AN ANISOTROPIC DAMAGE MODEL FOR THE PREDICTION OF THE DEGRADATION BEHAVIOUR OF NOVEL TEXTILE REINFORCED COMPOSITES

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Summary Novel textile reinforced composites are very suitable for applications in lightweight structures, since they can resist high mechanical and thermal load. In this paper a phenomenological damage-mechanics-based model for these 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. Special emphasis is given to the interaction between fibre failure due to fibre stress and matrix failure due to transverse and shear stress. The predictive capability of the presented model is evaluated by carrying out a series of tensile tests using acoustic emission techniques to detect the strength and the failure behaviour of CF/PEEK, GF/RP and CF/RP. The performance of the model strongly depends on the correct determination of the material parameters. Thus, model parameters may be determined either by experimental measurement, by micromechanical models or by crack density studies.

INTRODUCTION

The optimum utilisation of special multi-axial textile reinforcement, in particular, could make a significant contribution to developments of highly innovative lightweight structures, which will be of great interest not only from a scientific-technical, but also from an economic point of view. The component optimisation requires adapted analytical and numerical simulation techniques as well as suitable realistic failure criteria which take into account the occurring damage mechanisms. Composite failure conditions have to cover the full failure behaviour, fracture conditions and the non-linear analysis of the degradation behaviour within the composite. Though, in recent years first investigation has been undertaken to determine the damage mechanisms and the degradation behaviour of textile reinforced composites. MATZENMILLER et al. [1] proposed a model, based on continuum damage mechanics, for the non-linear analysis of fiber composites. LANGKAMP [2] proposed a method that enables the use of physically based failure criteria for the description of the initial fracture of textile-reinforced composites. The phenomenological failure model [2] and the degradation model [1] are combined to describe the degradation behaviour of braided composites, of glass-fibre reinforced multi-layered composites and of multi-layered carbon fibre reinforced PEEK [3]. However, the performance of all these models strongly depends on the correct determination of the introduced damage parameters. On this account, special emphasis in this work is given to the experimental observation of stiffness loss and crack initiation.

PHENOMENOLOGICAL ASPECTS OF DAMAGE IN TEXTILE COMPOSITES

In recent years, novel textile reinforcements, composed of multi-axial reinforcing layers have been developed (Fig. 1). The reinforcing yarn systems provide a high composite strength and stiffness as well as a very good impact behaviour of the composite material.

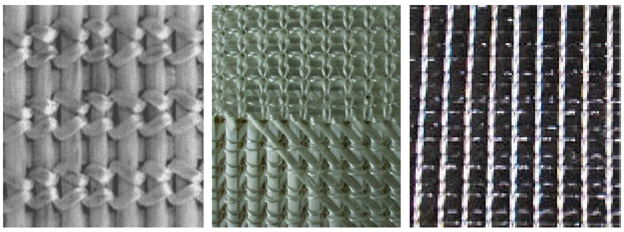

Fig. 1: Different textile preforms for composite applications

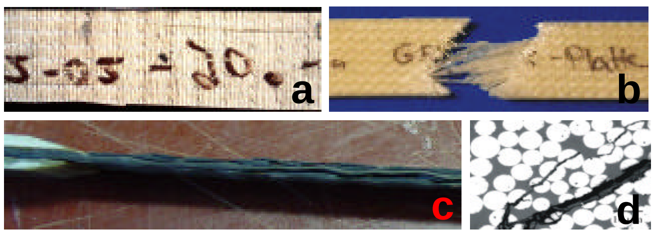

Fig. 2: Experimentally observed failure modes in textile reinforced composites

Due to the complexity of the geometry and the fracture mechanisms of these heterogeneous textile reinforced composites, a convenient structural failure analysis causes extensive difficulties, since the micro-structural configuration is of vital importance for the description of the degradation behaviour. It becomes apparent that a successful damage analysis initially requires a phenomenological determination of all occurring damage mechanisms. Although matrix micro-cracking (Fig. 2a) is normally not the most important failure mode of a textile composite structure, it can trigger fibre failure (Fig. 2b), delamination (Fig. 2c) or compressive failure (Fig. 2d), which is far more important in practical cases.

FAILURE CRITERIA

In order to formulate physically based fracture conditions, different fracture modes, namely „fibre failure“ (FF) and „inter-fibre failure“ (IFF), have to be distinguished. On the basis of the assumption that fracture is determined by the stresses of the fracture plane, the proposed criterion records the failure modes FF and IFF by different failure conditions, which take into account only the acting stresses in the fracture plane. It is assumed that FF is solely initiated by the fibre-parallel stress $\sigma_1^{\pm}$ and remains unaffected by other stresses that occur:

$$\left(\frac{\sigma_1}{\gamma_{\parallel}^{(\pm)} R_{\parallel}^{(\pm)}}\right)^2 = 1.$$

The fracture conditions for IFF are, in comparison to the FF criterion, clearly more complex as different types of failure such as adhesive failure of the fibre-matrix interface or cohesive failure of the matrix as well as different failure modes such as tension, longitudinal shear and cross-sectional shear failure need to be realistically described. The failure initially occurs parallel to the fibres in a plane variable with the fracture angle θ_B. The associated failure criterion then results in the following general formulation

$$\max_{\theta} F(\sigma_n, \tau_{nt}, \tau_{n1}) = 1.$$

DAMAGE MECHANICS MODEL

The stress-strain response of textile reinforced composites is known to be non-linear especially for shearing. However, linear elasticity is assumed to hold if the damage state does not change. All non-linear effects are attributed to damage. The microscopic damage phenomena are represented by internal damage variables (D_{11}, D_{22}, D_s) 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. In this case, plane stress conditions (CLT) are assumed adequate to model the stress-strain behaviour of the textile composite:

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

The proposed failure criteria act as damage threshold for the damage mechanics model. Since the different physical nature of the degradation parameters is clear (D_{11} as degradation parameter due to fibre damage, D_{22} as degradation parameter due to matrix cracking and D_s as the shear degradation parameter), it is possible to determine the damage evolutions laws experimentally.

EXPERIMENTAL INVESTIGATION AND RESULTS

The phenomenological method consists of measuring the internal structural changes by their effects on the mechanical response. Since direct measurement of damage in textile composites is not feasible, an adapted acoustic emission (AE) technique is used to classify and qualitatively analyse the occurring damage mechanisms. The capability of acoustic emission analysis to determine matrix micro-cracking, fibre failure and fibre-matrix debonding will be shown. Additionally, the change of the effective elastic constants has been measured using long-range strain-twist extensometers. The experimentally measured curves have been approximated by the stress-strain curve resulting from the failure calculation. Examples of the predictions of the proposed model will be given.

CONCLUSIONS

The demand for a high degree of lightweight design is, for scientific and technical interests, increasingly becoming the focus of design efforts in the development of a new generation of textile reinforced structural components. Currently, in the sense of developing practical composite failure conditions, endeavours have not only focused on a realistic description of the initial failure but also on the non-linear analysis of novel textile reinforced composites. The proposed results are of the greatest practical significance for innovative developments in high-performance lightweight applications.

References

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