Research and Analysis on Tensile and Compressive Fatigue Performance of Cryogenic Axial Insulation Breaks

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Abstract The composite axial insulation breaks (IBs) are key components of the superconducting magnet system for the international thermonuclear experimental reactor (ITER). In order to ensure the safe operation of the IBs during the 20 year lifespan of ITER devices, tensile and compressive fatigue tests were conducted by simulating actual working conditions and optimizing the test programs. The IBs were evaluated by testing their helium tightness after mechanical fatigue tests. In addition, fatigue analysis was performed using ANSYS software and an experimental S-N curve. The test data showed that the maximum helium leakage rate was less than $1.0 \times 10^{-9}$ Pa·m$^3$/s, which met the design requirements of the ITER IBs. ANSYS analysis results are also consistent with the test results from the theoretical viewpoint.

Keywords: axial insulation break, helium tightness property, fatigue test
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1 Introduction

Fiber reinforced epoxy resin composites (FRP) have been widely employed in cryogenic engineering fields including superconducting apparatus, for example ITER magnet systems. The IBs made from FRP, which need to be helium tight at cryogenic temperature and high-voltage electric field, are an important part of the liquid nitrogen or liquid helium insulation channel in the ITER magnet systems. The IBs work in a harsh environment with high tension/compression load and high-voltage electric field, due to fast discharge for superconducting magnets at cryogenic temperature. Helium tightness at cryogenic temperature and fatigue conditions is a serious concern for IBs. Helium leakage would result in devastating damage not only to the magnet device, but also to the whole ITER device \[1\].

The design of ITER IBs is based on successful experience gained from the experimental advanced superconducting tokamak (EAST) IBs \[2\], which must meet the following requirements: withstand a 56 kV voltage, 4 MPa inner pressure at liquid nitrogen, tensile and compressive force of 2000 N. In order to ensure safe operation of the IBs over the 20 year lifespan of the ITER device, theoretical analysis and experimental study on fatigue performance should be carried out according to the technical specification for ITER axial IBs. The IBs are loaded with sixty thousand cycles at 50% of the conventional load in the axial direction for tension and compression. The safety factor considered for the cycle loading is 2. We need to ensure that its helium tightness meets the design requirements after the fatigue test of sixty thousand cycle times of 1000 N tensile and compressive loading. Firstly, the finite element method was used for fatigue analysis of the IBs at liquid nitrogen temperature. Secondly, mechanical fatigue tests were conducted by simulating actual operating conditions and optimizing the test programs. Finally, helium tightness and destruction experiments were performed on the samples after the mechanical fatigue tests.

2 Structural design of the insulation break

The axial insulation break consists of three parts: metal electrode, inner insulated pipe and external reinforced insulation layer. A metal pipe acts as the electrode withstanding high voltage, which is combined with insulating material. The middle part is an inner insulated pipe, which is connected to both ends of the stainless steel tube via a low-temperature resin. The external reinforced layer is wounded to the designed dimension, using low-temperature resin and glass fiber filament as ingredients \[3\]. The structural schematic diagram is shown in Fig. 1.

![Fig.1 Section sketch of the axial insulation break (color online)](image-url)
3 ANSYS fatigue analysis of the insulation breaks

3.1 The design of material fatigue strength

When the glass fiber-reinforced epoxy resin composite material is subject to fatigue loads, its outer side bears physical work, which leads to three sets of results. One part of the physical work is stored, another part converts into heat energy and sound energy, the third residue part causes various types of cracks inside the material. The number of cracks continues to accumulate during the loading times. When life-span of the material runs out by repetitive loading, and cracks extend to a critical point, damage of the material occurs. Fatigue life curve is monotonously decreasing, meaning that the fatigue life is reversely related to the applied load monotonically. This fatigue curve is called the $S$-$N$ curve. The $S$-$N$ curve of glass fiber-reinforced epoxy resin composite material is derived from fatigue test data.

