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Experimental and numerical investigation of mechanical behaviors of 2.5D woven composites at ambient and un-ambient temperatures

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ABSTRACT

An angle-interlock 2.5D woven composites (2.5D-WC), as a man-made new structural layout in the family of woven composites, have recently attracted increasing interest in its promising applications in the fields of astronautics and aeronautics. Nevertheless, published results are rarely associated with the temperature-dependent mechanical behaviors of this material. The current work emphasizes on the evaluation of the thermo-mechanical behaviors, damage propagation and failure mechanisms of 2.5D-WC at ambient and un-ambient temperatures by using experimental and numerical approaches. Experimental results show warp mechanical modulus and strength experience a decrease trend when the temperature increases. However, the weft strength is not sensitive to temperature, giving an indication of anisotropic behavior. There is no necking phenomenon near the fracture surface regardless of temperature and loading direction, indicating a brittle fracture mode. Temperature and fiber yarn arrangement direction play a critical role in alternating the damage propagation and failure mechanisms. Additionally, simulation results quantitatively elaborate the corresponding experimental findings and proposed mechanisms, which can be used to evaluate the temperature-dependent mechanical behaviors of 2.5D-WC. Ultimately, we hope these findings could further promote the engineering applications of 2.5D-WC, especially in aero-engine fields.

1. Introduction

Nowadays, textile composites have played an important structural material in advanced engineering industries, especially in the astronautics and aeronautics fields, owing to their excellent mechanical performances, i.e. high stiffness and strength at low density, outstanding delamination resistance [1,2]. Among them, a new class of 2.5D woven composites (2.5D-WC) with layer to layer angle-interlock structure has been proposed. It can be facilely weaved compared to 3D woven composites and possesses a superior delamination resistance in comparison with 2D laminated composites.

Recently, several studies have reported the mechanical performances of resin-matrix 2.5D-WC at ambient temperature. Lu et al. [3] experimentally investigated the warp mechanical performances of 2.5D-WC at ambient temperature and obtained the tension and compression responses. John et al. [4] analyzed the micro-structural damage in the warp direction of 2.5D-WC in the case of tensile loading by experiment at ambient temperature. Zhang et al. [5] studied the stress field distribution of warp-reinforced 2.5D woven composites using an idealized meso-scale voxel-based model at ambient temperature. Zheng et al. [6] investigated the ambient yield condition of 2.5D-WC in the weft direction and established the original yield criteria of this material loaded in weft. Likewise, Qiu [7], Dong [8], Lu et al. [9] predicted the mechanical properties of 2.5D-WC based on finite element method at ambient temperature.

To be best of our knowledge, most of aero-engine components expose to the long-term thermo-mechanical environment, which inevitably gives rise to the difficulty in manufacturing and investigating the temperature-dependent mechanical behaviors of resin-matrix woven composites [10]. To solve this issue, a series of thermosetting resins have been developed, and the counterpart composites can be therefore fabricated. For 2D laminated resin-matrix composites, the mechanical performances generally decrease, alongside much more delamination and resin failure damage modes, with the temperature increases [11–13]. For 2D/3D woven resin-matrix composites, Selezneva et al. [14] investigated the failure mechanism in off-axis 2D woven composites at ambient temperature and 205 °C by experiment, and found that the woven yarns begin to straighten out and rotate towards the loading direction just prior to failure. Vieille and Taleb [15] studied the effect of temperature (20 °C and 120 °C) and matrix ductility

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Nomenclature

V_f	fiber volume fraction of whole composite panel
ρ_f; ρ_m	density of fiber and matrix
$g(x)$	extended outlines of warp yarns
L_x; L_y	periodic boundary in warp and weft directions
M_j; M_w	warp and weft arranged density
A_j; A_w	cross-sectional area of warp and weft yarns
N_h	number of layers in weft direction
U_i $(i = x, y, z)$	deformation of ith nodes
L_j $(j = x, y, z)$	boundary length
S_j	area of corresponding boundary surface
σ_{ij} $(i, j = x, y, z)$	average stress of six independent directions
S_{12}; S_{13}; S_{23}	shear strength of yarn
$\mathbf{C}(V_f, T)$	undamaged stiffness matrix
$\mathbf{M}(d)$	Murakami's damage matrix
E_{11}; $E_{22}(E_{33})$	Young's moduli along the longitudinal and transversal
μ_{ij} $(i, j = 1, 2, 3)$	Poisson's ratio
$\{\alpha\}$	coefficient of expansion vector
m_1; m_2	pre-casting mass, post-casting mass
$f(x)$	cross-sectional configuration of weft yarns
W_{1w}	width of weft yarns
N_k; N_j	amount of weft and warp yarns at the same height along the warp and weft directions
T_e	linear densities of yarns
P_j; P_w	fiber volume fraction inside of warp and weft yarns (called fiber aggregation density)
θ	inclination angle of warp yarns
ε_{ij} $(i, j = x, y, z)$	average strain of six independent directions
P_{ij}	resultant traction on the boundary surface
x_j^+; x_j^-	deformation of opposite boundary surfaces
X_{11}; Y_{22}	longitudinal and transversal strength of yarn
X_m	strength of resin
$\overline{C}(V_f, T)$	damaged stiffness matrix
d_i $(i = 1, 2, 3)$	damage factor
G_{23}; $G_{31}(G_{12})$	shear moduli
$\{\Delta\varepsilon\}$; $\{\Delta u\}$	strain and displacement vectors
$\{\overline{T}^{n+1}\}$	surface load vector in the $(n+1)$th load step

