1. Introduction

1.1 Introduction

Self reinforced composites

Nowadays, self reinforced composites such as Curv™, MFT, PURE and Armourdon [12] are attractive, very popular and proved to be very useful as well. These composites are being used in many applications throughout the multi billion dollar industries. Especially these materials found applications in the automotive and aerospace industries. These types of materials are very popular in the automotive and aerospace industries because these self reinforced composites shows some important properties such as light weight, high impact resistance, smooth surface finish, hardwearing, thermo-formable, abrasion resistance and their better recycling potential as compared to thermoset composites which is an important property as per environmental issues and environmental laws are concerned. These material parts could be shaped using thermoforming or stamping processes which are similar to the stamping process of sheet metal parts. Thus allowing cycle time reductions to levels needed in the automotive and aerospace industries [4]. These self reinforced composites are being used to manufacture exterior and interior components of the automotive and transportation structures, protective material such as personal protective equipment and sport s goods, performance product like audio products or travelling suitcases, industrial pallets, surf and kite boards [12].

In order to promote the usage, accurate virtual forming technology is needed, like Finite Element (FE) simulation technology, this technology also helps to reduce manufacturing costs significantly. So as to solve the momentum balance equations during forming, these simulations required appropriate constitutive models. Forming characterisation experiment is a key factor in determining such models. Generally, there are two characterisation experimental procedures which are very popular, picture frame testing and bias extension testing, to determine the intraply shear properties and wrinkling of these self reinforced composites [8].

1.2 Objectives

Initial objectives were:

1. With the help of static friction, determine the integrity of the existing picture frame test rig.
2. To make an arrangement so that picture frame rig would held in a square shape during the loading of picture frame rig into the tensile testing machine.
3. To perform picture frame tests at two different clamping conditions.
4. To perform bias extension tests and to compare end results of both picture frame tests and bias extension tests with each other.
5. By doing visual analysis, determine experimental shear angle.
6. To compare the end results obtained from picture frame tests and bias extension tests and to determine the formability of the self reinforced composite.

1.3 Objectives achieved

Through the course of the project following objectives were successfully achieved.

After doing some testing on picture frame rig at two different temperature conditions, it was concluded that there is small amount of friction but it could be neglected. The two different temperature conditions with which testing have been carried out were room temperature, 200° and again room temperature.

Concluding that the picture frame test rig works correctly, an idea through which the picture frame could be held in a perfect square position is implemented. A CAD design is then made and manufactured. This idea is then successfully implemented to the picture frame rig. Thus, the purpose of holding the picture frame test rig in a perfect square shape during the time of loading the picture frame rig into the tensile testing machine is achieved.

Once the requirement of holding the picture frame test rig in a perfect square is completed then testing is carried on the same rig with two different clamping conditions, one was tightly clamped sample and the other one was loosely clamped sample. Graphs which compare theoretical shear angle values with experimental shear angle values were plotted. Also the bias extension tests were carried out with tightly clamped sample and same graphs as picture frame testing were drawn. All the end results and graphs were collected and processed.

1.4 Motivation of the project

The purpose of this project has been divided into two sections – long term motivation and short term motivation. They are as follows –

Long term motivation of the project was to develop virtual forming technology.

We are going to perform characteristic tests on the composite material and these experiments investigate material's intrinsic properties. These experiments includes shear testing which could not only be used to predict the characteristic of the material but also develop numerical simulation and for the same purpose we are going to conduct this project.

Short term motivation of the project was

i) To investigate the effect of boundary conditions on picture frame results.
ii) To compare PF and BE data and therefore characterise the forming behaviour of the self reinforced composites.

As these self reinforced composites were recently being developed or invented, their implementation is not up to the mark. That is because the manufacturers or the investors have little lack of knowledge of to these self reinforced composites, their intrinsic properties and their manufacturing capability. Thus, these manufacturers or investors might be losing a big profit in terms of money. In an attempt to reduce the overall cost and increase the efficiency of the product or the equipment significantly, we also have to concentrate on the material being used to manufacture the product or the equipment.

1.5 Structure

This report is about self reinforced composites and the tests which help to determine their important properties to promote their usages or applications. The first chapter is about general introduction of the self reinforced composites, project objectives and motivation of the project. The second chapter is literature review which gives some important data regarding to the material characteristic experiments and some mechanisms involved in these characterisation tests. The third chapter is methodology which talks about methods or experimental setups and procedures used to conduct the tests such as friction test, sensitivity test, picture frame test, bias extension test and arrangement made to hold the picture frame in a perfect square shape. The fourth chapter is findings and analysis. In this chapter all calculations and results are put together and analysis based on that is presented. The fifth chapter is conclusion and it talks about the whole project whatever we had concluded. This chapter also contains the limitations and future work regarding the characterisation tests.

2. Literature review

2.1 Introduction

In this section, important information related to characterisation test is mentioned. This information is provided by some authors who are working on these self reinforced composites. According to these authors characterisation experiment plays an important role in determining a good constitutive model which can be simulated further using Finite Element Simulation Technology. A characterisation experiment includes picture frame test and bias extension test; both these tests are very famous among the researchers and scientist community. Generally, both these tests help to determine the intra-ply shear properties and wrinkling of these self reinforced composites.

2.2 Picture Frame Test

Harrison *et. al.* presented a method of using both Picture Frame (PF) and Bias Extension (BE) (to be discussed later) tests to characterise accurately the trellis shearing resistance of engineering fabrics under low in-plane tension conditions. In their research paper, they brought the causes of error for the test to the focus and suggested methods of avoiding those errors.

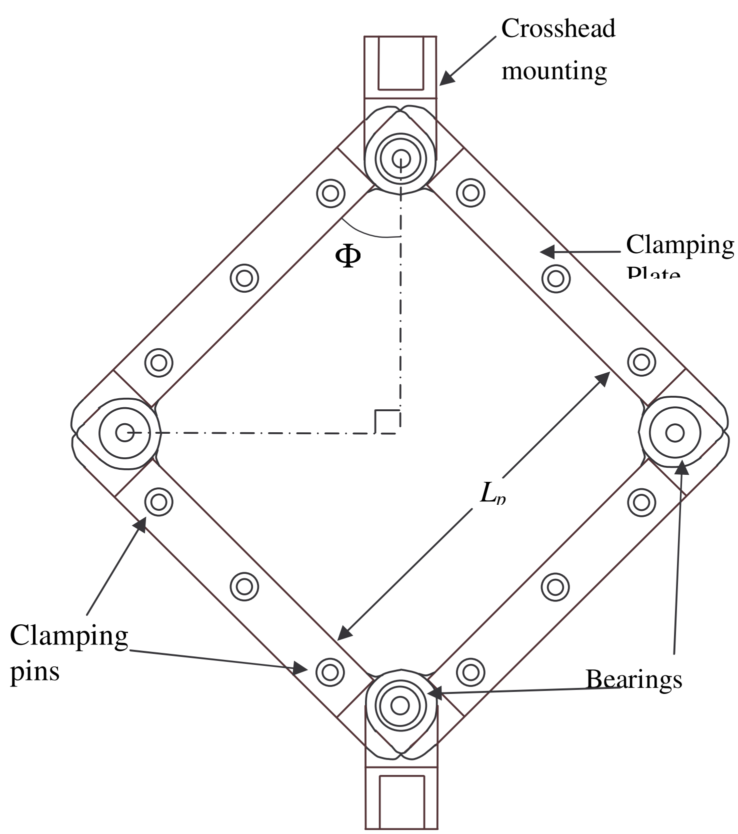

Figure 1. Picture frame shear rig. L_{pf} is the side length measured from the centre of the hinges and the shear angle, θ, is defined as $\pi/2-2\Phi$ [1]

In this test, a square shape frame is used as shown in the figure 1. A composite is clamped to each arm of this frame. This composite is clamped so that the fibres are parallel to the arms and the frame remains perfectly square before performing a test. After that a tensile force is applied across diagonally opposing corners of the Picture Frame rig causing the Picture Frame to move from an initially square configuration into a rhombus and accordingly the sample that is fixed in the frame experience the trellis shear [1].

These tests are performed on a tensile testing machine which can measure all forces at the crossheads so that we could know the force required to deform the composite as a function of crosshead displacement. Also we can calculate the shear angle and angular shear rate as they are function of displacement and displacement rate respectively [1].

