§13. Cryogenic Tensile Fatigue 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 electrical and thermal insulation, and structural support. Efficient utilization of woven composites requires a thorough understanding of their performance in a variety of loading and environmental conditions. The mechanical behaviors of woven composites under static and cyclic loadings are important for their structural applications, and static and fatigue strengths are the fundamental material properties for the designer of composite structures. Recently, our research group proposed the use of the open hole specimen for cryogenic strength property measurement in plain weave GFRP composite laminates, in order to avoid the cryogenic testing problems, such as the specimen slippage.[1] The purpose of this research is to characterize the fatigue strength of woven GFRP laminates under tensile cyclic loading at cryogenic temperatures by a combined method of open hole fatigue test and finite element analysis.[2]

2. Procedure

In this work, National Electrical Manufacturer's Association grade G-11 woven GFRP laminates were employed. The open hole specimens were machined from panels of G-11 woven laminates to the dimensions shown in Fig. 1. The thickness of the specimen was equal to 2 mm. Tension–tension fatigue tests were performed on the open hole specimens under load control with constant amplitude at room temperature, 77K and 4K. The load cycle was sinusoidal and the ratio of the minimum applied load $P_{\min}$ to the maximum applied load $P_{\max}$ (load ratio R) was equal to 0.1 for all of the experiments. The maximum load $P_{\max}$ was applied as a percentage of the tensile static failure load P_c for the open hole specimens, and fatigue tests were conducted at $P_{\max}/P_c$ = 0.3, 0.6 and 0.9. The cyclic frequency was 4Hz for the room temperature tests. For the tests at 77K and 4K, the frequency was 4Hz up to 10^5 cycles, and then increased to 10 Hz until the completion of the tests.

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 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 distributions near the hole with the damage zone for the maximum applied loads were determined. The hole edge damage zone length D was assumed to be the same as the length of the critical damage zone (i.e. the damage zone just before specimen failure) for tensile static loading.[1] The numerically evaluated uniform stress σ_0 was regarded as the material fatigue strength σ_f at the number of cycles to failure (fatigue life) N_f of the test specimen.

3. Results

Fig. 2 shows the uniform stress σ_0 in the hole edge damage zone versus fatigue life N_f relationships (*S-N* diagrams) at 4K from the combined numerical-experimental method. The uniform stress σ_0 was evaluated for each condition by the finite element method and then plotted at the fatigue life N_f of the open hole specimen tested under the same condition. The uniform stresses σ_0 for the static loading case from the similar method[1] are also plotted at N_f = 1. For comparison, the fatigue strength σ_f versus fatigue life N_f relationships from the tests on the unnotched G-11 specimens[3] are shown in the figure. It is found that the *S-N* curves from the combined method are in good agreement overall with the unnotched specimen test results. Hence, the present combined method can be a viable tool for avoiding the specimen gripping problems and obtaining the cryogenic fatigue data for composite materials with small scatter.

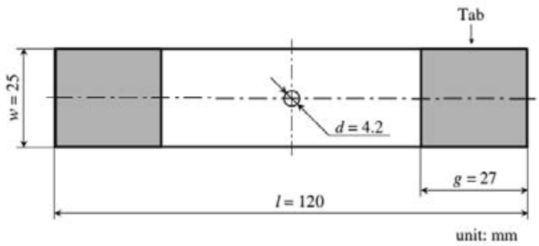

Fig. 1. Open hole specimen.

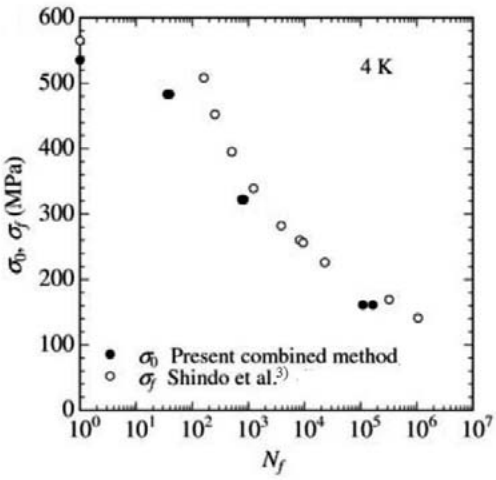

Fig. 2. *S-N* diagrams at 4 K.

1) Shindo, Y. et al.: J. Mech. Mater. Struct. **6** (2011) 545.
2) Shindo, Y. et al.: J. Compos Mater. **47** (2013) 2885.
3) Shindo, Y. et al.: Cryogenics **46** (2006) 794.