DEGRADATION BEHAVIOUR OF TEXTILE-REINFORCED POLYPROPYLENE UNDER FATIGUE LOADING

M. Gude, W. Hufenbach, I. Koch*
Institute of Lightweight Engineering and Polymer Technology, TU Dresden, Germany
* Corresponding author (ilja.koch@tu-dresden.de)

Keywords: *fatigue, textile reinforcement, polypropylene, glass fibre*

1 Introduction

Textile-reinforced thermoplastic composites offer huge application potentials for a rapid manufacturing of lightweight components with versatile possibilities of integrating functions such as active vibration damping systems. For a wider industrial application of these materials, a detailed understanding of the material behaviour under fatigue loading is required. In this study the new group of multi-layered flat bed weft-knitted glass fibre/polypropylene composites (GF-MLG/PP) based on hybrid yarns has been tested under tension and shear fatigue loading. Besides the elaboration of S-N-curves for different material configurations under tension-tension fatigue loading the influence of shear loading with different stress ratios on the material degradation has been investigated.

2 Material specification

Hybrid yarns (HG) consist of reinforcing filaments and a thermoplastic matrix component, in this case in form of filaments integrated into the yarn structure. The achievable fibre impregnation is often insufficient because the matrix cannot completely penetrate the reinforcement fibre bundles during the consolidation process. The highest potential of a homogeneous distribution of reinforcement and matrix filaments over the yarn cross section can be found in commingled hybrid yarns. The advantage of textile preforms made of hybrid yarns is the efficient manufacturing of composite parts without any separated impregnation process.

Glass fibre multi-layer knits (GF-MLG) made of commingled hybrid yarns and consolidated in a fast hot pressing process result in high levels of stiffness and strength of the composite, because the load-bearing warp and weft threads are in straight orientation without major ondulations. In addition, the glass fibre knitting loop threads that secure the fibre interlock prevent the delamination between the individual layers [1,2]. In this paper composites with multi-layer knit reinforcement consisting of a 2-layer flat knit with E-glass fibres (GF) for warp (0°-direction), weft (90°-direction) and loop fibres are used.

Four different material setups have been characterised with the same textile architecture as well as the same reinforcement fibres (Twintex-R PP 82 and $[0/90//90/0]_s$ layup), but with different knit thread types according to Table 1.

Table 1: Applied knit thread setup

Material	knit thread type	knit thread fibre volume fraction
A	HG-Standard	51,6 %
B	HG-Special	51,6 %
C	Culimeta EC9	100 %
D	Prolen-H	0 %

3 Experimental setup and results

3.1 Specimen

tensile stress loading

Flat specimens according to DIN 527-4 Type 3 with a symmetric lay-up of two textile layers have been used for the quasistatic as well as tension-tension fatigue experiments. The specimens were water jet cut from hot pressed plates and were equipped with GF-reinforced end taps.

intralaminar shear loading

For the fatigue test under in-plane shear stresses tube specimens according to Fig. 1 have been used, which consist of two preconsolidated GF-MLG/PP sheets. The thin textile-reinforced sheets were rolled and pressed into a heated steel mould by an inflated hose.

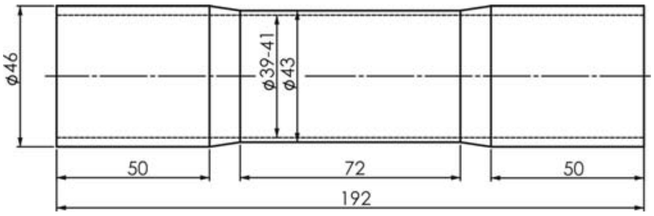

Fig. 1: Dimensions of tube specimen for cyclic interlaminar shear loading

3.2 Test procedure

The quantification of the material degradation under fatigue loading is based on the analysis of the variation and deformation of the stress-strain-hysteresis during cyclic loading. The characteristic stiffness drop as well as the development of plastic strain has been evaluated. Furthermore the damage mechanisms have been monitored by micro graphs and computer tomography(CT)-scans.