With the help of picture frame test we can measure the in-plane shear and wrinkling, this test is also known as material characterisation test. The material characterisation experiment has an important criterion and that is measured properties should be independent of the test method or sample dimensions [1].

With the help of pre-tensioning apparatus we can improve the fibre alignment of dry fabrics within the picture frame test [1]. Picture frame test could be used to investigate effects of in-plane tension on the shear behaviour of the material [2, 3]. But measuring of this tension during testing is little bit difficult. A recent attempt to do so has been made by mounting load cells along the side-bars of a picture frame rig [5]. The force required to pull the crosshead of the testing machine is recorded and the trellis shear force per unit length is subsequently calculated using,

$$N_s = \frac{F_1}{2L_1 \cos\Phi}$$

Where Φ is frame angle, F_1 is the measured axial picture frame force and L_1 is the distance between the centres of bearings of the picture frame rig. The test data is always analysed to give graphs of shear force against shear angle and the shear angle (θ) is given by [1],

$$\theta = \pi / 2 - 2\Phi$$

Throughout the experiment axial force is plotted instead of shear force. Due to this comparing picture frame results with bias extension results becomes less difficult. Also shear angle in the material can be related directly to the crosshead displacement, d_1 and the shear angle is given by,

$$\theta = \frac{\pi}{2} - 2\arccos\left[\frac{1}{\sqrt{2}} + \frac{d_1}{2L_1}\right]$$

Where, d_1 is the displacement of the crosshead mounting. It has been seen that the shear angle measured in the material during the testing may deviate by up to plus or minus two degrees from the ideal shear angle depending on the shape of specimen. Also shear angle and current angular shear rate of the fabric could be assumed to directly relate to the crosshead displacement and displacement rate of the rig with boundary conditions imposed on the specimen. Loose clamping of the sample edges in the clamps could lead to failure of required kinematics, however tight clamping of the sample edges could produce spurious results even though the sample is slightly misaligned [1, 3, 6].

It has been observed with this test that different specimen dimensions gives different load to displacement curves and this could be considered by normalizing the recorded load by the shearing area of the specimen. Also in the Picture Frame test lack of reproducibility of the results has been observed and this is due to the inherent difficulty to align the fibres properly with frame and also to maintain the frame at 90° while clamping the fibres and before starting the test [4].

2.3 Bias Extension test

According to Harrison *et al.* this is probably the simplest method to test the characteristic of the material. A rectangular biaxial material is cut at bias that is at 45° direction [9] and clamped in such a way that wrap and weft tows are orientated initially at plus or minus 45° to the direction of the applied tensile force. Generally this biaxial material is in rectangular shape and provides clamping area wider as compare to the test area. Due to this, slippage of yarns from the underneath the clamps reduces [1, 4]. The sample dimensions can be characterised by the sample's length / width ratio, $\lambda = L_o / w_o$, where the total length of the material sample, L_o, must be at least twice the width, w_o. The reason for this is associated with 'end effects' due to the clamping constraint imposed at the two ends of the fabric. This can be seen when analysing the idealised deformation of a material sample in a bias extension test [1]. Actually, this test is less sensitive to clamping and alignment errors in comparison to a picture frame test [7]. Figure 2a shows the three regions and shear zone 'A' hear zone 2b shows experimental set-up used to evaluation of intra-ply shear properties of the textile composite and figure. These three regions provide better understanding of the effects of shearing on the samples [4].

As per Harrison *et al.* bias extension tests are simple to perform and provide reasonably repeatable results. The test provides an excellent method of estimating a material's locking angle; the angle at which the material's deformation kinematics begin to deviate from trellis shear to a combination of trellis shear and intra-ply slip [8]. Unlike the Picture frame test, as long as the material sample is tightly clamped, the boundary conditions are much less relevant to the test result. On the other hand, Potluri *et al.* suggest that the test does suffer from certain drawbacks. First, it has been seen from the experiments that the non shear region near the clamps does not remain constant but reduces during the test. This is due to the tow slippage. As a result the shear angle in the material could not be calculated accurately from the displacement of crosshead and a camera has to be used to grab the images from the pure shear region and analysed the same for shear angle [7]. This is time consuming and slow visual analysis process, as the images have to be analysed frame by frame which can be complicated further if the sample is to be heated during testing. Second, the deformation field within the material is not homogenous this makes analysis more complicated to get the results. Finally, the test induces a combination of both pure shear and intra-ply slip, from Harrison et al. [8]. In terms of analysis this presents extra difficulty, though conversely, this deformation may be used to advantage as a means to investigate intra-ply slip as a potential deformation mechanism of woven fabrics.

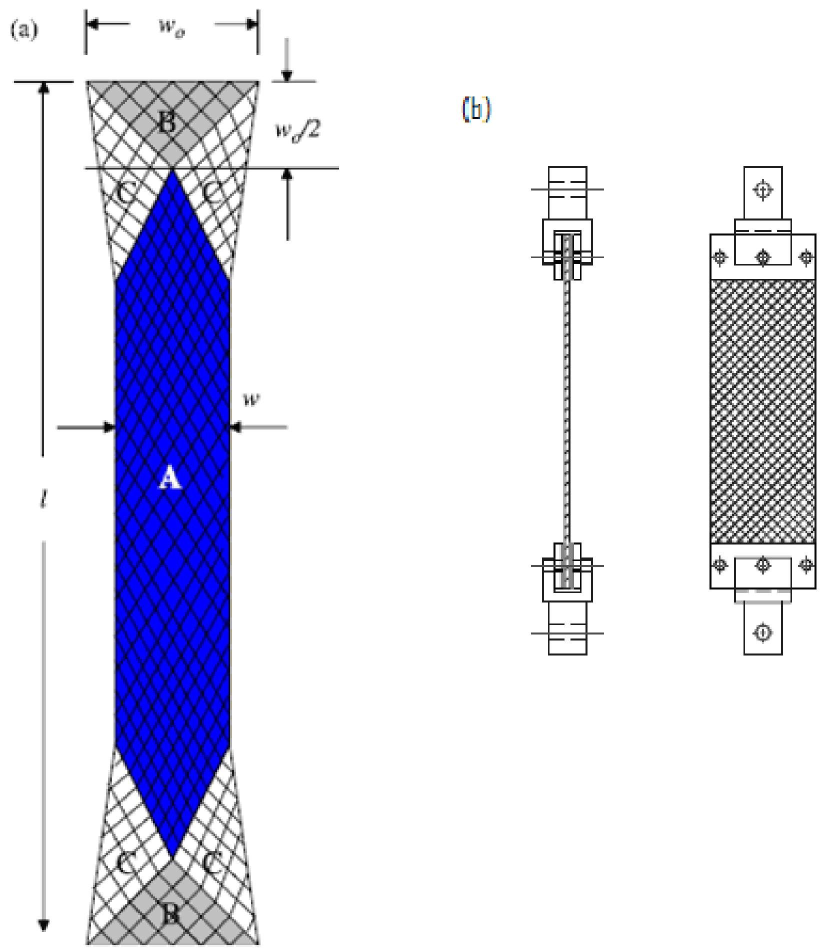

Figure 2 (a) Sample showing three regions and shear zone 'A' and (b) experimental arrangement of a bias extension test to evaluate the intra-ply shear properties of the textile composite [4].

There is a difference between the theoretical and practically measured shear angles and this has been found out due to the onset of yarn slippage beyond the lock limit [7, 9].

As per Potluri *et al.* recently it has been found that a sample such as woven fabric, wider than the clamp could overcome the limitations of a conventional bias extension test. A wider sample provides the pure shear region this is a complete rhombus and because of this the yarn slippage could be significantly reduces. With the help of this modification, calculated shear angles were in good agreement with the experimental values up to 50° of shear angle. Beyond this the computational error is introduced because of yarn elongation. It has been also seen from the experiment that during bias extension test wide-strip sample suffers from wrinkling [7, 9]. This problem has been resolved by applying a small transverse force and this method of testing is known as biaxial shear test. Also the wider samples could minimise inter-tow slippage due to the fact that each yarn has many more interlacements and because of this the sample fails at a much higher load. Due to this the shear angles could be computed from crosshead displacements up to much higher shear angles. It has been observed that the sample frays near the clamping areas and hence the width is not repeatable for each experiment [9].

