NONPROPORTINAL MULTIAXIAL FATIGUE BEHAVIOUR OF A SHORT-FIBRE REINFORCED POLYAMIDE – EXPERIMENTS AND CALCULATIONS

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Keywords: Multi-axial fatigue on plain and notched specimen, short fibre reinforced polyamide, failure hypothesis, fatigue calculation

Abstract

This paper deals with the fatigue behaviour of a short fibre reinforced thermoplastic under multi-axial cyclic stress. Based on experimental results on notched and plain specimens, limits of existing methods for the fatigue life estimation in the design process of components exposed to complex multi-axial loads were investigated. 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 between the stress components. Striving for a verified multi-usable fatigue life assessment method, multiaxial load cases were examined experimentally. The experimental results on unnotched and notched specimens and the fatigue life estimation on the basis of the Tsai-Wu-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 the injection moulding technique. Highly loaded components may be reinforced with short fibres in order to assure their functioning over the specified service period. 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 creep effects and thermal expansion may be achieved. A systematic and economical design and dimensioning, especially for the evaluation of notch effects, requires knowledge of the material and component dependent properties. With short fibre reinforced plastics (SFRP), 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 the injection moulding technique, the fibre alignment and thus the degree of anisotropy depends on the component's wall thickness [8], [12] Due to the melt polymer flow during the manufacturing process, within the regions close to the mould walls, shear stresses cause a skin layer where the fibres are 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 (Fig. 1a).

Finally, the cold mould walls create a very thin layer with random fibre orientation near the surfaces. The thickness of the skin layer remains constant over varying wall size, whereas the perpendicular aligned core layer reduces relative to the overall wall thickness [8], [12].

Hence, with a reducing wall thickness, the comparative influence of the fibre alignment within the skin layer, i.e. the degree of anisotropy in stiffness and strength, increases. It should be noted that, due to the layered structure, the impact of anisotropy depends on the loading type, tension or shear. In addition to the loading, complex component geometries cause notches and notches cause locally, highly loaded areas, which also have to be evaluated [22]. In automotive design, during operation structures made from short fibre reinforced plastics (SFRP) may not be exposed just to static loads but also to cyclic loads. Also, not only uni-axial loads acting in the main material direction, i.e. along or perpendicular to the predominant fibre alignment, are to be expected.

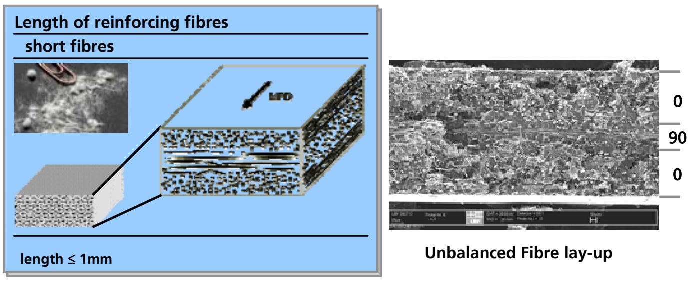


Figure 1a: Fibre orientation [3]

These simple uni-axial loads cause complex multi-axial stress states within an anisotropic material. For the dimensioning of cyclic loaded safety components, multi-axial stress states that may arise from these arbitrary external uni-axial and multi-axial load scenarios need to be paid special attention to [7], [14], [16].

The failure hypothesis that the design is based on must take all relevant stress components into account, including their interaction and must consider the material's anisotropic strength behaviour. In particular, the assessment of multi-axial 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 the present day, the design of FRP components is prevalently based on static characteristics such as tension strength, yielding strength or ultimate strain. If there are cyclically loaded safety components, these values are not sufficient. Customarily, influencing factors such as fibre orientation, temperature, aging, mean stress, multi-axial stress states, dynamic/cyclic loading and scatter are accounted for with empirical diminishing coefficients. The concept presented in this paper follows a different approach for the dimensioning of components made of SFRP. Therefore, in the present study, combined loading of tension and shear on plain and notched tube-like specimens will be considered.

