt}}{g_{\perp\perp}^{(A)}R_{\perp\perp}^{(A)} - p_{\perp\perp}^{(-)}\tilde{\sigma}_n}\right)^2 + \left(\frac{\tilde{\tau}_{n1}}{g_{\perp||}R_{\perp||} - p_{\perp||}^{(-)}\tilde{\sigma}_n}\right)^2 - r_{iff1,c} = 0 \tag{12}$$

The effective stresses acting in the fracture plane are calculated using the general state of stress and the common transformation

$$\begin{Bmatrix} \tilde{\sigma}_1 \\ \tilde{\sigma}_n \\ \tilde{\sigma}_t \\ \tilde{\tau}_{nt} \\ \tilde{\tau}_{t1} \\ \tilde{\tau}_{n1} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & c^2 & s^2 & 2sc & 0 & 0 \\ 0 & s^2 & c^2 & -2sc & 0 & 0 \\ 0 & -sc & sc & c^2 - s^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & c & -s \\ 0 & 0 & 0 & 0 & s & c \end{bmatrix} \begin{Bmatrix} \tilde{\sigma}_1 \\ \tilde{\sigma}_2 \\ \tilde{\sigma}_3 \\ \tilde{\tau}_{23} \\ \tilde{\tau}_{31} \\ \tilde{\tau}_{21} \end{Bmatrix} \quad (13)$$

with $s = \sin\theta$ and $c = \cos\theta$.

Damage evolution law

Numerous models with various damage evolution laws for fibre composites are proposed in the literature, e.g. [6, 8]. The main problems to consider for the practical user is the formulation of physically based damage evolution laws and degradation parameters, subsequently. Additionally, the possibility of an accurate and efficient determination of these parameters has to be considered. It is an appropriate approach to determine the damage evolution laws experimentally, instead of deducing them from thermodynamic potentials. Within this study, the principal damage growth law proved to be a reasonable choice (Fig. 1).

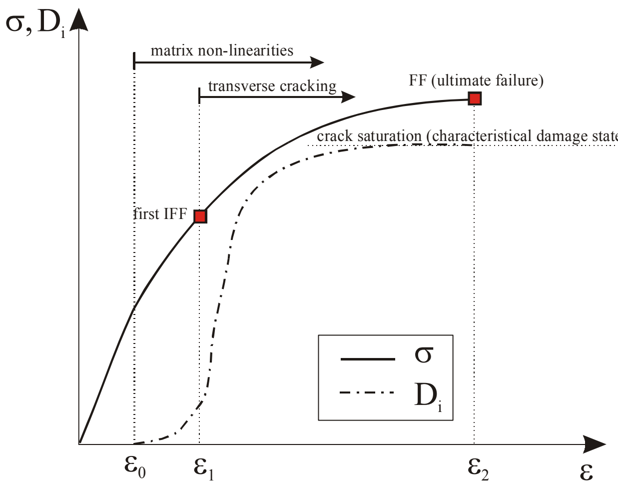

Fig. 1. Principal sketch of damage behaviour
Rys. 1. Ogólny szkic przebiegu uszkodzenia

$$D_i = \begin{cases} 0 & \text{if} \quad \varepsilon_{ij} < \varepsilon_0 \\ D_m(\varepsilon_{ij}) & \text{if} \quad \varepsilon_0 < \varepsilon_{ij} < \varepsilon_1 \\ D_m(\varepsilon_{ij}) + D_c(\varepsilon_{ij}) & \text{if} \quad \varepsilon_1 < \varepsilon_{ij} < \varepsilon_2 \\ 1 & \text{if} \quad \varepsilon_{ij} > \varepsilon_2 \end{cases} \quad (14)$$

The stress-strain curve, and as a consequence the damage evolution law, too, is subdivided into four parts. Within the first part, the stress-strain curve is linear and no damage occurs ($D_i = 0$). If $\varepsilon_{ij} > \varepsilon_0$ matrix non-linearities are assumed to occur [9]. Therefore, the damage function controlling matrix non-linearities $D_m(\varepsilon_{ij})$ is introduced. After the first IFF, effects due to transverse matrix cracking have to be superimposed to the effects due to matrix non-linearities and the damage function becomes $D_m(\varepsilon_{ij}) + D_c(\varepsilon_{ij})$. Depending on the textile structure (e.g. fibre distance or distance between stitching yarns), the characteristical damage state (CDS) is reached: no further cracks are assumed to occur in the damaged layer. Accompanied by further IFF, the structure is damaged until the ultimate failure (FF) occurs ($D_i = 1$). The parameters in the damage evolution law describe the gradient of the damage function and should be correlated with experimental data.

