THREE-DIMENSIONAL THERMOELASTIC ANALYSIS OF PLAIN WEAVE GLASS/EPOXY COMPOSITES WITH CRACKS AT CRYOGENIC TEMPERATURES

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Summary This study presents a numerical investigation of the thermo-mechanical behavior of G-11 woven glass/epoxy laminates with cracks subjected to tensile loading at cryogenic temperatures. Three-dimensional finite elements are employed to model the architecture of the two-layer woven laminates. Numerical results for the Young's modulus, Poisson's ratio, and stress distributions and concentrations are obtained and discussed in detail.

INTRODUCTION

Composite materials have received increased attention for applications in cryogenic environment because of their unique and highly tailorable properties [1]. In recent years, carbon-fiber/epoxy-resin composites have been evaluated for cryogenic tankage in RLV (reusable launch vehicle) [2]. Woven-fabric glass/epoxy laminates are used as thermal insulation, electrical insulation, structural support and permeability barrier in superconducting magnets which are essential components of most current and planned fusion devices [3]. Residual thermal stresses develop in these materials when they are exposed to cryogenic temperatures. These stresses are the result of a difference in the CTEs (coefficients of thermal expansion) between the reinforcement and the matrix. The non-zero state of residual thermal stresses at cryogenic temperatures is the underlying cause of microcracking in composites and the microcracks could have an important influence on their performance [4]. To secure the structural integrity of superconducting magnets, understanding of the thermo-mechanical behavior of cracked woven-fabric glass/epoxy laminates at cryogenic temperatures is of great importance.

Recently, Takeda et al. have studied the influence of residual thermal stresses and cracks on the mechanical behavior of two-layer [5] or multi-layer [6] G-11 woven glass/epoxy laminates under tension at cryogenic temperatures by a finite element method. The approximation for two-dimensional finite element model appears to be a serious oversimplification, which models only a portion of the woven structure. It is necessary, therefore, to develop a complete three-dimesional model which leads to more accurate predictions. In this paper, the thermo-mechanical behavior of G-11 woven glass/epoxy laminates with cracks under tension at cryogenic temperatures is investigated using three-dimensional finite element analysis.

STATEMENT OF THE PROBLEM

Consider a two-layer woven laminate with the out-of-phase stacking configuration, which implies the mirror symmetry about the middle plane, and cracks, as shown in Fig. 1. A rectangular Cartesian coordinate system (x, y, z) is used with the x-axis coinciding with the direction of mechanical load. The two-layer woven laminate of thickness $2H$ occupying the region ($|x| < \infty$, $|y| < \infty$, $|z| \leq H$) consists of two sets of interlaced fiber bundles and pure resin matrix. The fiber bundles which run in the x-direction are the warp fiber bundles. The fiber bundles running perpendicular to these are the fill fiber bundles. Based on the experimental observations of Kriz and Muster [7], it is assumed that the cracks of length a lie in the fill fiber bundles. The crack fronts are situated at equal distances away from the boundaries of the fill fiber

