Composite Structures 141 (2016) 24–31

Contents lists available at ScienceDirect

Composite Structures

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

Determination of the elastic properties of woven composite panels for Lamb wave studies

W.H. Ong [a,*], N. Rajic [b], W.K. Chiu [a], C. Rosalie [b]

[a] Department of Mechanical and Aerospace Engineering, Monash University, Wellington Rd, Clayton, VIC 3800, Australia
[b] Defence Science & Technology Group (DSTO), 506 Lorimer St, Fishermans Bend, VIC 3207, Australia

ARTICLE INFO

Article history:
Available online 18 January 2016

Keywords:
Woven composite
CFRP plate
Lamb wave simulation
Elastic properties

ABSTRACT

Typically, numerical simulations of Lamb wave propagation are done using material properties which originate from tensile testing. This approach is well established in relation to isotropic homogenous structures such as aluminium plates. However if this approach is used for woven composites such as carbon fibre reinforced plastics (CFRP), inaccuracies can arise that stem from vastly different stress distributions, strain rates and amplitudes during Lamb wave propagation. In order to account for this, an approach is presented where the elastic properties in a numerical Lamb wave model are optimised to achieve good correlation between model predictions and experimental observations. Since the material properties are determined under a Lamb wave propagation regime, the strain rates and amplitudes are consistent with the intended modelling application. The approach is validated with an experimental case study involving a M18/G939 carbon-epoxy system. The methodology is shown to yield property estimates that furnish simulations that closely match observed behaviours. The optimised properties were significantly different to those supplied by the manufacturer, as much as 52% for the in-plane stiffness. The findings demonstrate that large errors are possible if elastic properties determined using conventional quasi-static testing are used in Lamb wave simulations pertaining to woven composite materials.

1. Introduction

Composite materials such as woven carbon fibre reinforced plastics (CFRP) have become increasingly prevalent in aerospace applications. Lamb wave based methodologies are an important class of monitoring technique that can be used to monitor defects in these structures. In determining the efficacy of Lamb wave based methodologies, numerical simulations are relied upon for predictions and insight. The majority of studies in the literature address isotropic materials such as aluminium [1–6]. When modelling the propagation of Lamb waves in such media, the widely practiced approach is to rely on elastic properties obtained from published material data. In most cases such a result yields acceptable levels of simulation accuracy. For example, Ong et al. [7] presented a set of dispersion curves derived from measured multi-modal Lamb waves in an aluminium test plate over a frequency bandwidth between 200 kHz and 1000 kHz. They reported excellent agreement between the experimental results and theoretical predictions from DISPERSE [8]. The elastic constants used for the aluminium plates were selected from the DISPERSE material library which is similar to that available in finite element software.

The literature shows that using published material properties can be a valid approach when applied to composite panels made from unidirectional laminates. Ng C-T [9] presented a set of results on the numerical modelling of Lamb waves in composite plates made from unidirectional material. Adequate agreement with their experimental data was achieved by using engineering constants from constituent fibre and resin materials to evaluate the equivalent material properties using micromechanics theory. Similarly, Li et al. [10] also achieved good agreement with the use of material properties determined using mechanical tests in their dynamic Lamb wave simulations.

To date, there is limited work reporting on the Lamb wave dispersion characteristics of composite plates made from woven CFRP. An accurate set of elastic properties of woven composite plate is essential for an adequate theoretical prediction of the Lamb wave dispersion characteristics in this material. Unlike composite plates made from unidirectional fibres, woven composites are characterised by the weave parameters. Naik [11] reported that the stiffness of woven composite panels is governed by weave parameters such as weave architecture, yarn sizes, yarn spacing and yarn crimp. The concept of the repeating unit cell (RUC) was

* Corresponding author.
E-mail address: wern.ong@monash.edu (W.H. Ong).

http://dx.doi.org/10.1016/j.compstruct.2015.12.017
0263-8223/

used to help define the elastic properties of woven composites [12]. Gommers et al. [13] applied a similar RUC concept to determine the elastic properties of knitted fabric reinforced composites. The inherent difficulties in determining the elastic properties of woven material are highlighted in these works. Gommers et al. [13] showed large discrepancies between the experimentally obtained and predicted values of Young's modulus in a woven composite when using Voigt and Reuss methods [14].

It is known that the Lamb wave modes supported by a test plate can have length-scales that are comparable to the RUC of a woven composite plate [15]. Poe et al. [16] reported a strain gauge length less than the RUC length can return a modulus up to 17% different to that measured by extensometer or longer gauge lengths. This suggests that woven composites have small scale stiffness inhomogeneities; an observation that is supported by the literature [17–19]. Mishra [19] illustrates this with finite element modelling showing substantial stress and strain variations within a RUC under simple tensile loading.

