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An improved fatigue failure model for multidirectional fiber-reinforced composite laminates under any stress ratios of cyclic loading

Vahid Ghaffari Mejlej[a,*], Daniel Osorio[a], Thomas Vietor[a]

[a] *Institut für Konstruktionstechnik, Technische Universität Braunschweig, Hermann-Blenk Strasse 42, D-38108 Braunschweig, Germany*

* Corresponding author. Tel.: +49-531-391-66684; fax: +49-531-391-4572. *E-mail address:* v.ghaffarimejlej@tu-braunschweig.de

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Abstract

This paper improves an existing model to predicting the fatigue life and material property degradation of arbitrarily oriented composite laminates under different stress ratios. Residual strain energy density is used to model fatigue behavior via a VUMAT subroutine in FEM package. The effects of strength and stiffness reduction are considered to obtain higher predictive accuracy than that derived with the stress-based method. Hashin failure criteria are employed to identify damage onset in the fiber, matrix, and in-plane shear of layers. Based on developed model, a sensitivity analysis is conducted to evaluate geometrical effects on the fatigue life of composite structures.

Keywords: Composite, Progressive fatigue damage, Fatigue life, Material degradation, Geometrical effects

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1. Introduction

During recent decades, composite materials have been developed as substitutes for metals in marine, aerospace, and automotive industries. Accordingly, the fatigue behavior of composite parts in structures that are subjected to cyclic loading has motivated scientific research. However, given that fatigue testing involves considerable time and investment and may sometimes be impossible for large structures, a numerical model of fatigue behavior is necessary. A comprehensive and reliable fatigue model should cover the following requests:

- Consider the effects of environmental conditions, such as temperature and moisture;
- Require minimal input data;
- Consider multi-axial load effects;
- Apply to all kinds of composite materials with different layer sequences and stress ratios [1–3].

Existing fatigue models are categorized into two groups [4, 5], namely, microscopic and macroscopic models. *Microscopic models* consider the existence of initial resin effects, such as cracks and voids, without the need for large-scale experimental testing. The aforementioned defects can occur during the manufacturing process or under the cold or hot mechanical works conducted after production. *Macroscopic models* use S-N curves to predict fatigue behaviors without considering the real mechanisms that underlie failures, such as cracks or in-plane delamination. Macroscopic models are favored over microscopic models because the former exhibit better reliability and collectivity.

Macroscopic models are classified into two groups, the first of which uses a fatigue criterion and introduces the criterion into analysis in accordance with fatigue life.. Some well-known models under this classification are those put forward by Shokrieh [6], Ellyin [7], and Awerbuch [8]. These models use S-N data for certain angles and stress ratios and do not require numerous experimental tests to calculate the fatigue life of composite materials with any fiber orientations and stress ratios. The second group of macroscopic models predict fatigue life by using a static failure model in conjunction with experimental S-N curves. Some of the models under this category are those introduced by Reifsnider [9] Philidopos [10] and Jen MH[11], who used Tsai's static failure model as basis

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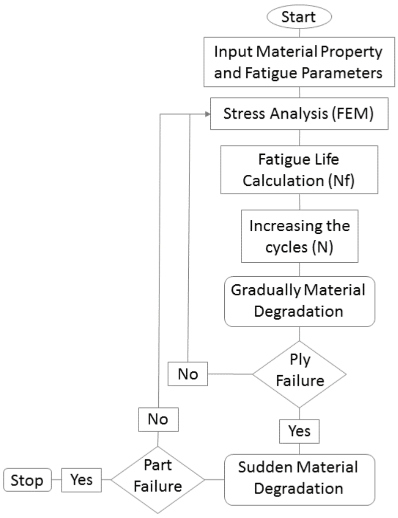
for model development. Static failure models are usually based on stress, similar to Hashin [12] criteria, and consider only the strength factor in predicting fatigue defects [13–33] or predict fatigue delamination with reference to Nikishkov [15]. Krüger [17] introduced a physically based fatigue damage model which combines the advantages of existing models and couples stiffness and strength degradation by using the energy approach. To consider both strength and stiffness degradation in fatigue life, Shokrieh [6] used Sandhu criteria [18] under positive stress ratio. In the present research, the fatigue model of Shokrieh [6] is improved in the following respect:

- The fatigue life of unidirectional composite laminates is predicted under both positive and negative stress ratios.

A comparison of the accuracy of the improved model and the experimental results on other models in the literature shows relatively good agreement. The improved model is used to evaluate geometrical effects on the fatigue life of a composite structure under multiaxial loading.

2. Model of progressive fatigue damage

Flowchart 1 illustrates the algorithm of the improved fatigue model in this study.



Flowchart 1. Process of improved fatigue model in this study.

