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A Cooperative Benchmark Effort on Testing of Woven Composites

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ABSTRACT: Rapid forming of woven composites has the potential to open up a large number of new applications to structural polymer composites. However, there are still many unknowns for these relatively new material systems, both in proper methods to experimentally obtain material properties and in analysis and simulation of forming behaviours. Systematic benchmark tests on the material characterization of woven composites and the modelling of its forming process are clearly needed to accelerate the implementation of these promising processes. This report is the first report of an international cooperative benchmark effort, focusing on material properties. The experiments include shearing tests (picture frame tests) and bias extension tests for both balanced and unbalanced fabrics. These experiments play an important role in the study on woven fabric composites, by providing data for material characterization and verifying models.

Key words: woven composites, benchmark, bias extension, picture frame, material properties

1 INTRODUCTION

Woven fabric reinforced composites (hereafter referred to as woven composites) have attracted a significant amount of attention from industry and academia, due to their high specific strength and stiffness and supreme formability. To design effective and economic manufacturing processes for woven composites requires extensive simulation and experimental research, in which benchmark tests can play an important role.

Several research groups have set up an international forum exclusively for research on forming of woven composites at <http://www.gtwebsolutions.com/nwbenchmark>. Three types of woven fabrics/preforms are currently being tested. Their material properties are listed in Table 1 reported by the material supplier and benchmark participants. Bias extension and trellis shear tests have been developed and conducted by different groups as listed in Table 2. In this paper, we will present the experimental setups and results.

	Fabric 1	Fabric 2	Fabric 3
Manufacturer's style	TPECU53XXX	TPEET44XXX	TPEET22XX X
Yarns	Glass/PP	Glass/PP	Glass/PP
Fibre diameter, μm	21	18.5	18.5
Weave	Twill 2/2	Twill 2/2	Plain
Area density, g/sq. m	1816	1485	743
Yarns linear density, tex	2400	1870	1870
Picks/ends count, yarn/cm			
Warp	3.39	5.56	1.91 (KUL) 1.93 (HKUST)
Weft	1.52	3.75	1.90 (KUL) 1.93 (HKUST)
Yarn width in the fabric, mm (*standard deviation)			
Warp	2.72±0.38* (KUL)	1.62±0.107* (KUL)	4.18±0.140* (KUL) 4.20 (HKUST)
Weft	3.58±0.21* (KUL)	2.32±0.401* (KUL)	4.22±0.150* (KUL) 4.20 (HKUST)

Table 1. Parameters of the fabrics reported by Saint-Gobain unless specified otherwise.

Groups	Picture Frame			Bias Extension	
	Fabric Type				
	3	2	1	3	2
Hong Kong University of Science and Technology (HKUST)	Y	X	X	Y	X
Katholieke Universiteit Leuven (KUL)	Y	Y	Y	X	X
Laboratoire de Mécanique des Systèmes et des Procédés (LMSP)	Y	Y	X	X	X
Northwestern University (NU)	X	X	X	Y	Y
University of Massachusetts at Lowell (UML)	Y	Y	Y	X	X
University of Twente (UT)	Y	Y	X	Y	Y

Table 2. Tests by different research groups (X: data not presented; Y: data presented)

2 PICTURE FRAME TEST

A picture frame is a fixture used to perform a trellis test for woven composites. Fig. 1 shows its structure.

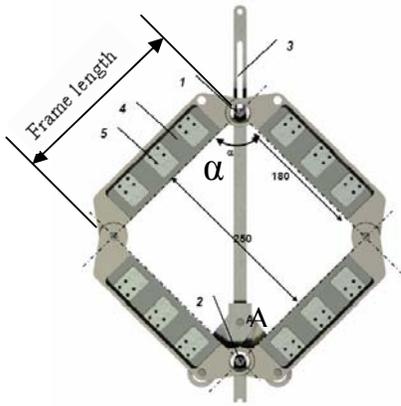


Fig. 1. Picture frame: 1,2 – hinges, 3 – groove, 4 – lip, 5 – plate with screws.

