

Fatigue Analysis of Continuously Carbon Fiber Reinforced Laminates

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ABSTRACT

Lightweight constructions and the reduction of production time and costs is of increasingly importance. Therefore, engineers make a lot of effort to replace metallic parts by other materials. Carbon fiber reinforced laminates are suitable in many cases because of their high specific strength and the low specific weight. The available material-data of this material group from datasheets are mostly static values like tensile strength and fracture elongation. For the fatigue assessment of parts regarding geometry, loading conditions and material behavior, static material data are not sufficient, but also the knowledge of the local S-N curve is necessary. Component specific effects, such as fiber orientation, type of loading, mean stress, temperature, production process and many more, essentially influence these local S-N curves, determined by the material. For fatigue life prediction an assessment method was established, which takes into account the fiber orientation and considers different types of failure mechanisms like fiber fracture, inter fiber fracture and delamination. As input data, structural stresses are needed analyzed by the Finite Element Method, where the local orthotropic material behavior for each ply has been considered. A hypothesis for fatigue life prediction of orthotropic carbon fiber reinforced materials has been derived based on the well-known static failure criterion of Puck, implemented into a standard fatigue software tool and verified so far with component tests. The hypothesis is applicable even for general random-like and multi-axial loads.

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INTRODUCTION

Continuously fiber reinforced composites have been increasingly applied in various applications during the last decades due to their usability in lightweight constructions and outstanding mechanical properties. To assure both weight reduction and safety, material utilization has to be optimized by producing load-tailored and individually designed composite parts. Assessing expected stresses and possibly occurring failure is of tremendous importance to achieve these objectives and can be realized by conducting mechanical tests and using predictive theories. In contrast to most metallic materials, highly anisotropic material behavior has to be taken into account influencing not only the mechanical properties but also damage mechanisms.

Among different theories describing and predicting composite failure, Puck [1, 2, 3] characterized failure under quasi-static loads with a stress-based criterion considering five different failure modes. Due to the differentiation between fiber and matrix dominating failure mechanisms, Puck's criterion can consider physically motivated material behavior rather than criteria by e.g. Hashin or Tsai-Hill [4, 5]. Puck's five failure modes are defined as two modes for fiber failure (FF) under tension and compression load and three modes describing inter-fiber failure mechanisms (IFF). The IFF modes distinguish between matrix failure due to tension (Mode A), compression (Mode B) or combined compression and shear load

(Mode C) [3] (Figure 1). Consequently, Puck's criterion allows not only the prediction of critical stresses but of the expected failure mode as well. Failure criteria are often visualized by fracture surfaces or fracture bodies. Puck's criterion and Tsai-, Hill- or Wu-like global stress criteria for the $(\sigma_1, \sigma_2, \tau_{21})$ -space are compared in a schematic way in Figure 2 [6]. The definition of the parameters can be found in the section "Nomenclature" at the end of the paper.

If composite structures are exposed to cyclic loads such as mechanical loads or temperature changes, which is a very likely scenario during their operation time, the prediction of the material behavior becomes even more complex due to the occurring damage mechanisms. Common damage mechanisms in composite materials are matrix cracking, fiber matrix debonding, delamination or fiber fracture. These damage mechanisms may change, progress or interact during fatigue-life and decrease the mechanical properties such as stiffness and strength [7, 8, 9]. Additionally, fatigue-induced damage mechanisms depend not only on the direction of fibers in relation to the applied load, but also on the amplitude and frequency of the cyclic load [10], and on the mechanical mean stress. Due to the described material behavior, accurate fatigue-life prediction tools considering the variety of aspects of continuously fiber-reinforced materials are still in their early stages. Various studies regarding this issue have been published in the last decades pursuing different approaches e.g. [11, 12, 13, 14].

