DESIGN OF THE SUPERCONDUCTING MAGNET SUPPORTING POST FOR KSTAR TOKAMAK

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Abstract

A magnet supporting post installed between the lower TF(Toroidal Field) coil cooled by 4.5 K supercritical helium and the cryostat base is one of the most important components of the superconducting magnet supporting structure for KSTAR(Korea Superconducting tokamak Advanced Research) tokamak. This structure should be flexible to absorb thermal shrink of the magnet and also should be rigid to supports the magnet weight and the plasma disruptions load. The post was designed with stainless steel 316LN and CFRP that has low thermal conductivity and high structural strength at low temperature. In this study, structural analysis of the post under the low temperature was performed. And, in order to verify the fabricability and the structural safety, a whole scale prototype of the KSTAR magnet supporting post was manufactured and tested. Both static and compressive cyclic load test under the maximum plasma vertical disruption load and the magnet dead weight were performed. The test and analysis results showed that the magnet supporting post of KSTAR tokamak was fabricable and structurally rigid.

1 INTRODUCTION

The magnet supporting structure of the KSTAR tokamak is composed of one supporting ring and eight supporting posts. It should be flexible such as to absorb thermal shrink of the superconducting magnet and it also should be rigid such as to support the magnet weight of 320 ton and the plasma disruptions loads. Plasma disruption is a sort of plasma instability, which involves a sudden loss of confinement and a rapid decay of the whole current, leading to an end of the discharge [1]. The supporting ring and post are cooled by 4.5 K supercritical helium and 80 K gaseous helium (GHe), respectively. They have been designed to satisfy the design requirement [2]. Since the supporting post is critical for the design of the KSTAR magnet supporting structure, it is important to analyze the post in detail.

In this study, structural analysis of the post under the design loads was performed. And, in order to verify the fabricability and the structural safety, a whole scale prototype of the KSTAR magnet supporting post was manufactured and tested. Both static and compressive cyclic load test under the maximum plasma vertical disruption load and the magnet dead weight were performed.
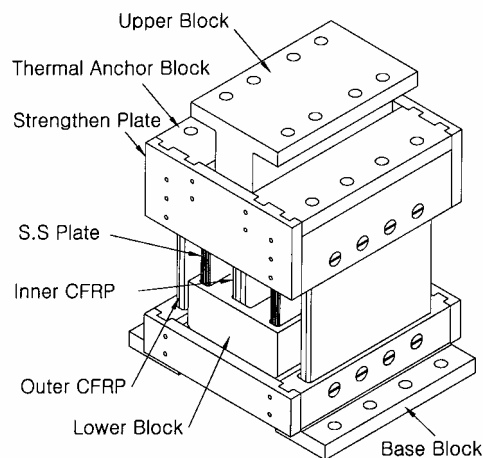

Figure 1: Magnet supporting post for KSTAR

2 DESIGN

The magnet supporting post was mainly made of Stainless Steel(SS) 316LN and Carbon Fiber Reinforced plastic(CFRP) material which had low thermal conductivity and high structural strength at the low temperature. Material property test of the CFRP composite for the supporting post of KSTAR was performed based on the ASTM code at the ambient and low temperature.

The isometric view of the post is shown in Fig. 1. The overall dimension of the post was 1 m height and 0.8 m width and depth, respectively. The post was composed of upper block, inner CFRP plate, lower block, stainless steel plate, thermal anchor block, outer CFRP plate, base block, and strengthened plate. Inner CFRP plate is connected to the upper and lower block using the pin. And the outer CFRP plate was connected to the thermal anchor block and the base block. A circular shaped stainless steel bush was used between the pin and the hole of the CFRP plate to protect the surface of the hole against the friction. Inner and outer CFRP plates consist of four and two 20 mm thin plates, respectively. Stainless steel plates consisted of four 8 mm thin plates to absorb the magnet shrinkage. These plates were assembled into the thermal anchor block and lower block. Strengthened plate attached on the thermal anchor block and base block will protect the bending of the outer CFRP plate when the vertical load is acted.

3 STRESS ANALYSIS

The supporting post should be designed to resist all loads and load combinations that are within the design basics. The design criteria strategy based on the conventional pressure vessel codes and the ITER cryogenic structural design code has been developed for the post design and construction.

3.1 Load Condition

Based on the operating states of the magnet system, combined loads were applied on the supporting post as shown in Table 1. In assemble state, the post loaded 50 ton of vertically considered magnet dead weight and deformed 5 mm to outside radial direction considered shrinkage of the magnet after cool down. After cool down of the magnet, the temperature distributed on the post will be from 4.5 K on the upper block to 296 K on the base block. The maximum load applied on the post during the operation will be on the plasma Vertical Disruption Event(VDE) and Radial Disruption Event(RDE) [3]. ANSYS was used for the stress analysis.

Table 1: Load combinations for the post design

Event	Load combinations
Assemble	RT, Fz=50 ton, Ux=5 mm
Cool down	Temp.(4.5~296K), Fz=50 ton
VDE	Temp.(4.5~296K), Fz=80 ton
RDE	Temp.(4.5~296K), Fz=70 ton, Fy=40 ton

3.1 Stress Analysis Results

In the 3-D FEM analysis, we assumed that all components including CFRP and SS plate were assembled rigidly inside of SS block. The static loads described in Table 1 were acted on the upper block. To evaluate the cool down effect, the temperature boundary of 4.5 K on the upper block, 77 K on the thermal anchor block, and 296 K on the base block were considered.

