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Effect of neighbouring plies and 3D-loop-threads on the fatigue life of glass fibre reinforced polypropylene

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Abstract

Using textile composites with straight fibre orientation in-plane, improved lightweight structures can be designed and produced, where the fibres are specifically positioned in line with the flux of force induced by external loads. Here, the structural properties are dominated by the material properties of the 0°-fibres under static as well as under fatigue loading. It is well known, the failure behaviour in fibre direction is affected by textile loop threads and adjacent plies, for example by notch effects of inter fibre cracks. For the experimental characterisation of the influence of 3D-loop threads as well as adjacent plies on the fatigue performance, the degradation behaviour of unidirectional and textile glass fibre reinforced polypropylene in tension-tension fatigue loading has been analysed. The material configurations have selectively been chosen to achieve identical fibre volume fraction of the reinforcement fibres in loading direction and therefore gain a high comparability in fatigue loading. The driving damage mechanisms are observed using imaging methods, such as light microscopy and computer tomography.

The achieved experimental results will be incorporated into the failure mode dependent fatigue analysis models already been published by the authors.

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Keywords: glass fibre, polypropylene, fatigue, textile reinforced composites

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1. Introduction

Textile reinforced composites with straight fibre orientation in-plane and a high proportion of reinforcing filaments in thickness direction, such as weft knitted fabric reinforced thermoplastics, show high stiffness and strength and extraordinary delamination resistance. Using these textile composites, improved lightweight structures can be designed and produced, where the fibres are specifically positioned in line with the flux of force induced by external loads. The German research foundation set up a collaborative research center SFB639 “Textile-Reinforced Composite Components in Function-Integrating Multi-Material Design for Complex Lightweight Applications” (Chairman: Prof. Dr.-Ing. habil. Prof. E.h. Dr. h.c. Werner Hufenbach). The scope is the development and characterisation of the complete process chain from the filament to a function integrated demonstrator. A fundamental aspect of this research is the design chain, wherein design tools as well as material models for the comprehensive modelling of novel textile reinforced composites are developed. The subproject C1 focuses on the fatigue behaviour of biaxial weft knit reinforced composites among others.

The structural properties of textile reinforced composites with straight fibre orientation are dominated by the material properties of the 0°-fibres under static as well as under fatigue loading. A key factor for the comprehensive modelling of the fatigue behaviour of these composites is the understanding of the influence of the textile architecture and neighbouring plies. From literature the influence of, for example, inter fibre cracks in adjacent layers to the fatigue behaviour of glass and carbon fibre reinforced thermosets in fibre direction is well known, as reported by Schürmann et. al., Puck and Schulte et. al.. For a layer wise strength analysis, knock down factors within the range of 0.5 to 0.9 for load carrying 0°-layers with adjacent damaged 90°-layers are proposed. Beside the damage accelerating effect of inter fibre failure an influence of stitches and textile loop threads for glass fabric reinforced thermosets has been experimentally and analytically proven for instance by Böhm, Adden et. al. and Koch.

For the experimental characterisation of the influence of 3D-loop threads as well as neighbouring plies on the fatigue performance of glass fibre reinforced polypropylene, the degradation behaviour of unidirectional as well as glass fabric reinforced polypropylene in tension-tension fatigue loading has been analysed.

| Nomenclature |
|---------------|
| GF            | glass fibre     |
| UD            | unidirectional  |
| MLG           | multi layer weft knit |
| CP            | cross ply       |
| CT            | computer tomography |
| CDS           | characteristic damage state |
| R             | stress ratio    |
| SFB           | collaborative research center |
| //            | new textile layer |
2. Materials

Within the collaborative research centre glass fibre reinforced polypropylene is focussed. Beside commercially available commingled hybrid rovings and fabrics of Fibre Glass Industries (FGI) of the type Twintex© with E-glass and isotactic polypropylene also specifically designed hybrid yarns are used as base materials. The materials are further on treated by a knitting process for creating biaxial weft knit as shown in Fig. 1. Using hot press technologies, the polypropylene filaments are melted and after annealing a laminate with comparably high stiffness and strength has been built.

