Failure behaviour of textile reinforced thermoplastic composites made of hybrid yarns -
II: Experimental and numerical studies

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Abstract

A novel probabilistically based damage model for textile reinforced composites that was developed in part I of this study is validated by experimental and numerical methods.
A clear identification of the particular damage entities in combination with a determination of the corresponding stress-strain-curves is an essential condition for the model validation. Different experimental approaches for that purpose are presented in this paper. The generated experimental data is used to determine the uncertain stiffness and strength properties for woven and weft knitted thermoplastic composites. The results are additionally used to perform numerical studies with respect to failure probability and damage propagation.

1 Introduction

Textile reinforced composites offer significant advantages for industrial high-performance applications. Because the material characterisation forms the origin of structural simulations, the formulation of material laws and failure criteria are of major importance for the design of such composite structures. The latest developments in the sector of technical textiles enable the design of load adapted reinforcements for different composite structures of complex shape [1]. By means of the novel group of the textile reinforced composites, innovative complex components with multi-axial or even three-dimensional variable-axial fibre reinforcement can be realised [2]. However, such textile reinforced composite structures are used rather conservatively in engineering praxis and are often oversized due to the lack of verified material models and damage criteria [1, 3]. Only the consideration of the degradation behaviour after the occurrence of first damage entities enables the full utilisation of such composites [3]. The necessary material models have to reproduce the statistically dominated failure and damage mechanisms as well as the resulting anisotropic degradation behaviour in a realistic way [4, 5].
The verification of degradation models is often one of the main difficulties because no single experimental method alone is suitable for their complete validation [3, 6]. Therefore, the concept of a problem-related experimental and numerical verification strategy is tracked here. This strategy contains the combination of different direct and indirect experimental methods for the damage analysis of glass fibre reinforced polypropylene (GF/PP) composites. Among the focused techniques are classical multi-axial test methods with flat samples and tube specimens, ultrasonic measurements for the direct determination of the stiffness degradation and microscopic analysis for identification of the damage mechanisms on the micro scale [3]. In addition, these methods have been completed by numerical investigations.

