Heat Testing of a Prototypical SiC-Foam-Based Flow Channel Insert

S. Sharafat, A. Aoyama, N. Ghoniem, B. Williams, and Y. Katoh

***Abstract*—As part of the U.S. ITER test blanket module development effort, several flow channel insert (FCI) concepts using a variety of porous SiC and SiC/SiC composites are being developed. Using porous SiC, prototypes of FCI segments as large as $0.12\ \mathrm{m} \times 0.75\ \mathrm{m} \times 0.015\ \mathrm{m}$ were fabricated and heat tested with a maximum ΔT of $\sim 150\ ^\circ\mathrm{C}$ across the FCI walls. In this paper, we report on two heat tests of the FCI prototypes. The first test used radiative heating of the inside of the FCI along with convective cooling of the outside of the FCI, which resulted in a temperature drop of about $\sim 147\ ^\circ\mathrm{C}$ across the FCI wall. The second test involved partial submersion of the FCI structure in liquid PbLi, resulting in an inner wall surface temperature of about 600 °C and an outer wall temperature of about 450 °C ($\Delta T \sim 150\ ^\circ\mathrm{C}$). Detailed thermomechanical analyses of the tests were conducted, and results of the simulations are discussed in the context of actual FCI operating conditions.**

***Index Terms*—Flow channel inserts (FCIs), open-cell foam, porous, silicon carbide (SiC).**

I. Introduction

THE U.S. ITER dual coolant lead–lithium (DCLL) test blanket module (TBM) concept [1] uses silicon carbide (SiC)-based flow channel inserts (FCIs) [2] to provide electrical and thermal insulation between a flowing lead–lithium (PbLi) breeder/coolant and a helium-cooled ferritic/martensitic steel TBM structure. A review of the overall research and development status of the U.S. ITER DCLL TBM is given in [3]. FCI structures must exhibit low electrical and thermal conductivity and must be compatible with PbLi up to relatively high temperatures of ~ 700 °C. Other key performance requirements of FCIs are discussed in [4]. Three variations of SiC-based FCI structures are under development: one is based on an open-cell SiC-foam core, which is integrally bonded between two thin CVD SiC face sheets [4], the second is based on SiC/SiC composites having geometric features, which result in low thermal and electrical conductivities [5], and the third is based on a syntactic closed-cell SiC-foam core between CVD SiC face sheets [6]. Here, we report on the thermomechanical analysis results of the open-cell SiC-foam-based FCI prototype structures.

Thermal testing of the FCI structure was conducted by inductively heating the inner wall to 600 °C while keeping the outer wall at 453 °C, setting up a maximum ΔT of about 150 °C across the wall. Stereo microscope inspection did not reveal any visible damage or microcracks. A detailed 3-D model of the FCI prototype was developed to simulate the thermomechanical performance under these test conditions. The results of the thermomechanical simulations are discussed in the context of actual FCI operating conditions.

II. FCI Prototype

The FCI is positioned inside the TBM PbLi flow channels to insulate the TBM structure from the high-temperature PbLi. There is a 2-mm gap between the FCI and the TBM wall, which is filled with PbLi. Fig. 1 shows the schematic of the FCI inside the TBM and a full-scale FCI prototype, which was fabricated by Ultramet, Inc., using porous SiC. The FCI structure was made with an open-cell CVD SiC-foam core bonded between two 1-mm-thick CVD SiC face sheets. Fig. 2 shows a cross-sectional view of typical FCI wall structures. Details on the FCI prototype fabrication can be found in [4].

III. Inductive Heat Test

The photographs of the thermal test of a 0.15-m-tall foam-core FCI segment are shown in Fig. 3. The inside is inductively heated, and the outside wall temperature is controlled with flowing Ar gas. The wall temperatures were monitored by placing thermocouples at the midpoints of the opposing inside and outside walls. The measured values are listed in Table I.

Using stereo microscope inspection, the inner and outer walls were examined for microcracks, and none was found within its resolution.

IV. Testing in Liquid PbLi

Fig. 4 shows an schematic of the liquid-PbLi heat testing of the FCI prototype, and Table II lists the prototype and heat testing parameters.

