Normalisation Of Shear Test Data For Rate-Independent Compressible Fabrics

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Abstract. Normalisation methods for both Picture Frame (PF) and Bias Extension (BE) tests [1] on rate-independent compressible fabrics undergoing trellis shear are presented. Normalisation of PF test results is relatively straightforward and involves dividing the force results by a characteristic length. A normalisation procedure for BE test results has been developed based on an energy argument that uses a number of simple assumptions to account for the non-uniform shear strain field induced across the whole of the BE samples during testing. A discussion of the more usual method of monitoring a gauge section of the deforming sample during tensile testing highlights potential problems that can occur as a result of the highly anisotropic nature of textile composites, problems that may lead to misinterpretation of data. The derivation and application of the energy method is relatively complicated but permits normalisation of results from samples with any length / width ratio. Smaller length / width specimen ratios have proved to be preferable since these samples tend to maintain their integrity better during testing than specimens with higher length / width ratios; an issue particularly important for more fragile fabrics.

Keywords: Normalisation, bias extension, picture frame, compressible dry fabrics
PACS: 83.10.Bb, 83.60.-a

INTRODUCTION

The automated draping and subsequent resin infusion of dry reinforcing woven and non-crimp fabrics offers a viable route to manufacturing three dimensional Continuous Fibre Reinforced Composite (CFRC) components. Potential decreases in manufacture costs through simulation technology are currently driving the development of both macro [2-3] and meso-scale material models [4-5] and associated characterisation experiments for dry reinforcing-fabrics. Two such characterisation experiments, specifically designed for measurements of large in-plane shear compliance and wrinkling behaviour, include the Picture Frame (PF) [1, 6] and Bias Extension (BE) [1] test methods (see Figure 1). These test methods have also found widespread application in the closely related field of viscous CFRC rheology [1].
An important criterion of a material characterisation experiment is that measured material properties should be independent of the test method or sample dimensions. In this paper normalisation methods for treating experimental data from both PF and BE test methods are described for shear strain rate independent materials, such as dry fabrics, undergoing so-called trellis shear. Normalisation of PF data may depend on specimen shape [7] though becomes relatively straightforward when using square samples that completely fill the area of the PF. In this case the measured force is normalised simply by dividing by the side length of the sample specimen. This can be justified using simple energy arguments [1]. Normalisation of BE test data is complicated by the non-uniform strain profile occurring in the sample. It has been suggested that one method of avoiding this complication is to measure the strain field in a gauge section of the deforming sample [6]. However, here we show how for fabrics that possess extremely high ratios between the magnitude of their tensile and shear stiffness, E/G, the dimensions of the test sample can dramatically affect results when using the gauge section approach to determining shear stiffness. An analogous normalisation method for shear rate dependent, pre-impregnated viscous CFRC has been presented previously [1].

FIGURE 1. Left: Simulation of Picture Frame test showing four-bar linkage hinged at each corner. The bars induce uniform trellis deformation throughout the sample. Right: Deformation of specimen in Bias Extension test, the test produces inhomogeneous shear deformation throughout the sample.

PICTURE FRAME TEST

A schematic of the PF test is presented in Figure 1. A tensile force is applied across diagonally opposing corners of the PF rig causing the PF to move from an initially square configuration into a rhombus. Consequently the sample held within the frame experiences trellis shear. Fibre misalignment within the PF rig can lead to large errors in the measured results [10]. This and the need for specialized testing apparatus are the main disadvantages of the PF test.
Normalisation of Picture Frame Force

A simple argument is used to justify normalisation of PF test results by the side length of the PF rig. The argument was presented [1] and is omitted here due to space limitations. The argument resulted in the equation:

\[
\frac{c_A T_A}{k_2} = \frac{F_1}{L_1} = \frac{F_2}{L_2}
\]  

(1)

where \(T_A\) is the instantaneous thickness of the sheet for a given shear angle, \(\theta\), \(c_A\) is the power storage/dissipation per unit current volume at a given \(\theta\), \(k_2\) is a function that depends on \(\theta\) and \(\dot{\theta}\), the angular shear rate, and thus is a constant for any given \(\theta\) and \(\dot{\theta}\). The equation states that for the same material two picture frame tests of different size will give the same size ratio between force and side length when sheared to the same angle, \(\theta\).

BIAS EXTENSION TEST

Energy arguments indicate that PF test results can be normalised by the side length of the PF rig (or any other characteristic length), see Eq (1). Similar arguments apply also to the BE test, thus BE results could be normalised by a characteristic length for comparison with results from tests on different sized samples with the same length / width ratio, \(\lambda\). However, a method of normalising BE data for comparison with PF tests is less obvious because of the different shape of the test specimen and the different deformations induced by the two experiments.