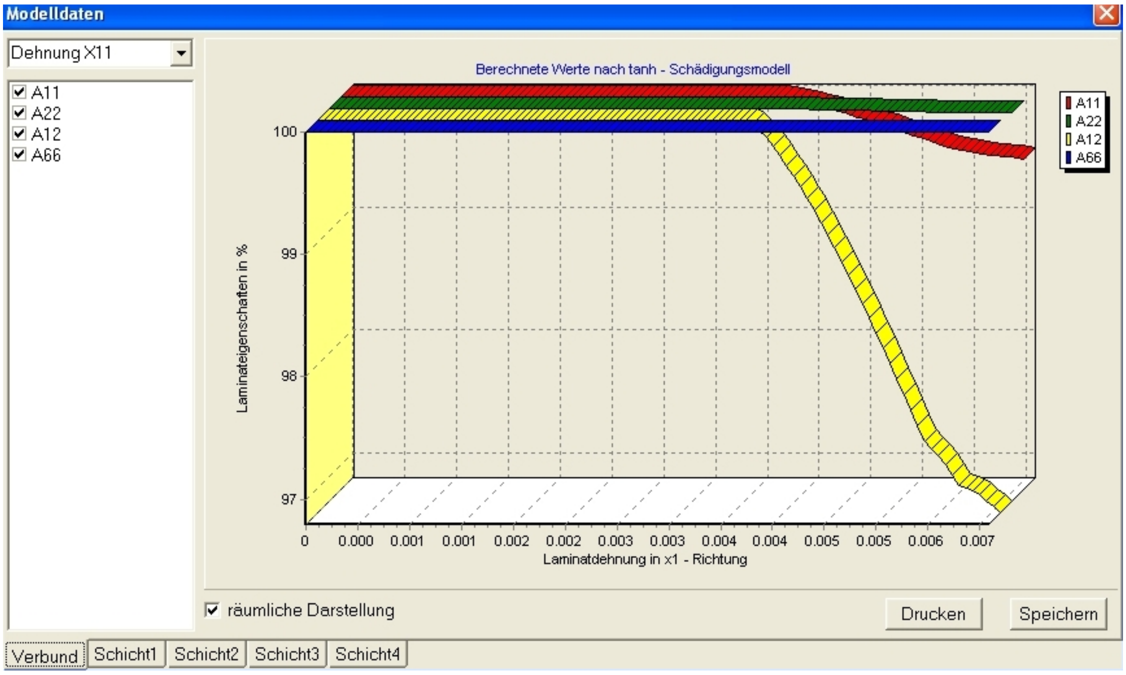
2 Probabilistically based damage models

2.1 Degradation analysis of GF/PP composites

The virtual diverge of the textile reinforced composites into so-called idealised unidirectional or woven balanced basic layers forms the origin for the calculation of the degradation behaviour of GF/PP composites [3, 7]. Then, the definition of suitable damage tensors for composites with dominating diffuse damage allows the mechanical description of the deformation of the damaged textile basic layers. The initiation of diffuse and discrete damage has been characterised by means of especially modified probabilistic failure criteria [7]. For the coverage of the gradual damage progress, fracture mode related evolution laws have been formulated. They enable the recording of the degradation of single stiffness components as well as a coupled degradation of multiple stiffness values. Thus, the novel models enable a calculation of failure probabilities as well as the analysis of the specific stiffness and strengths degradation of GF/PP composites.

2.2 Development of a software tool for an efficient degradation analysis

For parameter identification and model validation, the developed models have been implemented into an easily manageable and a modular built computer programme [3]. By using the programming language C++, an independent Windows compatible programme with a graphical user interface has been elaborated. The operation of fast mathematics libraries secures a performance of pure mathematical programmes.



Dehnung X11

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Fig. 1: Output mask of the developed software tool [3]

The programme allows a direct graphical analysis of stress-strain-curves and degradation curves of the significant stiffnesses as well as a tabular output of these values (Fig. 1). For a direct comparison of experimental data and theoretical predictions, an import of experimental curves is possible via an interface. Thereby, a layerwise degradation analysis as well as an analysis of composite properties can be performed. The severed storage of layer stresses and strains, layer stiffnesses, damage parameters and damage thresholds on the one hand and composite stresses, strains and stiffnesses on the other hand enables flexible and efficient parameter studies dependent on the existing experimental data.

3 Experimental validation

Due to the complex damage phenomenology in textile reinforced composites and the connected high number of material parameters, alongside with the considerably higher experimental effort the necessity for the development of continuative test methods is given [3]. Because no single experimental method alone suits for a full model verification, different direct and indirect experimental methods are coupled here synergetically.

3.1 Fracture tests with material adapted test methods

To verify the damage models experimentally, it is necessary to develop adapted test techniques that enable a targeted multi-axial application of load [8]. This is why test procedures for tension/compression torsional tests (T/C-T tests) and compression-internal pressure tests (C-p tests) on GF/PP tube specimens were devised to enable strength investigations in the (σ_1, σ_2, τ_{21}) stress space to be conducted.

In the T/C-T tests, the failure-critical stress combination along a prescribed path of loading was realised with the aid of a further developed load-controlled multi-axial test machine with an adapted elongation-twisting extensometer. The extensometer allows the elongation and the distortion to be recorded as well as the successive course of failure.

The tests carried out on the tube specimens serve, on the one hand, to determine fracture stresses as well as the associated fracture phenomena, and, on the other hand, to characterise the elementary fracture types. The large amount of information that the T/C-T test supplies permits initial fundamental physical fracture phenomena to be explained.

In order to analyse the failure behaviour of GF/PP composites under combined tension/compression loading, a compression-internal pressure test apparatus was developed [8]. The tensile stress is applied by internal pressure, while the axial pressure force induces the compressive stress. Within these tests, it is analysed, how far the fracture modes mutually influence the brittle tensile fracture and compressive instability failure.

