§13. Cryogenic Tensile Strength Evaluation of Composite Insulation Systems for Superconducting Magnets Using the Open Hole Specimens

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1. Purpose

Superconducting magnets may use large quantities of woven glass fiber-reinforced polymer (GFRP) composite laminates as thermal and electrical insulation and structural support. Hence, the cryogenic mechanical properties of woven composite laminates must be characterized for the design of cryogenic systems. Tensile tests have been a fundamental method of characterizing the mechanical response of composite materials. However, cryogenic tensile testing presents significant challenges, and the slippage between the specimen and the grips is one of the major problems. An attractive alternative to the tensile test for the determination of the cryogenic composite strength is the open hole tensile test. Since the hole causes a stress concentration, the failure of the open hole specimen occurs at loads far below the failure load of the unnotched specimen. Therefore, the open hole tensile test offers a potentially attractive approach for avoiding cryogenic testing problems. The purpose of this research is to characterize the tensile strength of woven GFRP laminates at cryogenic temperatures by a combined method of open hole tensile test and finite element analysis.[1,2]

2. Procedure

In this work, National Electrical Manufacturer's Association grade G-11 woven GFRP laminates were used. The geometry and dimensions of the open hole specimen are shown in Fig. 1. The thickness of the specimen was equal to 2 mm. Tensile tests were conducted at room temperature, liquid nitrogen temperature (77 K) and liquid helium temperature (4 K), and the failure loads P_c were measured. Also, the fracture surfaces were examined and the length of the critical damage zone (that is, the damage zone just before catastrophic failure), D_c, was determined from the fracture surface morphologies.

Finite element simulations were carried out, and plane stress conditions were assumed. The finite element model treated the entire plain weave fabric composite as one homogeneous material with orthotropic material properties. The damage zone was modeled as a strip with the critical damage zone length D_c ahead of the hole edge, and the normal stress in the loading direction was assumed to be uniform (σ_0) within the damage zone. The stress distribution corresponding to the experimentally obtained failure load P_c and critical damage zone length D_c was determined from the

finite element analysis, and the σ_0 value was evaluated. The numerically evaluated uniform stress σ_0 was regarded as the ultimate tensile strength of the specimen material.

3. Results

Fig. 2 shows a typical fracture surface morphology of a failed specimen at 4 K. The fracture surface near the hole edge at cryogenic temperatures exhibits fiber pullout and suggests that the length of the fiber pullout region corresponds to the critical damage zone length D_c. Table I presents the numerically determined uniform stresses σ_0 at room temperature (RT), 77 K and 4 K. For comparison, the ultimate tensile strengths σ_{ult} from the tensile tests on the unnotched G-11 specimens[3] are given in the table. The numerically determined uniform stresses σ_0 are in good agreement with the σ_{ult} values. This suggests that the uniform stress from the present combined numerical-experimental method is a reliable estimate of the composite tensile strength. Therefore, the present method provides a novel approach to measuring the cryogenic tensile strength of high-strength advanced composite materials. [4]
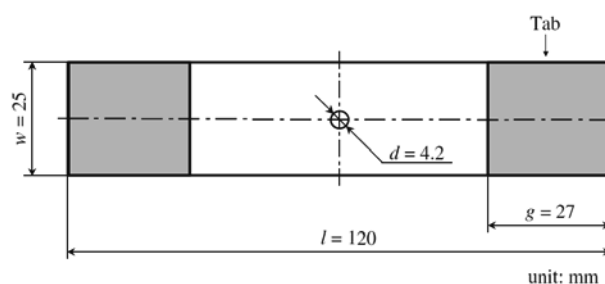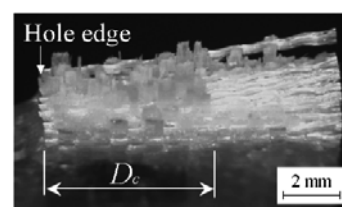

Fig. 1. Open hole specimen.

Fig. 2. Fracture surface morphology at 4 K.

Table I. Predicted and experimental ultimate tensile strengths of G-11 woven composite laminates.

RT		77 K		4 K	
σ_0 (MPa)	σ_{ult} (MPa)	σ_0 (MPa)	σ_{ult} (MPa)	σ_0 (MPa)	σ_{ult} (MPa)
331	310	548	610	535	579

1) Shindo, Y. et al.: J. Mech. Mater. Struct. **6** (2011) 545.
2) Shindo, Y. and Fu, S. -Y.: Methods for strength characterization of woven fabric composites at cryogenic temperatures, L. Nicolais and A. Borzacchiello (Eds.) John Wiley & Sons, in press.
3) Shindo, Y. et al.: Adv. Cryog. Eng. **52** (2006) 249.
4) Watanabe, S. et al.: ASTM J. Test. Eval. **39** (2011) 690.