![Fig. 1. Biaxial multi layer weft knit](image)

For the described experimental characterisation three material configurations according to Table 1 have selectively been chosen to achieve identical fibre volume fraction and similar micro structure of the reinforcement fibres in loading direction and therefore gain a high comparability under fatigue loading. As the benchmark material, unidirectional reinforced polypropylene (GF-UD/PP) – hot pressed in single cavities – is used. As an example for cross ply laminates (GF-CP/PP), four layers of the above mentioned biaxial weft knit with loop threads consisting of pure PP-filaments (Prolen-H) have been chosen, resulting in an laminate with [90/0/0/90], layup. The representative material with a significant amount of 3D-reinforcement (GF-MLG/PP) is of the same structure as the cross-ply laminate but with 51.6 % glass fibre content in the loop thread. The textile reinforced materials are hot pressed into plates (300 x 300 mm²) and water jet cut to straight edged flat specimens according to DIN EN ISO 527-4. All specimens are equipped with bevelled cap strips.

| Material            | reinforcement fibres (warp, weft) | Textile type     | layup          | GF fraction by loop thread | specimen geometry |
|---------------------|-----------------------------------|------------------|----------------|---------------------------|-------------------|
| GF-UD/PP            | Twintex©-R PP 82                  | unidirectional rovings | [0]_{42R}     | -                         | (250 x 15 x 2) mm |
| GF-CP/PP            | Twintex©-R PP 82                  | biaxial weft knit  | [90/0/0/90],       | 0 %                      | (250 x 25 x 2) mm |
| GF-MLG/PP           | Twintex©-R PP 82                  | biaxial weft knit  | [90/0/0/90],_s   | 6.8 %                    | (250 x 25 x 2) mm |

The microstructure of the materials, especially in the area of the load carrying warp fibres, is characterised with the help of micro sections (see Fig. 2). The fibre volume fraction within the rovings in load direction is analysed by area count of a representative number of micro sections with 70 % (GF-MLG/PP), 66 % (GF-CP/PP) and 63 % (GF-UD/PP) respectively. Therefore a high comparability of the materials has been gained.
3. Material behaviour under static loading of GF/PP

In advance of the fatigue experiments, static tension test according to DIN EN ISO 527-4 have been performed. The strength results are displayed in Fig. 3 a. The strength of the unidirectional material with almost 1200 MPa emphasises the potential of the material combination. The textile (GF-MLG/PP) and the cross ply material (GF-CP/PP) show significant lower strength values due to 50 % off axis fibres in the cross section. Comparing these materials, the cross ply laminate shows slightly higher strength values but within the variance of the results. Hence an influence of the textile loop thread may not be evaluated. To achieve a detailed view of the load carrying capability of the 0°-filaments the static strength has been divided by the 0°-fibre volume fraction, whereby an efficiency factor for the validation of the influence of adjacent layers and loop threads to the load carrying fibres has been gained. In Fig. 3 b the calculated fibre strength for the investigated materials is displayed. Using unidirectional material the fibres reach the highest strength values with about 1900 MPa. For biaxial weft knit composites and for cross ply laminates, the load carrying capacity of the fibres is significantly lower whereby the textile reinforcement shows slightly improved fibre strength. This effect may be explained by a softer notch effect of inter fibre failures in the textile reinforcement. Whereas in cross ply laminates the inter fibre failures may open during loading and introduce overstresses to the aligned fibre layer, they are kept closed by surrounding textile loop threads in case of the biaxial weft knit.
Fig. 4. Damage phenomenology after static loading (specimen surface) a) GF-UD/PP b) GF-MLG/PP c) GF-CP/PP

The damage phenomena of the unidirectional material are dominated by extensive fibre failure and secondary inter fibre failure due to whiplash effects. For textile reinforced material, one dominating angular crack in the area of loop threads accompanied with extensive delaminations between the textile layers have been recognised. In contrast to that, the failure of the cross ply laminate is characterised by a single delamination and a straight global crack perpendicular to the loading direction (see Fig. 4).

4. Material behaviour of GF/PP under cyclic tension-tension loading

In analogy to the procedure in static loading the fatigue behaviour of GF/PP at R = 0.1 (tension-tension fatigue) has been characterised. Besides the analysis of the fatigue strength, the stiffness degradation as a measure of the material damage is examined failure mode wise.

4.1. Fatigue strength behaviour

The S-N-curves in the semi logarithmic diagrams of Fig. 5 are derived by least square method using the wear-out-model according to VDI 2014. The static as well as the fatigue data points have been incorporated. Besides the S-N-curve for a probability of survival $P_s = 50\%$ curves for $P_s = 90\%$ and $10\%$ are displayed too. The direct comparison of the derived S-N-curves for the focused glass fibre reinforced materials in Fig. 5 a shows the typical behaviour with extraordinary strength of unidirectional materials and very close S-N-curves for the bidirectional materials on a much lower level. The advantage in static strength of GF-CP/PP remains also for the low cycle and the high cycle regime until $10^6$ cycles.