The tensile machine measures the vertical displacement of point A (Fig. 1). The displacement determines the angle of the frame, α , and the shear angle of the frame, $\gamma=90^\circ-\alpha$. To establish this dependency, the picture frame is calibrated before use. The KUL [1] and HKUST groups have observed that there is a very good correlation between the actual shear angle measured from the fabrics and the calculated one from the crosshead displacement through a straightforward geometric analysis.

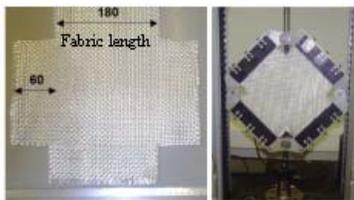


Fig. 2. Cross-shaped sample (by KUL)

Fig. 2 shows a typical cross-shaped sample with corner cut-outs to provide ease of rotation, and

a sample mounted in the picture frame. One can eliminate the contribution from the edge parts by carefully removing the fringe yarns from the arm sections, i.e., all the fibre yarns which are not clamped in the picture frame, as shown in Fig. 3. Care must be taken to prevent the remaining yarns from loosening.

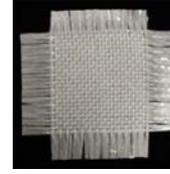


Fig. 3 Specimen for pure shear test (by HKUST)

During the test, one can take pictures of the deforming sample and later use an image mapping system, such as the Aramis system [2], which is able to produce technical strain over facets on the 2D image of the sample. The Aramis software analyzes the difference between two subsequent images and sums them up to yield the full displacement difference. The data Aramis system produced allow calculation of von Mises strain, which in this particular test is proportional to the local shear angle. Fig. 4 gives an example of such a field.

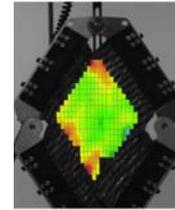


Fig. 4 Image of the fabric and the central region with the field of local shear angle (by KUL)

Group	Frame (mm)	Fabric (mm)	Speed (mm/min)	Temp.(C°)
HKUST	180	140	10	20
KUL	250	180	20	20
LMSP	245	240	n/a	20
UML	216	140	120	20
UT	250	180	1000	20

Table 3. Frame and fabric sizes reported from groups.

The HKUST group observed that if the specimen was oblique orientated, one group of yarns would be under tension while the other would be under compression. Since the yarn itself cannot be compressed, it has to be curved, buckling out of the original plane. This accelerates the wrinkling of the specimen. UT actually stopped their tests at the onset of wrinkling, as the deformation is no longer uniform afterwards. The UML group noted that by “mechanically conditioning” the specimen, i.e., by shearing the fabric in the frame several times before recording the final shear load versus angle data, some of this variability in tension and local orientation could be eliminated. This again stresses

the importance of the precise handling of the sample and fixtures.

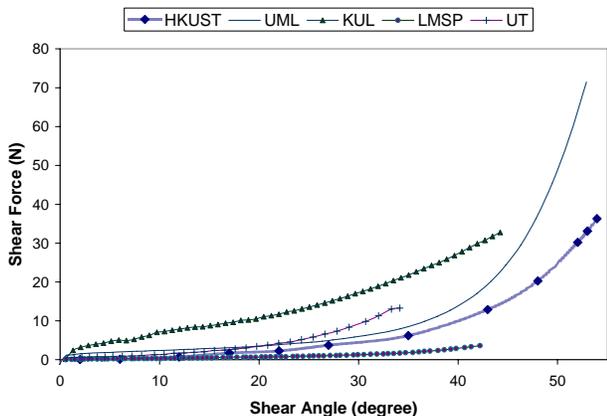


Fig. 5 Shear force vs. shear angle, fabric 3

Table 3 listed the frame and fabric sizes used by different groups. To compare data (shear force vs. shear angle) obtained from different groups, we use two methods to normalize them – (1) dividing shear force with frame length and (2) using the following equation [3]:

$$F_{normalized} = F_{original} K = \frac{F_{original} L_{frame}}{L_{fabric}^2} \quad (1)$$

The shear force is defined as:

$$F_{shear} = \frac{F_{tensile}}{2 \cos(\alpha / 2)} \quad (2)$$

where α is defined in Fig. 1. Fig. 5 shows the raw data of fabric 3 at room temperature. Notice that all the data are shifted such that the shear force is zero at 0° shear angle. The results of two normalization schemes are shown in Fig. 6 and Fig. 7. It can be seen that equation (1) is an effective way to bring the curves “closer”.

