USE OF DIGITAL IMAGE CORRELATION TO OBTAIN MATERIAL MODEL PARAMETERS FOR COMPOSITES

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SUMMARY

The development of material parameters for FEA is heavily reliant on precision material data that captures the stress-strain relationship with fidelity. While conventional methods involving UTMs and extensometers are quite adequate for obtaining such data on a number of materials, there are important cases where they have been known to be inadequate. The testing of composites to obtain directional properties remains a complex task because of the difficulty related to measuring these properties in different orientations. Digital Image Correlation (DIC) methods are able to capture the stress-strain relationship all the way to failure. In this paper, we combine DIC and conventional methods to measure directional properties of composites. We exploit the unique capability of DIC to retroactively place virtual strain gauges in areas of critical interest in the test specimen. Utilising an Iosipescu fixture, we measure shear properties of structured composites in a variety of orientations to compute the parameters of an orthotropic linear elastic material model. Model consistency is checked by validation using Abaqus.

KEYWORDS

Material parameters, composites, testing, orthotropic, (DIC) digital image correlation, anisotropy, Iosipescu

1: Introduction

Material modelling of structured composites is an increasingly ‘hot’ topic today as these materials enter the mainstream of new product development. The primary mover still remains the aerospace industry, which has made great inroads incorporating these high-strength materials into structural components for aircraft. The success of these initiatives is clearly evidenced in the Airbus A380 and Boeing 787 Dreamliner projects where significant economic and technical advantage was attained from their use. Now, other industry verticals like the automotive industry are following suit, with strong research initiatives to convert a hitherto batch process to a production-line type operation.

Structured composites are made up of layers of polymer resin-impregnated fabric (prepreg) fused together in different orientations to create a sheet with desired properties. As many as 6 to 20 layers may be used in a typical composite with repetitions of orientations in 0º, 90º and 45º, though other orientation angles may also be used [1]. The end result may be to tune the resulting sheet to have certain desired directional properties for a particular application. This capability gives great flexibility to the designer in creating materials and geometries for various load-bearing applications. The use of structured composites to replace metals comes however, with a difficult design challenge. Metals are by and large linear elastic and isotropic in nature rendering their simulation to be relatively easy. To describe the elastic behaviour of a metal requires little more than a modulus and Poisson's Ratio. A shear modulus is easily calculated from these two properties. With composites, on the other hand, the material is not isotropic and the modulus can differ greatly depending on the orientation. This directionality is controlled by careful placement of each layer of the composite to achieve the desired directional properties. Elastic modulus, Poisson's Ratio and shear modulus all become dependent upon the orientation. It is clear that isotropic material models become ineffective for the simulation of composites. Anisotropic material models must be used. The matrix of required directional properties now becomes large and difficult to measure. Consequently, simplifying assumptions are often made when modelling composites. Orthotropic and transversely-orthotropic material models greatly reduce the number of required measurements [2]. While for the anisotropic material, a second order tensor and up to 21 material property constants are required, for orthogonal isotropy only 9 constants are needed to describe the relationship between forces/moments and strains/rotations.

Pre-processor software exists today to assemble lay-ups and then compute an appropriate material model based on the properties of the individual layer [3]. A laminate is defined as comprising a number of layers. The software computes the properties of the laminate and then exports the calculated material data and the lay-up information in a native format of the FE tool. Materials can also be exported as such without any laminate lay-up data. These estimations have been found to be very useful because of the difficulty with obtaining measured properties of the composite. The predictive nature of this approach carries the risk that the actual composite may not have theoretically postulated properties. Many factors can contribute to this: improper cure of the composite layers, voids, interlaminar defects as the layers are fused, inexact orientation of the lay-ups, to name a few. It is therefore of more than academic value to have test methods to actually measure the anisotropic properties of these composites. Only a few of these measurements are easy. The shear properties are quite difficult. Other required properties are virtually impossible to measure. Additional difficulty arises from knowing that the material model, once assembled, needs to be self-consistent because, just as with hyper-elastic behaviour, the properties comprising the model are inter-related. Checks are necessary to ensure this self-consistency; the material model must be able to replicate some of the more complex material tests in simulation. This is not just a confidence-building step but a core requirement for composite material model calibration.

