

Design and Optimization of Support Posts for Cryogenic Components in FFHR

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FFHR is a concept design of a steady-state fusion reactor that has been studied to demonstrate a large helical device (LHD)-type fusion power plant. The weight and thermal contraction of cryogenic components are sustained by support posts. A folded multi-plate-type post adopted in the LHD could be feasible for the FFHR. The dimensions of the post were determined according to the buckling load estimation against a gravitational load. Using this fundamental design, the flexibility and stress distribution of the post were calculated by a finite element method. The flexibility against the radial displacement was 24 kN/mm, and the maximum stress for a carbon-fiber-reinforced plastic and stainless steel plate was 155 and 544 MPa, respectively, which were below their allowable levels. The heat loads were calculated as 10.5 kW at 80 K and 0.34 kW at 4 K; the results revealed that the heat load at 4 K was almost 1/20 compared with that on a post made entirely of stainless steel. Natural frequencies were analyzed to assess safety against external loads such as an earthquake. The results showed that the LHD-type support post was suitable for the FFHR from the mechanical and thermal viewpoints.

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1. Introduction

FFHR is a concept design of a steady-state fusion reactor that has been studied to demonstrate a Large Helical Device (LHD)-type fusion power plant [1–3]. Figure 1 shows a schematic of the cryogenic components in the FFHR. The total weight of superconducting coils and support structure exceeds 16,000 tons. Since the cryogenic components are mainly made of stainless steel, thermal contraction between the room and cryogenic temperatures is about 0.3%. For example, the maximum displacement caused by thermal contraction is almost 55 mm at 18 m from the center of the device in the radial direction, where

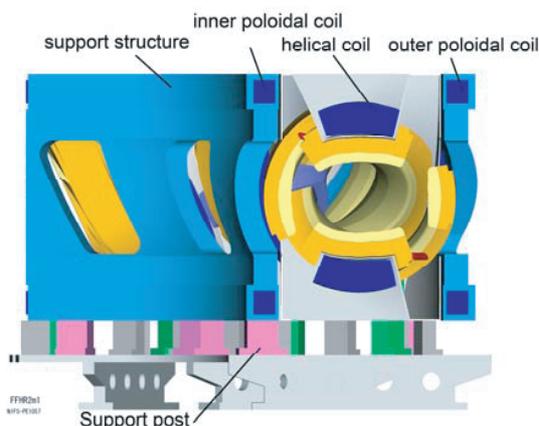


Fig. 1 Schematic of the cryogenic components in FFHR.

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outer poloidal field coils are set. The weight and deformation are sustained by support posts that are set on a base plate of a cryostat vessel kept at room temperature. The support post must perform the following functions: support the weight of the cryogenic components, reduce heat leakage into the lower temperature side, absorb thermal contraction, maintain cyclic deformation, and provide a margin of safety against an external load such as an earthquake.

The LHD has a major radius of 3.9 m and cold mass of 850 tons. In addition, it has a “folded multi plate”-type post [4, 5]. The post consisted of carbon-fiber-reinforced plastic (CFRP) and stainless steel (SS) plates. The SS plates were cooled down to 80 K to serve as a thermal anchor region, and were connected to the CFRP plates using thick SS blocks. For minimizing the heat leakage into the low-temperature side, the CFRP plates were placed between region at the room temperature and the thermal anchor region, as well as between the thermal anchor region and the region at the cryogenic temperature. The maximum thermal contraction at the post position was 13 mm; the post absorbed the contraction because of its flexibility against the radial displacement of the components. The CFRP was chosen since it has much larger compressive strength than other low-heat-conductive materials such as glass-fiber-reinforced plastic. This type of a post can also be used as a support post of the FFHR. A conceptual design and specifications of the folded multi-plate-type post are introduced, and the stress distribution under several types

of operational situations is discussed in this paper. The deformation mode and the natural frequency of the cryogenic components including the post are also calculated, and safety against an earthquake is discussed.