![Fig.2 S-N curve of the FRP material (color online)](image)

FRP materials for fatigue tests are standard tensile specimens. All the specimens are loaded with different levels of cyclic stress, to get the ultimate stress under a variety of cycle times. Then, the $S$-$N$ curve of the FRP material is plotted as the ultimate stress against the logarithm of cycle time, as shown in Fig. 2. The $S$-$N$ fatigue curve can be expressed by the following Wohler Equation (1),

$$
\sigma_X N = \sigma_{-1} N_0 = C,
$$

in which $N_0$ is the cardinal number of cycle time, $\sigma_{-1}$ is the corresponding ultimate stress; $N$ is the random number of cycle time, $\sigma_X$ is the corresponding ultimate stress; $X$ is an index related to the material and the form of stress and $C$ is a constant. For FRP material in this experiment, $N_0 = 10^7$, $\sigma_{-1} = 170$ MPa, $X = 42$, so when $N = 6 \times 10^4$, all known physical quantities are substituted into the above equation to calculate the value of $\sigma_X = 233$ MPa. Under sixty thousand times of fatigue load cycles, the corresponding fatigue strength is 233 MPa. The safety factor of 3 corresponds to the allowable fatigue strength of FRP material of 75 MPa.

![Fig.3 Finite element model of the insulator (color online)](image)

3.2 Establishment of the finite element model

The IBs are made of SS316L and FRP composite material; ANSYS13.0 structural analysis is used for static and fatigue analysis of these two different materials, respectively. A SOLID185 unit is used to constitute the solid model for the SS316L tube and the FRP composite material tube. The finite element model is shown in Fig. 3, including a total of 412,353 nodes and a unit number of 382,020.

3.3 Tensile and compressive static analysis and fatigue analysis of IB

3.3.1 Tensile static analysis

The initial temperature of the overall insulator is room temperature. The test temperature is set at liquid nitrogen temperature (LN$_2$). The tensile force is applied in stress analysis, with the following boundary conditions: one end is the $x$-direction constraint, and the other end is subjected to a 1000 N tensile force.

<table>
<thead>
<tr>
<th>Material Performance</th>
<th>4 K</th>
<th>RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS316L</td>
<td>1385</td>
<td>520</td>
</tr>
<tr>
<td>Maximum intensity (MPa)</td>
<td>700</td>
<td>210</td>
</tr>
<tr>
<td>Yield stress (MPa)</td>
<td>1467</td>
<td>1140</td>
</tr>
<tr>
<td>Design stress (MPa)</td>
<td>124 (60,000 times)</td>
<td></td>
</tr>
<tr>
<td>Allowable fatigue strength</td>
<td>75 (60,000 times)</td>
<td></td>
</tr>
<tr>
<td>FRP</td>
<td>675</td>
<td>350</td>
</tr>
<tr>
<td>The compression strength of layer (MPa)</td>
<td>450</td>
<td>233</td>
</tr>
<tr>
<td>Design strength (MPa)</td>
<td>75 (60,000 times)</td>
<td></td>
</tr>
</tbody>
</table>
The maximum equivalent Mises stress of the IB is located in the constraints of the stainless steel tube, and the maximum stress is 1080 MPa, which is smaller than the ultimate strength. Stress falls in the allowable range. The equivalent stress of the insulation part is 122 MPa, less than the design strength of 233 MPa, as shown in Fig. 4. According to mechanical design standards, a tensile force of 1000 N is safe at an operating temperature of RT for the IB.

3.3.2 Compressive static analysis

The initial temperature of the overall insulator is RT. The test is done at liquid nitrogen temperature, and stress analysis is carried out for a 1000 N tensile force loading. The boundary conditions and loads are as follows: one end has an x-direction constraint, the other end is subjected to a 1000 N compressive force.

The maximum equivalent Mises stress of the IBs occurs in the constraints of stainless steel tube. The maximum stress is 1090 MPa, not exceeding the ultimate strength, and falling in the allowable range. The equivalent stress of the insulation part is 121 MPa, less than the minimum design strength of 233 MPa, as shown in Fig. 5. According to mechanical design standards, a 1000 N compressive effect is safe at an operating temperature of RT as well.

