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Effect of manufacturing defects on mechanical properties and failure features of 3D orthogonal woven C/C composites

Ai Shigang [a], Fang Daining [b,*], He Rujie [b,1], Pei Yongmao [b]

[a] Institute of Engineering Mechanics, Beijing Jiaotong University, Beijing 100044, PR China
[b] State Key Laboratory of Turbulence and Complex System, College of Engineering, Peking University, Beijing 100871, PR China

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ABSTRACT

For high performance 3D orthogonal textile Carbon/Carbon (C/C) composites, a key issue is the manufacturing defects, such as micro-cracks and voids. Defects can be substantial perturbations of the ideal architecture of the materials which trigger the failure mechanisms and compromise strength. This study presents comprehensive investigations, including experimental mechanical tests, micron-resolution computed tomography (μCT) detection and finite element modeling of the defects in the C/C composite. Virtual C/C specimens with void defects were constructed based on μCT data and a new progressive damage model for the composite was proposed. According to the numerical approach, effects of voids on mechanical performance of the C/C composite were investigated. Failure predictions of the C/C virtual specimens under different void fraction and location were presented. Numerical simulation results showed that voids in fiber yarns had the greatest influences on performance of the C/C composite, especially on tensile strength.

1. Introduction

Carbon fiber reinforced carbon composites (C/C) have high thermal stability, thermal shock resistance, strength and stiffness in non-oxidizing atmosphere. Due to its superior specific strength and toughness, C/C composites can be considered as favourite materials for highly demanding thermostructural lightweight applications e.g. in aerospace and nuclear industry [1–6]. Nowadays C/C components are leading candidates for applications under extreme conditions. C/C composites are produced by chemical vapor infiltration (CVI) of a textile fiber preform. After the CVI process and high temperature heart-treatments, generally, manufacturing defects exist inner the materials. In particular, porosity/voids and micro-cracks are typical defects in C/C composites, and seriously affect the performance of the composites [7–9]. So, it is mandatory to account for the effects of defects and their evolution, even in the early stages of the design process. With the increasing use of C/C composites as advanced structural materials, the determination of damage criticality and structural reliability of composites has become an important issue in recent years.

Defects–mechanical property relationships of fiber reinforced composites have always been of interest to scientists addressing the composite performance. In Gowayed et al.'s work [10], defects in an as-manufactured oxide/oxide and two non-oxide (SiC/SiNC and MI SiC/SiC) ceramic matrix composites were categorized and their volume fraction quantified using optical imaging and image analysis. Aslan and Sahin [11] investigated the effects of delaminations size on the critical buckling load and compressive failure load of E-glass/epoxy composite laminates with multiple large delaminations by experiments and numerical simulations. In Masoud et al.'s work [12] effects of manufacturing and installation defects on mechanical performance of polymer matrix composites appearing in civil infrastructure and aerospace applications were studied. Damage onset and propagation were studied used time-dependent nonlinear regression of the strain field. In Refs. [13–17], the finite element method (FEM) was followed by various authors to study the delamination problems. FEM is preferred than analytical solutions because it can handle various laminate configurations and boundary conditions.

In recent decades, high-fidelity X-ray micro-computed tomography (μCT) technology has been used to characterize defects and reconstruct meso-structure of textile composites [18]. In Cox et al.'s work [19–21], three-dimensional images of textile composites were captured by X-ray μCT on a synchrotron beamline. Based on a modified Markov Chain algorithm and the μCT data,

* Corresponding author.
E-mail addresses: sgai@bjtu.edu.cn (F. Daining), rujh@163.com (H. Rujie).
[1] Co-corresponding author.

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a computationally efficient method has been demonstrated for generating virtual textile specimens. In Fard et al.'s work [22], manufacturing defects in stitch-bonded biaxial carbon/epoxy composites were studied through nondestructive testing (NDT) and the mechanical performance of the composite structures was investigated using strain mapping technique. In Desplentere et al.'s work [23], X-ray μCT was used to characterize the micro-structural variation of four different 3D warp-interlaced fabrics. And the influence of the variability of the fabric internal geometry on the mechanical properties of the composites was estimated. In Guillaume et al.'s work [24] effects of porosity defects on the interlaminar tensile (ILT) fatigue behavior of carbon/epoxy tape composites were studied. In that work, CT measurements of porosity defects present in specimens were integrated into finite element stress analysis to capture the effects of defects on the ILT fatigue behavior. In Thomas et al.'s work [25] X-ray microtomography technology was adopted to measure the dimensions and orientation of the critical defects in short-fiber reinforced composites. Generally, geometry reconstruction based on μCT data is a huge and complex work, sometimes, virtual specimens explored through this approach are difficult to use for numerical analysis. For 3D fabric composites, because of the complex architecture, studies of the defects–mechanical property relations under meso-structure level have rare reported.

