CHARACTERISATION OF PROPERTIES GOVERNING THE COMPRESSIVE STRENGTH OF PULTRUDED UNIDIRECTIONAL FIBRE COMPOSITES

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SUMMARY

This paper concerns the characterisation of properties governing the compressive strength of unidirectional carbon fibre reinforced composites. The shear modulus and shear yield strain are determined using the Iosipescu shear test combined with DIC. The fibre misalignment is determined by a newly developed image analysis algorithm called FTMA. The obtained results are evaluated through a compressive strength model.

Keywords: Carbon Fibre Composites, Pultrusion, Compressive Strength, Fibre Misalignment, Image Analysis, Iosipescu Test, Digital Image Correlation

INTRODUCTION

The use of carbon fibre reinforced composites in industrial applications such as wind turbine blades, automotive and marine applications is rapidly increasing. Because composites are complex materials the industry has an equally increasing need for new tools to assist in the development, design and testing/validation of future products.

The work presented in this paper focuses on the compressive strength of unidirectional (UD) carbon fibre reinforced composites (CFRP). This value is often less than 60% of the tensile strength [1], and thereby often a limiting design factor.

Micromechanical modelling of compressive failure in composite materials has received a significant amount of attention. Early models describe compressive fibre failure as an elastic instability event and later as a rigid perfectly plastic kinking [2].These models were then extended into an elastic perfectly plastic model by Budiansky [3] assuming that the failure mechanism is micro buckling of an infinite kink band normal to the fibre direction as seen in Fig. 1. According to [3] the compressive stress σ_c is given as:

$$\sigma_c = \frac{G}{1+\phi_0/\gamma_y} \quad (1)$$

The governing model parameters are the initial fibre misalignment ϕ_0, the shear yield strain γ_y and the shear modulus of the composite G.

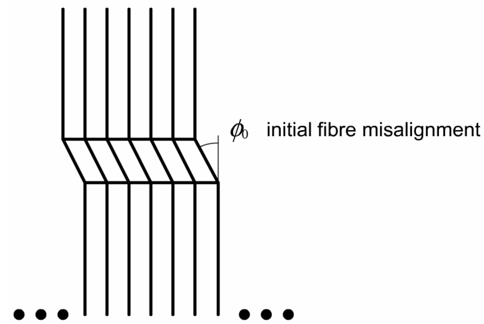

Figure 1. Cut-out of infinite kink band normal to the fibre direction.

More sophisticated models taking into account parameters such as fibre bending stiffness [1] and finite element analysis studying finite misaligned regions [4-5] have also been developed. The addition of finite fibre bending stiffness does, however, not change strength predictions significantly [6]. To keep the model simple focus is therefore put on the analytical linear elastic perfectly plastic by Budiansky [3].

Especially fibre misalignment has shown to be difficult to quantify accurately. Yurgartis [7] proposed a cross sectioning method, where the orientation of individual fibres where derived from measurements in high magnification optical microscopy. Others have suggested using confocal laser scanning microscopy (CLSM) to measure the fibre misalignment in glass fibre composites [8]. CLSM is however not applicable to carbon fibres. Newer methods use digital image analysis. The multiple field image analysis method (MFIA) [9] tracks intensity variations in the image and derives fibre orientations. The newest method, which has been used in the present study, is the Fourier transform misalignment analysis (FTMA) [10].

The shear modulus and shear yield strain can both be determined by the ASTM standardised Iosipescu shear test [11]. In the Iosipescu test a V-notched specimen is applied an anti-symmetric 4 point loading as shown in Fig. 2.

