Short Fibre Reinforced Thermoplastics under Multiaxial Cyclic Stress – A Method for the Fatigue Life Estimation

K.Jaschek[a], A. Büter[a]

[a] Fraunhofer-Institute of Structural Durability and System Reliability, Bartningstr. 47, 64289 Darmstadt, Germany

Abstract In this study, the fatigue behaviour of a short fibre reinforced thermoplastic under multiaxial cyclic stress has been investigated. Based on experimental results a method was derived for the fatigue live estimation in the design process of components exposed to complex multiaxial loads. During the manufacturing process of short fibre reinforced thermoplastic components, a lightly anisotropic behaviour in stiffness and strength arises. Because of the materials anisotropy, classical failure hypotheses for the assessment of multiaxial load cases do not apply. In this study a fatigue failure hypothesis was implemented that assesses the stress components in accordance with the correlating fatigue strengths in the material coordinate system, considering potential interaction. Striving for a verified multi-usable fatigue life assessment method, complex multiaxial load cases were examined experimentally. The experimental results and the fatigue life estimation on the basis of the failure hypothesis will be presented.

1 INTRODUCTION

Due to their specific weight, plastics hold a great potential for lightweight structures, especially in automotive design. For instance, polyamides allow cost-effective production of complex components by injection moulding technique. Heavily loaded components may be reinforced with short fibres in order to assure their functioning over the specified service period (2). The fibre reinforcement – type, volume fraction, alignment and length - has a great impact on the material properties of the plastic components. Stiffness and strength, for instance, may be enhanced and a reduction of creeping effects and thermal expansion may be achieved (5). A systematic and economical design and dimensioning requires knowledge of the material and component dependent properties. With FRP, as the actual composite material arises from the production process, the type of manufacturing has a considerable effect on fibre orientation and fibre volume. Regarding injection moulding technique, the fibre alignment and thus the degree of anisotropy depends on the components wall thickness (3). Due to the melt polymer flow during the manufacturing process, within the regions close to the mould walls, shear stresses cause a skin layer with the fibres being aligned along the material flow direction (MFD), within the centre region extensional flow prevails and a core layer with a perpendicular alignment of the fibres develops (figure 1). Finally, the cold mould walls create a very thin layer with random fibre orientation near the surfaces. The thickness of the skin layers remains constant over varying wall size, whereas the perpendicular aligned core layer reduces relative to the overall wall thickness. Hence, with a reducing wall thickness, the comparative influence of the fibre alignment within the skin layers, i.e. the degree of anisotropy in stiffness and strength, increases. It should be noticed, that due to the layered structure, the impact of anisotropy depends on the loading type, tension or bending. In the present study, bending will not be considered.

Figure 1. Fibre orientation (19).

Especially in automotive design, during operation structures made from short fibre reinforced plastics (SFRP) may not just be exposed to static loads but also to cyclic loads. Besides, not just uniaxial loads acting in the main material direction, i.e. along or perpendicular to the predominant fibre alignment, respectively, are to be expected. Those simple uniaxial loads cause complex multiaxial stress states within anisotropic material. For the dimensioning of cyclic loaded safety components, multiaxial stress states that may arise from those arbitrary external uniaxial and multiaxial load scenarios need to be paid special attention to. The failure hypothesis, the design is based on, must take all relevant stress components into account, including their interaction and considering the material's anisotropic strength behaviour. In particular the assessment of multiaxial stress at cyclic loading becomes a rather complex task. The stress components may act out-of-phase, i.e. with a phase shift, or at different frequencies, in each case with or without mean stress of the different stress components. Up to today, the design of FRP components is prevalently based on static characteristics such as tension strength, yielding strength or ultimate strain. When it comes to cyclic loaded safety components, these values are not sufficient. Customarily, influencing factors such as fibre orientation, temperature, aging, mean stress, multiaxial stress states, dynamic/cyclic loading and scatter are accounted for with empirical diminishing coefficients (9). The concept presented in this paper follows a different approach for the dimensioning of components made of SFRP.

