Ceramics International 44 (2018) 6433–6442

Contents lists available at ScienceDirect

Ceramics International

journal homepage: www.elsevier.com/locate/ceramint

Modelling shear behaviors of 2D C/SiC z-pinned joint prepared by chemical vapor infiltration

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ARTICLE INFO

Keywords:
Joining
Z-pinned joint
Progressive damage analysis
Micro-CT
Composite

ABSTRACT

Progressive failure model is developed to investigate shear behaviors of 2D C/SiC z-pinned joint prepared by chemical vapor infiltration (CVI). It includes progressive failure model of 2D C/SiC composites and cohesive model of faying plane, in order to describe joint nonlinear shear behaviors and z-pin shear-off failure mode, respectively. All cohesive parameters are directly obtained from mechanical properties of 2D C/SiC composites. Results show that the model can almost reproduce joint shear behaviors and z-pin shear-off failure process. Joint failure results from coupled fiber tensile and fiber–matrix shearing damages at faying plane. The model also successfully demonstrates that joint shear properties can be effectively improved by changing z-pin density and diameter. The relationship between joint properties and mechanical properties of 2D C/SiC composites are subsequently obtained with the model. In this sense, joint shear strength increases with cohesive or in-plane shear strengths of 2D C/SiC composites.

1. Introduction

Long fiber-reinforced silicon carbide matrix ceramic matrix composites (CMC-SiCs) are widely used for designing and manufacturing large complex lightweight hot structures or thermal protection systems (TPS) such as body flap, leading edge, rudder, and nozzle of reusable launch vehicles (RLVs) [1–6]. While being in service under high temperature and oxidizing environments, the joint areas typically become the weakest regions because of the low shear strengths of the CMC-SiC composite [7–9] and the severe oxidation damage induced by strength reduction [10–15]. Developing anti-oxidation CMC-SiC joining methods is therefore listed as one of the key technologies for building future space vehicles [2]. In our previous papers [16–18] we developed a novel on-line z-pinned joint made of two-dimensional (2D) carbon fiber-reinforced silicon carbide composites (2D C/SiC) with excellent oxidation resistance and controllable shear properties. The results revealed that cracking of the SiC matrix and carbon fiber bridging played a significant role in joint strengthening and toughening. The relationship between the mentioned toughening mechanism and the mechanical properties (e.g., tension [19–23] and shear [7,9,24–26]) of 2D C/SiC composites has been widely studied. However, the relationship between the characteristics of the joint and the mechanical properties of 2D C/SiC composites still remains unknown.

Current research has focused on the prediction of the joint behaviors without considering the failure process of the 2D C/SiC z-pin. He et al. [27] investigated the bending failure mechanisms of 2D C/SiC two-layer beams joined by 2D C/SiC pin-bonded hybrid joints and showed that the joint failure initiated at the hole/pin bonding interface. Li et al. [28,29] obtained a linear relationship between the number of pins and the joint shear strength based on a linear numerical study. Zhang et al. [30] showed that the joint shear behaviors could be affected by slight changes in the joint microstructures such as non-uniform density distribution. Despite of the above progresses, the non-linear shear behaviors of 2D C/SiC z-pinned joints have not been comprehensively investigated, especially regarding the failure process of the 2D C/SiC z-pin. Moreover, the effects of the design parameters directly related to the microstructural characteristics of the joint such as density and diameter of the z-pin have not been considered.

In this paper, we develop a progressive failure model to investigate the joint failure mechanisms and the relationship between the characteristics of the joint and the mechanical properties of the 2D C/SiC composites. The model is subsequently applied to investigate the effects of the initial density and diameter of the z-pin on the joint behaviors. The above-mentioned relationship is verified upon comparison with the experimental results.

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https://doi.org/10.1016/j.ceramint.2018.01.038
Received 13 December 2017; Received in revised form 5 January 2018; Accepted 6 January 2018

Table 1
Mechanical properties of the 2D C/SiC plates.

	E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	ν_{12}	ν_{23}	ν_{31}	G_{12} (GPa)	G_{23} (GPa)	G_{31} (GPa)
2D C/SiC	92.14	92.14	40	0.01	0.01	0.01	23.18	23.18	23.18

2. Experimental procedures

2D C/SiC composites were prepared by isothermal chemical vapor infiltration (I-CVI) and the details can be found elsewhere [27,30]. The average mechanical properties of the 2D C/SiC composites are listed in Table 1, and the material directions were determined by the natural plain-woven fiber direction.

The 2D C/SiC z-pinned joint was prepared by three main steps namely, preparation of the member plates and z-pins, assembly of the joints, and re-infiltration of the SiC matrix up to final densification [16]. During the process, the apparent densities of the z-pins were measured by the Archimedes' method before joint assembly. It should be noted that the apparent density of the z-pin was taken as the initial density instead of the final density. Details on the preparation processes can be found elsewhere [27]. The geometry dimensions of the final specimen are illustrated in Fig. 1(a). Two groups of specimens were prepared according to the initial density and the diameter of the z-pin.

