# PROBABILISTIC SIMULATION FOR FAILURE ANALYSIS OF TEXTILE-REINFORCED COMPOSITES

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## Abstract

*Textile-reinforced thermoplastic composites offer huge application potentials for a rapid manufacturing of high performance lightweight components. Particularly with regard to the application for safety-relevant structural components, a reliable prediction of the textile-immanent complex failure behaviour is required. For that purpose a lot of physical-based design concepts have been developed on the basis of representive deterministic material parameters. On the other hand, a quantification of the reliability of such approaches is still missing.*

*Due to their complex textile structure, composite materials manifest a distinctive material uncertainty. Thus, a consideration of the material property distributions is required. By using Monte Carlo simulations, a deterministic failure model can be combined the stochastic material data. Based on the experimentally determined distribution functions for each failure mode, the characteristic strength values for the probabilistic simulation are calculated. As a result of the probabilistic simulation, a reliable prediction of the failure probability for defined stress states is possible.*

## 1 Introduction

Due to the high variability of the textile structure and the very good mechanical properties, composite materials are increasingly important for the development of high performance lightweight structures. Much progress in the development of mechanical material models for composite materials has been made in the last years. Today, even complex mechanical problems, like the degradation behaviour due to damage, the behaviour under highly dynamic loading or fatigue can be discribed by phenomenological models [1-8].

To transfer the new material into applications, the failure analysis must carried out with respect to the ultimate strength of the material. Until today, a safety concept is used that has been derived from isotropic materials. To consider the material-specific uncertainties, this concept was modified by a global safety factor. This leads to a oversizing of the textile structures. First studies have presented that stochastical approaches enable a better use of the high lightweight potential of textile composites [9-12].

The presented analysis starts with a elaborate statistical material characterization for novel hybrid yarn textile thermoplastic-(HYTT)-composites. In addition with the already established deterministic failure mode concept, a probabilistic failure formulation can be deduced and verified by experimental and numerical analysis. As a significant result of the study, a material-adapted and statistically verified design concept for textile-reinforced composites is available.

## 2 Multi-axially reinforced textiles made of commingled yarns

Within this investigation, novel HYTT-composites made of commingled hybrid yarns consisting of reinforcing glass fibres (GF) and a thermoplastic polypropylene (PP) matrix are used. These commingled hybrid yarns have a high potential for a homogeneous distribution of reinforcement and matrix filaments within the yarn cross section. The desired ratio of fibre to matrix can be achieved by variation of the number of filaments during the yarn production.

The focus within the probabilistic investigation was set on multi-layered flat bed weft knitted fabrics (MKF), which have been developed by the Institute of Textile Machinery and High Performance Material Technology of the Technische Universität Dresden [13]. Figure 1 shows the basic architecture of the MKF-composite. While woven fabrics show a high crimp, the flat bed weft knitted fabrics are characterised by a stretched fibre arrangement, which leads to very good in-plane stiffnesses and strengths. Additionally, the knit thread offers a reinforcement in z-direction, which significantly improves the delamination behaviour of the composite.

