Design and Optimization of Support Post for Cryogenic Components in the FFHR

Hitoshi TAMURA, Akio SAGARA and Shinsaku IMAGAWA

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

FFHR is a design of a steady state fusion reactor which has been studied to demonstrate LHD-type fusion power plant. The weight and the deformation of the cryogenic components are sustained by support posts. A folded multi plate type post which was adopted in the LHD could be used for the FFHR. The dimensions of the post were decided according to buckling load estimation against a gravitational load. Using this fundamental design, a flexibility and stress distribution of the post were calculated by using FEM analysis. The flexibility against a radial displacement was 24kN/mm and the maximum stress was 159MPa for CFRP plate and 390MPa for stainless steel plate, respectively. These were under allowable level for the materials. The heat loads were also calculated and 10.5kW to 80K and 0.34kW to 4K were obtained and the result showed that the head load to 4K was almost 1/20 compare with the post which was all made of stainless steel. The natural frequency was analyzed to estimate safeness against external load such as an earthquake. Those results showed that the LHD-type support post was practical for the FFHR in mechanical and thermal points of view.

Keywords: FFHR, fusion reactor, superconducting coil, cryogenic component, support post, modal analysis

1. Introduction

FFHR is a concept design of a steady state fusion reactor which has been studied to demonstrate LHD-type fusion power plant [1-3]. Fig. 1 shows the schematic draw of the cryogenic components in the FFHR. Total weight of superconducting coils and supporting structure exceeds 16,000 tons. Since the cryogenic components can be mainly made of stainless steel, the thermal contraction between room temperature and the cryogenic temperature is about 0.3%. For example, the maximum displacement caused by the thermal contraction is almost 55mm at 18m in radial position from the center of the device where the outer poloidal field coils are set. The weight and the deformation are sustained by support posts which are set on a base plate of a cryostat vessel whose temperature is room temperature. The support post must have following functions; support the weight of the cryogenic components, reduce heat leak to lower temperature side, absorb the thermal contraction, maintain a cyclic deformation, give a safe warranty against an external load such as an earthquake.

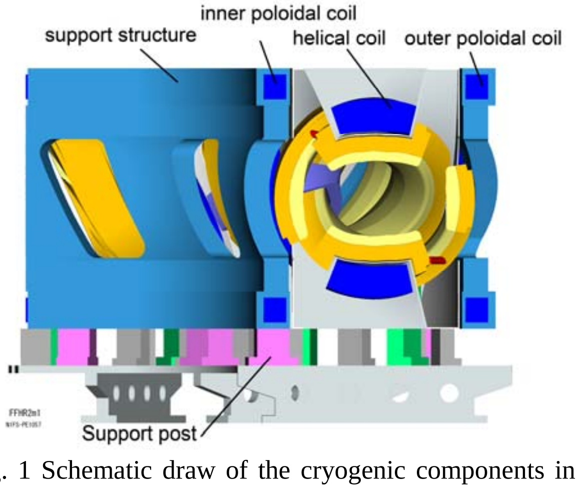

Fig. 1 Schematic draw of the cryogenic components in the FFHR.

The Large Helical Device (LHD) has 3.9m of major radius and 850 tons of cold mass. The LHD adopted a “folded multi plates” type post [4,5]. The post consisted of carbon reinforced plastic (CFRP) and stainless steel (SS) plates. The SS plates were cooled down to 80K to be a thermal anchor region and the plates were connected to the CFRP plates through the thick SS blocks. To minimize a heat leak to low temperature side, the FRP plates were used between room temperature and the thermal anchor region, and the thermal anchor region to the cryogenic temperature. The maximum thermal contraction at the post position was 13mm and the post absorbed the contraction by its flexibility against the radial direction of the components. The CFRP was chosen since it has much larger compressive strength than another low heat conductive materials such as glass fiber reinforced plastic. This type of

author’s e-mail:tamura@nifs.ac.jp

post can be also valid for the support post of the FFHR. A conceptual design and specification of the folded multi plate type post is introduced and stress distribution under several kind of operational situation are shown in this paper. The deformation mode and natural frequency of the cryogenic components including the post are also calculated and safeness against an earthquake is discussed.

