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Influence of Specimen Pre-Shear and Wrinkling on the Accuracy of Uniaxial Bias Extension Test Results

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Abstract

The influence of unintended specimen pre-shear and out-of-plane wrinkling on the accuracy of shear angle and axial force results, measured during a uniaxial bias extension (UBE) test on engineering fabrics, is examined. Three techniques of measuring test kinematics are investigated, including manual image analysis, 2-D and 3-D full-field analysis. Error introduced by specimen pre-shear is shown to influence test results in different ways, depending on analysis technique. Procedures to take specimen pre-shear error into account when interpreting results are demonstrated, though an important recommendation resulting from this investigation is to minimise pre-shear as much as possible. Out-of-plane wrinkling is shown to create significant errors in kinematic data when using 2-D analysis methods (up to 20% overestimates of measured shear angle). It is shown that wrinkle-error can be corrected if 3-D stereoscopic analysis methods are employed.

Key words: fabric, bias extension test, wrinkling, digital image correlation

1 Introduction

Typically, the uniaxial bias extension (UBE) test is used to measure the shear stiffness of both apparel (Cooper, 1963) and engineering fabrics, such as glass, carbon and aramid fabric (Boisse et al., 2016; Cao et al., 2008; Harrison et al., 2008). Test results are used to determine the shear-related constitutive parameters of engineering fabric models (Boisse et al., 2011; Gong et al., 2016; Harrison et al., 2017). The latter are of significant interest due to their utility in simulating the forming response of engineering fabrics during the manufacture of advanced composite products, with the ultimate goal of reducing production cost and improving part quality and design. Aside from providing a relationship between shear stress and shear strain, (the latter often quantified by the fabric shear angle) the kinematics of a UBE test specimen are usually only used to determine the point at which intra-ply slip becomes an important deformation mechanism (Harrison et al., 2008; Härtel and Harrison, 2014). Recent developments in the characterisation and modelling of engineering fabrics have demonstrated that valuable extra information can be collected when conducting a modified version of the standard UBE test (Harrison et al., 2017); modification to the

usual UBE test involves bonding aluminium to the test specimen to mitigate intra-ply slip in Region C and to create an 'encastre' boundary condition along the edge of Region B (see Figure 1a). Namely, the measured shear angle kinematics can also be used to infer the in-plane bending stiffness of the fabric (2nd order gradient effects) (Cuomo et al., 2016; D'Agostino et al., 2015; Ferretti et al., 2014; Giorgio, 2016; Harrison et al., 2017; Steigmann and Dell'Isola, 2015; Turco et al., 2016), while the out-of-plane kinematics (wrinkling onset angle) can be used to infer the torsional stiffness of the fabric when undergoing large shear strains (Harrison et al., 2017). Both of these measurements require very careful sample preparation, testing and subsequent image analysis if reliable and useful results are to be obtained.

Figure 1. (a) A modified UBE test with aluminium (painted black) bonded to Region C of a twill-weave, with a pronounced wrinkle (b) wrinkle prediction in finite element simulation (Harrison et al., 2017).

Typically, measurement of sample kinematics is performed via manual image analysis of recorded video footage of experimental tests (Cao et al., 2008; Harrison et al., 2017) using software such as ImageJ (Ferreira and Rasband, 2012). Sometimes bespoke image analysis algorithms have been used, e.g. (Arumugam et al., 2016; Harrison et al., 2008) while other investigations have made use of digital image correlation (DIC) (Cao et al., 2008; Carvelli et al., 2012; Colman et al., 2014; Lomov and Verpoest, 2006; Mohan et al., 2016; Pazmino et al., 2015; Pierce et al., 2015; Vanclooster et al., 2009; Willems et al., 2009). The latter is a well-established experimental technique capable of measuring full-field strains. If a stereoscopic system is employed, DIC can also measure the full-field 3-D shape and strain across non-planar surfaces (Pazmino et al., 2015; Vanclooster et al., 2009). For most purposes, manual image analysis can produce sufficient information to characterise the forming mechanics of a fabric to a reasonably high level of accuracy, providing information on, not just shear stiffness, but also the fabric's in-plane and torsional stiffnesses (Harrison et al., 2017). A disadvantage of DIC is that preparation of the surface of the fabric can change its mechanical properties (Harrison et al., 2017). Nevertheless, DIC and other full-field techniques (Arnold et al., 2016; Khiem et al., 2017; Rashidi and Milani, 2016) offer the possibility to efficiently extract much greater quantities of kinematic data, and with higher precision, than is possible via manual image analysis. Full-field information can be used to examine the in-plane strain in greater detail than

manual image analysis, such as the width of the transition zone between the different regions of a deforming UBE test specimen (Ferretti et al., 2014); a measurement strongly linked to the fabric's in-plane bending stiffness. Full-field data also offers the possibility to characterise non-linearity of the in-plane stiffness via inverse modelling, while stereoscopic DIC (Harrison et al., 2017; Mohan et al., 2016), photogrammetry (Glaser and Caccese, 2014; Khiem et al., 2017; Mallach et al., 2016), shape-from-focus (Arnold et al., 2016) and laser scanning techniques (Rashidi and Milani, 2016) facilitate measurement of the onset and growth of out-of-plane wrinkling via 3-D position measurement. There are however, potential pitfalls in conducting the UBE test that can lead to inaccurate data. The benchmarking study of Cao et al. (2008), in which several groups compared UBE tests on the same fabrics, showed large variation between UBE test results; variability occurred both intra and inter-group. The size of this variability increased dramatically as the samples reached higher shear angles. Such variability is common in the literature and is no doubt partly due to the intrinsic material properties of the fabric, however, ***it is proposed that much of the variability is caused by imperfect sample preparation, the method of analysing results and specimen wrinkling.*** Consequently, ***we aim to demonstrate the importance of these issues, examine their impact on the accuracy of the resulting data and suggest possible solutions to mitigate error.*** Two important sources of error are discussed in Sections 1.1 and 1.2.