By dividing the stress amplitude by the $0^\circ$-fibre volume strength the S-N-curve in fibre stress amplitude is gained according to Fig. 5 b. In difference to the behaviour under static loading, the fatigue strength curves of the reinforced materials collapse to one master curve from $10^2$ to $10^6$ cycles. Therefore the influence of adjacent plies and loop threads, which has been clearly seen under static loading, is significantly reduced under tension-tension fatigue loading. Using the fibre stress amplitude, the fatigue life can be modelled for unidirectional, multi layer weft knitted as well as cross ply laminated glass fibre reinforced polypropylene with a single S-N-curve.
4.2. Stiffness degradation behaviour

For the validation of this hypothesis, the stiffness degradation in form of the normalised modulus vs. the numbers of cycles is displayed in Fig. 6 a for selected tests. The unidirectional reinforced material (black line) shows almost linear stiffness degradation. Due to only one affected failure mode during pulsating tension loading, the whole stiffness reduction is due to fibre failure in the tension mode.

In case of the biaxial materials, typical three stage stiffness degradation is recognised (dark and light grey lines). The decreasing stiffness degradation is due to the development of discrete inter-fibre failure and diffuse damage in the area of loop threads. These damage phenomena reach their saturation limit at about 20 % of the lifetime resulting in the characteristic damage state (CDS). The consecutive stage with constant stiffness degradation is due to fibre failure in tension mode. According to Fig. 7 the damage phenomena in fibre direction of textile as well as unidirectional material show great similarities. The secondary constant stiffness degradation of textile and cross ply laminate during CDS may therefore be compared to the linear behaviour of unidirectional material. The third stage with an increasing damage growth is characterised by roving rupture and the development of the global crack.

By defining a general damage parameter

$$D = \left(1 - \frac{E}{E_0}\right),$$

with the help of the equivalence of the normalised stiffness $E/E_0$ and damage parameter $D$ of the continuum damage mechanics, the fibre damage increment $dD/dn$ in tension mode can be extracted. The damage increment of the different types of materials and fatigue loads is displayed over the maximum fibre stress in Fig. 6 b and the selected stiffness degradation results are marked. It can be clearly seen, that the experimental data points for all materials form a single exponential curve. Therefore the above postulated hypothesis of uninfluenced fibre fatigue behaviour for the selected materials is validated.
The damage phenomenology for the investigated material, as shown by specimen surface and computer tomography of a $0^\circ$-layer in Fig. 7, is similar. The damage behaviour of unidirectional material (GF-UD/PP) in Fig. 7 a is characterised by perpendicular roving rupture, subsequent damage growth along the fibres and final breakage with wide spread filament failure. In case of the textile reinforcements this phenomenology takes place stepwise in every roving with a global angular crack and minor delaminations. In contrast to the majority of the published results for brittle thermosets, that describes significant damage interaction, the comparatively soft matrix material polypropylene reduces the crack tip stresses by plastic yielding and minimises the interference of inter fibre failure to fibre failure.

Fig. 6. Stiffness degradation of GF/PP during cyclic loading a) exemplary graphs of the normalised modulus over the rel. life b) constant fibre damage increment during CDS as a function of the maximum fibre stress

Fig. 7. Damage phenomenology after fatigue loading (CT and specimen surface) a) GF-UD/PP b) GF-MLG/PP c) GF-CP/PP (1 – side view, 2 – front view)
5. Conclusion

The static as well as the fatigue performance of fibre reinforced composites varies with the direction of the reinforcement whereas in fibre direction the best properties are reached. With the help of multi layer weft knit composites, which are developed within the collaborative research center SFB639 at the TU Dresden, the strength and stiffness of the fibres can be retained very well due to their straight fibre orientation. Glass fibre reinforced polypropylene in form of unidirectional material, cross ply laminates and glass fibre weft knit composites with a high amount of textile loop threads have been extensively tested to study the influence of adjacent plies and loop threads to the fatigue performance in fibre direction. The material configurations have selectively been chosen to achieve identical fibre volume fraction of the reinforcement fibres in loading direction and therefore gain a high comparability. A comparison concerning the load carrying fibres is possible by dividing strength values by the 0°-fibre volume fraction.

In static loading the unidirectional reinforced material reaches the highest values of the fibre strength. Within biaxial weft knit composites and cross ply laminates the load carrying capacity of the fibres is significantly reduced due to the influence of adjacent layers and textile loop threads.

In contrast to the behaviour under static loading, the S-N-curves of the reinforced materials collapse to one master curve. Therefore the influence of neighbouring plies and loop threads is significantly reduced under tension-tension fatigue loading. This also agrees with the stiffness degradation during cyclic loading. Using the fibre stress, the slope of the stiffness degradation during the characteristic damage state can be modelled for all materials with a simple exponential model.

The achieved experimental results will be incorporated into the failure mode dependent fatigue analysis models already published by the authors.

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