Failure Behaviour of Textile Reinforced Thermoplastic Composites Made of Hybrid Yarns - I: Probabilistically Based Damage Models

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Abstract

The paper presents a probabilistically based damage model for textile reinforced composites in the framework of continuum damage mechanics, where damage is defined as the change of the tensor of elasticity. Damage variables are introduced to describe the evolution of the damage state and subsequently the degradation of the material stiffness. New probabilistic failure criterion considers different composite failure modes as well as further fracture types influenced by the textile reinforcement. Additional questions regarding the experimental and numerical validation are presented in part II of the paper.

1 Introduction

Several studies have shown the numerous advantages of multi-axial textile-reinforced composites with thermoplastic matrix for the use in lightweight structures for automotive and aerospace applications. The limited fundamental knowledge of the material behaviour currently prevents the exploitation of the promising material potential. To overcome those difficulties, multidisciplinary approaches that involve theoretical material modelling as well as numerical strategies and experimental work are essential.

High-tech applications increasingly require the use of load-adapted lightweight materials where the stiffnesses, strengths and crash properties can optionally be adapted to the loading profile. Conventional composite components meet these demands only on a limited scale. In this context, the use of textile reinforced composites with its high flexibility offer important advantages with regard to the adjustment of the material structure to complex loading conditions and component contours.

For the application of textile reinforced composites in safety relevant structural components, reliable predictions about their failure and damage behaviour are currently missing [1, 2]. Here, questions with regard to the damage tolerance, the damage identification including its mechanical description and life cycle prediction are insufficiently investigated and not purposefully conditioned for industrial applications so far [2]. This is the main reason for the well known and often observed discrepancy between theoretical and experimental predictions with regard to the damage behaviour of textile reinforced composites [2, 3]. As a result, the development of trustworthy design strategies and material models taking into account the specific degradation behaviour is indispensable to help the young material class of textile reinforced composites to get accepted in high-tech industries [1, 3].

Reliable material models must realistically consider the gradual failure behaviour and the resulting damage evolution as well as the characteristic scattering in the failure process [4]. Preliminary work shows that the combination of fracture mode related degradation models with probabilistic theories exhibit outstanding approaches [5, 6].

2 Mechanical behaviour of thermoplastic composites made of hybrid yarns

2.1 Matrix system and textile fabrics

The thermoplastic composites used in this study are made of commingled hybrid yarns consisting of reinforcing glass fibres (GF) and polypropylene (PP) filaments. Such hybrid yarns assure that the matrix material is located as close as possible to the reinforcing fibres. Thus, short flow paths during the consolidation process are guaranteed [7]. Another advantage of the commingling process consists in the very good draping behaviour of the hybrid yarn and the resultant textile performs [8]. Within this investigation, woven fabrics[1] and multi-axially reinforced weft knitted fabrics[2] made of GF/PP fibres are used (Fig. 1).
An elementary disadvantage of woven fabrics is the layerwise construction and the absence of reinforcement in the thickness direction of the composite. Thus, woven textile-reinforced composites tend to delaminate, in particular if the composite structure is damaged by impact [9]. In contrast, multi-axially reinforced weft knitted composites are characterised by an additional reinforcement in z-direction. The textile reinforcement combines the advantages of a stitched fibre architecture with craned reinforcing fibres that are included in the stitch. The multi-axially reinforced weft knitted composites feature good impact and crash properties as well as high stiffnesses and strength [10].

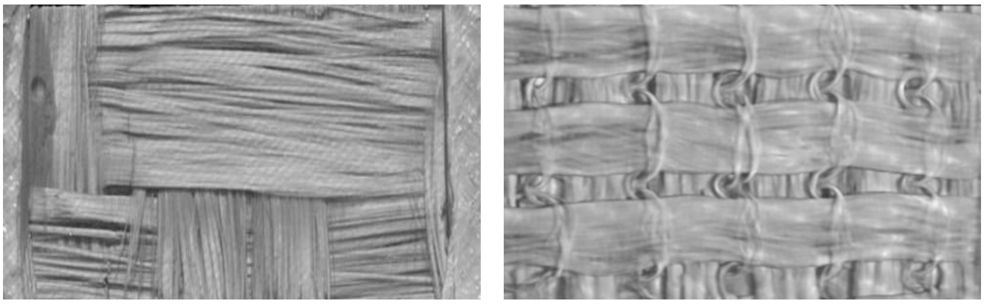


Fig. 1: Computer tomography picture of a woven GF/PP composite (left) and a biaxially reinforced weft knitted GF/PP composite (right) [7]