For the determination of the basic material properties quasistatic tension tests and for the fracture-type related damage evolution analysis constant amplitude tests with uniaxial tension-tension loading with a stress ratio of R = 0.1 and in-plane shear loading with R = 0.1 and -1 were carried out. The test frequency was chosen with 5 Hz and 1 Hz respectively due to significant warming of the specimen under cyclic shear stresses.

3.3 Results

tension-tension

As a reliable basis for the fatigue analysis the material properties of the focused GF-MLG/PP with different knit thread under quasisstatic tensile loading have been elaborated and displayed in Fig. 2 normalized by property parameters of material A. A clear improvement of the material properties have been monitored for all knit thread variations. Especially for variation C an improvement of the static strength (R_M), the elongation (ε_M) as well as the Young's modulus (E) has been achieved.

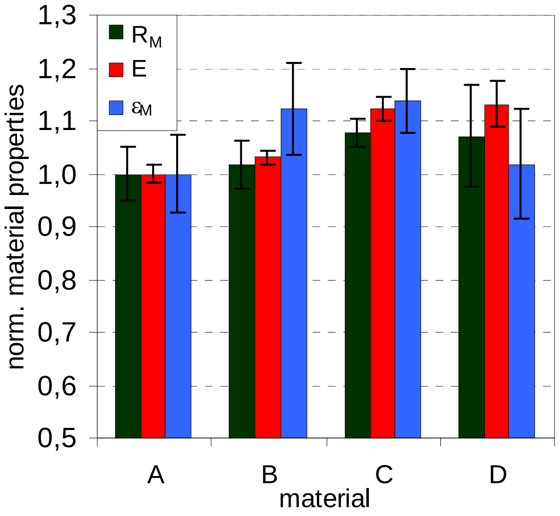

Fig. 2: Influence of the knit thread on the material properties of GF-MLG under static loading

In contrast to the improved quasistatic material properties, the material C is subjected to significant strength degradation during fatigue loading. The appropriate S-N-curve in Fig. 3 is characterized by a strong decrease until 10^3 cycles and the comparatively lowest cyclic strength at 10^6 cycles.

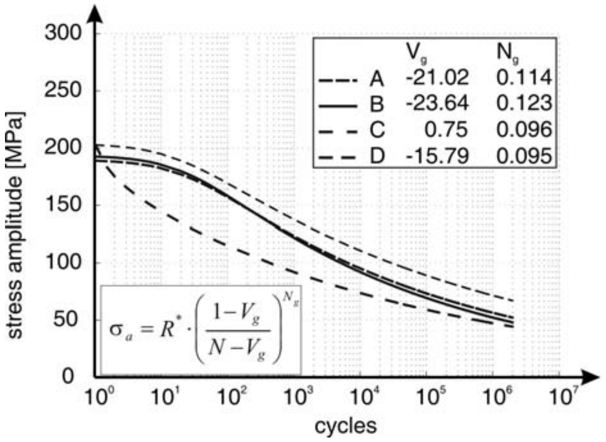

Fig. 3: Fatigue performance for GF-MLG/PP with different knit threads (P_s = 50 %)

The varying behaviour is caused by an insufficient infiltration of material C. Due to the high volume fraction, a load transfer from macroscopic tension to local bending of the warp fibres by the loop thread takes place under tension loading and is failure dominant (see Fig. 4).

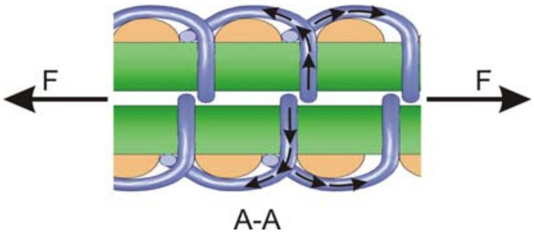

Fig. 4: Load transfer mechanism under tensile loading of GF-MLG/PP (C)

Whereas the load transfer mechanism is guaranteed up to high quasistatic tensions stresses, the complex cyclic stresses lead to a significant localized loss of stiffness and strength by the knit thread. In consequence, the damaged zone after quasistatic loading is dominated by delaminations due to the whiplash effect whereas the fatigue fibre failure occurs in an early stage of the loading history within a small damage zone without major delaminations.

