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Effect of manufacturing defect on mechanical performance of plain weave carbon/epoxy composite based on 3D geometrical reconstruction

Panding Wang[a,b], Hongshuai Lei[c,*], Xiaolei Zhu[d,*], Haosen Chen[c], Changxian Wang[a], Daining Fang[a,c]

[a] State Key Laboratory for Turbulence and Complex System, Department of Mechanics and Engineering Science, College of Engineering, Peking University, Beijing 100871, PR China
[b] Shanghai Weilun Testing Technology CO, LTD, Shanghai 201413, PR China
[c] Beijing Key Laboratory of Lightweight Multi-functional Composite Materials and Structures, Beijing Institute of Technology, Beijing 100081, PR China
[d] School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing 210009, PR China

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ABSTRACT

The investigation on the effect of manufacturing defect on the mechanical performance of composite is essential for the design and application in practice. In this study, the plain weave carbon fiber reinforced polymer (CFRP) laminates are fabricated by the autoclave process and vacuum bag process (VBP), respectively. Uniaxial tensile testes are conducted with a digital image correlation (DIC) system to obtain the macroscopic mechanical performance and local strain distribution. The internal microdefects of composite laminates are captured by micron-resolution computed tomography (μCT) detection technique, including the size and distribution of void, total volume fraction and geometrical parameters of yarns. Based on the Texgen software and Monte-Carlo algorithm, virtual samples with various void contents are constructed to evaluate the impact of defect using finite element solver ABAQUS/Standard. To substantiate this work, we present a comparative study considering both autoclave and VBP. The effect of void defect on the mechanical performances of CFRP laminate is analyzed through finite element method (FEM). The results reveal that the effect of void defect on the surface strain distribution of laminate is significant, especially the value of maximum strain, which will increase obviously with the void defect content. In addition, the overall stiffness predicted by numerical simulation, taking the effect of void defect into account, is lower than that of theoretical.

1. Introduction

Fiber reinforced polymer (FRP) composites are increasingly used in place of conventional metals due to their remarkable mechanical properties, such as specific stiffness, strength and impact resistance [1]. In contrast with the unidirectional fiber reinforced composite materials, the woven fabric reinforced composites present higher delamination and crack propagation resistance [2]. The macroscopic mechanical performances of fabric composites are obviously dependent on the material properties (fiber and matrix), weaving architecture, volume fraction and geometrical parameters [3,4]. It should be noted that the internal void defect of composite structure, which is induced by manufacturing process, can result in the significant degradation of mechanical properties and failure of overall structure [5]. With the wide application of fabric composite in practice, it is essential to investigate the effect mechanism of void defect on the mechanical performance and structural reliability of fabric composite.

The generation and evaluation processes of void defect in composite structure fabricated by various processes has been discussed [6,7]. The influence of manufactured defects on the mechanical properties and failure behavior was analyzed through experimental test [8–14]. To clearly present the void, nondestructive testing techniques have been used to detect the void defects in composite [6,15]. Bodaghi et al. [6] employed the optical microscopy to study the void size and content of composite samples manufactured by high injection pressure resin transfer molding (HIPRTM) process. Their results show that the HIPRTM composite laminate produced without gap closure has a very low void content ($< 0.05\%$). However, the three-dimensional structure of the void defect in plain weave CFRP laminate has not been studied yet. Recently, high-fidelity X-ray micro-computed tomography (μCT) technology has been widely used as a non-destructive testing method for defect detection and meso-structure reconstruction of textile composites [16–21]. In fact, it is difficult to discriminate or recognize the elements of carbon-fiber composites using μCT, especially the region

* Corresponding authors.
E-mail addresses: leihongshuai@pku.edu.cn (H. Lei), zhuxiaolei856028@126.com (X. Zhu).

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between co-aligned neighboring tows. Djukic et al. [22,23] aimed to improve the contrast enhancement in visualization of woven carbon fiber reinforced epoxy composite. Fiber tows were coated in a material of higher density and woven into fabric, while the influence of additional material on the mechanical properties of structure was not discussed. To sum up, μCT scans is a useful tool to reconstruct the three-dimensional structure of the void defect.

In addition to experimental works mentioned above, a vast number of studies investigating the mechanical properties of woven composite structure, without considering the effect of void defect, have been conducted based on the finite element method (FEM) [24–28]. The software package WiseTex and Texgen are widely used to implement a generalized modelling of meso-structure for the textile and woven plain composite [29–32]. It is integrated with the modelling of resin flow, weft-knitted and non-crimp warp-knit stitched fabrics and laminates, thermodynamics and micromechanical property calculation of woven. It is worth mentioning that there exist several other methods to build the virtual sample for finite element analysis (FEA). Said et al. [24] proposed a novel Voronoi tessellation to create the virtual model for the heterogeneous material. Blacklock et al. [26] used the Monte-Carlo reconstruction algorithm based on the Markov chain formulation to generate virtual sample. The constructed virtual geometrical structure fits well with experimental results. μCT has been used to scan the dry fabric and built the high fidelity numerical models [18,19,22,23]. Naouar et al. [19] proposed a direct method to transform the X-ray tomography images to prism finite element model based on the real geometry of 3D composites reinforcements. However, void defects are neglected in previous FEA models [18,19,22–32], which are important for the determining of material performance. Ai et al. [13,33] constructed a virtual sample of 3D orthogonal textile carbon/carbon (C/C) composites with manufacturing defects by adjusting the stiffness of elements, which were chosen by Monte-Carlo algorithm to be regarded as void defects.

