Polymer Testing 44 (2015) 143–152

Contents lists available at ScienceDirect

Polymer Testing

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

Test method

# Comparison of laminate stiffness as measured by three experimental methods

Kaspar Lasn [a, b, *], Andreas T. Echtermeyer [b], Aleksander Klauson [a], Farid Chati [c], Dominique Décultot [c]

[a] Department of Mechanics, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia
[b] Composites and Polymers, Department of Engineering Design and Materials, Norwegian University of Science and Technology, Richard Birkelandsvei 2B, N-7491 Trondheim, Norway
[c] Laboratoire Ondes et Milieux Complexes – UMR CNRS 6294, Université du Havre, 75 rue Bellot, 76085 Le Havre, France

ARTICLE INFO

*Article history:*
Received 27 February 2015
Accepted 13 April 2015
Available online 22 April 2015

*Keywords:*
Composite laminates
Mechanical properties
Non-destructive testing
Vibration testing
Ultrasonics

ABSTRACT

Three independent stiffness measurement techniques are applied to characterize virgin glass fiber laminates. Natural frequency based measurements of laminate stiffness are compared to results from simple quasi-static testing and Lamb wave dispersion curves. Genetic algorithm (GA) and a modified two-stage Simplex optimization are employed to solve parameter identification inverse problems. The two-stage Simplex method is shown to converge to similar solutions as global genetic algorithms for Lamb wave optimization. The identified elastic and shear moduli show very good agreement, confirming the feasibility of these methods for material characterization. Poisson's ratios on the other hand were not reliably obtained from these two indirect methods due to low sensitivity.

## 1. Introduction

Stiffness is a fundamental material property and is typically measured from quasi-static testing on unidirectional specimens. The material is tested in different directions to obtain the full set of orthotropic elastic constants. Properties of composite laminates with fibers running in different directions can, subsequently, be calculated by laminate theory. If no material damage is present, the stiffness of a composite material is determined solely by its intrinsic properties.

Various non-destructive test methods can identify laminate stiffness indirectly, i.e. not by directly measuring the force-deformation response. These techniques can be divided into wave propagation and vibration based categories. Waves propagating along plate-like waveguides are commonly referred as Lamb waves, after the discoverer of these phenomena. High frequency (hundreds of kilohertz), dispersive phase velocities of Lamb waves are measured along different composite plate directions. Vibration based methods employ periodic, low frequency structural movements, typically up to a few thousand hertz. When testing at similar temperature and humidity, the main difference between static, vibration and Lamb wave methods is due to the strain rate and maximum strain applied to the specimens. This potentially creates issues for characterizing materials with viscous properties or with non-linear stress-strain curves.

Through thickness bulk wave measurements [1] or vibrating beam tests [2,3] are commonly used for isotropic materials, revealing stiffness information about one material direction. Lamb wave and natural vibration based methods can also be applied to flat plates, characterizing in-plane and out-of-plane properties, making these more suitable for anisotropic materials. Recent research about stiffness determination by Lamb wave

---

* Corresponding author. Department of Mechanics, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia.

*E-mail addresses:* kaspar.lasn@ttu.ee, kaspar.lasn@ntnu.no (K. Lasn).

http://dx.doi.org/10.1016/j.polymertesting.2015.04.006
0142-9418/© 2015 Elsevier Ltd. All rights reserved.

methods can be found in [4–10]. Summarized reviews and research about vibration testing of plates and its use for the elastic constant determination are presented in [11–24]. Although advanced modelling also employs damping or attenuation, e.g. [1,13,25], these energy dissipation mechanisms can typically be disregarded for thermoset laminates without introducing overly large errors to the identified stiffnesses.

The two indirect methods based on vibration or wave velocity measurements are quite different in terms of ease of practical application, complexity of equipment and the number of obtained constants. Very few comparisons exist about measurements conducted on the same material with several advanced methods — e.g. [26] where resonant plate, resonant beam and tensile test results are compared. Static, vibration or Lamb wave based methods are often separately employed to evaluate composite materials. Various different composite material systems are studied and, for this reason, individual results in the literature are typically incomparable. There have not been any comparative studies to characterize composite materials by these three independent measurement techniques. In order to have confidence in individual methods the results need to agree.

