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A physically based micromechanical approach to model damage initiation and evolution of fiber reinforced polymers under fatigue loading conditions

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ABSTRACT

The hypothesis of this work is that the fatigue behavior of a composite material is governed by its matrix. By characterizing and modeling the quasi-static and cyclic behavior of the pure polymer matrix, the transverse crack initiation and evolution of a composite under fatigue loading can be studied on a micromechanical level. Extensive characterization of the epoxy resin system Araldite LY564/Aradur22962 is conducted with special emphasis on the hystersis energy. A novel physically based fatigue failure criterion for polymers under multiaxial loading conditions is derived from these experimental results. To overcome the limitations of experimental accuracy and scatter, a compensation procedure is presented.

For the incorporation in a micromechanical analysis, a viscoplastic material model from the literature is modified and utilized. A linear viscous network of Maxwell elements is compared with a nonlinear approach. It is found that even though the results show an indication of viscous nonlinearity, the linear network is capable of capturing the cyclic response with sufficient accuracy. For both models, a multiaxial generalization and a calibration procedure is presented in order to incorporate the material model in the commercial finite element software Abaqus.

With the implementation of the material model and the developed failure criterion, a micromechanical model of a fiber reinforced polymer is set up. With the developed fatigue modeling framework, the damage initiation and evolution are evaluated using data available in the literature. The damage behavior is in good qualitative agreement with the reported mechanisms proving the general suitability of the failure criterion.

1. Introduction

With design considerations like sustainability, energy efficiency, and environmental protection becoming more important, lightweight solutions are increasingly demanded. Fiber reinforced polymer materials offer extraordinary mass specific mechanical properties and are getting more popular throughout many industries like the aerospace, the energy, and the automotive industries. For these lightweight applications, reliability issues are to be addressed in order to obtain a damage-tolerant or safe-life design depending on the certification requirements. Even though the fatigue behavior of composite materials is under investigation ever since the material is used for structural applications, these analyses and the design remain challenging. Case studies like the one by Chou et al. [1] or Chen et al. [2] as well as recent reviews like presented by Alderliesten [3] indicate that the complexity of the damage behavior and the lack of reliable and accurate design tools still calls for extended research in understanding the fatigue behavior of composites.

Experimental studies of fatigue behavior are expensive. Especially for composites, the numerous material combinations, layups, frequency dependency, etc. make a systematic experimental and phenomenological analysis of the behavior challenging if not impossible. Thus, the experimental database is usually very thin for a specific combination of material, layup, and environmental condition. Simulation techniques can support the experimental investigations as isolated changes to the model can significantly help to understand the underlaying phenomena. As reviewed by

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Degrieck and Van Paepegem [4], numerous approaches exist to model the fatigue behavior of composites on a meso-, i.e. ply- or macro-scale. Available in various degrees of complexity ranging from global fatigue life models down to physically and mechanism based damage mechanics approaches, it becomes apparent that a large number of models are limited to very specific applications like special materials, fiber architectures, failure mechanisms, or loading conditions.

With high-resolution imaging techniques like x-ray computed tomography widely available to material scientists, the microstructure of composites has gathered increasing attention. As fatigue damage in composites initiates at this scale, a micromechanical analysis can provide a helpful understanding of the underlaying mechanisms potentially improving larger scale fatigue models. Talreja [5] describes the development of fatigue modeling over the past 40 years and points out that micro scale and mechanism based approaches are the consequent steps towards a profound understanding of the damage and fatigue behavior of the composite material. The same conclusion is made by Quaresimin et al. [6] who state “reliable multiaxial criteria must be defined on the basis of the damage mechanisms at the microscopic scale”. Applications of micromechanical approaches in terms of both basic mechanical properties and damage behavior have been shown by Refs. [7–13] to name a few.

Special attention in these approaches is paid to the behavior of the matrix material. It turns out that a nonlinear mechanical response of a composite as well as the complexity of the damage and fatigue behavior is dominated by the matrix material, especially for fiber reinforced polymers. Therefore, special importance has to be dedicated to the mechanical behavior of this component as done in Refs. [11,12,14] for both thermoplastic and thermosetting matrices under quasi-static loading conditions. Thorough research on polymer fatigue has been presented in Ref. [15] as well as [16] which provide an inside into the underlying mechanisms of fatigue even down to the molecular level. A more “engineering”-based study has been published by Shen et al. [17] and Xia et al. [18] who develop a material model capable of capturing the cyclic response of an epoxy resin based on cyclic and creep test data.