2: Materials

The composite used for this study was a multi-layer high strength carbon fiber fabric composite #8181K36 readily available from McMaster Carr [4]. It is composed multiple layers of a solution coated epoxy-fabric prepreg. The details of the lay-up are not available. The material is available in 3.2 mm (1/8") thick sheet form and test specimens were cut from the sheet using CNC methods. For the purpose of describing orientation, a coordinate system prescribed by ASTM D5379 [5] was used as shown in Figure 1 below.

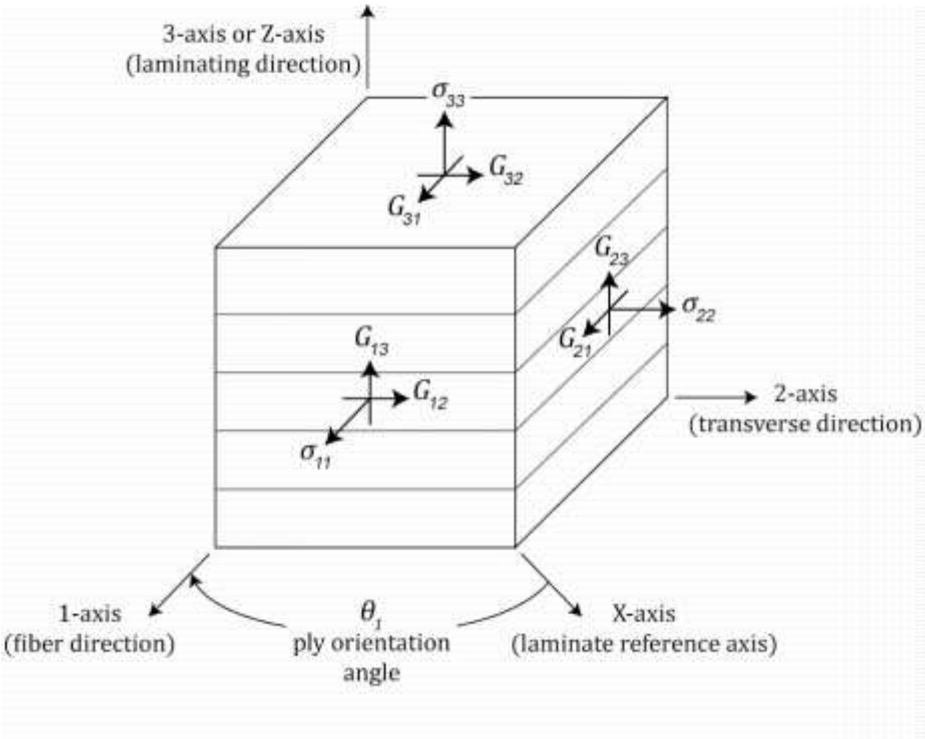

Figure 1: Composite coordinate system

In this orientation, the thickness direction was taken to be the 3 –direction while the 1 and 2 directions were taken to be in the plane of the material. The 1 direction was arbitrarily taken to be the one exhibiting the higher tensile modulus. For the shear modulus Gij, the i refers to the direction of resultant rotation that arises from a deformation applied in the j direction.

3: Material Model

The orthogonal linear elastic material model is often applied to the simulation of composites, exploiting the fact that the properties in some of the orientations are equivalent; particularly, NUij/Ei = NUji/Ej. This simplification greatly reduces the number of required measurements to 9 and also makes it much easier to test the model for self consistency. The model, shown below requires an equal number of tensile moduli, Poisson's ratios and shear moduli as described below [6].

$$\underline{\underline{S}} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix}$$

Figure 2: Orthotropic material model matrix

Of these, E1, E2 and NU12 and NU21 are relatively easy to measure. NU13 and NU23 are feasible with the right metrology. G12 can be measured using 2 techniques with moderate difficulty. Additionally, we propose a method for measuring G31 and G23. E3, the modulus in the thickness direction is virtually impossible to measure, as are the Poisson's Ratios connected with this orientation. This is because structured composites are typically in sheet form and therefore, the 3 direction is very thin; 3 mm in the current study. Reliable methods to not exist to clamp and pull a specimen of such dimension. While a compressive test is easily performed it is not clear that a compressive modulus would be the same as a tensile modulus for such a material.