1.1 Error Source 1: Initial specimen pre-shear

Experience suggests that a few degrees of positive or negative pre-shear is very difficult to avoid when installing UBE test specimens in the test machine. The size of this error will vary from one researcher to the next, depending on the level of care employed when installing the test specimens in the test machine. As will be demonstrated, this pre-shear has implications for the accuracy of subsequent kinematic measurements and because of the standard practice of 'zeroing' the measured force once the specimen is in its start position; it also affects the accuracy of the axial force measured during the tests. To give an idea of the initial pre-shear typically observed in actual experiments, images of UBE test specimens, just prior to the beginning of each test, from 6 different investigations, conducted by 4 different undergraduate and postgraduate research students over the past 2 years at the University of Glasgow, on various different fabrics have been analysed retrospectively. Some of the investigations provided repeatable, high quality data, while others contained large variability. Table 1 summarises the average initial shear angle and standard deviation from each set of tests. These metrics are found to serve as a very good indicator of the quality of the subsequent axial-force versus measured shear angle data and kinematic data, resulting from the tests (e.g. much better repeatability and lower variability of both the axial force versus measured shear angle data and measured shear angle versus ideal shear angle data). The results suggest that good/useful data is obtained when the average pre-shear angle prior to testing is less than $\sim 0.5^\circ$ and the standard deviation of the initial pre-shear angle is less than $\sim 2^\circ$.

Table 1. Average and standard deviation of initial pre-shear angle measured retrospectively from six distinct investigations.

Researcher number	Number of tests in investigation	Average initial pre-shear angle	Standard deviation of initial pre-shear angle	Quality of Results
1	12	0.18	1.97	Very Good (Harrison et al., 2017)
2	8	3.76	1.20	Poor
2	16	-0.26	1.57	Very Good
3	6	7.0	8.0	Poor
3	12	1.56	1.84	Reasonable
4	27	4.71	4.15	Poor

1.2 Error Source 2: Out-of-plane Wrinkling

A second possible source of error when measuring shear angle data in the UBE test is out-of-plane fabric wrinkling (see Figures 1 and 2). Out-of-plane wrinkling often (but not always) occurs towards the later stages of a UBE test. The severity of wrinkling depends on the fabric's mechanical forming properties and the size of the test specimen; larger specimens tend to wrinkle at lower shear angles and are more severe (Harrison et al., 2017). It is clear that any non-orthogonality of the specimen surface in relation to the observer changes the perceived shear angle measured from the surface of the specimen. Wrinkling creates a complex undulating surface, usually at the centre of the test specimen (Harrison et al., 2017; Mohan et al., 2016; Rashidi and Milani, 2016) precisely where shear angle kinematics tend to be measured (see Figure 1). This can influence the accuracy of the measurement in a complex and as yet, unquantified way. Specimen wrinkling might help to explain the large variability of data obtained at high shear angles reported in Cao et al. (2008) as the different groups used different sized specimens. This investigation aims to understand the severity of this issue and will offer solutions to understand and potentially correct for this the effect.

1.3 Structure of Paper

The remainder of this paper is organised as follows: in Section 2, the general strategy of the investigation is explained and detailed accounts of the three shear angle measurement methods: manual image analysis, 2-D full-field analysis and 3-D full-field analysis are given. The theory behind the full-field analysis is explained and the resulting algorithms implemented in this investigation are verified. In Section 3, the influence of the two types of error: pre-shear (see Section 1.1) and out-of-plane wrinkling plane (see Section 1.2), on each of the three measurement methods are presented and discussed. Section 4 presents the conclusions of the investigation.

2 Method

Finite element simulations of the UBE test are used to examine the accuracy of kinematic data measurement techniques used in most experimental investigations. Simulations are employed to evaluate the measurement methods as opposed to using actual experimental results, as all kinematic quantities are known precisely. Any deviation from these known kinematics, can thus be ascribed to error in the shear angle measurement technique. The simulations undergo pronounced out-of-plane wrinkling during the later stages of the test, see for example, Figure 1b and Figure 2, making them ideal for examining the effect of wrinkles on kinematic data extraction.

Figure 2. Cross-section through mid-height of simulation shown in Figure 1b at various instances in time during the UBE test, showing the evolution of wrinkle amplitude and shape. The shear at the centre of Region A angle is provided at each instance. The broken line represents the cross-section through the undeformed specimen.

Pre-shear can easily be introduced into the simulation by applying a vertical displacement, either up or down. The pre-sheared simulation can then be considered as the initial position for subsequent image analysis, mimicking the pre-shear error typically encountered when conducting actual experiments (see Table 1). Three UBE test cases are considered, one with no initial pre-shear, a second simulation with 4.48° of positive pre-shear and a third simulation with -4.28° of negative pre-

shear (measured at the centre of Region A). The three simulations are shown in their initial pre-test states in Figure 3, the colour legend indicates the initial full-field shear angle at the specimen's start position in the test. The length/width (L/W) aspect ratio of the specimen refers to the dimensions of the specimen in its un-sheared state and is the same for Figures 3a to 3c. In these simulations $L=416.3\text{mm}$, $W=203.7\text{mm}$ and $\lambda=2.04$. The simulations use a comprehensive modelling approach (including tensile, shear, out-of-plane bending, in-plane bending and torsional stiffness, all convecting with the fibre directions). All constitutive model parameters were fitted previously and correspond to the forming mechanics of the untreated twill weave carbon fabric described in Harrison et al., 2017. The systematic characterisation approach described in that paper demonstrates a method of determining all the mechanical forming properties of the fabric using just two experimental test methods; a cantilever bending test and a modified version of the UBE test (shown in Figure 1a). The reader is referred to Harrison et al. 2017 for further details on the fabric, the experimental tests and the finite element based modelling approach.

