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A progressive damage model of textile composites on meso-scale using finite element method: Fatigue damage analysis

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ABSTRACT

A finite element (FE) approach for tension–tension fatigue damage in textile reinforced composites on meso-scale level (fabric unit cell) is proposed. S–N curves of a unidirectional composite (UD) out of the fatigue tests in fibre, transverse-fibre, in-plane-shear and out-of-plane-shear directions are used as the input for the impregnated yarns. The algorithm of multi-axial fatigue is applied to matrix-dominated fatigue, while the fibre-dominated fatigue is separately considered. The continuum damage mechanics method is used to describe the properties' deterioration. The stress redistribution introduced by stiffness degradation conjugates the damage evolution. Averaged mechanical properties of the unit cell in pre- and post-fatigue damage stages are calculated at predefined load cycle numbers, using a numerical homogenization technique. The numerical results are validated by experiments of two types of carbon/epoxy plain weave composites, which have the same fibre/resin system but different textile structures. The validation showed good agreement between modelling and experiment.

1. Introduction

Textile reinforced composites are increasingly applied in automotive, aerospace, wind energy and other high-tech industrial areas. Due to the anisotropy and inhomogeneity of the material properties as well as the various architectures and design parameters of the reinforcement, the fatigue design criteria are usually experimentally determined. A considerable amount of tests have to be performed and overestimated safety factors are often adopted. Therefore, a reliable numerical method linking the internal architecture to the apparent properties, for instance the fatigue strength delineated by S–N curves, will be of great value.

Comprehensive literature reviews of fatigue damage modelling work have been provided by Van Paepegem and Degrieck [1], Post [2], Passipoularidis [3] and Xu [4], respectively. According to Xu [4], the existing fatigue models can be classified into three categories: Miner's-rule-like models, phenomenological models and progressive damage models. Earlier modelling work on progressive fatigue damage of multi-directional (MD) composites was carried out by Shokrieh and Lessard [5,6] using polynomial fatigue failure criteria. Similar work has been published by Lian and Yao [7], aiming to predict the fatigue life and damage evolution in laminates with arbitrary stacking sequences based on the S–N curves of the UD laminates loaded under longitudinal/transverse tension and in-plane-shear, respectively. However, a meso-scale progressive damage model for textile composites is still not available. The meso-level modelling can be considered as a bridge of the micro-model, calculating the mechanical properties of homogenized yarns or fibrous plies, and the macro-model, analyzing the structures using the homogenized properties [8].

As discussed in static modelling [9], the meso-scale fatigue modelling of textile composites has to be provided with an adequate geometrical description of a unit cell, which can be created using a textile geometry generator [10,11] and converted afterwards to the FE model assisted by a FE mesher [8,12].

Facilitated by those software packages, a fatigue model based on a meso-FE formulation [13] was proposed by Hanaki et al. [14]: the six independent components of the stiffness matrix of the impregnated yarns (taken as UD material) and the matrix material are cumulatively deteriorated, governed by Palmgren–Miner's rule. In Hanaki's model, however, the predicted static strength for carbon/epoxy plain weave composite, based on which the fatigue load levels are determined, shows pronounced deviation off the test data. Moreover, the concept of multi-axial fatigue, disregarded in his model, is important and has to be taken into account: although globally loaded on-axis, the heterogeneous materials, such as textile composites, locally tend to be

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multi-axially stressed, especially after the initiation of cracks with diverse orientations.

Kari et al. [15] proposed a numerical approach to evaluate the mechanical properties firstly on micro-level, namely the impregnated fibre bundles, using FE method. Later the computed properties are reapplied to calculate the mechanical properties on meso-level. However, in this work no experimental validation for the proposed method is given.

Inspired by the work of Hanaki et al. [14], in this paper a model for tension–tension fatigue is developed based on a meso-FE model of a textile composite. To guarantee an accurate failure analysis, the stress/strain fields have been carefully validated in the author's previous work [9]. The features of the model are:

1. The impregnated yarns are considered as a UD composite with a certain fibre volume fraction [8]. The mechanical properties of the 'UD composite' are calculated by Chamis' equations [16].
2. S–N curves of UD composites are used as input, which are obtained from fatigue test by means of longitudinal tension–tension, transverse tension–tension, in-plane shear and out-of-plane shear.
3. An anisotropic degradation model [17] is employed to evaluate the degraded stiffness.
4. The concept of multi-axial fatigue, proposed by Liu [18,19] is adopted to describe the matrix-dominated fatigue behavior; fibre-dominated fatigue damage, governed by Palmgren–Miner's rule, is considered separately.
5. The release of residual stress and stress redistribution [20], which may lead to further properties' degradation, is realized at each step of damage evaluation.

