INVESTIGATION OF THE DAMAGE BEHAVIOUR OF NOVEL BIAXIAL REINFORCED WEFT KNITTED COMPOSITES

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ABSTRACT

Textile composites are suitable for applications in lightweight structures, since they provide an assessable composite strength and stiffness. Furthermore, the textile preforms offer a high drapability as well as a good impact behaviour of the composite material. Novel textile reinforcement systems such as unique biaxial reinforced weft knitted fabrics are composed of biaxial reinforcing layers that are held together by a 3D-stitching yarn system. Reinforcing yarns, e. g. glass fibres or carbon fibres can be used within all yarn systems.

Especially the failure behaviour and the phenomenology of damage of those new textile reinforced composites have been barely investigated so far. In this paper, the damage behaviour of the biaxial reinforced weft knitted composites is studied based on experimental measurements. The failure modes and the resulting degradation of the mechanical properties are evaluated by carrying out a series of tensile tests using acoustic emission techniques to detect the crack distribution of $[0/90]_s$ and $[+45/-45]_s$ GF/EP composites. Subsequently, a phenomenological plane stress damage mechanics based model for these composites has been developed. 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 performance of the model strongly depends on the correct determination of the material parameters. Thus, the damage parameters and their evolution laws are determined having regard to the performed experimental crack density studies. By means of micromechanical models, the reduced stiffness properties of the damaged $[0/90]_s$ composites can be found depending explicitly on the crack densities of the damaged layers. The results of the theoretical damage model show good agreements compared to the experimental test data and provide a useful framework for further development of the proof of design of highly loaded structures made of textile reinforced composites.

1 INTRODUCTION

During the last years, an increased use of textile reinforced, high performance composites is observed. The material combines low weight and a high strength with a good impact behaviour, which makes it ideal for the use in the automotive or aerospace industry, in particular. 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 design process of textile reinforced composite components requires adapted analytical and numerical simulation techniques as well as suitable realistic failure criteria which take into account the occurring damage mechanisms. Such composite failure conditions have to cover the full failure behaviour, fracture conditions and the non-linear analysis of the degradation behaviour. Though, in recent years first investigation has been undertaken to determine the damage mechanisms and the degradation behaviour of textile reinforced composites. The various models differ, however, in their formulation of the failure criteria and in their representation of damage in the form of appropriate damage variables. These models are either based on the principals of continuum damage mechanics, on micromechanics or on physically based failure criteria. LANGKAMP [1] developed a method that enables the use of physically based failure criteria of PUCK [2] and CUNTZE [3] for the description of the initial fracture of textile-reinforced composites.

MATZENMILLER et al. [4] proposed a model, based on continuum damage mechanics, for the non-linear analysis of fibre composites. The phenomenological failure model [1] and the adapted degradation model [4] are combined by HUFENBACH et al. [5] to describe the degradation behaviour of textile reinforced composites. Based on numerous experimental studies [6], the predictive capability of this method is shown for multi-layered carbon fibre reinforced PEEK [5]. Micromechanical studies allow the determination of the effective elastic properties of a cracked structure. But they are based on the assumption of a given distribution of cracks and a simple composite geometry. For $[0/90]_s$ fibre composites, KASHTALYAN et. al. [7] determine the effective elastic moduli depending on crack density parameters. The micro-mechanical approach requires that the microscopic mechanisms of degradation are all identified and the geometry and the distribution of cracks are simple and regular.
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 as well as to their mechanical description.

2 BIAXIAL REINFORCED WEFT KNITTED 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-axle loading conditions. A special group of textile area-measured material are the knitted fabrics, whereas it will be differentiated between warp knitted fabrics and weft knitted fabrics (Fig. 1). Knitted fabrics exhibit the best drape behaviour of all textile fabrics, but because of the twisting structure only very lox fibre-volume contents and clearly lower stiffnesses and strengths can be achieved in comparison to composites reinforced with woven fabrics, so that the conventional knitted fabrics are not suited as preforms for high-performance composites. To increase the stiffness of knitted fabrics, warp knitted fabrics and weft knitted fabrics could be reinforced with weft threads [8]. So called biaxial reinforced weft knitted fabrics, which were developed at the Institute of Textile and Clothing Technology at the University of Technology Dresden, are a unique development in the field of textile technology. In contrast to woven fabrics, in knitted fabrics these reinforcing filaments are lying roughly craned in the textile preform, so that the stiffnesses and strengths characteristics in these textile composite are frequently exceeding the stiffnesses and strengths of composites reinforced by woven fabrics.

