FATIGUE DESIGN OF SHORT FIBRE REINFORCED POLYMERS

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Abstract

At the present time, the amount of fibre reinforced polymers used for lightweight design applications is increasing steadily. Mainly in the high loaded region of a component, a complex multi axial stress concentration emerges, which is difficult to characterise due to its anisotropic material properties. Material data that consider the anisotropic properties for multi axial stress concentration are often not available. Additionally, the knowledge of the fatigue performance of multi axially loaded components and the design of such components is a great challenge in application.

This paper presents the results achieved in investigations of the fatigue design and the durability performance of a complex short fibre reinforced structural component, the "Multi Tester". The MultiTester is a novel internal pressure test specimen. The loading induces a complex multi axial stress concentration in the highly loaded region. By the use of the Tsai-Wu failure hypothesis, the life time of the MultiTester will be determined and compared with experimental test results.

1. Introduction

Polymers are being increasingly used for functional- and safety components [1] [2] [3] [4]. Polymers offer several advantages, in addition to lightweight design properties, such as new design methods, integration of functions and better acoustic properties.

For example, polyamides have been identified as being convenient for the cost effective mass production of complex structural components, manufactured by the injection moulding technique. Several types of polyamides have special advantages due to their use in a high temperature range, in aggressive fluids or in aging conditions. Heavy loaded structural components made of polymers can be reinforced with fibres to assure their functions over their whole use.

The reinforcement with fibres has a great impact on the mechanical properties and the manufacturing processes of components. Fibres increase stiffness and strength and, additionally, a reduction in creep effects may be achieved. For reinforcement, different fibre lengths and types are available on the market. These are classified into three different groups (figure 1 left). Fibres up to 2 mm maximum length are denoted as short fibres, long fibres lie in the range from 2 mm up to 10 mm and longer fibres are termed continuous.

A leading production process for short fibre reinforced polymers (FRP) is the injection moulding technique. The fluid flow of the material in the mould creates anisotropic material properties.

The shear flow creates a fibre orientation lengthwise in the flow direction in the marginalised layer and the elongational flow causes a fibre orientation crosswise in the flow direction in the intermediate layer (figure 1 right).

These properties of anisotropic materials mean that the design and dimensioning is much more complex than for isotropic materials. Stiffness and strength depend on fibre direction. If the anisotropic properties are considered in the design process, the full potential of structural durability and lightweight design can be realised.

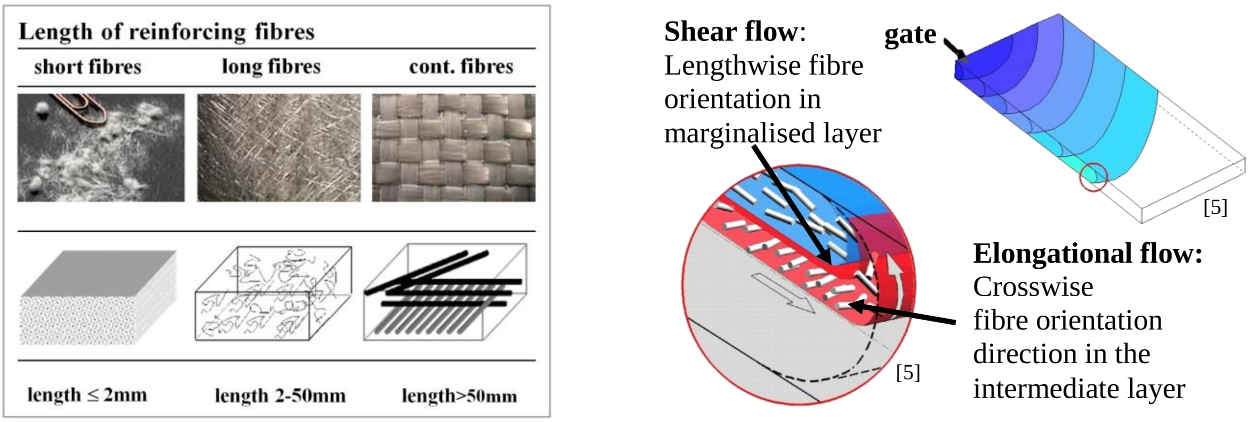

Figure 1. Classification of fibre reinforcement and different fibre orientation induced by the injection moulding technique [5]

Compared to isotropic materials, different failure mechanisms for FRP have to be considered. Within one layer it is necessary to differentiate between fibre failure and inter fibre failure.