The algorithms for damage accumulation and stiffness degradation are implemented in the Abaqus® User-defined Material (UMAT). Averaged mechanical properties in pre- and post-damage stages are calculated by using a homogenization technique under 3-D periodic boundary conditions (PBCs) [8].

Complete test data of UD carbon fibre epoxy (AS4/3501-6) composites were reported by Shokrieh [6]. These data sets are processed to produce the S–N curves used as input for computing the fatigue characteristics of textile composites. To validate the model, test data of two plain weave carbon/epoxy composites, published in [21], are used.

2. Fatigue modelling

The fatigue behavior of textile composites is highly dependent on the loading conditions, for instance the stress ratio, $R = \sigma_{min}/\sigma_{max}$, and also dependent on the cyclic load frequency, if the generated heat cannot be dissipated in time. The stress ratio and load frequency have to be kept consistent between the input data and the data for validation. For the given data sets at different stress ratios or load frequencies, a characteristic curve [22] can be adopted for adaptation.

2.1. General algorithm

The proposed approach is comprised of three computational modules: **A**, **B** and **C** shown in Fig. 1(b):

(A) Quasi-static loading is applied to the intact unit cell as the first half cycle. The unit cell is numerically loaded up to the magnitude of the maximum fatigue stress σ_{max}, as shown in Fig. 1(a). Within this scenario, some Gaussian points are identified as failed by Tsai–Wu damage criterion [23] and their stiffness is degraded following the anisotropic damage model [8,13]. The degraded properties are passed to Module **B**.

(B) Material is 'worn out' due to increasing number of load cycles. Within a predefined 'N_jump' [24], all the Gaussian points are continuously experiencing the fatigue weakening effect. Governed by the input S–N curves, this weakening effect is the function of the N_jump and local stresses states (see Sections 2.2 and 2.3). According to the Palmgren–Miner's rule,

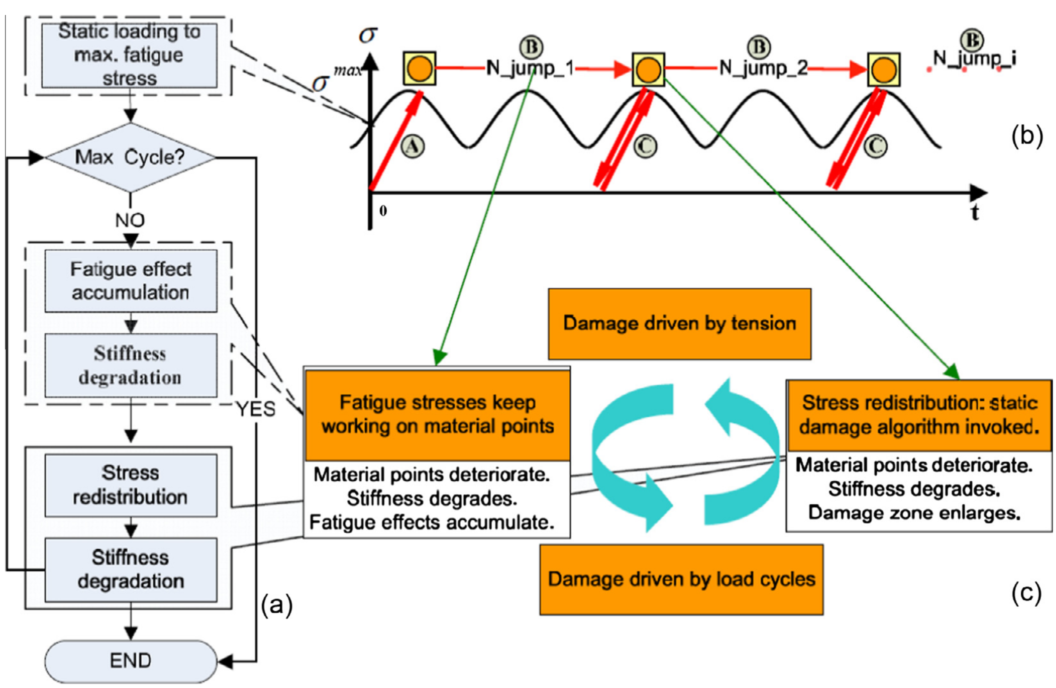

Fig. 1. Sketch map of fatigue algorithm: (a) flow chart of the calculation; (b) modules A, B and C, and cycle jump; and (c) degradation introduced by the number of load cycles and by the stress redistribution.