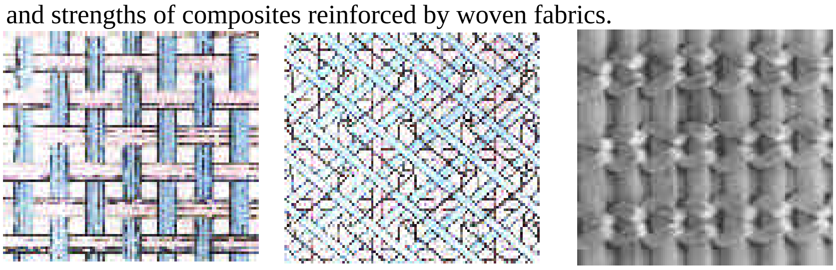

Fig. 1: braided/woven fabric; warp knitted fabric; weft knitted fabric

3 PHENOMENOLOGICAL ASPECTS OF DAMAGE IN BIAXIAL REINFORCED WEFT KNITTED COMPOSITES

3.1 Failure modes

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.

Matrix cracking has been recognised as the first observed damage mode. Its presence mainly causes the stiffness reduction of the textile composite. Because it does not necessarily result in an catastrophic failure, matrix cracking is normally not the most important failure mode. But it can trigger fibre failure or delamination, which is far more important in practical cases.

Subjected to tensile loading, three different modes of matrix cracking could be observed in $[0/90]_s$ composites, transverse cracking in the 90°-layer, splitting in the 0°-layer and debonding of the 3D stitching yarns (Fig. 2)

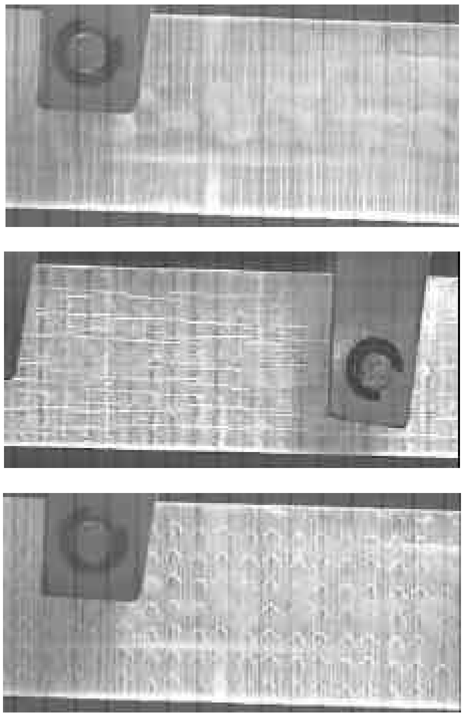

Fig. 2: Matrix cracking failure modes: transverse cracking, splitting and debonding of the stitching yarns

3.2 Crack Density Studies

To describe the degradation of the elastic properties depending on the crack initiation and the crack propagation, respectively, experimental crack density studies have been performed. Therefore, $[0/90]_s$ and $[\pm 45]_s$ textile composites are loaded in tensile direction and the tensile test is observed by a high-speed camera. Subsequently, the reduced elastic properties of the $[0/90]_s$ composites could be compared with the reduced moduli predicted by the micromechanical degradation model of KASHTALYAN et. al. [7]. Based on the experimental and analytical crack density studies on such composites, conclusions regarding the determination of damage parameters of more complex composites could be drawn.

3.3 Tensile tests and acoustic emission analysis

The proposed phenomenological method of damage detection consists of measuring the internal structural changes by their effects on the mechanical response. Since direct measurement of damage in textile composites is not always possible, an adapted acoustic emission 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 is used to find cross connections between the occurrence of matrix cracks and the acoustic emission data. Additionally, the change of the effective elastic constants has been measured using long-range strain-twist extensometers.

4 DAMAGE MECHANICS MODEL

4.1 General assumptions

The damage behaviour of the biaxial reinforced weft knitted composites will be described with a continuum damage mechanics based model and adapts the work of MATZENMILLER et al. [3] to textile composites. This model is feasible under the following assumptions:

- The textile composite can be recomposed by idealised uni-directional (i-UD)-layers or woven balanced (WB)-layers, respectively, as equivalent single layers [1].
- All damage modes are experimentally separable, well known and could be considered in a sufficiently accurate manner by using physically based failure criteria [1-3]
- All nonlineaer 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 [5]. The analysis described below is conducted layer-wise having regard to the real textile structure by the use equvalent layers. The failure criteria act as a set of boundary conditions (damage threshold) for the damage mechanics model.