2 Theoretical Background

Due to the fibre alignment of the injection moulded SFRP, the material behaves overall in an orthotropic manner. Accordingly, a respective coordinate system, in the following termed the 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 such as 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 uni-axial loading depends on the direction of the load with respect to the material CS (along/perpendicular to the predominant fibre direction) and, in the case of off-axis loading, this may additionally cause complex multi-axial stress states. Thus, the deduction of an equivalent stress in the case of multi-axial stress is not advisable for anisotropic materials. Different failure hypotheses for anisotropic, usually continuously fibre reinforced, materials exist in the literature [4], [10], [11], [19], [20], [23]. Common to most hypotheses, a rather phenomenological approach, assuming homogenous material behaviour over the thickness, is adopted. Continuous fibre reinforced multilayer laminates are therefore customarily evaluated layer wise with rotational symmetry about the fibre axis and, in general, with a plane stress state assumption, i.e. the (small) stresses in the thickness direction are disregarded. Rarely is the laminate evaluated as a whole, neglecting the lay up [17]. Obviously, the condition of the layer wise evaluation is that of 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. Firstly, the components of the stress tensor in the material CS were evaluated directly with respect to possible interaction in a rather mathematical/global way [13], [23], [1]. Later, the assessment was based on invariants considering the transverse isotropy [11], [4]. 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 combinations of the stress components are evaluated with respect to the physical section plane that 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 [19]. The benefit of the latter is the detailed physical inspection, which is not just able to differentiate between different failure mechanisms, but also to predict the failure section plane and assess it with reference to 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 of predicting overall failure. Thus, obviously, direct mode failure hypotheses give more detailed information and are based on physical means. However, extensive experimental investigations are needed in order 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 [17]. 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 in which the fibres are aligned along the loading direction, matrix failure will be preceded by steadily increasing fibre pull out [18]. With matrix failure being the crucial failure mechanism and with the application of a failure estimation approach that neglects the layer wise composition, differentiation between different failure mechanisms becomes obsolete. From the economical point of view, the use of an easy-to-implement global hypothesis therefore seems reasonable. In the investigation presented here, the global Tsai-Wu failure hypothesis for plane stress states was adopted and the local plane stress state on the component's surface was analysed. As opposed to other global failure hypotheses, 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 [23]. 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 in uni-axial loading with respect to the material CS, $R_{m,\sigma1,t}$, $R_{m,\sigma1,c}$, $R_{m,\sigma2,t}$ and $R_{m,\sigma2,c}$ as static tension (t) and compression (c) strength in 1 (fibre) and 2 (perpendicular to fibre)-directions and $R_{m,\tau}$ as static shear strength.
Thus, before application of the failure hypothesis, the basic uni-axial 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 collectivist of estimated critical multi-axial stress states may be displayed as a failure envelope in a 3D stress space with σ_1, σ_2, τ_{12} as coordinate axes. A particular stress state may be visualized as a vector and the application of the failure hypothesis may be interpreted as the determination of the distance between the vector and the envelope. It should be noted that, in the case of (uni-axial or multi-axial) off-axis
loading, the resulting stress components need to be transformed to the material CS before application of the failure hypothesis. 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 in the definition of the hypothesis [5]. Then, each envelope represents the fatigue strengths at the specific failure number of cycles correlating to the uni-axial 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 [17]:

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

with the components of the failure tensors given by:

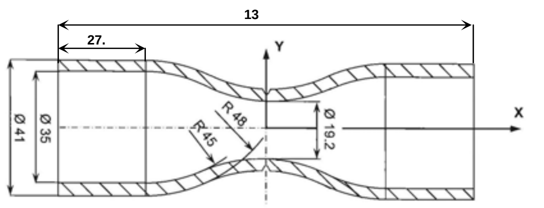
$$F_{11} = \frac{1}{XX'}\,;\quad F_1 = \frac{1}{X} - \frac{1}{X'}\,;\quad F_{22} = \frac{1}{YY'}\,;\quad F_2 = \frac{1}{Y} - \frac{1}{Y'}\,;\quad F_{12} = -\frac{1}{2}\sqrt{F_{11}\,F_{22}}\,;\quad F_{66} = \frac{1}{S^2}$$

where , $X = \sigma^{N,R}_{x,t}$, '$X' = \sigma^{N,R}_{x,c}$ Tension (t)/Compression (c)-fatigue strength' in x-direction at N stress cycles at stress ratio R (Y and Y' analogue) and
$S = \tau^{N,R}_{x,t}$ Shear-fatigue strength at N stress cycles at stress ratio R

