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A NORMALISATION PROCEDURE FOR BIAXIAL BIAS EXTENSION TESTS

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ABSTRACT: Biaxial Bias Extension tests have been performed on a plain-weave carbon fibre engineering fabric. The test results have been normalised using both the upper and lower bound method proposed by Potluri et al. [1] and also using a novel alternative normalisation method based on energy arguments. The normalised results from both methods are compared and discussed.

Key words: Textile composite, Forming, Shear characterisation, Biaxial bias extension test

1 INTRODUCTION

Several prior studies have examined the issues surrounding the shear characterisation of textile composites and engineering fabrics during forming [2]. Two tests in particular have received considerable interest; the Picture Frame (PF) and the Uniaxial Bias Extension (UBE) test. Each of these tests has its relative merits and disadvantages, for example the PF test induces approximately homogeneous deformation throughout the test specimen but is known to be susceptible to errors resulting from its boundary conditions; sample misalignment may produce large forces due to tensile strain along the fibre directions [2]. The UBE test is less susceptible to sample misalignment but can be used only to characterise textile-based materials to relatively low shear angles, typically around 40 degrees, before test specimens begin to deform through mechanisms other than trellis shear, such as intra-ply slip. Such mechanisms are a result of the specific conditions imposed by the UBE test and are not particularly representative of actual press or diaphragm forming conditions.

A third option, the Biaxial Bias Extension (BBE) test has been proposed [1, 3]. This test can potentially avoid many of the aforementioned problems associated with the PF and UBE tests, i.e. the results are less influenced by the test's boundary conditions and test samples are less prone to intraply slip. The test can also be used to investigate the effects of in-plane tension on shear behaviour. However, as with the UBE test, the deformation field induced throughout the test sample is not homogeneous. This fact leads to added complexity when normalising the test data. In recognising this issue, Potluri et al. [1] suggested an upper and lower bound when normalising wide strip BBE force data, using Eqs (1) and (2) respectively.

$$F_{upper} = \frac{2F_a \cos(\pi/4)}{(l_o - w_o)} \tag{1}$$

$$F_{lower} = \frac{F_a \cos(\pi/4)}{(l_o - w_o)} \tag{2}$$

where F_{upper} and F_{lower} are the upper and lower normalised axial forces, F_a is the axial force measured in the BBE test, l_o is the length of the sample and w_o is the width of the clamped boundary of material. Eq 1, the upper bound, is effectively the same equation used to normalise PF test data, i.e. by normalising the force by the side length of the central region (Region A in Fig 1) and therefore gives an overestimate of the true normalised force.

This method of using an upper and lower bound effectively gives an indication of the potential error due to the non-homogeneous strain field when normalising the force data. An alternative energy-based approach to normalisation was taken in a prior investigation concerning UBE test data [4]. The normalisation scheme takes into account the sample's non-homogeneous strain field. The present work uses a similar energy-based analysis in deriving expressions that can be used to normalise BBE test data. The results of this normalisation method should lie between the upper and lower bounds proposed by Potluri et al. [1].

2 NORMALISATION THEORY FOR BIAXIAL BIAS EXTENSION TESTS

2.1 Analysis assumptions

For the purposes of this analysis the material response is considered to be rate independent. Thus, the analysis is applicable only to dry engineering fabrics rather than prepregs. Furthermore, the fabric is assumed to deform only through the trellis shear mechanism i.e. the tows of the fabric are considered inextensible and therefore all the deformation energy is considered to be due to shearing rather than extension of the fibres. Intra-ply slip is assumed negligible. Finally, the power dissipated by a given material (compressible or incompressible) at a given deformation and deformation rate is considered to increase linearly with the initial volume of material deformed. Thus, for a given initial material area, the stress-power generated in shearing material at a specified angle and angular shear rate will increase linearly with the initial area of the sample. This argument assumes that the material properties of the sample are homogeneous throughout, irrespective of sample size (and therefore the tension in the tows).

2.2 Analysis

Three different test specimen geometries are considered in this normalisation, see Fig 1. By cutting the specimen along the dotted lines, tensile stresses generated along the fibre reinforcement due to sample misalignment can be avoided. Clearly the influence of Region B on the deformation force increases moving from shape Figure 1(a) to (c). If the assumptions of the normalisation theory are correct then the normalised force produced from tests on the different specimen geometries should be the same. Unlike the PF and UBE tests the total axial force measured in a BBE test, F_a, is comprised of two components, one part is due to the material response to deformation, F_n, the other contribution, F_R, is a reaction force due to the transverse force, F_c, applied across the specimen. It can be shown that

$$F_R = \frac{F_c}{\tan\left(\frac{\pi}{4} - \frac{\theta}{2}\right)} \qquad (3)$$

