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Influence of parameter variations on the fatigue behavior of magnet insulation systems

K. Bittner-Rohrhofer, K. Humer, H.W. Weber*

Atomic Institute of the Austrian Universities, Vienna University of Technology, 1020 Vienna, Austria

Abstract

The application of glass-fiber-reinforced plastics (GFRP's) as insulation materials for fusion magnet coils (e.g. of ITER) requires the full characterization of their mechanical performance under ITER relevant conditions. Tension–tension fatigue is a useful procedure to simulate the pulsed tokamak operation of the ITER coils in the relevant range of 10^4–10^5 cycles. The fatigue parameters, such as the R-ratio and the load frequency, may influence the material behavior under cyclic load. Therefore, investigations were made under load control and at 77 K on an industrial glass-fiber-reinforced/epoxy compound. Stress–lifetime diagrams were generated with R-values between 0.1 and 0.5 and frequencies between 5 and 20 Hz. The results are discussed with respect to the lifetime performance of ITER.

Keywords: Mechanical properties; Fatigue parameters; Tension; Cryogenic temperatures

1. Introduction

The reliable application of glass-fiber-reinforced plastics (GFRP's) as insulation materials for fusion magnet coils (e.g. the toroidal field coils of ITER) requires the full characterization of their mechanical performance under ITER relevant operating conditions [1–4]. One of the common methods to investigate the material's response under dynamic load is the tension–tension fatigue test procedure according to the ASTM D3479 standard. This test can be used to simulate the pulsed tokamak operation of the ITER coils over a lifetime of more than 20 years, where 10^4–10^5 cycles are expected. Furthermore, information on the interlaminar shear stress behavior can be obtained, if the standard is combined with a double-lap-shear specimen geometry [5,6].

In order to simulate the operation conditions of ITER as closely as possible, several fatigue parameters can be specified in the test programme, e.g., the minimum-to-peak stress ratio R, the frequency f, and the load control mode of the sinusoidal load function. All of these parameters may influence the mechanical response of an insulation system under cyclic load. Therefore, it is highly desirable to investigate the influence of these parameter variations on the measured stress–lifetime diagrams.

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* Corresponding author. Tel.: +43 1 58801 14140; fax: +43 1 58801 14199.
E-mail address: weber@ati.ac.at (H.W. Weber).

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In the past, extensive scaling experiments were carried out on tensile [7,8] and double-lap-shear [6,8] specimen geometries, in order to obtain small sample dimensions suitable for irradiation and cryogenic test programs [9]. Epaarachchi and Clausen [10] proposed a fatigue model for glass-fiber-reinforced plastics, where the stress ratio *R*, and the frequency *f*, are independent variables. They found excellent agreement between theoretical predictions and experimental data for a wide range of GFRP's. Demers [11] performed tension–tension fatigue tests on E-glass FRPs and found, that the fatigue life increased with increasing *R*-ratio between 0.05 and 0.9 at frequencies between 1 and 5 Hz. In addition, no loss in fatigue life was observed for frequencies of 3 and 5 Hz, in contrast to results at 1 Hz. Ellyin and Kujawski [12] studied the fatigue behavior of GFRP's and found different rate/frequency effects, depending on the type of glass-fiber reinfocement. Hartwig and Knaak [13] investigated the fatigue behavior of various polymers at 77 K. At $R = 0.1$, they observed no frequency dependence between 0.5 and 100 Hz, whereas experiments at $R = -1$ (tension/compression) showed a pronounced dependence on frequency. Tsai et al. [14] confirmed this fatigue performance in the frequency range from 0.01 to 10 Hz.

In the present study, such investigations on an industrial glass-fiber-reinforced composite impregnated with epoxy resin were performed at 77 K. In the load controlled mode, *R*-values from 0.1 to 0.5 and frequencies from 5 to 20 Hz were chosen and stress–lifetime diagrams (S/N-curves, Wöhler-curves) recorded. The results are discussed with respect to the operating conditions of ITER.

2. Experimental

The investigated laminate, ISOVAL 10/E (NEMA/ASTM: G 10; ISOVOLTA AG, Austria), consists of a two-dimensional orthotropic E-glass-fiber reinforcement (0°/90°) in epoxy (DGEBA). The tension–tension fatigue tests were carried out at 77 K with a servohydraulic MTS 810 TestStar II Material Testing System. The static ultimate tensile strength (UTS) was measured on 3 mm thick samples according to the standards DIN 53455 and ASTM D638, whereas the fatigue tests were done according to ASTM D3479 in load control using a sinusoidal load function. In order to obtain stress–lifetime diagrams (S/N-curves, Wöhler-curves), various load levels ranging from 80 to 40% of the UTS were chosen and investigated up to 10^6 cycles to failure.

The fatigue tests were run either with different load frequencies of 5, 10 and 20 Hz at a minimum-to-peak stress ratio of $R = 0.1$, or with different *R*-ratios of 0.1, 0.3 and 0.5 at a load frequency of 10 Hz. Four samples were measured for each data point.

3. Results and discussion

Investigations of the fatigue behavior of the insulating material require a close simulation of the actual operating conditions of ITER [1,2] over the plant lifetime (20 years) with regard to the pulse duration and their number (i.e. 200–500 s and 3×10^4 cycles, respectively [3]). Of course, the real pulse duration cannot be simulated because of time limitations, but a proper low load frequency (10 Hz) was chosen. On the other hand, the *R*-ratio of 0.1 simulates a "worst-case-scenario" for the ITER coils quite well.

With respect to the influence of the *R*-ratio at a constant frequency of 10 Hz (Fig. 1, upper panel), the material shows the lowest fatigue lifetime for $R = 0.1$, as expected. Between the load levels of 0.85 and 0.55 UTS, a sharp decrease of the S/N-curve is observed, indicating rapid material fatigue in this range. A further reduction of the load level to 0.4 UTS leads initially to a considerably higher number of cycles to failure, but ends up in the life endurance limit of the material. At $R = 0.3$, the S/N-curve is continuously shifted to higher load cycles. The maximal shift is found at 0.45 UTS, where the number of cycles increases by a factor of 4.5 compared to $R = 0.1$, without reaching the life endurance limit. Reducing the lower stress level to $R = 0.5$, leads to a further increase in the fatigue performance. Because of time constraints, the experiments were stopped at 2.3×10^6 cycles, without having reached the life endurance limit. In general, the results indicate an enhancement in the residual strength by about 10% at a certain number of cycles. The measured life endurance limit also increases from 40 to ∼45%. With respect to ITER relevant operating conditions, i.e. at 3×10^4 load cycles, about 10% higher residual stress levels were obtained in this laminate,