4: Experimental Work

Testing was carried out using Instron universal testing machines (UTM). All testing was carried out at room temperature on test specimens conditioned after machining for at least 40 hours at 50% relative humidity. Tensile properties were measured in conformance with ASTM D638 [7], a standard commonly used to test plastics. Test specimens of ASTM D638 Type I geometry were machined from the sheet. They were tabbed in the grip region to protect them from damage from the clamps.

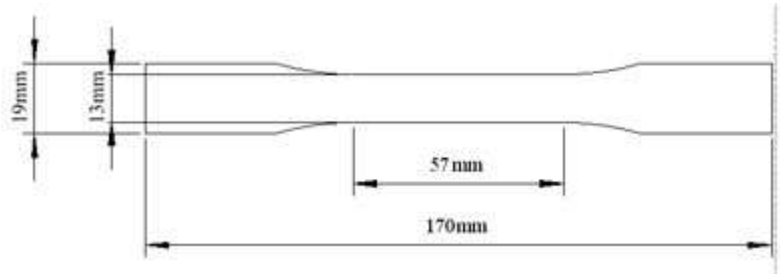

Figure 3: ASTM D638 Type I test specimen geometry

A high strength 100KN load frame was employed, given the very high tensile modulus of this material. A test speed of 5 mm/min was used. Careful consideration was given to the choice of strain measuring devices. While strain gauges are widely specified for testing of composites, we rejected these devices as being quite subjective, depending on the skill of the technician for proper placement and the resultant accuracy being quite dependent on proper attachment. Hence the degree of uncertainty associated with their use could not be properly quantified. We also considered digital image correlation (DIC), which will be described in more detail later, but did not use it for the tensile property measurements. We felt it unnecessary for measurements where the stress-strain response is essentially linear with no significant plasticity prior to failure. In findings to be published separately, we show that the tensile stress-strain response is not different from contact extensometry as long as there is no localization of strain. Contact extensometry, on the other hand, was found to be most suitable for this case because of the linear deformation of the material plus the added benefit of control over the uncertainty of the measurement; an NIST traceable device that could be predictably attached rendering a well quantified strain measurement. Two contact extensometers were used, one to measure the linear strain and a transverse extensometer to measure the strain in the 2 and 3 direction respectively. From these measurements, the tensile moduli E1 and E2 could be measured, as well as four Poisson's Ratios: NU12, NU13, NU21 and NU23. Because the specimens were properly tabbed, the specimens failed through the mid-plane on opposite ends right at the onset of the radius. The failure stress σ_f and strain ε_f were therefore considered to be reliable and the stress-strain relationship was confirmed to be linear elastic followed by failure.

E1 (MPa)	σ_{f1} (MPa)	ε_{f1} %	E2 (MPa)	σ_{f2} (MPa)	ε_{f2} %	NU12	NU13	NU21	NU23

81531	1014	1.2	62117	838	1.3	0.034	0.361	0.042	0.489

Figure 4: Tensile properties of the composite

The measurement of shear modulus was considerably more difficult. Three test methods were investigated. One of the simplest methods for measuring shear modulus is the plate-twist method described in ISO 15310 [8]. A 100 mm square of the sheet is twisted at opposing corners using a UTM. The in-plane shear modulus is readily calculated from load and crosshead displacement, using the equations provided. The measured value would theoretically appear to be the average of the shear moduli G12 and G21. In the case of composites layered so that NU12/E1 = NU21/E2, the measured shear modulus would be appropriate because G12=G21, but this is not always the case as we found in this study. The greatest advantage of ISO 15310 is ease of measurement. It cannot be used to measure shear moduli in the 2 and 3 directions. It is also unsuitable for failure properties. With this method, an in-plane shear modulus of 4458 MPa was measured.

All other shear property measurement methods are rendered considerably more difficult on account of the need to measure a shear strain. This is strictly a local measurement which must be performed in a region of the test specimen which is in a purely shear state. The situation is rendered complex because there is not always an *a priori* knowledge of this location prior to test to enable the proper placement of strain measurement devices. It is in this case that the DIC methods came to the fore.

