Chinese Journal of Aeronautics, (2014),**27**(5): 1180–1187

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Determination of thermal expansion coefficients for unidirectional fiber-reinforced composites

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Received 3 September 2013; revised 13 November 2013; accepted 10 February 2014
Available online 19 March 2014

KEYWORDS

Analytical solution;
Coefficient of thermal expansion;
Thermo-elastic;
Transversely isotropic;
Unidirectional composites

Abstract In the present work, the coefficients of thermal expansion (CTEs) of unidirectional (UD) fiber-reinforced composites are studied. First, an attempt is made to propose a model to predict both longitudinal and transverse CTEs of UD composites by means of thermo-elastic mechanics analysis. The proposed model is supposed to be a concentric cylinder with a transversely isotropic fiber embedded in an isotropic matrix, and it is subjected to a uniform temperature change. Then a concise and explicit formula is offered for each CTE. Finally, some finite element (FE) models are created by a finite element program MSC. Patran according to different material systems and fiber volume fractions. In addition, the available experimental data and results of other analytical solutions of CTEs are presented. Comparisons are made among the results of the cylinder model, the finite element method (FEM), experiments, and other solutions, which show that the predicted CTEs by the new model are in good agreement with the experimental data. In particular, transverse CTEs generally offer better agreements than those predicted by most of other solutions.

1. Introduction

As we know, composite materials have been undergoing extraordinary technological advances and enjoying widespread applications in different fields. However, as a result of their complex properties, such as wettability, chemical compatibility, anisotropic mechanics, heat absorption and conductivity abilities, their complete characterization has not been achieved so far.

Coefficient of thermal expansion (CTE) is defined as the fractional change in length of a body under heating or cooling through a given temperature range,[1] and it is usually given as a coefficient per unit temperature interval at a given temperature. It is a key material property especially when a composite structure works in a temperature-changing environment. Here, the focus was placed upon on studying the longitudinal and transverse CTEs of continuous fiber-reinforced unidirectional (UD) composites.

The problem of relating effective properties of a fiber-reinforced material to its constituent properties has drawn great attention. As a result, many analytical solutions have been made to predict the upper and lower bounds of CTEs of UD composites, which are composed of isotropic or anisotropic

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2014.03.010
1000-9361

fibers and matrices.[2–12] In a series of studies by van Fo Fy,[3–5] analytical solutions were presented to predict both axial and transverse CTEs of a UD composite through its constituent properties. However, the results were very sensitive to the elastic modulus and Poisson's ratio of the UD material. Levin[6] expanded Hill's method and gave the upper bounds of a certain glass fiber-reinforced composite's CTEs, and the results were in much better agreement with the data in Van Fo Fy's study[3] than other predictions in that paper. Schapery[2] has derived expressions for longitudinal and transverse CTEs of composites with isotropic fibers embedded in isotropic matrices by adopting extreme energy principles. Sideridis[12] and Chamis[9] applied different methods and obtained the same longitudinal CTE expression, while the transverse expressions were quite different. In general, the predictions of longitudinal CTEs were always in good agreement with experimental data, while those of transverse CTEs failed to agree. An exception was Rosen and Hashin's prediction[10] as an extension of the work of Levin.[6] However, it is inconvenient to obtain results by Rosen and Hashin's solution, because to solve the CTEs of a composite, the mechanical properties of both the composite and its constituents must be determined first.

At the same time, as computation capability has grown dramatically over the last three decades, numerical solutions such as the finite element method (FEM) are being extensively applied to determine the CTEs of composite materials. Islam[13] and Rupnowski et al.[14] investigated the linear CTEs of UD composites systematically by the FEM. Karadeniz et al.[15] explored the CTEs of different material systems by micromechanical modeling using the FEM, and comparisons were carried out among their results, analytical solutions, and experimental data. However, discrepancies still exist between FEM results and experimental data.