For short fibre reinforced polymers, inter fibre failure may be a predominant failure mechanism. The inter fibre failure starts with a local material degradation. Initially there is separation of fibres and matrix (debonding). The low tensile strength of the matrix material compared to the fibres causes matrix cracking in the vicinity of these areas. [6]

The design and dimensioning of structural components made from FRP requires knowledge of the material’s strength and stiffness. These are controlled by the types of fibres, the fibre volume and the direction of the fibres. In particular, the manufacturing process has a direct influence on the local fibre orientation. To use all of the benefits, which are fundamental for lightweight design, detailed experimental material investigations are necessary.

During use, lightweight structures suffer different types of loadings. These are not only static loadings but also dynamic and cyclic loadings. In addition to the mechanical loadings and the geometric shape of the component, it is essential to consider ambient conditions, such as temperature, operating medium and climate.

Loadings under operational conditions and the anisotropy of FRP often induce a multi axial stress state, which is a great challenge for the consideration of these properties in designing and dimensioning structural components.

For the quantitation of complex multi axial static loadings for isotropic materials, several mean stress concepts have been established. For anisotropic materials, a number of concepts exist for the evaluation of multi axial stress state. The most familiar concepts are Norris (1962), Tsai-Hill (1965), Hoffmann (1967), Tsai-Hahn (1980) and Tsai-Wu (1971). The application and use of such concepts is very complex and needs much user experience. Additionally, special material data have to be investigated in experimental testing for different types of loading.

Structural components made from polymers are often dimensioned using static mechanical property values and safety factors. These methods can be used for dimensioning structural components, but do not realise the full potential of structural durability and lightweight design. The interaction of several influencing factors such as:

- Notches,
- Fibre orientation,
- Temperature,
- Aging,
- Influence of corrosive fluids,
- Multi axial loading and
- Scatter

will not be considered by these methods [7]. Additionally, the determination of safety- and knock-down factors could lead, on the one hand, to an excessively heavy design, or, on the other hand, to an unsafe design.
To use the full lightweight potential of the material, several complex material properties for dimensioning a structural component made of short fibre reinforced polymers have to be considered. The nonlinear material behaviour of polymers requires complex design methods such as integrative simulation, which considers the local fibre orientation from injection moulding for the numerical calculation of short fibre reinforced structural components.
In this paper, a new approach will be presented for the fatigue design of multi axially loaded anisotropic structural components. Therefore, a new test specimen, the MultiTester, is used, which is loaded with internal pressure. By the application of the Tsai-Wu failure hypothesis and a local stress concept, the durability of the MultiTester will be determined. Through a comparison of experimental testing and numerical lifetime assessment, the accuracy of the concept will be evaluated.

2. Fatigue analysis

Fatigue tests were carried out on the MultiTester to determine the fatigue performance for cyclic internal pressure loading. The MultiTester's design concept is constructed so that failure occurs lengthwise in the pressure barrel (figure 2, left).

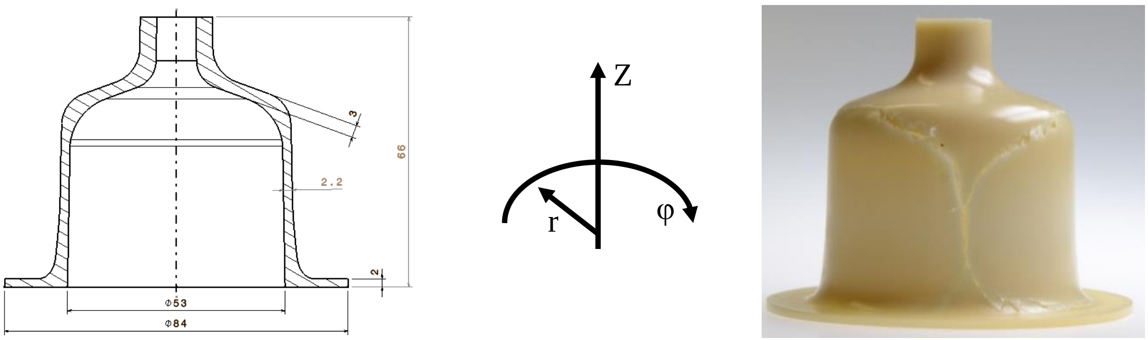

Figure 2. Geometric shape of the MultiTester (left), cylindrical coordinate system (middle), failure mode of the MultiTester for inner pressure loading (right)

In the region of the failure, a multi axial stress concentration is generated in the structure by the internal pressure. The multi axial loading, defined in cylindrical coordinates (figure 2 middle) consists of three different components:

- Tension in the axial direction (Z-direction)
- Tension in the circumferential direction (φ-direction)
- Shear in the plane of the axial direction and radial direction (Plane of Z- and r-direction)