Figure 5: Iosipescu shear fixture

The Iosipescu method [5] has been in existence for a half century. It is capable of imparting a uniform local shear state to a material and requires the placement of strain gauges in this region for the measurement of strain. The technique is not commonplace because of the complexities related to accurate gauge placement plus ensuring that the predetermined strain gauge locations are truly in a location of pure shear [9]. In our work, we prepared and notched the test specimens as prescribed in the standard using CNC methods. The specimen surface was then sprayed with a speckle pattern in preparation for the DIC measurement. The specimen was placed in the Iosipescu fixture and then subject to shear deformation using an Instron servo-hydraulic UTM. The measured force and displacement data was transmitted to the DIC apparatus.

An Aramis DIC apparatus manufactured by GOM was used. The DIC apparatus focuses twin stereo-cameras on the speckled surface of the test specimen. As the test progresses, a stereo video recording is made that is capable of capturing the relative displacement of the pattern to sub-pixel (micro-strain) resolution. The progression of the test clearly identifies the three-dimensional displacements in the test specimen. The unique construction of the Iosipescu experiment creates a region of pure shear in the region of interest in the test specimen and this can be physically observed by the DIC apparatus through the progression of the test. A virtual strain gauge is placed in this region ensuring that it is completely within the pure shear region throughout the test. The shear strain is captured in this way with fidelity. The force data from the UTM is used to compute the shear stress. Both the G12 and G21 directions were measured in this way.

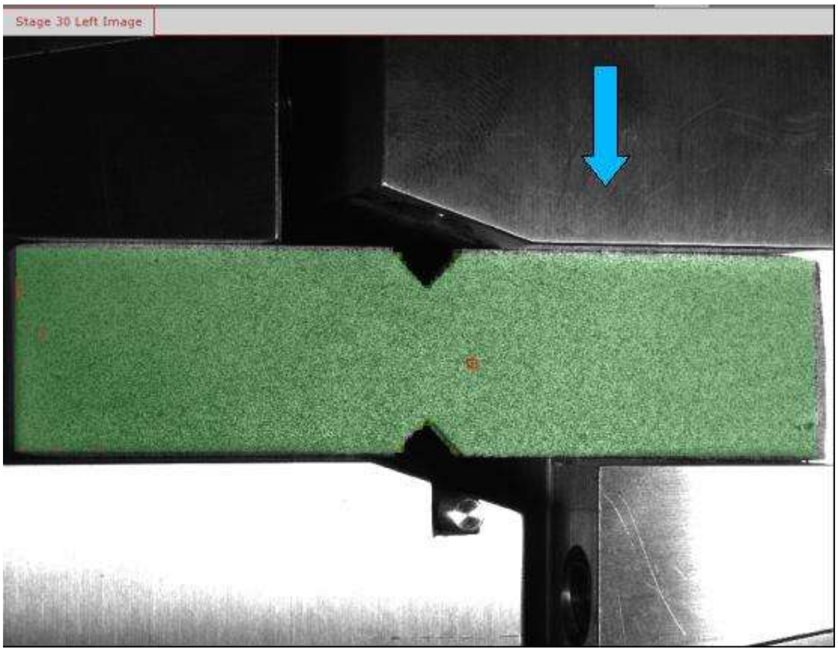

Figure 6: Speckle coated specimen in Iosipescu Fixture

The ASTM D5379 standard also shows how the other shear directions can be measured. By simply laying up additional layers to the desired thickness, it is possible to measure shear properties in the 2 and 3 directions. Practical considerations related to preparing such specimens could prevent these measurements unless one has the in-house capability to produce test layups of thickness enough to create specimen slices in the 2 and 3 planes. Accordingly, we adopted a modified strategy that would make these tests feasible while preserving the essence of the measurement. For the 3 direction, a rectangular test specimen 12.7 mm wide was tabbed with steel plates to create a test specimen that could be clamped in the Iosipescu fixture.

The thickness face of the specimen was speckled in preparation for DIC measurements. During the test, the deformation was made in the 3 direction while measuring shear angle in the 1 direction, thus obtaining the G13 measurement. A specimen cut in a 90º orientation to this rendered a G23 measurement.