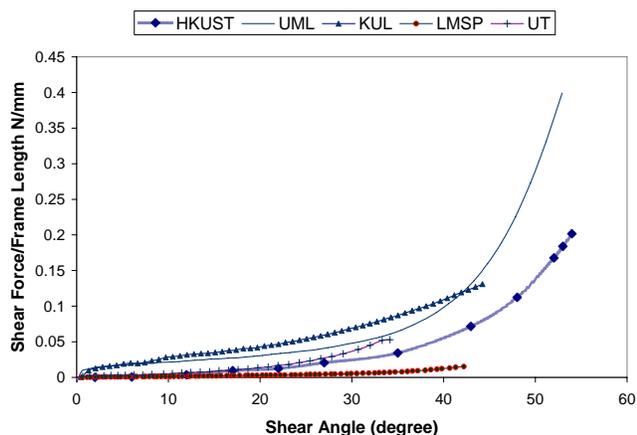


Fig. 6 Shear force/frame length vs. shear angle, fabric 3

Fig. 8 and Fig. 9 show the normalized shear force vs. shear angle curves for the twill woven composites – fabric 1 and fabric 2.

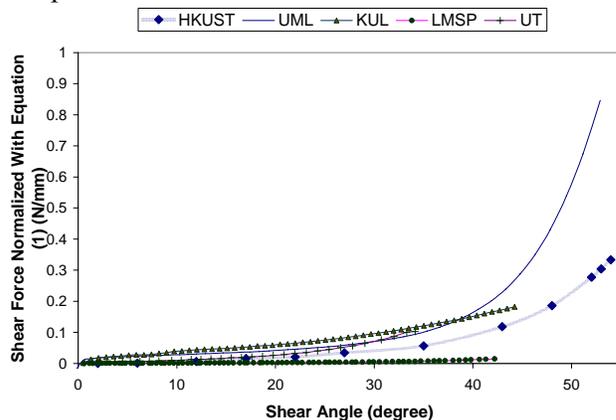


Fig. 7 Shear force normalized with equation (1) vs. shear angle, fabric 3

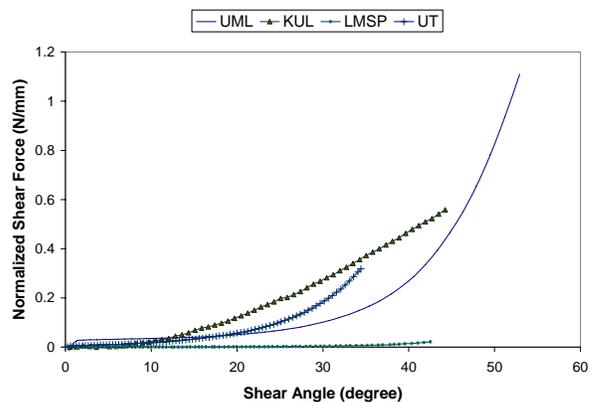


Fig. 8 Shear force normalized with equation (1) vs. shear angle, fabric 2

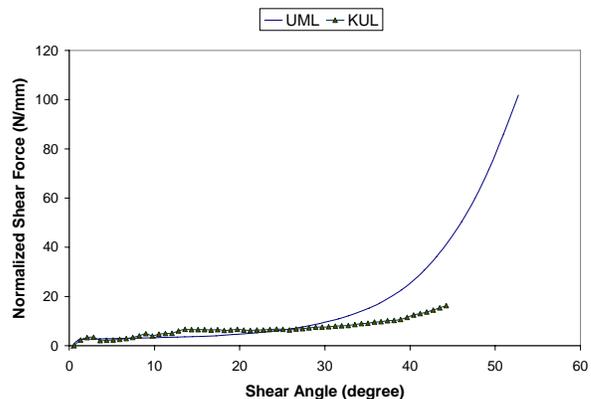


Fig. 9 Shear force normalized with equation (1) vs. shear angle, fabric 1

3 BIAS EXTENSION TEST

Besides picture frame tests, bias extension tests have also been used to study the properties of woven composites. The specimen is rectangular with initially a 45° angle between two groups of

