THREE-DIMENSIONAL CRYOMECHANICS ANALYSIS OF SATIN WOVEN CARBON/POLYMER COMPOSITES WITH CRACKS

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Summary We present a cryomechanics analysis for five harness satin woven carbon fiber reinforced polymer composite laminates with cracks under tension. The three-dimensional finite element model assumes the cracks to be located in the transverse fiber bundles. Numerical calculations are carried out, and the Young's modulus and stress distributions near the crack fronts at cryogenic temperatures are obtained. Results of this analysis demonstrate the effects of the residual thermal stresses and cracks on the mechanical behavior.

INTRODUCTION

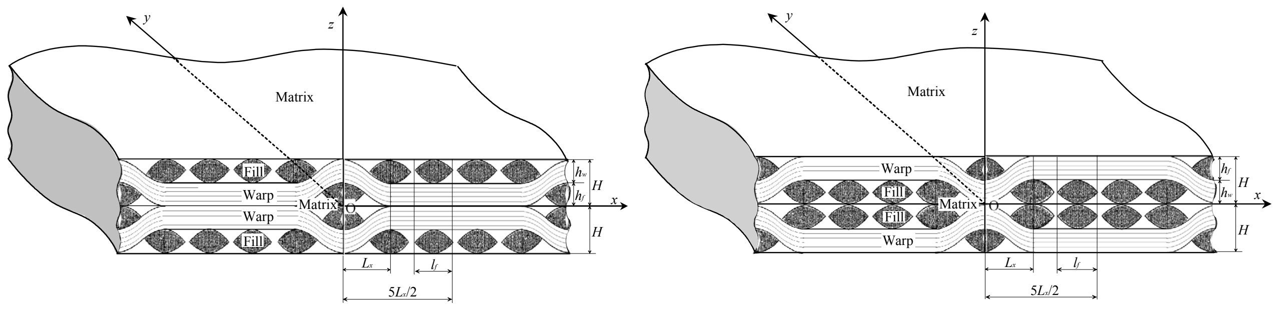
For the future transportation systems such as reusable launch vehicles (RLVs) to be viable, it is necessary to minimize airframe weight in order to increase the ability to carry more fuel. In order to accomplish this goal, woven carbon fiber reinforced polymer (CFRP) composite laminates have been under consideration for the cryogenic fuel tanks. However, residual thermal stresses arise because of the mismatch in the thermoelastic properties between the fibers and the matrix in woven laminates at cryogenic temperatures. High residual stresses can cause premature internal damage such as microcracks. Therefore, there is a need to fully understand the cryogenic behavior of cracked woven laminates. In this paper, the thermo-mechanical behavior of five harness satin (5HS) woven CFRP composite laminates with cracks under tension at cryogenic temperatures is investigated using three-dimensional finite element method.

GEOMETRY OF CRACKED 5HS WOVEN COMPOSITE LAMINATES

5HS woven composite laminates with T800H carbon fiber (Toray Industries, Inc., Japan) and 3633 toughened epoxy resin matrix (Toray Industries, Inc., Japan) subjected to tensile loading are considered in the present study. Fig. 1 shows the symmetry stacked two-layer 5HS woven laminates with cracks. A rectangular Cartesian coordinate system O-*xyz* is used with the *x*-axis coinciding with the direction of mechanical load. The two-layer woven laminates of thickness $2H$ occupy the region ($|x| < \infty$, $|y| < \infty$, $|z| \leq H$). 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. It is assumed that the cracks of length a are located in $x = 5nL_x$ (n is an integer) planes of the fill fiber bundles. When the fill is main fiber bundles on the surfaces of woven laminates, the woven laminates is denoted "Case 1" (see Fig. 1(a)). L_x and L_y stand for the fill and warp fiber bundle spacings, l_w and l_f denote the widths of the warp and fill fiber bundles, and h_w and h_f represent the thicknesses of the warp and fill fiber bundles. The subscripts w and f correspond to the warp and fill fiber bundles, respectively. The undulations of the fiber bundles are assumed to be sinusoidal. Similarly consider Case 2, i.e., the surfaces of woven laminates are dominated by the warp fiber bundles (see Fig. 1(b)). 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.

TEMPERATURE-DEPENDENT MATERIAL PROPERTIES

The elastic and thermal properties of the 3633 toughened epoxy resin matrix are taken to be temperature dependent and



(a) (b)

Fig. 1 Two-layer 5HS woven laminates with cracks for (a) Case 1 and (b) Case 2

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are assumed to be the same as those of the bisphenol-A epoxy resin [1]. The elastic and thermal properties of the T800H carbon fiber is assumed to be temperature independent. The property data of the T800H carbon fiber are used when available, and the remaining properties are assumed to be the same as the T300 carbon fiber properties. The fiber bundles are treated as transversely isotropic unidirectional T800H/3633 composites. The composite cylinder assemblage (CCA) model [2] is used to predict the elastic and thermal properties of the fiber bundles.

THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS

5HS woven composite laminates can be represented as a periodical array of the representative volume element (RVE). Therefore, the periodic boundary conditions must be applied to the RVE models. The RVE has the length $5L_x$ ($-5L_x/2 \leq x \leq 5L_x/2$), width $5L_y$ ($0 \leq y \leq 5L_y$), and thickness H ($0 \leq z \leq H$). In addition, we consider the infinite-layer woven composite laminates. The Young's modulus in the x-direction of the two-layer and infinite-layer woven laminates is obtained applying the energy equivalence method [3]. The finite element models use four-noded, three-dimensional, linear, tetrahedral elements.

RESULTS AND DISCUSSION

The geometrical parameters of T800H/3633 5HS woven composite laminates are measured using the digital microscope. The value of a fiber volume fraction in the fiber bundles is taken as 0.85. The stress-free temperature Φ_s is assumed to be 453 K. The fill fiber bundle cracks are assumed to be of the through-thickness type (i.e., $a/h_f = 1.0$).

The Young's modulus decreases with decreasing of the temperature, and formation of cracks in the fiber bundles decreases Young's modulus. Fig. 2 shows the stresses σ_{xxw} in the warp fiber bundle of the two-layer woven laminates for Case 1 and Φ = 293 K (room temperature), 90 K (liquid oxygen temperature), 77 K (liquid nitrogen temperature), 20 K (liquid hydrogen temperature), 4 K (liquid helium temperature) at $x = 0$ and $y = 0$ ($h_f \leq z \leq H$) under combined mechanical and thermal loads (i.e., σ^*_{xx} = 100 MPa) as a function of the distance from the internal crack front Z (= $(z - h_f)/h_w$). The stresses σ_{xxw} near the internal crack front and surface of the woven laminates are larger than those in the interior. The stresses σ_{xxw} in the interior decrease with the decrease in the temperature. The stresses σ_{xxw} in the warp fiber bundle of the infinite-layer woven laminates for Case 1 and σ^*_{xx} = 100 MPa at $x = 0$ and $y = 0$ ($h_f \leq z \leq H$) are shown in Fig. 3, as a function of the distance from the crack front Z (= $(z - h_f)/h_w$). The stresses σ_{xxw} for Case 2 at $x = 0$ and $y = 0$ ($0 \leq z \leq h_w$) as a function of the distance from the crack front Z (= $(h_w - z)/h_w$) are also provided. The stresses σ_{xxw} in the warp fiber bundle of the infinite-layer woven laminates decrease with distance from crack front.

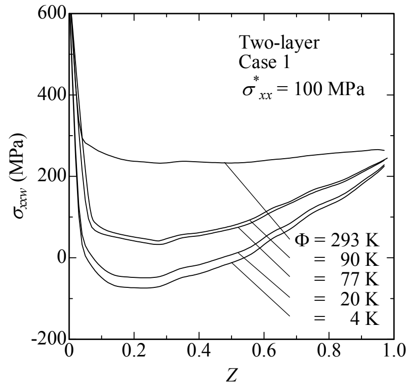

Fig. 2 Variation the stresses σ_{xxw} in the warp fiber bundle of the two-layer woven laminates at $x = 0$ and $y = 0$ for σ^*_{xx} = 100 MPa (Case 1)

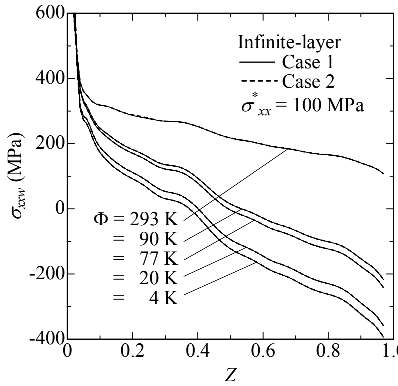

Fig. 3 Variation the stresses σ_{xxw} in the warp fiber bundle of the infinite-layer woven laminates at $x = 0$ and $y = 0$ for σ^*_{xx} = 100 MPa (Cases 1 and 2)

CONCLUSIONS

The focus of this paper is the study of the thermo-mechanical behavior of woven CFRP composite laminates with cracks at cryogenic temperatures. A study of the cryogenic mechanical response of cracked woven composite laminates would serve as guidelines for focusing attention on failure mechanisms of such composites for use on the cryotanks of RLVs.

References

[1] Watanabe S., Shindo Y., Takeda T., Narita F., Sanada K.: Cryogenic Behavior of Cracks in Satin Woven CFRP Laminates under Tensile Loading. *J. Solid Mech. Mater. Eng.* **3**:22-37, 2009.

[2] Hashin Z.: Analysis of Properties of Fiber Composites with Anisotropic Constituents. *ASME J. Appl. Mech.* **46**:543-550, 1979.

[3] Zhang W.C., Evans K.E.: Numerical Prediction of the Mechanical Properties of Anisotropic Composite Materials. *Comput. Struct.* **29**:413-422, 1988.