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A new biaxial and shear protocol for architectural fabrics

Alison L. JACKSON*, Benjamin N. BRIDGENS[a], Peter D. GOSLING[a]

*[a] Newcastle University
School of Civil Engineering and Geosciences, Room 1.10, Drummond Building,
Newcastle upon Tyne, NE1 7RU
Alison.Jackson@ncl.ac.uk

Abstract

Architectural fabrics are translucent, lightweight and flexible allowing impressive forms to be achieved unlike any other material. However in order to create the required double curved structural form, flat fabrics must undergo shear deformation during installation. Due to the woven nature of architectural fabrics contact between neighbouring yarns during shearing leads to an increase in shear stiffness, shear lock-up and subsequent wrinkling.

A picture frame shear test accessory has been designed for the biaxial test rig which enables a known biaxial stress state to be applied to the fabric and maintained throughout the shear test. A shear testing protocol is proposed for medium term loading conditions. This enables the shear characteristics of architectural fabrics to be identified for use in analysis and design.

Shear behaviour is presented from initial experiments and a range of shear modulus values are proposed for loading and unloading in the shear deformation range of zero to 15°.

Keywords: coated woven fabric, architectural fabric, shear modulus, shear deformation, biaxial, protocol, picture frame, experimental.

1 Introduction

Modern fabric structures using synthetic materials have been in use for about forty years although research into their behaviour is limited and new structures are designed on the basis of past experience rather than a full understanding of material properties. A fabric membrane acts as both structure and cladding, providing structural solutions with reduced weight, cost and environmental impact compared to conventional materials. Architectural fabrics are translucent and flexible allowing impressive forms to be achieved unlike any other material (Bridgens, Gosling et al. [4]).

Architectural fabrics have negligible bending and compression stiffness, they are designed with sufficient curvature to enable environmental loads to be resisted as tensile forces in the plane of the fabric. Structures are pre-stressed to ensure that the fabric remains in tension under all load conditions and to reduce deflections. The surface of the canopy must be double-curved to resist both uplift and downward forces (typically due to wind and snow respectively). For a flat panel to form a surface with double curvature the membrane must undergo shear deformation. Due to the woven nature of architectural fabrics contact between neighbouring yarns during shearing leads to an increase in shear stiffness, shear lock-up and subsequent wrinkling.

Coated woven fabrics are composed of an open weave mesh of orthogonal yarns with a waterproof coating that encloses the mesh on both sides. The main woven fabrics used for architecture are glass fibre fabric with a PolyTetraFluoroEthylene (PTFE) coating and polyester fabric with a PolyVinylChloride (PVC) coating. Recently Tenara, a woven PTFE coated with PTFE, developed by clothing maker Gore has gained in popularity. The characteristics of these main types of fabric are different, but the underlying deformation mechanisms are very similar. Under biaxial tensile loading the behaviour of coated woven fabrics is highly non-linear and anisotropic. Geometric non-linearity occurs in the yarns, and in the finished fabric due to crimp interchange, which leads to fundamentally non-linear stress-strain behaviour (Bridgens, Gosling et al. [4]).

2 Aims and scope

The aim of this work is to identify the shear behaviour of architectural fabrics for use in analysis and design. A number of experiments have been designed to identify properties that affect the shear behaviour. This work gives details of the effects of load history, rate, duration and intensity on the shearing behaviour of coated woven architectural fabrics. A protocol for identifying the medium term shear behaviour, namely the shear modulus, of the fabric is proposed.

This work focuses on medium term behaviour of PVC/polyester materials. The effects of temperature, biaxial stress and creep are not considered here. This research assumes global (frame) and local (internal fabric) behaviour are consistent.

3 Context

3.1 Background

The shear and biaxial response of coated woven architectural fabrics is hysteretic due to the coating and fibre properties and inter-fibre and inter-yarn friction. Stress-strain behaviour is inelastic, non-linear, time and temperature dependent. Long-term creep is also significant. Fabric response varies between batches of fabric and even across the width of a single roll.