Figure 3. Three UBE test cases. (a) no initial pre-shear, (b) 4.85° of positive pre-shear and (c) -4.97° of negative pre-shear.

Three different kinematic data extraction techniques will be examined:

- manual measurement of the shear angle at the centre of Region A of the simulations (see Figure 1b) using Imagej (see Section 2.1),
- automated analysis of x-y nodal displacements to calculate 2-D full-field shear angle data (see Section 2.2) and
- automated analysis of x-y-z nodal displacements to calculate 3-D full-field shear angle data (see Section 2.3).

As mentioned in Section 1, DIC is a popular and powerful experimental method often used to analyse the kinematics of the UBE test. The fundamental role of DIC is to track the position of points on a surface. The main output from a DIC experiment is the position of these points at selected time increments. Using these positions, surface strains can be calculated using standard DIC software. In this investigation, DIC is not directly used, instead nodal co-ordinates from the simulations provide equivalent data to the points tracked by DIC measurements. Nevertheless, the principal of surface strain calculation remains the same. Technique (B) is therefore equivalent to using a one-camera 2-D DIC setup, while technique (C) is equivalent to using a two-camera stereoscopic 3-D DIC setup,

though here nodal coordinates replace experimentally measured ‘pixel’ positions as the input of the strain calculation algorithms. The ‘apparent’ measured shear angle obtained from each of these approaches will be compared against the ‘true’ result provided by the finite element simulations. In so doing, the effect of specimen pre-shear and out-of-plane wrinkling on the measured shear angles will be investigated.

2.1 Shear Angle Measurement Method (A): Manual Image Analysis

Typically, lines are marked on an engineering fabric, along the two sets of tows passing through the centre of the specimen, as shown in Figure 4. For the purposes of this study, the borders of the elements within the simulations can be used in a similar way to track the fibre directions and allow manual measurement of the shear angle at the centre of the specimen.

Figure 4. (a) Marker lines drawn on UBE carbon fabric specimen to measure shear angle using imagej (b) close-up view of Region A and tracking lines (c) finite element simulation used to evaluate the manual image analysis method; side of elements used to measure shear angle using imagej.

Analysis of the three simulations was performed using Imagej, by measuring the shear angle as a function of axial displacement (see, for example, Figure 4c). In each case, the set of manual measurements was repeated four times. The average measured shear angle is plotted against the ideal shear angle for each of the three cases (see Figure 9 in Section 3.1), error bars indicate ± 1 standard deviation due to the human error involved in making the measurements. Such graphs are important in that they can be used to estimate the in-plane bending stiffness of the fabric (Harrison et al., 2017) and the onset of intraply slip (Harrison et al., 2008; Härtel and Harrison, 2014). The equation normally used to predict ideal shear angle, Eq (1), or variations on the same equation e.g. (Boisse et al., 2016; Cao et al., 2008; Deghboudj et al., 2017; Haanappel et al., 2014; Harrison et al., 2004; ten Thije and Akkerman, 2008), assumes pin-jointed net (ideal) kinematics. The equation usually takes no account of unintentional sample pre-shear; though there are exceptions (Lebrun et al., 2003). If the pre-shear angle is considered, then Eq (1) is simply modified to Eq (2) (Harrison et al., 2017),

$$\theta = \frac{\pi}{2} - 2\cos\left[\frac{d}{2(\lambda-1)L_A} + \frac{1}{\sqrt{2}}\right] \quad (1)$$

$$\theta = \frac{\pi}{2} - 2\cos\left[\frac{d}{2(\lambda-1)L_A} + \cos\frac{\phi_{ic}}{2}\right] \quad (2)$$

where d is the vertical axial displacement of the test specimen, L_A is the side length of Region A of the UBE test sample and ϕ_{ic} is the initial inter-fibre angle at the centre of Region A. Figure 5 shows the geometry of Region A, for a specimen with length/width ratio, $\lambda = 2$. By plotting the predictions of Eq (1) versus Eq (2), it can be shown that when using Eq (1) the size of the pre-shear error increases with increasing shear angle; doubling in size by the time the shear angle at the centre of the UBE test specimen reaches 50° . In Section 3.1, the effect of using Eq (2) rather than Eq (1) on typical kinematic data, when unintended pre-shear of the sample is present at the start of a test, is demonstrated.

Figure 5. Kinematics of Region A when the ratio length/width ratio, $\lambda = 2$

2.2 Shear Angle Calculation Using Full-Field Analysis

In this section the theory behind the full field shear angle measurement is described for both Method B, the 2-D full-field analysis (in Section 2.2.1) and Method C, the 3-D full-field analysis (in Section 2.2.2). The algorithms use nodal co-ordinates from the finite element simulations as input and the output is a full-field shear angle calculation. Results of the 3-D algorithm are first of all verified in Section 2.2.3 by comparing the output with a prediction from a UBE test simulation that shows severe wrinkling. In Section 2.2.4 a method to initialise the full-field tow angle distribution to account for unintended specimen pre-shear is explained.

