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Comparison of static shear test methodologies; test results and analysis

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ABSTRACT:

Blade designers are in need of accurate strength and stiffness data for the materials used in their design. In some parts of the blade, loading is dominated by shear. For accurate modeling of the design, an appropriate description of the shear characteristics of the material is required, including the non-linearity in shear/strain responses. The objective of this paper is to compare different methods of obtaining shear characteristics of fiber reinforced plastics. The differences in measured shear modulus are significantly smaller than the differences in observed maximum shear strengths.

Keywords: *wind turbine blade, shear properties, test method*

1 INTRODUCTION

Blade designers are in need of accurate strength and stiffness data for the materials used in their design. In some parts of the blade, loading is dominated by shear. For accurate modeling of the design, an appropriate description of the shear characteristics of the material is required.

Many (standardised) test methods exist for shear characterisation, using various geometries and fixturing, and different laminates. This paper evaluates different shear test methodologies to explore potential differences in results. The following test methods are compared experimentally using, where possible, the UPWIND/INNWIND reference laminate [1]:

- ±45º tension
- 10º off-axis
- Iosipescu in 0º- and 90º-direction
- V-notched rail test

Shear strength and modulus are the main compared aspects, but some qualitative differences between the methods also exist.

2 DESCRIPTION OF THE TEST PROGRAM

In all tests, the UPWIND/INNWIND reference material was used. This is a combination of glass-fibre epoxy which is extensively characterised in these projects. The reference laminate, which is representative of wind turbine composites used today, consists of 4 layers of unidirectional fabric and an epoxy matrix (Hexion RIM 135 system), see [1]. For some tests described below, a different configuration had to be used.

Specimens were manufactured, tabs to protect the gripping area were adhesively bonded where necessary. If tabs were applied, the specimens were postcured an additional 2 hours at 65º, on top of the 10 hours at 70ºC during plate manufacturing.

Detailed measurements were made of the specimens' dimensions. Strain gauges were applied to the specimens, either in a 0º-90º or 0º-45º-90º configuration. Typically, the strain gauges were tared after gripping the specimen on one side, before closing the other grip. The specimens were subjected to a monotonously increasing load at a rate of 1 mm/min, until failure. Load, displacement, strains and temperature were measured and stored continuously.

±45^0 Tension test

Shear strength is measured by performing a tensile test on a ±45º laminate [2]. This should be a symmetrical and balanced laminate. In this case, specimens were manufactured from an unstitched stack of reference laminate UD layers. The standard tensile test set-up is shown in Figure 1.

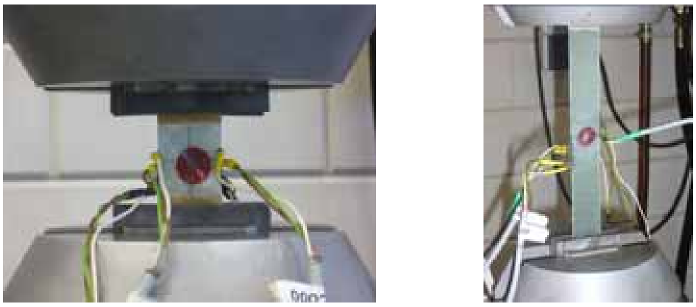

Figure 1: Test set-up for ±45º and 10º tension

10^0 Off-axis tension test

This test method is very similar to the ±45^0 tension test, except for the laminate. In this case, the reference laminate was cut at an angle of 10º. The length of the gauge section was chosen such, that no fibres run from one grip to the other. Rectangular tabs were used, but Sun et al [3] have shown, that oblique tabs have the potential of improving the results.

Iosipescu

The Iosipescu test uses a notched specimen and a specialised fixture, which is loaded in compression, in an axial test machine [4]. Although shear strength should not be affected by the orientation of the laminate in the test specimen, this test is applied in 0^0- and 90^0-direction of the laminate (corresponding to G_{12} and G_{21}, respectively). The test set-up is shown in Figure 2.

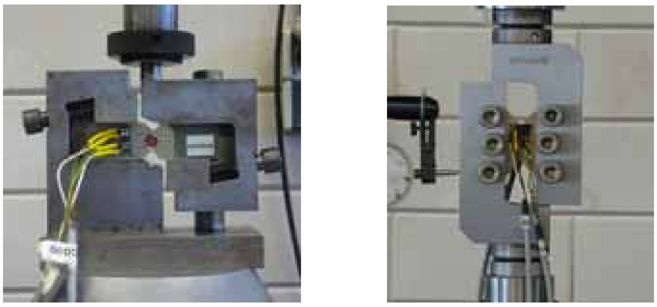

Figure 2: Iosipescu and V-notched rail shear test set-ups

V-notched rail

This method is essentially a modified Iosipescu test [5]. The distance between the notches is larger (mitigating any potential influence from laminate anisotropy), and the load is introduced via the specimen faces instead of through side-loading. This means, that the sensitivity to damage through load introduction is reduced and thinner laminates can be tested. See Figure 2 for a test set-up.