A maximum ΔT of 150 °C was measured between the ID and OD of the FCI walls. The first set of tests resulted in a crack along the inside and outside corners of the FCI prototype, which was attributed to excessive force applied during the first

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S. Sharafat, A. Aoyama, and N. Ghoniem are with the Department of Mechanical and Aerospace Engineering, University of California at Los Angeles, Los Angeles, CA 90095-1597 USA (e-mail: shahrams@ucla.edu).

B. Williams is with the Product Research and Development, Ultramet, Inc., Pacoima, CA 91331 USA (e-mail: brian.williams@ultramet.com).

Y. Katoh is with the Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6132 USA (e-mail: katohy@ornl.gov).

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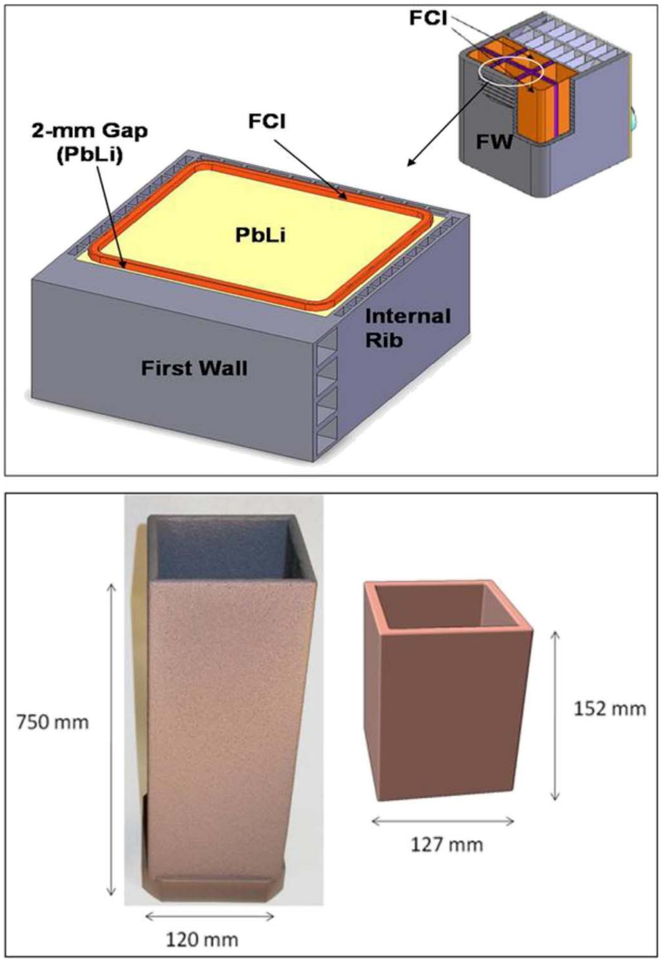

Fig. 1. (Top) Model of a DCLL ITER TBM section, showing the location of the FCI inside the TBM (TBM full height: ∼1.66 m). (Bottom) (Left) Full-scale FCI prototype and (right) CAD model of the heat-tested FCI segment.

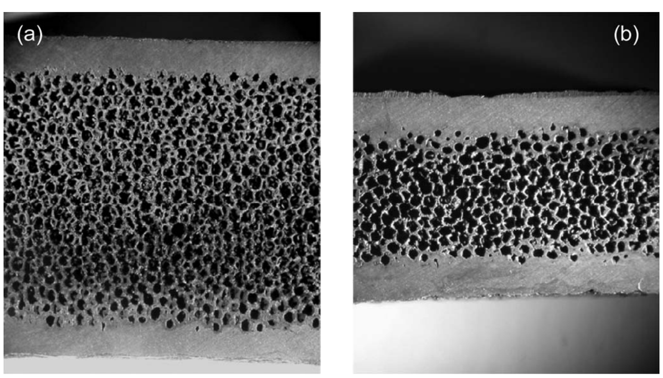

Fig. 2. (a) Cross-sectional photograph of a 10-mm-thick 12% dense SiC foam (100 ppi) with 1.8-mm-thick CVD SiC face sheets. (b) Photograph of a 5-mm-thick 22% dense SiC foam (100 ppi) with 1.8-mm-thick CVD SiC face sheets. Both 5 ×. (Ultramet, Inc.).

test. The subsequent test did not result in any visible cracks or damage.