4.2 Non-linear stress-strain relationsship

The stress-strain response of most 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. 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 scale of the equivalent layer. The unknown damage variables are treated as phenomenological variables, since they have no direct relation to the micromechanical phenomena. In this case, the damaged or effective material stiffness matrix, which is a function of the undamaged elastic constants and the damage state can be written as:

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

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.

4.3 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 in textile composites [1, 6]. 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 $\boldsymbol{s}_1^{\pm}$ and remains unaffected by other stresses that occur:

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

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 q_{B}. The associated failure criterion according to the criterion of PUCK then results in the following general formulation

$$\max_{q} F\left(s_{n}, t_{nt}, t_{n1}\right) = 1.$$

4.4 Damage growth laws

Numerous models with various damage evolution laws for fibre composites are proposed in the literature, e.g. [4, 5]. 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. Based on the performed crack density studies, it is an appropriate approach to determine the damage evolution laws experimentally, instead of deducing them from thermodynamic potentials.

5 RESULTS

Uniaxial tensile tests have been performed at the ILK with [0/90/90/0], [90/0/0/90] and [45/-45/-45/45] biaxial weft knitted composites with to record the non-linear stress-strain-curve, the crack densities of the several layers and the acoustic emission data. Thus, conclusions could be drawn between the accurate experimental measured damage phenomenology and the acoustic emission data, on the one hand, and the experimentally measurable elastic moduli reduction, respectively (Fig. 3). A comparison between the experimental measured and the theoretically predicted degradation of the elastic moduli shows good agreements (Fig. 4). Subsequently, these crack density curves act as input data for the damage evolution laws of the proposed damage model.

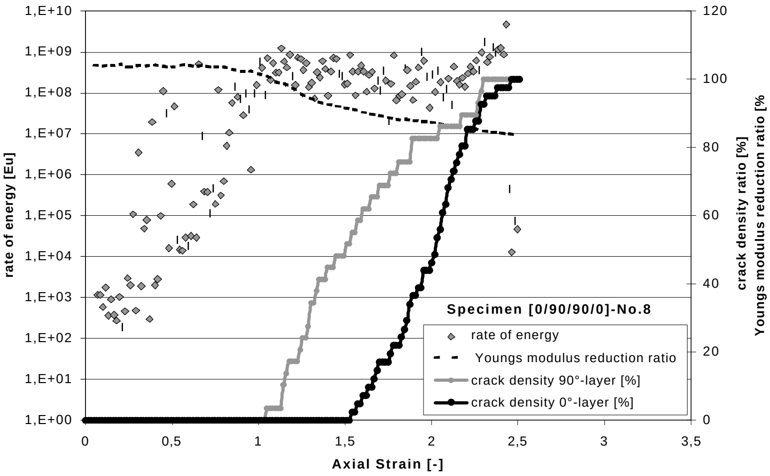

Fig. 3: Experimental data: Youngs modulus reduction, crack densities and acoustic emission data as a function of axial strain

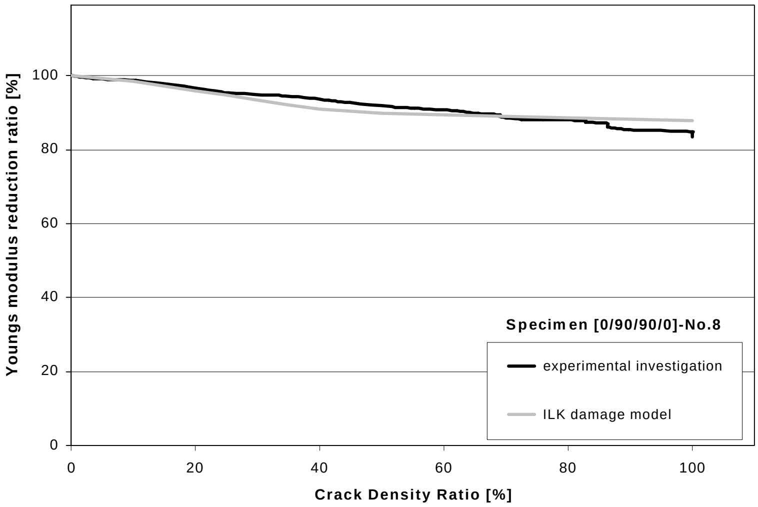

Fig. 4: Crack density studies: experimental and theoretical elastic moduli reduction

6 CONCLUSIONS

The demand for a high degree of lightweight design is 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 failure analysis of novel textile reinforced composites. The proposed results are of the great practical significance for innovative developments in high-performance lightweight applications.

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