2. Basic geometry of the folded multi plates

The cryogenic components which are cooled down to cryogenic temperature are superconducting helical coils, superconducting poloidal coils, and the coil supporting structure. Total weight of the cryogenic components in FFHR has been estimated 16,000ton so far. Considering a symmetrical and homogeneous distribution of the gravitational load, number of the posts were decided 30; 20 posts were located under the outer poloidal coil and other 10 posts were set under the inner poloidal coil. The span of each outer and inner post was 5.7m and 6.2m, respectively. The CFRP plates in the folded multi plate type post are subjected to a compressive load while the SS plates are subjected to a tensile load. The geometrical dimensions of the CFRP plates were decided according to buckling load estimation against a gravitational load with bent long column model. The buckling load in this model can be describes as follows.

$$P_k = \frac{\pi^2 EI}{4L^2}, \quad I = \frac{bh^3}{12}, \qquad (1)$$

where, E is Young's module of 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 defined that the safety factor against the buckling load was over 5 times larger than the nominal weight; (16,000ton)/(30posts)*(safety factor 5)=2667tons. The cross sectional dimensions of the CFRP plate were assumed 1200mm in width and 80mm in thickness considering a setting space. Fig. 2 shows the buckling load against plate length with the parameters of the number of the plate. Since the post must have flexibility, longer plate was desirable but an increase of number of the plate makes the size and weight bigger. 1.2m of the length was chosen and 5 plates and 3 plates were adopted for the center column and outer column, respectively. For the stainless steel plate, 1.2m in width, 30mm in thickness, 1.0m in length, and 3 plates for both side were chosen considering the tensile load and the strength of SS material. Fig. 3 shows the setting up of the support post and its dimension. The weight of a post itself was 10 tons in this case.

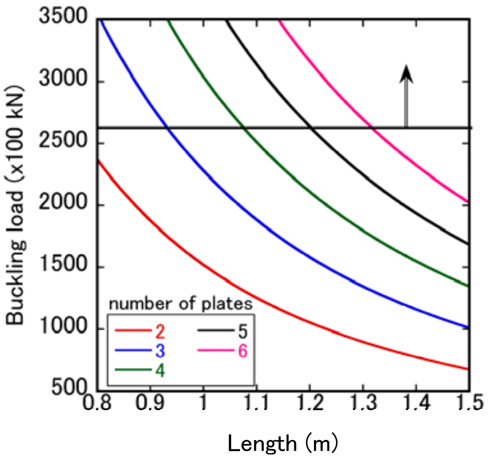

Fig. 2 Buckling load of the CFRP plate with the cross section 1200mm x 80mm using the bent long column model.

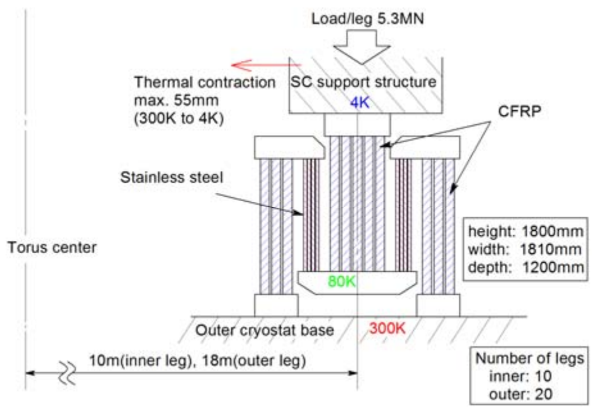

Fig. 3 Schematic draw of the support post for the FFHR.

3. FEM analysis

Using the basic geometrical design of the folded multi plates, a flexibility and stress distribution of the post were calculated by using FEM analysis. The FE model of the support post was prepared by using 3D beam element for a rigidity estimation and 3D shell element for a stress distribution analysis. A thermal condition was also investigated by 3D shell model. The entire 3D model included cryogenic components. Since the cryogenic components were rigid enough compared with support post, we prepared a simple torus shaped structure having not only the same weight of the components but also the same geometrical location of the center of gravity. This torus shaped structure was set on 30 support posts. The natural frequency of this structure was calculated by using this model. Physical properties of the stainless steel used in the analysis were from data base software [6]. The property of the CFRP material was an experimental data of the support post of LHD measured by a manufacture. ANSYS was used for calculation.

3.1 Static analysis

The flexibility against a radial direction was 22.9kN/mm and the maximum stress when 55mm of forced displacement was subjected to the top of the post was 155MPa for CFRP plate and 544MPa for stainless steel plate, respectively. These were under allowable level for the materials and they could be reduced by setting the post to the deforming direction in advance. For example, if the post bent 27.5mm to the outward direction and then the cryogenic components were set on the post, the final position of the top of the post could be 27.5mm bent to the inward direction since the thermal contraction of the cryogenic components forcibly acted the post. The stress level caused by the thermal contraction could be reduced to almost the half by this philosophy. The circumferential direction was more than 10 times as rigid as the radial direction.