The manufacturing process of the MultiTester is the injection moulding technique. The viscous thermoplastic resin enters the mould in the bottle neck of the specimen via a fan gate. The material used is a Polyamide 66 with 50 weight percent glass fibres (PA66 GF50). As mentioned earlier, the fluid flow of the viscous thermoplastic resin involves lengthwise fibre orientation in the flow direction in the marginalised layers. In the middle layer, a crosswise fibre direction arises in the flow direction of the viscous thermoplastic resin.
Fatigue tests were carried out to determine S/N-curves for the MultiTester to investigate the durability for internal pressure loading. Therefore, the MultiTester was loaded with constant amplitudes (Woehler). The medium used for internal pressure testing was hydraulic oil and the tests were carried out at room temperature. The stress ratio for cyclic internal pressure testing on the MultiTester, R, was R = 0.1 and is defined as the ratio of minimum to maximum pressure of the loading (see equation 1).

$$R = \frac{P_{min}}{P_{max}} \tag{1}$$

The test frequency for cyclic testing has an influence on local warming of the specimen. Hence, the test frequency was set to values, where the local warming of the specimen is minimised [8] [9]. The failure criterion was the rupture of the specimen or the achievement of the maximum number of load cycles $N_{max} = 4 \cdot 10^6$. In figure 3 right, the clamping device for cyclic internal pressure testing is displayed.

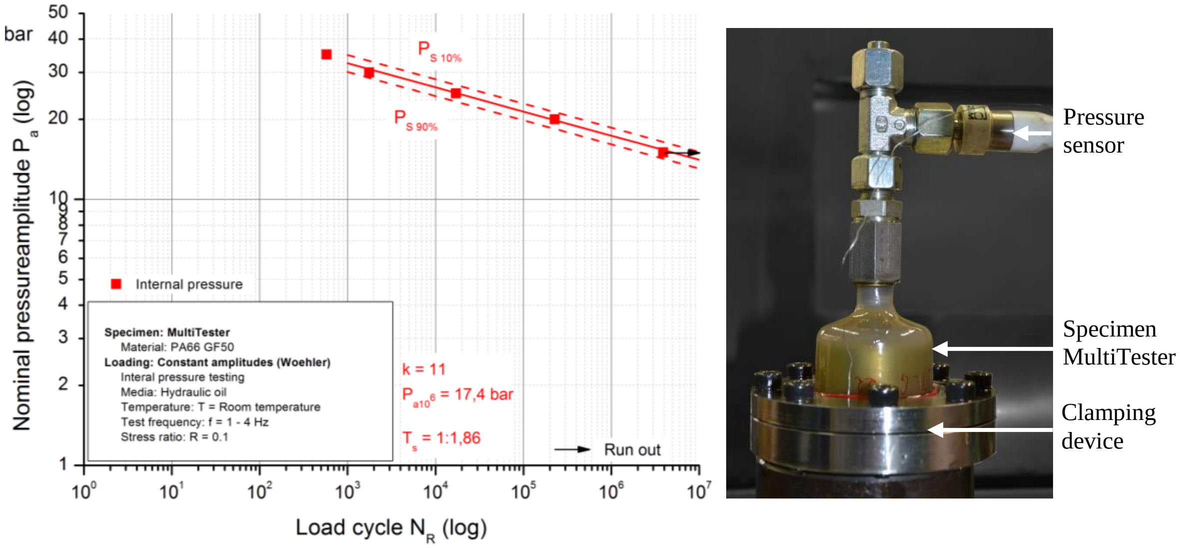

Figure 3. S/N-curve of the MultiTester, loading by internal pressure

The results of the cyclic internal pressure testing are displayed in an S/N-curve in figure 3. It should be pointed out that there is a low scattering of the results and additionally the rupture of the specimens was lengthwise in the wall thickness (figure 2 right) as was expected from the numerical calculation and the local fibre direction. The S/N-curve defining parameters have the following values, the slope k is k = 11, the nominal pressure amplitude for 10^6 load cycles is $P_{a,10^6} = 17.4$ bar and the scatter band T_P is $T_P = 1:1.86$.

3. Numerical approach

3.1 Tsai-Wu failure criterion

Instead of the classical stress hypothesis, the Tsai-Wu failure hypothesis does not identify a reduced stress level but a vector as reference value for multi axial loading. The three stress components of the plane stress σ_x, σ_y, and τ_{xy} are plotted as vectors in a three dimensional stress space with $\sigma_1 = \sigma_x$, $\sigma_2 = \sigma_y$, $\tau_{12} = \tau_{xy}$, as coordinate axes (figure 4) [6].

