STRENGTH OF UD-LAMINATES DEPENDING ON THE FIBER VOLUME CONTENT: EXPERIMENTAL TESTS AND MODELLING

Siegfried Galkin[1] and Luise Kärger[2]

[1]Karlsruhe Institute of Technology (KIT), Institute of Vehicle System Technology (FAST), Department of Lightweight Technology, Rintheimer Querallee 2, Karlsruhe, Germany
Email: siegfried.galkin@kit.edu, Web Page: https://www.fast.kit.edu/lbt/
[2]Karlsruhe Institute of Technology (KIT), Institute of Vehicle System Technology (FAST), Department of Lightweight Technology, Rintheimer Querallee 2, Karlsruhe, Germany
Email: luise.kaerger@kit.edu, Web Page: https://www.fast.kit.edu/lbt/

Keywords: strength of laminates, fiber volume content, failure criteria, digital image correlation, non-linear behavior, off-axis tension, off-axis compression

Abstract

To determine the influence of the fiber volume content on the transverse strength and the shear strength, UD laminates with three different fiber volume contents were manufactured. For each fiber volume content, UD and off axis coupons for tension and compression were tested. To evaluate the resulting strength, the knowledge of the true strain is necessary. Therefore, digital image correlation was used to capture the strain field. Since off axis coupons tend to in plane bending due to coupling between membrane and bending behavior, the rigid body motion and additional fiber rotation was taken into account to get the true strain. To model the structural response of the composite, a constitutive model is used, which describes the nonlinear behavior in fiber and transverse direction up to failure. Additionally, a failure criterion is presented that considers the strength depending on the fiber volume content and defines the failure initiation of the lamina. The experimental results of different fiber volume contents are compared with the modelling results. In this context, also experimental limitations like fiber kinking due to off axis compression are considered and discussed.

1. Introduction

Continuous fiber-reinforced polymers (CoFRP) are ideal lightweight materials and have high weight-specific stiffness and strength. Full potential of such materials is achieved, if the load is transferred directly into the fibers. However, depending on the geometrical complexity of composite parts, the fibers cannot always be aligned in loading direction. Therefore, the load is transferred transverse to the fiber, where stiffness and strength are much lower as in fiber direction. The knowledge of the maximum load capabilities are essential to avoid abrupt inter fiber failure. One of the main advantages of FRPs is the wide possibility to adapt the mechanical behavior by the fiber volume content. Stiffness and strength in fiber direction can be tailored to the specific load case. For tension load cases in fiber direction, the stiffness and strength of the composite can be calculated by utilizing Voigt rule of mixture. For all other load cases, the stiffness can be estimated by advanced rules of mixture. In contrast to the stiffness, the strength is difficult to estimate for different fiber volume contents. The lack of information regarding the strength transverse to the fibers limits the applicability of commonly used failure criteria to determine the correct point of failure. Therefore, the potential of composite materials cannot fully be employed. New experimental tests and numerical models are needed to be able to predict the strength transverse to the fiber for different fiber volume contents. In addition, the influence of fiber parallel stresses must be considered to determine the failure envelope for a specific fiber volume content.

2. Experimental setup

2.1. Samples manufacturing and preparation

A unidirectional carbon fiber non-crimp fabric (UD-NCF) of the type PX35 from Zoltek was used for samples manufacturing. The PX35 fabric has a pre-applied powder binder and 50 K rovings, which are fixed in place with a polyester stitching yarn. The target areal weight is 330 g/m². As resin Sika Biresin CR170 and Biresin CH150-3 hardener ware used which is a fast curing resin system and typicaly used in the high pressure resin transfer molding (HP-RTM) process. After manufacturing the laminates, the sheets were tempered at 140°C for 4 hours. Different fiber volume contents were adjusted by changing either the number of plies in the laminate or by changing the thickness of the laminate. The resulting fiber volume content is calculated via equation 1 where n_L is the number of plies, m_w is the areal weigth of the fabric, ρ_f is the density of the fibers and t the thickness of the laminate. A summary of the manufactured laminates with different fiber volume contents is given in Table 1. All samples were cut by water jet cutting. Each specimen has GFRP cap strips to prevent stress concentrations in the clamping support.

$$\varphi = \frac{n_L m_w}{\rho_f t} \tag{1}$$

Table 1. Manufactured laminates with different fiber volume contents.

