TWO-SCALE THERMO-MECHANICAL ANALYSIS OF MULTIDIRECTIONAL CARBON/CARBON COMPOSITES USING IMAGE-BASED FINITE ELEMENT METHOD

A Thesis submitted

In fulfilment of the requirements for the degree of

Doctor of Philosophy

By

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This Ph.D. work is dedicated to my Mother, Father and Teachers

Declaration by the Research Scholar

I hereby declare that the entire work embodied in this thesis is the result of investigations carried out by me in the School of Engineering, Indian Institute of Technology Mandi, under the supervision of **Dr. Rajneesh Sharma** (School of Engineering) and **Dr. Syed Abbas** (School of Basic Sciences), and that it has not been submitted elsewhere for any degree or diploma. In keeping with the general practice, due acknowledgements have been made wherever the work described is based on findings of other investigators.

Place: Signature:

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Declaration by the Research Advisors

We hereby certify that the entire work in the thesis entitled **"Two-Scale Thermo-Mechanical Analysis of Multidirectional Carbon/Carbon Composites using Image-Based Finite Element Method"** has been carried out by **Md Zahid** under our supervision in the School of Engineering, Indian Institute of Technology Mandi, and that no part of it has been submitted elsewhere for any degree or diploma. We further certify that this thesis has been prepared in conformity with the rules and regulations of the institute and has attained a standard required to award a Ph. D degree.

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Date: Date:

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Abstract

Carbon/Carbon (C/C) composites consist of carbon fibers and carbonaceous matrix as the main constituents. In these composites, the carbon fibers are oriented in different directions to achieve tailored properties. Two of such architectures are three-dimension hybrid (3DH) and four dimensions inplane (4DIN) C/C composites widely used in thermal protection systems in aerospace applications. These composites are very popular in the applications where the dimensional stability of structures is highly needed under severe thermo-mechanical loading conditions. Therefore, in the present study, these composites have been studied in detail using the image-based finite element method and two-scale asymptotic homogenization scheme. This includes some of the inherent geometrical imperfections directly in the finite element meshes and also accounts for the micro-structure hierarchy.

First of all, the 2D images of these composites were reconstructed using an X-ray computed tomography facility. The inherent imperfections that are primely raised during the heat treatment procedure of fabrication were explored. The inherent imperfections were categorized as voids (Micro voids and big voids), cracks (intra-bundle, matrix, and interfacial), and bundle distortions. With the help of 2D images of microstructure, a three-dimensional (3D) model of these composites was reconstructed and discretized into finite element mesh. The resulting finite element model of realistic microstructure successfully included some of the inherent imperfections such as irregularly shaped big voids and bundle distortion directly.

Further, two-scale asymptotic expansion homogenization was utilized under periodic boundary conditions to predict the effective thermo-mechanical properties such as effective thermal conductivity and effective thermal expansion coefficient. The Laser flash experiment was performed to measure the effective thermal conductivity of 3DH C/C composite in the in-plane direction up to 1000°C for the numerical model's validity. The measured TC is found in a very good agreement with predicted results that successfully validate the proposed IBFE model. The effect of interfacial debond was also incorporated in terms of effective thermal gap conductance that caused a decrease in the effective thermal conductivity of the composite. In the case of 3DH C/C composite, around 14.85% and 7.98 % reduction in the in-plane TC of the 3DH C/C composite was observed at 27°C and 1227°C respectively. However, the out-of-plane TC was reduced by 6.2 % and 2.8 % at the respective temperatures. On the other hand, TC was reduced by around 5% due to the imperfect interface for the full range of temperatures; thus, Interfacial debond shows a significant effect on the behavior of 3DH

C/C composite compared to 4DIN C/C composite. Further, it was observed that the local distribution of field variables (temperature and heat flux) is significantly affected due to the presence of imperfections. Next, the effective thermal expansion coefficients (CTEs) of these composites were studied. In the numerical predictions of effective CTEs of 4DIN C/C composite, the effect of the three interfacial conditions, namely i) perfectly bonded, ii) imperfectly bonded, and iii) completely debonded interface was included using surface-based cohesive behavior. The effective CTEs in x and z directions decreased significantly due to the imperfect interface, while opposite behavior was noticed for CTE in the y-direction. For the validation of numerical findings, effective CTEs of 4DIN C/C composite were measured experimentally in the temperature range of 200-2500 °C. The in-plane CTE varied from 0.56 to 2.66 x 10^{-6}/°C. The predicted CTEs corresponding to the imperfect interface were found in very close proximity with experimental results. It was also found that interfacial damage initiates at around 247 °C with the corresponding strains of 0.008%, 0.06 %, and 0.009% in x, y, and z directions respectively.

Finally, the thermal shock resistance (TSR) of 4DIN C/C composite was predicted in terms of critical laser power density as a function of laser beam diameter using the finite element-based simulation of laser pulse irradiation technique. The temperature dependency and anisotropic behavior of material were included in the analysis. A homogenous cylindrical body was assumed as a test specimen, and shear strength as a failure criterion. The yz-plane was predicted as a critical plane. The locations near the laser beam periphery around 1.5-2 mm below the irradiated surface were observed as the critical location for shear failure. Apart from this, the temperature and shear stress distribution at critical LPD values were studied in detail. It was noticed that the TSR of 4DIN C/C composite is 10-18 times higher than that of 2D C/C composite.

The presented study concludes that the IBFE method is an effective route to include the inherent imperfections realistically into the FE analysis. The microstructural imperfections such as voids, bundle distortion, and imperfectly bonded interfaces cause a significant reduction in effective thermo-mechanical properties of multidirectional C/C composites.

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