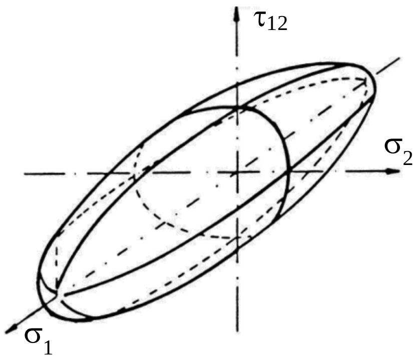

Figure 4. Tsai-Wu failure envelope in 3D stress space, $\sigma_1 = \sigma_x$, $\sigma_2 = \sigma_y$, $\tau_{12} = \tau_{xy}$ [10]

In general:

$$F_{i,j} \cdot \sigma_i \cdot \sigma_j + F_i \cdot \sigma_i = 1 \quad (2)$$

Transversally isotropic case (e.g. UD layer) with coordinate system for plane stress state (1 = x, 2 = y) in fibre direction

$$F_{xx}\sigma_x^2 + 2F_{xy}\sigma_x\sigma_y + F_{yy}\sigma_y^2 + F_{ss}\tau_{xy}^2 + F_x\sigma_x + F_y\sigma_y = 1 \quad (3)$$

The coefficients are:

$$F_{xx} = \frac{1}{X \cdot X`};\ F_x = \frac{1}{X} - \frac{1}{X'};\ F_{yy} = \frac{1}{Y \cdot Y'};\ F_y = \frac{1}{Y} - \frac{1}{Y'};\ F_{xy} = -\frac{1}{2} \cdot \sqrt{F_{xx} \cdot F_{yy}};\ F_{ss} = \frac{1}{S^2} \quad (4)$$

$X = \sigma_{x,t}^{N,R}$ Tension fatigue strength in x-direction at N load cycles at stress ratio R
$X' = \sigma_{x,c}^{N,R}$ Compression fatigue strength in x-direction at N load cycles at stress ratio R (Y and Y` analogue)
$S = \tau_{xy,t}^{N,R} = \tau_{xy,c}^{N,R}$ Shear fatigue strength at N load cycles at stress ratio R

If the stress vector varies over the load period, the stress vector changes its direction and length within one load cycle. The strength of the set of all possible multi axial and uniaxial stress combinations defines an envelope around the coordinate system origin and is called the failure envelope (figure 4). The failure envelope is defined by a quadratic polynomial and is based upon the three static plane stress state material strength properties for uniaxial loading. In this approach, the Tsai-Wu quadratic failure hypothesis used is modified to consider cyclic loading. Therefore, a programmed data base fits data input for cyclic loading. The fatigue strength has to be investigated experimentally using specimens for cyclic loading with different fibre orientation. [6]

S/N-curves were determined for the fibre orientations 0°, 45 ° and 90° and two different stress ratios R = 0 and R = -1. The S/N-curve defining parameters investigated experimentally, the slope k and the nominal stress amplitude for 10^6 load cycles $\sigma_{a,10^6}$, were integrated into a programmed data base, which fits the data into a three dimensional numerical Tsai-Wu failure envelope.

3.2 Numerical calculation

The numerical calculation via Finite Element Analysis (FEA) is used to determine the local stress concentration of the MultiTester. Therefore, the MultiTester was meshed with second order quadratic elements. The loading is internal pressure and the boundary conditions are equal as in the experimental testing. In general the stress concentrations in the axial direction and the circumferential direction are displayed for the internal pressure of P = 104.7 bar (figure 5).

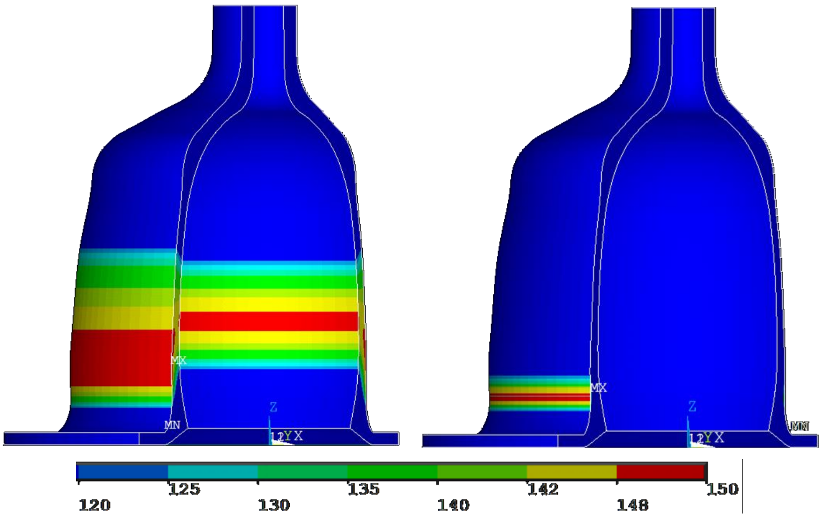

Figure 5. Numerical local stress calculation of the MultiTester via FEA; left: stress in axial direction; right: stress in circumferential direction