Generally, the transverse CTE prediction of a UD composite was not as good as that of the longitudinal CTE. However, an exact transverse CTE of a UD composite is rather important in designing high-dimensional stable structures. Therefore, we tried to achieve a practical solution of CTEs by doing thermo-elastic analysis in this paper, especially the transverse CTE was paid much attention to. In addition, results of analytical solutions, the FEM, and experiments available in literatures were compared for justifications.

2. Theoretical analysis

2.1. Proposed model

The cross-section of a UD fiber-reinforced composite is shown in Fig. 1, and a typical representative volume element (RVE) could be a cylinder fiber embedded in a cube, in which the cylinder stands for the fiber, while the cube symbolizes the matrix.

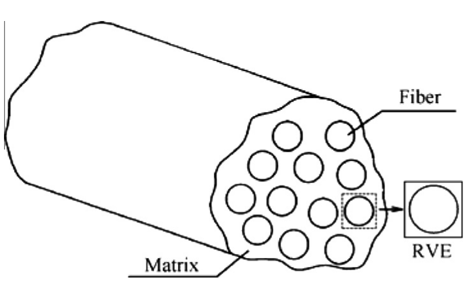

Fig. 1 Cross-section of UD fiber-reinforced composite.

To make this thermo-elastic analysis easier, the cubic RVE is transformed into a concentric cylinder model (see Fig. 2) according to the following assumptions: (1) both the cubic model and the cylinder model have the same fiber radius; (2) two models with the same fiber volume fraction; (3) two models with the same length in the longitudinal direction.

Consider that the radius of the fiber r_1, the fiber volume fraction V_f, and the length of the RVE h are all known.

The cross-section of the cubic model is defined by a circle with a radius of r_1 surrounded by a $2l \times 2l$ square (see Fig. 2(c)), while the new model is composed of two concentric cylinders with radii of r_1 and r_2 respectively (see Fig. 2(d)). The fiber contents in the two models are

$$V_{f(a)} = \frac{\pi r_1^2 h}{(2l)^2 h} = \frac{\pi r_1^2}{(2l)^2} \tag{1}$$

$$V_{f(b)} = \frac{\pi r_1^2 h}{\pi r_2^2 h} = \frac{r_1^2}{r_2^2} \tag{2}$$

According to the assumption, both models have the same fiber volume fraction V_f, that is

$$V_{f(a)} = V_{f(b)} \Rightarrow 2l = \sqrt{\pi} r_2 \tag{3}$$

When there is a change of r_2 by Δr_2, the strain in the transverse direction of the cubic model (see Fig. 2(a)) is

$$\varepsilon_{t(a)} = \frac{\Delta(2l)}{2l} = \frac{\sqrt{\pi}(r_2 + \Delta r_2) - \sqrt{\pi} r_2}{\sqrt{\pi} r_2} = \frac{\Delta r_2}{r_2} = \varepsilon_{t(b)} \tag{4}$$

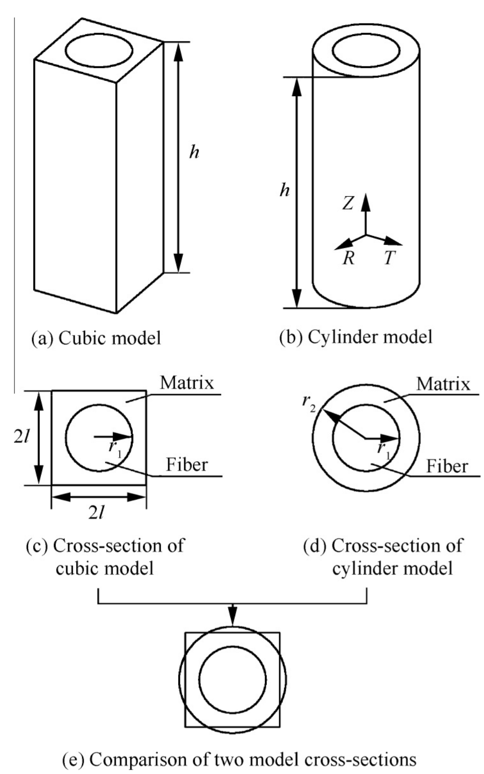

Fig. 2 Transformation of cubic model into cylinder model.