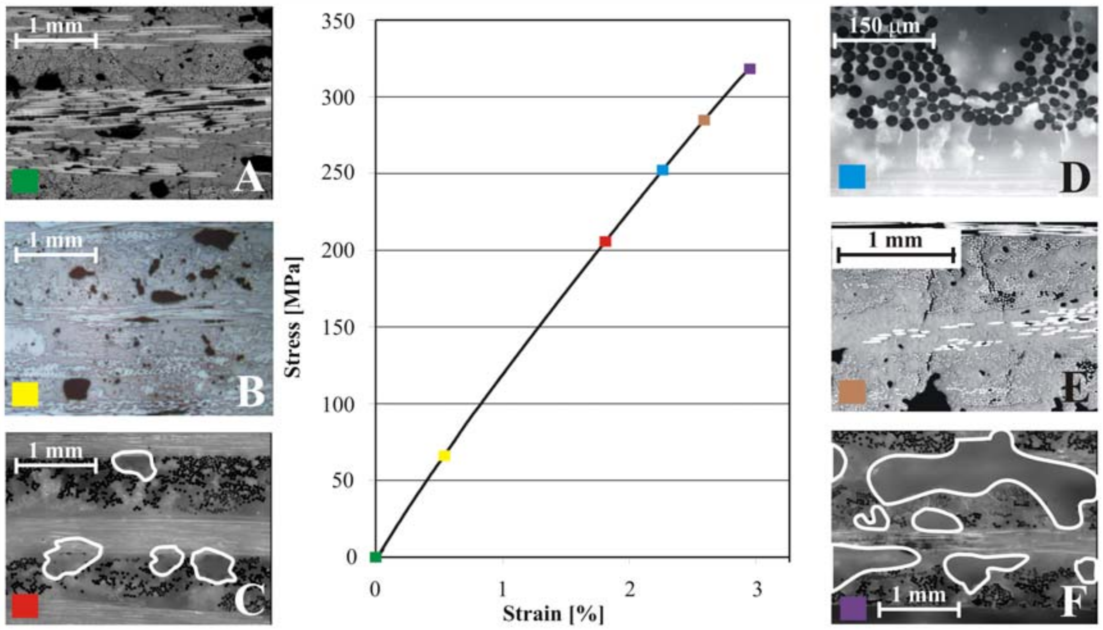
2.2 Phenomenology of failure

Dependent on the specificity of so-called discrete and diffuse damage mechanisms[3], textile reinforced composites could be classified into two damage classes: composites with dominant discrete damage and composites with dominant diffuse damage [11]. In textile composites, discrete and diffuse damage mechanisms always occur in certain characteristic combinations. Diffuse damage mechanisms can be detected in both damage

[1] commercially available by Saint-Gobain Vetrotex International
[2] available from ITB, Faculty of Mechanical Engineering, TU Dresden
[3] *Discrete damage* describes damage processes that can be quantified with justifiable effort on the mesoscale or macroscale. In textile composites discrete damage mechanisms contain fibre failure, inter fibre failure (that can be quantified by the value *crack density*) and delaminations. All damage mechanisms that either exhibit no local character or could not be quantified with justifiable effort are called *diffuse damage mechanisms.* Interface failure, ductile matrix behaviour, void growth or the so-called whitening are counted among this group of damage mechanisms [11].

groups and always appear at first in the loading history. Due to diffuse damage, a critical damage accumulation can arise before discrete damage emerges.

The investigated GF/PP-composites belong to the damage class with dominating diffuse damage. In such composites, no clear separation of the damage mechanisms vs. loading history can be conducted. So, a clear identification of damage phases is not possible. In most cases, multiple damage mechanisms occur simultaneously in different directions. On the macroscale, a noticeable localisation does not appear. As an example fig. 2 shows the correlation of the damage state and the respective stress-strain-level for a woven GF/PP-composite loaded in tension. Here, a continuous change from void formation and void growth to superimposed micro-cracking can be merely identified.