A significant data processing effort is required to obtain the elastic constants from raw measurement data when working with plate specimens. This is because the elastic constants are only indirectly measured and need to be back-calculated. Parameter identification inverse problems are typically solved by an optimization algorithm working iteratively with a numerical calculation model. In recent decades, researchers have started to use different versions of genetic algorithms (GA) to identify elastic constants or to detect damage, e.g. [7,8,10,24,27–29]. Although converging slowly, GA optimization does not require an initial guess and easily escapes local minima. Simplex optimization is, however, faster, but local minima can often be obtained.

This research summarizes an experimental technique based on natural frequency measurements. The obtained elastic constants are compared to results of static and Lamb wave measurements. Unidirectional and cross-plied plates are studied. Coupons in principal material directions are measured by tensile and flexural testing. The structure of the paper is as follows. First, the specifics of test specimens are discussed, followed by descriptions of experimental set-ups. The inversion process describes how the elastic moduli are obtained from measured data. This is explained in detail for vibration measurements, whereas a previously developed method from literature is employed for the Lamb wave data. In the final sections, the results from three independent methods are compared and conclusions drawn.

## 2. Materials and experiments

### 2.1. Test specimens

Non-destructive testing of glass fiber material is less frequently reported compared to composites made from advanced fibers e.g. carbon. In addition, the current study on virgin specimens is followed by an investigation of matrix cracking, which has a more pronounced effect on glass fiber laminate stiffness. Therefore, glass/epoxy and glass/vinylester material systems are used in this work. The details of materials and production are laid out in Table 1. The plate specimens are labeled *EP* and *VE* after epoxy and vinylester resin systems. Straight sided coupons 1, 2 and 3, 4 are cut from the same cross plied laminates as plates *EP*12 and *EP*34, respectively. Both plate specimens *VE*1 and *VE*2 are cut from the same laminate, *VE*1 for measurements by Lamb wave ultrasound, and *VE*2 for vibration measurements.

It can be seen that differences between laminates are mainly due to thickness and the matrix constituent. The VARI (vacuum assisted resin infusion) production process, specimen cutting and ply thicknesses (0.8 mm on average) are similar for two systems. The internal structure was without noticeable large voids, a typical micrograph is shown in Fig. 1. Specimen dimensions and physical properties are elaborated in more detail in the following sections.

### 2.2. Quasi-static testing

Quasi-static testing was employed to determine the stiffness of glass/epoxy coupon specimens. Uniaxial tensile and three-point flexural testing were used. These techniques are well known and only a brief overview of details is given.

Test machines Zwick/Roell Z250 (with videoXtens optical extensometer) and Zwick/Roell Z2.5 were used to apply the load and measure the response for tension and

**Table 1**
The production details of glass fiber material systems.

| Property | Glass/epoxy | Glass/vinylester |
|---|---|---|
| Fibers | E-glass (layer weights 1152 g/m$^2$ and 51.2 g/m$^2$ in 0° and 90° directions) | E-glass (layer weights 1134 g/m$^2$ and 50.2 g/m$^2$ in 0° and 90° directions) |
| Matrix | Epoxy (Epikote MGS RIMR 135, Epikure MGS RIMH 137) | Vinylester (Dion IMPACT 9102-75 series) |
| Production | VARI, post curing following the manufacturer's recommendations | |
| Specimen cutting | Diamond saw | |
| Fiber vol. fraction | 58 % on average (burn-off) | 55–61% (calc. estimation) |
| Details | Release fabrics (peel plies) were used on both faces of the plates | |
| | Thickness: 4.86 mm (average)<br>Density: 1946 kg/m$^3$ (average) | Thickness: 6.6 mm (average)<br>Density: 1930 kg/m$^3$ (average) |
| Specimens | Two ca. 30 × 30 cm$^2$ plates:<br>*EP*12 $[90_2/0_2/90_2]$<br>*EP*34 $[0/90_4/0]$<br>4×3 straight sided coupons:<br>1*a*, 1*b*, 1*c* $[90_2/0_2/90_2]$<br>2*a*, 2*b*, 2*c* $[0_2/90_2/0_2]$<br>3*a*, 3*b*, 3*c* $[0/90_4/0]$<br>4*a*, 4*b*, 4*c* $[90/0_4/90]$ | Two ca. 30 × 30 cm$^2$ plates:<br>*VE*1 $[0_8]$<br>*VE*2 $[0_8]$ |