2.4 Deformation mechanisms

As per Harrison *et al.* during the Bias Extension experiments the sample is extended by a distance, *d*, in the bias-direction along the longitudinal axis of the specimen as shown in the figure 3. In practical manner, the test sample gets that extension through various mechanisms, like intra-ply shear, intra-ply slip, tow un-crimping and fiber extension. Each of these mechanisms' contributions depends to the total sample extension depends on the relative efficiency of the mechanisms in the increasing the sample length that is the material deforms in the most energy efficient manner possible [8].

As the fibre stiffness is extremely high compared to the shear stiffness of the sample, energy arguments are used to show that fibre extension would provide only a negligible contribution to the sample extension. Extension of the sample due to tow un-crimping could be determined by assuming the tows initially follow either sinusoidal or in the extreme case a square wave path. During testing because of in-plane tension the tow path could be straightens out. These two assumptions provide maximum strains of between 0.15 and 2.5 percent. So that while modelling un-crimping it might be important to refine the accuracy of constitutive models for forming simulations, these un-crimping strains were insignificant as compared to strains measured in bias extension test [8].

Practically, most of the measured strain achieved at high extensions in bias extension tests could be contributed directly to intra-ply slip mechanisms. Generally two such mechanisms had been recognised. The first one is inter-tow slip and second one is intra-ply slip that is inter crossover slip. It had been found that when the inter-tow slip is absent in the mechanism the inter-tow slip angle is equal to the material shear angle and s remains equals to zero at all the time. On the other hand inter crossover slip allows tows to slide across each other, that means the tows are not pinned in place. According to Harrison *et al,* occurrence of this type of mechanism means increase in the distance *U* [8, 1].

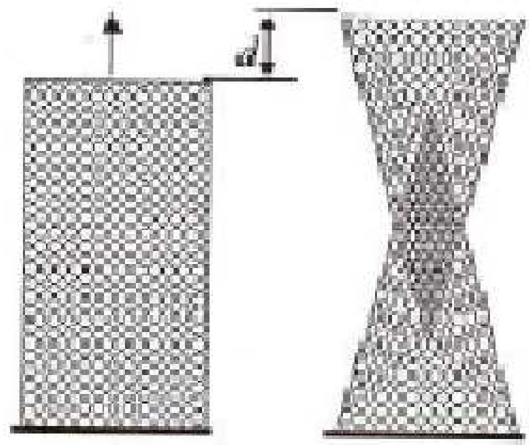

Figure 3 A sample of textile composite undergoing idealised ‘pin-jointed net’ kinematics [8].

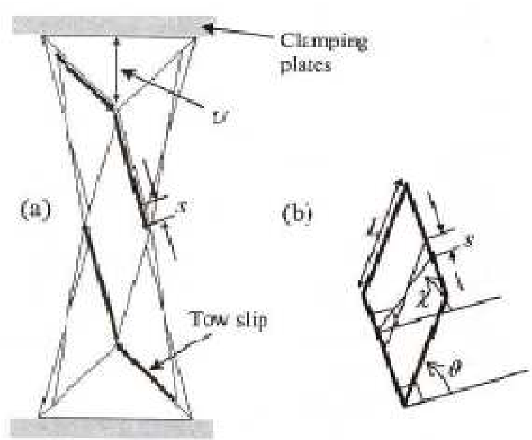

Figure 4 Intra-ply slip mechanism occurring during bias extension test.
(a) Tows which are not clamped at the end are able to slip against adjacent tows, ‘inter-tow slip’ and effectively increase the length of sample without increasing the shear angle. The slip distance ‘s’ is shown in the figure. A second form of intra-ply slip, ‘crossover slip’, allows the distance, *U*, to increase during the experiment.
(b) Illustration of shear angle, θ, and slip angle, χ, in central region of the sample [8].

However, tested sample showed inter crossover slip mechanism is of less important as compare to the inter-tow slip due to which the sample get extended during bias extension test [8]. Also high elongated bias extension test shows good characterised deformations and these deformations are some what different from those shown during picture frame test and low elongation bias extension test, as shown in the figure 4 [8, 10]. A geometrical analysis of figure 4 had been done and it is found that,

$$s = \frac{W - 2L_o \sin(\phi/2)}{2\sin(\phi/2)}$$

Where L_o is the original side length of the central region before inter-tow slip occurs and W is the width of the mid section of the specimen. This equation uses the assumption that the specimen remains flat without any wrinkling. The total crosshead displacement d can be given by,

$$d = 2\cos(\phi/2)(L_o + s) - \sqrt{2}L_o$$

2.5 Image Analysis

According to Harrison *et al.* the aim of the visual analysis is to calculate shear angle throughout the test. Image analysis software has been developed by the authors to decrease the time and effort expended in this process, and also to improve accuracy of the analysis. A digital video camera is used to record the deformation of the bias extension sample during testing. The digital video images were stored as files on a computer [1]. The figure 5 shows the window of software used for visual analysis.

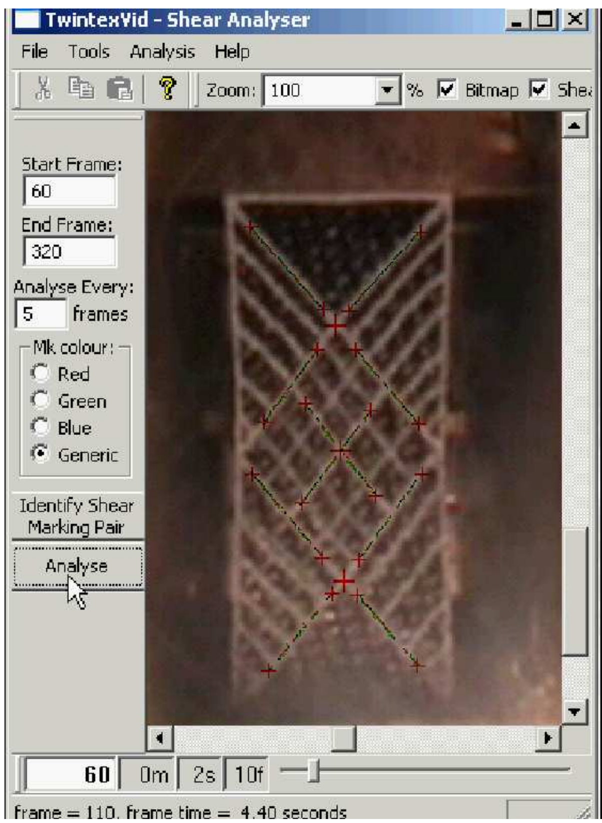

Figure 5 showing window of the software used during image analysis. The shear angle could be measured at several points within the region A simultaneously [1].

Before testing, lines are drawn along the tow directions on the sample. The image analysis software fits linear equations to the lines drawn on the sample with the help of a simple search algorithm. Using the fitted equations the inter-fibre angle is readily calculated at several points within Region A of the specimen and following equation is used to determine the shear angle.

$$\theta = \pi / 2 - 2\Phi$$

In the fitting process errors are inevitable due to the finite thickness and varying contrast of the drawn lines. This is apparent as 'noise' during determining the shear angle. Although this error is small and negligible as compared to the error include during manual visual analysis. On the other hand, automated method had allowed the collection of a much larger number of data points [1].

It is possible to catch images of the specimen before it goes under deformation test. Initially inter-tow angle of 90° is the ideal situation but it has been experienced that during handling and loading these specimens could invariably leads to variation of small degree of fabric shear before the testing. These initial shearing of the specimens could dramatically affect the repeatability of the test data. Hence, careful analysis of these images could bring a fair chance in improvement of quality of measured data [1].

2.6 Normalisation

As per Harrison *et al.* there is a method called normalisation in which both picture frame and bias extension tests are used together. A woven fabric has been tested. This method helps in characterise accurately the trellis shearing resistance of engineering fabrics which are under low in-plane tension conditions. To interpret bias extension data accurately, automated image analysis software has been developed which further makes analysis easier or more comfortable. Results that have been produced by bias extension test had shown that the fabric shear angle could vary across a bias extension sample, even within regions which were typically expected to deformation homogeneously. This variability can lead to inaccuracy in the data. A method of correcting these results is known as method of normalisation and to account for this inaccuracy had shown to produce dramatic improvement in test repeatability. As mention earlier there are some possible causes due to which errors are introduce in the analysis, to avoid or eliminate those errors normalisation method is used. [1].