For cyclic loading the local stress tensor components vary over time. Multi-axial stress states may arise in two different ways: off-axis, uni-axial cyclic loading of anisotropic material causes stress tensor components, which are proportional to each other (in phase); in a more complex scenario, the resulting components from external multi-axial cyclic loading may be proportional or non-proportional, depending on potential phase shifts of the cyclic external loads. Several definitions of proportional loading are possible [21]. For the application of the failure hypothesis described above, the definition of proportionality should be connected with a constant plane stress vector direction in the plane stress space, where calculation of the reserve based on the fatigue failure hypothesis being the minimum distance between the vectors within one stress cycle and the envelope is straight forward. Non-proportional stress states, however, are rather complex to validate. Various approaches have been published that consider proportional loading, [6], [8], [24]. Only a few attempts have been undertaken of the additional investigation of non-proportional loading [2], [7], [14]. In [16] one method for the evaluation of the non-proportional stress state were tested on unnotched and notched specimens. This method based on the consideration of the real stress vector distribution by continuously computing the reserve within the load cycle. Here the fatigue life estimation is based on the most critical vector didn't work very well (method 1).
Based on this, we integrated a damage accumulation considering the different stress states maximum shear stress and maximum tension stress (method 2). Compared to method 1 the calculated results are much better.

3 Experimental investigations on specimens with multiaxial loading

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 [8], [24]. Non-proportional local stress states are caused by non-proportional external loading. For the investigation of the material exposed to these stress states, notched and plain hollow tubular (tube-like) 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 to the specimens [7]. The fatigue tests were carried out at different load ratios R (R=0 and R=-1), temperatures (Room temperature, RT= 23°C and 130°C) and notch factors (K_{ta}=1 for axial load, K_{tt}=1 for torsional load, K_{ta}=4,9 and K_{tt}=2,4 referring to the medial plane of the specimen) with constant load amplitude and frequency.



plain with t=3 mm, $K_{ta} = K_{tt} = 1$ and
notched with r=0,2 mm, t*=2 mm, $K_{ta} = 4.9$, $K_{tt} = 2.4$

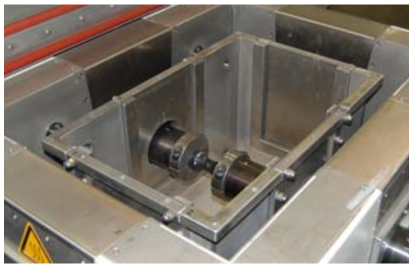


Figure 2. Experimental Setup: (a) Specimen and (b) Test Rig at LBF

The experimental program was performed on a servo-hydraulic testing machine (Fig. 2). 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 of each other.

4 Investigations on Plain Specimens

For the determination of the basic uniaxial material fatigue strengths, pure axial loading and pure torsion loading were first experimentally investigated. Under pure cyclic torsion, the specimen was left free to move in the axial direction, allowing the necessary axial displacements to keep the axial load at zero. Due to the tubular geometry, in pure axial loading, because lateral contraction is restricted, an additional circumferential stress in-phase with the axial stress develops. This circumferential stress component was consequently neglected for all load cases, as it is an inevitable consequence of a tubular component's being exposed to axial loading. For further investigations, additional internal pressure can be generated, for the examination of arbitrary cyclic plane stress states. For the 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 nominal stresses $\lambda_{S,n}=\tau_{xy,n}/\sigma_{x,n}=1$ and tests under combined out-of-phase (phase shifting angle δ_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, tests with combined in-phase tensile-torsional loading with biaxiality ratio on net stresses $\lambda_{S,n}=\tau_{xy,n}/\sigma_{x,n}=1/3$ were conducted. By way of example, the results for RT are shown in [7]. Both tension and shear stress amplitudes are nominal stresses that refer to the net cross sectional area. It can be observed, from the fracture patterns, 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 and pure torsion load initiates a crack along the axis [7]. For combined loads, in-phase loading activates a different fracture line (at 45° with respect to the specimen axis) whereas the out-of-phase loading shows similar fracture to the pure loading cases at crack initiation, i.e. depending on the biaxiality ratio, a fracture line perpendicular to ($\lambda_{S,n}$=1/3) or along the longitudinal axis ($\lambda_{S,n}$=1) of the specimen arises. Only at larger stress amplitudes, does the fracture pattern of the out-of phase loading tend to look similar to the in-phase loading. Thus, for moderate stresses, depending on the biaxiality ratio for out-of-phase loading, a controlling stress component may be defined, whereas, for in-phase loading, both stress components seem to contribute equally to the failure of the material. These effects are reflected in the Wöhler curves: comparing the in-phase with the out-of-phase loading scenario, the reduction for combined loading tends to be less pronounced in the latter case.