2 THEORETICAL

Due to the fibre alignment of the injection moulded SFRP, the material behaves overall orthotropic. Accordingly, a respective coordinate system, in the following termed as material coordinate system (CS), may be defined in the plane of the injection moulded component's wall with an alignment of one axis according to the direction of the predominant fibre alignment. Loads acting along the material axes are termed on-axis. They do not cause additional coupled stress components like shear arising from axial stresses as opposed to off-axis loads, which act at a defined angle with respect to the orthotropic axes. Classical failure hypotheses for isotropic materials are not applicable to the assessment of anisotropic materials. Even the evaluation of simple uniaxial loading depends on the direction of the load with respect to the material CS (along/perpendicular to predominant fibre direction) and, in the case of off-axis loading, additionally may cause complex multiaxial stress states. Thus, deduction of an equivalent stress in the case of multiaxial stress is not advisable for anisotropic materials. Different failure hypotheses for anisotropic, usually continuously fibre reinforced, materials exist in literature (4). Common to most hypotheses, a rather phenomenological approach assuming homogenous material behaviour over the thickness is assumed. Continuous fibre reinforced multilayer laminates are therefore customarily evaluated layerwise with rotational symmetry about the fibre axis and in general plane stress state assumption, i.e. the (small) stresses in thickness direction are disregarded. Rarely, the laminate is evaluated as a whole, neglecting the lay up (12). Obviously, condition of the layerwise evaluation is the preceding single layer investigation. This is not easily done in the case of injection moulded materials as manufacturing of such single layer plates is quite a complex task. Thus, in the present case, the layer setup of the SFRP will not be considered. As a result, the inhomogeneous strength and stiffness distribution over the thickness is neglected and the material CS is defined by one axis being the predominant fibre direction.

Three in principle different approaches for anisotropic failure hypothesis formulations exist according to their date of publication. First, the components of the stress tensor in the material CS were evaluated directly with respect to possible interaction in a rather mathematical/global way (11)(13)(15)(18). Later, the assessment was based on invariants considering the transverse isotropy (16)(17). These formulations aim at an evaluation by physical means because they distinguish between different controlling stress components in terms of the possible failure mechanisms fibre failure (FF) and inter fibre failure (IFF). According to the most recent approach, regarding the inter fibre failure assessment, the combination of the stress components are evaluated with respect to the physical section plane they act on. Therefore, next to the material CS another CS with a varying orientation needs to be defined which is always normal to a fibre parallel inter fibre section plane (7). The benefit of the latter is the detailed physical inspection, not just being able to differentiate between different failure mechanisms, but to predict the failure section plane and assess it regarding total failure. Compared to the critical section plane approach developed for isotropic materials, this approach takes into account the anisotropic material behaviour, because the reference coordinate system is aligned according to the fibre direction. Failure hypotheses, which distinguish between different failure mechanisms are termed direct mode formulations as opposed to global formulations, which are simply capable to predict overall failure. Thus, obviously direct mode failure hypotheses give more detailed information and are based on physical means. However, extensive experimental investigations are needed to determine the various material parameters that are needed. Global formulations, on the other hand are rather empirical but easy-to-apply and from experience, nevertheless may give reasonable results, even with continuous fibre reinforcement (12). With SFRP, due to the short fibre length, fibre failure is unlikely to occur. The matrix is the predominant stress-bearing phase. Within the layers at which the fibres are aligned along the loading direction, matrix failure will be preceded by steadily increasing fibre pull out (1). With matrix failure being the crucial failure mechanism and at application of a failure estimation approach neglecting the layerwise composition, differentiation between different failure mechanisms becomes obsolete. From the economical point of view the implementation of an easy-to-implement global hypothesis seems therefore reasonable. In the presented investigation the global Tsai-Wu failure hypothesis for plane stress states was adopted and the local plane stress state on the components' surface was analysed. As opposed to other global failure hypothesis, on the one hand the Tsai-Wu formulation allows for detailed adoption of the interaction of normal stresses along and perpendicular to the fibre by means of an interaction term. Here, the interaction term proposed by Tsai-Hahn was implemented (13)(15). On the other hand, it takes implicitly into account different strength values in tension and compression. In its original form for static strength evaluation, for plane stress states the failure hypothesis applies a quadratic polynomial based upon the 5 material static strengths at uniaxial loading with respect to the material CS, $R_{m,\sigma1+}$, $R_{m,\sigma1-}$, $R_{m,\sigma2+}$, $R_{m,\sigma2-}$ and $R_{m,\tau}$. Thus, before application of the failure hypotheses, the basic uniaxial material strengths need to be investigated experimentally. By means of the polynomial, the strength for arbitrary sets of plane stress states, described with respect to the material CS, may then be assumed. For the plane stress state, the collectivity of estimated critical multiaxial stress states may be displayed as failure envelope in a 3D stress space with σ_1, σ_2, τ_{12} as coordinate axes (figure 2).