V. Thermomechanical Model

Solid models of the FCI segment were created for a thermostructural analysis of the two heat tests, which are shown

Fig. 3. Photographs of the inductive heat testing of a 0.15-m-tall FCI segment at (left) intermediate (∼ 200 °C ID) and (right) high (∼ 600 °C ID) temperatures (Ultramet, Inc.).

TABLE I
Steady-State Thermal Data for the FCI Segment

Inner Wall (°C)	*Outer Wall (°C)*	*ΔT (°C)*
100	81	19
150	121	29
200	160	40
250	199	51
300	242	58
350	277	73
400	321	79
500	390	110
560	429	131
600	453	147

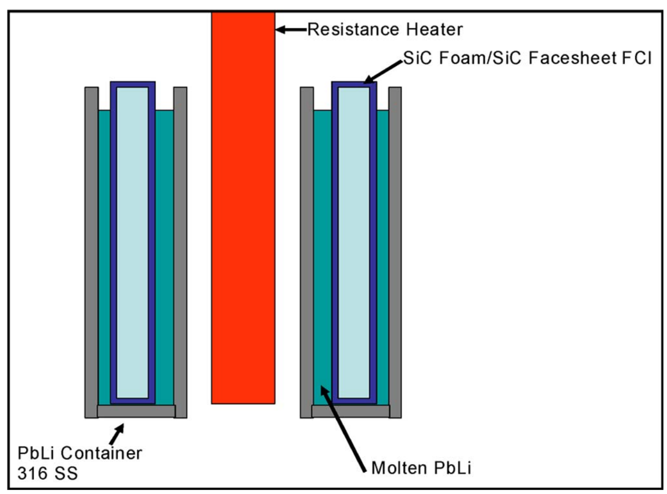

Fig. 4. Schematic of the FCI prototype liquid-PbLi testing apparatus.

TABLE II
FCI Dimensions and Heat Test Conditions

Parameter	*Value*
Height (mm)	152
Filled Height (mm)	~ 50
Inner width (mm)	100
Outer width (mm)	127
X-Sectional Area (cm^2)	61
Filled Volume (ml)	797
Mass (g)	937
Wetted Surface (cm^2)	1242

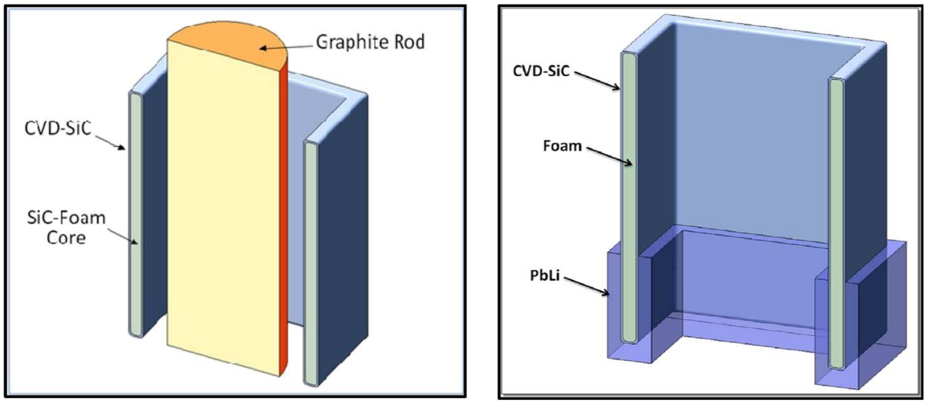

Fig. 5. CAD solid models of the FCI segments for thermo mechanical analysis. (Left) for inductively heating test. (Right) for PbLi submersion test.

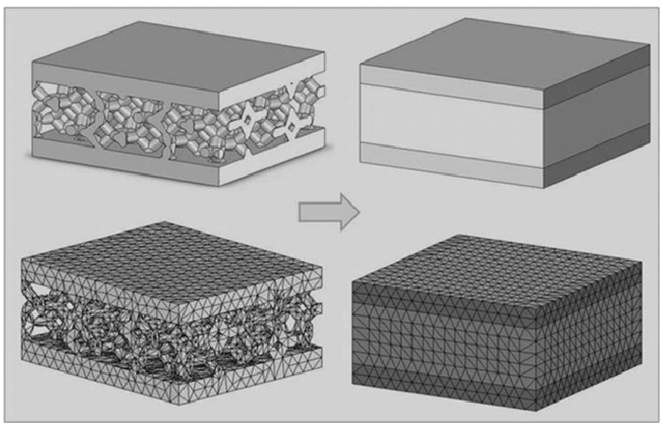

Fig. 6. Detailed (top) 3-D solid and (bottom) meshed model of a section of the open-cell SiC-foam FCI structure (wall: ∼1 mm; foam: ∼3 mm thick). (Right) FCI wall model represented by homogeneous materials.