3.2 Ultrasonic-based determination of stiffness degradation

In anisotropic media, the phase velocity of ultrasonic waves travelling through the material depends on the direction of propagation and the corresponding stiffness [9]. Based on this dependency, the stiffness constants can be obtained by running time measurements [3, 10, 11]. Neglecting any body forces and damping effects, an eigenvalue problem arises

$$(C_{ijkl} n_j n_l - \rho V^2 \delta_{ik}) p_i = 0 . \tag{1}$$

Here, V is the phase velocity of the wave, n_j and n_l are two components of the unit vector describing the propagation direction of the wave and δ_{ik} is the Kronecker symbol. With $\Gamma_{ik} \equiv C_{ijkl} n_j n_l$, eq. (1) can be written in the form:

$$\det(\Gamma_{ik} - \rho V^2 \delta_{ik}) = 0 . \tag{2}$$

Solving the inverse problem of Eq. (2) leads to the unknown stiffness tensor components C_{ijkl} [11]. Therefore, a set of experimentally determined velocity data in distinct directions n is needed. These phase velocity measurements are realized using an immersion technique.

In each of the examination planes (Fig. 2), the phase velocities are determined by measuring the change of running time between emitter and receiver of a pulse with and without specimen and for a range of angles. Consequently, a set of velocity data of quasi-longitudinal (QL) and quasi-transversal (QT) wave modes is obtained.

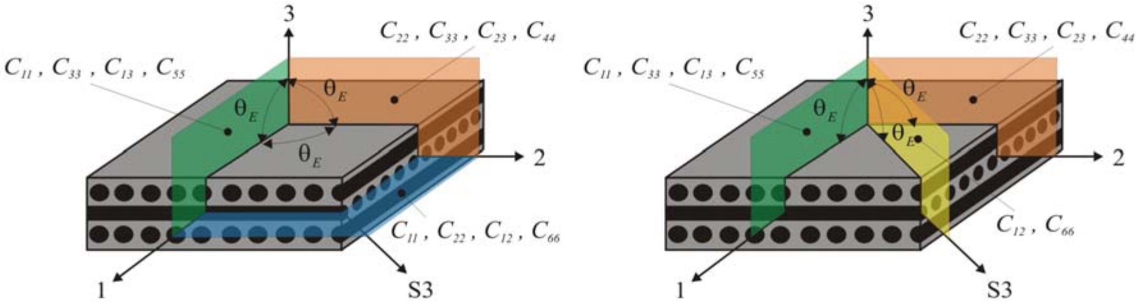

Fig. 2 Stiffness recovery by means of measurements in the planes of symmetry (left), stiffness recovery if in-plane measurements are not possible (right) [3, 11]

From this data, the associated stiffness values are calculated performing a Levenberg-Marquard optimisation procedure. Experimental data points and the optimised velocity profile can be visualised in polar diagrams (Fig. 3). Generally, the velocity level of an undamaged sample is higher than the velocity level of a damaged sample. Thus, the reduction of stiffness can be measured directly.

3.3 Micrograph analysis

Particularly the detection of diffuse damage phenomena requires a detailed investigation of the micro-structure of damaged textile composites by means of micrograph analysis. Therefore, multiple test series have been performed where specimen with identical configuration (geometry, lay-up, loading history) have been loaded gradual up to a certain load level. Subsequently, micrograph pictures have been produced from the pre-damaged specimens that document the specific damage state. The micrograph pictures have been analysed using the reflected-light microscopy. If the micrograph pictures are opposed with the respective stress-strain-curves, exact information about the initiation and the progress of diffuse and discrete damage mechanisms are possible (Fig. 4).

