Composite Structures 185 (2018) 176–185

Contents lists available at ScienceDirect

Composite Structures

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

Characterization of elastic constants of anisotropic composites in compression using digital image correlation

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ARTICLE INFO

Keywords:
Laminates
Elastic constants
Digital image correlation
Microstructural analysis

ABSTRACT

Experimental determination of elastic constants of anisotropic composite laminates in all orthogonal directions is generally a complex process. In this paper a simple direct technique to determine a broad set of elastic moduli is presented based on compression testing of a prism sample. Digital image correlation is used to measure the full-field deformations that allow the determination of Young's moduli and all six Poisson's ratios for the three orthogonal directions based on a single sample. Finite element model is used in evaluation of the effect of friction on the measured properties. In addition to quantitative characterization of the material properties, local strain mapping is used in qualitative evaluation of the sample structures.

1. Introduction

To utilize fiber reinforced polymers (FRPs) materials efficiently, it is necessary to have comprehensive knowledge of the material behavior. FRPs are typically transversely isotropic but normally their state of symmetry is orthotropic or in some case fully anisotropic [1,2]. In traditional design of composite structures, the properties of the fabricated materials are routinely estimated and simulated with well-recognized models and theories. Although computer aided calculations are the basis for the design of composites nowadays, experimental testing is still required to confirm the simulations. Also, if the mechanical behavior of a composite structure is to be studied but the exact input data, such as the ply structure or the material properties of the constituents, are unknown, the uncertainty in the simulation results is greatly increased.

Generally, the mechanical testing of FRPs is challenging due to the anisotropic nature, which necessitates numerous tests to be carried out to determine the constants required in describing the mechanical behavior [3,4]. In addition to symmetry-related anisotropy causing orientation-dependent heterogeneity, the microstructure of FRPs is often far from ideal e.g. due to imperfections of manufacturing. These features can cause severe local anomaly differing greatly from the behavior of the global structure. Typically, the tests are carried out using test coupons cut off the laminates fabricated for the purpose. However, it is common for composites that the manufacturing process can have strong influence on the structure, including e.g. reinforcement orientation and volume fraction. In some cases, it can actually be questioned if a simple test coupon correlates with the actual material of the final application or not.

Traditional experimental determination of elastic constants is based on the measured data of the load and the deformations induced in the material. Recently, new indirect determination techniques have also been introduced e.g. based on vibration testing or wave propagation combined with the utilization of genetic algorithms [3–6,8]. In direct measurements extensometers and electrical resistance strain gauges are routinely used in mechanical testing, and they give averaged strains over the set gauge length. However, the distribution of reinforcements in FRPs is normally in the millimeter range or less [7,9]. If local deformations in composites are to be studied, the spatial resolution of the strain gauges and extensometers is thus not high enough. The anisotropic FRPs call for full-field strain measuring techniques, which include for example Moiré interferometry [10], grating shearography [11], Raman spectroscopy [7], and digital image correlation (DIC) [9,12–14]. Especially DIC has recently proven to be efficient technique in the studies of composite structures. In this non-contact measuring technique, strain fields in materials can be studied in conventional manner similar to strain gauges yet simultaneously it allows so called local strain mapping to be carried out offering precise examination of the deformation distribution in a material [7,12,13,15].

Digital image correlation is an optical non-contact method to measure full-field displacements of the studied surface. The technique developed already in 1980s is well-known and has been described by

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https://doi.org/10.1016/j.compstruct.2017.11.008
Received 22 February 2017; Received in revised form 18 September 2017; Accepted 6 November 2017

several authors [12,17–19]. In practice, the imaged surface applied with a random speckle pattern is divided into small subsets and the deformations of the surface are computed via algorithms by tracking the spatial shift of the subsets per image to image. As a result, a complete full-field displacement map of the studied surface is obtained, from which desired deformation analysis can be post-processed. The deformations can even be determined at a sub-pixel accuracy and the measuring frequency depends purely on the performance of the cameras used. While 2D deformations can be measured with one camera, 3D deformations require use of two cameras both of measuring the changes of the deformed surface at different angles.

This work presents a technique to experimentally evaluate a broad set of elastic constants. A similar technique was used earlier by Wang [16] in analysis of properties of anisotropic cartilages. With the technique three Young's moduli and six Poisson's ratios can be determined from a single bulk specimen minimizing thus the need of material quantity. The advantages of the presented technique based on mechanical testing and full-field strain measuring with DIC include: 1) several properties can be determined from a single small test coupon if, for example, only limited amount of material is available, 2) the samples can be made from bulk material fabricated with the identical parameters as the final product and 3) measured off-plane properties of the real component are available. In addition, local strain mapping can be used to examine the micro or macro structure of the extracted samples.