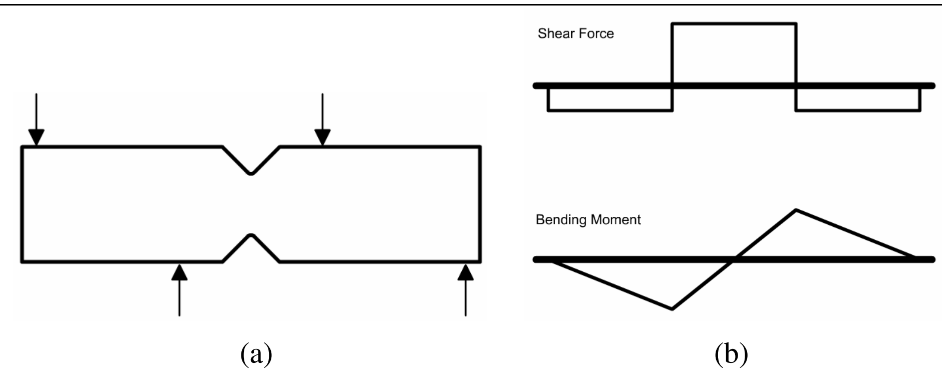

Figure 2. (a) Free body diagram of a V-notched Iosipescu specimen with anti–symmetric 4 point loading. (b) The shear force curve and bending moment curve resulting from the anti-symmetric loading in a.

However, the Iosipescu test has been shown to be sensitive to axial splits in the V-notch when testing UD [12] composites. The Iosipescu test setup has therefore been subject to a thorough examination and modification in this study. This includes finite element analysis (FEA) studies of different geometries, which have been compared to 2-D strain fields obtained experimentally for pultruded UD CFRP composites using Digital Image Correlation (DIC). With these analysis methods the material parameters governing the compressive strength according to the model of Budiansky [3] have been determined experimentally, and subsequently used to estimate the compressive strength of UD CFRP composites.

METHODS

Fibre Misalignment

The Fourier transform misalignment analysis method, FTMA-method, is a recently developed method [10] used to quantify fibre misalignment. The FTMA-method analyses digital micrographs of planes parallel to the fibre direction. Thereby fibres will appear as elongated white features as seen in Figs. 3(a) and 4(a)

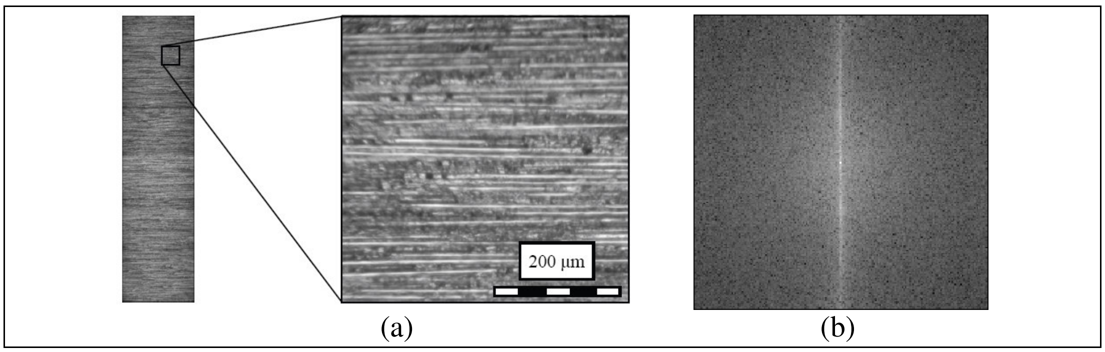

Figure 3.(a) Micrograph of pultruded UD CFRP. Fibre filaments appear as elongated white features. (b) Visualisation of frequency domain obtained from 2D Fourier transformation. The vertical bright line represents the fibre pattern.

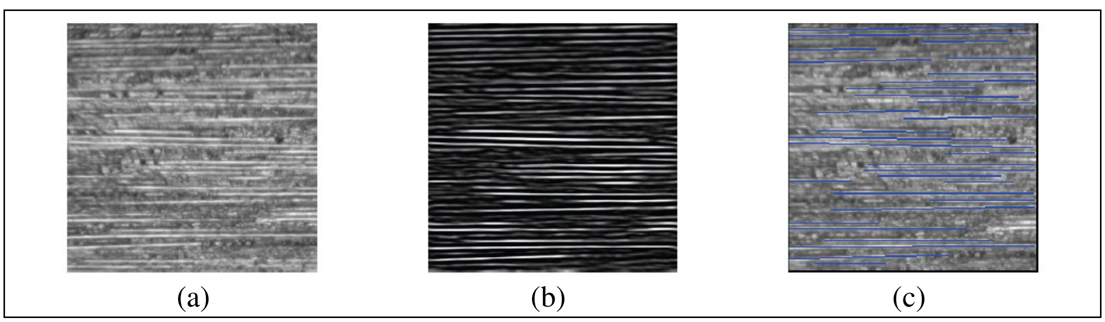

Figure 4.(a) The original micrograph. (b) Enhanced fibre patterns obtained from noise filtering. (c) Result visualisation - lines representing the individual fibres and their orientation superimposed onto the original micrograph.