A - Initial voids induced by manufacturing
B - New void formation and void growth
C - Continuous void growth
D - Formation of diffuse micro-cracks
E - Combined occurence of inter fibre failure and voids
F - Exponential void growth on the verge of total failure

Fig. 2: Damage behaviour of composites with dominant diffuse damage – Woven GF/PP-composite loaded in tension (TWINTEX® [0/90//90/0]$_s$)

2.3 Statistical spread within the failure process

Within the scope of this study, all experimental data was statistically analysed. Due to the fuzziness of the prevailing manufacturing parameters, a characteristic statistical spread of the material properties can be observed [11]. Fig. 3 exemplifies the broad scatter of the strength values of a woven GF/PP-composite in the σ_1-τ_{12} stress plane. It becomes obvious that the failure and damage behaviour of this material group can only be adequately characterised by means of probabilistically based damage models.

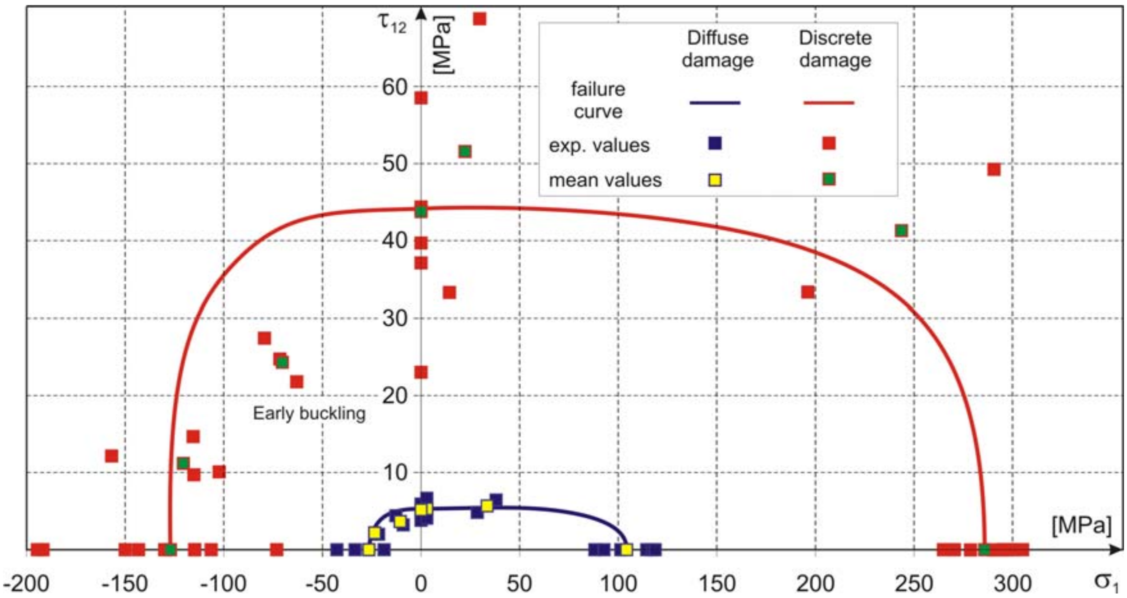


Fig. 3: Characteristical failure curves and related experimental values of a GF/PP-composite (TWINTEX® $[0/0//0/0]_s$) in the σ_1-τ_{12} stress plane [11]

3 Probabilistically based damage models

3.1 Objective and Assumptions

The inner geometry of textile reinforced composites is very complex. Due to this complexity and manufacturing restrictions, a detailed description of arbitrary cracking and statistically distributed void formation seems not very meaningful [5]. Compared to "classical" approaches from statistical damage mechanics [12-17], the aim of the proposed model is to provide a tool for structural engineering. For the novel group of textile reinforced composites, the relevant design variables stiffness and strength will be characterised by means of a probabilistic approach where deterministic failure criteria and damage laws are replaced by probabilistic descriptions.