3 COMPARISON OF TEST RESULTS

Test results are summarised in the table below, and in Figure 3.

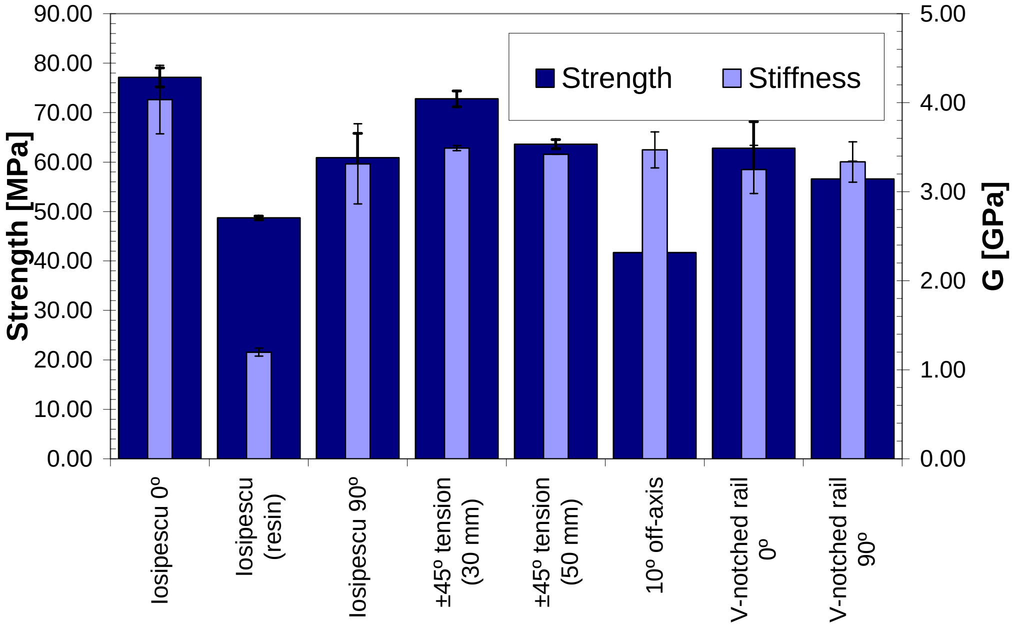

Figure 3: Results summary

For comparison, Iosipescu shear tests done on pure resin are included.

The stress strain curve of all test results is highly non-linear. The shear modulus, G, is taken from linear regression of the shear stress-strain curve between 1500 and 5500 μstrain. In order to describe the stress-strain curve for non-linear modelling purposes, a polynomial could be fit to the stress-strain curve.

Shear stress in the specimen was determined by the ratio of F_{max}/A, where A is the cross-sectional area determined by the width in the middle of the specimen and the thickness. For ±45º tensile tests, $F_{max}/2A$ was used. In case of the 10º tension tests, shear stress was determined using $F_{max}/A*1/2\sin 2\alpha$, with $\alpha = 10º$, as described in [6].

For the ±45º tension tests, no continuous fibres should be running from one grip to another, to prevent part of the load being carried by tension in the fibres, resulting in incorrect (i.e. too high) values for the apparent shear strength. Tests were done on 2 different geometries; one with a gauge length of 30 mm, and one with a gauge length of 50 mm (3 tests each). Although in both cases, the length of the gauge section was larger than the width, the longer gauge length yielded higher values for the strength than the shorter one. Shear modulus was roughly the same for both lengths.

The shear moduli of the different test methods where comparable with each other. Ultimate shear strengths varied more from one test method to another.

Although theoretically, shear properties measured on a laminate at either 0º or 90º should be equal, a difference was seen in shear strength, both for the Iosipescu and V-notch rail specimens, although for the latter the difference was significantly less pronounced. This suggests, that stitching configuration might be resulting in more pronounced anisotropy for the narrower Iosipescu specimens, resulting in different behaviour perpendicular and parallel to the stitching.

Stiffness results from the tests described in this paper are lower than the ~4.46 Gpa determined using the resonalyser method described in [7].

