Available online at www.sciencedirect.com
SCIENCE DIRECT®
Composite Structures 74 (2006) 25–29
COMPOSITE STRUCTURES
www.elsevier.com/locate/compstruct

Mechanical characterization of the interfaces in laminated composites

Huiyu Sun *, Ning Pan

Department of Biological and Agricultural Engineering, University of California, Davis, CA 95616, USA

Available online 26 April 2005

Abstract

A new mechanical model representing the interfaces in laminated composites is proposed in this paper. The interfaces are treated as a three dimensionally anisotropic entity of distinct mechanical characteristics from both the bulk adhesives and the constitutional laminae in the composites. The classical composite laminate theory is generalized by including the interfaces (termed bonding-layers in this paper) as additional laminae in the composite system, thus establishing the basis for the analysis of the interface problem. Compared to existent three-dimensional models for the interfaces, the proposed approach is more convenient to acquire the mechanical parameters of the interfaces, avoiding complicated laboratory tests. A numerical example demonstrates the use of the method to give various mechanical properties of the interfaces in laminate composites, exhibiting the promises of the method in tackling the problems of strength and debonding for laminated composites.

Keywords: Laminate composites; Mechanical properties of interlaminar interfaces; Theoretical and numerical results

1. Introduction

The past few decades have seen tremendous advances in materials and structures technology. The increasing use of laminated composites in different branches of engineering stimulates advances in the analysis of this kind of materials. The bonding state at interfaces between two adjacent laminates clearly plays a critical role in determining the mechanical behavior of composite laminates. In most analytical and numerical work on composite materials, a perfect interface which implies the continuity of both displacements and tractions across this idealized interlaminar interface has been assumed. However, from a more rigorous physical point of view, the existence of a perfect interfacial bond in a real laminated composite seems impossible, since such an idealized interface cannot be delaminated. An appropriate model of composite laminates with imperfect interfaces should therefore be adopted as a more realistic approach to the study of laminates.

Literature indicates the interfaces in the analysis of composite laminates fall into two categories: two-dimensional interfaces with zero thicknesses, and three-dimensional interfaces. Desai et al. [1] proposed the existence of a thin solid interface, referred to as a thin-layer interface between structural and geological materials. The shear stiffness for the thin-layer was found from special laboratory tests and the normal stiffness was assumed to be composed of participations of the thin-layer interface and the adjoining solids. Hohberg and Schweiger [2] discussed the penalty behavior of thin-layer elements and explained certain locking phenomena observed in thin solids and layer elements. Mal et al. [3] studied the feasibility of using their developed ultrasonic technique to determine certain macroscopic properties of the interface zones of composite laminates. The thickness and elastic properties of the interlaminar interface zone in a cross-ply graphite–epoxy laminate were estimated by the proposed approach.

* Corresponding author. Tel.: +1 530 7528984; fax: +1 530 7527584.
E-mail address: hsun@ucdavis.edu (H. Sun).

0263-8223/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compstruct.2005.03.005

Allix and Ladevèze [4] used a two-dimensional entity to model interlaminar interfaces for the prediction of delamination initiation and growth in the case of static loadings. Schellekens and de Borst [5] carried out eigenmode analyses of the element stiffness matrices to assess the impact of the applied integration scheme on the stress predictions of two- and three-dimensional interface elements. It was demonstrated that large stress gradients over the element and coupling of the individual node-sets of the interface element might result in an oscillatory type of response.

Pandey and Sun [6] developed a non-linear viscous interlaminar interface model to describe the effect of interlaminar slip on the deformation of thermoplastic composite laminates subjected to processing conditions. Cheng et al. [7] introduced a spring-layer to model imperfectly bonded interfaces of multilayered composites. By modeling the composite laminates as a set of monolayers separated with zero-thickness adhesive interfaces, Bui et al. [8] investigated the effects of imperfect interlaminar interfaces on the overall mechanical behavior of composite laminates. Recently, Wang et al. [9] monitored interlaminar thermal damage in continuous carbon fiber polymer-matrix composites in real time during thermal cycling by measurement of the contact electrical resistivity of the interlaminar interface.

In this paper, an alternative approach is presented to characterize the mechanical behavior of composite laminate interfaces. The theoretical analysis is mainly based on the generalized composite laminate theory. The interface model proposed in this paper belongs to the category of three-dimensional ones, but the distinguishing feature of the model herein lies in the convenience of deducing the mechanical parameters for the interfaces using data obtained via convenient standard measurements, thus avoiding cumbersome laboratory tests.