G12 (MPa)	G21 (MPa)	G13 (MPa)	G23 (MPa)
4478	3131	3410	2817

Figure 7: Directional Shear Moduli measured using Iosipescu/DIC methods

5: Simulation and Correlations

Simulations of the Iosipescu G12 experiment were performed using Abaqus Standard Release 6.11. The composite was nominally modelled in 3 layers of equal thickness, 0º, 45º and 90º. A composite material model was used with the engineering constants option, which assumes symmetry of properties along the diagonal of the matrix shown in Figure 2. In other words, NUij/Ei = NUji/Ej. The measured property data seems to indicate that this is not strictly true for the tested material. However, this option has the advantage of requiring less properties than ‘classic orthotropy’. The details of the material card are below.

E1	E2	E3	NU12	NU13	NU23	G12	G13	G23
81531	62117	1000*	0.032	0.361	0.489	4478	3410	2817

Figure 8: Engineering constants for Abaqus orthotropic composite material model

Because it was not possible to measure E3, we assumed a value of 1000 MPa, as being typical of the tensile modulus of the epoxy matrix material. We reasoned that the fibers would not contribute as much to the 3 direction stiffness, being perpendicular to this plane.

Boundary conditions were applied to mimic the clamping and displacement imposed by the Iosipescu test fixture. The left side of the sample was fixed in space and the right hand side had a displacement of -0.2 mm applied. The simulation result is shown below.

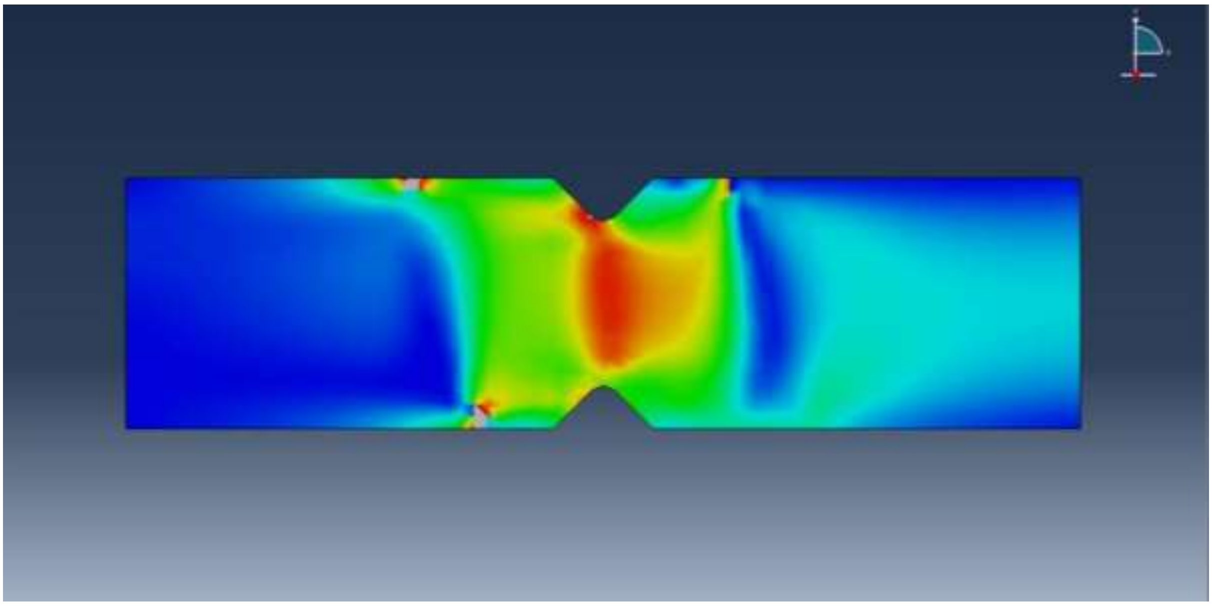

Figure 9: Shear region at 0.2 mm crosshead displacement - Simulation

The figure below shows the actual shear stress-strain response data obtained by DIC for the same displacement.