2.2.1 Method B: 2-D Full-Field Image Analysis

The 2-D full-field algorithm uses just x-y nodal co-ordinates (equivalent to the points produced using a single camera 2-D DIC set-up). Consequently, the surface of the specimen is assumed to be perfectly flat, ignoring any out-of-plane displacement, and can therefore be meshed using 4-node linear, or 9-node quadratic elements, together with their corresponding linear or quadratic shape functions. In this investigation, 4-node linear elements are used. The technique used to track the tow directions for the 2-D algorithm is identical to that outlined in Pierce et al. (2015), itself based on earlier work by Peng and Cao (2005) and is briefly repeated here for completeness. In the following, bold capital letters indicate 2nd order tensors while bold lower case letters indicate vector quantities.

Tracking of the tow direction during deformation is achieved using the deformation gradient tensor, $\mathbf{F}$, and the initial tow orientation, represented using the vector, $\mathbf{f}_i$. In this analysis, all tensor and vector quantities are defined with respect to the 2-D global co-ordinate system shown in Figure 6. Here $\mathbf{f}_1$ corresponds to the initial warp and $\mathbf{f}_2$ corresponds to the initial weft tow directions within a biaxial fabric. Because the finite elements represent a surface and all strains occur within that surface, $\mathbf{F}$ is a 2-D tensor and is determined in terms of the elemental coordinate system using standard finite element theory (Bathe, 1996; Pierce et al., 2015). A schematic of the tow directions in a fabric before and after deformation is shown in Figure 6.

Figure 6. Tow directions before and after deformation.

A material Cartesian coordinate system is also defined using an orthonormal basis, $\mathbf{e}_i$ with $\mathbf{e}_1$ initially co-linear with the global x-axis and $\mathbf{e}_2$ co-linear with the global y-axis. For simplicity, here it is assumed that, $\mathbf{f}_i$ and $\mathbf{e}_i$ initially coincide, though in Section 2.2.3 it will be shown that $\mathbf{f}_i$ can be initialised with arbitrary directions. Using $\mathbf{F}$, it is possible to obtain both the symmetric right stretch tensor,

$$\mathbf{U} = \sqrt{\mathbf{F}^T \mathbf{F}} \quad (3)$$

and the orthogonal rotation tensor

$$\mathbf{R} = \mathbf{F} \mathbf{U}^{-1} \quad (4)$$

via polar decomposition. The material frame rotates with the average rigid body rotation of the material as,

$$\mathbf{e}'_i = \mathbf{R} \cdot \mathbf{e}_i \quad (5)$$

The updated tow directions are calculated in the deformed state as

$$\mathbf{f}'_i = \frac{\mathbf{F} \cdot \mathbf{f}_i}{\|\mathbf{F} \cdot \mathbf{f}_i\|}, \quad i = 1, 2 \quad (6)$$

Finally, by computing the angles between tow and material axes in the deformed state,

$$\cos \alpha_i = \frac{\mathbf{e}'_i \cdot \mathbf{f}'_i}{\|\mathbf{e}'_i\| \|\mathbf{f}'_i\|} \quad (7)$$

$$\sin \alpha_i = \frac{\mathbf{e}_i' \times \mathbf{f}_i'}{\|\mathbf{e}_i'\| \|\mathbf{f}_i'\|} \quad (8)$$

the shear angle can be calculated as

$$\theta = \alpha_1 + \alpha_2 \quad (9)$$

2.2.2 Shear Angle Calculation Method C: 3-D Full-Field Image Analysis

Normally, a 3-D full-field algorithm, which uses x-y-z nodal co-ordinates (equivalent to the points produced using a dual camera stereographic DIC set-up), would use 3-node triangular elements together with linear shape functions to represent an arbitrary 3-D surface. However, the simulations employed in this investigation use 4-node linear membrane elements and every membrane element is considered to remain perfectly flat, irrespective of its in-plane deformation and out-of-plane rotation. Consequently, the membrane's nodal displacements can be used to calculate the 2-D deformation gradient tensor, $\mathbf{F}$, despite the arbitrary form of the sample during wrinkling (in actual fact, close inspection of individual finite elements does reveal some slightly non-planar nodal displacements but, to a very good approximation, the elements do remain flat).

Calculation of the shear angle during deformation in the 3-D algorithm is performed in much the same way as for the 2-D full-field analysis, except now an extra step is introduced since the membrane elements are no longer constrained to 2-D motions within the x-y plane. Out of plane motion in 3-D space occurs, especially when the sample begins to wrinkle. In order to use the same theory as described in Section 2.2.1, each element is rotated from its current orientation in 3-D space back to the x-y plane using quaternion rotation of the element normals. This process maintains the in-plane deformations, consequently $\mathbf{F}$ and θ can be calculated and the latter can be displayed in the deformed configuration.

2.2.3 Verification of Full-Field Algorithms

The MatLab algorithm uses the nodal co-ordinates from the finite element simulation as input. In order to verify the MatLab-based 3-D tow tracking algorithm implemented in this investigation (and consequently, also the 2-D tracking algorithm as this is just a simplified version of the 3-D tracking algorithm), the full field shear angle predicted by the algorithm is compared with the shear angle predicted by finite element simulations, produced by the associated vumat user subroutine (Harrison et al., 2011; Yu et al., 2002, 2005). The comparison employs a simulation with the specimen predicted to undergo strong out-of-plane wrinkling, see Figure 1b and Figure 2. The result from the 3-D tow-tracking algorithm is shown in Figure 7 and demonstrates the algorithm works well with maximum differences in the resulting shear angle of less than 0.25° (or 0.4%) at around 60° of specimen shear. The error is thought to be due to the slightly non-planar geometry observed in some of the 4-noded finite elements of the specimen at high shear angles; ideally all 4 nodes of each linear element should lie in the same plane.