in Fig. 5. An accurate thermomechanical analysis of the FCI structure would require that a very detailed geometric model of the foam would have to be created and sandwiched between two face sheets. This would necessitate the construction of a 3-D foam geometry, including individual foam ligaments. An analysis of such a structure would be computationally prohibitive. Instead, we represent the foam by a homogeneous material to which we assign material properties that are derived from a detailed FEM analysis using a small-scale 3-D foam CVD SiC face sheet model. The model and the meshed FEM are shown in Fig. 6.

A. Foam-to-Homogeneous Material Properties

A thermomechanical analysis of the small-scale FCI model (Fig. 6) was performed, and equivalent homogeneous material properties were established. Fig. 7 shows a comparison of the FEM analysis results of the detailed foam geometry with those of the equivalent homogeneous material (surrogate material for foam). The derived surrogate foam material properties are listed in Table III. For the thermomechanical analysis of the complete FCI segment (Fig. 5), the CVD SiC face sheet material properties were taken at 500 °C [4], and surrogate material properties were used for the foam material between the face sheets.

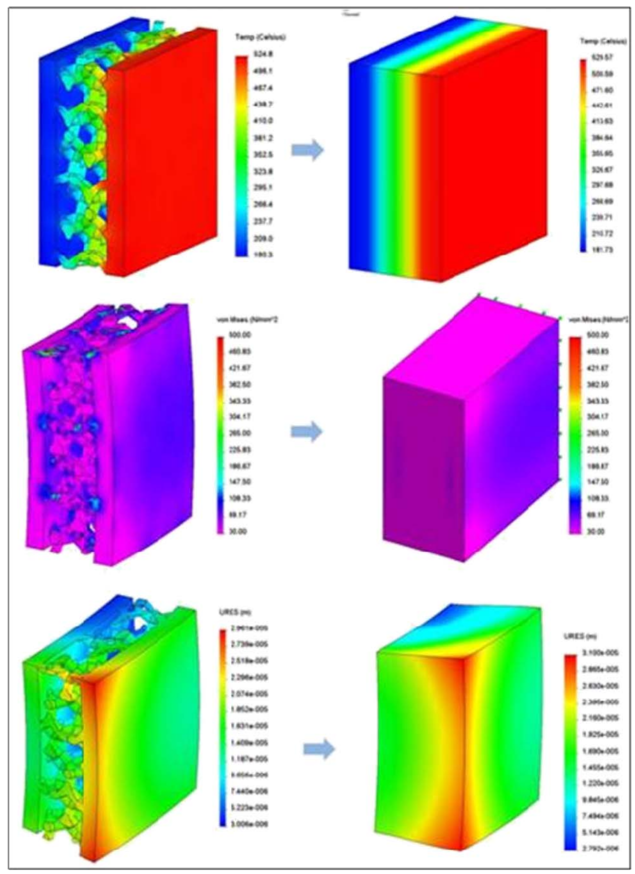

Fig. 7. FEM analysis of the detailed foam geometry for establishing the homogeneous material properties of a surrogate SiC-foam material: (Top) Temperature, (middle) von Mises stress, and (bottom) displacement.

TABLE III
CVD SiC AND DERIVED SURROGATE SiC-FOAM MATERIAL PROPERTIES

PROPERTY	***SiC-Foam* (CVD)***	***Surrogate Material*****
Elastic Modulus (Gpa)	412	11
Poisson's Ratio	0.21	0.21
Thermal expansion (10^{-6} K^{-1})	4.96	4.5
Mass Density (kg/m^3)	3210	600
Thermal Conductivity (W/m-K)	48	5
Specific Heat (J/kg-K)	1096	200

*SiC material properties were taken at 500 °C and used for the CVD SiC face sheets [4]

**The surrogate material properties were used for the homogeneous material representing the foam in the FCI model (Fig. 5).