4. Application

By the use of the fatigue strength of short fibre reinforced uniaxially loaded specimens from experimental testing, a failure model was derived. Based on the Tsai-Wu quadratic failure hypothesis for the material investigated, the fatigue service life of the multiaxially loaded MultiTester should be theoretically approximated and compared to the actual service life. In figure 6, the experimental and the calculated life time, based on the Tsai-Wu quadratic failure hypothesis, are displayed.
The comparison of experiment and theory highlight that the Tsai-Wu failure hypothesis is an efficient and economic tool for the life time assessment of short fibre reinforced polymers. It should be noted that the Tsai-Wu failure hypothesis slightly underestimates the material's performance. One possible reason for this effect could be the determination of the numerical material defining values for the FEA and creep effects during testing, which are not considered in the calculation. In summary, the life time under operating conditions of multi axially loaded structural components can be estimated by the appropriated Tsai-Wu failure hypothesis.

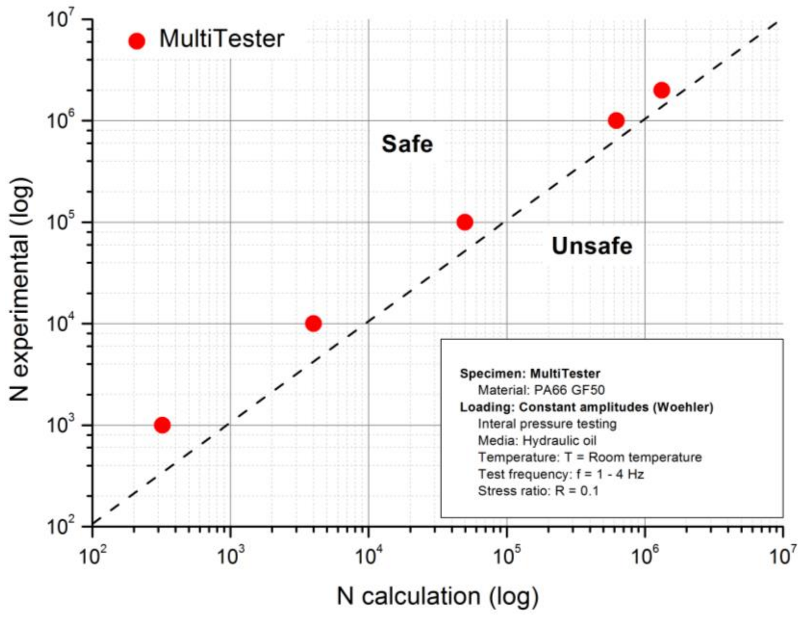

Figure 6. Comparison of experimental results and the estimation of the fatigue service life with the Tsai-Wu failure hypothesis

5. Outlook

This paper concerns the life time assessment of unnotched structural components with multi axial loading. Only the stress ratio of R = 0.1 was considered in the comparison of experiment and numerical calculation. Structural components are often loaded with different stress ratios and variable amplitudes during service life. Therefore, further investigations are necessary to apply the failure hypothesis to different stress ratios and variable amplitude loading.

Most structural component designs include notches. Hence, the application of the failure hypothesis on notched structural components has to be investigated next. Therefore, fatigue strength of notched specimens has to be investigated and integrated into the Tsai-Wu failure hypothesis. Additionally, an evaluation of the numerical life time assessment and experimental component testing has to be carried out. For notches, it is difficult to characterise a maximum, which can be used as a level for design. Therefore, the concept of highly stressed material volume, V_{80} as it is mentioned in [11], should be applied in using the Tsai-Wu quadratic failure hypothesis for the lifetime assessment on components loaded with internal pressure. Therefore the MultiTester has to be redesigned, that failure occurs in the notched region of the MultiTester.

For safe and reliable lightweight structures, it essential to consider the real loadings under service conditions. The presented tool optimises component design and points out weak spots at an early stage of design. This method can save a large amount of money and reduce time to market extensively.

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