The so-called „diverge" of the textile reinforced composite into equivalent layers forms the origin for the used mesomechanical description of the degradation process [3, 11]. There, that equivalent layer is best advantageous for the calculation of the degradation behaviour that represents the geometry of the textile reinforcement sufficiently accurate as well as that accommodates the observed damage phenomenology. Dependent on the textile architecture and the damage phenomenology, the different textile composites could be classified into two groups: composites that can be broken up into idealised unidirectional basic layers (i-UD-layer) and composites that must be disentangled into woven balanced basic layers (WB-layer), see Fig. 4.

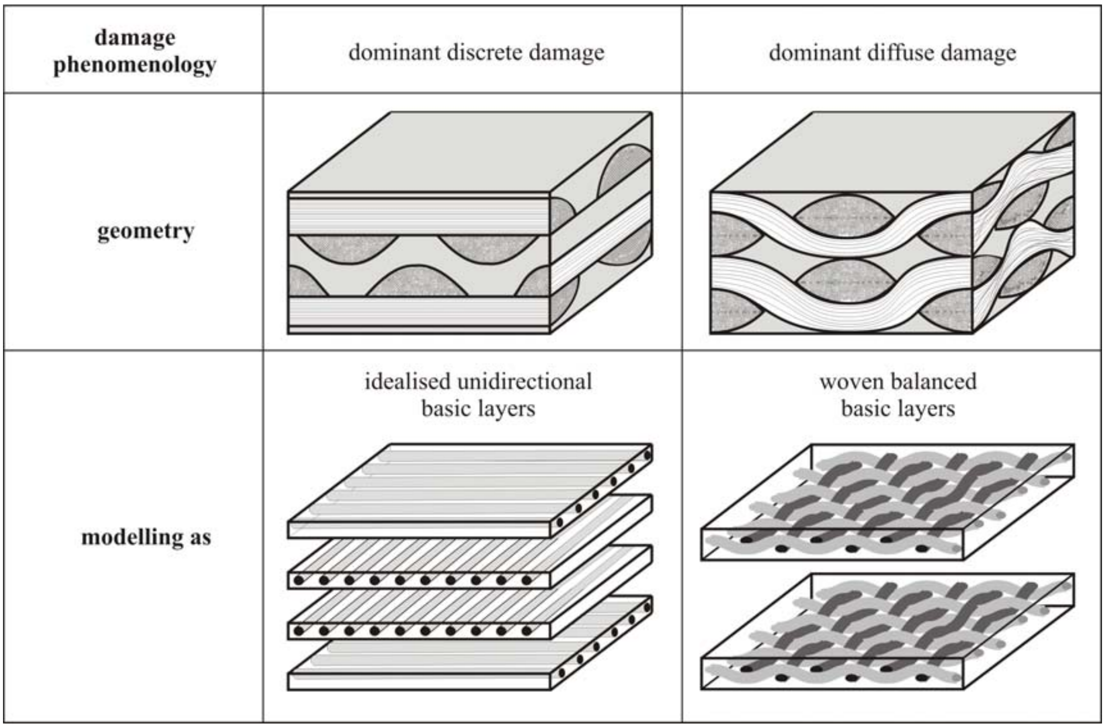


Fig. 4: Diverge of textile composites into equivalent layers depending on textile architecture and damage phenomenology [11]

3.2 Constitutive law for the damaged WB-layer

A suitable damage model without generalising assumptions about microcrack initiation and geometry was suggested by BASTE [18]. The model is valid for the general case of anisotropic damage and, consequently, is also applicable if the principal material axes or even the symmetry class of the woven balanced layer changes during the damage process. The elastic constants of the WB-layer itself are used for the description of the material damage. The origin of the model is the dispartment of the stiffness tensor in

$$\tilde{C}_{ij} = C_{ij}^{0} - \Delta C_{ij} \tag{1}$$

with C_{ij}^{0} as initial stiffness and ΔC_{ij} as the stiffness loss due to damage. The change of the stiffness

$$D_{ij} = \Delta C_{ij} = C_{ij}^{0} - \tilde{C}_{ij} \tag{2}$$

is used as internal damage variable that characterises the particular damage state in the WB-layer. Traditionally, in continuum damage mechanics, the definition of damage variables takes place in such a way that these variables can only reach values between zero in the initial state and one in the completely damaged state [18]. For the perpetuation of this definition and to assure that the stiffness tensor remains positive definite, the damage tensor components D_{ij} must be normalised to their thermodynamically admissible values $D_{ij}^{\lim}$. The normalised components of the damage tensor finally result to