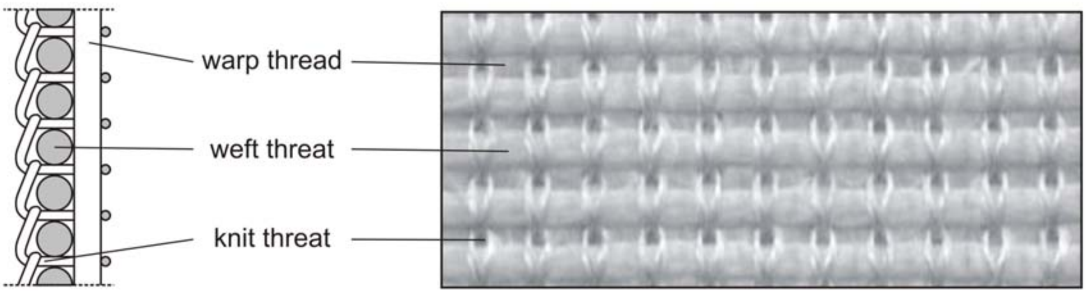


**Figure 1.** Basic architecture of multi-layered flat bed weft knitted fabrics (MKF)

## 3 Statistical material characterisation

The statistically verified material characterisation is carried out by means of uniaxial and multiaxial tests on flat specimens and tube specimens. To ensure the essential reliability of the experimental results, the test setup was chosen following the standardised materil characterisation. The tests were carried out on the universal testing machine *Zwick Z250* with a temperature chamber. The force- and moment detection was realised by a load measuring box. The strain data was determined by the optical 3D mesurement system *PONTOS*. For the probabilistic investigation, four layers of multi-axial knitted fabrics (MKF) have been stacked and manufactured to plates with press technology. For the characterisation of the direction-dependent material properties, elastic constants and strengths were statistically analysed.

### *3.1 Elastic properties*

The elastic properties shows the expected symmetric distribution. The material specific uncertainties (e.g. local scattering fibre volume fraction, voids or fibre ondulations) do not mutually influence each other, so that the uncertainties can be superposed. This typical effect results in a discription with a Gaussian distribution. Figure 2 shows the symmetric distribution of the in-plane shear modulus $G_{12}$ and the Young's modulus in weft direction $E_1$.

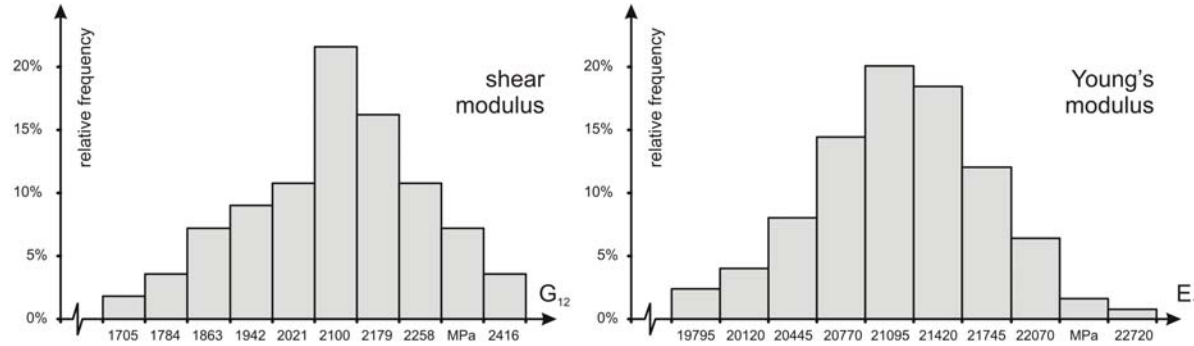


**Figure 2.** Histogram for the elastic properties of the MKF-composite

As a result, the statistical model parameters are presented in Table 1.

**Table 1** Statistical model parameters of the elastic properties

| material parameter | $E_1$ | $E_2$ | $G_{12}$ |
|---|---|---|---|
| sample size | 57 | 56 | 51 |
| characteristic value | $\mu$ = 21085 | $\mu$ = 19165 | $\mu$ = 1839 |
| parameter scatter | $\sigma$ = 499.99 | $\sigma$ = 422.47 | $\sigma$ = 33.26 |
| distribution category | Gaussian | Gaussian | Gaussian |

### *3.1 Strength parameters*

First studies have shown that the distribution category depends on the fracture behaviour of the actual failure mode [9]. Particularly the brittle fracture behaviour in fibre direction leads to an extremal value distribution based on the model of the weakest chain link by WEIBULL or the fibre bundle model by DANIELS. The shear failure behaviour on the other hand is dominated by the thermoplastic matrix material. That causes into a symmetric distribution comparable to the elastic properties. In Figure 3, the characteristic distribution of the parameters is exemplarly visualised for the shear strengths $R_{12}$ and the tensile strengths $R_1$.