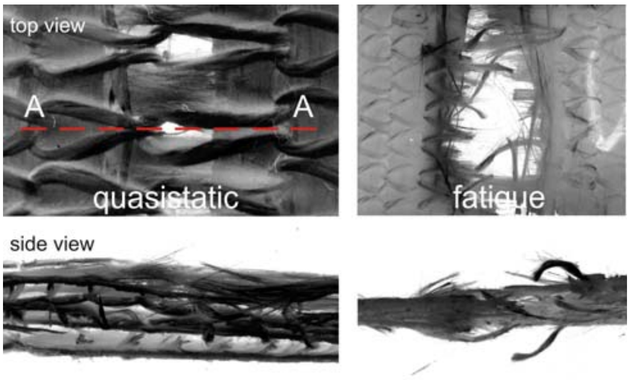

Fig. 5: Different failure mechanisms for quasistatic tension and fatigue loading (t-t) of GF-MLG/PP (C)

In comparison the other focused materials show a better matrix infiltration and therefore better fatigue performance. Material A and B have almost identical fatigue behaviour.

Due to a slightly higher fibre volume fraction on the one hand and the optimised straight fibre layup without interacting knit threads after the hot forming process (see Fig. 6) on the other hand, material D represents the best compromise with regard to quasistatic and fatigue performance.

Fig. 6: Straight fibre orientation and failure mechanism of GF-MLG/PP (D) due to fatigue loading (CT-scan)

For the materials A, B and D the fatigue failure is initialised by transverse cracks in the weft fibre layer. Accumulated transverse cracks lead to significant stiffness drop and act as a damage initiation point for the fatigue degradation of the load carrying warp fibres. The final failure is driven by fibre failure and pullout effects in the area of adjacent 90°-fibre bundles due to damage interaction.

The stress-strain behaviour of GF-MLG/PP under tension-tension fatigue loading is characterised by the development of remaining strain (Fig. 7 left) and a significant stiffness degradation (Fig. 7 right).

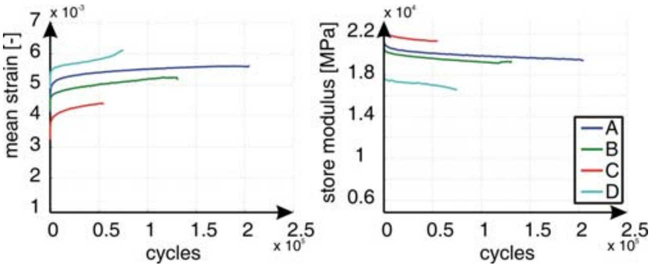

Fig. 7: Exemplary degradation behaviour of GF-MLG/PP under fatigue loading

As already reported for glass fibre weft knit reinforced epoxy [2], the stiffness degradation caused by the development of transverse cracks (matrix cracking and fibre-matrix-debonding) and gradually fibre failure. Because of almost identical cycle dependent property courses of the stiffness, the material damping (tan δ) and the mean strain a continuum damage model may further on be used for the advanced modeling of the inelastic stress-strain behaviour of GF-MLG/PP under cyclic loading.

in-plane shear

The degradation behaviour of multi-layer weft knit composites with polypropylene matrix under cyclic shear loading has been characterised on material A exemplary.

Due to the complex shape of the knit loop and the initiation of cracks in different failure planes, a significant difference between the cyclic degradation behaviour under pulsating and fully reversed shear stresses is expected (see Fig. 8).