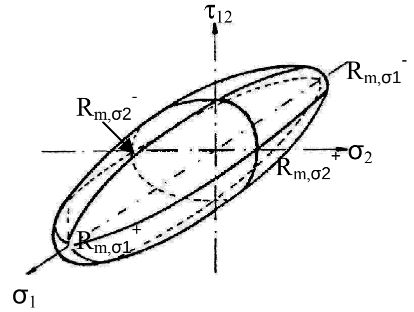

Figure 2. Plane stress state failure envelope.

A particular stress state may be visualized as vector and the application of the failure hypothesis may be interpreted as determination of the distance between the vector and the envelope. It should be noted, that in the case of (uniaxial or multiaxial) off-axis loading, the resulting stress components need to be transformed to the material CS before application of the failure hypotheses. Also, it should be taken into account, that due to the anisotropy, off-axis loading causes additional coupled stress components. For fatigue life assessment, the original formulation needs to be modified by adopting fatigue strengths instead of static strengths at definition of the hypothesis (14). Then, each envelope represents the fatigue strengths at the specific failure number of cycles correlating to the uniaxial fatigue strengths at definition. Furthermore, the failure envelope applies only for the fatigue strengths' stress ratio. The formula of the adapted Tsai-Wu failure hypothesis for fatigue strength evaluation of a plane stress state for transversally isotropic material has the following form (12):

$$F_{11}\sigma_1^2 + 2F_{12}\sigma_1\sigma_2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + F_1\sigma_1 + F_2\sigma_2 \leq 1 \quad (1)$$

with the components of the failure tensors given by:

$$F_{11} = \frac{1}{XX'}, F_1 = \frac{1}{X} - \frac{1}{X'}, F_{22} = \frac{1}{YY'}, F_2 = \frac{1}{Y} - \frac{1}{Y'}, F_{12} = -\frac{1}{2}\sqrt{F_{11}F_{22}}, F_{66} = \frac{1}{S^2} \quad (2)$$

where

$$X = \sigma_{x,t}^{N,R}, \; X' = \sigma_{x,t}^{N,R} \quad (3)$$

Tension/Compression-fatigue strength' in x-direction at N stress cycles at stress ratio R (Y and Y' analogue)

$$S = \tau_x^{N,R} \quad (4)$$

Shear-fatigue strength at N stress cycles at stress ratio R

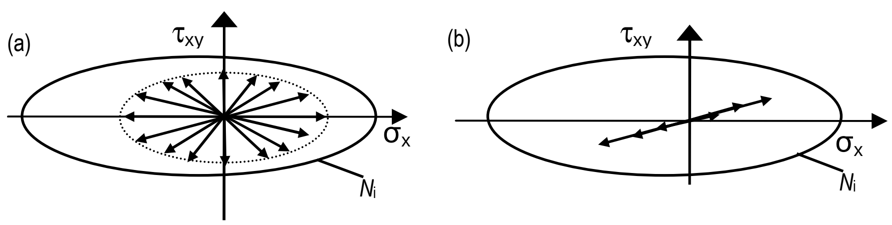

Figure 3. Fatigue failure envelope (σ_y=0) and local stress vector; (a) non-proportional loading (90° phase-shift) , (b) proportional cyclic loading.