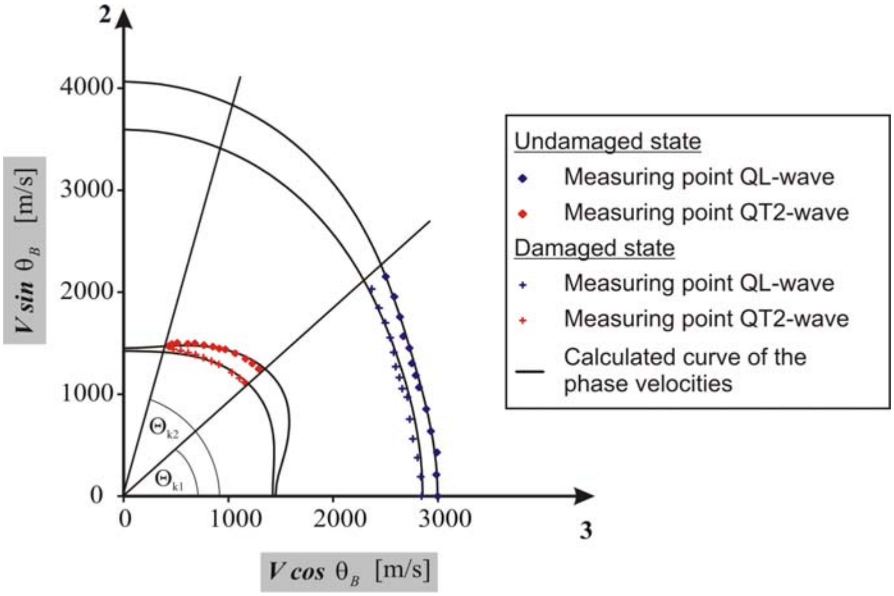

Fig. 3 Experimental velocity values and optimised velocity profiles for a damaged and an undamaged GF/PP specimen [3]

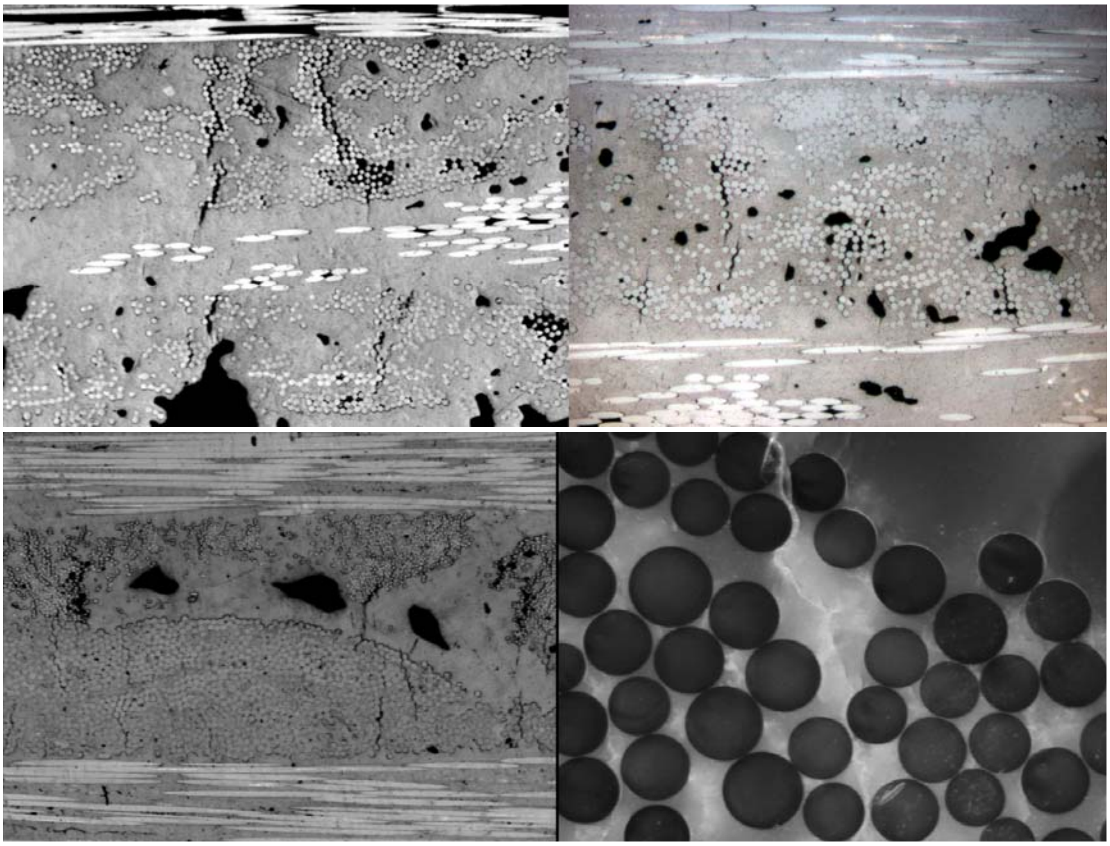

Fig. 4: Damage state of a weft knitted GF/PP composite at $\sigma = 280$ MPa (top); state of a woven GF/PP composite at $\sigma = 250$ MPa (bottom)