$$D_{ii} = 1 - \frac{\tilde{C}_{ii}}{C_{ii}^{0}} \qquad i = 1,2,\ldots,6 \tag{3}$$

$$D_{ij} = \frac{C_{ij}^{0} - \tilde{C}_{ij}}{C_{ij}^{0} + sgn\left(C_{ij}^{0} - \tilde{C}_{ij}\right)\sqrt{C_{ii}^{0}\left(1 - D_{ii}\right)C_{jj}^{0}\left(1 - D_{jj}\right)}} \qquad i, j = 1,2,...,6; i \neq j. \tag{4}$$

The main advantages of the proposed damage model are the general validity and its purely phenomenological character. Because no assumptions about crack initiation, crack geometry and crack growth are required at all, the damage model is primarily suited for textile composites with dominating diffuse damage. For plane states of stress states, the constitutive law for the damaged WB-layer finally results in

$$\sigma_i = \tilde{Q}_{ij}\varepsilon_j \tag{5}$$

with

$$\tilde{Q}_{11} = \left(1 - D_{11}\right)\frac{E_1}{1 - \nu_{12}\nu_{21}}; \quad \tilde{Q}_{22} = \left(1 - D_{22}\right)\frac{E_2}{1 - \nu_{12}\nu_{21}}$$

$$\tilde{Q}_{66} = \left(1 - D_{66}\right)G_{12}; \quad \tilde{Q}_{12} = \tilde{Q}_{21} = \left(1 - D_{12}\right)\frac{\nu_{21}E_2}{1 - \nu_{12}\nu_{21}} - D_{12}\sqrt{\left(1 - D_{11}\right)\left(1 - D_{22}\right)\frac{E_1E_2}{\left(1 - \nu_{12}\nu_{21}\right)^2}}.$$

There, D_{11} and D_{22} describe the stiffness degradation due to diffuse damage in the principle axis of orthotropy and D_{66} the stiffness degradation due to shear. The additional parameter D_{12} is used to model the influence of damage on the Poisson´s ratio.

3.3 Probabilistic failure criteria

As shown in Fig. 3, the physical nature of the failure process of the investigated GF/PP-composites is stochastical. That means, instead of a deterministic failure effort, a failure probability has to be calculated. In general, the failure probability is defined by the probability that the resistance *R* of the material is lower than the applied stress *S*. The principle correlations are shown in Fig. 5 and are given by:

$$P_f = P\left(R \leq S\right) \tag{6}$$

For the most two-dimensional cases with two independent normal or lognormal distributed variables, the failure probability P_f and a resulting reserve factor β can be calculated analytically [19].

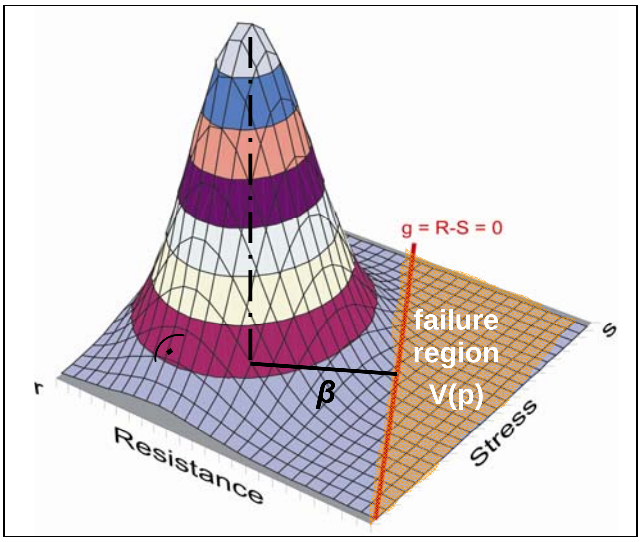


Fig. 5: Two-dimensional visualisation of the failure probability

The calculation of the failure probability for textile reinforced composites is much more complex. The characteristic failure behaviour of such composites is characterised by different fracture modes [20]. Eq. 7 and 8 show the characteristic failure conditions for initiation of diffuse damage and total failure (plane state of stress), respectively as described by BÖHM [11]. In terms of the failure mode concept of CUNTZE, the interaction between the single failure modes are taken into account by the interaction coefficients $\dot{n}$ and $\dot{m}$.