At cyclic loading the local stress tensor components vary over time. Multiaxial stress states may arise in two different ways: Off-axis uniaxial cyclic loading of anisotropic material cause stress tensor components which are proportional. More complex, the resulting components from external multiaxial cyclic loading may be proportional or non-proportional, depending on potential phase shifts of the cyclic external loads. Several definitions of proportional loading exist (21). For application of the failure hypotheses described above, the definition of proportionality should be connected with constant plane stress vector direction in the plane stress space (figure 3). Calculation of the reserve based on the fatigue failure hypothesis being the minimum distance between the vectors and the envelope within one stress cycle is straight forward. Non-proportional stress states, however, are rather complex to validate. Various approaches are published considering proportional loading (6)(10)(19). Only very few attempts have been undertaken regarding additional investigation of non-proportional loading (8)(20). Two different methods for the evaluation of the non-proportional stress state are presented in (20): Exclusive observance of the maximum value of each stress component within one load cycle (approach 1) neglecting their actual common appearance within one load cycle. Alternatively, consideration of the real stress vector distribution by continuously computing the reserve within the load cycle (approach 2) (figure 3). In the latter case, fatigue life estimation is based on the most critical vector. In the present paper the methods will be discussed based on experimental results.

3 EXPERIMENTAL

The fatigue behaviour of the SFRP material exposed to proportional local stress components may be investigated experimentally by easy-to-conduct uniaxial off-axis cyclic tension tests on flat specimens (6)(10)(19). Non-proportional local stress states are caused by non-proportional external loading. For investigating the material exposed to those stress states, hollow tubular specimens of 3 mm thickness and with a reduced diameter in the middle were manufactured by injection moulding and axial and torsion loading was applied on the specimens (20). The fatigue tests were carried out at different load ratios R (R=0 and R=-1) and temperatures (Room temperature, RT= 23°C and 130°C) with constant load amplitude and frequency. The experimental program was performed on a servo-hydraulic testing machine. The loading function was sinusoidal and the tests were conducted under load control. The testing system can generate and control the axial and the torsion loads independently from each other. For determination of the basic uniaxial material fatigue strengths, pure axial loading and pure torsion loading was experimentally investigated at first. Under pure cyclic torsion the specimen was left free to move in axial direction, allowing the necessary axial displacements to keep the axial load to zero. Due to the tubular geometry, at pure axial loading, because lateral contraction is restricted an additional circumferential stress in-phase with the axial stress develops. This circumferential stress component was neglected consequently for all load cases as it is an inevitable consequence of tubular components exposed to axial loading. Ongoing investigations focus on applying additional internal pressure for examining arbitrary cyclic plane stress states, the results of which will be presented in the near future. For investigation of the proportional and non-proportional multiaxial local stresses, tests under combined in-phase tensile-torsional loading (R=0 and R=-1 at RT and 130°C) with biaxiality ratio on net stresses $\lambda_{S,n} = \tau_{xy}/\sigma_x = 1$ and tests under combined out-of-phase (phase shifting angle $\delta_S = 90°$) tensile-torsional loading (R=0 and R=-1 at RT and 130°C) with biaxiality ratio $\lambda_{S,n} = 1$ were carried out. Additionally, combined in-phase tensile-torsional loading with biaxiality ratio on net stresses $\lambda_{S,n} = \tau_{xy}/\sigma_x = 1/3$ were conducted. The number of cycles to failure covered by the tests is between 10^2 to 10^7 cycles. Exemplarily, the results for RT are shown in figure 4. Both tension and shear stress amplitudes refer to the net cross section area.