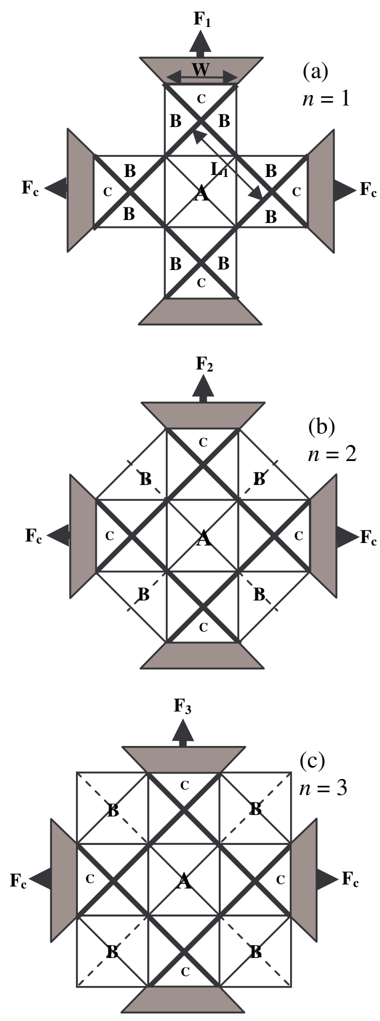

Fig 1. Diagram construction lines (thin black lines) have been left in the diagram to help illustrate the relative areas of the different regions. Consider each of the diagram construction triangles to equal 1 unit or area. (a) Cruciform biaxial test specimen: Region A area = 8 units, Regions B area = 8 units. (b) Octagonal specimen: Region A area = 8 units, Region B area = 16 units. (c) Square specimen: Region A area = 8 units, Regions B area = 24 units. The thick black lines show the boundaries between the different regions, A, B and C. Dashed lines indicate where to cut the specimen to prevent misalignment stresses.

Thus, before normalising the material response, F_R

has to be extracted from the total measured force using

$$F_n = F_a - F_R \tag{4}$$

By considering the relative volumes of Regions A and B in Fig 1 for the three different geometries, it is possible to derive an expression for the power dissipation / storage per unit area of Region A, i.e. ψ.

$$\psi(\theta) = \frac{F_n k_2}{L_1} - \left[\frac{n}{2}\right]\left\{\frac{\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\pi}{4}-\frac{\theta}{4}\right)}{\cos(\theta)\sin\left(\frac{\pi}{4}-\frac{\theta}{2}\right)}\right\}\psi\left(\frac{\theta}{2}\right) \tag{5}$$

where the shear angle

$$\theta = \frac{\pi}{2} - 2\cos^{-1}\left[\frac{d_1}{2L_1} + \frac{1}{\sqrt{2}}\right] \tag{6}$$

and

$$k_2 = \frac{\dot{d}_1}{L_1 \cos\theta} \tag{7}$$

where the axial force is F_n and d_1 and $\dot{d}_1$ the displacement and rate of displacements are measured during BBE tests. L_1 and n are known from the initial sample geometry (see Fig 1). If $\psi(\theta)$ can be found using Eq (5) then a direct comparison with PF tests can be made using Eq (8).

$$\frac{\psi(\theta)}{k_2} = \frac{F_{pf1}}{L_{pf1}} = \frac{F_{pf2}}{L_{pf2}} \tag{8}$$

where F_{pfi} are the measured axial forces in PF tests of arbitrary size. Thus, all the terms on the right hand side of Eq (5) are known apart from $\psi(\theta/2)$. In order to evaluate Eq (5) an iterative scheme can be implemented similar to that used in [4].

In Fig 2(a) a hypothetical linear axial force versus shear angle curve is shown. Four different normalisations have been employed: the upper and lower bound methods postulated in [1], i.e. Eqs (1) and (2), and the energy method, Eq (5), assuming specimen shapes n=1 and n=3, as shown in Fig 1. Following normalisation it is clear that the energy normalisation assuming shape n=1 gives a prediction closer to the upper bound than n=3, i.e. closer to the effective PF normalisation. This is to be expected since the n=1 shape provides a closer approximation to the PF geometry than the n=3 specimen shape, i.e. the influence of Region B is greater for n=3. Thus, a simple PF style normalisation can be employed for the n=1 geometry resulting in a fairly accurate normalised curve. However, in practice the n=1 geometry is more prone to intra-ply slippage during testing than the n=3 geometry, hence the proposed use of a wide-strip geometry suggested in [1]. In this case Fig 2(a) demonstrates the increased error associated with the normalisation when using a simple PF type normalisation, i.e. Eq 1. In both cases Eq 2 significantly underestimates the true normalised force. Fig 2(b) illustrates how the shape of the force versus shear angle curve can influence the normalised results. In this case the energy normalisation result, even when using n=3, is almost identical to the upper bound normalisation.