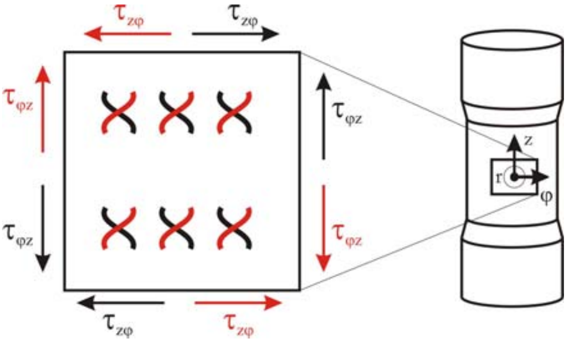

Fig. 8: Initiation of cracks in the knit loop thread in different failure planes due to fully reversed cyclic shear stresses

In contrast to that, the warp and weft layer are damaged in the same manner. The occurring inter-fibre failure with failure planes parallel to fibre orientation and fibre-matrix debonding has been found in almost the same amount in both cyclic shear load cases (Fig. 9).

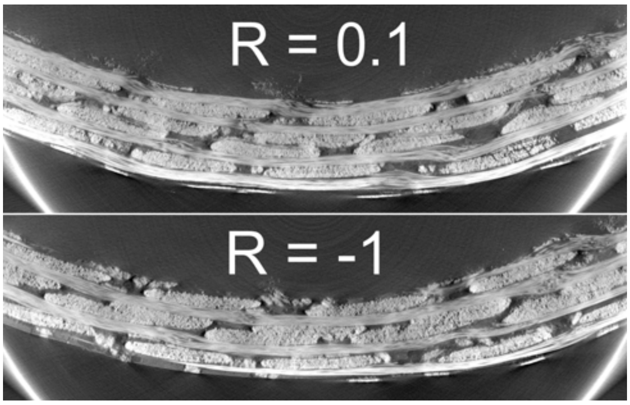

Fig. 9: Identical damage behaviour in the warp fibres due to pulsating and fully reversed cyclic shear stresses

The deformation behaviour at cyclic in-plane shear stresses is mainly driven by the development of remaining strain. Especially for fatigue loading with a positive mean stress (R = 0.1) a significant amount of remaining strain was monitored. Due to the development of multiple cracks in the area of the reinforcement fibres independent of the stress ratio additionally stiffness degradation and rising material damping is present (Fig. 10 and Fig. 11).

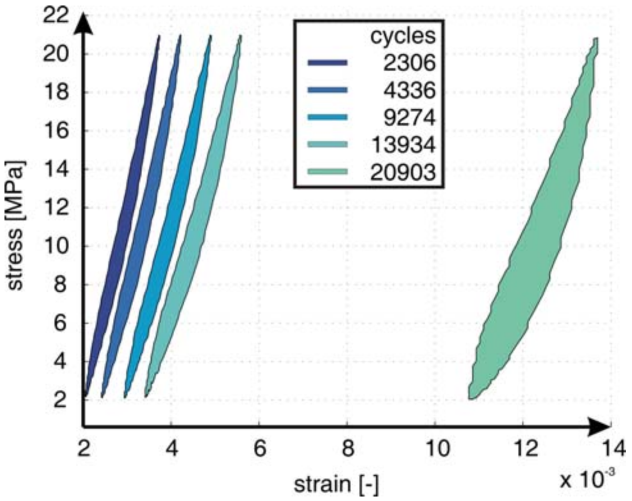

Fig. 10: Stress-strain behaviour of textile-reinforced PP for cyclic shear stresses with positive mean stress

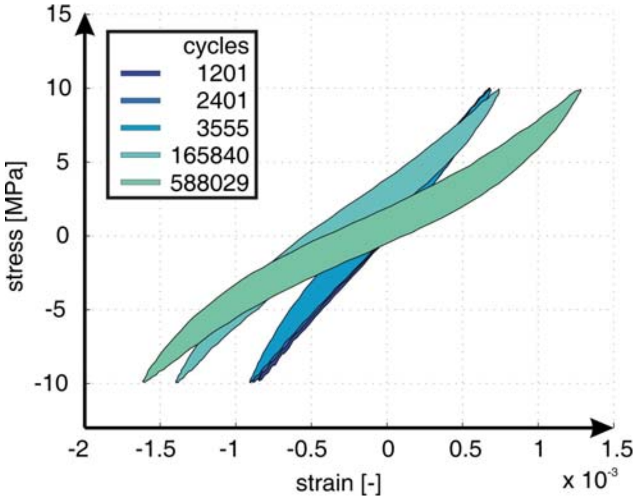

Fig. 11: Stress-strain behaviour of textile-reinforced PP for fully reversed cyclic shear stresses