Figure 7. (a): ABAQUS VUMAT computed shear angle, (b) MATLAB computed shear angle produced using the nodal displacement output predicted in (a), and (c) the difference between the full-field shear angles shown in (a) and (b).

2.2.4 Initialisation of Full-Field Tow Directions to Correct for Sample Pre-shear

The issue of fabric pre-shear is just as much a problem when using DIC to measure sample kinematics as when using manual image analysis. Normal practice when using DIC is to assume that the fibres are perfectly straight and initially orientated at $\pm 45^\circ$ to the direction of loading. As discussed in Section 2.1, this can be a problem when analysing the deformation of textiles in the UBE test where tows are rarely exactly orientated at $\pm 45^\circ$ at the start of the test, usually showing some degree of unintended pre-shear (see Table 1) and therefore some degree of in-plane tow curvature across the UBE test specimen; a natural consequence of the different tow directions in Regions A-C, as shown in Figure 1a. In addition, there can also exist a small amount of random ‘tow meander’ across the specimen, see for example Figure 11 in Harrison et al. (2008). To accommodate these imperfections, the automated algorithm implemented in this investigation is designed such that the full-field tow orientations can be ‘initialised’ at an arbitrary number of selected positions across the sample. The full-field initial shear angle can then be interpolated between these points. In practice, this can be achieved using a grid of lines, carefully marked on the UBE test specimen during sample preparation, with the lines closely following the tows within the fabric. In this numerical investigation, element edges instead of marked lines are used to initialise the full-field tow directions. The tow direction at every corner of each grid cell is measured via manual analysis and provided as the initial input to the MatLab code. The internal angle at each grid corner is then interpolated across each cell using bilinear interpolation. The finer the grid, the more accurate will be the full-field initialisation, though from a practical perspective a finer grid requires more time to draw and so a coarse grid would be preferred if it can provide sufficient accuracy. In this investigation, a grid measuring $3\times$ the single finite element edge length is used, as shown by the black grid in Figure 8. Using this information, the initial full-field shear angle can be output at any point within the initialised region. Note that, as the pre-shear of the UBE test sample increases, the edges of each cell grid become slightly non-linear (especially if a coarse grid size is used). To accommodate this effect, the curved edges of each grid cell are linearised using a MATLAB first order polynomial fitting algorithm. Also note that only the projected x-y coordinates of the nodes are used

in the initialisation which may introduce a very small amount of error if out-of-plane displacement is present across the specimen in its initial state, e.g. in the case of negative pre-shear.

Figure 8. Grid spacing used in the full-field fibre direction initialisation, for initialisation/correction of fabric pre-shear using DIC.

3 Results

In Sections 3.1 to 3.4, the influence of fabric pre-shear and wrinkling, on the accuracy of shear angle measurements made when using the three techniques, Methods A to C, is quantified. In Section 3.5, the effect of kinematic measurement error due to pre-shear and wrinkling, on the form of the subsequent axial force data measured shear angle data is briefly examined.

3.1 Kinematic Pre-shear and Wrinkle Error using Method A

Figure 9 shows the measured angle versus the calculated 'ideal' angle found using Eq (1) for cases (a-c) and found using Eq (2) for cases (d-f). Cases (a) and (d) show results from the simulation with no pre-shear (see Figure 3a). Cases (b) and (e) show results from the simulation with an initial positive pre-shear (see Figure 3b). Cases (c) and (f) show results from the simulation with an initial negative pre-shear (see Figure 3c). Figure 9a, the case with zero pre-shear, shows that shear angles measured using manual image analysis accurately follow the true shear angle provided by the simulation (indicated by the red line in all cases shown in Figure 9) until about 37° of shear but begin to diverge at the point where out-of-plane wrinkling starts (at about $37-38^\circ$). The divergence increases with increasing shear angle due to the increasing severity of the wrinkle (see Figure 1b and 2), becoming about 10° higher than the true shear angle when the specimen reaches over 50° of shear. The results demonstrate that specimen wrinkling causes a significant overestimate (by up to 20%) of the apparent measured shear angle after wrinkling begins, when using manual image analysis to analyse the test results. Figures 9b and 9c, the cases with positive and negative initial pre-shear, show poor correlation with the actual simulation result (red lines). The additional error is due to the method of calculating the 'ideal' shear angle; Eq (1) takes no account of the initial pre-shear angles of $+4.85^\circ$ in case b and -4.97° in case c, i.e. when the test displacement is 0mm, the ideal shear angle prediction is 0° . This issue can be easily solved by using Eq (2) rather than Eq (1). Here the calculated shear angle is corrected using the measured initial shear angle, resulting in a much better correspondence with the actual result provided by the simulation – see Figures 3(d-f). In so doing, the effects of specimen pre-shear can be eliminated from the kinematic data produced by the UBE test, improving its utility when determining the in-plane bending stiffness of the engineering fabric. It should be

born in mind that in order to estimate the in-plane bending stiffness using an inverse modelling approach (Ferretti et al., 2014; Harrison et al., 2017), the error in the kinematic measurements must be smaller than the effect that the in-plane bending stiffness has on the sample's kinematics. This effect is relatively small, indicated by the difference between the observed sample kinematics and the ideal kinematics prior to specimen wrinkling (in other words, the difference between the black 45° line in Figure 9 and the measured data points prior to the wrinkle onset angle). This requirement motivates the need to fully understand the errors involved in measuring the kinematics of a UBE test.

Figure 9. The black line in each plot indicates the situation where the measured angle is exactly equal to the calculated angle. The points are manual measurements made using Imagej after analysing 2-D images of the simulation. The red line indicates the true Abaqus result for the following cases: (a) No pre-shear plotted vs Eq 1, (b) Positive pre-shear plotted vs Eq 1, (c) Negative pre-shear plotted vs Eq 1, (d) No pre-shear plotted vs Eq 2, (e) Positive pre-shear plotted vs Eq 2 and (f) Negative pre-shear plotted vs Eq 2.