To avoid long FEM calculations for material degradation in all cycles, representative cycles are used as the specific cycle numbers [34]. To this end, a VUMAT subroutine in ABAQUS is applied, see Fig. 1.

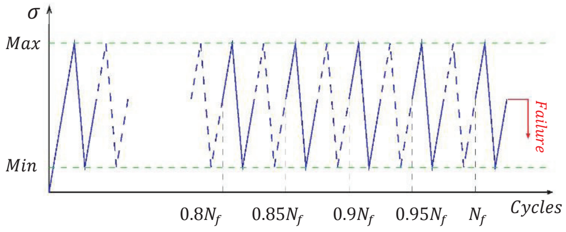


Fig. 1. Schematic of implementation of representative cycles until N_f

2.1 Calculation of fatigue life

This section primarily describes Shokrieh's [6] fatigue model in brief and in continue illustrates the improvement scheme on original model. Shokrieh used a condensed form of Ellyin [7] fatigue life model as a relation of total input energy and fatigue life (N_f):

$$N_f = (K/\Delta W^*)^{1/\alpha} \tag{1}$$

Where *k* and α obtains from a set of S-N curve data for each material regardless to the stress ratio and fiber orientation and ΔW^* is sum of normalized strain energy density components in fiber, matrix, and shear direction, Eq. (2).

Based on Sandhu [18] failure energy criterion for composite material, shokrieh introduced sum of normalized strain energy density in each state of stress as a unified fatigue model for various fiber orientation angles and different stress ratios:

$$\Delta W^* = \Delta W_1^* + \Delta W_2^* + \Delta W_3^* = \frac{\Delta\sigma_1 \Delta\varepsilon_1}{X\varepsilon_{u1}} + \frac{\Delta\sigma_2 \Delta\varepsilon_2}{Y\varepsilon_{u2}} + \frac{\Delta\sigma_6 \Delta\varepsilon_6}{S\varepsilon_{u6}} \tag{2}$$

Where $\Delta\sigma_1, \Delta\sigma_2, \Delta\sigma_6$ and $\Delta\varepsilon_1, \Delta\varepsilon_2, \Delta\varepsilon_6$ represent the range of stress and strain components in fiber, matrix, and in-plane direction respectively. X, Y, and S are maximum static strengths and $\varepsilon_{u1}, \varepsilon_{u2}, \varepsilon_{u6}$ are maximum static strains in material directions. Normalized strain energy density in fiber direction may be written as:

$$\Delta W_1^* = \frac{\Delta\sigma_1 \Delta\varepsilon_1}{X\varepsilon_{u1}} = \frac{(\sigma_{1max}\varepsilon_{1max} - \sigma_{1min}\varepsilon_{1min})}{X\varepsilon_{u1}} \tag{3}$$

In three different state of stress ratios, ΔW_1^* obtains through Eqs. (4), (5), and (6):

$$if\ \sigma_{1max} > 0 \quad and \quad \sigma_{1min} > 0$$

$$\Delta {W_1}^* = \frac{(\sigma_{1max}\varepsilon_{1max} - \sigma_{1min}\varepsilon_{1min})}{X_T\varepsilon_{u1}} \tag{4}$$

$$if\ \sigma_{1max} < 0 \quad and \quad \sigma_{1min} < 0$$

$$\Delta {W_1}^* = \frac{(-\sigma_{1max}\varepsilon_{1max} - (-\sigma_{1min}\varepsilon_{1min}))}{-X_C\varepsilon_{u1}}$$

$$= \frac{(\sigma_{1max}\varepsilon_{1max} - \sigma_{1min}\varepsilon_{1min})}{X_C\varepsilon_{u1}} \tag{5}$$

$$if\ \sigma_{1max} > 0 \quad and \quad \sigma_{1min} < 0$$

$$\Delta {W_1}^* = \frac{(\sigma_{1max}\varepsilon_{1max} - (-\sigma_{1min}\varepsilon_{1\text{min}}))}{(X = X_T\ res.\ X_C)\varepsilon_{u1}}$$

$$= \frac{(\sigma_{1max}\varepsilon_{1max} + \sigma_{1min}\varepsilon_{1\text{min}})}{({X_T}^2 + {X_C}^2)^{0.5}\varepsilon_{u1}} \tag{6}$$

Where $(X = X_T\ res.\ X_C)$ in dominator, shows the resultant of maximum strength of material in compression and tensile. Eq. (6) extends the capability of Eq. (3) to calculate ΔW_1^* in tension- compressive state as an improved expression of Shokrieh's model in fatigue life prediction.

Similar equations are performed for the matrix and shear directions (ΔW_2^*, ΔW_3^*) but are excluded from the discussion for simplicity.