Normalisation of picture frame test data may depend on the shape and size of the sample material though it becomes relatively straightforward when using square samples, which completely fills the area of picture frame. In case of picture frame test the measured force was normalised by simply dividing the side length of the sample specimen and this had been justified by using simple energy arguments. A similar argument was presented by Harrison *et al.* [1, 10]. While normalisation of bias extension test results for direct comparison with picture frame data or even compared with bias extension results generated by tests which were conducted on samples of different aspect ratios is also more complicated. During testing, the method of normalisation uses a number of simple assumptions which account for the non-uniform shear strain field caused across bias extension samples. Normalised results from bias extension tests on samples of different aspect ratios have been compared and provide validation of the theory. Finally, results from picture frame tests and bias extension tests were compared and a method of producing the most accurate material characterisation curve over a wide range of shear angle was suggested [1].

According to Harrison *et al.* [1, 10], with the help of normalisation method it has been shown that the amount by which results must be corrected not only depends on sample dimensions but also the form of the material's force versus shear angle displacement curve. All other advantages of the normalisation method are also manifest: bias extension tests with a minimum initial length / width ratio ($\lambda = L_o / w_o$) of just two can be treated, so that there is no gauge section. This is advantageous as tests on specimens with large length / width ratios could produce or elaborate difficulties associated with handling the fabric, particularly when dealing with loose fabrics that tend to disintegrate easily. Use of smaller length / width ratios could also help to decrease the amount of material required for testing [1].

Also Harrison *et al.* suggest that the validation of normalisation technique depends on the shear angle of region A. The normalisation technique remains valid until the measured shear angle of the region A corresponds to the calculated theoretical shear angle. As soon as the measured shear angle starts to divert from the theoretical shear angle the shear distribution within the sample no longer matches the assumed distribution. After this point the material undergoes both trellis shear and inter-tow slips. Hence during the test measurements of shear angle in region A versus displacement should be made. This helps in determining the range of displacement under which the normalisation method remains valid [1, 10]. The effect of in-plane tension on the fabric shearing behaviour is another factor which could be neglected in the procedure of normalisation. Although experimental and theoretical results have been proven that shear properties of dry fabric are weakly affected by in-plane stresses [1, 10, 11]. Hence, the point which gives the small values of stresses had been reasonably considered to neglect during the development of the normalisation procedure [1].

3. Methodology

3.1 Introduction

This section gives information about the methods or experimental procedures that should be used in order to achieve our objectives. Two characterisation experiments were being used here, one is picture frame testing and other is bias extension test. But before performing the picture frame test, it is necessary to determine the sensitivity of the picture frame rig. If the picture frame rig is working correctly, then to avoid or reduce the misalignment of the fibres or slippage of the fibres from clamps, it is important to keep the picture frame rig in a perfect square shape before starting the test.

3.2 Experiments

3.2.1. Investigating friction in the picture frame rig

Before starting the picture frame testing it is necessary to make sure that picture frame rig itself is working correctly. That is with negligible friction present in between the flexible joint of the picture frame rig and without fundamental flaws, otherwise it could affect the final results obtained by using picture frame test. To determine this friction and define the flaws number of tests were conducted and a solution is presented. This test is known as friction test.

To determine the integrity of the final results which will obtained from testing, the rig itself has to be tested so that we can able to estimate the amount of friction present in the rig. This test is carried out for number of times and with different temperature conditions which further helps to regain fully comprehensive results sets.

During each testing the picture frame rig was started in a perfect square shape with the help of the rectangular bar and loaded into the tensile machine. In this machine the picture frame rig was extended from its original orthogonal shape to its full extension. Although while testing of the composites, the picture frame rig will never have to extend to this extent. It is very important to know the friction of the picture frame rig over its entire displacement range.

Each friction test has been carried out at 1kN load cell and at the rate of 200 mm/min. The same load cell and rate would be used for testing the composites. In all nine tests were carried out in three sets. The first set was at room temperature, second set was at 200° C and third set was again at room temperature. All these tests were conducted on a same day.

In the following graph, blue lines are indicated for the data gathered at room temperature, red lines indicates that the data was gathered at 200° C and yellow lines shows that the data gathered at again room temperature. Friction could be determined from this graph.

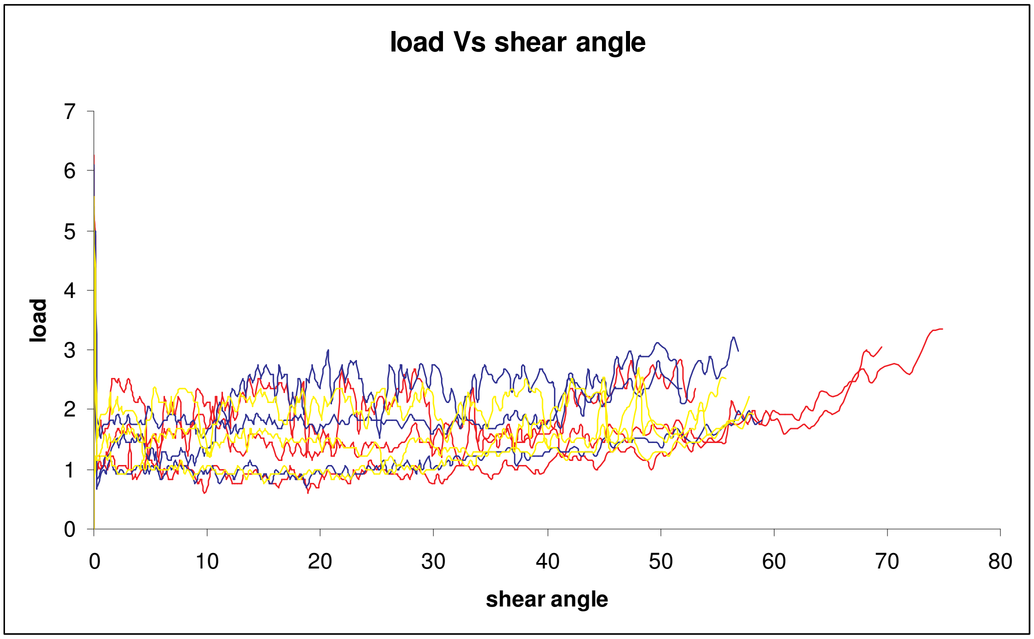

Figure 6 shows graph of load versus extension for the friction test.

3.2.2 Conclusion

From the above graph it can be concluded that small amount of friction is present in the picture frame rig. At the start the graph shows high amplitude of the friction and after that this amplitude falls gradually. At the end amplitude of friction again increases but this increase is due to very less space present in between the two flexible joints of picture frame rig that is the picture frame rig is fully extended and now it is little difficult to extend the rig beyond this limit.

3.3 Sensitivity test

It is necessary to evaluate the sensitivity of the testing machine as soon as friction tests have been concluded. Hence, to determine the calibration errors and the system's sensitivity, the sensitivity tests have been carried out.

Initially, the picture frame is unloaded and the mass of 9N is attached to moving end of the tensile testing machine. The machine is zeroed before starting the test. As soon as the test starts, the crosshead displacement gives the displacement or extension presented in the graph. The weight is extended through approximately 85 mm. Required data is obtained from the load versus extension graph. The same test is repeated two more time and the graph of load versus extension is plotted.

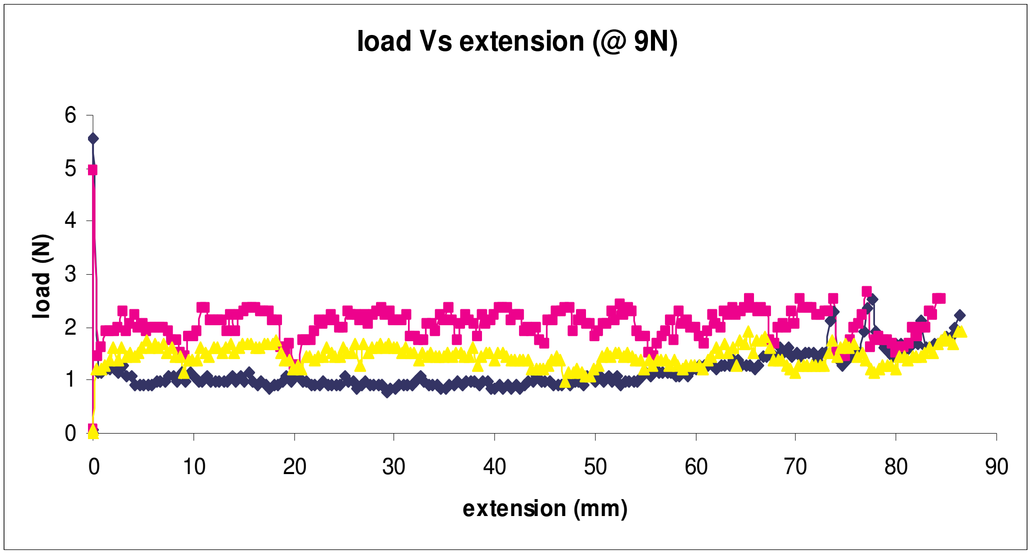

Figure 7 showing sensitivity of the tensile testing machine with the weight of 9N attached to it.

