Evaluation of the cryogenic mechanical properties of the insulation material for ITER Feeder superconducting joint

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Abstract. The Glass-fiber reinforced plastic (GFRP) fabricated by the vacuum bag process was selected as the high voltage electrical insulation and mechanical support for the superconducting joints and the current leads for the ITER Feeder system. To evaluate the cryogenic mechanical properties of the GFRP, the mechanical properties such as the short beam strength (SBS), the tensile strength and the fatigue fracture strength after 30,000 cycles, were measured at 77K in this study. The results demonstrated that the GFRP met the design requirements of ITER.

1. Introduction

The ITER feeder system consists of 31 units, which was distributed around the Tokamak and connects the ITER magnet systems to the power supply [1-2]. The main function of the feeders is to convey the cryogenic supply and electrical power to the coils as well as house the instrumentation wiring. In the Feeder systems, hundreds of superconducting joints are used to assemble the segments of the superconducting busbars and to connect the busbars to the coil terminals, as shown in figure 1. In general, GFRP was selected as the insulation material and mechanical support material for the superconducting joints and the current leads of the ITER Feeder system due to its excellent mechanical, thermal and electrical properties [3-4]. During operational conditions, the joint insulation sustains stress from the large temperature gradient, the long term thermal cycle and the high electromagnetics force. To ensure the system reliability and performance, ITER established several acceptance criteria and expectations for the mechanical properties of the joint insulation and support material, including 77K static ultimate tensile strength (UTS) > 500 MPa, interlaminar shear strength >60 MPa, and residual UTS > 200 MPa after 30,000 cycles load for both the warp direction (0°) and the weft direction (90°). To evaluate the reliable application of GFRPs, their mechanical performance was characterized under static and dynamic load conditions at 77 K. In this paper, the results of the mechanical properties tests on GFRP fabricated by the vacuum bag process are described.
2. Experimental

2.1. Sample preparation
The investigated GFRP laminate was fabricated using the vacuum bag process by Nanjing Fiberglass Research & Design Institute, which consists of a two-dimensional glass fabric and epoxy resin. All specimens were cut from the laminate, as shown in figure 2. Considering the anisotropic properties of the composite, the samples were cut in the warp direction (0°) and the weft direction (90°) according to the ITER requirement. The outer dimensions and the diagrams of the samples are provided in table 1 and figure 2, respectively.

![Figure 1. Schematic diagram of ITER Feeder superconducting joint.](image1)

![Figure 2. Schematic diagram of the test samples](image2)

Table 1. The outer dimensions of the samples.

| Sample             | Length (mm) | Width (mm) | Thickness (mm) |
|--------------------|-------------|------------|----------------|
| SBS test sample    | 15          | 5          | 2.5            |
| Tensile test sample| 250         | 25         | 4              |
| Fatigue test sample| 250         | 25         | 4              |

2.2. Test procedures
The short beam strength was assessed by the short-beam test according to the guidelines given in ASTM D2344. The short-beam test at 77 K was done using a cross-head speed of 1 mm/min with a SUNS UTM4204 universal testing equipped with a liquid nitrogen cryostat. The span-to-thickness ratio was 5:1 and the radius of the nose and supports was 3.0 mm. The SBS can be calculated using the following formula:

\[
SBS = \frac{0.75P_m}{b \cdot h}
\]

where \(P_m\) is the maximum load, N; \(b\) is the specimen width, mm; \(h\) is the specimen thickness, mm.

The UTS was measured according to the guidelines given in ASTM D3039. All tensile testing at 77K were carried out using an MTS-SANS 5000 universal testing with a cross-head speed of 2
mm/min. In order to prevent gripping damage, the samples were equipped with aluminum end-tabs of 2 mm thickness.

The tension–tension fatigue tests were performed at 77 K according to the standard ASTM D3479 in load control using a sinusoidal load function. The fatigue tests were run with different peak load of 200, 300 and 400MPa for 0° sample, and 100, 150 and 200MPa for 90° sample. All fatigue testing was carried out at a load frequency of 5Hz with a minimum-to-peak stress ratio of R= 0.1 using an Instron 8850 axial tension-torsion fatigue machine. The fatigue experiment was stopped manually after 30,000 load cycles. Then, the static UTS of the sample after the fatigue test was measured at 77 K.