Number of plies n_L (-)	Laminate thickness t (mm)	Fiber volume content φ (%)
12	4.3	51
12	4.0	55
14	4.2	61

2.2. Strain field measurement

To track the strain field a speckle pattern was applied to the specimen. The strain field was monitored along the front side and along the thickness of the sample. To capture the strain field two cameras were used. The strain field was calculated via digital image correlation by using MATLAB. Applying a quad mesh to the tracked points and by using the displacement of each correlation point the deformation gradient $\boldsymbol{F}$ is calculated (cf. equation 2).

$$\boldsymbol{F} = \boldsymbol{R}\boldsymbol{U} \tag{2}$$

The deformation gradient is needed to distinguish between the rigid body motion $\boldsymbol{R}$ from the stretch $\boldsymbol{U}$ of the strain field, which is used to calculate Hencky strain or logarithmic strain. Especially if off-axis tension or off-axis compression tests are performed the rigid body motion due to the coupling of the shear stresses with normal stresses occur and need to be eliminated. The logarithm of the stretch tensor $\boldsymbol{U}$ defines the Hencky strain (cf. equation 3). Using the deformation gradient allows also calculating true stresses from the technical stresses, which are necessary for a validation of simulation results. Another advantage of the deformation gradient is the knowledge of the fiber rotation that is crucial to know to model FRPs more precisely. If the initial fiber orientation is defined by a vector $\vec{v}_0 = (1\ 0\ 0)^T$, the deformed fiber orientation is determined via equation 4.

$$\boldsymbol{\varepsilon} = \ln(\boldsymbol{U}) \tag{3}$$

$$\vec{\boldsymbol{v}}_{new} = \boldsymbol{F}\vec{\boldsymbol{v}}_{\boldsymbol{0}} \tag{4}$$

Additionally the perpendicular axis to the fiber orientation can also experience a rotation. Since the deformed axes define the framework of the strain, they need to be considered to be able to calculate the true stress.

2.3. Experimental plan

To evaluate the strength at different fiber volume contents and to be able to determine a fiber volume dependent failure criterion for FRPs tension and compression tests were performed. A summary of the test program is given in Table 2. All tests were performed at a strain rate of $\dot{\varepsilon} = 10^{-4}$. For compression tests the free length of the specimen were varied between 15mm (UD-90°) and 50mm (off-axis 10°). To keep the strain rate constant the traverse speed was adapted to the new free length.

Table 2. Performed test program.

Fiber volume content φ (%)	Load direction	Fiber loading angle (°)
51, 55, 61	tension + compression	90
	compression	50
	compression	20
	compression	10
	tension	75
	tension	45
	tension	30

3. Definition of a fiber volume content dependent failure criterion

Predicting failure was a major part of the World-Wide-Failure I and II exercise [1,2]. It was concluded that besides others the Puck failure criterion [3] for inter fiber failure can predict the failure of FRPs sufficient enough. This criterion defines the failure in three modes: mode A for transverse tension $\sigma_2 \geq 0$, mode B for transverse compression $\sigma_{22} < 0$ and $0 \leq |\sigma_{22}/\tau_{12}| \leq R_{\perp\perp}^{A}/|\tau_{12_c}|$, mode C for transverse compression $\sigma_{22} < 0$ and $0 \leq |\tau_{12}/\sigma_{22}| \leq |\tau_{12_c}|/R_{\perp\perp}^{A}$, where $R_{\perp\perp}^{A}$ is the fracture resistance of an action-plane action parallel to the fiber direction against its fracture due to $\tau_{\perp\perp}$ stressing acting on it and τ_{12_c} determines the stress for $\sigma_{22} = R_{\perp\perp}^{A}$. In the present work, the failure criterion of Puck (cf. equation 5) is extended by fiber volume content dependent strengths.