2. Basic Geometry of the Folded Multi Plates

The cryogenic components that are cooled down to the cryogenic temperature are superconducting helical coils, superconducting poloidal coils, and the coil supporting structure. The total weight of the cryogenic components in the FFHR was estimated to be 16,000 tons. Considering a symmetrical and homogeneous distribution of the gravitational load, the number of posts was chosen as 30; 20 posts were located under the outer poloidal coil and the remaining were set under the inner poloidal coil. The spans of each outer and inner post were 5.7 and 6.2 m, respectively. The CFRP plates in the folded multi-plate-type post are subjected to a compressive load, whereas the SS plates are subjected to a tensile load. The geometrical dimensions of the CFRP plates were chosen according to the buckling load estimation against a gravitational load with a bent long column model. The buckling load was considered for a beam whose one terminal was completely fixed and the other was free, as shown in Fig. 2. This is the most severe case of buckling. The buckling load P_k by this model can be expressed as follows:

$$P_k = \frac{\pi^2 EI}{4L^2}, \tag{1}$$

$$I = \frac{bh^3}{12},$$

where E is Young's modulus in the longitudinal direction, I is the flexural rigidity, b is the width, h is the thickness, and L is the length of the plate.

We specified that the safety factor against the buckling load should be five times larger than the nominal weight, $(16,000 \text{ tons}) / (30 \text{ posts}) \times (\text{safety factor } 5) = 2667 \text{ tons}$. Although the center columns are directly subjected to this nominal weight, one side of the outer columns bears half of this weight. The cross-sectional dimensions of the CFRP plate were assumed to be 1200 mm in width and 80 mm in thickness, considering a setting geometry. Figure 3 shows the buckling load against the plate length, considering the number of plates. Since the post must have flexibility, a longer plate is desirable; however, an increase in the number of plates increases the size and weight. The length was chosen as 1.2 m, and 5 and a pair of 3 plates were chosen for the center and outer columns, respectively. In the case of the SS plate, the width was 1.2 m, thickness was 30 mm, length was 1.0 m, and 3 plates for both the sides were chosen, considering the tensile load and strength of the SS material. Figure 4 shows the setup of the support post and its dimensions. The weight of the post in this case was 10 tons.

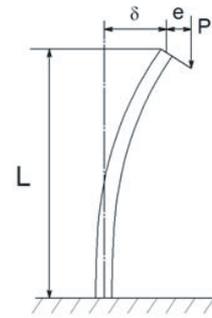


Fig. 2 A buckling model for a long beam column.

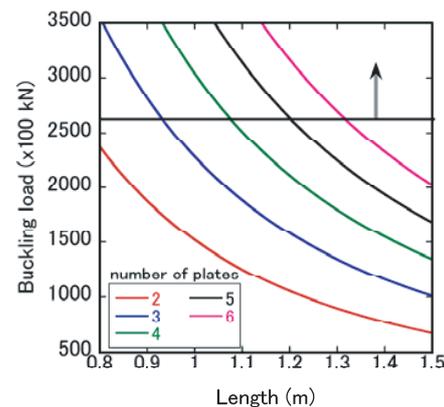


Fig. 3 Buckling load of the CFRP plate with a cross section of 1200 mm × 80 mm considering the number of plates using the bent long column model.

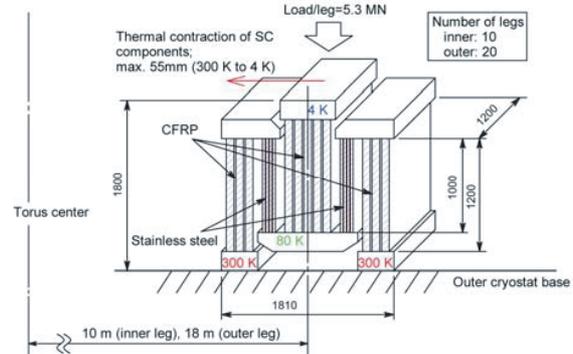


Fig. 4 Schematic draw of the support post for the FFHR.

3. FEM Analysis

Using the basic geometrical design of the folded multi plates, the flexibility and stress distribution of the post were calculated by performing an FEM analysis. The FE model of the support post was prepared using a 3D beam element for rigidity estimation, and a 3D shell element was used for a stress distribution analysis. A thermal condition was also investigated using the 3D shell model. The 3D model included cryogenic components. Since the cryogenic components were sufficiently rigid compared with the support post, we prepared a simple toroidal structure

having not only the same weight of the components but also the same geometrical location of the center of gravity. This toroidal structure was set on 30 support posts. The natural frequency of this structure was calculated using the 3D model. The physical properties of SS used in the analysis were obtained from a database [6]. The properties of CFRP were obtained from experimental data for the LHD support post provided by the manufacturer. ANSYS was used for calculation.