4 Numerical validation

For a constitutive description of the correlation of the characteristic damage phenomena and the scatter in the material behaviour of GF/PP composites, the presented damage approach was methodically verified in a substantial numerical parameter study.
Initial point of the damage initiation and progress in the numerical simulation is the conversion of the present distribution of the material parameter into statistically defined parameter functions. Thereby, the real occurring material varieties (like voids or local cracks) are numerically included.
On the basis of the experimentally determined density functions for the elastic parameters and the strengths (Fig. 5), the theoretical expected material parameters for the numerical validation has been estimated and included in a finite element model.

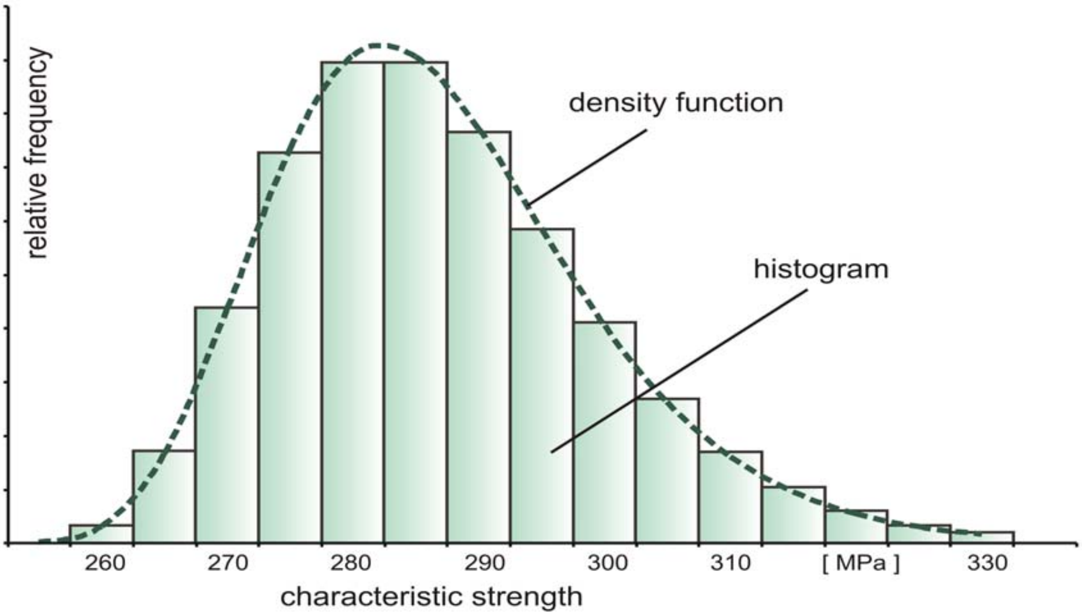

Fig. 5: Density function of the tensile strengths of woven GF/PP composites

The significant probabilistic estimation of the degradation behaviour has been carried out in numerical studies. Opposite to a sharp failure prediction, this probabilistic approach admits the estimation of the failure probability dependent on the load increase (Fig. 6).