2. Analysis

During laminated composite manufacturing, an adhesive (e.g., epoxy resin) is usually applied between unidirectional composite prepregs before the composite system is cured under pressure. A third phase thus forms at the interface between the two components (the lamina and the adhesive) where a certain amount of polymeric chain interpenetration occurs [10]. The molecular entanglements play a major role in the transfer of stresses. So we define the thin entity between the lamina and the adhesive as the interface, or more appropriately [10], the interphase. An example of the interphase is shown in Fig. 1(a).

The interphase between the lamina and the adhesive results from polymeric intermolecular interactions [11]. The mechanical characteristics of this interphase are different from those of either the bulk adhesive or the lamina. The effect of the interphase on the mechanical properties of the laminated composites is to be incorporated into the conventional composite laminate theory hereafter in order to more accurately represent the composite laminates.

Between two adjacent composite laminae, all the components including the two interphase layers and the pure adhesive between them can be treated as an equivalent layer termed herein the bonding-layer, as shown in Fig. 1(b), whose thickness can be determined by nondestructive and mechanical testing [12]. The properties of the bonding-layer in fact vary along its thickness dimension gradually from those of the lamina to those of the adhesive. However, for practice we ignore the gradient and focus on the average or the equivalent properties.

In order to determine the mechanical properties of this bonding-layer, the classical composite laminate theory is generalized here by considering the laminated composite as a system consisting of laminae and the bonding-layers. The assumptions for the classical laminate theory are still adopted in this paper, e.g., piecewise homogeneous material, linearly elastic deformation for a lamina and a bonding-layer, and perfect connection between a lamina and a bonding-layer.

For a laminate composite made up of m_k ($k = 1, 2, \ldots, n$) laminae with in-plane stiffness Q_{ij}^k in a reference coordinate system, it is reasonable to assume that the bonding-layers between the composite laminae are identically homogeneous material with equivalent

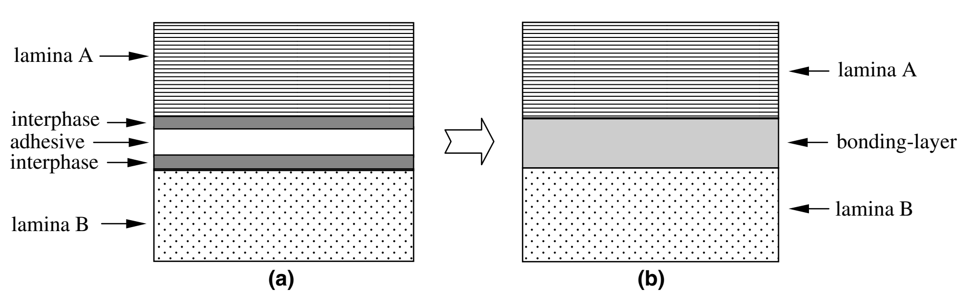

Fig. 1. Sketch of interphases and bonding-layers.

in-plane stiffness Q_{ij}^{b}. According to the composite laminate theory [13], the overall in-plane stiffness of the composite system Q_{ij}^{s} can be derived as

$$Q_{ij}^{s} = \frac{m_1 h}{h^s} Q_{ij}^{1} + \frac{m_2 h}{h^s} Q_{ij}^{2} + \cdots + \frac{m_n h}{h^s} Q_{ij}^{n} + \frac{h^b}{h^s} Q_{ij}^{b} \tag{1}$$

where the superscripts s and b denote the laminated composite system and the bonding-layers, respectively. So h^s is the total thickness of the composite system, h^b is the total thickness of the bonding-layers in the composite system. h is the thickness of each lamina. Because

$$\frac{(m_1 + m_2 + \cdots + m_n)h}{h^s} + \frac{h^b}{h^s} = 1 \tag{2}$$

Substituting (2) into (1) leads to

$$Q_{ij}^{s} = \left(1 - \frac{h^b}{h^s}\right) \frac{m_1 Q_{ij}^{1} + m_2 Q_{ij}^{2} + \cdots + m_n Q_{ij}^{n}}{m_1 + m_2 + \cdots + m_n} + \frac{h^b}{h^s} Q_{ij}^{b} \tag{3}$$