3.3.1 Conclusion

From figure 7 it has been concluded that there is little amount of friction approximately of 2N. We can also see that at the start there is sudden increase in the amplitude of the friction. This sudden increase in the amplitude of friction is also presented during friction testing. After that sudden increase, amplitude of friction falls down and remains in the range of friction 1N to 2N approximately.

Now to evaluate the sensitivity to the further extent, the same test as of sensitivity test is carried out but this time without any weight attached or with only self weight. That is this time the tensile machine runs without any experimental set up attached to it. Again the crosshead displacement gives the values of extension or displacement of the movie end of the tensile machine. Required data is then plotted as a graph of load versus extension.

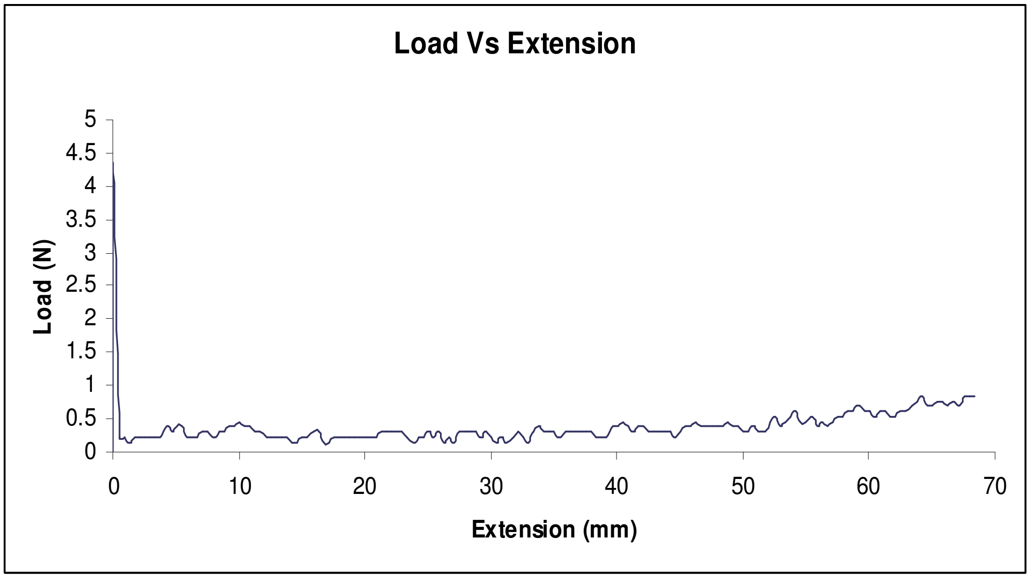

Figure 8 shows sensitivity of the tensile machine.

3.3.2 Conclusion

The same graph of load versus extension is plotted. From the figure 8 we can conclude that self-friction of the tensile machine is significant. The friction amplitude which is very high at the starting of each and every test was also present here. This amplitude of friction goes up to 4.35N approximately during this test. This friction introduced in the test may be because of initial jerk of the tensile machine which present in the machine by default. After the increase in the amplitude of friction it again falls down and remains approximately constant between 0N to 1N. We can see from the graphs 2 and 3 that the self-friction reduces as the load reduces.

From these two tests we can conclude that picture frame rig is working correctly and there is no need to recheck the parameters of the picture frame rig or to redesign it.

3.4 Designing of rectangular plate

3.4.1 Introduction

During loading of the picture frame test, to avoid or to reduce the misalignments or slippage of the fibres, it is necessary to hold the picture frame in a perfect square position. This position must me maintained at the time of loading the picture frame rig into tensile testing machine. This rectangular plate is so designed that it will not only hold the picture frame in required position but also it will keep the picture frame rig steady while loading the sample.

3.4.2 Material

Aluminium is used to manufacture this rectangular plate. As we know that aluminium is light weight, low cost, have good mechanical properties and have good machinability. Cast iron was another option but this material is little bit expensive, heavy and response quickly to corrosive conditions, although its have good mechanical properties and good machinability. Hence, cast iron was kept aside and we decide to manufacture this rectangular plate using aluminium.

3.4.3 Design

The following figure 9 shows the design of the rectangular bar. This plate contains two holes which can accommodate the picture frame rig's two diagonally opposite nuts easily. The distance between these two holes is such that when the two diagonally opposite nuts of the picture frame rig were accommodate in those holes, the picture frame rig will be in a perfect square shape.

The measurements were taken according to the picture frame rig. The required dimension of this plate was 265mm x 45mm x 15mm. The distance between the two holes is 240mm and diameter of each hole is 15mm. Four corners of this plate were well rounded to avoid sharp edges. The 3D drawing was draft in 'Solidedge V14' CAD software.

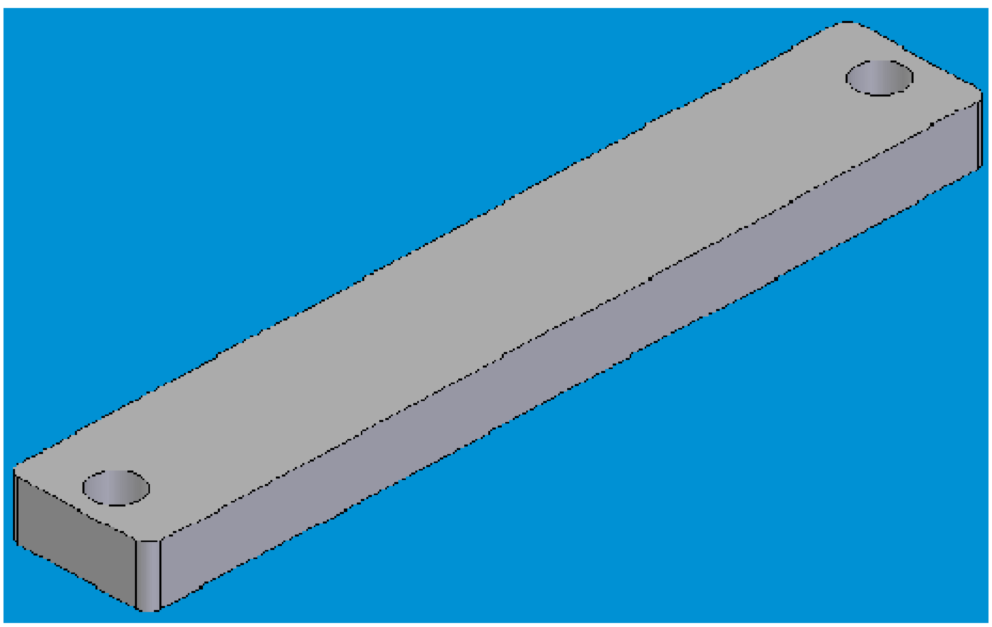

Figure 9 shows designed the rectangular bar.

3.4.4 Manufacturing

The complete 3D drawing and information of the suggested material for the plate is then handed to the workshop department and the technician manufacture the component as per the material and design given to him.

First of all he took the plate of material and machined that plate on lathe machine. With the help of turning operation the plate is machined to the required dimension as per the drawing provided. Then by using grinding operation all sharp edges were rounded and after that using drilling operation two holes of 15mm diameter were drilled according to the design. Finally all dimensions of the plate were checked. During the whole manufacturing process lubrication is provided to the component.

Thus the rectangular plate was ready to use in the picture frame test.