A final point to note in relation to Figure 9 is that the Abaqus prediction (red line) drops below the ideal shear angle calculation due to finite extension occurring in the fibre directions. In practice, an even greater reduction in the measured shear angle typically occurs at high levels of shear for real fabrics, though not because of fibre extension, but rather because of the effects of intra-ply slip (Harrison et al., 2008).

3.2 Wrinkling Error Associated with Method B: 2-D Full-Field Analysis

As discussed in Section 2.2, nodal co-ordinates of the simulations are assumed to be equivalent to output produced by either 2-D DIC (using just the x-y nodal co-ordinates), or 3-D DIC (using the x-y-z nodal co-ordinates). Shear angle measurements made using 3-D full field analysis (corresponding to stereoscopic DIC), were shown in Section 2.2.2 to be largely unaffected by out-of-plane wrinkling (see Figure 4). In this section, the error associated with out-of-plane wrinkling when using a purely 2-D full-field analysis of the UBE test is considered. Figure 10 shows that at low shear angles, in the

absence of out-of-plane wrinkling, the 2-D and 3-D algorithms produce almost identical results. However, at a shear angle of 60° when the sample is strongly wrinkled (see Figure 2 for evolution of wrinkle versus shear angle), the shear angle output from the two algorithms is significantly different. In the region of the wrinkle, the 2-D approach overestimates the measured shear angle by as much as 12° (around 20%). In other words, Method B (equivalent to the 2-D DIC approach) suffers from the same issue as Method A (manual image analysis) discussed in Section 3.1; both significantly overestimate the measured shear angle when wrinkling occurs. The issue of specimen pre-shear is not explicitly discussed in relation to the 2-D full field approach, instead the pre-shear problem is deferred to the next section, where it is discussed in relation to the 3-D full field approach.

Figure 10. Left-hand column (a), (d) and (g), show 2-D analysis at 3 successive instances during the test. Middle column, (b), (e) and (h), shows equivalent 3-D analysis. The colour legend to the right of the middle column indicates the shear angle for both the 2-D and 3-D analyses. Right-hand column (c), (f) and (i), shows 3-D analysis minus 2-D analysis, i.e. the difference between the 2-D and 3-D

results. The colour legend to the right of the right-hand column indicates the difference in shear angle.

3.3 Evaluation of Pre-Shear Error in Full Field Analysis

The issue of sample pre-shear is equally important to both 2-D and 3-D full-field analysis and affects both to the same degree. For this reason, to avoid repetition, the influence of fabric pre-shear, and its subsequent correction using full-field shear angle initialisation, is demonstrated only for the 3-D full-field algorithm. Figures 11a-c show the Abaqus simulation result when a small positive pre-shear of the UBE test is introduced (also shown in Figure 3a), at three subsequent instances during the test. Figures 11d-f show the shear angles calculated using the 3-D full field algorithm if the tows are incorrectly assumed to be orientated initially at exactly $\pm 45^\circ$ at the start of the test, i.e. if the specimen pre-shear is ignored and no steps to correct the initial pre-shear are taken. Figures 11g-i show the difference between the simulation and the full-field analysis and is effectively the error in the 3-D full field measurement due to unintended positive fabric pre-shear when installing the sample in the test machine. Figure 12 shows the same information for the negative pre-shear case (the initial negative pre-shear state is shown in Figure 3c).

Figure 11. (a-c) Abaqus shear angle prediction at 3 instances in time. A small positive pre-shear is introduced in the initial state (d-f) 3-D full field shear angle at the same 3 instances, calculated assuming tows are orientated initially at exactly $\pm 45^\circ$ (g-i) difference between Abaqus prediction and 3-D full field algorithm.

Figure 12. (a-c) Abaqus shear angle prediction at 3 instances in time. A small positive pre-shear is introduced in the initial state (d-f) 3-D full field shear angle at the same 3 instances, calculated assuming tows are orientated initially at exactly $\pm 45^\circ$ (g-i) difference between Abaqus prediction and 3-D full field algorithm.

An interesting point to note in both cases is that the error due to initial pre-shear tends to decrease as the shear angle increases. This result is not particularly intuitive but can be verified via analytical

analysis of the deformation occurring in Region A of the test specimen. The analysis examines how the deformation changes the apparent tow directions and apparent shear angle, when the assumed tow directions are not properly aligned with the true tow directions.

Figure 13. Pure shear deformation in Region A of UBE test.

Consider pure shear deformation in the x - y co-ordinate system shown in Figure 13. The square region (dashed line) represents Region A prior to deformation. The thin black line shows Region A after α° of shear (a positive pre-shear), while the thick black line shows Region A after a further β° of shear, i.e. the total shear angle is $\theta = \alpha + \beta^\circ$. It can be shown that the deformation gradient tensor, $\mathbf{F}_x$, involved in shearing the sample from α° to β° is,

$$\mathbf{F}_x = \begin{bmatrix} 1 & \frac{\sin(\alpha+\beta)}{\cos\alpha} - \tan\alpha \\ 0 & \frac{\cos(\alpha+\beta)}{\cos\alpha} \end{bmatrix} \quad (11)$$