That is,

$$Q_{ij}^{s} - \frac{m_1 Q_{ij}^{1} + m_2 Q_{ij}^{2} + \cdots + m_n Q_{ij}^{n}}{m_1 + m_2 + \cdots + m_n} = \frac{h^b}{h^s} \left(Q_{ij}^{b} - \frac{m_1 Q_{ij}^{1} + m_2 Q_{ij}^{2} + \cdots + m_n Q_{ij}^{n}}{m_1 + m_2 + \cdots + m_n} \right) \tag{4}$$

Here $\frac{m_1 Q_{ij}^{1} + m_2 Q_{ij}^{2} + \cdots + m_n Q_{ij}^{n}}{m_1 + m_2 + \cdots + m_n}$ is the average stiffness properties of the laminae in relation to the reference coordinates, and $\frac{h^b}{h^s}$ is the thickness ratio of the total bonding-layers relative to the composite system. If Eq. (4) is divided by $\frac{m_1 Q_{ij}^{1} + m_2 Q_{ij}^{2} + \cdots + m_n Q_{ij}^{n}}{m_1 + m_2 + \cdots + m_n}$, then the normalized relationship between the mechanical properties of the bonding-layers and the whole composite system is obtained as follows:

$$\frac{Q_{ij}^{s}}{\frac{m_1 Q_{ij}^{1} + m_2 Q_{ij}^{2} + \cdots + m_n Q_{ij}^{n}}{m_1 + m_2 + \cdots + m_n}} - 1 = \frac{h^b}{h^s} \left(\frac{Q_{ij}^{b}}{\frac{m_1 Q_{ij}^{1} + m_2 Q_{ij}^{2} + \cdots + m_n Q_{ij}^{n}}{m_1 + m_2 + \cdots + m_n}} - 1 \right) \tag{5}$$

wherein Q_{ij}^{b} and Q_{ij}^{s} are normalized from being divided by the average stiffness properties of the laminae in the composite system, which are thus denoted by $\underline{Q}_{ij}^{b}$ and $\underline{Q}_{ij}^{s}$, respectively. So the formula (5) can be rewritten as

$$\underline{Q}_{ij}^{s} - 1 = \frac{h^b}{h^s} \left(\underline{Q}_{ij}^{b} - 1 \right) \tag{6}$$

The relationship between the two normalized parameters $\underline{Q}_{ij}^{s}$ and $\underline{Q}_{ij}^{b}$ is plotted in Fig. 2. It shows apparently that the normalized stiffness $\underline{Q}_{ij}^{s}$ of the composite system is in direct proportion to the normalized stiffness $\underline{Q}_{ij}^{b}$ of the bonding-layers. The proportionality factor is the thickness ratio $\frac{h^b}{h^s}$. All lines cross at the point (1, 1) as dictated by the Eq. (6). There are two extreme cases, where the thickness ratio $\frac{h^b}{h^s}$ approaches to 0 and 1, respectively. In fact, only the areas bounded by the two extreme lines are the allowable composite systems. Therefore, in the area on the right side of the point (1, 1), the two normalized stiffness parameters $\underline{Q}_{ij}^{s}$ and $\underline{Q}_{ij}^{b}$ are both greater than 1, indicating that stiffer bonding-layers of $\underline{Q}_{ij}^{b}$ reinforce the composite system. On the left side of Point (1, 1), however, the two normalized stiffness parameters are less than 1, meaning softer bonding-layers yield a softer composite system. Note all these are independent of the properties of the constituent laminae. Furthermore, when the thickness ratio $\frac{h^b}{h^s}$ is unity, this special case represents a system composed of bonding-layers only. When the thickness ratio $\frac{h^b}{h^s}$ is zero, i.e., the thickness of the bonding-layers vanishes, so that the normalized stiffness of the composite system remaining a constant 1, i.e., equal to that of the average stiffness properties of the laminae. This represents exactly the laminated composite without considering the effects of the bonding-layers on the composite system according to the classical laminate theory, revealing that the generalized composite laminate theory developed in this paper indeed depicts various cases for the effects of the bonding-layers on the laminate system.

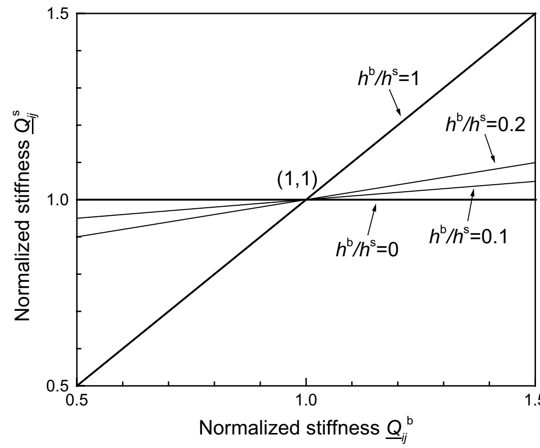

Fig. 2. Relationship between the normalized stiffness of the composite system and the normalized stiffness of the bonding-layers.