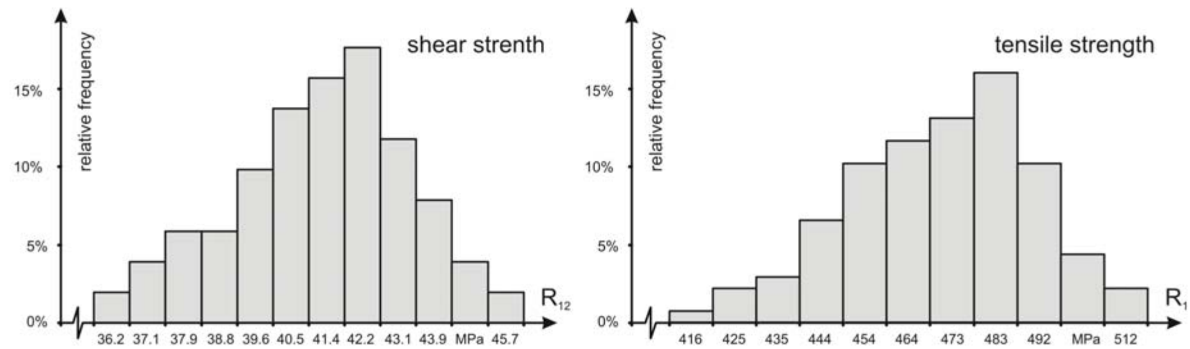


**Figure 3.** Histogram for the shear strength and tensile strength of the MKF-composite

On the experimental basis, the characteristic distribution functions and density functions were identified. In Table 2, the resulted statistical model parameters for the direction-dependent strength parameters of the GF/PP-MKF-composite are summarised.

**Table 2** Statistical model parameters of the strength values

| material parameter | $R_1$ | $R_2$ | $R_{12}$ |
|---|---|---|---|
| sample size | 57 | 56 | 51 |
| characteristic value | $\alpha$ = 428.8 | $\alpha$ = 479.1 | $\mu$ = 3.747 |
| parameter scatter | $\beta$ = 26.8 | $\beta$ = 25.7 | $\sigma$ = 0.0187 |
| distribution category | Weibull | Weibull | Lognormal |

The statistically evaluation of the experimental data shows very clearly that a probabilistic model for the description of the failure behaviour is needed to include the inherent material uncertainties.

## 4 Probabilistic simulation of the failure behaviour

Phenomenological deterministic failure models prevailed for the engeneering design of composites. Based on such deterministic approaches, an evaluation of the stochastical accuracy and reliability for the calculated results is not possible. For a probabilistic analysis, the Monte Carlo method was used here. Thereby, the uncertain experimental material data was combined with the deterministic failure mode concept of CUNTZE. Figure 4 shows the schematic workflow for the probabilistic Monte Carlo simulation.

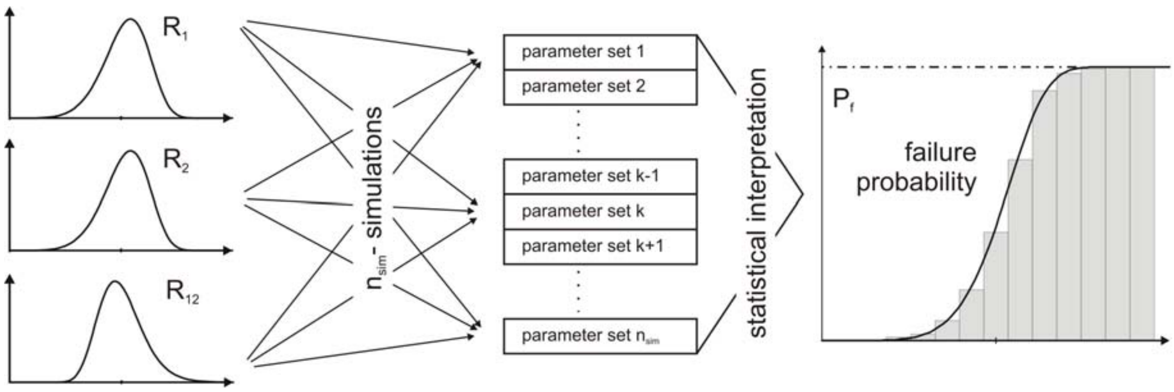


**Figure 4.** Schematic sequence of a Monte Carlo simulation

Accordingly, a probable strength value based on the distribution parameters in Table 4 will be estimated and the critical failure stress will be calculated by the following failure criterion for bi-directional reinforced composites [5].

