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Effects of inter-fiber spacing and thermal residual stress on transverse failure of fiber-reinforced polymer–matrix composites

Lei Yang, Ying Yan *, Jian Ma, Bo Liu

School of Aeronautic Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China

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ABSTRACT

The effect of thermal residual stress on transverse failure of fiber-reinforced polymer matrix composites is investigated by computational micromechanics with finite element method (FEM). Especially, the effect of inter-fiber spacing on thermal residual stress and then its effect on the transverse failure of composites are studied through microstructures with random fiber distribution and controllable minimal inter-fiber spacing. The residual stress is supposed to be introduced by thermal contraction of both resin and fiber as a result of cooling from the curing temperature to room temperature. The calculated residual stresses generally increase with the increase of fiber volume fraction and decrease of minimal inter-fiber spacing. And initial matrix and interface damage may be induced by thermal residual stress, especially when the inter-fiber spacing is quite small. For the particular composite system studied and the assumed parameters, it is concluded that the existence of residual stress can have significant effects on the failure behavior of composite when subsequent external load is applied, obviously changing the damage initiation locus and damage evolution path, and causing significant decrease in the transverse strength of the composite. Generally, there is a trend of more significant decrease in the transverse strength for higher fiber volume fraction and smaller inter-fiber spacing. In conclusion, this paper reveals how inter-fiber spacing and thermal residual stress affect the transverse failure behavior of composites, and thus can provide some guidance for both design and analysis of composites when thermal residual stress is concerned.

1. Introduction

After curing and subsequent cooling of composite materials from the relatively high processing temperature to room temperature, thermal residual stresses arise due to the significantly different thermal and mechanical properties of the matrix and the inclusions. For fiber-reinforced polymer–matrix composites, residual stresses can be introduced by two contributions [1]: (1) volume shrinkage of matrix resin from the crosslink polymerization during isothermal curing, (2) thermal contraction of both resin and fiber by different amount due to the mismatch in the coefficients of thermal expansion of the constituents after cooling from the curing temperature to room temperature. Residual stresses have significant influence on the mechanical behaviors of composites [2], sometimes even high enough to initiate material damage such as interface debonding and matrix microcracking before loading [3,4]. Though they will decrease with time and tend to certain asymptotic values after some time, the remaining parts still have significant influence on the damage initiation and evolution of the composites under subsequently superimposed loading [5]. Therefore, residual stresses should be taken into account in both design and analytic modeling of composites involving damage and fracture behaviors if they exist.

Thermal residual stress was first studied by Nairn and Zoller [6] in fiber reinforced thermoplastic composites through experimental method [7]. Ever since, a lot of experimental techniques [8] have been developed to investigate thermal residual stress in composites. But experimental approaches are often too complicated and costly and not able to quantitatively reflect the effect of residual stress on the failure behavior of composites. Though macroscopic thermal residual stresses in composite materials can be calculated through the classical laminate theory or other analytic methods; however, the microscopic stress and strain fields and damage features cannot be well predicted by these methods. Therefore, many researchers investigated residual stresses on the micromechanical level by numerical methods [9–24]. Generally, a regular or periodic geometrical fiber array [10–16] in the matrix is assumed, which allows the representation of the material by a small unit cell and thus leads to lower computational costs. Zhao et al. [1,10] studied the cure residual stress and its effect on damage in fiber-reinforced polymer–matrix composites using micromechanical unit cell models and the finite element method. Predicted damage initiation and evolution are clearly influenced by the inclusion of residual stress,

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* Corresponding author. Tel.: +86 10 82315947; fax: +86 10 51736199.
E-mail address: yingyan@buaa.edu.cn (Y. Yan).

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which could be detrimental or beneficial depending on the state of existing residual stress and the loading conditions. Fiedler et al. [15,16] investigated the influence of local fiber volume fraction on the thermal residual stresses and transverse composite strength. However, fiber-reinforced composites are far from being ordered materials since the fibers are randomly distributed through the matrix and the random fiber array has a significant influence on residual thermal stresses and failure behavior of composites [17–22]. Fletcher et al. [17] found that the change from a regular to a random arrangement generally increased the maximum tensile stress produced in the epoxy resin, which tended to occur at positions within the smallest gap between two fibers. Jin et al. [20] indicated that the random arrangement of fibers had a significant influence on residual thermal stresses especially at high fiber volume fractions. Hobbiebrunken et al. [21] also proved that regular models did not represent the actual distribution of maximum interfacial stresses and therefore cannot be used in failure analysis.

When referring to random fiber array of composites, the inter-fiber spacing is a key parameter, which is also believed to have a significant influence on the thermal residual stress [11] and thus on the failure behavior of composites under subsequent mechanical load. This influence has been studied by Maligno et al. [12] for unidirectional composite materials under transverse and longitudinal tensile loading. It was demonstrated that residual stress and inter-fiber spacing played an important role over the curing process and in case of micro-gaps between fibers (~0.05 μm) even small values of chemical shrinkage are likely to cause matrix failure. The presence of residual stresses also affected damage initiation sites especially in micro-model in which inter-fiber spacing is of the order of few micro-meters (~0.05 μm). However, the study was based on a hexagonal packing array and thus the applicability for real composite materials still requires validation. Vaughan et al. [25,26] investigated the effect of thermal residual stress on the transverse damage behavior of a unidirectional carbon fiber reinforced epoxy composite with random fiber distribution. They indicated that the magnitude of the compressive interfacial normal stress between neighbouring fibers after thermal cool-down increased as the inter-fiber spacing decreased. The same conclusion was drawn by Hojo et al. [22]. However, no systemic investigation has been conducted about the effect of inter-fiber spacing on thermal residual stress and subsequent failure behavior of the composite.