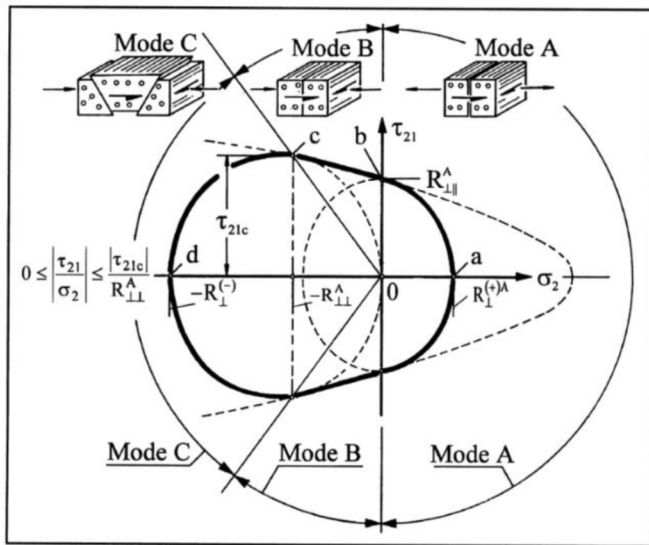


Figure 1. Inter-fiber fracture (IFF) modes A, B and C for $\sigma_1 = \text{zero}$ [2].

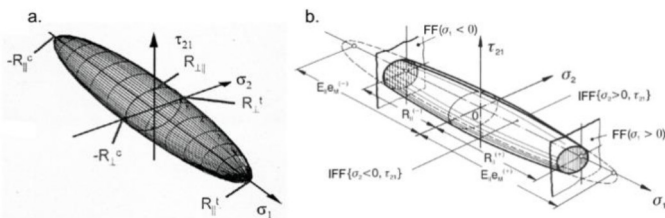


Figure 2. Visualization of fracture criteria for unidirectional fiber reinforced composites: (a) Tsai-, Hill- or Wu-like global stress based criteria and (b) the 2D representation of Puck's action plane related criteria referring to [6] named "Puck's fracture cigar".

For metallic materials, theories based on fatigue strength, usually represented by stress versus number of cycles curves (S-N curves), are widely spread and have been implemented successfully in software tools for fatigue-life prediction. One software tool is Finite Element Fatigue (FEMFAT) developed by Magna Powertrain Engineering Center Steyr GmbH & Co KG (St. Valentin, Austria) [15]. In contrast to the studies published for composite materials so far, a very comprehensive, engineering approach is used. The real part geometry, quasi-static and fatigue material data reflecting effects on the material behavior, the applied load-time history caused by the application and local stresses calculated by finite element (FE) analysis are taken into account. For each node of the finite element mesh, local S-N curves are predicted [16, 17]. Critical damages are calculated according to the critical plane concept [18, 19, 20]. Thereby, damage accumulation is performed for all planes at defined angles, at each node. The plane, in which the calculated damage reaches a maximum, is considered as critical. The equivalent stresses occurring in the critical planes are classified by rainflow-counting. Subsequently, damages are calculated based on the local S-N curves and accumulated to the total damage sum. This software tool has been successfully adapted for fatigue-life prediction of orthotropic materials [21]. For injection molded short fiber reinforced plastics, anisotropic material behavior and effects caused by the injection molding process can already be taken into account. The functionality

of simulation chains from injection molding simulation to lifetime prediction has been presented and validated in different studies [22, 23, 24, 25].

FATIGUE LIFE PREDICTION METHOD FOR LAMINATES

To meet the fatigue characteristics of continuously fiber reinforced composites, the fatigue solver FEMFAT has been extended with a new module for lifetime estimation of laminates. Within this software tool for laminates, standard methods for the assessment of metallic parts based on S-N curves have been adapted for laminates. In order to take the characteristic damage modes of composite materials into account, the three failure modes FF, IFF and optionally delamination according to Puck are included in the software. For each ply of the laminate, the lifetime prediction is performed.