$$F^m = \left(\frac{\sigma_1^{(+)}}{R_1^{(+)}}\right)^m + \left(\frac{\sigma_1^{(-)}}{R_1^{(-)}}\right)^m + \left(\frac{\sigma_2^{(+)}}{R_2^{(+)}}\right)^m + \left(\frac{\sigma_2^{(-)}}{R_2^{(-)}}\right)^m + \left(\frac{\sigma_{12}}{R_{12}}\right)^m = 1$$

Based on the law of large numbers, the frequency of the simulated failure events moves towards the failure probability $P_f$ with the accumulative number of the failure events $n_f$ and the total number of simulations $n_{sim}$.

$$P_f = \frac{1}{n_{sim}} \sum_{k=1}^{n_{sim}} P(F=1) = \frac{n_f}{n_{sim}}$$

The distribution of the material-specific mode interaction coefficient m cannot be measured directly and is approximated by a simple Gaussian distribution function. Figure 5 shows all numerical estimated failure events for the GF/PP-MKF-composite. The failure curves for defined probability levels can be derived from a subsequent statistic analysis of the simulation results.

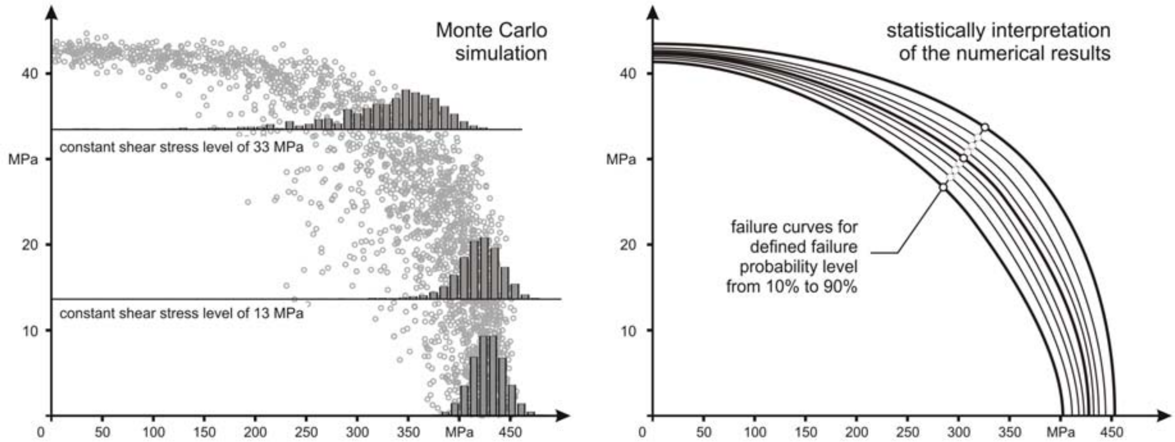


**Figure 5.** Schematic sequence of a Monte Carlo simulation

On that basis, a probabilistic prediction of the failure probability for HYTT-composites is possible. Furthermore, the Monte Carlo simulation enables virtual tests to identify sensivities of the uncertain material parameters.

## 4 Conclusions

For the application of textile-reinforced components in security-relevant structures, material adapted design strategies based on stochastic methods are required. Based on an experimantal statistically verified material characterisation, a probabilistic formulation of the uncertain direction-dependent failure behaviour was presented. With a probabilistic Monte Carlo simulation and an established deterministic failure criterion the failure probability analysis can be numerically executed. The statistical interpretation of the results enables a prediction of the uncertain failure probability.

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