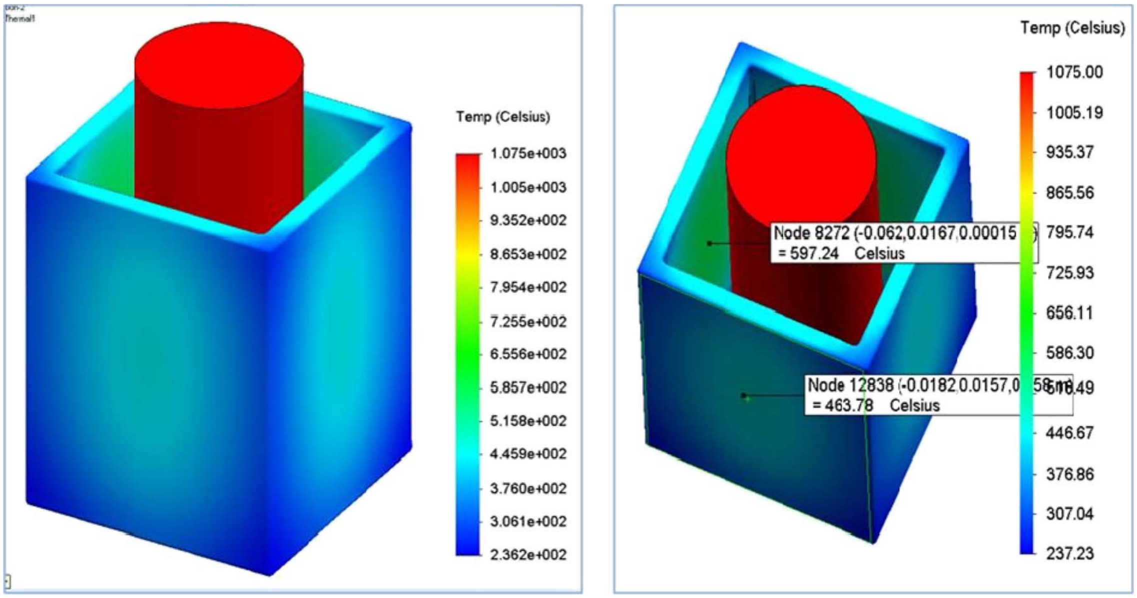

Fig. 8. Simulated steady-state temperature contours of the radiatively heated inner walls (note the uneven temperature distribution along the FCI inner and outer walls).

VI. Thermomechanical Analysis Results

A. *Radiative Heat Testing*

The heating of the inner FCI walls was modeled as surface-to-surface black body radiation (see the CAD model in Fig. 5). The outer walls of the FCI radiate heat to the room (ambient temperature) for which we also assumed black body radiation. The model also includes convection along the outer FCI walls. The temperature of the graphite rod and the convection coefficient were adjusted until the approximate experimental maximum inner and outer FCI wall temperatures (Table I) were reached.

Fig. 8 shows the resulting temperature contours and the locations of the maximum temperature nodes on the inner and outer FCI walls. The maximum inner and outer wall temperatures are about 597 °C and 464 °C, respectively. The maximum simulated temperature difference across the FCI is 133 °C, which is slightly lower than that of the thermal test ($\Delta T \sim 147$ °C). Due to the geometrical arrangement between the heating element, a round graphite rod inside a rectangular FCI box, heating and cooling of the FCI walls are nonuniform as shown in Fig. 7.

The inner and outer edges remain cooler relative to the middle sections of the walls. Consequently, the stress distribution is highly nonuniform, which is shown in Fig. 8. Based on these thermomechanical analysis results, the upper and lower rims of the FCI structure bow outward [see Fig. 8 (right)], and the middle section of the tall edges also shows a distinct outward bow.

The maximum stress concentration occurs at the upper and lower four corners of the FCI structure. The estimated maximum stress level is above 380 MPa, which is near the tensile strength of 300–400 MPa for high-purity CVD SiC. The outer (tall) edges of the FCI structure show stress levels on the order of 300 MPa.

For ceramic structures, the resulting strain might be a better indicator of performance than the stress. Fig. 9 shows the strain contours, which indicate a maximum strain of about 0.12% (Fig. 10).