Uniaxial tensile strip tests are routinely carried out by fabric manufacturers to determine the tensile strength of the fabric, and are clearly defined by standards (BS EN ISO 1421:1998). Biaxial fabric testing is much more specialist with no European standards, although a design guide has recently been published by TensiNet ([9]).Contractors commonly carry out biaxial testing at low load to determine compensation values. Shear testing is less common and little is known about the behaviour of architectural fabrics sheared under biaxial stress; designers generally use rules of thumb to estimate the shear characteristics of the fabric.

3.2 Methods of shearing fabric

In practice a fabric roof is installed and biaxially stressed to create the desired double curved form and generate tension to resist environmental loads. Shear testing methods which do not re-create a uniform, controllable biaxial stress state across specimen during testing are therefore not appropriate.

There are four commonly used experimental methods for shear testing of fabrics; bias cut (Cao, Akkerman et al. [5]), Mörner and Eeg-Olofosson (Treloar [10]), inflated cylinder (Bassett, Postle et al. [1]) and picture frame (Cao, Akkerman et al. [5]). The bias cut, and Mörner and Eeg-Olofosson methods restrain the fabric in one axis only resulting in an unknown biaxial stress state. The inflated cylinder method requires a seam within the specimen; the impact of this on experimental results is difficult to verify. The picture frame method, employing a square frame pinned at the corners into which the fabric is gripped, enables a known biaxial stress state to be applied to the fabric and maintained throughout the test.

3.3 Previous frame testing

3.3.1 Testing on architectural fabrics

The Membrane Structures Association of Japans [MSAJ] Testing Method ([7]) provides the only published information about shear testing of architectural fabrics using a picture frame. Biaxial stress is applied related to the type of fabric with a warp: fill ratio of 1: 1. The frame is deformed three times at a rate of 10 mm/min, to a maximum angle of 1°. The first cycle is disregarded and an average of the 2nd and 3rd, positive and (absolute) negative values are taken to calculate the shear stiffness using equation (1).

$$Gt = \frac{F_1+F_2}{\sqrt{2}\,L\,(\gamma_1+\gamma_2)} = \frac{N_{XY1}+N_{XY2}}{\gamma_1+\gamma_2} \tag{1}$$

where Gt= shear modulus, F_1 & F_2= ± applied load, L= frame length, γ= ± shear strain

Testing is carried out at 20°C, and, importantly it is noted that a change in temperature of ±2° can affect the shear stiffness by up to 10%. The fabric is maintained at test temperature for 4 hours prior to experimentation.

3.3.2 Testing on commingled glass and polypropylene

Picture frame shear testing is more widely used for commingled glass and polypropylene in the manufacturing industry. Although this material is woven it is generally uncoated and as a result has lower shear stiffness than coated fabrics. The processes of biaxial conditioning, shear frame installation, testing, and calculation methods for shear modulus derived from this can be applied to coated architectural fabrics with some adjustment to the preparation methods.

The importance of installing the shear frame parallel to the direction of the warp and fill fibres is highlighted in the majority of papers (Nguyen, Herszberg et al. [8; Willems, Lomov et al. [12]). This ensures both a constant tensile yarn load, and that the fabric shear angle corresponds to that of the frame.

Willems, Lomov *et al.* ([12]) experimented with a variety of biaxial stress levels and concluded that the effects were not significant to the shear response as curves followed a similar trend regardless of applied biaxial load. The hysteretic curves were seen to move down as biaxial stress levels increased.

Frame dimensions and load rates used by other researchers vary significantly although most fall within the range 5-162mm/min (Nguyen, Herszberg et al. [8; Lebrun, Bureau et al. [6]). Wang, Paton *et al.* ([11]) found minimal variation in results when testing was carried out at extension rates of 1-10mm/min.

