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Computational fatigue life prediction of continuously fibre reinforced multiaxial composites

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ABSTRACT

The potential of a fatigue-life prediction method for continuously fibre reinforced carbon/epoxy laminates has been investigated. Stress analysis conducted with a finite element solver in combination with the experimentally measured anisotropic S–N curves was used as input parameters. Subsequently, lifetime of a unidirectional and a multidirectional composite was calculated for a cyclic tension–tension load case and validated with experimental fatigue tests. The predicted lifetime of the unidirectional laminate correlated well to the experimental results. For the fatigue-life calculation of multidirectional composites, the software underestimated the experimental data. Results and possible improvements based on the presented calculations are discussed in detail.

1. Introduction

Continuously fibre 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 utilisation has to be optimised 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 realised by conducting mechanical tests and using predictive theories. In contrast to most metallic materials, highly anisotropic material behaviour 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 [1–3] characterised failure under quasi-static loads with a stress-based criterion considering five different failure modes. Due to the differentiation between fibre and matrix dominated failure mechanisms, Puck's criterion can consider physically motivated material behaviour rather than criteria by e.g. Hashin or Tsai-Hill [4,5]. Puck's five failure modes are defined as two modes for fibre failure (FF) under tension and compression load and three modes describing inter-fibre 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] (Fig. 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 visualised by fracture surfaces or fracture bodies. Puck's criterion and Tsai-, Hill- or Wu-like global stress criteria for the (σ_1, σ_2, τ_{12})–space are compared in a schematic way in Fig. 2 [6].

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 behaviour becomes even more complex due to the occurring damage mechanisms. Common damage mechanisms in composite materials are matrix cracking, fibre matrix debonding, delamination or fibre fracture. These damage mechanisms may change, progress or interact during fatigue-life and decrease the mechanical properties such as stiffness and strength [7–9]. Beyond that, fatigue-induced damage mechanisms depend not only on the direction of fibres in relation to the applied load, but on the amplitude of the cyclic load and on the mechanical mean stress in addition. Due to the described material behaviour, accurate fatigue-life prediction tools considering the variety of aspects of continuously fibre-reinforced materials are still in their early stages. Various

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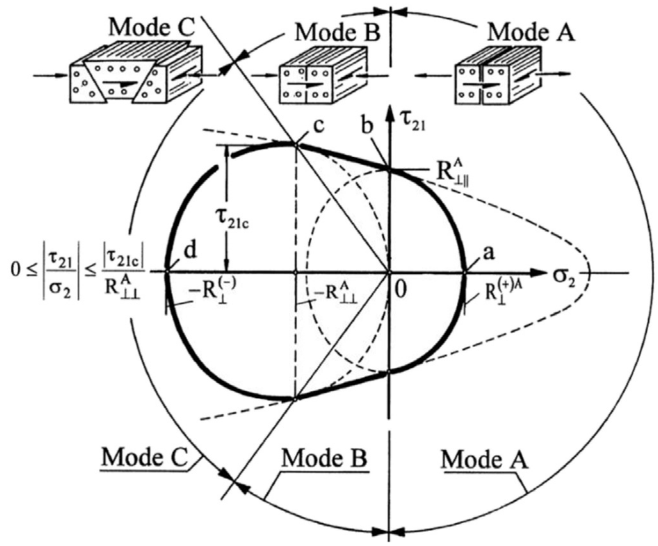

Fig. 1. Inter-fibre fracture (IFF) modes A, B and C for $\sigma_1 = 0$ [2].

studies regarding this issue have been published in the last decades pursuing different approaches e.g. Refs. [10–13].

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) [14]. 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 behaviour, 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 [15,16]. Critical damages are calculated according to the critical plane concept [17,18]. 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 [19]. For injection moulded short fibre reinforced plastics,

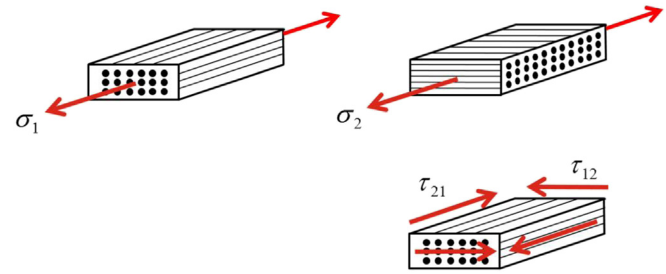

Fig. 3. Left: stress leading to fibre failure, right: inter-fibre failure by normal and shear stress.

anisotropic material behaviour and effects caused by the injection moulding process can already be taken into account. The functionality of simulation chains from injection moulding simulation to life-time prediction has been presented and validated in different studies [20–23].

2. Fatigue life prediction method for laminates

To meet the fatigue characteristics of continuously fibre reinforce composites, the software routine has been extended with a new module for lifetime estimation of laminates recently. 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 two failure modes FF and IFF 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 fibre orientation is calculated by linear superimposition of in general multiaxial load channels (Fig. 3). A rainflow counting algorithm is applied to obtain an amplitude-mean-rainflow-matrix of closed load cycles. Subsequently, the partial damages are analysed by using experimentally measured material S–N curves and are linearly accumulated according to Palmgren/Miner [24,25]. For the IFF modes illustrated in Fig. 1, the same procedure is performed for the normal stress σ_2 transverse to the fibre orientation and for the in-plane shear stress τ_{12} and the respective material S–N curves in the fatigue-life software. To apply Puck's criterion, according to Fig. 1, also combinations of σ_2 and τ_{12} have to be considered [1–3]. Nevertheless, for non-proportional loading the stress vector spanned by σ_2 and τ_{12} may change its direction with respect to time. It is difficult to apply a rainflow counting procedure in such a case. To solve this problem a

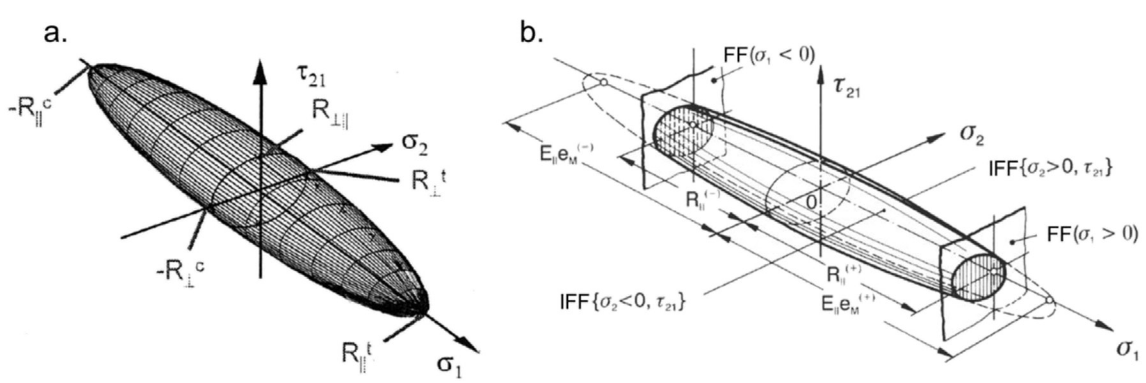

Fig. 2. Visualisation of fracture criteria for unidirectional fibre reinforced composites: (a) Tsai-, Hill- or Wu-like global stress based criteria and (b) the 2D representation of Puck's action plane related criteria referring to [6].