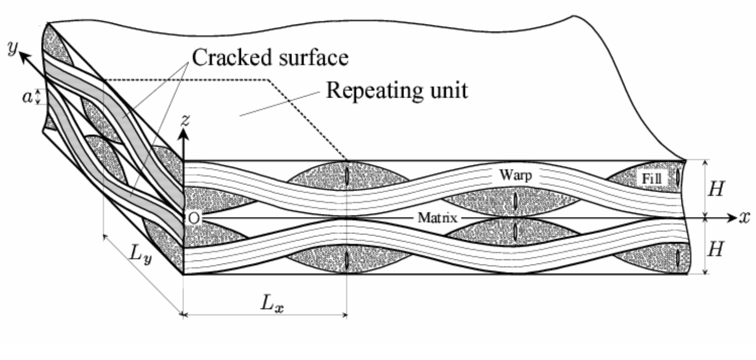

Fig. 1 Two-layer woven laminate with cracks

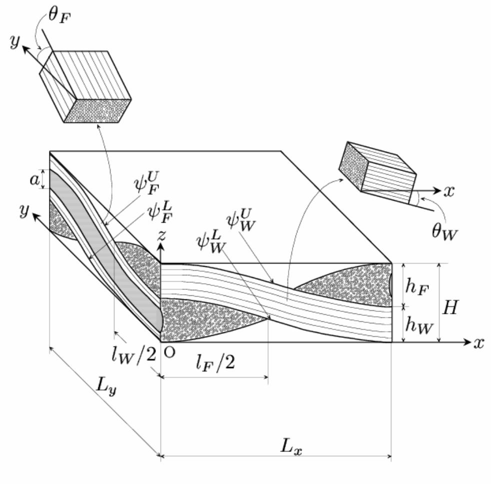

Fig. 2 Repeating unit

bundles. We will consider two cases: two-layer woven laminate with cracks located in $x = \pm 2nL_x$ (n = 0, 1, 2, …) planes of the fill fiber bundles (Case 1) and woven laminate with cracks in all fill fiber bundles (Case 2). Then, from symmetry and periodicity only the repeating unit illustrated in Fig. 2, which is also identified in Fig. 1 using dashed lines, needs to be analyzed. The undulation of fiber bundles is assumed to be sinusoidal functions $\psi_W^L, \psi_F^L, \psi_W^U$ and ψ_F^U. As depicted in this figure, L_x and L_y stand for the length of the repeating unit in the x- and y-directions, l_W and l_F denote the width of the warp and fill fiber bundles, h_W and h_F represent the thickness of the warp and fill fiber bundles, θ_W is the local angle between the warp fiber bundle and the x-axis of the global coordinate system, and θ_F is the local angle between the fill fiber bundle and the global y-axis.

Suppose that the woven laminate is subjected to the thermal load of $\Phi - \Phi_s$ and the mechanical mean stress σ^*_{xx} in the x-direction, where Φ is the temperature of the woven laminate and Φ_s is the stress-free temperature, often assumed to be the cure temperature. The mechanical mean stress σ^*_{xx} induces the uniform displacement in the x-direction at $x = L_x$ plane of the repeating unit.

THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS

We use a commercial finite element package ANSYS to perform the analysis. The finite element model uses four-noded, three-dimensional, linear, tetrahedral elements. A typical finite element mesh utilizes a total of 49859 elements which lead to a total of 10834 nodes.

RESULTS AND DISCUSSION

The geometrical parameters of G-11 woven glass/epoxy laminates used in the present investigation are the actual dimensions measured with a SEM (scanning electron microscope) [8] and listed in Table 1. The fiber volume fraction in the fiber bundles is taken to have the value of 0.75, corresponding to that of actual G-11 woven laminates. The cure temperature of the thermal strain free state Φ_s is assumed to be 395 K.

Table 1 Geometrical parameters of G-11 woven glass/epoxy laminates

L_x (mm)	L_y (mm)	H (mm)	l_W (mm)	l_F (mm)	h_W (mm)	h_F (mm)
0.81	0.63	0.19	0.63	0.65	0.11	0.08

Table 2 shows a comparison of the Young's moduli (E_x^0, E_x^c) at Φ = 293, 77, 4 K from the three-dimensional finite element analysis (3-D FEA) with those from the micromechanics model [8] by Hahn and Pandey [9] and experiments [8]. Also shown are the results for the Poisson's ratio (ν_{xy}^0, ν_{xy}^c). Figure 3 provides the stresses σ_{xxW} in the warp fiber bundle at x = 0 and y = 0 as a function of the distance from the crack front $(z - h_F)/h_W$ for Φ = 293, 77, 4 K. For this figure, solid and dashed lines indicate the three-dimensional finite element results with and without thermal effects, respectively.

Table 2 Elastic properties of two-layer G-11 woven glass/epoxy laminates

Young's moduli			293 K	77 K	4 K
E_x^0 (GPa)	3-D FEA		26.75	33.10	36.04
	Micromechanics model		26.66	32.98	35.94
	Experimental		27.9	32.7	36.9
E_x^c (GPa)	3-D FEA	Case 1	25.88	31.89	34.69
		Case 2	25.51	31.23	33.89
Poisson's ratios			**293 K**	**77 K**	**4 K**
ν_{xy}^0	3-D FEA		0.140	0.193	0.214
	Micromechanics model		0.13	0.19	0.21
	Experimental		0.17	0.19	0.23
ν_{xy}^c	3-D FEA	Case 1	0.137	0.188	0.209
		Case 2	0.132	0.182	0.202

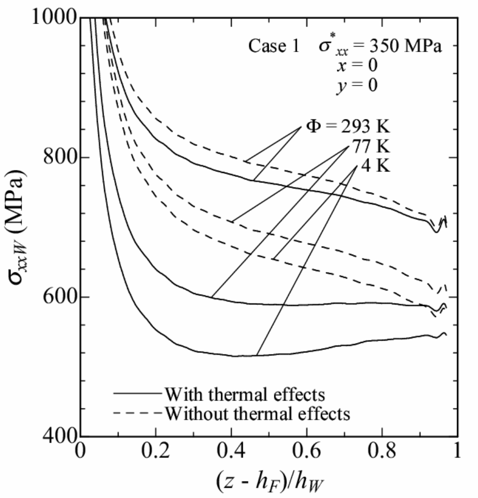

Fig.3 Variation of stresses σ_{xxW} at x=0 and y=0 (Case 1)

References

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