For the assessment of FF, the stress history of the normal stress σ_1 longitudinal to the fiber orientation is calculated by linear superimposition of in general multiaxial load channels (Figure 3 and 4). A rainflow counting algorithm is applied to obtain an amplitude-mean-rainflow-matrix of closed load cycles. Subsequently, the partial damages are analyzed by using experimentally measured material S-N curves and are linearly accumulated according to Palmgren/Miner [26, 27]. For the IFF modes illustrated in Figure 1, the same procedure is performed for the normal stress σ_2 transverse to the fiber orientation and for the in-plane shear stress τ_{21} and the respective material S-N curves in the fatigue-life software. The material S-N curve for shear can be measured with specimens consisting of $\pm 45^\circ$ lay-ups, see Figure 4.

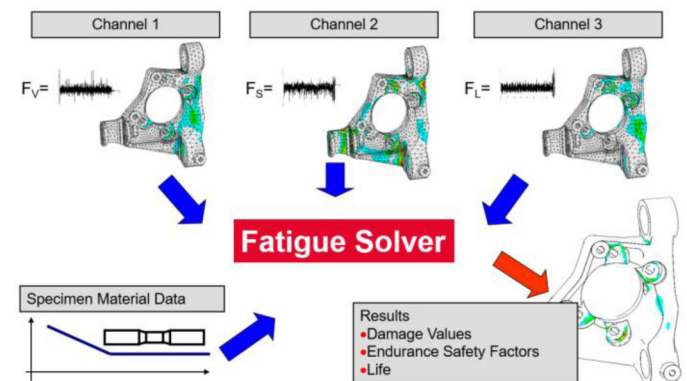


Figure 3. Fatigue analysis of multi-axially loaded components by linear stress superposition.

To apply Puck's criterion, according to Figure 1, also combinations of σ_2 and τ_{21} have to be considered [1, 2, 3]. Nevertheless, for non-proportional loading the stress vector spanned by σ_2 and τ_{21} may change its direction with respect to time (Figure 5 top). It is difficult to apply a rainflow counting procedure in such a case. To solve this problem, a simplified version of the so-called "Critical Plane - Critical Component" approach was developed [19, 20, 28]. The stress vector is projected onto several fixed directions with the given unit vector $\vec{v}_i$ (1).

$$\sigma_{eqv}(t) = \vec{\sigma}(t) \cdot \vec{v}_i = \sigma_2(t) \cos \varphi_i + \tau_{21}(t) \sin \varphi_i$$

$$i = 1, \dots, N$$
(1)

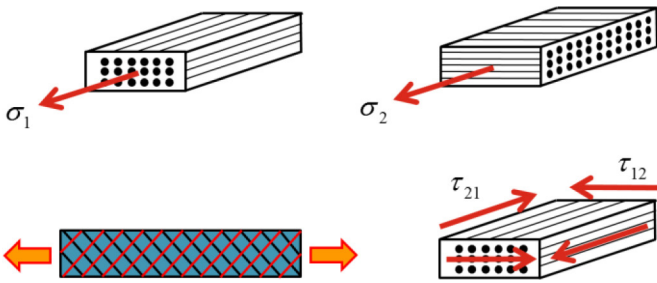


Figure 4. left top: Stress leading to fiber failure, right: Inter-fiber failure by normal and shear stress. Left bottom: Specimen with $\pm 45^\circ$ fiber orientation for the experimental measurement of the shear S-N curve.

For each orientation direction, rainflow counting and damage analysis of the resulting equivalent stress can be performed without any restrictions. The direction, which delivers the maximum damage, is assumed critical for fatigue failure. It can be mathematically interpreted as the critical component of the stress vector and it defines the type of failure mode A, B or C. To assure that each mode is covered by at least one direction, an angle of 30° is used between directions as default, leading to six directions in the σ_2 - τ_{21} -plane as illustrated in Figure 5 bottom. For the damage analysis of the intermediate directions S-N curves are used, which are obtained by interpolation between the S-N curves for σ_2 and τ_{21} .