If the tow direction after the pre-shear of α° is correctly assumed to lie along the red arrow (the unit vector $\sin\alpha\mathbf{i} + \cos\alpha\mathbf{j}$) then application of $\mathbf{F}_x$ will increase the shear angle in Region A, θ , to $\alpha + \beta^\circ$. However, if the initial pre-shear is ignored, and instead of the red arrow, the green arrow (the unit vector $\mathbf{j}$) is incorrectly assumed to represent the initial tow direction (effectively ignoring the sample pre-shear), then application of $\mathbf{F}_x$ increases the apparent shear angle in Region A to,

$$\theta_{\text{apparent}} = \text{atan} \left\{ \frac{\sin(\alpha+\beta) - \sin\alpha}{\cos(\alpha+\beta)} \right\} \quad (12)$$

The difference between the actual shear angle, θ , and the apparent shear angle, θ_{apparent} , calculated using Eq (12), is plotted as black lines in Figure 14. The numerical results for the positive and negative pre-shear cases are also plotted as red lines for comparison and are seen to be very close to the analytical result. The difference is due to the slightly non-ideal kinematics occurring in the simulation due to the influence of the in-plane bending stiffness on the sample kinematics (an effect ignored in the analytical analysis). The difference between the actual shear angle, θ , and the analytical apparent shear angle, θ_{apparent} , for various other values of sample pre-shear (from -4° to $+4^\circ$) are also shown in Figure 14. The graph shows that, for all pre-shear angles, the difference between the apparent and true shear angles decreases as the true shear angle increases. Both the numerical and analytical results indicate that the error decreases relatively slowly with increasing shear angle and effectively persists throughout all the recorded data for each test.

Figure 14. Evolution of error due to pre-shear in Region A, the number in blue indicates the initial pre-shear error and the black lines show how the analytical error decreases with an increase of the true shear angle. The red line shows how the numerical error decreases with an increase of the true shear angle.

3.4 Correction for Specimen Pre-Shear in Full-Field Analysis

In order to correct for unintended fabric pre-shear, manual full-field initialisation of the shear angle across a specified region of the test specimen has been performed, as explained in Section 2.2.4. This is the full-field equivalent to using the inter-tow angle at the centre of Region A, ϕ_{ic} , to correct the results produced via manual image analysis (see Section 2.1). Figures 15 and 16 show the technique applied to the positive and negative pre-shear cases discussed in Section 3.3. The left-hand columns show the Abaqus result at three instances during the course of the test, the middle column shows results of the full-field analysis at the same instances in time but when pre-shear is ignored, and the right-hand column shows the full-field results after initialisation (which is conducted at the start of the analysis). To allow easier visualisation of the results, the initialised region in the right-hand column has been superposed over the Abaqus prediction. The slight variability in the initialised region comes from the human error introduced by measuring the initial tow directions by hand. Manual initialisation has been employed in order to demonstrate the typical accuracy that might be expected when using the same technique in actual experiments (initialising using the exact results from Abaqus produces almost exactly the same result as the simulation; a task conducted in order to check the validity of the initialisation code but not shown here). The results shown in Figures 15 and 16 are noticeably better than those shown in Figures 11 and 12, despite the introduction of a small amount of variability due to manual initialisation. Thus, it can be concluded that use of 3-D full-field measurements techniques, such as stereoscopic 3-D DIC, combined with careful analysis involving initialisation of tow directions, should be able to eliminate virtually all kinematic measurement errors related to both out-of-plane wrinkling (see Figure 7) and fabric pre-shear in the UBE test.

Figure 15. Positive pre-shear correction using full-field initialisation within the area shown by the dotted black line. (a), (d) and (g) show the Abaqus results at 3 instances in time, (b), (e) and (h) show the full-field analysis at the same instances in time when ignoring the initial positive pre-shear, (c), (f) and (i) show the full-field analysis after initialising the tow directions to account for the initial positive pre-shear.

Figure 16. Negative pre-shear correction using full-field initialisation within the area shown by the dotted black line. (a), (d) and (g) show the Abaqus results at 3 instances in time, (b), (e) and (h) show the full-field analysis at the same instances in time when ignoring the initial negative pre-shear, (c), (f) and (i) show the full-field analysis after initialising the tow directions to account for the initial negative pre-shear.

3.5 Error in Force Data due to Specimen Pre-shear and Wrinkling

Thus far, the investigation has focused on understanding the effects of pre-shear and wrinkling on the accuracy of kinematic measurements. As already emphasised, understanding and mitigating the error in kinematic measurements is an important pre-requisite to accurately estimating the in-plane bending stiffness of the fabric (D'Agostino et al., 2015; Ferretti et al., 2014; Harrison et al., 2017; Steigmann and Dell'Isola, 2015). Specimen pre-shear and fabric wrinkling also introduce errors when measuring the shear stiffness of the fabric; usually the primary purpose of the UBE test. This error arises for two reasons. First, the shear stiffness of the fabric is derived from the axial force versus measured shear angle data; any error in the measured shear angle kinematics will thus influence estimates of the shear stiffness. The second point is again related to specimen pre-shear, but this time is caused by the combined effect of specimen pre-shear and the standard experimental practice of zeroing the force recorded by the test machine at the start of a test. To demonstrate the latter point, the measured axial force versus shear angle data predicted by the Abaqus simulation is plotted in Figure 17. Normalised axial force versus shear angle predictions, produced by the simulation, are plotted for cases a and b (involving no pre-shear and a 4.85° positive pre-shear). The side length of Region A, L_A , is used to normalise the axial force. Mimicking the usual practice followed in experimental investigations, the axial force is zeroed when the UBE test specimen is in its initial position. This procedure introduces a small error in the form of a vertical shifting of the axial force versus measured shear angle curve (see Figure 17). Note that the error introduced by a negative pre-shear is likely to be less significant than that produced by a positive pre-shear as negative pre-shear tends to cause the specimen to buckle rather than shear, and consequently has less impact of the initial axial force.