The bias extension test is essentially a uniaxial tensile test. For most materials the usual procedure is to monitor the strain in a gauge section of the material while measuring tensile stress in order to determine the tensile modulus. This method can cause problems when applied to engineering fabrics, as discussed in the next section.

Gauge Section Method of Normalising Bias Extension Test Results

To illustrate the complication that can occur for high E/G ratio materials such as engineering fabrics when using the gauge section method, consider the deformation of two test samples of different geometries as shown in Figure 2. The material behaviour is the same for both and is inextensible along the fibre directions indicated by the dashed lines. Figure 2a shows a square specimen before (top left) and after deformation (bottom left), Figure 2b shows a larger (twice the area) square specimen before (top right) and after deformation (bottom right). The strain in both specimens is homogenous and equal. Since the constitutive behaviour of both samples is the same the shear stress induced throughout both samples is equal and therefore the strain energy density in both samples is the same (note that inextensible fibres do not contribute to the strain energy density of the material, irrespective of the tensile stress they support since their tensile strain is zero). Since twice as much material undergoes
deformation in Figure 2b compared with Figure 2a, twice the total elastic energy is stored. Since the distance moved in the direction of the applied force in both cases is equal then it follows that the extension force is twice as high in Figure 2b compared with Figure 2a, as indicated in the diagram. The implication of this is that the tensile stress across the gauge section A-A’ is half that across B-B’. This may seem to produce a paradox – the same type of material deformed to the same strain should produce the same stress. This thinking is an implicit assumption of the gauge section method of determining material properties. However, the situation shown in Figure 2 is possible since greater tensile stresses are induced along the inextensible fibres in Figure 2b compared to Figure 2a due to the extra deforming material. These fibre stresses allow the balance of forces across any given section to be maintained. The higher the E/G ratio, the less energy is stored in the fibres and the greater the ability of the fibres to transmit stresses throughout the specimen. Evidently then, the shape and deformation field induced across the entire test specimen have to be taken into account if the correct material properties are to be determined from the strain measured in the gauge section. With this in mind a normalisation method has been developed and is presented in the following section.

**FIGURE 2.** (a) Square specimen before (top left) and after deformation (bottom left). (b) a larger square specimen before (top right) and after deformation (bottom right). The fibre direction is shown as a dashed line. Use of the gauge method to determine the shear stiffness in the two cases would result in two different values of the shear stiffness, case (b) being twice as stiff as case (a) even though the same material is used.
Energy Method of Normalising Bias Extension Test Results

An alternative method of normalising the BE data is through the use of energy arguments. The argument involves determining the relative contribution to the deformation energy from regions A and B of the sample, illustrated in Figure 3. It is based on a number of simple approximations that are described below. The derivation of Eq (2) is lengthy and so a detailed description of the derivation is omitted here.

\[ \psi(\theta) = c_A T_A = \frac{(\lambda - 1) F_3 k_2}{(2\lambda - 3) L_B} - \frac{\psi(\theta/2)}{2} \left( \frac{1 + \cos \theta/2 - \sin \theta/2}{1 + \cos \theta - \sin \theta} \right) \]

(2)

where \( \lambda \) is the ratio between original length / width ratio of the test specimen. \( F_3 \) is the axial force, \( L_B \) is the side length of region B and \( \psi \) represents the power dissipation / storage per unit area of region A at a given shear angle. If \( \psi(\theta) \) can be found using Eq (2) then a direct comparison between the BE and PF test can be made using Eq (1). To do this, examine Eq (2), \( F_3 \) and \( d_s \) are measured during BE tests and \( \lambda \) and \( L_A \) are known from the initial sample geometry. Assuming ideal kinematics the shear angle and angular shear rate can be found from \( d_s \) and \( L_A \) using trigonometry. Thus, all the terms on the right hand side of Eq (2) are obtained apart from \( \psi(\theta/2) \). In order to determine \( \psi(\theta) \) in Eq (2) an iterative scheme must be used. Such a scheme can be implemented in a spreadsheet or simple computer code. Examples of the use of the normalisation method for BE test results are presented in Figure 4. Figure 4 shows the effect of normalising (a) a linear shaped axial force versus shear angle curve and (b) a cubic-shaped axial force versus shear angle curve. As expected, the shape of the force versus shear angle curve has a significant effect on the difference between the normalised and unnormalised results.

**FIGURE 3.** A bias extension test specimen undergoing shear. Three distinct regions can be seen. In region A the shear angle is \( \theta \), in region B the shear angle is \( \theta/2 \) in region C the material remains un-sheared, i.e. \( \theta = 0 \).
ACKNOWLEDGMENTS

The work outlined here was conducted with the support of the following organisations: EPSRC, Ford Motor Company, Dowty Propellors Ltd, ESI Software, Formax UK Ltd.

REFERENCES