B. *Modeling Liquid-*PbLi *Heat Testing*

For heat testing in PbLi, the FCI structure was pushed into the liquid PbLi (600 °C), with a force of about 77 N. The thermal resistance between the SiC face sheet and the PbLi was not measured; thus, for the thermomechanical analysis, we assumed perfect contact between SiC and PbLi. A heat flux of 0.117 $\mathrm{MW/m^2}$ was applied to the internal surfaces of PbLi, and the outer surfaces of PbLi were assumed to be cooled by convection in air with a heat transfer coefficient of 2000 $\mathrm{W/m^2 \cdot K}$ and an ambient air temperature of 350 °C. These conditions resulted in the measured heating profile of 600 °C on the ID and 450 °C on the OD of the FCI walls. Fig. 11 shows the resulting temperature profile through the FCI structure, and Fig. 12 shows the respective von Mises stress contours.

The stress concentrates along the edges and in the corners of the FCI structure. It is interesting to note that the maximum stress of ∼150 MPa is reached at the same locations where the cracks occurred during the first set of tests.

VII. Discussion

The inductive heating test of the FCI segment did not show any visible damage or microcracks following a maximum steady-state temperature gradient of about 147 °C, although the first set of liquid-PbLi heating tests did result in cracks due to overexertion of applied forces to lower the FCI into the liquid PbLi. Subsequent PbLi heat testing did not result in any visible

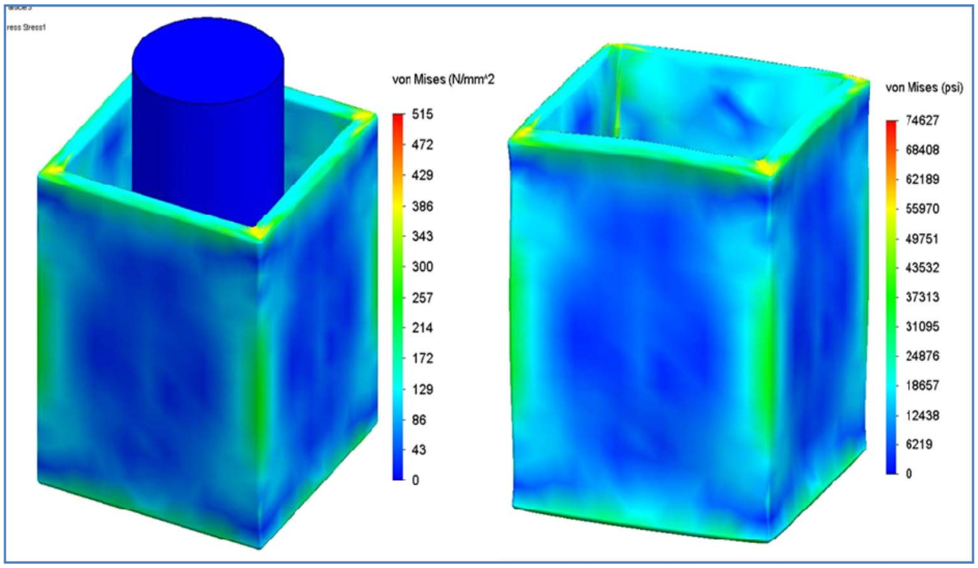

Fig. 9. Von Mises stress contours of the (left) FCI–graphite-rod assembly and of the (right) FCI prototype alone with a scaled up deformation (100 ×). Note the difference in units.

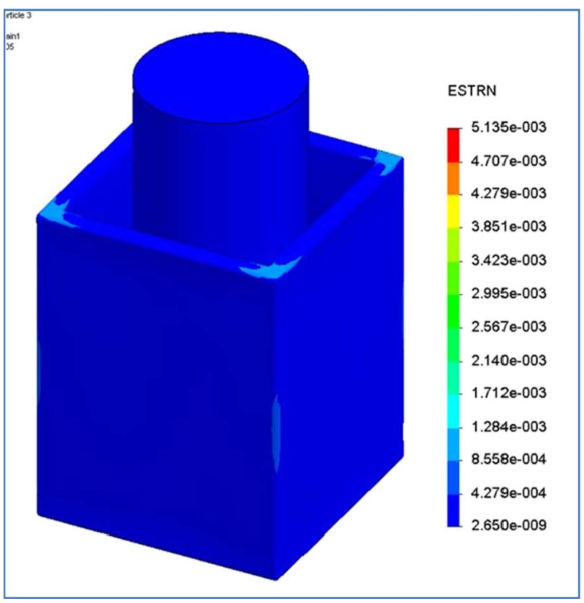

Fig. 10. Simulated strain contours of the inductively heated FCI segment.