$$H^{\dot{n}} = \left(\frac{\sigma_1^{(+)}}{R_{diff,1}^{(+)}}\right)^{\dot{n}} + \left(\frac{\sigma_1^{(-)}}{R_{diff,1}^{(-)}}\right)^{\dot{n}} + \left(\frac{\sigma_2^{(+)}}{R_{diff,2}^{(+)}}\right)^{\dot{n}} + \left(\frac{\sigma_2^{(-)}}{R_{diff,2}^{(-)}}\right)^{\dot{n}} + \left(\frac{\tau_{12}}{R_{diff,12}}\right)^{\dot{n}} = 1 \quad (7)$$

$$F^{\dot{m}} = \left(\frac{\sigma_1^{(+)}}{R_{disk,1}^{(+)}}\right)^{\dot{m}} + \left(\frac{\sigma_1^{(-)}}{R_{disk,1}^{(-)}}\right)^{\dot{m}} + \left(\frac{\sigma_2^{(+)}}{R_{disk,2}^{(+)}}\right)^{\dot{m}} + \left(\frac{\sigma_2^{(-)}}{R_{disk,2}^{(-)}}\right)^{\dot{m}} + \left(\frac{\tau_{12}}{R_{disk,12}}\right)^{\dot{m}} = 1 \quad (8)$$

Furthermore, the different distribution types for the input values must be considered in the failure probability analysis. The deterministic values of the failure conditions (Eq. 7 and 8) change into stochastically distribution functions. Here, the applied stresses σ are represented by normal distributed stress density functions *f(S)* and the strengths R of the material are realised by Weibull distributed resistance functions *f(R)*. Hence, the deterministic failure conditions H and F transform into the failure probabilities $P_{f,diff}$ and $P_{f,disk}$. By means of the transformation of the deterministic values into nonlinear probability functions, an interaction between the single failure modes automatically appears by a summation of the particular probability functions [22]. Thus, an additional empirical consideration by interaction coefficients (Eq. 7 and 8) can by avoided. Consequently, the probabilities for initiation of diffuse and discrete damage arise from:

$$\begin{aligned} P_{f,diff} &= P_{f,diff}\left(\sigma_1^{(+)} \geq R_{diff,1}^{(+)}\right) + P_{f,diff}\left(\sigma_1^{(-)} \geq R_{diff,1}^{(-)}\right) + P_{f,diff}\left(\sigma_2^{(+)} \geq R_{diff,2}^{(+)}\right) \\ &+ P_{f,diff}\left(\sigma_2^{(-)} \geq R_{diff,2}^{(-)}\right) + P_{f,diff}\left(\tau_{12} \geq R_{diff,12}\right) \end{aligned} \quad (9)$$

$$\begin{aligned} P_{f,disk} &= P_{f,disk}\left(\sigma_1^{(+)} \geq R_{disk,1}^{(+)}\right) + P_{f,disk}\left(\sigma_1^{(-)} \geq R_{disk,1}^{(-)}\right) + P_{f,disk}\left(\sigma_2^{(+)} \geq R_{disk,2}^{(+)}\right) \\ &+ P_{f,disk}\left(\sigma_2^{(-)} \geq R_{disk,2}^{(-)}\right) + P_{f,disk}\left(\tau_{12} \geq R_{disk,12}\right) \end{aligned} \quad (10)$$

In contrast to deterministic failure curves (like Fig. 3), so-called probability failure curves arise from Eq. 10 and 11 (Fig. 6).