3. Numerical illustration

In this section, a numerical example is given to demonstrate how to get the mechanical properties of the bonding-layers by this generalized composite laminate theory using the simple testing data of the composite. The data used here are excerpted from the Ref. [14]

for a $[0_2, 90_2]_{2S}$ carbon/epoxy laminate composite system; the system tensile modulus is 73.39 GPa and the Poisson's ratio is 0.04, which were determined through more than six individual tests on the laminated composite. The mechanical properties of a single carbon/epoxy ply for the composite are as follows: $E_{11} = 142$ GPa, $E_{22} = 9.0$ GPa, $\upsilon_{12} = 0.32$.

From Formula (5), one can easily write

$$\frac{Q_{ij}^{\mathrm{b}}}{\frac{Q_{ij}^{(0)} + Q_{ij}^{(90)}}{2}} - 1 = \frac{\frac{Q_{ij}^{\mathrm{s}}}{\frac{Q_{ij}^{(0)} + Q_{ij}^{(90)}}{2}} - 1}{\frac{h^{\mathrm{b}}}{h^{\mathrm{s}}}} \tag{7}$$

Given the mechanical properties of the laminate composite system and each lamina with fibers oriented along 0° or 90° axis, the relationship between the stiffness Q_{ij}^{b} of the bonding-layers and their total thickness ratio $\frac{h^{\mathrm{b}}}{h^{\mathrm{s}}}$ can be obtained. Then, from the stiffness Q_{ij}^{b}, it is ready to get the mechanical characteristics of the bonding-layers sandwiched between the composite laminae.

$$E_{11}^{\mathrm{b}} = \frac{Q_{11}^{\mathrm{b}} Q_{22}^{\mathrm{b}} - Q_{21}^{\mathrm{b}} Q_{12}^{\mathrm{b}}}{Q_{22}^{\mathrm{b}}} \tag{8}$$

$$E_{22}^{\mathrm{b}} = \frac{Q_{11}^{\mathrm{b}} Q_{22}^{\mathrm{b}} - Q_{21}^{\mathrm{b}} Q_{12}^{\mathrm{b}}}{Q_{11}^{\mathrm{b}}} \tag{9}$$

$$G_{12}^{\mathrm{b}} = Q_{66}^{\mathrm{b}} \tag{10}$$

$$\upsilon_{21}^{\mathrm{b}} = \frac{Q_{21}^{\mathrm{b}}}{Q_{22}^{\mathrm{b}}} \tag{11}$$

$$\upsilon_{12}^{\mathrm{b}} = \frac{Q_{12}^{\mathrm{b}}}{Q_{11}^{\mathrm{b}}} \tag{12}$$

From Formulae (8)–(12), it shows that the bonding-layers do not necessarily behave as isotropic materials as expected for a layer of resin. For the specific example presented here, the overall bonding-layers are in fact an orthotropic material. Moreover, E_{11}^{b} is equal to E_{22}^{b} and $\upsilon_{21}^{\mathrm{b}}$ is equal to $\upsilon_{12}^{\mathrm{b}}$, that is, the overall bonding-layers behave the same along the two principal axes, the so-called balanced system. The properties of the bonding-layers are now the functions of the thicknesses only and the Young's modulus E_{11}^{b} and the Poisson's ratio $\upsilon_{21}^{\mathrm{b}}$ with the variation of the thickness ratio $\frac{h^{\mathrm{b}}}{h^{\mathrm{s}}}$ are shown in Fig. 3. For a given thickness ratio $\frac{h^{\mathrm{b}}}{h^{\mathrm{s}}}$, the corresponding mechanical properties of the overall bonding-layers can thus be determined.

4. Conclusions

A new method is put forward to characterize the mechanical properties of the interfaces in a laminate composite system. The classical composite laminate theory is generalized by taking account of the interfaces as additional layers (termed bonding-layers in the paper) included in the laminate system. The generalized laminate theory forms the basis for the analysis of the interface problem in laminate composites.