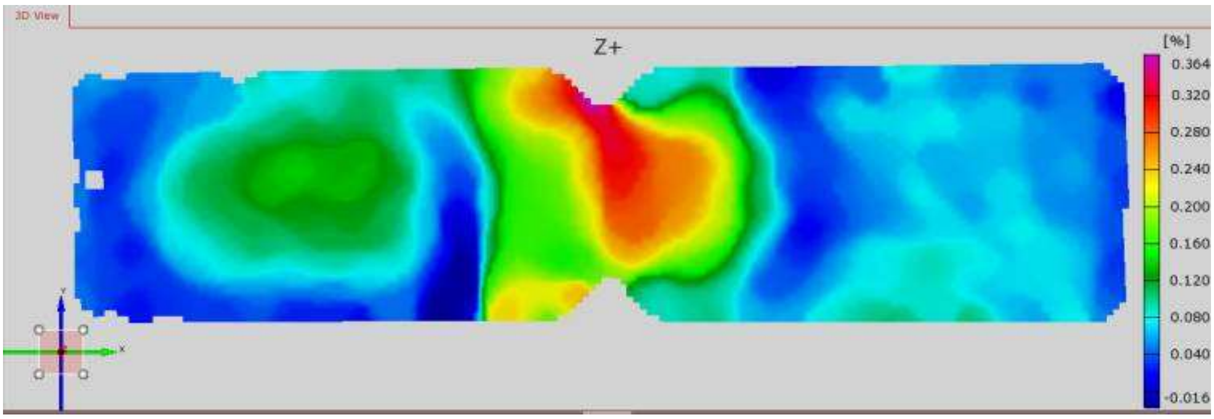

Figure 10: DIC Image of the G12 measurement at 0.2mm displacement

Shear stress-strain data from the simulation was reported at an element located directly between the notches. This was compared with shear data obtained from the DIC measurement.

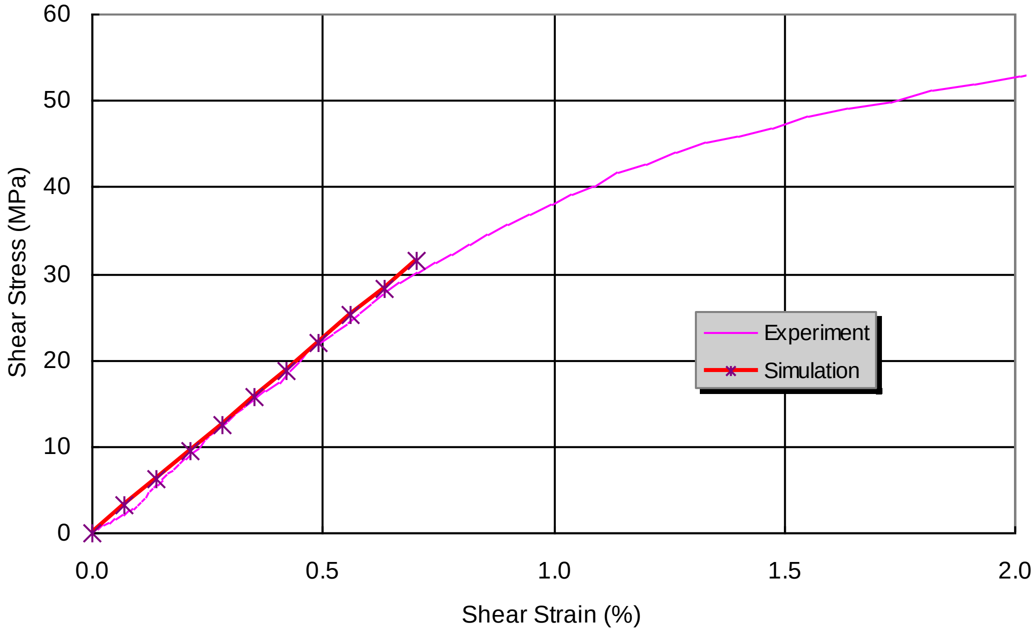

Figure 11: Comparison of shear stress-strain G12 (simulation v. experiment)

This first simulation was intended mainly as a sanity check to verify whether the simulation was functioning properly by returning the same shear modulus G12 as that which was supplied in the material model. Considering that the test specimen was experiencing pure shear in the 12 plane, we found that this was indeed the case with the simulation returning a modulus of 4478 MPa. The simulation also computed an E2 modulus of 62305 MPa, which is very close to the value of 62117 MPa measured from the tensile experiment.

A second simulation was performed of the ISO 15310 plate twist shear experiment. The simulation result is shown in the figure below.