MSAJ ([7]) and Zhu, Yu *et al.* ([13]) provide equations for the calculation of shear strain which assume an initial start angle of 45°. Similarly Willems, Lomov et al. ([12]) install a frame locked in a square position; assuming 90° corners. These methods are not applicable to architectural fabrics where the unsheared angle between of warp and fill can vary by up to 5°.

In order to quantify the behaviour of fabrics in shear, measurements of frame deformation and load are recorded and the behaviour of the specimen locally is based on these global characteristics (Nguyen, Herszberg et al. [8]; Cao, Akkerman et al. [5]). One exception to this is Willems, Lomov *et al.* ([12]) who use photographs from a CCD camera and 2D image correlation software to record behaviour.

3.4 Shear frame design

The shear frame [Figure 1] consists of four pairs of aluminium bars [Figure 3] pinned at the corners to allow freedom of rotation. Each pair of bars, which contain machined steel grips along the length of the inner face, are bolted together to grip the fabric and maintain a pre-defined biaxial stress state within the frame.

4 Methodology

4.1 Experimental

4.1.1 Sample preparation

A cruciform specimen is cut from the fabric roll in accordance with the Bridgens-Gosling method (Bridgens and Gosling [3]). Full biaxial conditioning is carried out on the specimen (Bridgens and Gosling [3]) to model medium term loading. Following conditioning the required biaxial stress is held for two hours prior to installation of the shear frame to minimise the effects of short term creep. For this research a biaxial load equal to pre-stress is applied [Figure 2]. Future work will investigate the effect of biaxial stress on shear behaviour.

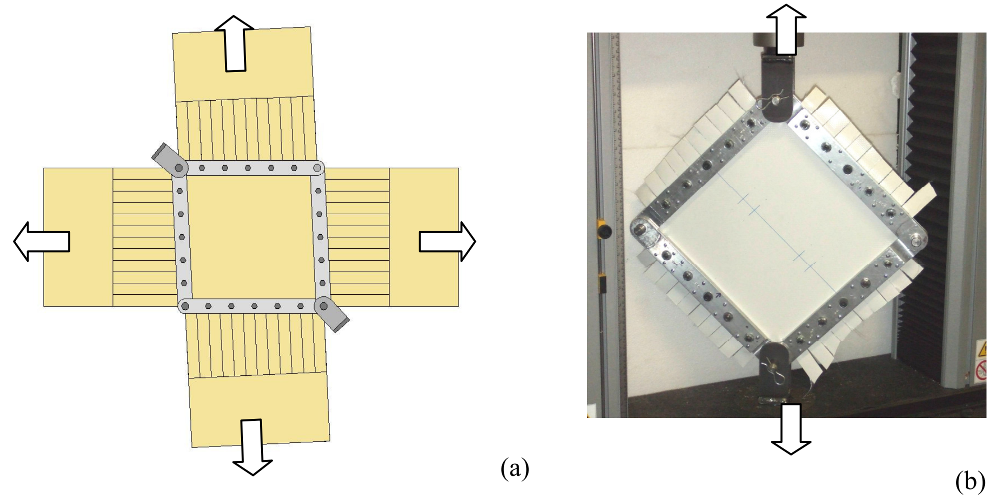


Figure 1 Shear frame installation, (a) on biaxial sample, (b) in tensile tester

Load	**Warp (%UTS)**	**Fill (%UTS)**
Pre-stress	1.3	1.3
Max. Conditioning	27.5	27.5
		Where UTS=Ultimate Tensile Stress (kN/m)