In this study, the effects of void defects on the mechanical properties of plain weave carbon fiber reinforce polymer laminates are studied. The overall flow diagram for this paper is shown in Fig. 1. Firstly, the uniaxial tensile tests with DIC system are carried out to obtain the mechanical response of plain woven CFRP composite. Secondly, the meso-structure and manufacturing void defects of samples are captured by μCT. The volume content and distribution of void defect are discussed based on the scanned images. To reconstruct the real architecture of tows, the cross section of tows is recognized from the tomography images to determine the shape and space trajectory. Finally, a representative volume element (RVE) is built in Texgen software package using the μCT data. A Monte-Carlo algorithm is proposed to generate void defects in RVE model. The volume fraction and number of void defect are controlled to match the real situation. The FEA results are compared with the experimental and theoretical results.

2. Experimental details

2.1. Materials

The plain weave carbon fiber pre-pegs (EV101, supplied by HENGSHEN Composite Co, LTD, China) is utilized as the reinforced material in this study. The thickness of layer measures 0.25 mm and the areal density is 200 g/m^2. The matrix is epoxy resin (HFW-200T) with a glass transition temperature of 130 °C.

2.2. Fabrication

2.2.1. Autoclave processing

Autoclave process is adopted to fabricate the carbon fiber reinforce polymer laminates (as seen in Fig. 2), which has been considered as the optimal choice for the high-performance composite structure [10]. Less void defects exist in laminates processed by autoclave than that processed by other techniques [6]. The compaction pressures (P_c) is computed by the total pressure difference between the pressure within vacuum bag (P_{in}) and the pressure in autoclave (P_{out}). The material is cured under the 7 bar compaction pressure (as seen in Fig. 3). The laminate has 10 layers, and the tows are oriented in [0°/90°] position. Two temperature stages are performed: 80 °C for 1 h and 130 °C for 1.5 h. After the curing process, the material is naturally cooled to 60 °C. A square laminate can be obtained with the dimension of 400 mm × 400 mm × 2.29 mm. The uniaxial tensile samples are cut from the laminate using water jet machine.

2.2.2. Vacuum bag processing

To obtain comparison samples with different volume fractions of void defect, vacuum bag process (VBP) is adopted and the specific process parameter is given in Fig. 4. The number of layer and stacking subsequence are similar with the autoclave process. The laminate is cured under vacuum with 130 °C for 2.5 h, and the compaction pressure is 1 bar.

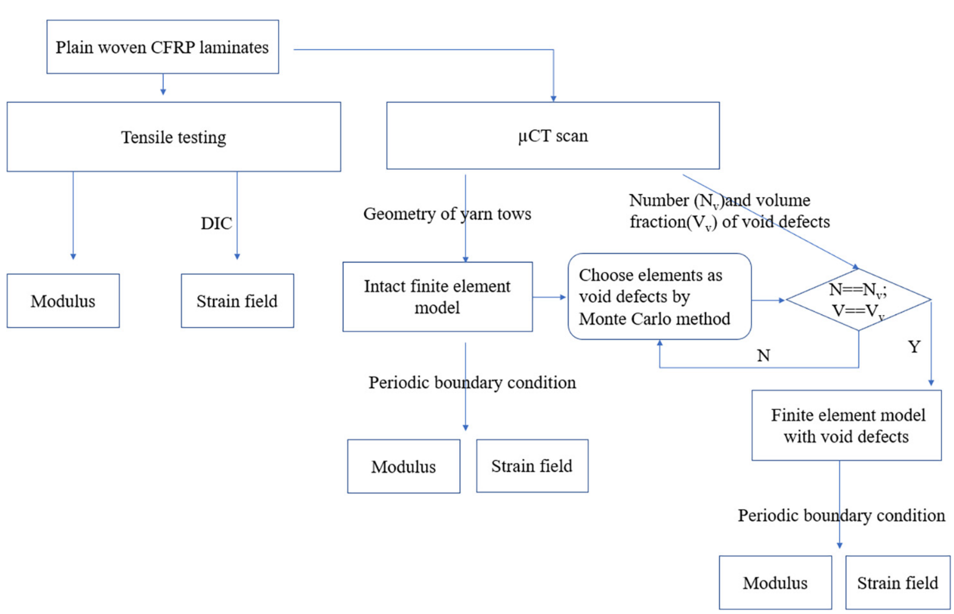

Fig. 1. Modelling approach overview.