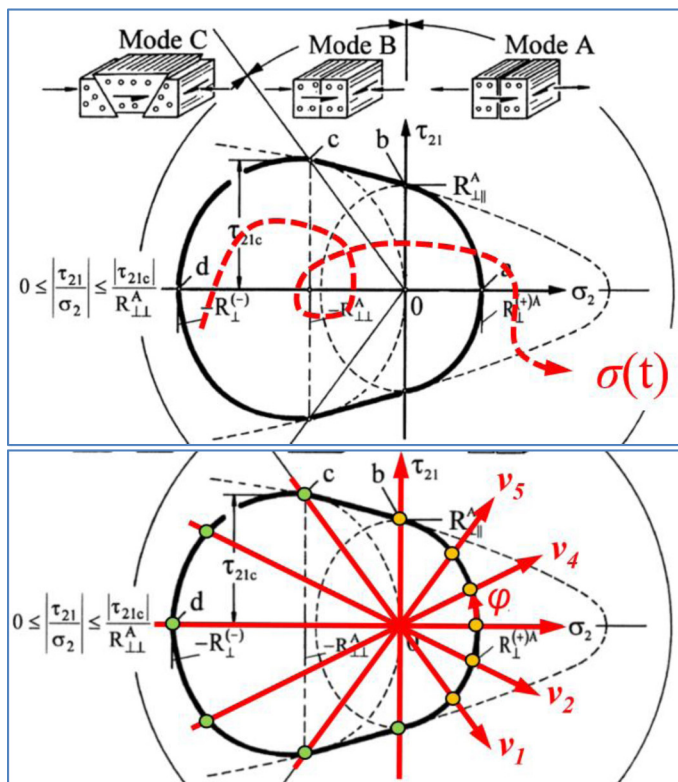


Figure 5. Top: Non-proportional loading path with respect to time; Bottom: Fatigue assessment of different loading directions in the laminate plane according to Equation 1. The dots mark the limits of the Haigh-surface in the tensile (yellow) and compressive (green) domain as shown in Figure 6.

To consider the influence of the mean stress, Haigh-diagrams are constructed from quasi-static and cyclic material parameters such as ultimate tensile strength, ultimate compressive strength, ultimate shear strength, alternating and pulsating fatigue limit for a given number of cycles as e.g. $5 \cdot 10^6$ [26, 27]. Due to the different strengths under tensile and compressive loads of composite materials caused by the anisotropic macroscopic material behavior, usually highly asymmetric Haigh-diagrams are obtained. For shear loading, the Haigh-diagram must be symmetric. For intermediate directions, which cannot all be covered by experimental tests, the Haigh-diagrams are interpolated with a smooth transition between tensile-compressive loading at an angle of $\varphi = 0^\circ$ and shear loading at $\varphi = 90^\circ$, resulting in a Haigh-surface as illustrated in Figure 6. The static limitations of the Haigh-surface at the left hand side (green line in compressive domain) and right hand side (yellow line in the tensile domain) are determined by Puck's criterion.

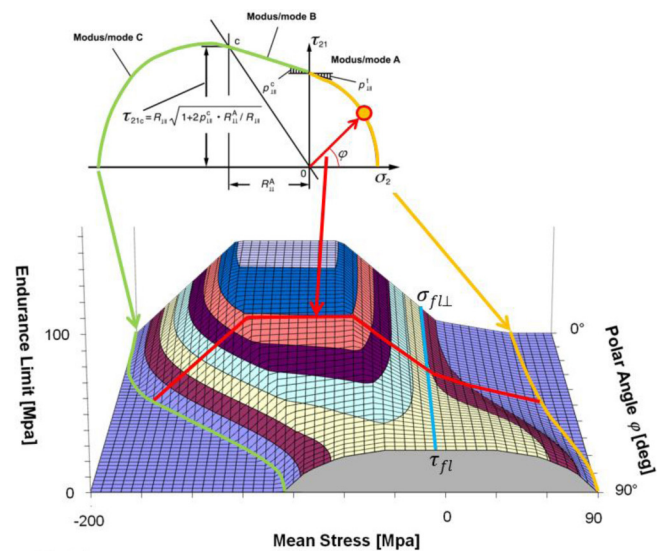


Figure 6. Haigh surface for IFF according to [19, 20, 28] with an interpolated Haigh-line (red) for a given angle φ of the considered loading direction.