2. Experimental

2.1. Materials and sample preparation

Three different fiber reinforced epoxy laminates fabricated with strip winding technique were studied (Table 1). In addition to these, a single laminate was made with vacuum infusion used in the comparative tests of two different compressive testing techniques. The initial height of the laminates ranged from 8 mm to 12 mm, where the nominal thickness of a fabric ply was 0.5 mm for the wound laminates, and 0.2 mm for the vacuum infused laminate. The sample preparation was carried out as follows: 1) cutting of a prism-shaped specimen with edge lengths of 12 mm in laminate 1–2 plane using precision circular saw and 2) grinding of the samples with an in-house built fine mechanical abrasive grinder to achieve highly parallel opposite edges of the prism sample (Fig. 1). The sample height was thus significantly lower than used in the standard compression tests of block samples, for example in ASTM D695 (Compressive properties of rigid plastics). However, the two other dimensions were in the same range. The variation in flatness along the sample surfaces was measured to be in the range of 10–50 μm using optical profilometer (Alicona InfiniteFocus G5). The inclination of the samples was low enough for successful compression testing.

Finally, a random speckle pattern with high contrast was applied on the surfaces of the specimen by spraying with matt alkyd paints. First thin (10–15 μm) constant layer of matt white was applied over which black speckles were applied having average diameter of approximately 150 μm and thickness of 5–10 μm, measured with the optical profilometer.

The reinforcement strip in the material A was aramid fiber mat, and in the materials B and C the strips were uneven-sided woven glass fiber fabrics. The fiber volume fractions were determined using optical microscopy and burn-off technique for the materials containing aramid and glass fibers, respectively. The vacuum infused epoxy laminate (D) consisted of 55 plies of plain weave E-glass fabric.

2.2. Compression testing

Compression testing of the rectangular parallelepiped samples was carried out using a servo-hydraulic universal testing machine (Instron 8800) with a 50 kN load cell and manually aligned compression plates with a low surface roughness (Fig. 2a). Self-aligning compression plates with spherical bearing system was tried first but the simultaneous use with DIC was difficult, and smaller manually aligned compression plates were used instead. The alignment was carried out with the help of rotating thin paper between the plates almost at contact and difference in flatness of less than 30 μm across the compression plates could be assumed. The testing rate and the end criteria for each test were set to 0.5 mm/min and 60 MPa, respectively. In each test linear elastic behavior without any significant plastic deformation was presumed, which was ensured by pre-tests. Silicone oil was used between the compression plates and the sample to decrease the effect of lateral friction.

Each sample (n = 3) was tested six times in a random order so that for each direction of loading (1-2-3) the deformations were measured from the other two directions as shown in Fig. 3. The tests were denoted by I_{jk}, where *i* is the sample name and indices *j* and *k* are the loading direction and the studied surface normal, respectively.

In addition to the compression method of the prisms, combined loading compression (CLC) method (ASTM D 6641) was used for comparative testing for single material. The text fixture was compressed with self-aligning compression plates using Instron 5967 universal testing machine with 30 kN load sensor (Fig. 4) The testing rate was 1.3 mm/min and end criteria was 10 kN. The samples cut from the laminate had dimensions of 12 × 9 × 140 mm where the long direction was the direction 1 in the laminate coordination. The gauge length of the unconstrained portion of the sample was thus 13 mm. Before testing electric resistance strain gauges were glued to gauge area: three-axial rosettes (gauge length 5 mm) in the perpendicular surfaces (surfaces 2 and 3) and a single gauge (5 mm) in the opposite side of the surface 3 to detect possible bending of the sample.

2.3. Digital image correlation analysis

In this study, the deformations were measured with a 3D-DIC system (LaVision) using lenses with a 100 mm focal length and a recording rate of 2 Hz (Fig. 2b). The spatial resolution of the displacement measurement was 15 μm/pixel and the RMS fit of the calibration 0.20 pixel in the first tests with samples A, B and C. In the later tests with material D, the same parameters were 4 μm/pixel and 0.51 pixel. For each measurement, strains were determined both parallel and transverse to loading direction, which enabled the calculation of Poisson's ratios. In addition, the full-field strain maps were used to study local microstructure in the samples.

Table 1
Tested materials. The percentage ratios of reinforcement denote fiber fractions in warp/weft directions.

Sample	Sample size [mm]	Sample height [mm]	Reinforcement (fabric strip)	Matrix	V_f [%]
A	12 × 12	7	Aramid mat	Silica-filled epoxy	8
B	12 × 12	9	Glass fabric (52%/48%)	Epoxy	38
C	12 × 12	10	Glass fabric (50%/50%)	Epoxy	29
D	140 × 12 and 12 × 12	9	Glass fabric (50%/50%)	Epoxy	–