3.1 Static analysis

Flexibility in the radial direction was 22.9 kN/mm, and when 55 mm of forced displacement was applied to the top of the post, the maximum stress was 155 MPa for the CFRP plate and 544 MPa for the SS plate. The allowable stress level for CFRP is 780 MPa [7] and that for SS (316LN) is 700 MPa [8]. The maximum stresses were below the allowable levels for the materials, which could be reduced by prior deformation of the post. For example, if the post was bent by 27.5 mm in the outward direction and then the cryogenic components were set on the post, the final position of the top of the post could be bent by 27.5 mm in the inward direction since the thermal contraction of the cryogenic components acted on the post. The stress level caused by thermal contraction could be reduced by almost

one-half by following this approach. The rigidity along the circumferential direction was more than 10 times that along the radial direction.

The heat loads calculated using the same model were 10.5 kW at 80 K and 0.34 kW at 4 K; these results showed that the heat load at 4 K was almost 1/20 compared with that on the post made entirely of SS. On the other hand, the heat load at 80 K was about one-half that on the SS post.

Here, we introduce three operating situations and calculate the stress distribution for each case.

(1) Gravity only

This situation simulated a normal condition before cooling. The top of the post was bent outward by 27.5 mm and had no thermal contraction. In this case, the maximum von Mises stresses in the CFRP and SS plates were 147 and 340 MPa, respectively. The contour expressions of the stress distributions are shown in Fig. 5.

(2) Gravity + cool down + 0.2 G of transverse acceleration.

This situation simulated the application of 0.2 G of transverse seismic load on the device when the cryogenic components are cooled down to 4 K. The maximum von Mises stresses in the CFRP and SS plates increased to 159 and 390 MPa, respectively, as shown in Fig. 6.

(3) Gravity + cool down + 0.7 G of transverse acceleration.

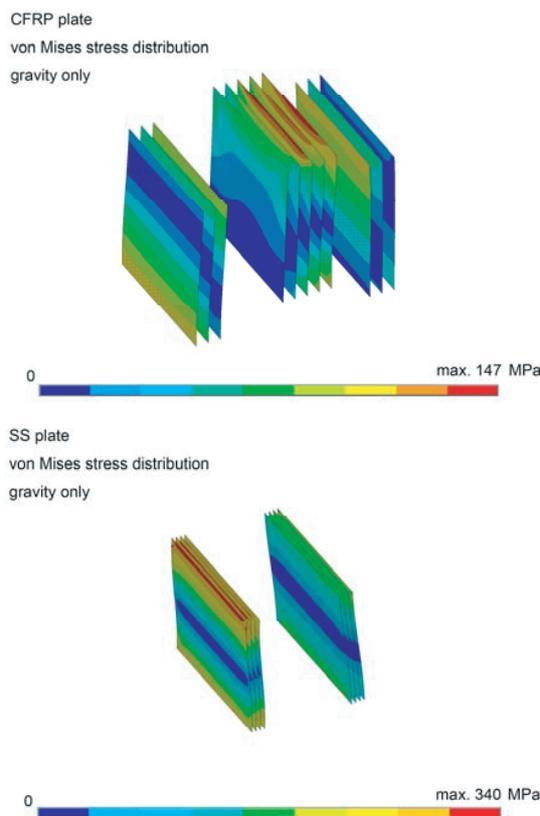


Fig. 5 Distribution of von Mises stress in CFRP plates (above) and SS plates (bottom) when only gravity load was applied.

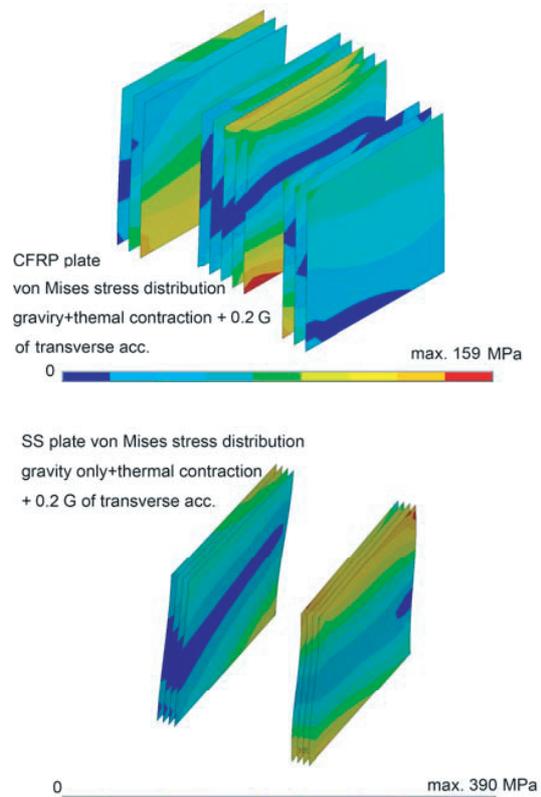


Fig. 6 Distribution of von Mises stress in CFRP plates (above) and SS plates (bottom) when gravity load and 0.2 G of transverse acceleration were applied together with thermal contraction.