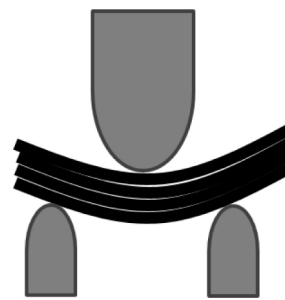


Figure 7. Sketch of a three-point bending test bench to measure interlaminar shear failure.

The intra-laminar stresses σ_1 , σ_2 and τ_{21} , which are acting in the plies, can be analyzed by the finite element method (FEM) with shell elements, whereas for inter-laminar stresses σ_3 , τ_{32} and τ_{31} , which are acting between plies and causing delamination, solid elements are needed, which is much more expensive. For the fatigue assessment of inter-laminar stresses, the same procedure is used as for intra-laminar stresses with different S-N curves and Haigh-diagrams. In Figure 8, σ_2 is just replaced by σ_3 and τ_{21} by τ_{31} and τ_{32} , respectively.

Nevertheless, it is difficult to measure S-N curves for interlaminar stresses. Interlaminar shear stresses can be generated by a three-point bending load applied to specimens as shown in Figure 7.

Acc. [36] (see also Figure 2 “Puck’s fracture cigar”), a high load in fiber direction reduces the strength for IFF by the following elliptical weakening factor with the two material parameters s and a :

$$\eta_w = \sqrt{1 - \left(\frac{\sigma_1/R_{\parallel} - s}{a} \right)^2} \quad \sigma_1/R_{\parallel} > s \quad (2)$$

For cyclic loading, the weakening factor may change during a load cycle because σ_i is generally a function of time. Therefore, the IFF strength is not unique for the damage analysis of the cycle. To overcome this theoretical problem, the stress components σ_2 and τ_{21} will be increased by the time dependent weakening factor instead, and assessed with the original non-reduced IFF strength:

$$\sigma'_2(t) = \frac{\sigma_2(t)}{\eta_w(t)} \quad \tau'_{21}(t) = \frac{\tau_{21}(t)}{\eta_w(t)} \quad (3)$$

The fatigue analysis procedure for a laminate component is exemplified in Figure 8. Up to six nested loops are required in order to cover the different scale levels of whole structures. All laminate elements resulting from the FE analysis, the nodes at the elements and the individual plies need to be considered. Furthermore, fatigue analyses have to be performed for each stress component at top and bottom side of each ply. To take the anisotropic material behavior into account, the different stress components σ_1 , σ_2 and τ_{21} are included. To enable the consideration of various, realistic time ranges, rainflow counting is applied. For acceleration of the procedure appropriate filters have been implemented to select only highly stressed plies for the fatigue analysis. In addition, a parallel analysis on several CPUs is possible. For this case the component is automatically divided into several parts, which are distributed to the CPUs for parallel computing. After finishing, the results are automatically merged together.

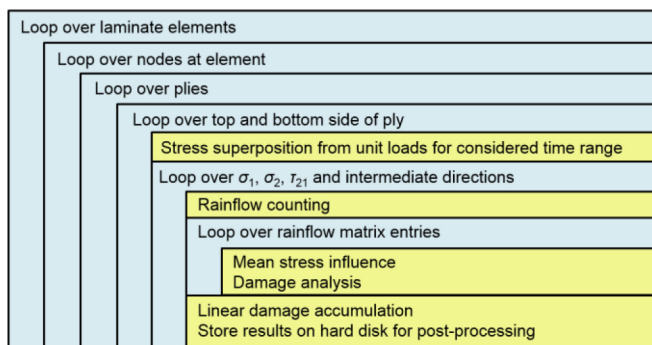


Figure 8. Fatigue analysis procedure for a laminate structure.

