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Fatigue life prediction model of 2.5D woven composites at various temperatures

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Abstract As one of the new structural layout in the family of woven composites, 2.5D Woven Composites (2.5D-WC) have recently attracted an increasing interest owing to its excellent properties, i.e. high specific strength and fatigue resistance, in the aerospace and automobile industry. In-depth understanding of the fatigue behavior of this material at un-ambient temperatures is critical for the engineering applications, especially in aero-engine field. Here, fatigue behavior of 2.5D-WC at different temperatures was numerically investigated based on the unit cell approach. Firstly, the unit cell model of 2.5D-WC was established using ANSYS software. Subsequently, the temperature-dependent fatigue life prediction model was built up. Finally, the fatigue lives alongside the damage evolution processes of 2.5D-WC at ambient temperature (20 °C) and un-ambient temperature (180 °C) were analyzed. The results show that numerical results are in good agreement with the relevant experimental results at 20 and 180 °C. Fatigue behavior of 2.5D-WC is also sensitive to temperature, which is partially attributed to the mechanical properties of resin and the change of inclination angle of warp yarns. We hope that the proposed fatigue life prediction model and the findings could further promote the engineering application of 2.5D-WC, especially in aero-engine field.

1. Introduction

Textile composites are being widely applied in the field of aerospace engineering due to their excellent mechanical properties, i.e. high specific stiffness/strength and outstanding fatigue resistance. 2.5D Woven Composites (2.5D-WC) not only possess a superior delamination resistance capacity in comparison with 2D laminated composites, but also have a simpler structural configuration than 3D textile composites. Recently, many parts in the aero-engine field, i.e. woven fan/compressor blades and casing, have been manufactured using resin matrix com-

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posites. Nevertheless, the characteristics of long-term service and elevated temperature environment in aero-engine inevitably result in difficulty of fatigue-related theoretical research, especially for the study with respect to the fatigue life prediction model at un-ambient temperatures.[1,2]

Many researches have reported about the mechanical properties and prediction models of woven composites based on experimental and finite element methods. Montesano et al.[3,4] investigated the mechanical behavior of 2D triaxially woven composites at different temperatures by experiment, and found that fatigue behavior was not sensitive to temperature at 120 °C. Selezneva et al.[5] experimentally investigated the failure mechanism in off-axis 2D woven laminates at ambient temperature (20 °C), 105, 160 and 205 °C, and demonstrated that the woven yarns began to straighten out and rotated towards the loading direction just prior to failure. Vieille and Taleb[6] studied the influence of temperature and matrix ductility on the behavior of notched 2D woven composites at ambient temperature (20 °C) and 120 °C, and the results revealed that the highly ductile behavior of thermoplastic laminates was quite effective to accommodate the overstresses near the hole at the temperature higher than the glass transition temperature T_{m}. Koumpias et al.[7] predicted the strength of 3D fully woven composites at ambient temperature based on a homogenized Representative Volume Element (RVE). Zhou et al.[8] studied the damage and failure characterization of 2D woven composites under different uniaxial and biaxial loadings at ambient temperature by adopting a two-step, multi-scale progressive damage analysis. Li et al.[9] developed a micromechanical finite element model to predict the effective mechanical properties of woven fabric composites at elevated temperatures. Although there have been several works in predicting mechanical properties of textile composites by simulation, the specific research pertaining to 2.5D-WC is scarce as yet. Previous works in terms of establishing and simulating the mechanical behavior of 2.5D-WC at ambient temperature have been done by us.[1,10,11] The geometric model, strength prediction model and damage behavior of 2.5D-WC under the warp and weft static loading at ambient temperature have been systematically analyzed.

Additionally, to the best of our knowledge, very few simulation models related to the fatigue life of woven composites have been reported. Dai and Mishnaevsky[12] simulated the fatigue life of hybrid fiber reinforced composites at ambient temperature based on X-FEM and unit cell models. Hao et al.[13] predicted the fatigue behavior of 3D 4-direction braided composites at ambient temperature based on the unit cell approach, where the prediction model takes into account the variation of stiffness and strength of components induced by cyclic loading. Qiu[14] proposed modified residual stiffness and residual strength models, in which the influence of fiber volume fraction was considered. Coupled with the progression damage approach, the fatigue life of 2.5D-WC was predicted at ambient temperature.

Surprisingly, there is almost no published literature about predicting the fatigue behavior of woven composites at un-ambient temperatures using numerical approach. However, the immense popularity of woven composites in the aero-engine generally experiences a long-term service under the un-ambient temperatures. Therefore, it is meaningful to establish a temperature-dependent fatigue life prediction model of woven composites, especially in the aero-engine field.

In this work, our principal objective is to establish the fatigue life prediction model that can evaluate the temperature-dependent fatigue behavior of woven composites. Taking 2.5D-WC as a specific research object, three stress levels of warp fatigue loading at 20 and 180 °C were employed to verify the rationality of fatigue life prediction model. Afterwards, the damage evolution histories at 20 and 180 °C were quantitatively observed based on the simulation model. Finally, the fracture morphologies at 20 and 180 °C obtained by simulation and testing were compared. This work could provide an available approach in predicting fatigue behavior at different temperatures, which will further facilitate the engineering application of 2.5D-WC.

2. Fatigue life prediction model

The temperature-dependent fatigue life prediction model of woven composites subjected to uniaxial tension-tension loading mainly includes: fatigue damage criteria, damage propagation model, geometry/finite element model and periodic boundary conditions.

2.1. Fatigue damage criteria

Several damage criteria in terms of composite materials, such as Misses, Tsai-Wu and Hashin criteria, have been proposed to solve different engineering issues. As the 3D Hashin criterion has been successfully applied in estimating the strength of woven composites at ambient temperature previously[15–17], a modified 3D Hashin criterion taking into account temperature and cycle number will be proposed in this work. Furthermore, based on the previous studies,[1] failure mechanisms of woven composites can be hypothetically related to two failure modes (two directions) for anisotropic fiber yarns: yarn breaking and matrix cracking. Nevertheless, in addition to temperature, the mechanical properties of fiber yarns are generally sensitive to the volume fraction of fiber in fiber yarns (or called fiber aggregation density).[14] Therefore, the corresponding failure criteria can be given as follows:

Yarn longitudinal damage (breakage in axial direction, or 1-axis direction):

$$\left(\frac{\sigma_{11}}{X_{11}(n,V_{\mathrm{f}},T)}\right)^2+\beta\left(\frac{\sigma_{12}}{S_{12}(n,V_{\mathrm{f}},T)}\right)^2+\beta\left(\frac{\sigma_{13}}{S_{13}(n,V_{\mathrm{f}},T)}\right)^2\geqslant 1 \tag{1}$$

where σ_{ij} (i, j = 1, 2, 3) are the stress components; X_{11} is the longitudinal tensile strength of fiber yarn; S_{12} and S_{13} are the shear strength of fiber yarn; β is the shear contribution factor; n is the cycle number; V_{f} is the fiber aggregation density; T is the temperature.

Yarn transversal damage (Interior matrix cracking or fiber-matrix shear-out failure in in-plane direction, or 2/3-axis direction):