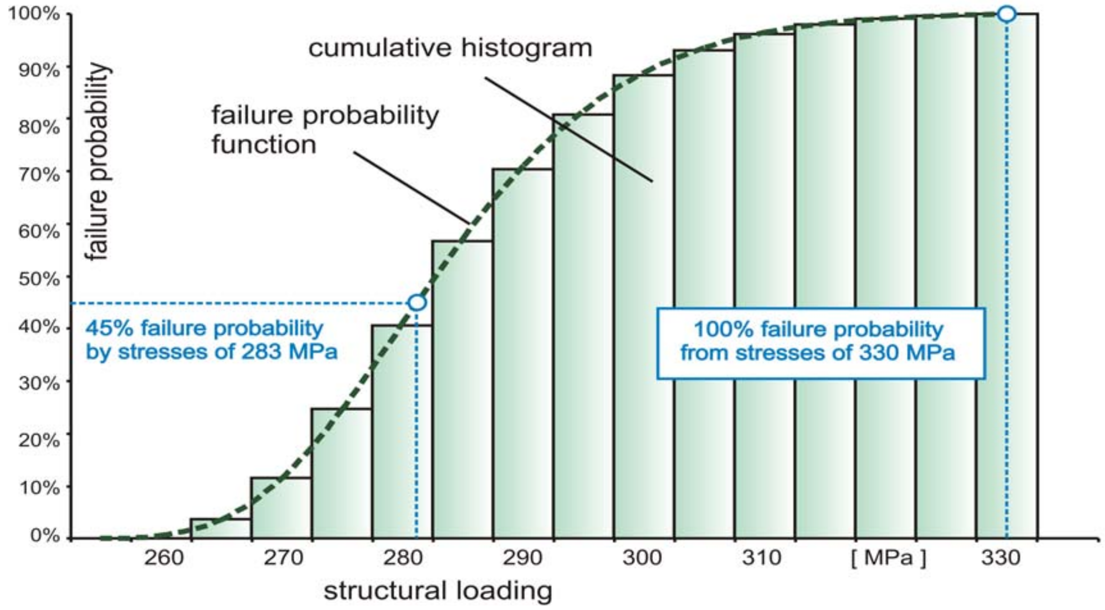

Fig. 6: Failure probability vs. load increase for woven GF/PP composites loaded in tension

The numerical consideration of the real existing statistically distributed damage entities admits a methodical investigation of the influence of the parameter distribution on the characteristic damage and failure phenomenology. Fig. 7 and Fig. 8 show the influence of the parameter distribution on the characteristic degradation progress for a uniaxially loaded tension specimen made of GF/PP unidirectional layers.

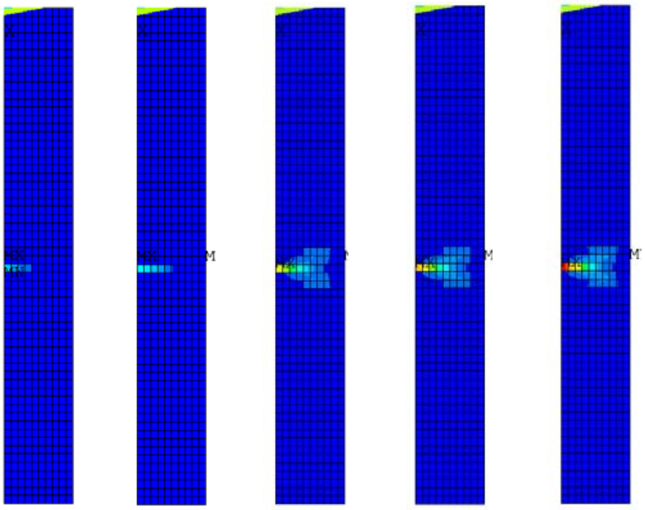

Fig. 7: Degradation progress of a GF/PP UD tensile specimen with locally marginal distributed parameters

The numerical specimens with locally marginal distributed strengths normally fail brittle and just in consequence of the first occurring damage events. The crack path is typically perpendicular to the present tensile stresses.

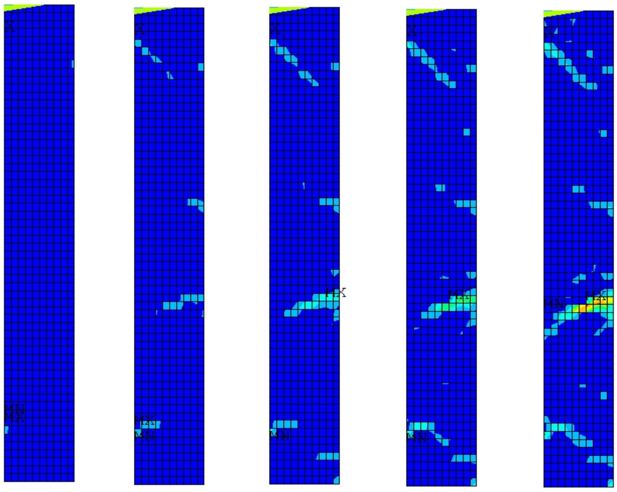

Fig. 8: Degradation progress of a GF/PP UD tensile specimen with strongly distributed parameters

The simulation of specimen with a strong distribution of the strengths shows a more ductile failure behaviour. The degradation progress is oriented on the local distinct weak material parameters of the composites.