Figure 2: Pre-stress and conditioning values for PVC/Polyester

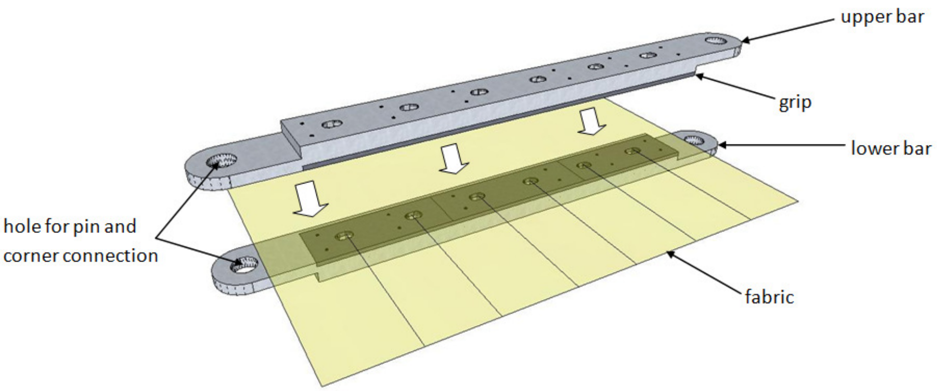


Figure 3: Shear bars

The shear frame is installed as illustrated in Figure 1 ensuring that the bars are parallel to the warp and fill and that no fingers (from the cruciform arms) are visible within frame.

The most significant advantage of the picture frame method is that any form of biaxial conditioning can be applied to the specimen prior to installation of the frame, and any biaxial stress state can be maintained within the specimen during shear testing. This gives the potential to apply loading regimes modelling all conditions from installation to long term loading.

4.1.2 Shear Testing

Five loading sets [Figure 4] are applied to the frame with each set consisting of five cycles [Figure 5]. This loading path is repeated at three loading rates; 10mm/min (test a), 100mm/min (test b) and 3.33mm/min (test c) on the same sample. Two initial experiments, each consisting of three tests (one at each loading rate) were carried out for this work [Figure 6].

Load (F), frame displacement ($\varepsilon-\varepsilon_o$) and initial frame length (ε_o) are recorded for all tests. Biaxial conditioning, frame installation and shear testing are carried out at 23°±2°.

Cycle set reference	Max shear deformation (°)	Max shear deformation (°)
A	2	-2
B	7	-7
C	2	-2
D	15	-15
E	2	2

Figure 4: Cycle set details

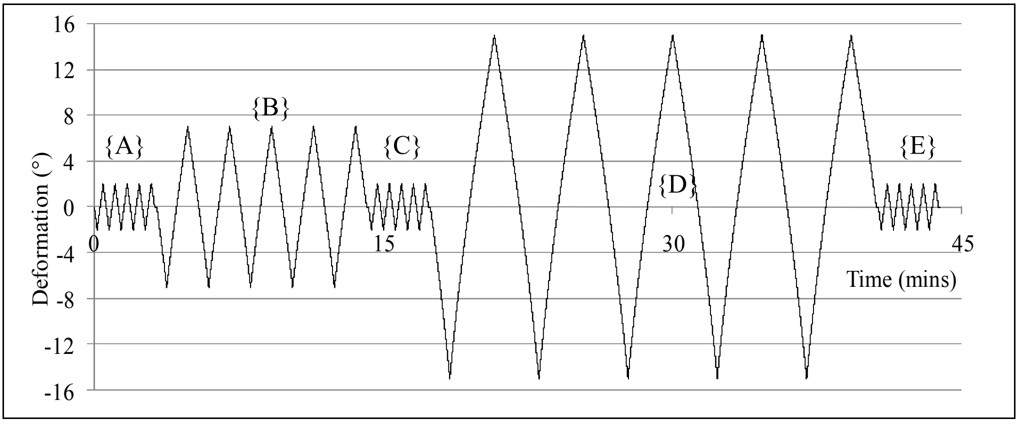


Figure 5: Test b: displacement and time at rate 100mm/min

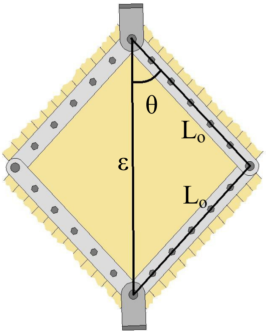
Experiment reference	Fabric	Warp load (kN/m)	Fill Load (kN/m)	Order of tests
004	Ferrari Précontraint 1002	1.0	1.7	a, b, c
007	Ferrari Précontraint 1502	2.9	2.1	b, c, a
Tests are labelled by experiment reference and test reference eg. 007b				