on the behavior of 2D woven composites. Montesano et al. [16,17] conducted several static and fatigue tests based on 2D woven composites at 20 °C and 225 °C. Although there have been several works in investigating the mechanical behaviors of woven composites at elevated temperatures, the specific studies pertaining to 2.5D-WC are scarce as yet, especially the temperature-dependent mechanical performances in the weft direction.

Since the thermosetting QY8911-IV resin with high glass-transition temperature ($T_g = 252$ °C) has an excellent fluidity at ~120 °C, it can be used to manufacture resin-matrix woven composites by resin transfer modeling (RTM) [13]. In this work, our primary objective will focus on investigating the thermo-mechanical behaviors of 2.5D T300/QY8911-IV woven composites in warp and weft directions. Three major aspects are required for the proposed study: (1) Experimental investigation of temperature-dependent warp and weft mechanical behaviors of 2.5D-woven composites in warp and weft directions; (2) Numerical investigation of temperature-dependent mechanical behaviors of 2.5D-woven composites in warp and weft directions; (3) Damage and failure mechanisms at ambient and un-ambient temperatures. We expect that the findings could be important for further understanding the thermo-mechanical behaviors of 2.5D woven composites, as well as for designing the 2.5D woven composites-based components from the engineering application view.

2. Materials and experimental methods

2.1. Materials and specimen

2.5D woven composites comprise of T300 carbon fiber yarns including 3 K filaments per bundle and thermosetting QY8911-IV with a glass transition temperature 256 °C. Table 1 gives the mechanical performances of basic components. All specimens with six plies of weft yarns were manufactured by using RTM technology, and the corresponding preparing process was shown in Fig. 1(a). DMA curve show that the glass transition temperature of QY8911-IV is about 259.6, but there is a sharp downward trend when the temperature exceeds 200 °C (Fig. 1(b)). Several specimens with nominal dimensions of 300 mm × 25 mm were finally fabricated, followed that two aluminum end tabs with 50 mm in length were bonded to each specimen. Table 2 illustrates the woven parameters of 2.5D-WC.

Table 1
Mechanical properties of component materials at ambient temperature.

	E_{f1}/E_m (GPa)	E_{f2} (GPa)	G_{f12}/G_m (GPa)	G_{f23} (GPa)	μ_{f12}/μ_m
T300-3K	230	40	17	4.8	0.3
QY8911-IV	4.16	—	—	—	0.34

2.2. Experimental platform, method and data processing

A MTS 810 hydraulic servo dynamic material test platform assisted by a MTS809 furnace was built to examine the thermo-mechanical behaviors of 2.5D-WC (Fig. 1(c)). Meanwhile, a 25.4 mm MTS-634-25 elevated temperature extensometer was used to record the strain information continuously (Fig. 1(d)). In order to make sure that the temperature in the chamber roughly remains constant, the furnace has two heating regions, each with a K-type thermocouple for temperature feedback to the controller.

In accordance with the standard ASTM D3039 [18], the static tensile tests in the weft direction were conducted under the displacement control at a constant rate of 0.05 mm/min at ambient temperature (~20 °C). However, for the un-ambient temperature (~180 °C in this work), the temperature was first ramped up to the target temperature at a rate of 10 °C per minute in force control, followed by a heat preservation process to make sure the uniform temperature field. Afterwards, the tensile tests were carried out according to ASTM D3039.

3. Temperature-dependent multi-scale prediction model

3.1. Geometric and finite element models

Generally, the woven fabric processes a repetitive topologic configuration determined by the corresponding woven technology, see Fig. 2(a). According to the cross-sectional photographs (Fig. 2(c)), the as-fabricated 2.5D-WC in this work remain a representative volume cell, it can be clearly seen that a spatial net-shape fabric by joining adjacent layers of the warp and weft yarns together is repeatedly distributed, in which there are six layers of weft yarns and seven layers of warp yarns in the thickness direction. However, the configurations of outmost layer yarns are different from those of inner ones owing to the influence of high manufacture pressure of RTM technology (Fig. 2(b)). The weft yarns nearly extend parallel and the cross-sectional outline of warp yarns are mostly rectangle (Fig. 2(d)).

To estimate the thermo-mechanical behaviors of 2.5D-WC by simulation, we therefore established the Inner-cell model and Full-cell model, respectively. The establishment method can be in detail described in the following part.