A basic compilation of the influence of the parameter distribution on the failure behaviour of woven GF/PP composites can also be validated (Fig. 9).

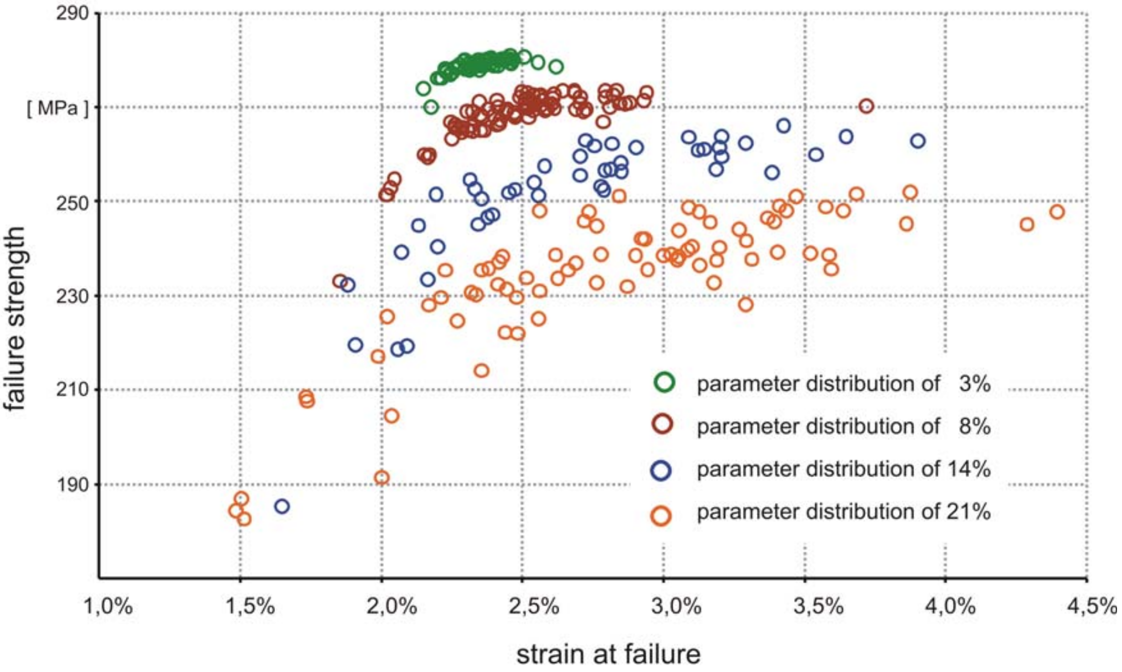

Fig. 9: Influence of the parameter distribution on the failure behaviour of GF/PP UD composites

The numerical validation on the basis of a probabilistic failure model shows the versatile applicability for a methodical consideration of damage influence on the material properties. With the presented probabilistic model, a robust prediction of the simulated failure probability for textile reinforced composites is possible.

5 Conclusion

For a full exploitation of the specific advantages of textile reinforced composite materials, the development of reliable material adapted design concepts is mandatory. For that purpose, material models have been developed that consider different fracture modes as well as the anisotropic damage behaviour taking into account the possible scatter of material data. These novel models provide a basis for a practice-orientated simulation of complexly loaded composite components.

Based on the presented problem-adapted verification strategy, a broad database has been generated which has been used for parameter identification and mode validation. For that purpose, a specially developed software tool was used that also allows efficient parameter studies and sensitivity analysis for a weighting of the different model parameters. Therewith, material cards can be generated for the typical representatives of GF/PP composites which are essential input values for later structural simulations. The presented degradation models can be used on the one hand for a damage tolerant design of textile reinforced components. On the other hand, they contribute for the inclusion of degradation phenomena into future design strategies.

Acknowledgement

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