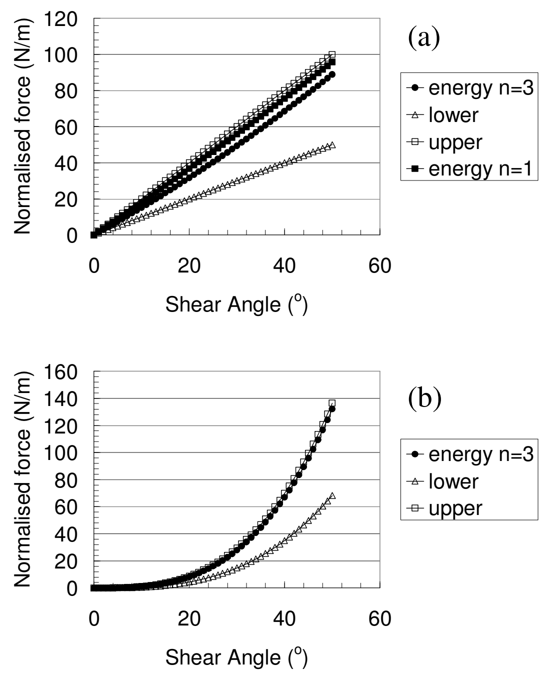

Fig 2. (a) Normalisation of a hypothetical linear force versus shear angle curve using Eqs (1), (2) and Eq (5) with n=1 and 3. (b) normalisation of a cubic curve using Eqs (1) and (2) and Eq (5) with n=3.

3 BIAXIAL BIAS EXTENSION TESTS

3.1 Material

BBE tests have been conducted on a plain weave carbon fabric containing 12K tows with the following attributes: 3 ends/cm, 3.3 picks/cm, area density = 528 gm^{-2}, fabric thickness = 0.89 mm (under a nominal pressure of 0.2 kPa). Specimen dimensions are shown in Fig 3 and correspond most closely to shape (a) in Fig 1, thus n=3 was used in Eq 5. 200g weights were attached to either side of the specimen to produce a transverse load. The material shear angle was obtained through image analysis of the recorded test. Fig 4 shows the un-normalised axial force, F_n, versus shear angle data for three repeat tests (note F_R has been subtracted). Fig 5 shows one of the curves from Fig 4 normalised using both Eqs (1) and (2) together with the energy normalisation, Eq (5) using n=3. As expected the energy normalised curve falls between the upper and lower bounds. However, comparing with Fig 2(b) and given the non-linear shape of the force versus shear angle curve one might have expected the energy normalised curve to lie closer to the upper bound. A possible reason why this is not the case may be because the experimentally measured force has a finite value at zero shear angle due to the static friction within the fabric. This causes numerical problems for the iterative algorithm when solving Eq (5). Oscillations in the normalised result can also be seen at low shear angles (see Fig 5). Further work is required to deal with this issue.

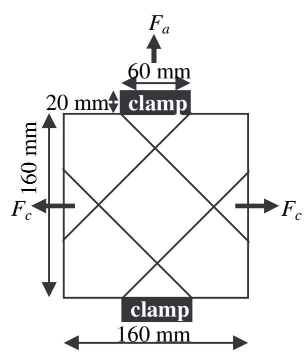

Fig 3. Specimen dimensions. The black regions indicate material underneath the clamps. F_a is the total axial force measured in the BBE tests and F_c is the transverse force applied to the specimen using a point force.

4 CONCLUSIONS

A novel energy-based normalisation method has been used to demonstrate the accuracy of the upper and lower bound normalisation method proposed in [1]. Normalisation of hypothetical axial force versus shear angle curves indicates that the shape of the curve is important in determining how close the true normalised curve lies in relation to the upper and lower bound approximations. On the other hand preliminary experiments suggest that an average of the upper and lower bound normalised curve may be a very good approximation (as suggested in [1]). In order to resolve this question further work is required on the numerical algorithm to cope with finite force at zero shear angle often associated with dry fabric test results. The assumption of ideal kinematics in BBE test specimens must also be investigated further.

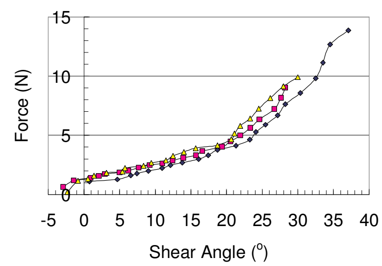

Fig 4. F_n versus shear angle for the plain weave carbon fabric before normalisation. This figure shows three repeats using the same test method.

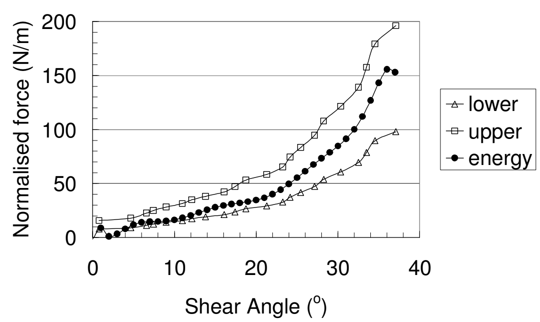

Fig 5. BBE data normalised using both the upper and lower bound normalisation limits proposed by Potluri et al. [1] and also using the energy normalisation method. As expected the energy normalised curves fall between the two limits.

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