Figure 6: Experiment details

5 Calculations

5.1 Shear deformation angle

Shear deformation is calculated using equation (2) derived from the cosine rule.



$$\gamma = \cos^{-1}\left(\frac{\varepsilon_o}{2L_o}\right) - \cos^{-1}\left(\frac{\varepsilon}{2L_o}\right) \qquad (2)$$

5.2 Shear Modulus

Equation (3) gives the empirical equation currently used by engineers to calculate the shear modulus for structural fabrics in analysis and design.

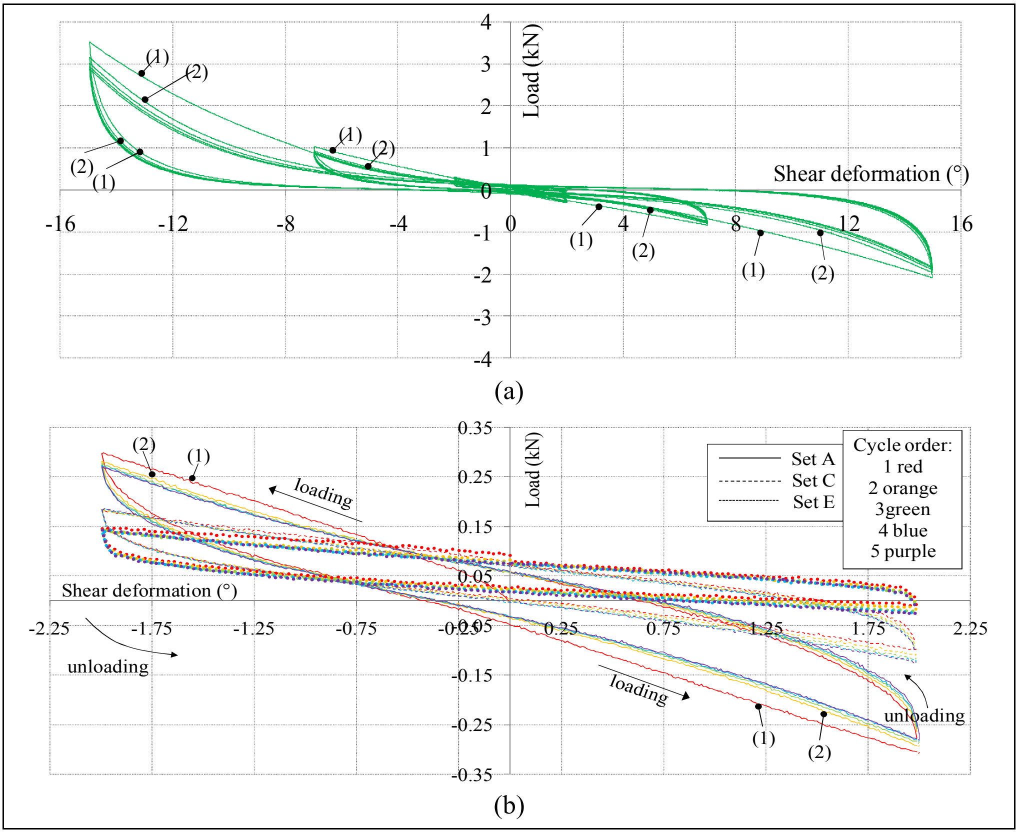
$$Gt = \frac{E}{20} \qquad (3)$$

where Gt = shear modulus (kN/m), E = elastic modulus (used as ~ 600kN/m for PVC/Polyester)

Substituting in E= 600kN/m into equation (3), this gives Gt = 30kN/m. This is compared in §0 with experimental results related to the gradient of Figure 10 and calculated from equation (4). Note that γ is measured in radians not degrees.

$$Gt = \frac{\Delta F}{\sqrt{2}.\Delta\gamma.L_o} \qquad \text{(MSAJ [7])} \qquad (4)$$

6 Results and discussion



(a)

(b)

Figure 7: Load and shear strain for test 004a, (a) all sets (A-E), (b) sets A, C, E

The shape of the hysteretic curve was found to be similar for all tests carried out. The results found in Figure 7-11 are representative of the testing carried out. The effect of the rate of loading was found to be of less significant than load history and for this reason the first tests from each experiment are compared here.