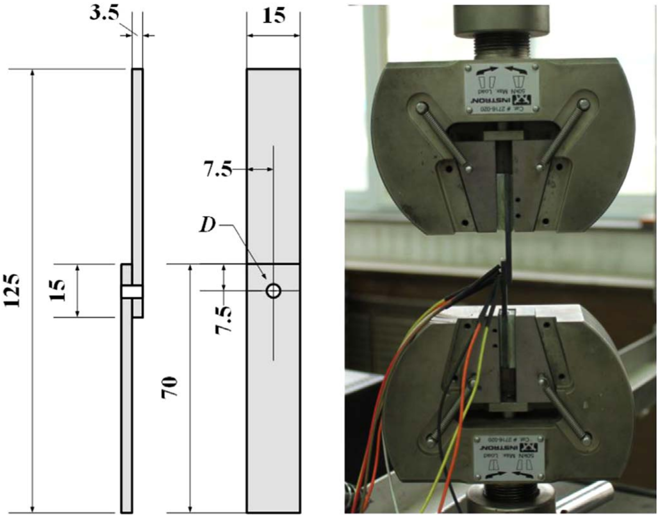
Before shear tests, the specimens were inspected by micro-computed tomography (Y. Cheetah, YXLON, German). The tests were conducted at room temperature on the universal material testing machine (Instron-5567) shown in Fig. 1(b). A displacement control mode was chosen with a loading rate of 0.2 mm/min. After the tests, the in-situ diameters of the z-pins were measured on an optical microscope (Stemi2000-C, Carl Zeiss), while the failure morphologies of the z-pinned joints were observed by scanning electron microscopy (SEM, Hitachi S-2700, Tokyo, Japan).

3. Finite element model of the 2D C/SiC z-pinned joints

3.1. Progressive damage model of the 2D C/SiC composite

3.1.1. Non-linear mechanical behaviors

Hahn and Tsai defined the complementary strain energy W^* with up to fourth-order by the high-order elasticity theory and deduced a widely used non-linear shear stress–strain relationship for unidirectional polymer matrix composites (PMCs) [31]. Yet, the nonlinear tensile stress–strain relationship was ignored owing to the corresponding linear behavior of PMCs. To characterize composites with in-plane nonlinear behaviors, Tomas redefined the energy as follows [32]:



(a) (b)

Fig. 1. (a) 2D C/SiC z-pinned single-lap joint configuration, (b) shear tests set-up.

$$W^* = \frac{1}{2}S_{11}\sigma_{11}^2 + S_{12}\sigma_{11}\sigma_{22} + \frac{1}{2}S_{22}\sigma_{22}^2 + \frac{1}{2}S_{44}\tau_{12}^2 + \frac{1}{3}S_{111}\sigma_{11}^3 + \frac{1}{3}S_{222}\sigma_{22}^3 + \frac{1}{4}S_{4444}\tau_{12}^4 \quad (1)$$

where S, σ, and τ are the compliance, tensile stress, and shear stress components, respectively. The subscripts denoted the relative directions, while the three elasticity parameters S_{111}, S_{222} and S_{4444} denoted the in-plane non-linear behaviors. Subsequently, the strains were calculated as:

$$\begin{aligned} \varepsilon_{11} &= \frac{\partial W^*}{\partial \sigma_{11}} = S_{11}\sigma_{11} + S_{12}\sigma_{22} + S_{111}\sigma_{11}^2 \\ \varepsilon_{22} &= \frac{\partial W^*}{\partial \sigma_{22}} = S_{12}\sigma_{11} + S_{22}\sigma_{22} + S_{222}\sigma_{22}^2 \\ \gamma_{12} &= \frac{\partial W^*}{\partial \tau_{12}} = S_{44}\tau_{12} + S_{4444}\tau_{12}^3 \end{aligned} \quad (2)$$

Therefore, both the tensile and in-plane shear nonlinear behaviors can be demonstrated. In this paper, we utilized the above equations to study the remarkable damage-induced pseudo-plastic behaviors of 2D C/SiC composites. As shown in Fig. 2, the fitting results verified these in-plane non-linear stress–strain formulas.

Owing to the laminated structures of 2D C/SiC composites, the through-thickness behaviors were hard to measure under out-of-plane stresses. However, since the deflection of matrix cracks at weak interfaces mainly controlled the non-linear behaviors of 2D C/SiC composites, the formulation under the in-plane shear can be adopted for out-of-plane shear deformations. Thus, the through-thickness tensile behavior should be linear because of the absence of fiber bridging:

$$\begin{aligned} \gamma_{13} &= S_{55}\tau_{13} + S_{5555}\tau_{13}^3 \\ \gamma_{23} &= S_{66}\tau_{23} + S_{6666}\tau_{23}^3 \end{aligned} \quad (3)$$

where the two elasticity parameters S_{5555} and S_{6666} denoted the in-plane shear non-linear behaviors.

Two damage parameters were used to characterize the in-plane nonlinear mechanical behaviors:

$$d_{ii} = \frac{\frac{2S_{iii}}{S_{ii}}\sigma_{ii}^{(k)} - \frac{S_{iii}(\sigma_{ii}^{(k)})^2}{\varepsilon_{ii}^{(k)}}}{1 + \frac{2S_{iii}}{S_{ii}}\sigma_{ii}^{(k)}}, \quad i = 1, 2 \quad (4)$$

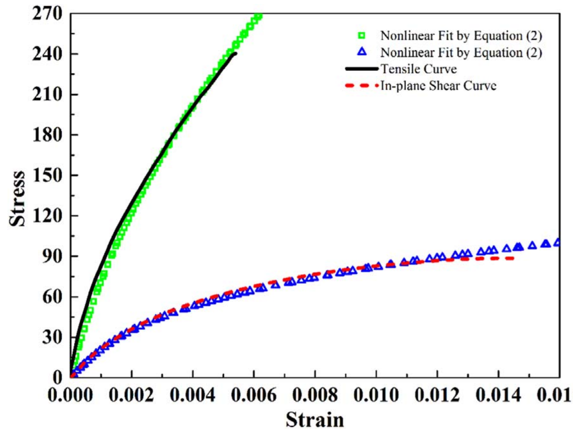


Fig. 2. In-plane mechanical curves of the 2D C/SiC composite fitted by the non-linear stress–strain relationship of Eq. (2).