As already reported for tension-tension loading, the occurring material property degradation is dominated by material damage in form of crack opening and closing in fibre and cross-fibre direction as well as fibre-matrix debonding which may be well modelled with the help of continuum damage mechanics. As a first approach the anisotropic stiffness C_{ij}, strength R^* and damping Λ^* are - in analogy to the experimental results - functions of the material damage parameters D_{ij} only

$$C_{ij}, R^*, \Lambda^* = f\left(D_{ij}\right). \qquad (1)$$

The damage increment dD_{ij}/dN is formulated as a sum of failure mode specific damage growth functions *f* which depend on the local material effort and the damage parameter itself

$$\begin{aligned}\frac{dD_{ij}}{dN} = {} & f_{ij}^{\parallel\sigma}\left(Eff^{\parallel\sigma}, D_{ij}\right) + f_{ij}^{\parallel\tau}\left(Eff^{\parallel\tau}, D_{ij}\right) + \\ & f_{ij}^{\perp\sigma}\left(Eff^{\perp\sigma}, D_{ij}\right) + f_{ij}^{\perp\tau}\left(Eff^{\perp\tau}, D_{ij}\right) + \\ & f_{ij}^{\perp\parallel}\left(Eff^{\perp\parallel}, D_{ij}\right).\end{aligned} \qquad (2)$$

The effect of the mean stress and cyclic loading with and without switching the failure mode will further on be considered by counting the cyclic stresses failure mode wise.

Conclusion

In this study the new group of multi-layered flat bed weft-knitted glass fibre/polypropylene composites (GF-MLG/PP) based on hybrid yarns has been tested under tension and shear fatigue loading for the development of reliable life time models. Besides the elaboration of S-N-curves for different material configurations under tension-tension fatigue loading, the influence of shear loading with different stress ratios on the material degradation has been investigated.

For the determination of the material degradation under fatigue loading constant amplitude tests with uniaxial tension-tension and torsion loading with stress ratios of R = 0.1 and R = -1 were carried out for a fracture-type related damage analysis of GF-MLG/PP. The quantification of the material degradation is based on the analysis of the variation and deformation of the stress-strain-hysteresis during cyclic loading. The characteristic stiffness drop as well as the development of plastic strain has been evaluated.

The experimental analysis shows a significant material degradation under fatigue with stiffness loss, mean strain development and the accumulation of material damping. Because of almost identical cycle dependent property courses a continuum damage model will be used for the modeling of the inelastic stress-strain behaviour of GF-MLG/PP under cyclic loading.

Acknowledgement

The authors gratefully acknowledge the financial support of the German Research Foundation (DFG) within the Collaborative Research program SFB 639, subproject C1.

References

[1] Hufenbach W., Adam F., Beyer J., Zichner M., Krahl M., Lin S., et al. „Development of an adapted process technology for complex thermoplastic lightweight structures based on hybrid yarns.” *In: 17th International conference on composite materials (ICCM 17)*, Edinburgh, July 27–31; 2009

[2] Koch, I.: Modellierung des Ermüdungsverhaltens textilverstärkter Kunststoffe, PhD-thesis, TU Dresden, 2010

[3] Schade M., Diestel O., Cherif Ch., Krahl M., Hufenbach W., Franeck J. et al. „Development and technological realization of complex shaped textile reinforced thermoplastic composites.” *In: Composites in automotive and aerospace* (5th International Congress on Composites), Munich, 2009.