6.1 Material properties

Whilst the hysteretic curves for experiments 004 and 007 are similar in shape, the shear stiffness of the heavier fabric (test 007, Ferrari 1502) is approximately double that of the lighter (test 004, Ferrari 1002) [Figure 7, Figure 9].

6.2 Initial behaviour

The hysteretic behaviour of the fabric during shearing is seen clearly in Figure 7. The first loading curve (marked (1)) of each set is separated from the other loading curves. The second loading curve (marked (2)) is also visibly different. This pattern can also be seen in

Figure 8 where the first and second point of each set is separated from the other data. Focusing on the medium term behaviour of fabric, this initial behaviour is disregarded. An average of the final three curves is taken, discarding data points 1&2 in each set in a similar way to MSAJ ([7]). These averaged results are used in Figure 9 and Figure 10.

6.3 Loading effects

6.3.1 Loading History

In Figure 7b the reduction in angle of the hysteretic curve over the three sets indicates a reduction shear stiffness as the test progresses. This is also visible in Figure 8 where the loading curves (♦ and ▲) show decreasing load requirements. The pattern of unloading behaviour (■, X) is more difficult to explain although shear stiffness appears to increase in sets B and D which deform through a larger angle.

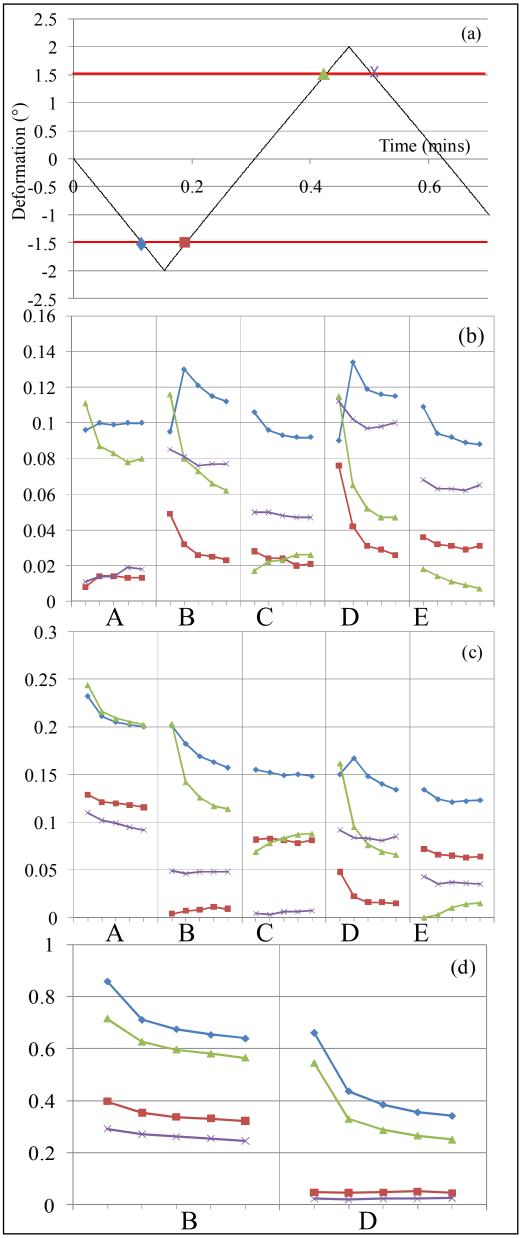


Figure 8: Cross section data for 004a (a) demonstration of data points, (b) 0.5°, (c) 1.5°, (d) 6.5°
{(b)-(d) vertical axis: applied force (kN)}

The loading behaviour at 0.5° in both experiments varies from that at other angles displayed here. Note that the unloading curves (■, X) steepen here indicating increasing stiffness. Further research at low shear angles will verify what is happening here.