3.5 Picture frame test

3.5.1 Preparation of samples

The material used in this investigation was a polypropylene. This polypropylene sheet was commingled, pre-consolidated, homogeneous and 2x2 twill weave textile composite. Figure 10 shows one of the prepared samples. The samples were cut such that the tested area measured 170 mm x 170 mm. The actual area of the samples was 190 mm x 190 mm, access area provides facility for clamping the samples. The thickness of the un-deformed sample was approximately 0.5 mm.

The tows were oriented plus or minus 45° to the outer edge of the sample. The corners of the sample may interfere with the corners of the picture frame that might affect the end results. To avoid this interference the samples corner were cut off. As we are also going to do a visual analysis we marked a cross using white heat resistant tipex pen. This mark is made at the centre of the samples which makes visual analysis little bit easier.

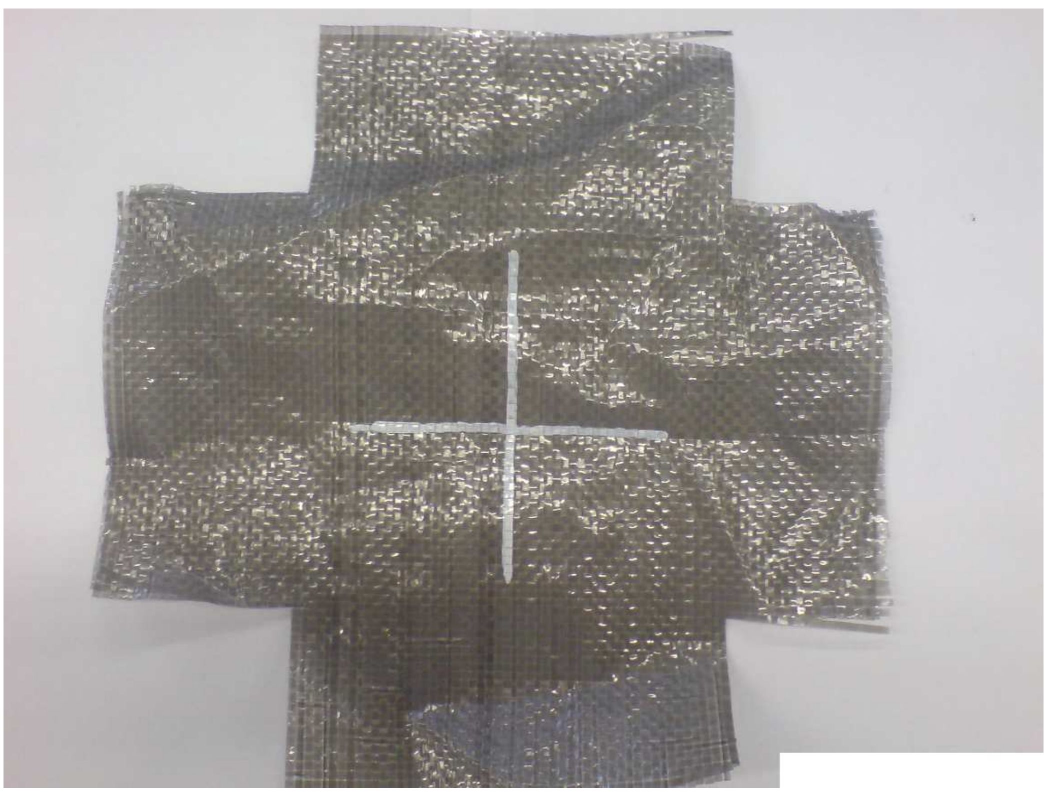

Figure 10 shows one of the prepared samples and a cross which makes visual analysis little bit easier.

The other important factor in preparing a samples are to draw holes in to the specifically cut samples. Samples were clamped in between picture frame rig and the cast iron plates with the help of bolts and these bolts run through from these holes on the sample. The alignment between this sample, plate and arms of the picture frame rig must be accurate so that the sample clamped in the picture frame rig in a correct way. The diameters of holes also have to be an exact fit for the bolts. Thus, it is insure that the sample is secured fully and no slippage occurs during the testing.

3.5.2 Testing procedure

We want to observe the effect of clamping and trellis shearing resistance during picture frame testing. Hence we decide to perform picture frame tests with two different clamping conditions and those clamping conditions were tightly clamped and loosely clamped. All the tests were carried out at room temperature. The tensile testing machine is set to operate at the rate of 200 mm/min and with 1 KN load cell.

First, we conduct picture frame tests for tightly clamped condition. In this test, the picture frame rig was placed on the rectangular bar which is resting on a flat surface of the table. This rectangular bar helps us to maintain perfect square position of the picture frame rig. The rectangular bar was so designed that it will not only maintain the square position of the picture frame rig but also keep the picture frame rig steady while loading the prepared sample. The prepared sample was made up of polypropylene sheet and this sample was clamped over all four arms of the picture frame rig with the help of four cast iron plates and bolts. This arrangement held the sample firmly in position. As we want to test this sample for tight condition, we had conformed that all bolts were tightly fasten.

After loading the prepared sample into the picture frame rig, the rig along with the rectangular bar attached to it was installed or loaded into the tensile testing machine. The purpose behind keeping the rectangular bar attached to the picture frame rig while loading the rig into the testing machine was to maintain the perfect square shape of the picture frame rig. Now for visual analysis we positioned a camera to record each and every moment of the testing. Analysis of this recording will help us to determine the value of experimental shear angle and wrinkling mechanism as well. Figure 11 shows the experimental setup for the picture frame test in which sample was clamped tightly.

The tensile testing machine is interfaced to the computer using ‘Lloyds’ software package. With the help of this software, allowed measured displacements and forces were compiled and a graph of load versus extension was displayed. The data stored in a computer is used during theoretical calculations of shear angle.

Once the setup is ready, we start the picture frame test by applying a tensile force across the crosshead. Then the force required to deform the sample clamped in the picture frame rig was recorded as a function of crosshead displacement. Thus the original square shape of the picture frame starts to change into rhombus. The sample clamped inside the picture frame rig start to deform. At the same time crosshead gives displacement and accordingly computer starts to plot a graph of load versus extension. Generally, at the extension of 85 mm the two corners of the picture frame becomes very close to each and at the same time amplitude of friction start to increase. This is because the picture frame is approximately fully extended and there is hardly any displacement occurs after that particular point. Hence to avoid this situation we decide to stop the test before reaching this point of saturation. Also during testing we can observe the wrinkling of the sample near about at 65° of shear angle.

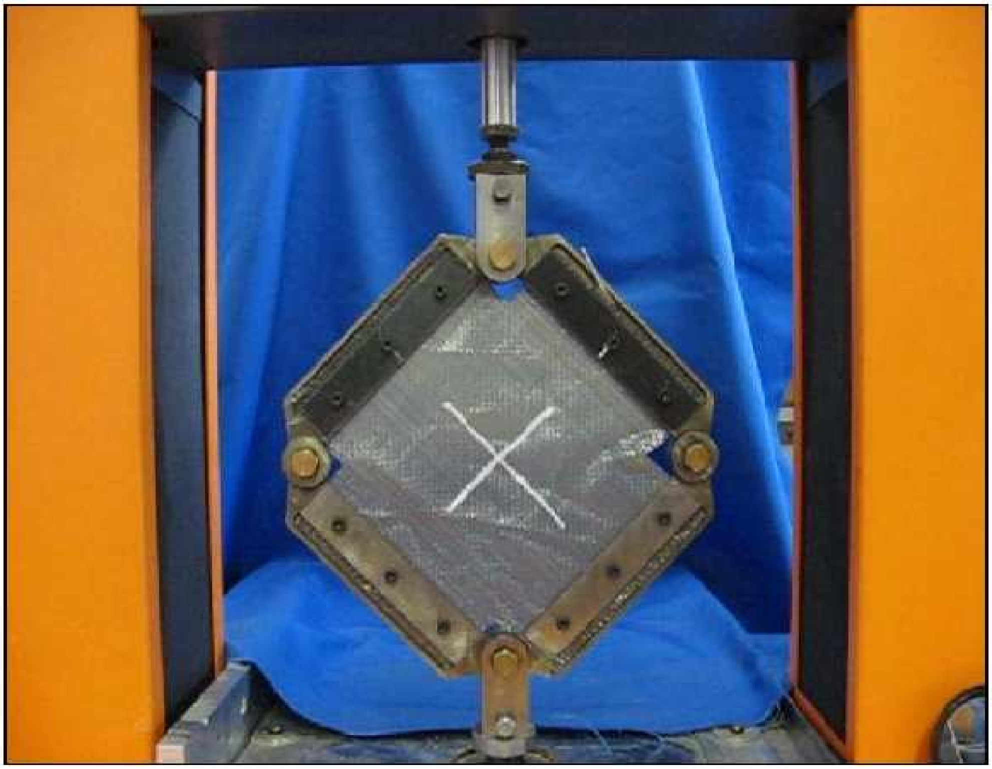

Figure 11 shows the experimental setup for the picture frame test in which sample was clamped tightly.