The chosen plane parallel to the fibre orientation is difficult to polish without a significant amount of noise, and it is therefore necessary with a noise filtering that isolates the fibre pattern. This is done in the frequency domain obtained from a 2D fast Fourier transformation. This is possible because the fibres, even though distorted, are organised in a pattern of parallel lines. Such repetitive patterns become clear in the frequency domain as seen in Fig. 3(b) as a bright line normal to the mean fibre orientation of the analysed domain. The bright line in the frequency domain is then isolated by a filtering mask and an inverse Fourier transformation performed. This reduces the noise and enhances the fibre pattern as seen in Fig. 4(b). From the noise filtered image in Fig. 4(b) the individual fibres can be isolated and their orientation computed by linear regression. The results from the linear regression can be visualised as shown in Fig. 4(c). The FTMA-method analyses sub-domains of micrographs as indicated in Fig. 3. By dividing micrographs into several sub domains larger areas can be analysed and thereby enabling the identification and isolation of thousands of fibre objects. The fibre misalignment can then be derived from the angular distribution of the fibres.

Shear Modulus and Shear Yield Strain

The starting point for determination of the shear modulus and shear yield strain is the ASTM standardised Iosipescu shear test [11]. In this test a symmetric V-notched specimen is anti-symmetrically loaded as seen in Fig. 2. This gives a bending free gauge zone in the vertical symmetry line of the specimen as illustrated in Fig. 2(b). The V-notched specimen geometry smoothes the shear stress distribution.

In the present study of pultruded UD CFRP with a high degree of anisotropy, the ASTM standard geometry with a 90° notch suffered from undesirable axial splits in the tensile stressed part of the notch as shown in Fig. 5.

(a) (b)

Figure 5. (a) Sketch indicating the location of the axial splits. (b) Axial splits captured during test illustrated using DIC. The image shows major strains superimposed onto an image of the test specimen.

Instead of sophisticated FEAs modelling the axial split such as in [12] it was attempted to avoid the axial splits from developing. The first attempt was to minimise the strain gradients by opening the notch angle. The optimum notch opening angle 2θ was determined by the relation [13]:

$$\tan(\theta) = \tan(\theta_{iso}) \Big/ \sqrt[4]{\frac{E_y}{E_x}} \qquad (2)$$

This relation relies on the optimum angle for isotropic materials, which is $2\theta_{iso}$=110deg. With the degree of anisotropy E_y/E_x being approximately 1/19 for the pultruded UD CFRP, the optimum notch angle 2θ becomes 143deg. But opening the V-notch angle did not prevent the cracks from developing prematurely.

In the ASTM guidelines [11] a uniform shear stress distribution is assumed defined as:

$$\tau = \frac{P}{wt} \qquad (3)$$

where *P* is the shear force, *w* is the gauge width and *t* is the specimen thickness.

From the FEA studies it is seen that the initial symmetric geometry with a notch angle of 143° has an almost uniform stress distribution, see Fig. 6. This agrees well with the ASTM assumption.