6.3.2 Maximum cycle angle

The maximum angle of each cycle appears to affect the fabric behaviour. This is seen on the negative loading cycle in sets B and D of Figure 8 where the load jumps up at the second data point.

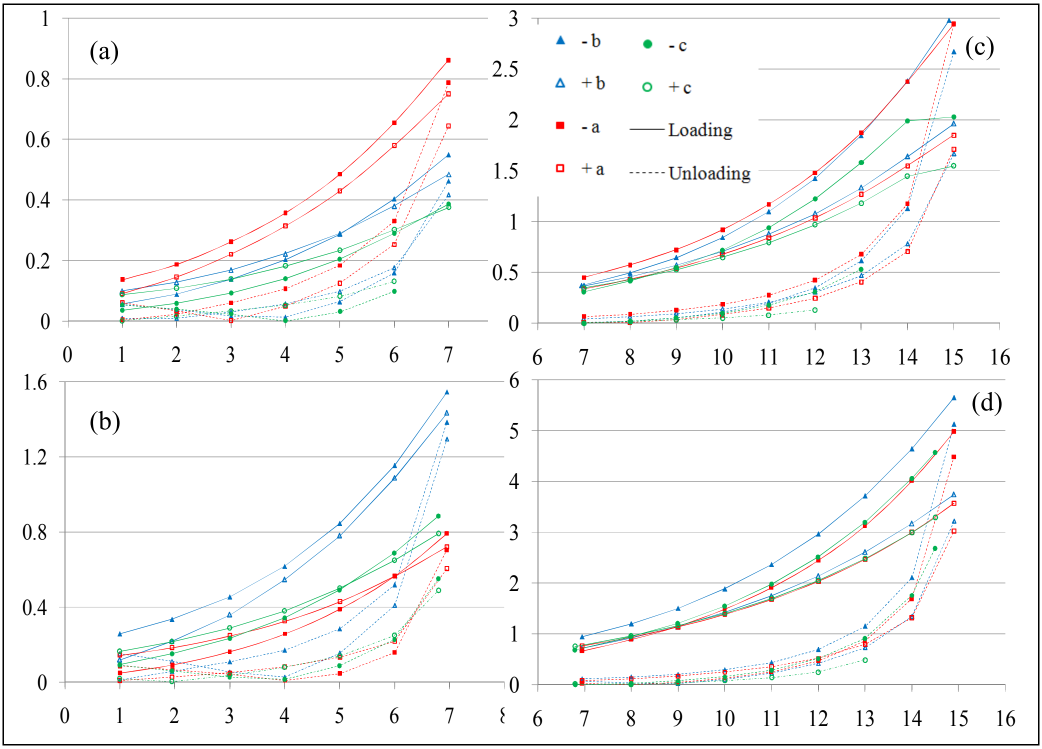


Figure 9: Rate comparison, (a) 004a Set B, (b) 007b Set B, (c) 004a Set D, (d) 007b Set D {vertical axis: applied force (kN), horizontal axis: deformation (°)}

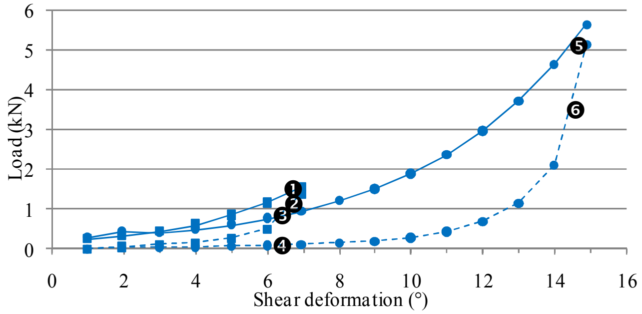
6.3.3 Creep

It is possible that results are affected by creep. This will result in a change in strain at zero load as seen for biaxial behaviour by Bridgens ([2]) who developed a procedure for removing residual strain caused by creep from test data. Further research into the effects of creep shear behaviour is required. Shear modulus is a function of the rate of change of load and shear deformation and hence will not be affected.