$$\begin{aligned}
&\sqrt{\left(\frac{\tau_{12}}{S_{12}(\varphi)}\right)^2 + \left(1 - p_{\perp||}^{(+)}(\varphi)\frac{Y_T(\varphi)}{S_{12}(\varphi)}\right)^2\left(\frac{\sigma_2}{Y_T(\varphi)}\right)^2} + p_{\perp||}^{(+)}(\varphi)\frac{\sigma_2}{S_{12}(\varphi)} = 1, \quad &Mode\ A\\
&\frac{1}{S_{12}(\varphi)}\left(\sqrt{\tau_{12}^2 + \left(p_{\perp||}^{(-)}(\varphi)\sigma_{22}\right)^2} + p_{\perp||}^{(-)}(\varphi)\sigma_{22}\right) = 1, \quad &Mode\ B\\
&\left(\left(\frac{\tau_{12}}{2\left(1 + p_{\perp\perp}^{(-)}(\varphi)\right)S_{12}(\varphi)}\right)^2 + \left(\frac{\sigma_{22}}{Y_C(\varphi)}\right)^2\right)\frac{Y_C(\varphi)}{(-\sigma_{22})} = 1, \quad &Mode\ C
\end{aligned} \tag{5}$$

The inclination parameters $p_{\perp||}^{(+)}$ and $p_{\perp||}^{(-)}$ are assumed to be equal to achieve a smooth transition between tension and compression failure envelope. A visualization of the extension of the proposed failure criterion is exemplarily given in Figure 1.

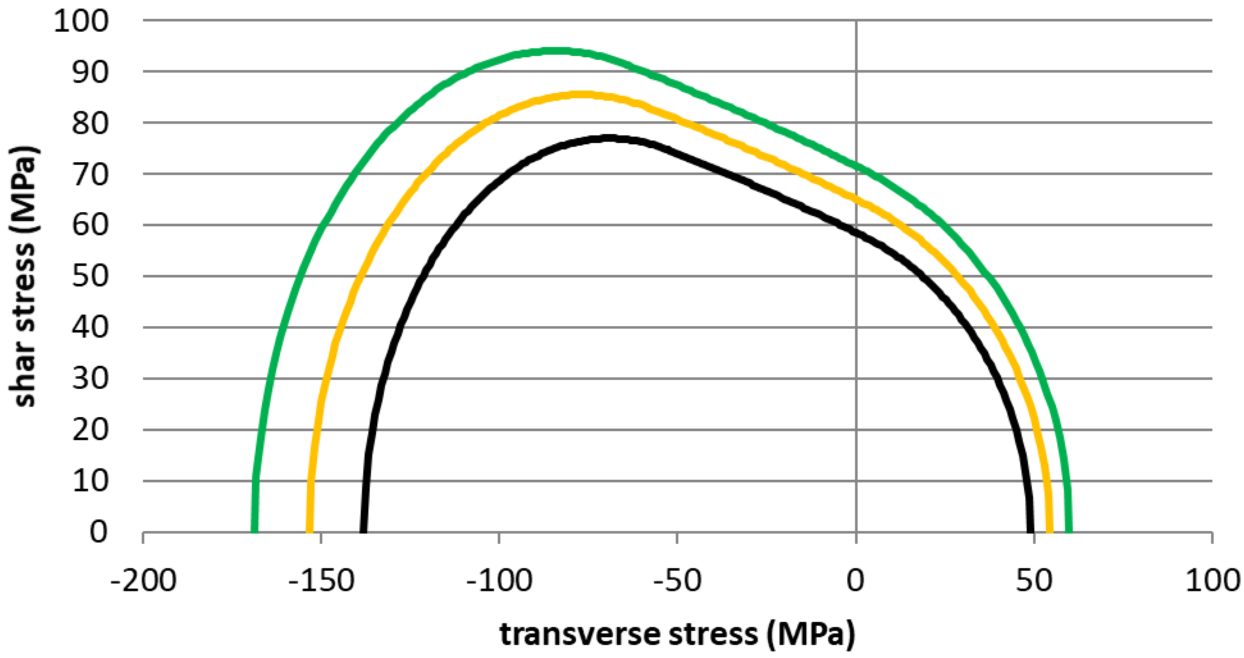

Figure 1. Exemplarily fiber volume content dependent failure criterion for inter fiber failure (green = high fiber volume content, black = low fiber volume content)