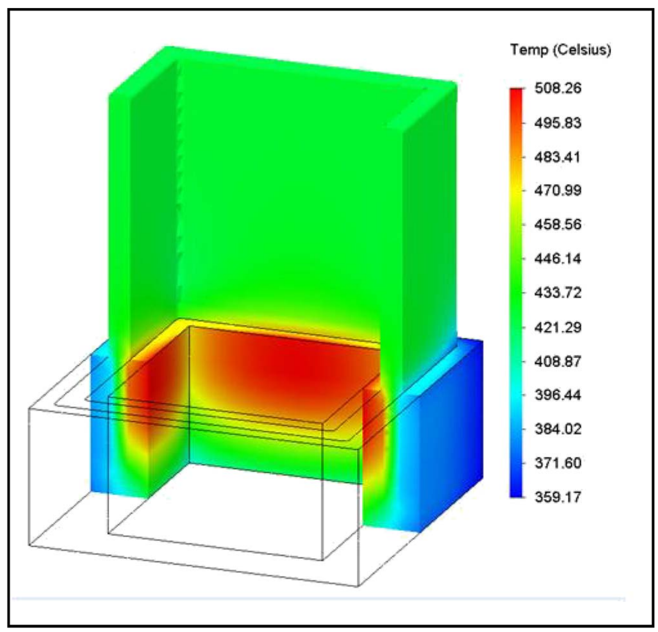

Fig. 11. Temperature contours in the FCI prototype structures for a ΔT of about 150 °C between the ID and OD of the FCI.

damage. The modeled high stress concentrations for both heat tests reached about 150 MPa, which is lower than the 400-MPa tensile strength of high-purity CVD SiC.

In the physical FCI structure, the foam is bonded integrally to the face sheet, while the CAD model assumes a sharp interface surface between the foam and the face sheets. The gradual transition between the foam and the CVD face sheets helps distribute loads. The CAD model does not allow for any gradual load distribution along the interface. This results in overestimating the stress due to a sharp interface.

A combination of the derived material properties for the SiC foam, along with geometric differences between the model and the real part, is deemed to overestimate the stress state of the FCI structure.

VIII. Conclusion

Under actual ITER operations, the heating profile of the FCI structure in the TBM will be less severe from that of the inductively heated test or the liquid-PbLi tests. For example, during TBM operation, the temperatures on the inner and outer walls will not be uniform, neither along nor across the FCI walls. Furthermore, during operation, the PbLi heats up as it traverses the FCI structure from the bottom to the top, which results in higher ΔT along the top sections of the FCI compared to the bottom [4]. This leads to relatively localized and less pronounced maximum temperature gradients across the FCI wall. Thus, the heating test and the analysis results reported

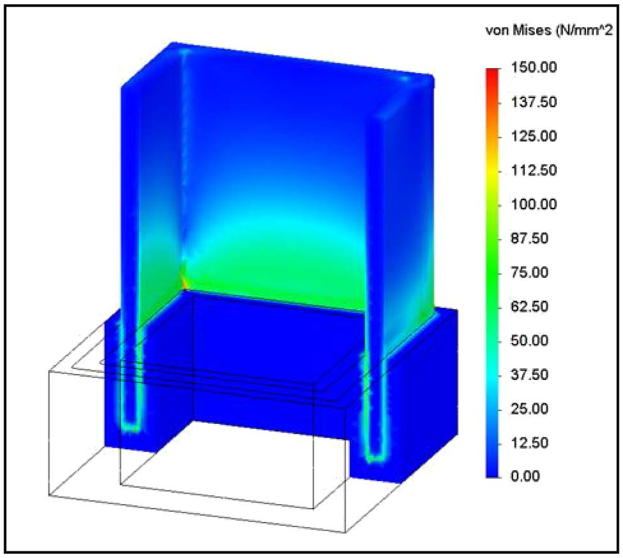

Fig. 12. Von Mises stress contours across the FCI prototype structure.

here represent far more severe conditions compared to actual FCI operations.

Despite the conservative heat test, the FCI segment performed without visible damage. This encouraging performance of the FCI segment implies that the open-cell foam-core-based FCI structure is a viable concept for TBM.

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