The heat loads calculated by using the same model were 10.5kW to 80K and 0.34kW to 4K were obtained and the result showed that the head load to 4K was almost 1/20 compare with the post which was all made of stainless steel. On the other side, heat load to 80K was about a half of the all SS made post.

Here we introduced three operating situations and calculated the stress distribution for each case.

(1) Gravity only

This situation simulated a normal condition before cooling down. The top of the post was bent 27.5mm to the outward and no thermal contraction. In this case, the maximum von Mises stress appeared in CFRP plates and SS plates were 147MPa and 340MPa, respectively. The contour expression of the stress distributions are shown in fig. 4.

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

This situation simulated 0.2G of transverse seismic load is subjected to the device while the cryogenic components are cooled down to 4K. The maximum von Mises stress appeared in CFRP plates and SS plates were both increased and the values were 159MPa and 390MPa, respectively as shown in fig. 5.

(3) Gravity + cool down + 1.0G of transverse acceleration.

In case of 1.0G of transverse acceleration was subjected, the maximum von Mises stress in CFRP plates was 429MPa and 881MPa in the SS plates.

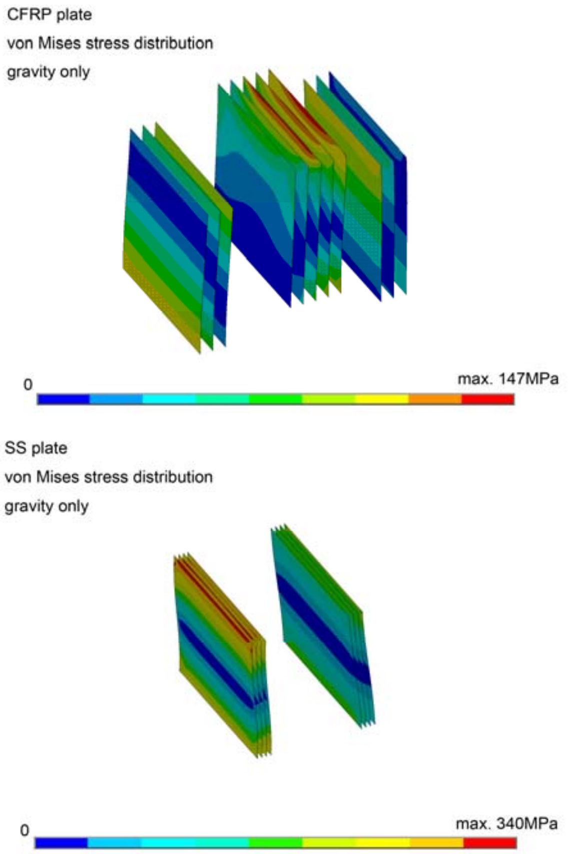

Fig. 4 The distribution of von Mises stress in the CFRP plates (above) and the SS plates (bottom) when the gravity load was only subjected.

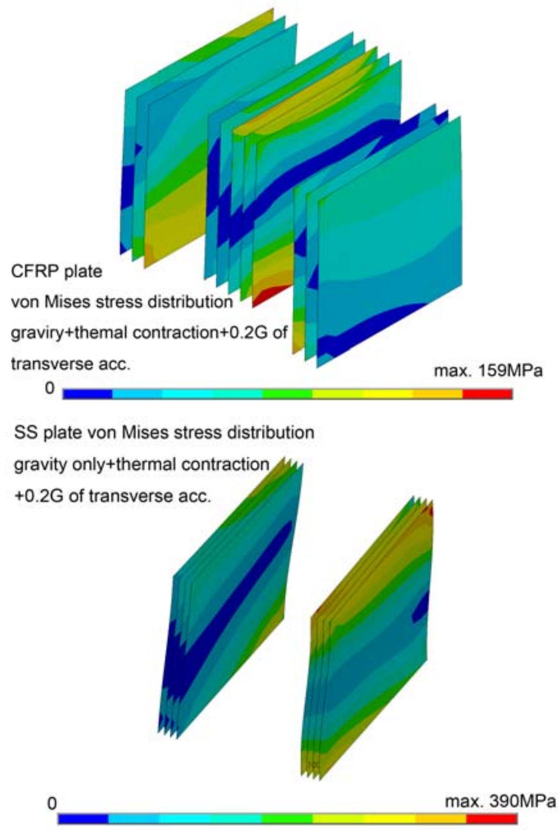

Fig. 5 The distribution of von Mises stress in the CFRP plates (above) and the SS plates (bottom) when the gravity and 0.2G of transverse acceleration were subjected together with the thermal contraction.