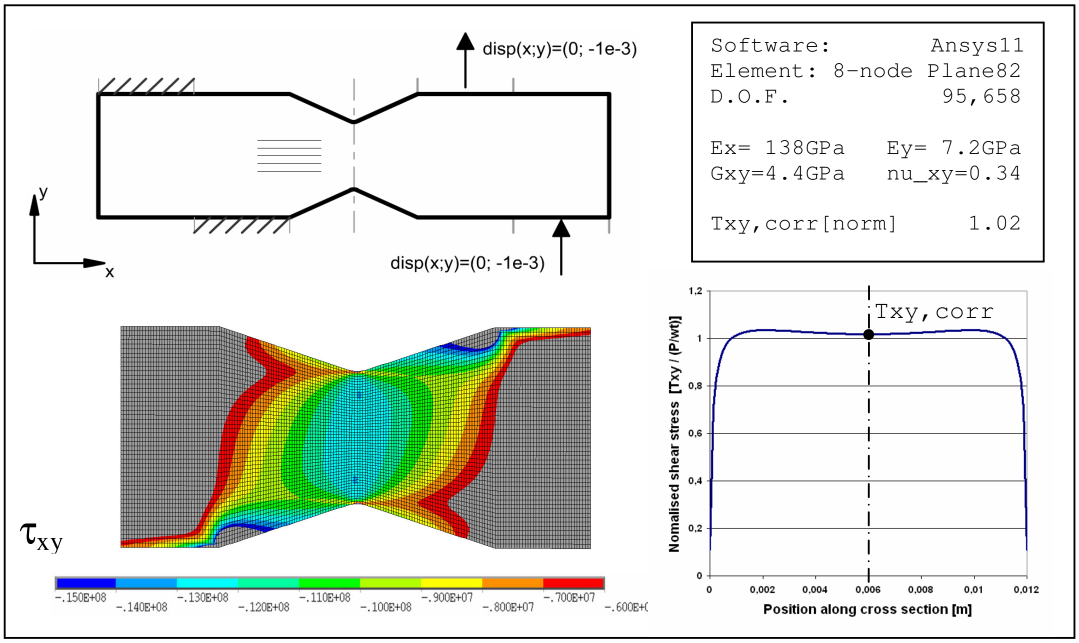

Figure 6. Result summary from linear FEA of symmetric UD CFRP Iosipescu specimen. The normalized shear stress plot represents the shear stress along the specimen centre line.

However, if axial splits develop horizontally from the notch sides (see Fig. 5) the stress distribution will gradually shift from being nearly uniform towards a parabolic distribution. With an aim of improving the measurement technique for measuring the shear properties this shift in stress distribution distorts the measurements and is therefore undesirable. A tabbed asymmetric Iosipescu specimen design as illustrated in Fig. 7 is therefore proposed.

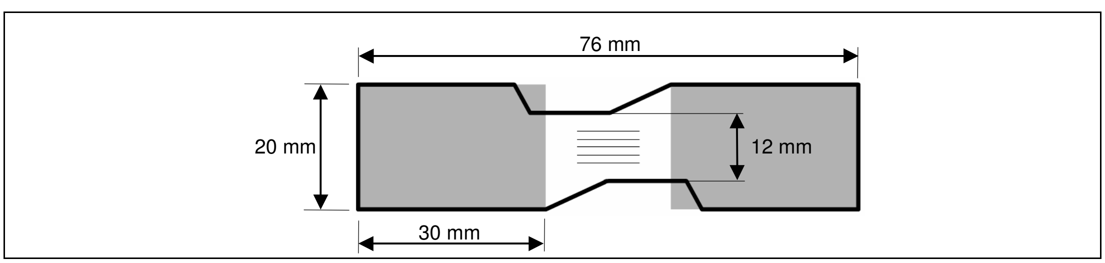

Figure 7. Sketch of proposed asymmetric Iosipescu specimen design. The grey areas illustrate tabs and the horizontal lines in the gauge area the fibre orientation.

The benefit of the asymmetric specimen design is that there is no UD material in the gauge area where axial splits can initiate, and thereby there will be no shift in stress distribution. The tabs that are glued on both sides of the specimen prevent crack initiation further away and improve the load transfer. However, the shear stress distribution is no longer uniform. FEA results for asymmetric specimen design, summarised in Fig. 9, show a more parabolic stress distribution than obtained for the symmetric specimen design.