Figure 17. Axial force per unit length versus true shear angle for two test cases. The red curve has no pre-shear while the blue curve involves a positive pre-shear. The difference in the two results is caused by zeroing the measured force at the start of the test.

The combined influence of errors due to the effects of specimen pre-shear and out-of-plane wrinkling, on axial force versus measured shear angle data are now plotted. The normalised axial force (including errors introduced by zeroing the test machine, as shown in Figure 17) versus the measured shear angle kinematics produced via manual image analysis, are shown by the points. Similar results might be expected if a 2-D DIC technique was used to measure the shear angle data instead of manual image analysis. The 'correct' result predicted by Abaqus is plotted as a red line,

almost identical results are provided by the zero pre-shear full-field analysis (not plotted here) while the initialised positive pre-shear full-field analysis is shown as the blue line.

Figure 18. Axial force versus measured shear angle data. The red line shows the true result predicted by the simulation. The data points show the results produced by manual image analysis in the case of no pre-shear and an initial positive pre-shear. The blue line shows the result from the 3-D full field analysis initialised for the positive pre-shear. The 3-D full field analysis in the case of no pre-shear co-incides almost exactly with the simulation result (red line) and is not shown here.

As discussed in Section 3.1, the occurrence of out-of-plane wrinkling leads to significant overestimates of the measured shear angle when using 2-D analysis techniques which has a significant impact on the form of the axial force versus shear angle curve (see Figure 18). The case examined in this investigation involves a severe wrinkle (see Figure 1b and Figure 2) leading to a large overestimate; less severe wrinkles can be expected to produce smaller errors. Use of stereoscopic 3-D DIC is an effective method of eliminating the wrinkle error from the kinematic measurements. The 3-D full field analysis in the case of no pre-shear co-incides almost exactly with the simulation result (red line) and for clarity, is not shown in Figure 18. The combined effect of specimen pre-shear and zeroing of the measured axial force produces a downward shift of the measured axial force versus shear angle curve, mainly affecting the form of the curve at low shear angles. The exact amount of shifting depends on the form of the curve and the size of the pre-shear angle. Both 2-D and 3-D analysis methods are susceptible to this type of error, as seen in Figure 18.

4. Conclusions

Sample pre-shear and out-of-plane wrinkling have been shown to introduce inaccuracies in UBE test shear angle measurements. These errors have important consequences when aiming to measure both the shear stiffness and in-plane bending stiffness of engineering fabrics. The size of the errors depends on the measurement technique employed to extract the kinematic data. 2-D analysis techniques are susceptible to errors due to out-of-plane wrinkles while both 2-D and 3-D analysis methods are susceptible to specimen pre-shear. Sample pre-shear is an entirely unwanted effect and the first step to improving the quality of UBE test results should be to eliminate it as much as

possible via careful sample preparation and careful installation of the test specimen in the test machine. Reporting the average pre-shear angle and the standard deviation of the pre-shear angle obtained from a given dataset serves to increase confidence in results. For example, experience suggests an average pre-shear angle of less than $\sim 0.5^\circ$ and a standard deviation of the initial pre-shear angle less than $\sim 2^\circ$ produces repeatable data. Nevertheless, some degree of specimen pre-shear is inevitable. This investigation demonstrates that the adverse influence of pre-shear can be mitigated by taking it into account when analysing results. This is simple to do when performing manual image analysis by swapping Eq (1) with Eq (2) when calculating ideal shear angle data; important information used in assessing the fabric's in-plane bending stiffness (Ferretti et al., 2014; Harrison et al., 2017; Steigmann and Dell'Isola, 2015; Turco et al., 2016). However, error associated with pre-shear and zeroing of the axial force at the start of a test is difficult to correct. A full-field initialisation technique has also been demonstrated to improve shear angle measurements made using either 2-D or 3-D digital image analysis of the UBE test; an important correction when aiming to examine the effects of in-plane bending stiffness of full-field shear kinematics.

A fabric's propensity to wrinkle during a UBE test is related to its mechanical forming properties and also to the size of the test specimen; larger specimens tend to wrinkle earlier and with greater severity (Harrison et al., 2017). This investigation shows that wrinkles can introduce errors (overestimates) of up to 20% when measuring the fabric's shear angle using either manual image analysis or 2-D full-field image analysis techniques such as 2-D single camera DIC. Initially, one may therefore wish to reduce wrinkling by decreasing the specimen size. Unfortunately, this can potentially have the adverse effect of reducing the specimen's cohesion and integrity (Gatouillat et al., 2013; Harrison et al., 2017, 2008; Pan et al., 2015), introducing undesirable error in measured versus ideal shear angle data due to intra-ply slip. Furthermore, measuring the wrinkle onset angle can provide valuable information on the torsional stiffness of a sheared fabric (Harrison et al., 2017). Wrinkling in the UBE test specimen is therefore not necessarily a behaviour to be prevented. Instead, a pragmatic approach is to measure the wrinkle onset angle during the UBE test, then anticipate the overestimate in the measured shear angle data when using manual image analysis or 2-D DIC, possibly adjusting the data accordingly. Alternatively, a more accurate but elaborate approach is to employ two-camera stereoscopic 3-D DIC to provide accurate full-field shear angle data even in the presence of out-of-plane wrinkling. Techniques to minimise the effect of surface treatment (application of a random speckle pattern) on a fabrics' mechanical forming properties still need to be explored, as even relatively low-impact techniques, e.g. Harrison et al. (2017), can result in significant changes in these properties. Ultimately, the main question is whether these material characterisation errors translate to noticeable changes in the forming and wrinkling mechanics of engineering fabrics during complex forming operations. This will be the subject of further investigation.

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