3.3.3 Tension and compression fatigue analysis of the axial insulation break

Stress amplitude is the difference between the tensile stress and the compressive stress. The stress at different nodes of the IB is obtained from the tensile and compressive static analysis. The stress amplitude distribution of IB can be taken from post-processing analysis and calculations, as shown in Fig. 6.

The maximum stress amplitude distribution of stainless steel part is 6.22 MPa, less than the allowable fatigue strength of 124 MPa. The maximum stress amplitude distribution of the insulated part is 1.54 MPa, which is smaller than the minimum allowable fatigue strength of 75 MPa, meeting the design requirements.

4 Fatigue test of the insulation break

The destructive behavior of material under cyclic loading is known as fatigue, which describes the failure process of the material when subjected to periodic stress or strain. Fatigue tests are carried out to simulate 20 years service life of the IBs. The fatigue tests include sixty thousand cycle times of 1000 N tension and compression loading.

4.1 Fatigue experiment system

In the fatigue testing, the fatigue test machine is the most important piece of equipment, in which the computer system controls the load and displacement of the IB through pressure sensors. The value of the imposed load, the duty cycle and cycle time of the fatigue test can be controlled by computer software.

The fatigue test of the IB is required to be carried out in a liquid nitrogen environment. A specially designed dewar device can not only enclose the liquid nitrogen to ensure that the IB is submerged, but also connect the IB with the fatigue test machine to play the role of fixation. In the designed device, the inside and outside boards of the dewar are made from composite materials. The gap between the boards is filled with foam material. One end of the IB is fixed to the inside surface of the dewar; the other end is connected to the fatigue testing machine’s pressure sensor through stainless steel joints. The movement of the IB is in phase with the hydraulic driving rod.

Liquid nitrogen is poured intermittently to keep the IB dipped in liquid nitrogen during the fatigue test using a 300 L self-pressurized stainless steel dewar. Such a
test system is specifically built to meet the test requirements, and Fig. 7 is an overall picture of the fatigue test system.

Fig. 7 An overall picture of the fatigue test system (color online)

### 4.2 Tensile and compressive fatigue test

The test system of insulation break under a tension and compression load at LN\(_2\) is shown in Fig. 8. The IB is installed between the dewar and a stretch connecting rod. One end of the IB is fixed on the stretch connecting rod, and the other end is fixed on the inner wall of the dewar, which is connected to the piston of the test machine to apply a 1000 N tension and compression load through the movement of the piston.

Fig. 8 A picture of the tensile and compressive fatigue test (color online)

The variation curve of the tension and compression load is shown in Fig. 9 (the curve contains only 16 cycles). For a 1000 N load with a load duty cycle of 0.8, sixty thousand cycles of fatigue tests take 75,000 s in all.

Fig. 9 Dynamic curve of a tensile and compressive fatigue test (color online)

### 5 Helium leakage tightness test after the fatigue tests

According to the technical requirements for ITER, air tightness of the IB is considered as qualified under the premise that the leakage rate is less than \(1.0 \times 10^{-9} \text{ Pa} \cdot \text{m}^3/\text{s}\). After mechanical fatigue tests, the insulation breaks need to be evaluated by helium tightness at both RT and LN\(_2\) temperatures. The proposed method for leak measurements is the Tracer Gas Method. In this method, the system is continuously evacuated. The test gas flowing into the pump passes through a detector section where its concentration is measured. The test device is the SFJ-261 leak detector, and the helium leak tightness test was done in vacuum environment at both RT and LN\(_2\) temperatures [5], as shown in Fig. 10.