In the present study, meso-structures and manufacturing defects of 3D orthogonal C/C composites were studied though μCT approach. Based on the μCT data, RVE models of the C/C composite were constructed. In the RVE model void defects were included, which have the same statistic parameters in void volume fraction and location as the real C/C composites. C/C specimens subjected to uniaxial tensile experiments were carried out to study mechanical performance of the materials and provide experimental benchmark for calibration of the proposed numerical models. A new progressive damage model for fiber yarns and carbon matrix was proposed. In the new damage model, material fracture is controlled by material fracture energy and strain. The damage model was integrated into ABAQUS though user's subroutine (UMAT). According to the damage model, failure behaviors and mechanical properties of the C/C composites were simulated and the results agreed well with the experimental results. Based on the numerical approach, effects of void defects on performances of the C/C composites were investigated. Parametric studies were also carried out to investigate the influences of void fraction and location on mechanical properties and failure features of the C/C composites. Numerical simulation results showed that void defects in fiber yarns has the greatest influences on the mechanical performances of the C/C composite, especially on tensile strength.

2. Material and experiments

Material studied in this article is C/C 3-D orthogonal woven ceramic composite (fabricated by National Key Laboratory of Thermostructure Composite Materials, Northwestern Polytechnical University, China) in which T300 carbon fiber (Nippon Toray, Japan) tows rigidified by carbon matrix. The C/C composite was prepared using chemical vapor infiltration (CVI) method. T300 carbon fiber was used as reinforcement of the C/C composites with the fiber volume fraction was 56.5%. The fiber preforms, as shown in Fig. 1a, were infiltrated with carbon matrix using multiple cycles of infiltration and heat treatment at 1373 K, 0.03 MPa (the thickness of the fiber preforms is about 5 mm). With increasing cycles, a matrix with near full density can be asymptotically approached, generally, it was about 10 cycles (1200 h). The C/C specimens are illustrated in Fig. 1b (the thickness of the tensile specimen is 5.0 mm). However, from the μCT images of the C/C materials, it was found that manufacturing defects such as voids and microcracks appeared inner the composites. It is because of the special material preparation process. The manufacturing defects are illustrated in Fig. 1c.

Uniaxial tensile experiments were carried out under a Shimadzu universal testing systems (Shimadzu WDW-10) at room temperature (about 300 K) to investigate the mechanical properties of the C/C composite. On the other hand, the testing results will provide experimental benchmark for calibration of the numerical model proposed in this study. In the experiments, constant displacement loadings were adopted and the loading speed was 0.5 mm/min. The C/C specimens in tensile experiments are illustrated in Fig. 1b. The test results are shown in Fig. 2.

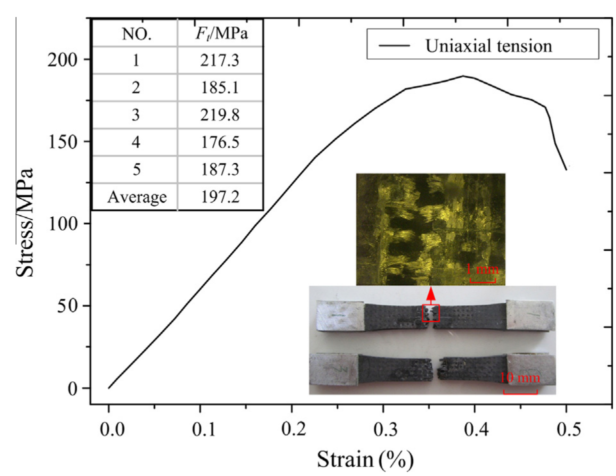

Fig. 2. Stress–strain curve of the C/C composite under uniaxial tension.

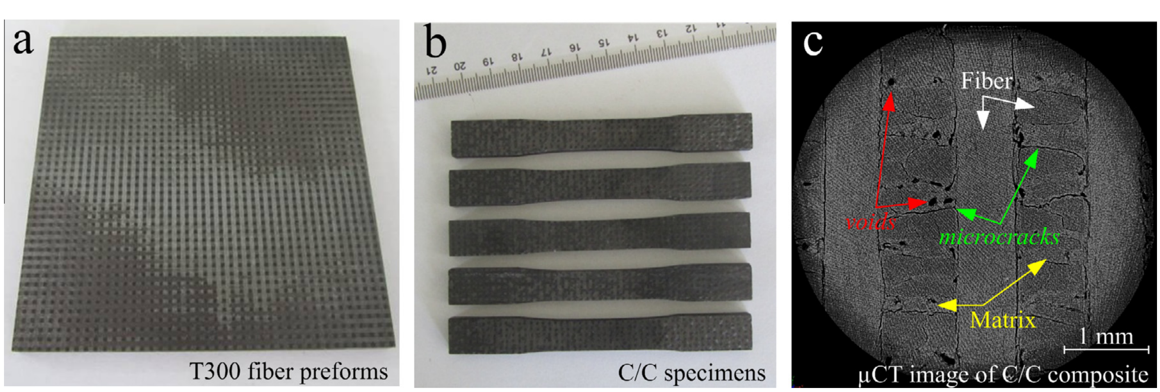

Fig. 1. C/C 3-D orthogonal woven composite.