Calculation Results: The comparison of the calculation results presented in [14] with the new results based on the damage accumulation are shown in Fig. 4a and Fig. 4b. The different stress states with 90° phase shift (Fig. 4b) shows a more satisfactory service life estimations. Compared to the results presented in Fig. 4a the calculated service life, at biaxial tension-torsion loading $\lambda_{S,n}$=1/3 and the biaxial tension-torsion loading $\lambda_{S,n}$=1, is moved to the save side. This may be caused by the influence of the non-proportional stress state, which enforces failure in the critical plane and takes into account by damage accumulation. Predicted service lives for $\lambda_{S,n}$=1 with R=0 are more on the safe side, whereas, the results for $\lambda_{S,n}$=1, R=-1, $\lambda_{S,n}$=1/3 R=0 as well as for R=-1 are lie within a narrow scatter band.

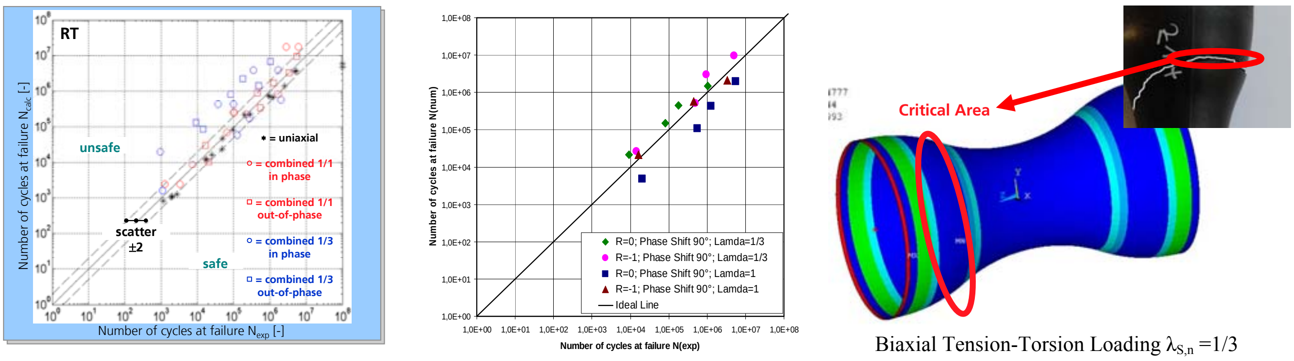


Figure 4. Comparison of experimentally and numerically determined service lives a) based on [14]; b) with the new accumulation method (90° Phase Shift) and c) Calculated lifetime (FE) [3]

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 more or less within a narrow scatter band, thus, for the investigated in-phase and out-of-phase load cases, the hypothesis provides a good estimate of the service life of the multi-axially loaded specimens. Hence, an initial tool for dimensioning components made of moderately anisotropic material such as SFRP is now to hand, which might even be adaptable for fatigue life estimation of metallic materials exhibiting moderately anisotropic behaviour. The dimensioning tool was implemented in a finite element program. A result, the computed lifetime distribution, is shown in Fig. 4c. Especially for biaxial torsion-tension loading $\lambda_{S,n}$=1/3, the calculated critical area is not in the minimum cross section, as expected, and this fits with the experimental result.

5 Investigations on Notched Specimens

In an analogous approach to that for the plain specimens, for determination of the basic uniaxial material fatigue strengths, pure axial loading and pure torsion loading were first of all experimentally investigated. For the 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 with biaxiality ratio on nominal stresses $\lambda_{S,n}=\tau_{xy,n}/\sigma_{x,n}=1$ and tests under combined out-of-phase loading (phase shifting angle δ_S = 90°) were made [9]. As an example, the results for RT are shown in Fig. 5. Both tension and shear stress amplitudes are nominal stresses that refer to the notches cross section.

It can be observed, from the fracture patterns, that all stress types, normal and shear stress, result in a fracture line in the notch, perpendicular to the longitudinal axis of the specimen.
In comparison to the plain specimens (K_{ta}=K_{tt}=1), the influence of the phase shifting was increased and interchanged. The lifetime for a given load-level is, in the case out-of-phase loading, smaller than in the case of in-phase loading. It seems that, for in-phase and out-of-phase loading, both stress components contribute equally to the failure of the material.