6.3.4 Loading Rate

Comparing the loading curves in Figure 9 the effect of loading rate appears less significant than load history. The load rates increase in order (c), (a), (b) although the shear stiffness reduces throughout both experiments which were carried out a,b,c (test 004) and b,c,a (test 007).

6.4 Physical properties



(a)

G for 007b (kN/m)	1.5°			6.5°				14.5°	
	A	C	E	B		D		D	
Loading	27.7	13.2	10.9	55.6	(1)	26.0	(3)	143.2	(5)
Unloading	45.9	22.9	17.2	123.2	(2)	3.4	(4)	428.6	(6)

(b)

G for 004a (kN/m)	1.5°			6.5°				14.5°	
	A	C	E	B		D		D	
Loading	17.1	8.9	5.0	29.4	(1)	12.6	(3)	75.2	(5)
Unloading	24.1	14.1	8.4	65.0	(2)	2.5	(4)	204.4	(6)

(c)

Figure 10: Shear modulus values for test 004a & 007b for negative shear deformation (a) Gradients used for calculations over 0.95°, (b) Shear modulus values for 004a, (c) Shear modulus values for 007b.

6.4.1 Lock-up angle

Results from all experiments produce smooth curves and there are no sudden changes in fabric behaviour to indicate lock-up.

6.4.2 Shear Modulus

The shear modulus has been calculated for the negative loading and unloading curves for the first test in each experiment. The values of shear modulus [Figure 10] calculated from results at 1.5° and 6.5° were found to be within the region of those empirically calculated from equation (3) (30kN/m), although large variations are seen due to the hysteretic form of the curve. Further work is required to identify the significance of these results. It appears unlikely that one value for shear modulus is applicable for a range of shear deformation angles and fabric weights.

7 Conclusions

The shape of the hysteretic curve was found to be similar for all tests carried out, with load history found to be more significant than loading rate. The fabric behaviour settles down after the first two loading cycles in each set. This initial behaviour is disregarded for medium term material properties by averaging the final three curves in each set. The maximum shear deformation applied in each cycle affects the fabric behaviour. A reduction in shear stiffness of the loading and unloading curves was identified over three cycle sets indicating that conditioning cycles prior to testing will prime the fabric for medium term behaviour.

The values of shear modulus calculated from results at 1.5° and 6.5° were found to be within the region of the empirically calculated 30kN/m although large variations are seen due to the hysteretic form of the curve. No obvious lock up angle was identified from experimental data. The heavier material tested was found to have higher shear stiffness

For medium term behaviour testing a cyclic load path is suggested consisting of three cycle sets with increasing maximum angles. A minimum of two conditioning cycles should be included at the start of each set and these should be repeated until the response of two consecutive curves are within 5% variation. A further two cycles should be applied and averaged to calculate shear modulus values. A loading rate of 10mm/min is proposed. The maximum cycle angle should be based on the typical maximum angle used in analysis. As shear modulus values vary significantly along the hysteretic curve the researcher should aim for this angle to fall within the central, flatter area of the curve e.g. to determine the shear modulus at 6°, maximum cycle set deformation should be 8°, 10° and 12°.

8 Further work

There are many new avenues to be explored given the advantages provided by the picture frame apparatus in allowing research into shear behaviour at a controllable biaxial stress state. The effects of biaxial stress, warp: fill ratio and pre-conditioning will be investigated. Understanding the relationship between global and local behaviour is essential to identify the true behaviour of the fabric. Investigations into the affects of load history and variations caused by the maximum angle of shear in each cycle will continue as well as a more detailed study of shear behaviour at low angles. The shear behaviour of PTFE/Glass and Tenara will also be investigated.

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