Fig. 10 Test device for the helium tightness experiment (color online)

The IB is installed in a vacuum chamber. One end is welded to a high pressure helium gas bottle; the other end is welded for air-tightness. In the experiment, the internal of the IB is under helium pressure and the outside is vacuumed in the vacuum chamber [6]. When the vacuum degree reaches \(10^{-2} \text{ Pa}\), the helium pressure is adjusted to 1 MPa at RT. A leakage rate of \(5.2 \times 10^{-11} \text{ Pa} \cdot \text{m}^3/\text{s}\) is observed on the leak detector. Then the vacuum chamber is immersed into the liquid nitrogen to maintain a low surface temperature. Once the temperature of the IB decreases to LN\(_2\), the helium pressure is adjusted up to 4 MPa and the pressure is maintained for 5 min; a leakage rate of \(1.1 \times 10^{-10} \text{ Pa} \cdot \text{m}^3/\text{s}\) is observed. The cooling curve of the IB is shown in Fig. 11, which shows the tightness test of the IB conducted at LN\(_2\).

As indicated by the above results, after fatigue tests, the maximum helium leakage rate is less than \(1.0 \times 10^{-9} \text{ Pa} \cdot \text{m}^3/\text{s}\) under 1 MPa at RT and 4 MPa at LN\(_2\), while the background value is \(5.0 \times 10^{-11} \text{ Pa} \cdot \text{m}^3/\text{s}\). These facts indicate that the IB works well after the fatigue tests.
6 Destruction test

The principle and apparatus of the destruction test for the IB are almost the same as the helium leakage tightness test with the unique difference that the helium pressure adds up to 10 MPa and is maintained for 5 min in the destruction test. On the premise that the vacuum degree of the system reaches $10^{-2}$ Pa, the leakage rate was observed to be $1.2 \times 10^{-10}$ Pa·m$^3$/s under 10 MPa pressure for 5 min. The results further demonstrate that the helium leak tightness of the IBs is satisfactory after the mechanical fatigue tests.

7 Conclusion

ANSYS software analysis is carried out with the help of experimental $S$-$N$ curve, which proves that the axial insulation break can survive sixty thousand cycles of mechanical fatigue loading in theory. All the IBs were tested via a mechanical fatigue test system, including both a 1000 N tensile fatigue load and a 1000 N compressive fatigue load for sixty thousand cycles. After the fatigue tests, both the helium tightness test and destruction test were conducted to inspect the quality of the IB.

Because the fatigue strength of stainless steel is greater than that of FRP material, the mechanism of fatigue crack initiation in the FRP material is emphasized. FRP consists of three physical ingredients, including fibers, a matrix phase and an interface phase. They have different moduli of elasticity. The modulus of elasticity for fiber is the biggest one, and the fiber accounts for 95 percents of the extension loading. The modulus of elasticity for matrix is very small; the matrix plays the role of a connection to fix the fiber, it also bears compressive stress and shear stress. The fatigue process of the resin matrix manifests in crack initiation and crack extension. For FRP, when the matrix responds to the stress-controlled fatigue, deformation of fiber is under inhibition; crack generates and expands in defects of the matrix until colliding with the interface. If the stress of the crack tip is not enough to make the fiber fracture, further expansion of the crack is suppressed. If the imposed strain is low enough, cracks are limited in matrix, only the number of cracks increases.

In the fatigue test, after sixty thousand tensile and compressive stress cycles, the energy stored in the insulator is insufficient to surpass the limitations of the fiber and the binding energy between the matrix and the interface, and the cracks will not propagate beyond the matrix. So the air-tightness and electrical insulation of the IBs are well preserved. From the results of the theoretical analysis and experimental tests, we are assured of:

a. Under sixty thousand cycle times of fatigue loads, the maximum stress amplitudes of the stainless steel part and insulated part are both less than their allowable fatigue strength. In the limited number of test cycles, the IBs survive against crack propagation and fatigue damage;

b. The IB could withstand 1 MPa of helium pressure at RT and 4 MPa helium pressure at LN$_2$, the value of the leakage rate was less than $1.0 \times 10^{-9}$ Pa·m$^3$/s;

c. The leakage rate of the IB was less than $1.0 \times 10^{-9}$ Pa·m$^3$/s under 10 MPa of helium pressure.

Based on the results of the ANSYS analysis and experimental tests mentioned above, the designed axial IBs can meet the technical requirements during the device’s 20 years service life, as proved by theory and tests.

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References


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