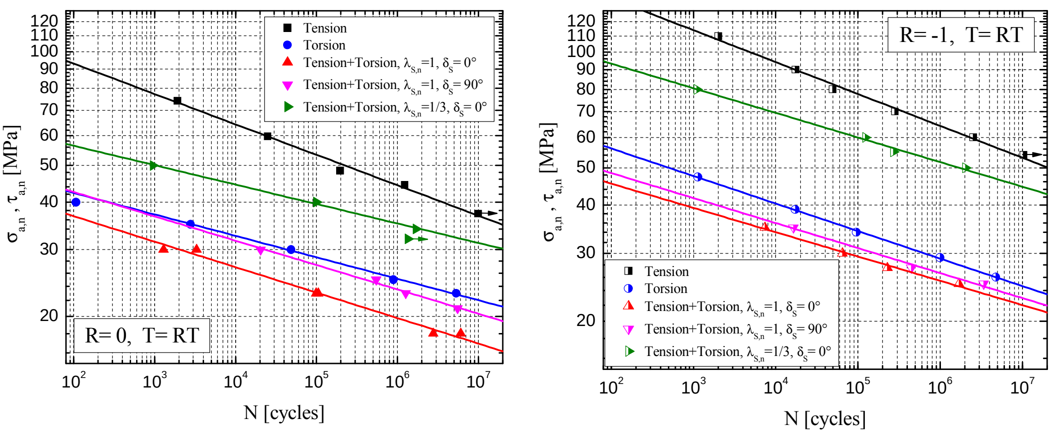

Figure 4. Woehler curves for tubular specimen at RT (200).

4 DISCUSSION

It can be observed from the fracture pattern, that both stress types, normal and shear stress, directly activate failure as pure axial loading results in a fracture line perpendicular to the longitudinal axis of the specimen, pure torsion load initiates a crack along the axis (20). For combined loads, in-phase loading activates a different fracture line (45° with respect to specimen) whereas the out-of-phase loading shows similar fracture as the pure loading cases at crack initiation, i.e. depending on the biaxiality ratio a fracture line perpendicular ($\lambda_{S,n}$=1/3) or along the longitudinal axis ($\lambda_{S,n}$=1) of the specimen arises. Just at larger stress amplitudes, the fracture pattern of the out-of phase loading tends to look similar to the in-phase loading. Thus, for moderate stresses, depending on the biaxiality ratio at out-of-phase loading, a controlling stress component may be defined, whereas at in-phase loading both stress components seem to equally contribute to the failure of the material. These effects are reflected in the woehler lines: comparing the in-phase with the out-of-phase loading scenario, the reduction for combined loading tends to be less pronounced in the later case. As can be shown upon the failure envelope, the applied hypothesis may consider these effects accordingly. However, by definition, approach1 does not distinguish between in-phase and out-of-phase loading, thus predicting equal service life for both loading scenarios. Comparing the fatigue strengths due to multiaxial loading with and without phase shift at RT in figure 4, this approach may be accepted for the load case without mean loading (R=-1). However, for R=0, fatigue life reduction of in-phase loading compared to out-of-phase loading is much more pronounced and may not be estimated realistically with the continuous approach. Approach 2 considers every instant within one load cycle, therefore considers possible phase-shifts between stress components. It produces satisfying service life estimations for the investigated in-phase and out-of-phase load cases. The results are shown in figure 5.

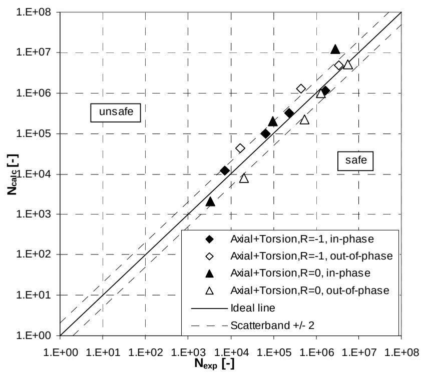

Figure 5. Comparison of experimentally and theoretically determined service lives.