In a former work the authors [27] studied the microscopic failure mechanisms of fiber-reinforced polymer–matrix composites under transverse loading by computational micromechanics, taking into account the random distribution of fibers and the two dominant damage mechanisms experimentally observed – matrix plastic deformation and interfacial debonding. The present paper is based on this study but introduces the consideration of thermal residual stress, focusing on the effects of inter-fiber spacing and thermal residual stress on transverse failure of fiber-reinforced polymer–matrix composites.

2. Computational model

2.1. Temperature dependent material properties

The composite constituents considered here are glass fiber and epoxy resin, whose properties are given by Maligno et al. [13]. The properties of glass fiber are assumed to remain constant and independent of the temperature change with Young's modulus $E_f = 80$ GPa and Poisson's ratio $\nu_f = 0.22$ and the coefficient of thermal expansion $\alpha_f = 4.9 \times 10^{-6}/°C$. While for the epoxy resin, the properties are defined as functions of temperature, taking into account the strong influence of glass transition temperature T_g on the mechanical properties. The relations are summarized as follows, which are first proposed by Zhang et al. [5] and then used by many researchers [1,12–14]:

(a) Poisson's ratio is assumed to be temperature independent with a value of $\nu_m = 0.4$.
(b) The total temperature range from curing to room temperature is divided into three regions with respect to the glass transition temperature to consider the change of Young's modulus E_m over the temperature.

When the temperature is around T_g, $T_g - \triangle T_1 \le T \le T_g + \triangle T_2$, the matrix is in a transition region, where E_m varies greatly:

$$E_m(T) = E_m(T_g - \triangle T_1)\exp\left(-k_2\frac{T - T_g + \triangle T_1}{\triangle T_1 + \triangle T_2}\right), \quad T_g - \triangle T_1 \le T \le T_g + \triangle T_2 \tag{1}$$

When $T \le T_g - \triangle T_1$, the matrix is in solid state and E_m changes only slightly:

$$E_m(T) = E_m(T_r)\exp\left(-k_1\frac{T - T_r}{T_g - \triangle T_1 - T_r}\right), \quad T \le T_g - \triangle T_1 \tag{2}$$

For $T \ge T_g + \triangle T_2$, the matrix is in liquid or rubbery state and E_m has a very small value:

$$E_m(T) = 0.01E_m(T_r), \quad T \ge T_g + \triangle T_2 \tag{3}$$

where $T_g = 110$ °C, $T_r = 23$ °C, $\Delta T_1 = \Delta T_2 = 35$ °C, $E_m(T_r) = 3.35$ GPa, $E_m(T_r - \Delta T_1) = 0.7E_m(T_r)$, $E_m(T_r + \Delta T_2) = 0.01E_m(T_r)$, $k_1 = 0.35667$, $k_2 = 4.2485$.

(a) The thermal expansion coefficient α_m is assumed to change linearly with the temperature with a slope of

$$K = \frac{\alpha_1 - \alpha_m(T_r)}{T_g - T_r} \tag{4}$$

where $\alpha_m(T_r) = 58 \times 10^{-6}/°C$ and $\alpha_1 = 139 \times 10^{-6}/°C$. The tensile and compressive strength of the resin are taken to be 80 MPa and 120 MPa, respectively [5].

2.2. FEM model

How to obtain the microstructure of the composite with random fiber distribution and needed inter-fiber spacing is a critical problem. And this is the main concern of a previous work by the authors [28], in which a novel method named Random Sequential Expansion (RSE) algorithm was developed to generate random fiber distribution for composites. The algorithm uses inter-fiber distance as one of the main parameters and thus can conveniently control the minimal inter-fiber spacing. In the present paper, the RSE algorithm is employed to generate the representative volume element (RVE) of the composite with designated fiber volume fraction and minimal inter-fiber spacing. Two different fiber volume fractions, 50% and 60%, are chosen to illustrate the effect of fiber volume fraction on the thermal residual stress. And then for the fiber volume fraction of 60%, five different minimal inter-fiber spacing, i.e., 0.8 μm, 0.5 μm, 0.3 μm, 0.2 μm and 0.1 μm, are chosen to investigate the influence of inter-fiber spacing on thermal residual stress and transverse failure behavior of the composite. Shown in Fig. 1 are the generated microstructures with different fiber volume fractions and different minimal inter-fiber spacing.

FEM models are generated in ABAQUS/Explicit, which uses an explicit direct-integration procedure to overcome the convergence difficulty of numerical analysis. The fibers and matrix are meshed with predominantly 4-node bilinear plane strain quadrilateral, reduced integration elements (CPE4R) with hourglass control and a