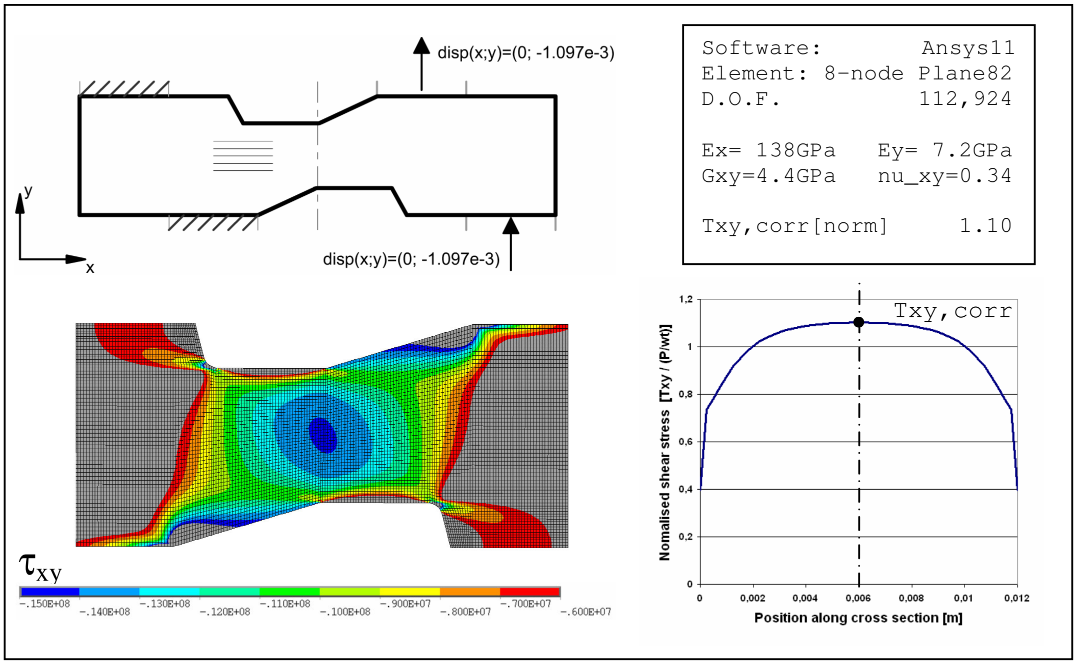

Figure 8. Result summary from linear FEA of UD CFRP Iosipescu specimen. The normalized shear stress plot represents the shear stress along the dashed line indicated on the sketch.

Based on the FEA results, it is possible to propose a "correction" of the shear stress level corresponding to each DIC measurement and thereby enable a more accurate estimation of shear modulus and shear yield strain. The correction factor is found from the normalised FEA based shear stress plots in Figs. 6 and 8. The normalised shear stress plots show the shear stress in the gauge area across the centre line normalised by the averages shear stress, Eq. (3). In the experiments the strain data were taken from the centre of the specimen. The shear stress "correction factor" $T_{xy,corr}$ should therefore also be taken from centre of the specimen. From the FE-studies it is thereby concluded that the shear stress correcting factor is 1.02 for the symmetric specimen and 1.10 for the asymmetric specimen.

The strain distributions of the test specimens were measured using DIC. The obtained data for each specimen were multiple 2D strain fields tagged with the corresponding load data measured by the load cell of the test machine.
The strain fields were used both for verifying the strain distributions and also to generate the stress-strain curves for computation of the shear modulus and the shear yield strain. Typical strain fields are shown in Figure 9.

From the shear strain fields shown in Fig. 9 it can be observed that there is an excellent correlation with the FEA predictions shown in Figs. 6 and 8. The symmetric specimen shown in Fig. 9(a) displays a nearly uniform shear strain distribution over the cross section. Furthermore, the strain field indicates that the shear strain in the centre is slightly lower the maximum strain which correlates well with FEA. The shear strain field obtained for the proposed asymmetric specimen shown in Fig. 9(b) displays near uniformity in a smaller and wider (compared with Fig. 9(a)) area near the centre part of the specimen and relatively lower strains near the edges of the specimen.