EXPERIMENTAL WORK

Unidirectional (UD) lamina made of carbon fibers and epoxy resin were tested at angles of 0° , 45° and 90° . Lay-ups consisting of $\pm 45^\circ$ and $[0^\circ/+45^\circ/-45^\circ/90^\circ/\text{symm.}]$ layers were also investigated and both lay-ups were symmetric referring to the middle plane. The required carbon/epoxy plates were produced in a pressure-driven vacuum assisted resin transfer molding process. The resin - hardener mixture was injected with a pressure of 6 bar into the cavity and all plates were cured at 80°C for 5 hours. Subsequently, specimens were milled from the plates with diamond blades. The fiber volume content of all produced specimens was 55 % (measured by thermo-gravimetric analysis as published in [29]). UD 0° plies consisted of four layers; all other specimens were made of eight layers. The specimens' geometry used in quasi-static tensile and tension-tension fatigue tests was $200 \times 10 \times 1$ mm (length x width x thickness) for UD specimens in fiber direction and $200 \times 20 \times 2$ mm for all other specimens. For quasi-static compression and tension-compression fatigue tests, specimens' geometry was $110 \times 10 \times 2$ mm (UD 0°) and $110 \times 20 \times 2$ mm, respectively. Aluminum tabs (length: 50 mm, thickness: 1 mm) were glued on both sides of all specimens. The schematic dimensions for UD 0° are illustrated for tension (Figure 9) and compression tests (Figure 10).

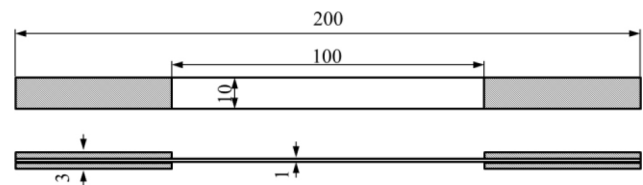


Figure 9. Schematic illustration of UD 0° specimens' geometry used for quasi-static tensile and tension-tension fatigue tests (in mm).

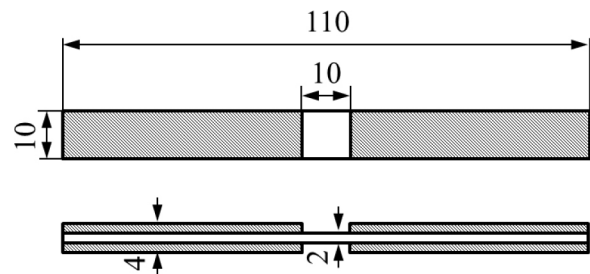


Figure 10. Schematic illustration of UD 0° specimens' geometry used for quasi-static compression and tension-compression fatigue tests (in mm).

Quasi-static and fatigue tests were performed on a servo-hydraulic test machine equipped with a load frame and load cell for 100 kN by MTS Systems Corporations (Minnesota, USA) at room temperature. Hydraulic wedge pressure of 5 MPa was chosen in order to prevent slipping without damaging the specimens. Good adhesion between aluminum tabs and carbon/epoxy specimens was assured in preliminary tests. Gauge length was 100 mm for tensile and 10 mm for compression loads. Quasi-static tension and compression tests were performed with a test speed of 0.5 mm/min until failure. During quasi-static tests a digital image correlation (DIC) system by GOM (Braunschweig, Deutschland) was used for strain measurement in and transverse to fiber direction in order to calculate Poisson's ratios. Tensile moduli were calculated according to 300 cycles as average moduli were evaluated between 0.001 and 0.003 absolute strain.