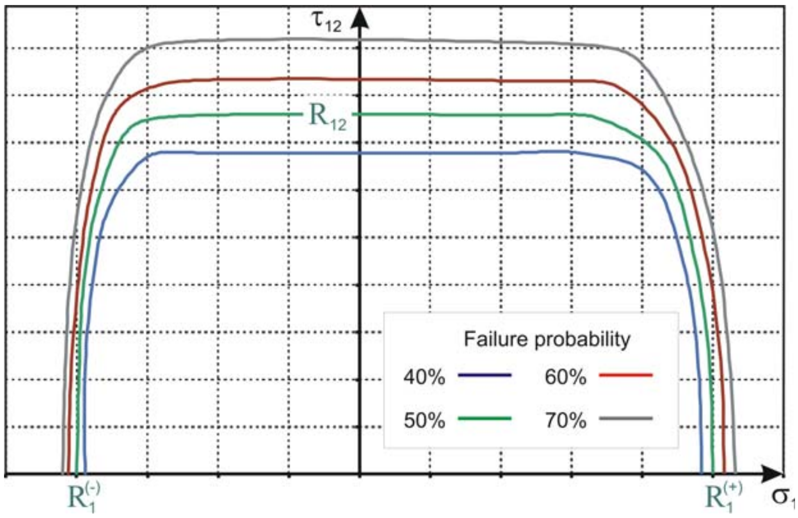


Fig. 6: Theoretical failure probability plot for a WB-layer in the σ_1-τ_{12} stress plane

3.4 Damage evolution laws

The dominant diffuse damage in GF/PP-composites can be generally taken into account by

$$[d_i] = \begin{bmatrix} D_{11} \\ D_{12} \\ D_{22} \\ D_{66} \end{bmatrix} = \begin{cases} [0] & \text{if} \quad \text{no damage} \\ [d_{diff,i}] & \text{if} \quad \text{diffuse damage} \end{cases}. \tag{11}$$

In terms of the continuum damage mechanics concept, it is assumed that the damage parameters exclusively depend on the stress components σ_i in the particular failure mode [11,21]. Moreover, the evolution laws must be able to consider an increase of a single damage parameter as well as the multiple increase of damage parameters. With the criterion for diffuse damage, the evolution laws for the WB-layer arise in

$$d_{diff,i}^{\dot{n}} = \sum_{j} \left(\phi_{diff}^{j} q_{diff,i}^{j}\right)^{\dot{n}}, \quad j = 1\sigma, 1\tau, 2\sigma, 2\tau, 12 \tag{12}$$

or alternatively

$$\begin{aligned} D_{diff,11}^{\dot{n}} &= \left(\phi_{diff}^{1\sigma} q_{diff,11}^{1\sigma}\right)^{\dot{n}} + \left(\phi_{diff}^{1\tau} q_{diff,11}^{1\tau}\right)^{\dot{n}} + \left(\phi_{diff}^{2\sigma} q_{diff,11}^{2\sigma}\right)^{\dot{n}} + \left(\phi_{diff}^{2\tau} q_{diff,11}^{2\tau}\right)^{\dot{n}} + \left(\phi_{diff}^{12} q_{diff,11}^{12}\right)^{\dot{n}}, \\ D_{diff,12}^{\dot{n}} &= \left(\phi_{diff}^{1\sigma} q_{diff,12}^{1\sigma}\right)^{\dot{n}} + \left(\phi_{diff}^{1\tau} q_{diff,12}^{1\tau}\right)^{\dot{n}} + \left(\phi_{diff}^{2\sigma} q_{diff,12}^{2\sigma}\right)^{\dot{n}} + \left(\phi_{diff}^{2\tau} q_{diff,12}^{2\tau}\right)^{\dot{n}} + \left(\phi_{diff}^{12} q_{diff,12}^{12}\right)^{\dot{n}}, \\ D_{diff,22}^{\dot{n}} &= \left(\phi_{diff}^{1\sigma} q_{diff,22}^{1\sigma}\right)^{\dot{n}} + \left(\phi_{diff}^{1\tau} q_{diff,22}^{1\tau}\right)^{\dot{n}} + \left(\phi_{diff}^{2\sigma} q_{diff,22}^{2\sigma}\right)^{\dot{n}} + \left(\phi_{diff}^{2\tau} q_{diff,22}^{2\tau}\right)^{\dot{n}} + \left(\phi_{diff}^{12} q_{diff,22}^{12}\right)^{\dot{n}}, \\ D_{diff,66}^{\dot{n}} &= \left(\phi_{diff}^{1\sigma} q_{diff,66}^{1\sigma}\right)^{\dot{n}} + \left(\phi_{diff}^{1\tau} q_{diff,66}^{1\tau}\right)^{\dot{n}} + \left(\phi_{diff}^{2\sigma} q_{diff,66}^{2\sigma}\right)^{\dot{n}} + \left(\phi_{diff}^{2\tau} q_{diff,66}^{2\tau}\right)^{\dot{n}} + \left(\phi_{diff}^{12} q_{diff,66}^{12}\right)^{\dot{n}}. \end{aligned} \tag{13}$$

