International Journal of Adhesion & Adhesives 71 (2016) 28–38

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

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

Adhesive material property evaluation for improved Lamb wave simulation

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:
Accepted 3 August 2016
Available online 26 August 2016

Keywords:
FM300
Film adhesive
Material property
Lamb wave
Numerical simulation

ABSTRACT

Lamb waves are commonly modelled in isotropic metals such as steel and aluminium which have well-known published properties. When attempting to model Lamb waves in polymer materials with viscoelastic properties such as epoxy adhesives, it is not sufficient to rely on published properties which are usually based on quasi-static mechanical testing. This is due to Lamb waves creating an elastic disturbance with a relatively low strain amplitude but high strain rate. Unlike in metals, the modulus of a viscoelastic material is dependent on strain rate. Therefore to accurately model the behaviour of Lamb waves in polymers, the properties of the host structure must be obtained using methods that reproduce the strain amplitudes and strain rates of the intended application. This paper presents an investigation of three ultrasonic methods for determining the material properties of a film adhesive. It is found that the elastic modulus required to accurately model Lamb waves in this adhesive is approximately 60% higher than the value determined by conventional quasi-static testing. Finally, a Lamb wave simulation is used to illustrate that such discrepancies can lead to significant differences in the scattered wave field from a bond-line defect.

1. Introduction

Lamb wave based structural health monitoring (SHM) technologies have the potential to radically improve the efficiency and effectiveness of inspections of structural fatigue [1] and other forms of structural damage in engineering assets. Lamb waves can propagate across plate structures, allowing them to inspect large areas. Lamb waves can propagate in two distinct modes (symmetric and antisymmetric) relative to the thickness plane of the plate. There are an infinite set of each mode type that can exist in a plate. Some of the modes can be sensitive to structural inhomogeneities and give rise to scattering and mode conversion. An understanding of these interactions for a given structural application can be obtained either empirically, analytically or by numerical modelling with the latter generally the most versatile and powerful. Typical implementations include finite element analysis (FEA) [2,3], local interaction simulation approach (LISA) [4,5] and spectral element method (SEM) [6]. The literature contains numerous examples of the successful application of FEA to model Lamb waves for structural inspection [3,7–10] in metallic structures. One of the fundamental requirements for an accurate predictive model is a precise set of elastic properties. Typically, elastic properties reported by manufacturers are determined from static testing. This has been shown to be sufficient when modelling the propagation of Lamb waves in metallic structures by Ong et al. [11] and also Ambrozinski et al. [12]. During the study dispersion curves generated using static material properties could be matched to experimentally measured dispersion characteristics. Similarly, Ambrozinski et al. [12] showed that ultrasonically obtained Young's modulus for aluminium was within 1% of that obtained using a quasi-static 3 point bending test.

In contrast, relying on statically determined elastic properties for viscoelastic materials such as adhesives can lead to significant error due to strain rate sensitivity. Rocheford and Brinson [13] conducted stress-strain measurements on FM-300 over a time period of 1, 10 and 30 min with each returning a different elastic modulus. The fastest measurement (1 min) returned the highest modulus. Similarly, Gilat et al. [14] found PR-520 epoxy had a Young's modulus of 3.54 GPa at 1.76 min^{-1} strain rate and 7.18 GPa at 420 min^{-1} strain rate. Therefore it is expected that modelling of high strain rates occurring during Lamb wave propagation in film adhesives, will require a higher modulus [13–17] when compared to static structural modelling. For this reason, Maheri and Adams [18] resorted to empirical relationships to model adhesives under dynamic loading. Therefore, the properties must be determined under experimental conditions that are appropriate to the

---

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

http://dx.doi.org/10.1016/j.ijadhadh.2016.08.008
0143-7496/

propagating Lamb wave in the adhesive layer. This potential difference in properties is highlighted by Ong et al. [11] where published properties originating from static testing were used to predict the dispersion curves for a composite plate. When the prediction was overlaid on measured dispersion curves, a 25% error in wavenumber was observable. While a composite plate differs from a film adhesive, the work is still relevant as the epoxy matrix in a composite also has viscoelastic properties.

Using statically derived properties when performing numerical studies can have widespread consequences on the predictive capability since bonded joints which employ film adhesives are commonly used in many aircraft structures. As noted by Lowe et al. [19], the transmission of Lamb wave across adhesively bonded joints has important industrial relevance. A good understanding of the science behind this phenomenon is crucial for the development of techniques for the inspection of adhesively bonded metal and composite joints. Work reported by Francesco and Rizzo [20] showed that the transmission coefficient of Lamb waves propagating across bonded lap-shear joints is affected by the elastic properties of the adhesive forming the joint. In their study, it was shown that the transmission coefficient across the bond was highly sensitive to whether the bond was fully or poorly cured which is closely related to the adhesive modulus.