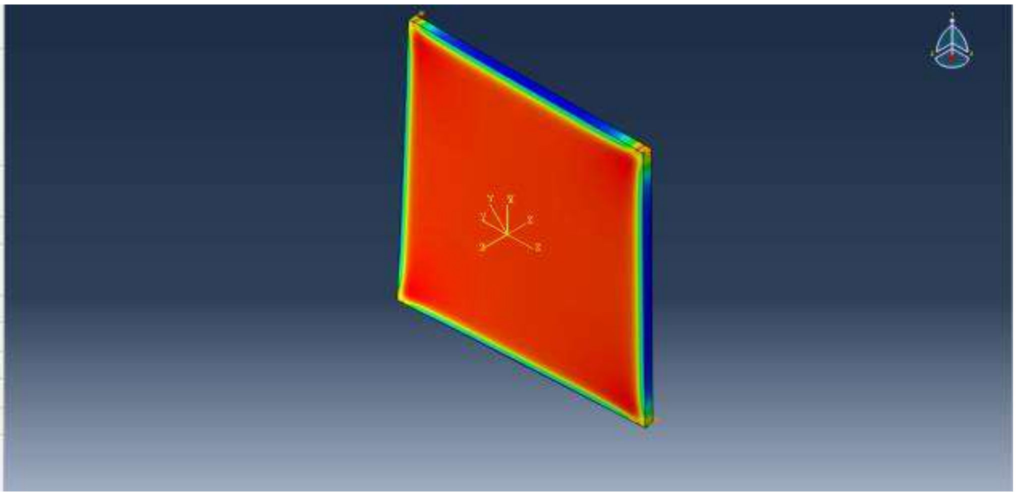

Figure 12: Plate twist simulation showing shear region.

Again, the slope of the shear stress-strain data returned a modulus of 4478 MPa, confirming that the plate twist experiment was in a state of 12 shear. The actual experiment measured a value of 4458 MPa as stated earlier.

The data shows that the simulation validates the experiment and that the linear elastic material model appears to perform quite well at small shear strains but will deviate from reality at larger strains because of the non-linear behaviour of the composite. The simulation will overpredict experiment by 14% at a shear strain of 1.5%.

6: Conclusions and Future Work

The linear elastic material model appears to perform quite well at small shear strains but will deviate from reality at strains exceeding 0.5% with errors as high as 15% at 1.5% strain because of the non-linear behaviour of the composite. The material model is capable of predicting composite behaviour in the plane of the material. Work is underway to validate the measurements in the thickness plane and for other more complex deformation modes.

In conclusion, we show that it is indeed possible to obtain almost all the material parameters with adequate precision for an orthotropic material model. Further, these parameters do not need significant optimisation in order to obtain acceptable results.

Composite material models in common use today do not capture the non-linear behaviour of these materials so that at moderate strains, there are deviations which degrade the ability of the simulation to provide good predictions. The availability of data at larger strains via DIC methods can provide an impetus for improved modelling. However in our work at least, it still needs to be ascertained that the large strain experimental data is free from artifact. The addition of non-linear capability to composite modelling should be considered. This step may positively impact efforts to simulate damage in the future.

7: Acknowledgements

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REFERENCES

1. Campbell, F.C. Jr., “Manufacturing Processes for Advanced Composites” Elsevier, (2003)

2. Abaqus Standard User’s Manual, Version 5.6, v1, 10.2.1-2 (1998)

3. Palantera, M. ESACOMP Software, private communication, Componeering Inc., Helsinki, Finland. (2013)

4. McMaster Carr # 8181K36 high strength light weight carbon fiber composite http://www.mcmaster.com/#catalog/119/3613/=llit0r (2013)

5. ASTM Standard D5379-05, “Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method”, American Society for Testing and Materials, (2005).

6. Boresi, A. P, Schmidt, R. J. and Sidebottom, O. M., 1993, Advanced Mechanics of Materials, Wiley.

7. ASTM D638, “Standard Test Method for Tensile Properties of Plastics”, American Society for Testing and Materials, (2010)

8. ISO 15310, “Fibre-reinforced plastic composites -- Determination of the in-plane shear modulus by the plate twist method “, International Organizatino for Standardization, (1999)

9. J.C. Xavier et al. / Composites: Part A 35, 827–840 (2004) http://home.utad.pt/~jmcx/pdf/Xavier2004.pdf