The scalar functions ϕ_{diff}^{j} describe the value of a single damage variable $d_{diff,i}$ in the failure mode j. The values $q_{diff,i}^{j}$ consider the coupling in the growth of different damage variables in the failure mode j.

For the evolution function ϕ_{diff}^{j} there are several possible growth laws with a different number of additional material parameters. As described by BÖHM [11], the following two functions are appropriate for textile composites and simple enough for the degradation description:

$$\phi_{diff}^{j} = \begin{cases} 0 & \text{if} \quad \text{no damage} \\ \tanh\left[\beta_j \left(r_j - r_{j0}\right)^{\kappa_j}\right] & \text{if} \quad \text{diffuse damage} \end{cases} \tag{14}$$

$$\phi_{diff}^{j} = \begin{cases} 0 & \text{if} \quad \text{no damage} \\ 1 - \left(\dfrac{1-\eta_j}{1+\beta_j \left(r_j - r_{j0}\right)^{\kappa_j}} + \eta_j\right) & \text{if} \quad \text{diffuse damage} \end{cases} \tag{15}$$

Fig. 7 exemplary shows the effect of the additional material parameters β_j and κ_j in Eq. 15. The run of the curves correspond to the characteristic crack density development in textile composites and can be determined experimentally [11,22]. The parameter β_j can be interpreted as the driving damage growth parameter whereas κ_j is an additional parameter to provide a smooth degradation curve. By means of the value η_j, a remaining stiffness can be modeled (characteristical damage state). The coupling values $q_{diff,i}^{j}$ must be adapted according to biaxial test results.

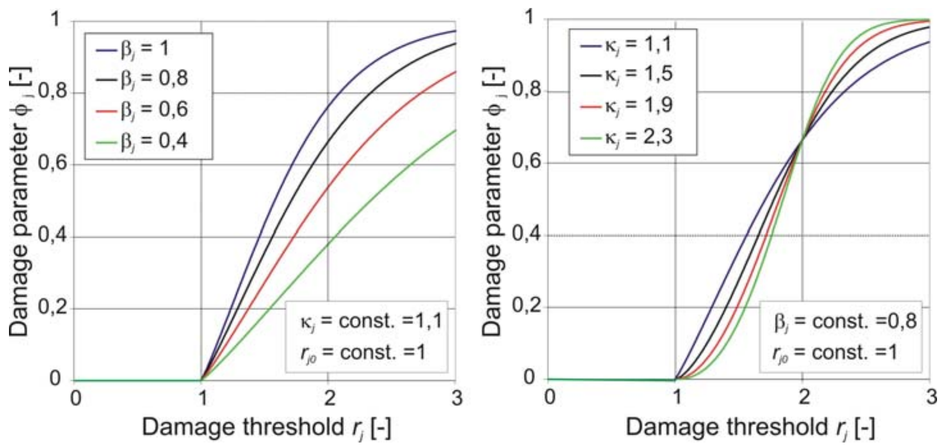


Fig. 7: Effects of the material parameters β_j and κ_j on the damage evolution in mode j

4 Conclusion

Novel probabilistically based damage models have been developed for different classes of textile reinforced composites. The method is based on continuum damage mechanics models and physically based failure criteria. The novel probabilistic damage models allow a reliable prediction of the complex material-specific damage mechanisms and the resultant stiffness degradation and strength reduction. The degradation models provide a very good basis for the calculation of the non-linear material behaviour of the novel group of textile reinforced composites with its high potential for innovations in lightweight engineering. In the field of material adapted design of composite components, an important gap has been closed. In addition, the presented model is well suited as a starting point for an implementation of degradation models into commercial finite-element-codes. For the verification of the developed degradation model, extensive experimental and numerical studies have been performed, which are presented in part II of the paper.

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