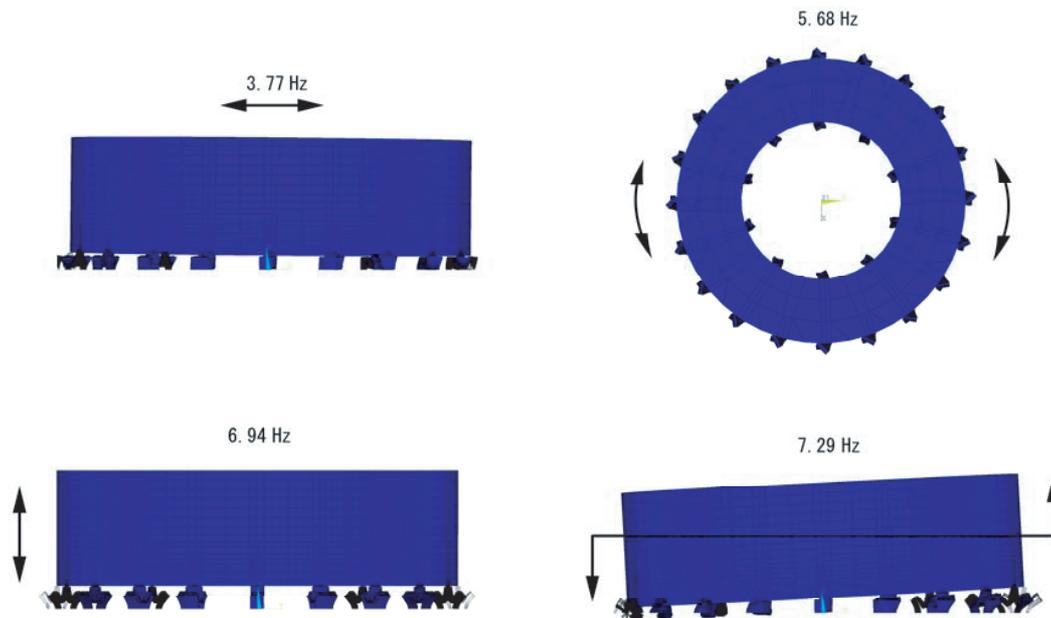


Fig. 7 Results of modal analysis. Natural vibration modes and their frequencies.

In the case of 0.7 G of transverse acceleration, the maximum von Mises stresses in the CFRP and SS plates were 322 and 681 MPa, respectively.

3.2 Modal analysis

The natural frequencies of the structure were in the range of 3 to 8 Hz. Figure 7 shows the first four modes of natural vibration and their frequencies. The first mode was horizontal vibration and the second one was rotational deformation on its axis. The third and fourth modes involved an up-down movement. The higher natural frequencies exceeded 15 Hz, and the deformation modes were applied mainly to the cryogenic components.

4. Discussion

The safety of the structure against an earthquake depends on the frequency and magnitude of seismic acceleration. Since a typical earthquake has a frequency range of 0.5 to 20 Hz, a structure that has a natural frequency close to this range may resonate. A response spectrum analysis of typical earthquakes, such as El Centro, TAFT, etc., revealed that the response accelerations of the frequency would range from 1.0 to 1.5 G. The analytic result for a transverse acceleration load of 0.7 G represents a reasonable limit, since the maximum von Mises stress did not exceed the permissible stress. One approach is to set a limit of 0.7 G for the response acceleration of the building.

5. Conclusions

The following conclusions were drawn from the “folded multi plate” design of the support post.

The flexibility against radial deformation was 24 kN/mm. The circumferential rigidity was more than 10 times the radial rigidity.

The total heat load at 4 K was estimated to be up to 340 W. This was almost 1/20 of the value for the post made entirely of stainless steel.

The maximum von Mises stress for the CFRP and SS plates was 159 and 390 MPa, respectively, when 0.2 G of transverse acceleration was applied to the components under cooled-down conditions. The stress levels were within the permissible range.

Several natural frequencies of the structure were close to the frequencies of a seismic vibration. Results of the static analysis revealed that the acceleration applied to the structure should not exceed 0.7 G to maintain safety of the device.

Acknowledgement

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