At the end when picture frame is fully extended and the sample got deformed as shown in figure 12a, we get a computer generated graph of load versus extension. After that we unload the picture frame from the tensile testing machine. Bring back the axis of tensile testing machine back to its original position. As we have to take total four tests for tightly clamped sample. We repeat again same test procedure for three times, keeping all the test parameters same as above one and collect the required data, graphs of load versus extension and observed the deformation of the sample which is to be tested.

At last we compare all these graphs with each other. Also we calculate experimental shear angle and theoretical shear angle and plot a graph of experimental shear angle versus theoretical shear angle.

Figure 12a shows fully extended picture frame rig and deformed tightly clamped sample.

Now we conduct the same picture frame test as above but this time changing the clamping conditions. Last time we had done the picture frame test by clamping the prepared sample tightly to the picture frame but this time we will clamp the prepared sample loosely. Clamping the sample loosely means after clamping we will make sure the bolts were fasten loosely. Keeping all other parameters same as for the first test we start the testing and observed the deformation of the sample. We perform this test for four times so that we could get better results. Again during whole test the camera was positioned to record each and every moment of the tests. At the end, this recording will help to make visual analysis of the picture frame and to determine the shear angle. During the test we can also observe the wrinkling mechanism on the sample, wrinkling starts approximately after 80° of shear angle.

The test ends when the picture frame rig is fully extended and the sample in side the rig get deformed as shown in figure 12b. Finally, collecting all the data from the computer and graphs of load versus extension we compared all the final results with each other. Also we calculate experimental shear angle and theoretical shear angle and plot a graph of experimental shear angle versus theoretical shear angle.

Figure 12b shows the fully extended picture frame and deformed loosely clamped sample.

3.5.3 Conclusion

From the above experiments we can see that for tightly clamped picture frame tests we got the shear angles at much higher loads and for loosely clamped picture frame we got the shear angles at comparatively lower loads. Hence if we want to determine the trellis shearing resistance with small values of loads then material loosely clamped in the picture frame could be preferred. We can also observe the wrinkling of material for both clamping conditions of picture frame. For loosely clamped material wrinkling occurs little bit earlier as compare to tightly clamped material.

3.6 Bias extension test

3.6.1 Preparation sample

To investigate bias extension test same material is used as for picture frame test. The material sheet is made up of commingled, pre-consolidated, homogeneous and 2x2 twill weaved polypropylene composite. The samples are cut such that the actual area of the sample will be 280 mm x 110 mm but the tested area is 220 mm x 110 mm and the thickness of the sample is 0.5 mm.

During this test length to width ratio, $\lambda = L_o / w_o$, is an important factor and we had keep λ = 2 constant for all bias extension tests. The way in which the composite sample is going to cut is also an important factor. The tows are oriented plus or minus 45° to the outer edge of the sample. This arrangement helps to produce pure shear during extension of the sample.

After that the samples were divided into three distinct regions by using a white, heat resistant tipex pen as shown in the figure 13. We mark a cross at the central region of the sample and this is the region where pure shear generally occurs. This cross is used to aid the visual analysis so that experimental shear angle and deformation can be calculated.

Figure 13 shows prepared sample for bias extension test with marking on it.

Another important aspect is holes which have to be drawn into the prepared sample. These holes must be perfectly aligned with the holes in to the bias extension rig's clamps. Bolts runs through these holes which ultimately provides a firm grip to the prepared samples. Due to this the prepared samples were clamped securely and no slippage occurs during the bias extension test.

3.6.2 Testing procedure

To determine shear angle and trellis shearing resistance we conduct the bias extension test. During this test we can also observe the wrinkling phenomenon on the sample. A prepared sample is tightly clamped in the bias extension rig and after that this rig is loaded in a tensile testing machine as shown in figure 14. The tensile testing machine has been set to run at the rate of 200 mm/min and with 1KN load cell. As mention earlier this tensile testing machine was interface to the computer with the help of 'Lloyds' software package.

Figure 14 shows experimental setup for bias extension test and a prepared sample clamped in it.

Once all the parameters are conformed and the bias extension test rig is loaded, tensile force applied across the crosshead. The required force to deform the material is then recorded as the function of crosshead displacement. Simultaneously the computer starts to plot a graph of load versus extension. After destructive deformation of the sample the test ends as shown in figure 15. During the whole testing a camera is used to record all the procedure and the deformation of the composite sample. This recording is used at the time of visual analysis to determine experimental shear angle.

For better results we conduct the same test for three times and in every test we keep all parameters same as in above bias extension test. We collect all graphs of load versus extension and the data from the computer and compared these with each other. We also calculate theoretical and experimental shear angle and compared it with each other.

Figure 15 shows destructive deformation of the composite sample.

3.6.3 Conclusion

From this test we get the results which are in agreement with the results obtained from picture frame rig for tightly clamped samples this can be verified from the graph shown below. This graph compares theoretical values of shear angle obtained during both tightly clamped picture frame test and bias extension test. Here blue lines represent the results obtained from tightly clamped picture frame test and red lines represents results obtained during bias extension test. As shown in figure 16.

Also during this test wrinkling of sample is observed. Camera records every moment of the test so this recording will help to determine the experimental shear angle.

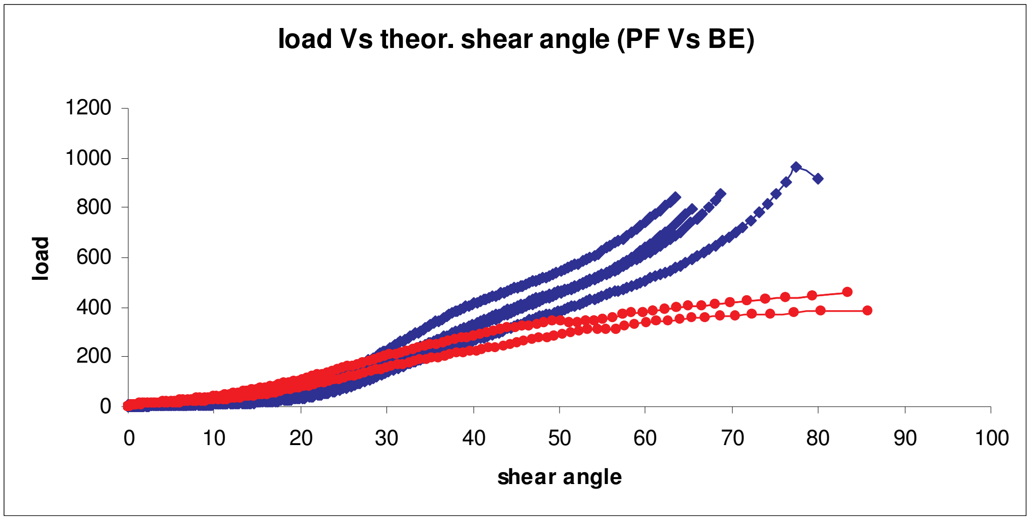

Figure 16 shows a graph of load versus shear angle and compare the results obtained from tightly clamped picture frame test and bias extension test.

4. Findings and analysis

4.1 Introduction

In this section all calculations related to both picture frame test and bias extension test are done to determine the theoretical shear angle. After that theoretical shear angles are compared with experimental shear angles. Also the calculations for friction test are also done.

4.2 Picture frame test calculations

The data gathered from the computer during the test is used to calculate the values of theoretical shear angle for particular displacement, by using following formula [1].

$$\theta = \frac{\pi}{2} - 2\arccos\left[\frac{1}{\sqrt{2}} + \frac{d_1}{2L_1}\right]$$

Where θ is shear angle, d_1 is displacement of crosshead or extension of the sample and L_1 is the distance between two consecutive bearings of picture frame rig which is equal to the length of the picture frame rig's arm, 170 mm.