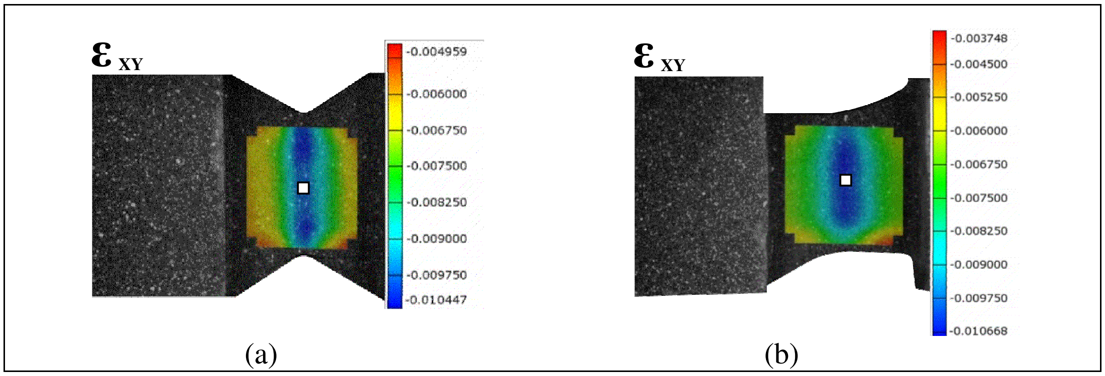

Figure 9. (a) DIC measurement of ε_{xy} distribution for tabbed symmetric specimen. (b) DIC measurement of ε_{xy} distribution for proposed tabbed asymmetric specimen.

For the generation of a stress-strain curve, shear strain fields and the corresponding loads were captured 3 times pr. second during the testing. The "average" shear strain was taken as the average shear strain measured over the centre surface indicated by the white squares shown in Figs. 9(a)-(b). The "corrected" shear stress was then derived using the following expression following the arguments presented above:

$$\tau_{xy,corr} = \frac{P}{wt} \cdot \mathrm{T}_{\mathrm{xy,corr}} \tag{4}$$

From the described shear strain and "corrected" shear stress data stress-strain plots as shown in Fig. 10 were generated.

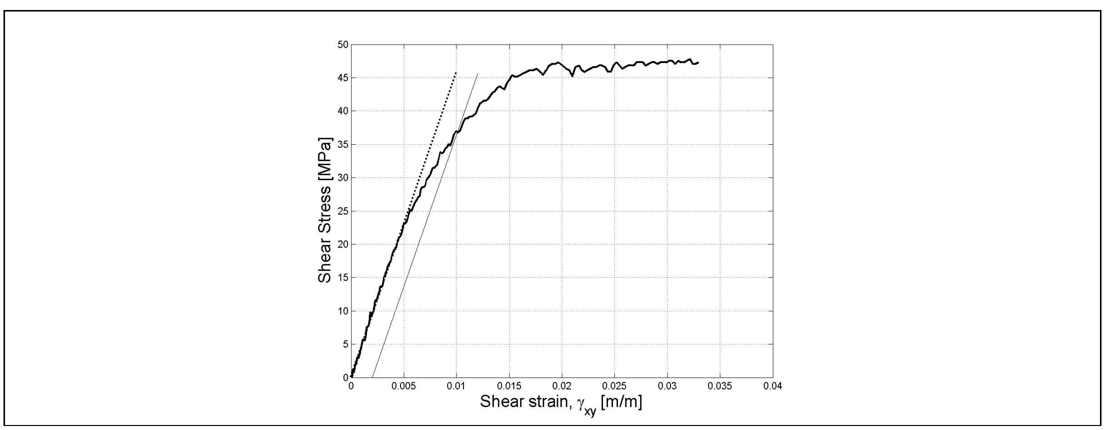

Figure 10. Shear stress – shear strain curve generated from DIC strain field and "corrected" shear stress. Please note that $\gamma_{xy}=2\varepsilon_{xy}$.

The shear modulus is computed by linear regression over the strain interval 0.1-0.5%. The gradient in this interval is shown by a dotted line in Fig. 10. The shear yield strain is determined by intersection between the stress-strain curve and a line offset 0.2% to the gradient line. From the graph in Fig. 10 a shear modulus of approximately 4.5GPa and a shear yield strain of 1% can be derived.