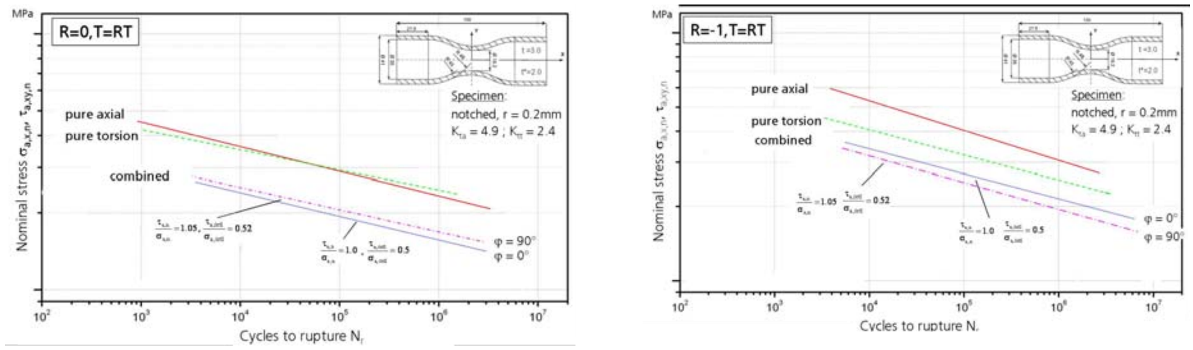


Figure 5. Wöhler curves of notched specimen at room temperature [9]

Calculation Results: Comparison of experiment and theory based on method 1 was shown in [16] and is presented in Fig. 6a. The hypothesis produces satisfactory service life estimations for the investigated in-phase load cases. Predicted service lives for in-phase loading of notched specimens are more or less in a small scatter band.
However, the reduction of service life for out-of-phase biaxial tension-torsion loading was not assessed realistically. These results suggest that damage occurs for various stress vector directions, referring to Fig. 4, and not only for the most critical stress vector direction, as currently assumed in the modelling. Figure 6b shows the comparison of experiment and theory based on a new calculation method for out-of-phase biaxial tension-torsion loading. Predicted service lives for in-phase loading of notched specimens are similar to Figure 6a. However, due to the damage accumulation considering the different stress states maximum shear stress and maximum tension stress implemented in the new calculation method 2, now the reduction of service life for out-of-phase biaxial tension-torsion loading was assessed realistically and the calculated and measured live time are located in a more or less small scatter band.

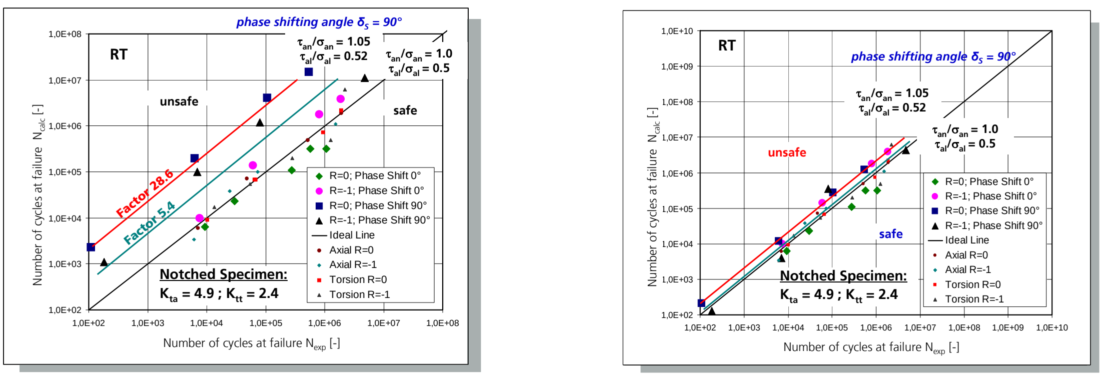


Figure 6. Comparison of experimentally & theoretically determined service lives a) based on [16] and b) with the new approach.

These results suggest that damage occurs for various stress vector directions, referring to Fig. 4, have to take into account. The consideration of the most critical stress vector direction only, is not enough. These results have to verify with additional out of phase test results based on various tension-torsion stress ratios as well as various phase shifts. After prove this failure hypothesis can be an appropriate tool for an economic computation of the service life of the notched SFRP material.

6 Summary and Conclusions

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. Considering the damage occurs for various stress vector directions the results lie within a narrow scatter band, for the investigated in-phase and out-of-phase load cases, the hypothesis provides a good estimate of the service life of the multi-axially loaded unnotched and notched specimens. An initial tool for dimensioning components made of moderately anisotropic material such as SFRP is now to hand, which might even be usable for in-phase and out-of-phase fatigue life estimation of metallic materials exhibiting moderately anisotropic behaviour.

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