Following the description of the mechanical behavior of the matrix, the damage behavior can be evaluated by means of failure criteria. For static loadings, McCarthy and Vaughan [7] introduce cohesive elements around the fibers for damage initiation. Once the fiber has de-bonded from the matrix, the stress state in between the fibers triggers an imposed yield criterion thus connecting the de-bond locations and resulting in a transverse crack. A more physical based approach has been recently published by Okabe et al. [13] who use a two-scale method for predicting the static crack initiation at free edges and interfaces. While the loads are derived on the ply-level, a micromechanical strategy is used to predict the onset of the instable crack growth. The physical basis for their failure criterion is the cavitation inducing dilatational total strain energy density similar to the works by Asp et al. [19,20]. Although their modeling strategy is quite similar to the one in this contribution, this work focuses on the initiation and evolution of transverse cracks under sub-critical fatigue loading conditions. The total strain energy density used by Okabe et al. [13] is a promising damage measure for transverse crack initiation under static loading which is also shown by Asp et al. [19,20]. For damage initiation due to fatigue, however, such a critical threshold based approach needs to be extended by a load level dependency and thus a time dimension. This procedure is demonstrated in this work and has not been utilized before on a micro-level. Here, the author investigates the suitability of the hysteresis strain energy density as a physical basis for such an approach. Similar to the static load case and thus to the findings in Refs. [13,19,20], the dilatational part of this energy is found to be critical for the fatigue crack initiation under transverse loadings.

In general, a failure criterion for fatigue should be physically motivated as the area of validity of empirical models is often limited or even unclear. Additionally, both the criterion as well as the mechanical model have to be multiaxial in order for them to be used in a micromechanical composite analysis. As for the failure criterion, Shen et al. [17] show that epoxy based polymers show a pronounced rate dependency causing a hysteresis when loaded cyclically. The hysteresis energy is the rallying point for all irreversible effects on the molecular level. Macro-scale phenomena like plasticity or specimen heat up can be traced back to a change in the molecular structure causing an irreversible dissipation of energy by, e.g. friction or bond cleavage within or in between the macromolecular chains, cf. [21]. In low-cycle-fatigue analyzes of metals, hysteresis-energy-based criteria exist to predict fatigue life, see e.g. Ref. [22]. Consequently, the hysteresis energy observed in the cyclic loading of polymers might provide a physical basis for the prediction of fatigue life. Critics stating that a significant amount of hysteresis energy is “used” for thermal heat up and not for damage dissipation are reminded that this thermal energy has to be generated by other irreversible effects like molecular friction which is in return expected to lead to an accelerated damage process.

Fatigue in composite materials is dominated by the matrix for most applications. Epoxy resins are the most commonly used types of polymers utilized as matrix materials in fiber reinforced composites. In this work, the epoxy resin Araldite LY564/Aradur 22962 is chosen for the investigation as it stands for a generic type of resin with low-viscosity, long pot-life yet high reactivity at higher temperatures, and low material cost. Based on thorough studies of the resin's mechanical behavior under quasi-static and cyclic loading conditions, a material model is adapted and calibrated. Together with a novel failure criterion, this gives the basis for a micromechanical fatigue modeling strategy for the whole composite. The therefore required investigations are presented in this contribution and are structured as follows. In the second section, the experimental investigations of the pure polymer are performed. Both quasi-static and cyclic tests are conducted and evaluated with special attention to the hysteresis energy. These results are used in the third section to extend a material model proposed by Kästner et al. [14]. The multiaxial generalization and the numerical implementation is described and the material parameter identification is performed. In the fourth section, a failure criterion based on the hysteresis energy is derived and discussed. Together with the polymer material model described in the third section, this failure criterion is then benchmarked in a micromechanical model of a fiber reinforced composite where the polymer is used as a matrix material. For this, mechanically idealized glass fibers are assumed and the degradation behavior is evaluated based on the micromechanical mechanisms described in the literature.

2. Experimental material characterization and failure behavior

The aim of this section is the phenomenological characterization of the material behavior of the epoxy resin system Araldite LY564/Aradur 22962 under both quasi-static as well as cyclic loading conditions. Material behavior can be categorized by rate-dependency and by the presence of a hysteresis in the stress-strain-response upon cyclic loading, see e.g. Ref. [14]. Both being rate-sensitive, viscoelastic and viscoplastic materials are differentiated by the shape of their so called equilibrium relation. This relation is the stress-strain response to an infinitesimally slow loading and unloading cycle. If the equilibrium relation shows no hysteresis, the material is viscoelastic; if the equilibrium relation