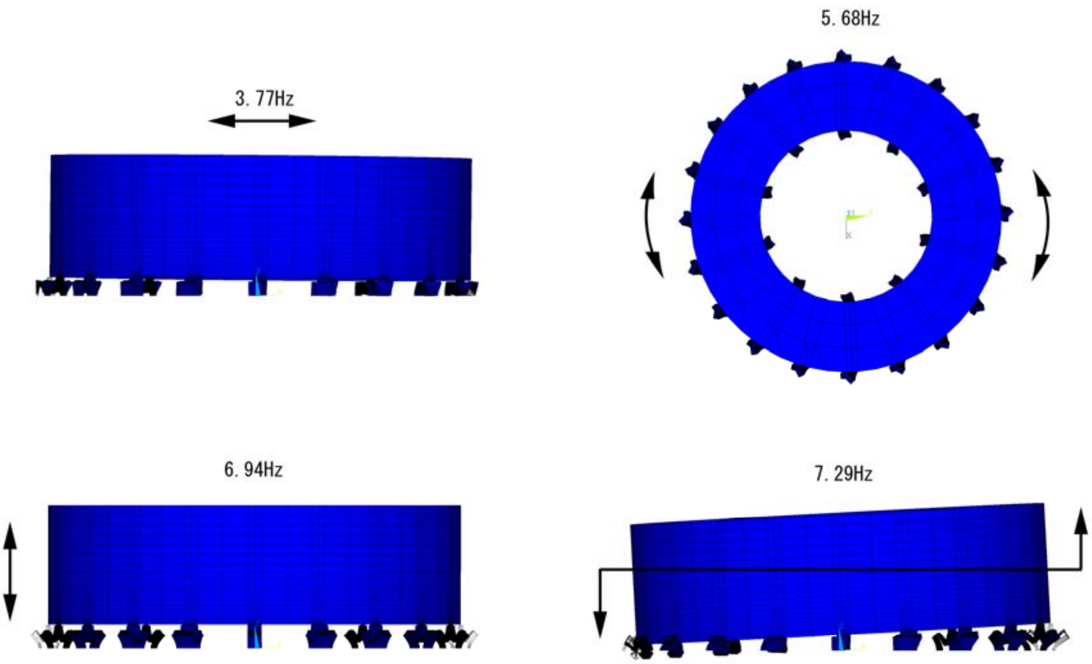

Fig. 6 Results of modal analysis. Natural vibrations mode and their frequency.

3.2 Modal analysis

The natural frequencies of the structure were in a range of 3Hz and 8Hz. Fig. 6 shows the first four modes of natural vibrations and their frequencies. The first mode was a horizontal vibration and the second one was rotational deformation on its axis. The third and fourth modes were concerning with an up-down movement. The higher natural frequencies exceeded 15Hz and the deformation modes were mainly in the cryogenic components.

4. Discussion

The safeness of the structure against an earthquake depends on a frequency and a magnitude of a seismic acceleration. Since a typical earthquake has the range of 0.5Hz to 20 Hz frequency, a structure which has a natural frequency near this range may resonate. From a response spectrum analysis of the typical earthquake such as El Centro, TAFT, etc, the response acceleration of this range would be 1.0 to 1.5G. The analytic result of 1.0G of transverse acceleration load seems that this case is a limit of transverse load since the maximum von Mises stress was slightly larger than permissible stress. This transverse load limit could be a criterion for a design of the building.

5. Conclusions

The “folded multi plates” support post was designed for the FFHR and obtained following conclusions.

The flexibility against a radial deformation was 24kN/mm. The circumferential direction was more than 10 times as rigid as the radial direction.

The total heat load to 4K was estimated not to exceed 340W. It was almost 1/20 value compare with the post which was all made of stainless steel.

The maximum von Mises stress was 159MPa for CFRP plate and 390MPa for stainless steel plate, respectively when 0.2G of transverse acceleration was subjected to the components under cooled down situation. Those stress level were allowable value.

Several natural frequencies of the structure closed to the frequencies in a seismic vibration. To keep the safeness of the device, the acceleration subjected to the structure should not be exceeded 1.0G from the results of static analysis.

Acknowledgement

This work was supported by National Institute for Fusion Science (07ULAA117).

References

[1] O. Motojima et al. Fusion Eng. Des. **81** 2277 (2006).
[2] Sagara A et al. Fusion Eng. Des. **81** 2703 (2006).
[3] Sagara A et al. Nucl. Fusion **45** 258 (2005).
[4] H. Tamura et al. Fusion Technology 1996 1019 (1996).
[5] H. Tamura et al. Adv. in Cryogenic Eng. **45** 753 (2000).
[6] Cryocomp software, Eckels Engineering and Cryodata Inc. (1997).