yarns and the edges. The ratio of the length to the width of the unclamped fabric area should be ≥ 2 to generate a proportionally large pure shear region in the centre. Spare regions are left for clamping beyond the upper and lower edges. For a group of tests, it is very important to make sure that every sample has the same number of yarns between the two gripping edges. High temperature results are achieved by putting the sample into a pre-heated oven during the test.

Group	Length (mm)	Width (mm)	Speed (mm/min)	Temp.(C°)
HKUST	230	115	10	20
NU	235	118	10	20
UT	200	75	300	20

Table 4. Initial specimen sizes reported from groups.

To measure the shear angle, the undeformed sample can be marked with colour lines (Fig. 10). The angles can then be measured during the test by hand or after the test using image processing software on pictures taken while the sample is being loaded. α is defined at Fig. 10 as the angle between two sides of the central diamond-shape region.

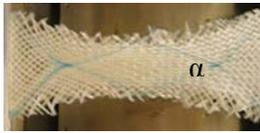


Fig. 10 A deformed sample with marked lines (NU)

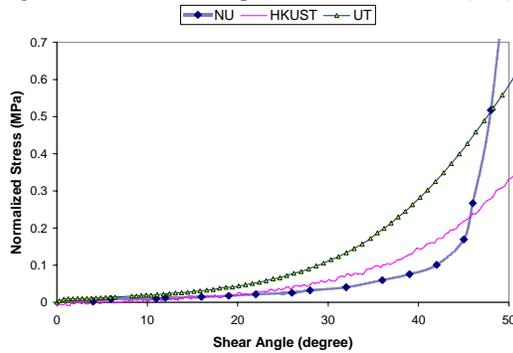


Fig. 11 Normalized stress vs. shear angle, bias extension, fabric 3

For bias extension, the axial stress σ_y can be found from the load F by

$$\sigma_y = \frac{F}{A} \quad (3)$$

with A as the current cross-sectional area, being the product of the thickness t and the width W . For dry fabrics, the thickness appears to be approximately constant until the onset of shear locking phenomena, appearing e.g. as wrinkling of the fabric. Using a geometric analysis as in [4], the width of the central section can be expressed as

$$W = W_0 \frac{\sin \frac{1}{2} \alpha}{\sin \frac{1}{2} \alpha_0} \quad (4)$$

from which the normalised stress can be found as

$$\sigma_y = \frac{F \sin \frac{1}{2} \alpha_0}{t_0 W_0 \sin \frac{1}{2} \alpha} \quad (5)$$

The material shear angle can be found using the same geometric analysis, leading to

$$\gamma = \alpha_0 - 2 \arccos \left(\frac{L_0 - W_0 + u}{2 (L_0 - W_0) \cos \frac{1}{2} \alpha_0} \right) \quad (6)$$

Normalising the bias extension data from the HKUST, NU and UT leads to the results depicted in Fig. 11. It should be noticed that the NU group measured the shear angle directly from the sample while HKUST and UT obtained it from the calculation based on the crosshead displacement.

4 CONCLUSIONS

The properties of woven fabrics and performs are very different from conventional materials, such as bulk metals and polymers. This leads to the requirement of benchmark tests specifically for woven composites. It has been shown that both bias extension tests and picture frame tests are able to produce valuable experimental data for analytical and numerical research on woven composites. Test results provided by different groups show consistency but still have some deviations. Further studies are underway to help develop a standard test setup, test procedure and normalization method for obtaining accurate and appropriate material properties.

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