DIAGNOSTIC OF DAMAGE IN TEXTILE COMPOSITE ROTORS

The majority of faults of modern rotating machinery is connected with rotor bearing system. For safety and economical reasons it is important to reliable diagnose these faults at an early stage [10]. Depending on the machine size and operating conditions, there are used different monitoring systems, that allow to collect and analyse diagnostic signals. Detection of fault and sometimes estimation of its extent and location [11-13] is possible only when the relevant signal properties and relations between them and faults are known.

Common rotor dynamic faults generate vibration due to system instability, and due to some externally applied load, such as in case of cracked or bent shafts and mass unbalance [10]. Above described failure mechanisms of composite rotor change its stiffness and thus its dynamical behaviour. It could be expected, that progressive degradation of rotor material leads to a new nature of its anisotropy and to non-symmetrical distortion due to centrifugal force. The resulting unbalance should be in this case depending on rotating speed, what can be determined during run-up or run-down of the machine. These conditions allow also the analyse of self excited vibrations at different frequencies (spectrogram analyse) and thus tracing of natural frequencies. Changes of these frequencies occur when material stiffness changes due to failure.

Using the above presented methods it is possibly to calculate the material properties and to estimate diagnostic signal properties for the given type and stage of failure. However, there exists generally no unequivocally solution for an reverse task - it is possible that different failures generate the same values of the given diagnostic signal properties. For this reason it is necessary to conduct further investigations in order to determine what additional information (e.g. resulting from consideration of rotor geometry influence on multi-channel vibroacoustic signal) could be taken into the consideration.

CONCLUSIONS

Textile reinforced composites offer the potential for a load adapted lightweight design of high performance rotors in high performance applications. Therefore, modified calculation methods and material adapted failure analyses have been applied to optimally exhaust the material anisotropy and tailor-ability of the rotor structure to fulfil the individual technical demands. The developed calculation methods are an efficient tool for purposeful parameter studies within the design and optimization process of enhanced textile reinforced composite rotors.

REFERENCES

[1] 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, 511-518.

[2] Offermann P., Cebulla H., Diestel O., Modelling and production of fully fashioned biaxial weft knitted fabrics, 1st Autex-Conference, Povoa de Varzim, Portugal 2001, 263-269.

[3] Köckritz U., Franzke G., Leopold T., Offermann P., Nähgewirkte Gelege aus CF-PEEK-Hybridgarn für textilverstärkte Faserverbundrotoren, (in:) Verbundwerkstoffe und Werkstoffverbunde, Wiley-VCH 2001, 44-48.

[4] Langkamp A., Bruchmodebezogene Versagensmodelle von faser- und textilverstärten Verbundwerkstoffen mit polymeren, keramischen sowie metallischen Matrices, Dissertation, TU Dresden 2002.

[5] Baste S., Audoin B., On internal variables in anisotropic damage, European Journal of Mechanics 1991, A/Solids, 10(6), 587-606.

[6] Matzenmiller A., Lubliner J., Taylor R.L., A constitutive model for anisotropic damage in fiber-composites, Mech. Mater. 1995, 20, 2, 125-152.

[7] Puck A., Schürmann H., Failure analysis of FRP laminates by means of physically based phenomenological models, Composite Science and Technology 1998, 58, 1045-1067.

[8] Hufenbach W., Kroll L., Langkamp A., Böhm R., Analysis of failure and damage of braided composite structures under biaxial loading, 1st International Symposium on Mechanics of Composites, Prague 2002, 61-68.

[9] Cuntze R.G., Freund A., The predictive capability of failure mode concept-based strength criteria for multidirectional laminates, Composite Science and Technology 2004, 64 (3-4), 343-377.

[10] Taylor J.I., Back to the basics of rotating machinery vibration analysis, Sound and Vibration 1995, 29(2), 12-16.

[11] Isermann R., Supervision, fault detection and fault-diagnosis methods - An Introduction, Control Engineering Practice 1997, 5(5), 639-652.

[12] Moczulski W., Kostka P., SPIE Discovery challenge data description, Proceedings 2000 SPIE Conference, Orlando, Florida.

[13] Moczulski W., Kostka P., Discovery of knowledge from diagnostic databases, 16th AeroSense Meeting on Aerospace/Defense Sensing, Simulation and Control, Orlando, 1-5.04.2002

Recenzent
Jan Ryszard Dąbrowski