Table 2 shows the maximum stresses on the components of the post. The levels of the maximum stresses were below the allowable stresses. Even though the stresses of the real post must be smaller than those of analysis results because of the pin joint condition, the stress concentration effect around the pin jointed hole of the CFRP and SS plate should be evaluated using the detail FE model.

Table 3 shows the maximum displacement on the top surface of the upper block. The maximum vertical displacement of 1.3 mm was calculated at the VDE. And the maximum horizontal displacement of 3.5 mm was calculated at the RDE. From the analysis results, we know that the magnet can't touch the thermal shield panel attached on the vacuum vessel during the plasma horizontal and vertical disruption.

Table 2: Maximum stresses on the post

Event	Max. stress(MPa)			
	Inner CFRP	Outer CFRP	SS plate	Upper block
Assemble	28	32	87	50
Cool down	227	202	127	228
VDE	234	208	169	239
RDE	259	231	314	257

Table 3: Maximum displacements on the upper block

Event	Max. displacement(mm)		
	Ux	Uy	Uz
Assemble	5	0	0~ -0.34
Cool down	±0.59	±0.78	-0.68
VDE	±0.62	±0.78	-0.93
RDE	±0.62	1.94~ 3.5	-0.19~1.3

4 PROTOTYPE MANUFACTURING

4.1 Prototype Manufacturing

The experiment of a whole scale post prototype is shown in Fig. 2 [4]. The stainless steel blocks and plates were made of SS316. The CFRP plate (model: HPW193/RS3232) was made of the plain woven T300 carbon fiber and epoxy resin. About 100 layers of the laminate were stacked and cured by vacuum bag and autoclave processes. The pin holes of the CFRP plate were drilled with larger tolerance than that of the inner block thickness. It was possible to make a surface contact around the CFRP plate joint when the plate was compressed vertically. The CFRP plate was examined by the ultrasonic test machine for the quality assurance after drilling a hole. In order to cool down the post, 4 sets of cooling modules composed of circular copper pipes were attached to the upper and low blocks as well as left and right thermal anchor block.

Figure 2: Prototype of the supporting post

4.2 Load Test System

A static and dynamic load test system that controls load amplitude and velocity at the room and low temperature was prepared for the test. The test vacuum chamber with dimension of 1 m diameter and 1.3 m height was manufactured to provide the low temperature environment for the test of the post prototype. The vacuum feed-through for the cooling module, thermocouple, and strain gauge were installed on the vacuum chamber. The bellows and the load interface components were assembled on the upper flange of the chamber to actuate the load on the post inside the chamber. The temperatures were measured by the T-type thermocouple attached on the measuring points. Eight strain gauges were attached to the steel plates and the CFRP plates for stress measurements. Based on the strain rate measured from the strain gauge the stress was estimated under the test load conditions. About 2000 liter of liquid nitrogen (LN_2) was consumed to cool down the post up to -160℃ from room temperature.

Dynamic actuator system which had 100 ton capacity was used to simulate the cyclic maximum compressive load of 80 ton for this test. During the load test the vertical displacement of the post was measured using the Linear Variable Differential Transducer (LVDT) attached on the load interface plate of the post. This vertical displacement of the post will be a main design parameter for the design of the magnet structure and the interface components, such as thermal shields, bellows of the vacuum vessel vertical ports.

4.3 Test Results

The load tests were performed to consider both the magnet dead weight of 320 ton and the maximum plasma vertical disruption load of 320 ton. Since these loads were applied to eight posts, the average dead weight per post was 40 ton and the maximum vertical disruption load per post was 40 ton. Three types of loads were tested for the magnet supporting post prototype. First, static load test at room temperature was preformed with 50 ton in order to account for both the magnet dead weight and its design margin of 25 percentage. Next, cooling static load test with 80 ton was performed in order to account for both the magnet dead weight and the maximum plasma disruption load. Finally, cyclic compressive load test was performed based on the steady loads of 40 ton and the cyclic loads of 40 ton. The cyclic loads account for the plasma vertical disruption loads with the iteration number of 15,000. This iteration number had a safety factor of 2. Because of the restricted test system, the frequency of the dynamic loading from 40 ton to 80 ton was 8 Hz and iteration periods was assumed to be 4 second even though the plasma disruption occurs quickly.

The maximum vertical displacements of the post were 1.2 mm and 3 mm under the static load of 50 ton at room temperature and under the static load of 80 ton at low temperature, respectively. The levels of the stress on the inner CFRP and SS plate center were smaller than the yielding strength of the material. During the cycle test no failure was discovered because no abrupt change of the displacement behavior occurred. The overall displacement behavior was similar to that of static load of 80 ton test result.

5 CONCLUSION

The magnet supporting post for the KSTAR Tokamak was designed and analyzed. The maximum stresses were compared with the allowable stresses of the material. We know that the detail evaluation of stress concentration effect around the pin jointed hole of the CFRP and SS plate under the RDE is necessary even though all of the stresses are below the allowable stresses. And from the displacement results, we know that the magnet can't touch the thermal shield panel attached on the vacuum vessel during the plasma disruption.

A whole scale prototype of the KSTAR magnet supporting post was manufactured to verify the fabricability and the structural safety. Two types of static load tests were performed at room temperature and at low temperature. A compressive cyclic load test under the maximum plasma vertical disruption load based on the plasma operation condition was performed. From the static load tests, it was found that the vertical displacements of the post were small. For the compressive cyclic load test, the structural safety of the post under the magnet dead weight and the cyclic plasma vertical disruption load was verified.

6 ACKNOWLEDGMENT

7 REFERENCES

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