In order to obtain the appropriate properties for modelling Lamb wave propagation in bonded joints, it is proposed that the material properties should be determined under ultrasonic excitation. Several methods have been published for this task. Spencer et al. [21] presented a time domain method which was used to fit the waveform from a model to an experimental target waveform by optimisation of the model's material properties. Similarly, Ambroszinski et al. [12] and Ong et al. [22] have presented frequency domain methods which iteratively optimise material properties in a model until the output dispersion curves match their experimental target. The present paper follows in the footsteps of these publications and examines three ultrasonics based methodologies for estimating the stiffness of structural epoxy adhesive. The main subject of the investigation is FM300-2K, a high performance epoxy film adhesive commonly used for secondary bonding applications in aerospace, although the methodologies proposed in this paper are applicable more generally.

The first method of determining the elastic properties of the adhesive relies on the propagation of bulk waves in a monolithic block of adhesive (i.e. in its bulk form). This is based on the work by Burst and Adams [23] who reported that the material properties of structural adhesives obtained in bulk form are valid for use in structural analysis of in-situ thin-film adhesives. The second method involves the use of a plate made from a sheet of adhesive. In both methods, the adhesive is unconstrained in the sense that it is not adhered to a substrate like in a bonded joint, nor is it consistent in thickness to a typical bond line. To assess whether such details are significant factors in the determination of elastic properties for Lamb wave modelling, a third method was developed. In this method the elastic properties of the film adhesive are derived indirectly from a Lamb wave transmission spectrum measured on an aluminium sample with a thin layer of epoxy. Prior to investigating these methods, the elastic properties of the subject material (FM300-2K) were determined using a standard quasi-static method. This was done with two main purposes in mind: (i) to establish a baseline, and (ii) to validate the elastic properties listed by the manufacturer, which in turn would provide assurance in the manufacturing process.

2. Property evaluation methods

Three different types of specimens: a monolithic block, a thin monolithic sheet and a metallic plate with a surface bonded strip of epoxy, were manufactured. All three were produced in an autoclave using a consistent cure cycle that conformed to the manufacturer's recommendations. However, the precise details of manufacture varied slightly between the specimen types; those details are discussed in the relevant subsections.

2.1. Quasi-static testing method

In this method, three narrow strips were cut from a thin monolithic sheet of epoxy using a milling machine. Each strip was fitted with a strain gauge and subjected to a tensile test using a mechanical testing machine as shown in Fig. 1. The tensile machine was set to stretch the specimen at a rate of 0.5 mm/min ensuring a low strain rate of 0.142 min^{-1}. The force applied was logged using a 1 kN load cell and the cross sectional area was measured using digital callipers to evaluate the stress in the specimen. Fig. 2 shows the result from the stress-strain data logging

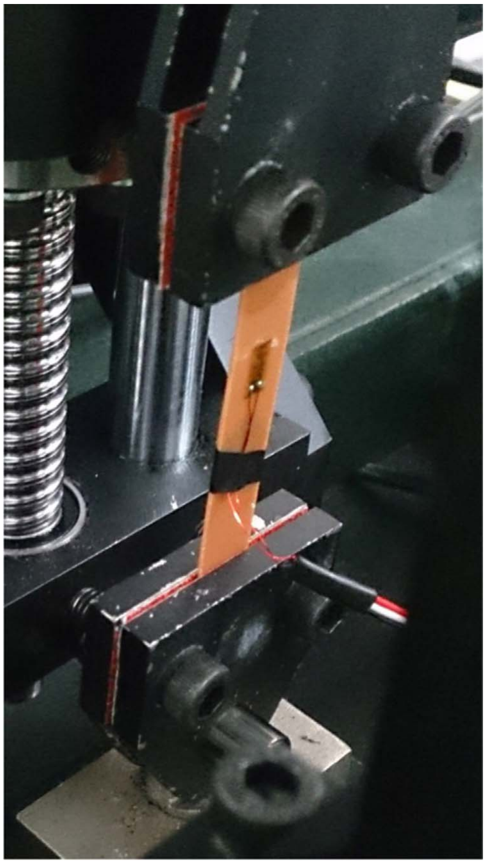

Fig. 1. FM300-2K specimen with strain gauge attached in tensile machine.

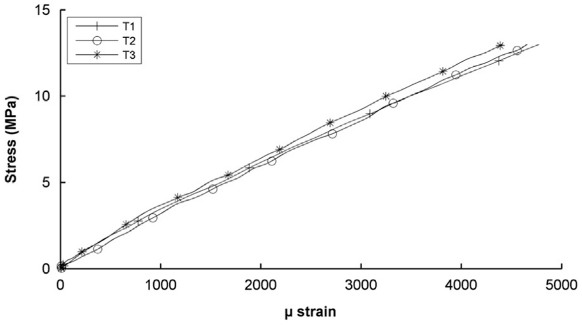

Fig. 2. Stress–strain curves from tensile testing FM300-2K specimens.