4. Numerical and experimental results

4.1. Experimental results

The resulting strengths for different fiber volume contents were evaluated. For all tests, the stiffness increases from lower to higher fiber volume contents. For uniaxial stress states such as UD-90 tension or compression a fiber volume content dependence could be observed for compression tests. The strength at UD-90 compression tests varies between 158 MPa at 51% fiber volume content to 190 MPa at 61% fiber volume content. This corresponds to an increase of 20% in strength from lower to higher fiber volume contents. On the oder hand for UD-90 tension tests the strength didn't increase as the compression tests. However, the scatter for tension tests has increased significantly, compared to compression tests, which results from a failure in the clamping support. The off-axis tests showed a slightly sensitivity in strength for different fiber volume contents, but since in off-axis stress cases fiber parallel stresses σ_{11}, transverse stresses σ_{22} and shear stresses τ_{12} it is assumed that the stresses interfere with each other and include the strength. In previous studies it could be shown that FRPs are sensitive to hydrostatic pressure [4,5]. A possible explanation for the increase of strength in compression direction for higher fiber volume contents could result from such hydrostatic sensitivity.

4.2. Numerical results

To model the change in strength due to fiber volume content, a function of each strength component for inter fiber failure according to equation 5 need to be updated. For compressive strength Y_C a linear correlation over the fiber volume content is sufficient. The strength for the model results in the following equation:

$$Y_C = a\varphi + b \tag{6}$$

where $a = 317$ MPa and $b = -4.3$ MPa in a range of $\varphi = 0.5\ to\ 0.6$. The parameters a and b result from experimental tests and are valid for the evaluated fiber volume contents. To determine the strength for all other fiber volume contents further tests or numerical studies can be performed. Reverse engineering from the off-axis tests the shear S_{12} and transvserse strength Y_T.are also assumed to be have a linear correlation over the fiber volume content.

5. Conclusions and outlook

In the present work, the influence of the fiber volume content on the strength of FRPs is evaluated. From the strains and stresses, a failure criterion is adopted to a fiber volume content dependent one. It has been shown that compression tests transverse to the fiber direction show a significant increase in strength of 20% from 50% fiber volume content to 60% fiber volume content. Further experimental tests will be conducted to evaluate the influence of fiber volume content on the strength in waviness and in case of gapping.

Acknowledgments

This work was performed within the research project "Experimental and virtual analysis of draping effects and their impact on the mechanical behavior of composite components" (KA4224/1-1, GU614/11-1) funded by the Deutsche Forschungsgemeinschaft (DFG). We would like to thank for the financial support, which enabled the detailed study of the draping effects. Additionally, the work is part of the research of the Young Investigator Group (YIG) "Tailored Composite Materials for Lightweight Vehicles" at KIT FAST, funded by the Vector Stiftung.

References

[1] Soden P, Hinton MJ and Kaddour AS. A comparison of the predictive capabilities of current failure theories for composite laminates. Composites Science and Technology 1998; 58: 1225–1254.
[2] Kaddour AS and Hinton MJ. Benchmarking of triaxial failure criteria for composite laminates: Comparison between models of ‘Part (A)’ of ‘WWFE-II’. Journal of Composite Materials 2012; 46: 2595–2634.
[3] A. Puck and H. Schürmann. Failure analysis of FRP laminates by means of physically based phenomenological models. Composites Science and Technology 1998; 58: 1045–1067.
[4] Shin ES and Pae KD. Effects of Hydrostatic Pressure on In-Plane Shear Properties of Graphite/Epoxy Composites. Journal of Composite Materials 1992; 26: 828–868.
[5] Shin ES and Pae KD. Effects of Hydrostatic Pressure on the Torsional Shear Behavior of Graphite/Epoxy Composites. Journal of Composite Materials 1992; 26: 462–485.