For the in-phase loading, the results are equal to those from the continuous approach. However, the phenomenon of a less pronounced reduction of the service life at out-of-phase loading in the R=0-case compared to R=-1 at RT is still not predictable realistically. This may be caused by circumferential normal tensile stresses, arising from axial compression stress at R=-1, which enforce shear stress failure in that plane. Predicted service life for R=0 are overall on the safe, for R=-1 on the unsafe side.

5 CONCLUSION

Comparison of experiment and theory proves the failure hypothesis to be an appropriate tool for an economic computation of the service life of the SFRP material investigated. The results lie within a narrow scatter band of +/-2, thus for the investigated in-phase and out-of-phase load cases it provides good estimate of the service life of the multiaxially loaded specimens. Hence, a first tool for dimensioning components made of lightly anisotropic material as SFRP is on hand, which might even be adaptable for fatigue life estimation of metallic materials exhibiting lightly anisotropic behaviour.

6 REFERENCES:

1. Predak, S. et al., Damage and its Evolution in Fiber-Composite Materials: Simulation a non-Destructive Evaluation. Edited by G. Busse, B.-H. Kröplin, K. Falk, 2006
2. Olz, R., Cavic, M., Schulz, T., *Kunststoffe*, 88, 1998, pp. 642-647
3. Hauck, C., Brouwers, G., *Kunststoffe*, 82, 1992, pp. 586-590
4. Flemming, M.; Roth, S., *Faserverbundbauweisen. Eigenschaften*, Springer, Berlin, 2003
5. Schwarz, P., Müller, U., Fritz, U., *Kunststoffe*, 82, 1992, pp. 239-242
6. De Monte, M., Moosbrugger, E., Quaresimin, M., *Proceedings of XXXV AIAS*, Università Politecnica delle Marche, 2006
7. Puck, A., Festigkeitsanalyse von Faser-Matrix-Laminaten: Modelle für die Praxis, München; Wien: Hanser, 1996
8. Bolender, K., Büter, A., Sonsino, C.M., *Polymer Forschung Darmstadt I*, 2005, pp. 62-63
9. Moosbrugger, E., Wieland, R., Gumnior, P., Gerharz, J., *DVM – Report* 131, 2004
10. Zago, A., Springer, G.S., *J. Reinf. Plast. Comp*., 20 (7), 2001, pp. 564-595
11. Hill, R., *The Mathematical Theory of Plasitcity*, Oxford University Press, London, England, 1950
12. Philippidis,T.P. and Vassilopoulos, A.P., *J. Comp. Mat.*, 33 (17), 1999, pp.1578-1599
13. Tsai, S.W., Wu, E.M., *J.Comp.Mat.*, 5, 1971, pp. 58-80
14. Degrieck, J. and van Paepegem, W., *Appl. Mech. Review*, 54, (4), 2001, pp.279-300
15. Tsai, S. W., Hahn, H. T., *Introduction to Composite Materials*, Technomic Publishing Co. Inc., Lancaster, USA, 1980
16. Hashin, Z., *ASME J. Appl. Mech*., 47, 1980, pp. 329-334
17. Cuntze, R.G., Deska, R. et. al., *VDI-Fortschrittbericht* (In German), 5 (506), 1997
18. Azzi VD, Tsai SW., Exp. Mech., 5, 1965, pp. 283-28
19. A. Bernasconi, P. Davoli, A. Basile and A. Filippi, Int. J. Fat., 29 (2), 2007, pp. 199-208
20. De Monte, M., Moosbrugger, E., Bolender, K., Quaresimin, M., *Proceedings of XXXV AIAS*, Università Politecnica delle Marche, 2006
21. Socie, D.F., Marquis, G.B., *Multiaxial Fatigue*, Society of Automotive Engineers, Inc., Warrendale, 2000