3. Results and discussion

3.1. SBS test

The SBSs of the 0° sample and the 90° sample were measured at 77 K. The fracture mode of all tested samples was interlaminar shear fracture. Typical stress-deflection curves are shown in figure 3(a). It can be seen that both curves show a nearly linear elastic trend during the early stage of loading and rise gradually to the peak load, then drop suddenly, which reflects an interlaminar fracture. The SBS of 0° sample is higher than that of 90° sample. The results of SBS are summarized in table 2. The measured SBSs were 125.0±1.1 MPa for 0° sample and 104.0±4.3 MPa for 90° sample, which are almost 2 times than the interlaminar shear strength required by ITER. It indicates that all tested samples should be able to meet the ITER requirement although the test results are not a direct measurement of the shear strength.

![Figure 3. SBS test curves (a) and UTS test curves (b) of 0° sample and 90° sample.](image)

3.2. Tensile test

Figure 3(b) shows the representative stress–strain curves obtained from the tensile test at 77K. As seen in figure 3(b), the slope of the stress–strain curve changed abruptly, presenting a knee behavior. The stress–strain behavior observed in this study is similar for all other woven-fabric glass/epoxy laminates [5-6]. The results of UTS for both directions are summarized in table 2. In 0° direction the UTS is 759±41.9 MPa, and in 90° direction 638±38.1 MPa. All test results are higher than 500 MPa which was required by ITER.
Table 2. The results of SBS and UTS measured at 77 K.

|       | SBS (MPa) | UTS (MPa) |
|-------|-----------|-----------|
|       | 0° direction | 90° direction | 0° direction | 90° direction |
| 1     | 126.6      | 106.7      | 711          | 638          |
| 2     | 125.4      | 98.8       | 770          | 606          |
| 3     | 124.6      | 109.2      | 801          | 665          |
| 4     | 124.9      | 104.7      | 719          | 685          |
| 5     | 123.5      | 100.5      | 794          | 595          |
| Mean  | 125.0±1.1  | 104.0±4.3  | 759±41.9     | 638±38.1     |
| ITER Requirement | 60° | 60°         | 500          | 500          |

a Interlaminar shear strength

3.3. Fatigue test

In this study, the fatigue tests were run with different peak load of 200, 300 and 400 MPa for 0° sample, and 100, 150 and 200 MPa for 90° sample. The total load cycle was 30,000 for each sample. All samples were not damaged after 30,000 load cycles. Then, the residual UTS of these samples at 77K was tested and the stress-strain curves and results were shown in figure 4 and figure 5, respectively. As shown in figure 4, it is seen that the stress-strain curve for the composite obtained from the static tensile test is significantly affected by fatigue load. The knee behavior is becoming less and less obvious as the peak stress used in fatigue tests increases.

From figure 5, it is seen that the fatigue load degraded the UTS of the composites and the residual UTS significantly decreases with increasing peak stress used in fatigue tests. The residual UTS of the 0° sample after 30,000 load cycles with the peak stress of 400 MPa is 518 MPa, degraded by 31% compared to the initial UTS. However, note that the residual UTS of all test samples satisfied the residual UTS > 200MPa after 30,000 load cycles required by ITER.

Figure 4. Tensile stress-strain curves of 0° sample (a) and 90° sample (b) after 30,000 cycles.
4. Conclusion
In the present study, the evaluation of the mechanical properties of the GFRP fabricated by vacuum bag process was performed. The SBS, the static UTS and the residual UTS after 30,000 cycles fatigue test of the composites for both directions satisfied the ITER requirements. In addition, the mechanical property in 0° direction is better than that in 90° direction. The fatigue load degraded the UTS of the composites and the residual UTS significantly decreases with increasing peak stress used in fatigue tests.

5. References
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Figure 5. The results of UTS for the 0° sample (a) and the 90° sample (b) after fatigue test.
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