§7. Multi-scale Stress Analysis of Superconducting Coils for FFHR-d1

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NIFS is developing a conceptual design of the LHD-type helical reactor, FFHR-d1. Several cooling schemes have been proposed for superconducting coils in FFHR-d1, including forced flow with a cable-in-conduit conductor (CICC) using a low temperature superconductor (LTS), indirect cooling with an LTS, and helium gas cooling with a high temperature superconductor (HTS). Multi-scale stress analysis is appropriate for assessing the mechanical behavior of a fusion magnet system because there are large differences among the scale order of components of the superconducting cable/tape, superconductor, and coil support structure[1].

At first, homogenization was applied to the unit cell of the superconductor model, which had a periodic symmetry in the width, height, and length directions. This allowed the equivalent physical properties of the unit cell to be obtained using the relationship between the strain and the averaged stress. The analysis was conducted using ANSYS®. As the result, the longitudinal rigidity was similar to that calculated using the rule of mixtures with an area fraction of the component materials, while the rigidity perpendicular to the longitudinal direction appeared to depend not only on properties of the material but also on the outline shape of the superconductor. The equivalent physical properties were used to describe the properties of the finite elements at the coil winding section in the general assembly model.

As part of a multipath strategy of the FFHR-d1[2], a *novel divertor design* has been proposed for the coil support structure with the aim of mitigating neutron irradiation of the divertor components[3]. We analyzed the stress on the coil support structure in this design. Fig. 1 shows the resulting von Mises stress distribution on the deformed shape using the gas-cooled HTS. The distribution of the stress, strain, and displacement were similar in the three types of candidate superconductor. For the HC, we investigated the axial strain in the longitudinal direction of the superconductor, and in-plane shear stress on the cross-section of the coil, perpendicular to the winding direction. The longitudinal rigidity of the superconductor was the dominant factor in the maximum stress and deformation of the coil support structure. In contrast, the in-plane stress in the HC rose as the shear module corresponding to the plane increased. The stress level of the coil support structure remained within the permissible limit for the stainless steel, and the maximum longitudinal strain was acceptable from the viewpoint of the tensile strength of the superconducting materials.

Based on the results of the stress analysis of the coil support structure, we analyzed the internal stress distribution of the superconductor (localization analysis). Local stress distribution in the superconductor was calculated by applying the strain of an element volume from the whole-structure analysis to the analytical model used in the homogenization analysis. We focused on the region of maximum in-plane stress, since shear stress on the insulator is one of the critical issues for the superconducting magnet system. The shear strength of an insulator using fiber reinforced plastic depends on the applied compressive load. Although the precise materials and composition of the insulator has not yet been decided, two estimations were conducted. One used the "LHD criterion" adopted for the assessment of the inner VFC of the LHD. The other used the "ITER criterion," referencing the estimation method for the insulator of the ITER TF coil. Fig. 2 shows the scatter plot of the shear stress and the normal stress on the insulator, in the gas-cooled HTS and the CICC LTS superconductors calculated in the localization analysis. The allowable limits under the LHD and ITER criteria are also shown. The shear stress was within both criteria, when the normal stress had a negative value, i.e. under compression. However, when both tensile and shear stress were applied simultaneously, the results fell outside the ITER criterion. Further experimental evaluation is needed for selection of the insulator.

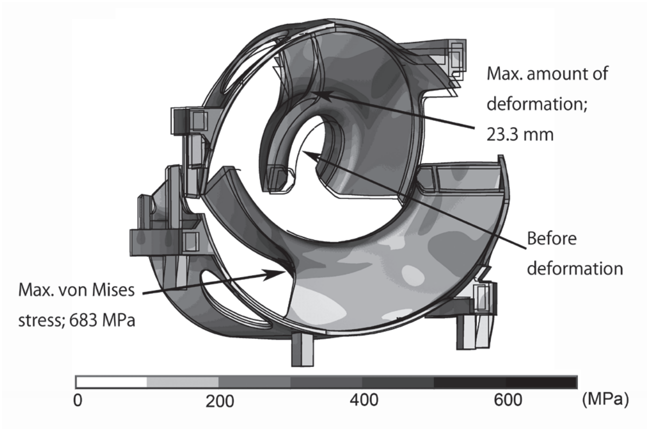

Fig. 1. Results from whole structure analysis.

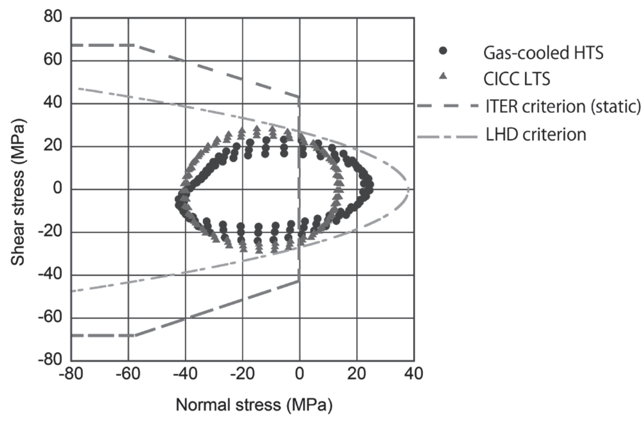

Fig. 2. Correlation between the shear stress and the normal stress in the insulator for the gas-cooled HTS type and the CICC LTS-type superconductor.

1) Tamura, H. et al.: *IEEE Trans. Appl. Supercond.* **26 (3)** (2016) 4202405.
2) Sagara, A. et al.: *Fusion Eng. Des.* **89** (2014) 2114.
3) Tamura, H. et al.: *Fusion Eng. Des*. **98/99** (2015) 1629.