Malcolm et al. [20] recognised that although the fibre waviness in woven composites can reduce the modulus under initial loading, the straightening of the wavy fibre tow will lead to an increase in the modulus with increasing tensile loading. In compression, the modulus of a woven composite is expected to be lower than a laminated unidirectional fibre composite due to fibre waviness. This infers that the elastic modulus at very low loads will be dependent on the applied force supported by the material. Given that the strain levels associated with Lamb waves are small, it can be inferred that using the elastic modulus of a woven composite plate determined from quasi-static tensile testing for the simulation of Lamb wave propagation may lead to significant errors (see Ong et al. [15]). For predictive Lamb wave modelling, a more reasonable approach is to determine the elastic constants using a loading regime that more closely matches the strain rates and strain amplitudes of Lamb wave propagation.

This paper reports on the development of a method to determine the elastic properties in a woven CFRP composite plate. The proposed method employs a numerical model and particle swarm optimisation (PSO) [21]. The PSO is a stochastic optimisation technique based on the movement of swarms. Prior to this study, a verification of the PSO was performed on aluminium. The results from that study are described in Ong et al. [7]. Optimisation of the material properties is achieved by comparing outputs from the numerical model against experimental data for a particular Lamb wave propagation regime. This ensures the optimised properties are relevant to Lamb wave simulation.

The paper begins with a brief explanation of some experimental details including the structure of the composite specimen and the method used to determine the dispersion curves for the first four modes. This data is used to illustrate the inaccuracies in the published material properties. A brief explanation of the PSO is presented along with descriptions of the finite element model and objective function. The optimised material properties are then applied to simulations that are compared to experimental observations.

2. Specimen and measurement of properties

The composite specimen was fabricated using Hexcel M18 prepreg with woven carbon G939 fabric. The plate to be characterised comprised 16 plies in the layup [0/90, ±45, ±45, 0/90, 0/90, ±45, ±45, 0/90]$_s$. Such a sequence leads to a quasi-isotropic structure. After curing, the plate was trimmed to a planar dimension of 400 mm × 400 mm. A Ø10 mm × 1 mm thick Ferroperm piezoceramic disc of type Pz27 was placed at the centre of the plate as shown in Fig. 1.

Hexcel [22] quotes a nominal ply thickness of 0.227 mm, which implies a 3.63 mm final plate thickness for 16 plies. Measurements taken on the plate edges differed from this nominal value, revealing an uneven thickness. Additional measurements were taken across the plate using a dial indicator and precision surface block. The thickness of the plate was measured along the lines indicated in Fig. 1. The thickness profiles for each line are shown in Fig. 2. The plate centre was approximately 4.4 mm thick, while the thickness approached 3.9 mm at the edges. The thickness profile data was used to calculate the volume of the plate which was used in combination with a measurement of the plate mass to calculate the material density (1434 kg/m^3). Fig. 3 defines the RUC of the material, which in the present case was approximately 7.6 mm × 7.6 mm.

The initial properties are summarised in Table 1 and consist of the published in-plane modulus from the manufacturer and general woven CFRP properties for the remainder. Note ν_{23} is the "minor" Poisson's ratio and is related to the "major" Poisson's ratio ν_{13} by the relation shown in Eq. (1) such that there are only 4 independent properties. These properties are used as the initial estimate for the optimisation problem described later in the paper. The coordinate system used in defining the properties is shown in Fig. 4.

$$\nu_{23} = E_{22}\frac{\nu_{12}}{E_{11}} \quad (1)$$

3. Laser vibrometry test facility

The dispersion curves of the test plate were calculated from data acquired using a laser vibrometry (LV) facility described in detail in [1,2]. The piezoceramic disc bonded to the plate was made to actuate Lamb waves by applying a 50 V peak-peak drive signal from a Krohn-Hite 7602 amplifier. Out-of-plane displacements associated with the Lamb waves were detected on the plate surface by a Polytec OFV 505 laser vibrometer. The positioning of the laser vibrometer relative to the plate was controlled by a stepper-motor driven high resolution X–Y table, set to 5000 steps per mm.

To obtain the reference dispersion curves, the plate was scanned along the 0° line shown in Fig. 1. The number of points scanned on this line resulted in a spatial resolution of 0.215 mm which is approximately a factor of ten shorter than the shortest wavelength studied. Multiple data sets were captured along this

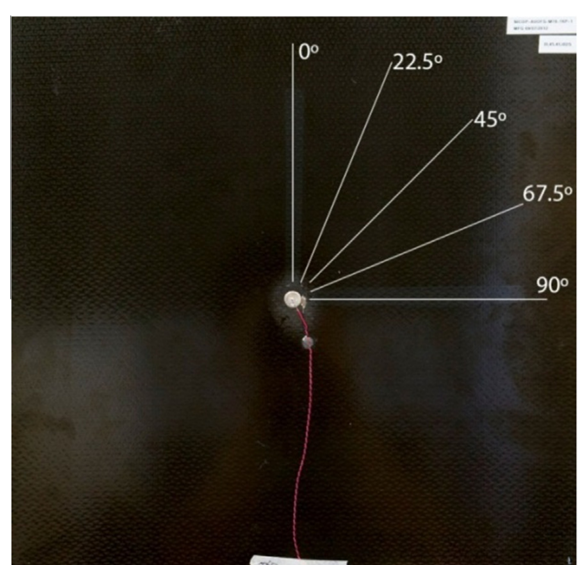

Fig. 1. Photograph of specimen showing scan lines.