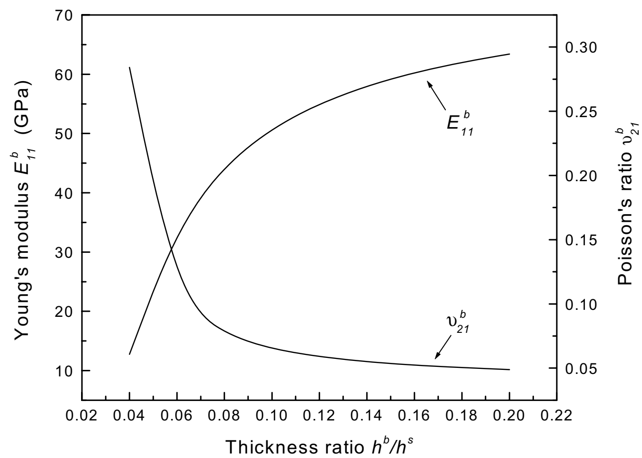

Fig. 3. Mechanical properties versus thickness ratio for bonding-layers.

The new method gives the relationship between the mechanical characteristics of the interfaces and their thickness ratio. As long as the mechanical properties of both the laminate system and the constituent laminae are known, the mechanical properties of the interfaces can be derived. Compared to the existing methods to determine the interface parameters experimentally, this approach avoids tedious laboratory experiments while provides reasonably accurate results.

This bonding-layer model for the interfaces in a laminate composite system can be improved, for instance by treating the bonding layer as a property gradient material, in order to more accurately describe the mechanical properties of the interfaces. It is believed that the bonding-layer model can be used to tackle such problems as the effects of the bonding-layers on the strength properties, interlaminar shear, debonding, and crack initiating and delaminating for laminate composites.

Acknowledgment

The financial support from the National Textile Center under the project F00-MD06 for the research work is greatly appreciated.

References

[1] Desai CS, Zaman MM, Lightner JG, Siriwardane HJ. Thin-layer element for interfaces and joints. Int J Numer Anal Meth Geomech 1984;8:19–43.

[2] Hohberg J-M, Schweiger HF. On the penalty behaviour of thin-layer elements. In: Pande GN, Pietruszczak S, editors. Numerical models in geomechanics: Proceedings of the fourth international symposium on numerical models in geomechanics, Swansea, UK, August 1992. p. 24–7.
[3] Mal AK, Karim MR, Bar-Cohen Y. Determination of the properties of composite interfaces by an ultrasonic method. Mater Sci Eng A 1990;126(1–2):155–64.
[4] Allix O, Ladevèze P. Interlaminar interface modelling for the prediction of delamination. Compos Struct 1992;22:235–42.
[5] Schellekens JCJ, de Borst R. On the numerical integration of interface elements. Int J Numer Meth Eng 1993;36:43–66.
[6] Pandey RK, Sun CT. Deformation of thermoplastic composite laminates under processing conditions. Mech Compos Mater Struct 1996;3:183–200.
[7] Cheng Z-Q, Jemah AK, Williams FW. Theory for multilayered anisotropic plates with weakened interfaces. ASME J Appl Mech 1996;63:1019–26.
[8] Bui VQ, Marechal E, Nguyen-Dang H. Imperfect interlaminar interfaces in laminated composites: bending, buckling and transient responses. Compos Sci Technol 1999;59:2269–77.
[9] Wang S, Mei Z, Chung DDL. Interlaminar damage in carbon fiber polymer-matrix composites, studied by electrical resistance measurement. Int J Adhes Adhes 2001;21(6):465–71.
[10] Richards RW, Peace SK, editors. Polymer surfaces and interfaces III. Chichester, NY: John Wiley & Sons Ltd.; 1999. p. 104.
[11] Ghatak A, Vorvolakos K, She H, Malotky DL, Chaudhury MK. Interfacial rate processes in adhesion and friction. J Phys Chem B 2000;104:4018–30.
[12] Desai CS. Mechanics of materials and interfaces: the distributed state concept. Boca Raton, FL: CRC Press LLC; 2001. p. 425–7.
[13] Agarwal BD, Broutman LJ. Analysis and performance of fiber composites. 2nd ed.. New York: John Wiley & Sons Inc.; 1990.
[14] Chen AS, Matthews FL, Sims GD. The effect of support conditions on the performance of CFRP plates subjected to biaxial flexure. Compos Sci Technol 1998;58:613–21.