RESULTS

Fibre misalignment

Using FTMA the fibre misalignment was measured over an area of 0.7mm by 2.8mm, the result is summarised in Fig. 11.

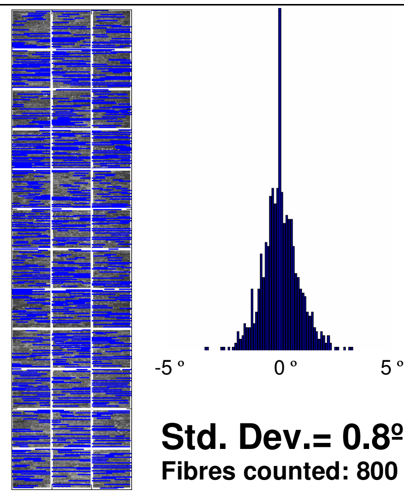

Figure 11. Result summary from FTMA.

Shear Moduli and Shear Yield Strains

Shear moduli and shear yield strains were determined for the following test specimen configurations following the procedure described above: 5 symmetric specimens with a notch angle of 120 deg, 5 symmetric specimens with a notch angle of 140 deg, and finally 6 specimens of the proposed asymmetric geometry. All the specimens were cut from pultruded lamella by water jet cutting. With the described procedure using DIC strain data were obtained and stress data corrected with the correction factors found by FEA. The measured shear moduli and shear yield strains from the experiments are given in Table 1.

Table 1.Shear moduli (left) and shear yield strains (right) measured by the Iosipescu shear test using DIC and stress correcting factors found from FEA.

Shear Modulus, G	No. spec.	Mean [GPa]	Std. dev. [%]	**Shear yield strain, γ_{xy},**	No. spec.	Mean [m/m]	Std. dev. [%]
20 Deg V-notch	5	5.0	5.0	**120 Deg V-notch**	5	0.0092	4.6
140 Deg V-notch	5	4.9	4.8	**140 Deg V-notch**	5	0.0094	2.0
Asymmetric-notch	6	4.9	1.6	**Asymmetric-notch**	6	0.0088	2.1

From the test results in Table 1 it is seen that the measured shear moduli are almost identical for the three geometries. A statistical ANOVA-analysis [15] has been conducted giving a p-value of 29% indicating that the differences between the three test populations are statistically insignificant. Had the stress correction not been used, the mean shear modulus for the asymmetric geometry would have been 4.5 GPa, and the statistical analysis would then give a p-value of 0.3% indicating that the difference between the three test populations would be statistically significant. It should be observed that the results obtained for the proposed asymmetric Iosipescu specimen design display a much lower standard deviation than obtained for the symmetric/standard geometries. This supports the hypothesis that the axial splits developing in the symmetric specimens scatter the results.

The results regarding the shear yield strain do not correlate as well. Two of the three test populations have standard deviations around 2%, which is considered low. But a statistical ANOVA-analysis reveals a p-value of 1%. This indicates that the difference between the mean values is statistically significant.

Having the experimentally measured the parameters controlling the compressive strength (Budiansky [3]) it is now possible to estimate the compressive strength using the Budiansky equation (1).

$$\sigma_c = \frac{G}{1+\phi_0/\gamma_Y} = \frac{4.9GPa}{1+\frac{0.8\,\mathrm{deg}\cdot\frac{\pi}{180\,\mathrm{deg}}}{0.0088}} = 1.9GPa \tag{5}$$

This result agrees well with 4 point bending result obtained for the pultruded UD CRRP lamella, which lies in the range 1.8-2.0GPa depending on manufacturing variations.

DISCUSSION

The FTMA method has shown to be an efficient tool for measuring the fibre misalignment. FEA studies have shown that the shear stress values should be corrected when testing asymmetric specimen geometries. The combination of the Iosipescu shear test and DIC enables accurate and low scatter measurements of the shear moduli and shear yield strains of pultruded UD CFRP composites.

The proposed asymmetric specimen has shown to display an extraordinary low standard deviation in the determination of shear modulus. However, the correlation regarding the shear yield strain is not as clear. The present study should therefore be extended to larger test populations to improve the statistical analyses and conclusions.

ACKNOWLEDGEMENTS

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