Test type	**ID**	**w [mm]**	**t [mm]**	**F_{max} [kN]**	**τ [Mpa]**	**$G_{average}$ [GPa]**	**T_{max} [ºC]**	**Remarks**
Iosipescu 0°	AO41I04	11.61	2.84	2.53	76.73	4.76	25.60	
	AO42I04	12.10	2.84	2.70	78.57	4.20	25.60	
	AO43I04	12.05	2.84	2.76	80.79	4.18	25.60	
	AO45I04	12.57	2.81	2.76	78.28	4.28	25.50	
	CO34I04	11.84	2.99	2.77	78.38	3.91	25.90	
	CO35I04	12.00	2.97	2.71	76.19	3.41	26.10	
	CO36I04	12.07	2.94	2.76	77.91	4.15	26.00	
	CO37I04	11.13	2.97	2.50	75.76	3.97	25.30	
	CO38I04	12.05	2.85	2.53	73.80	3.59	25.80	
	CQ27I04	11.77	2.93	2.58	74.85	4.22	25.50	
	CQ28I04	11.89	2.92	2.71	78.00	3.50	25.90	
	CR15I04	11.91	2.86	2.59	76.10	4.25	25.70	
average				**2.66**	**77.11**	**4.03**		
st. dev.				**0.10**	**1.91**	**0.39**		
Iosipescu (resin)	BR27I04	12.50	2.82	1.70	48.23	1.23	25.50	
	BR28I04	12.41	2.83	1.71	48.78	1.22	25.60	
	BR29I04	12.46	2.83	1.71	48.58	1.22	25.70	
	BR30I04	12.41	2.83	1.73	49.26	1.12	25.70	
	BR31I04	12.35	2.83	1.70	48.73	1.20	25.70	
average				**1.71**	**48.71**	**1.20**		
st. dev.				**0.01**	**0.37**	**0.04**		
Iosipescu 90°	AO35I049	12.38	2.86	2.39	67.50	3.32	26.50	
	AO36I049	12.00	2.83	2.14	63.02	3.60	26.40	
	AO37I049	12.08	2.78	2.22	66.23	3.25	26.40	
	AO38I049	12.31	2.86	2.34	66.46	3.56	26.20	
	AO39I049	12.22	2.81	2.18	63.49	3.90	26.10	
	CO40I049	11.87	2.95	1.89	54.09	3.13	23.30	
	CO41I049	11.89	2.94	2.03	58.10	4.01	25.20	
	CO42I049	11.82	2.93	1.90	54.72	3.05	25.80	
	CQ26I049	11.89	2.85	1.88	55.58	3.32	25.80	
	CQ30I049	11.78	2.93	2.17	62.73	2.46	25.60	
	CR17I049	11.94	2.93	1.95	55.92	2.85	25.10	
	CR18I049	11.85	2.89	2.14	62.60		25.80	strain not available
average				**2.10**	**60.87**	**3.31**		
st. dev.				**0.17**	**4.92**	**0.45**		
±45° tension 30 mm	DG01R02	24.79	2.85	10.50	74.44		22.80	strain not available
	DG02R02	24.86	2.90	10.27	71.23	3.47	23.40	
	DG03R02	25.11	2.91	10.60	72.66	3.51	23.80	
average				**10.46**	**72.78**	**3.49**		
st. dev.				**0.17**	**1.61**	**0.03**		
±45° tension 50 mm	DG04R01	24.86	2.87	9.10	63.74	3.42	23.50	
	DG05R01	25.09	2.87	9.00	62.60		23.70	strain not available
	DG06R01	25.02	2.89	9.31	64.46	3.42	23.30	
average				**9.13**	**63.60**	**3.42**		
st. dev.				**0.16**	**0.94**			
10° off-axis tension	CA03R10	24.80	2.99	17.00	39.27	3.24	26.40	
	CA04R10	24.86	2.95	17.10	39.94	3.51	24.00	
	CA05R10	24.89	2.88			3.45		no F_{max} available
	CA06R10	25.57	2.92	18.80	43.13	3.64	26.50	
	CA07R10	25.15	2.95	18.30	42.18	3.47	25.50	

Test type	ID	w [mm]	t [mm]	F_{max} [kN]	τ [Mpa]	$G_{average}$ [GPa]	T_{max} [ºC]	Remarks
	CA08R10	25.10	2.96	18.20	41.96	3.21	26.40	
	CA09R10	24.50	2.91	18.20	43.66	3.78		
average				**17.93**	**41.69**	**3.47**		
st. dev.				**0.72**	**1.74**	**0.20**		
V-notched Rail 0º	CX01I13	31.08	3.06	6.30	66.24	3.62		
	CX03I13	30.95	2.99	6.00	64.84	3.28		
	CX07I13	30.86	3.49	5.90	54.78	3.07		
	CX09I13	31.11	3.10	6.30	65.32	3.03		
average				**6.13**	**62.80**	**3.25**		
st. dev.				**0.21**	**5.38**	**0.27**		
V-notched Rail 90º	CX02I139	31.00	3.00	5.70	61.29	3.56		
	CX04I139	31.02	3.02	4.90	52.39	3.51		
	CX06I139	30.98	3.02	5.30	56.74	2.99		
	CX08I139	30.99	3.00	5.40	58.18	3.27		
	CX10I139	30.97	3.03	5.10	54.35	3.34		
average				**5.28**	**56.59**	**3.33**		
st. dev.				**0.30**	**3.44**	**0.23**		

4 CONCLUDING REMARKS

A comparison of shear test methods was made and presented. Measured shear moduli are very similar for different test methods. Values for ultimate shear strengths show more pronounced differences.

The orientation of the fibres and potentially the stitching configuration seem to influence the results of Iosipescu and V-notched rail tests, although this influence is less for the latter.

5 ACKNOWLEDGEMENTS

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