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Measurement of fiber reinforced composite engineering constants with laser ultrasonic

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ABSTRACT

In this paper, a noncontact laser ultrasonic method is proposed to determine the engineering constants of fiber reinforced composite. The method is based on the measurements of the transverse wave velocities as well as the longitudinal wave velocities. In the experiment, the unidirectional carbon fiber reinforced bismaleimide resin matrix composite is measured and the sample is equivalent to a transversely isotropic material. Two longitudinal wave propagation velocities and three transverse wave propagation velocities in two specific directions are measured, respectively. On this basis, all five independent elastic constants can be obtained according to the Christoffel equation. In the finite element analysis, the model of laser induced ultrasonic in the composites is established. The pulsed laser is equivalent to the surface load and the relationship between the physical parameters of the laser and the load is established by the correction coefficient. The numerical results match well with experimental measurements, which show that the method presented in this paper can achieve an accurate measurement of the elastic constants of fiber reinforced composite.

1. Introduction

Fiber reinforced composites have been widely used in various fields of industry because of their superior mechanical properties. The key characteristics of fiber reinforced composites are their high stiffness to weight ratio and strength to weight ratio. The anisotropy property of stiffness and strength allows the materials to be used in a given direction without increasing the extra weight. However, it is very difficult to measure the mechanical properties of the composite materials due to their complicated structure and composition. With traditional mechanical testing methods, elastic modulus of symmetric axes in different fiber reinforced composites must be determined by different uniaxial tests. The measurement of the shear modulus of the fiber reinforced composites is even more difficult. Moreover, traditional testing methods are complicated, time consuming, and prone to induce damages to the materials. Thus, the traditional measurement is not suitable for harsh environments, such as high-temperature, radioactive, and toxic condition.

Laser ultrasonic technique has several advantages, including noncontact, high-precision, non-destructive [1–5]. In recent years, laser ultrasonic has been widely used in defect detection [6,7], residual stress measurement [8,9] and elastic constants measurement for isotropic materials [10,11]. Since fiber reinforced composite materials are anisotropic in nature, the traditional mechanical and ultrasonic approach for measuring material constants in isotropic materials cannot obtain all of the anisotropic elastic constants. In the literature, there are extensive researches related to the application of ultrasonic in composite materials. Chimenti [12] analyzed the ultrasonic leaky lamb wave propagation in fiber reinforced, unidirectional composite laminates through the experimental measurement and the theoretical calculation method. Wu and Chiu [13] used the experimental method to study the propagation of horizontally polarized shear waves in a unidirectional thin fiber reinforced composite plate. Wu and Liu [14] utilized conventional ultrasonic methods to determine anisotropic elastic constants and three elastic constants of fiber reinforced composite plate experimentally. Audoin [15] utilized longitudinal and transverse waves to measure four coefficients of the stiffness tensor of a balanced composite material which was described by six coefficients. The effect of temperature on the anisotropy of the material was considered. Li et al. [16] studies the dependence of the longitudinal and transverse acoustic-wave velocities on reinforcement sizes and volume fractions in the short fiber and particle reinforced composites by a laser ultrasound technique. Materials were considered as isotropic and two independent constants were discussed. Veidt and Sachse [17] measured four elastic constants of thin

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fiber reinforced laminates using the laser ultrasonic technique. The experimental group velocity data was analyzed using a simple plane-wave, plane-stress model that described the propagation of quasi-longitudinal and quasi-transverse membrane waves. These works paved a way to apply ultrasonic in composite materials measurement, but the problem of high efficiency and precision detection of composite engineering constants still remains to be solved.

In this paper, a simple and practical laser ultrasonic method is proposed to determine the elastic constants of a fiber reinforced composite plate. The material is equivalent to a transversely isotropic material and all five independent elastic constants are obtained by measuring longitudinal and transverse wave propagation velocities in two specific directions. Then, the finite element analysis model of laser induced ultrasonic in the transversely isotropic composite is established. The pulsed laser is equivalent to the surface load which has the same distribution function as the laser in the time and space domain. The experimental results match well with the numerical results. It is indicated that the experimental and finite element methods presented are very effective for the study of laser ultrasonic in composites.

2. Theoretical basis

For an anisotropic linear elastic material with no body force, the equations of motion can be expressed as:

$$C_{ijkl}\frac{\partial^2 u_i}{\partial x_j \partial x_l} = \rho\frac{\partial^2 u_i}{\partial t^2} \tag{1}$$

where C_{ijkl} is the elastic constant, u_i is the wave displacement and ρ is the density of the material which is considered as a known parameter. The plane wave propagating in the medium can be expressed as:

$$u_i = U_i \exp[ik(n_j x_j - Vt)] \tag{2}$$

where U_i,k,n_j and V is the amplitude, wave number, wave normal and the propagation velocity of the plane wave, respectively. On substituting Eq. (2) into Eq. (1), the amplitude and the propagation velocity of the plane wave must satisfy the following equations:

$$(C_{ijkl} n_j n_l - \rho V^2 \delta_{ik})U_k = 0 \tag{3}$$

The above equation is called Christoffel equation [18]. The necessary condition for the amplitude U_k to have nonzero solutions is that the determinant is equal to zero:

$$|C_{ijkl} n_j n_l - \rho V^2 \delta_{ik}| = 0 \tag{4}$$

When the material is orthotropic and the planes of orthotropic symmetry are taken as the coordinate planes, it is easy to find that for plane waves propagating in the direction of the axis of orthotropic symmetry, three longitudinal and three transverse waves exist. We define V_{ij} as a wave propagating along the x_i axis direction with polarization in the direction of the x_j axis, then the six wave velocities can be expressed with a symmetric elastic constant matrix:

$$[\rho V_{ij}^2] = \begin{bmatrix} C_{11} & C_{66} & C_{55} \\ C_{66} & C_{22} & C_{44} \\ C_{55} & C_{44} & C_{33} \end{bmatrix} \tag{5}$$

where the elastic constants have been written in Voigt's contracted notation, in which 23 is replaced by 4, 31 by 5, 12 by 6, and 11 by 1.

The experimental sample is a unidirectional carbon fiber/bismaleimide resin composite plate which can be simplified as transversely isotropic symmetry. The independent elastic constants are reduced from nine for orthotropic material to five. The problem is further simplified so that it is possible to inverse the engineering constants of fiber reinforced composite using laser ultrasonic technique. As shown in Fig. 1, the x_1 axis is defined along the fiber direction, and the x_2–x_3 plane is the isotropic plane, the elastic constants retained are as follows:

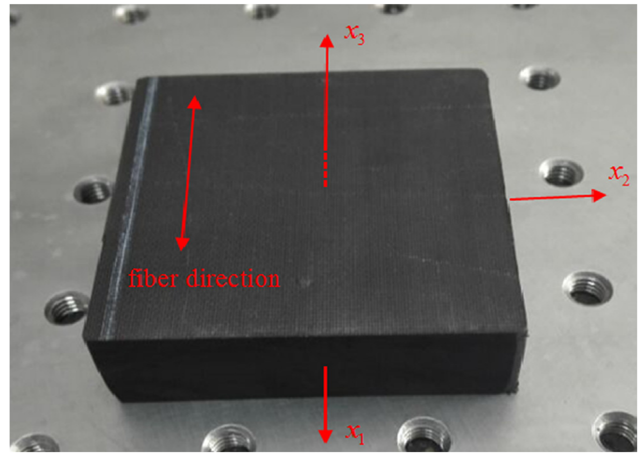

Fig. 1. The unidirectional carbon fiber reinforced composite plate.

$$[C_{ij}] = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{33} & C_{23} & 0 & 0 & 0 \\ C_{12} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{55} \end{bmatrix} \tag{6}$$

where $C_{44} = (C_{33} - C_{23})/2$, so the elastic matrix has five independent constants. The flexibility matrix **S** is defined as the inverse matrix of the elastic constant matrix. The elements of flexibility matrix can be represented by engineering constants of unidirectional fiber reinforced composite plate [19].

$$[S_{ij}] = [C_{ij}]^{-1} = \begin{bmatrix} 1/E_1 & -\nu_{12}/E_2 & -\nu_{12}/E_2 & 0 & 0 & 0 \\ -\nu_{21}/E_1 & 1/E_2 & -\nu_{22}/E_2 & 0 & 0 & 0 \\ -\nu_{21}/E_1 & -\nu_{22}/E_2 & 1/E_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{22} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{12} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{bmatrix} \tag{7}$$

where $G_{22} = E_2/2(1+\nu_{22})$, $E_1\nu_{12} = E_2\nu_{21}$, E_1 and E_2 are the elastic modulus of the fiber direction and transversely isotropic plane, ν_{12} and G_{12} are Poisson's ratio and shear modulus in the anisotropic plane, ν_{22} is Poisson's ratio in isotropic plane.

The pure longitudinal and transverse wave modes exist when the propagation direction is along or perpendicular to the fiber direction in fiber reinforced composite plate. For all the other propagation directions, the ultrasonic modes are quasi-longitudinal and quasi-transverse. Therefore, two longitudinal wave velocities (V_{11}, V_{33}) and three transverse wave velocities (V_{12}, V_{31}, V_{32}) are measured. V_{11} and V_{12} are measured when the excitation points and receiving points are respectively arranged on the front and back surface along x_1 direction. V_{33}, V_{31} and V_{32} are measured when the excitation points and receiving points are respectively arranged on the top and bottom surface along x_3 direction. The relationship between the propagation velocity of laser induced ultrasonic and the elastic constants of fiber reinforced composite plate can be obtained from Eq. (5) as:

$$V_{11} = \sqrt{\frac{C_{11}}{\rho}}, V_{12} = \sqrt{\frac{C_{12}}{\rho}}, V_{31} = \sqrt{\frac{C_{55}}{\rho}}, V_{32} = \sqrt{\frac{C_{44}}{\rho}}, V_{33} = \sqrt{\frac{C_{33}}{\rho}} \tag{8}$$

It can be seen from Eq. (8) that the five independent elastic constants can be obtained by measuring the propagation velocities of ultrasonic using laser ultrasonic technique. Then the engineering constants of transversely isotropic material can be obtained according to Eqs. (6) and (7).