4.2.1 Friction test

For friction test the sample calculation is shown below, this calculation uses the above formula.

$$\theta = (\pi/2) - 2 \text{ x } \cos^{-1}[(1/\sqrt{2}) + (29.979/340)]$$

Therefore, θ_1= 15.363°. (See appendix C)

Using the same formula we calculate the shear angle and compare it with load recorded. This comparison is represented in graphical form as shown in the figure 17.

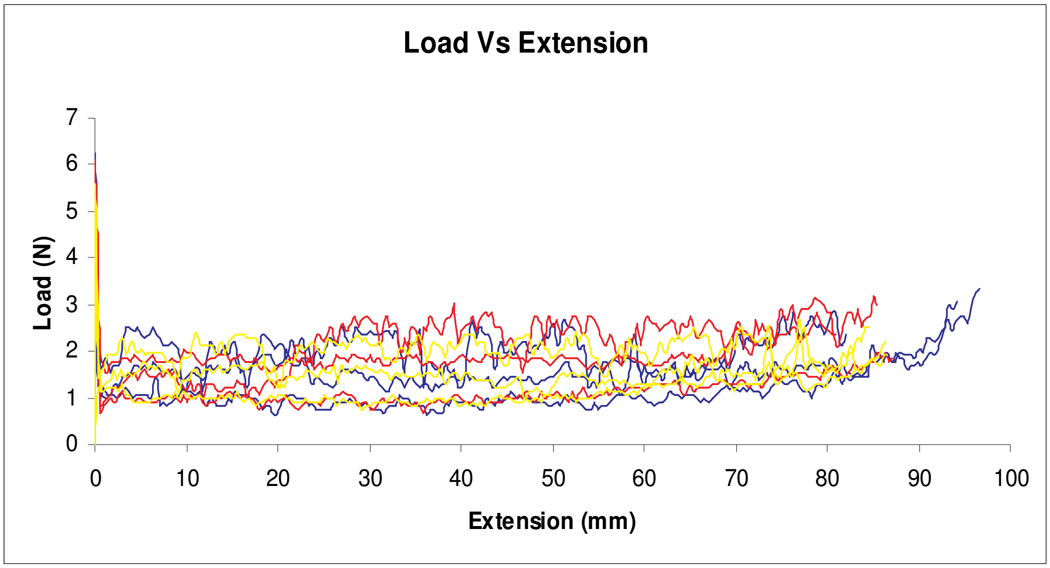

Figure 17 shows graph of load versus shear angle (for friction test).

In this graph blue lines represents data obtained at room temperature, red lines represents data obtained at 200°C and yellow lines represents data obtained at room temperature. From this graph we can observe the initial high amplitude of the friction; this is may be due to the initial jerk in the machine itself. After that this amplitude varies in between 0 to 3 N and then it goes on increasing little bit, but it does not goes beyond 3.7 N. From this graph we can conclude that the picture frame rig is working correctly and there is no need to recheck it.

4.2.2 Picture frame test for the composites with two clamping conditions one is tightly clamped and the other is loosely clamped.

For picture frame with tightly clamped and loosely clamped samples, calculations are shown below. As we know that d_1 is extension of sample during first picture frame test for tightly clamped sample. Say for d_1 = 29.667 mm and L_1 = 170 mm, then putting these values in the above equation and we get the value of shear angle (θ_1)

$$\theta = (\pi/2) - 2 \text{ x } \cos^{-1}[(1/\sqrt{2}) + (29.667/340)]$$

Therefore, θ_1= 15.189°. (See appendix C)

Same calculation is done with rest of the data and same applies for the calculations of picture frame clamped loosely. The values of theoretical shear angles, calculated by this way can be found in appendix C.

With the help of these calculated shear angle we can draw a graph of shear angle versus load as shown in the graphs 18 and 19. As we had done four picture frame test for tightly clamped samples and four for loosely clamped samples, every test is represented with different colour in both clamping conditions. Also load versus extension graphs can be drawn with the help of data gathered from computer. We had calculated experimental shear angle by visual analysis.

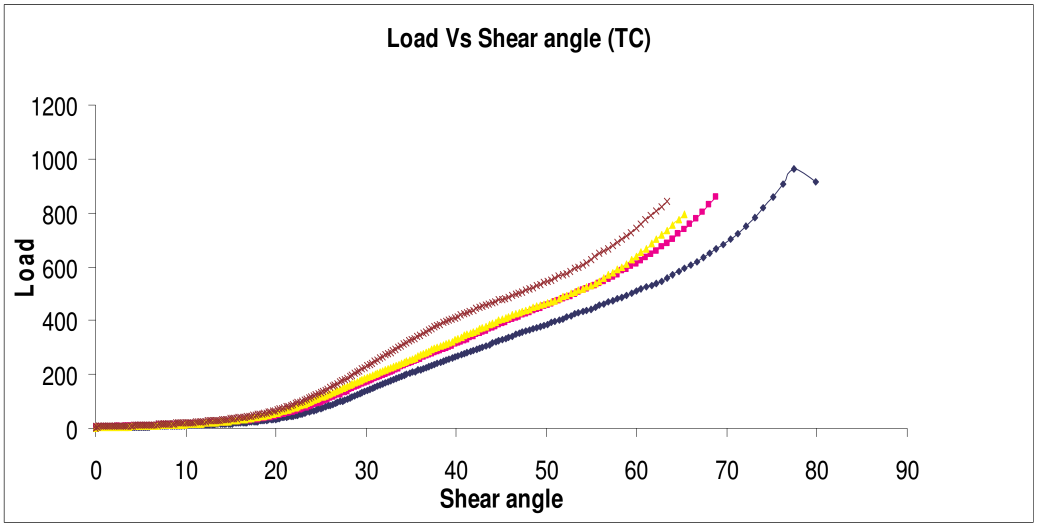

Figure 18 shows a graph of load versus theoretical shear angle for tightly clamped sample condition.

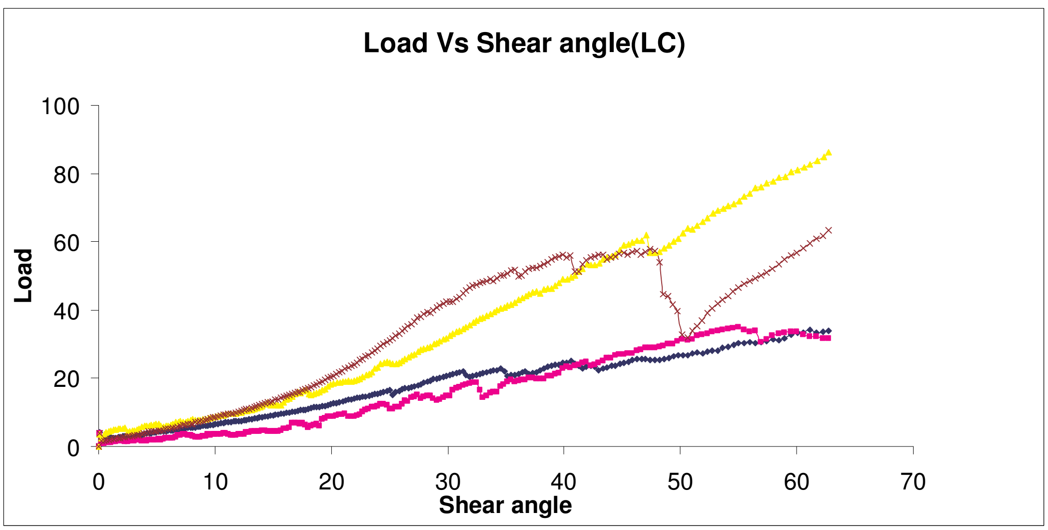

Figure 19 shows a graph of load versus theoretical shear angle for loosely clamped sample condition.

4.2.3 Conclusion

From the above graphs, we can conclude that the loosely clamped sample gets sheared but at low load as compared to tightly clamped sample. So to get the results at low loads loosely clamping arrangement could be used. Also we can get sharp curves as shown in graph 6 by using tightly clamping arrangement but at much higher loads. We can also observe wrinkling of sample during the tests. Generally, tightly clamped sampled wrinkles at shear angle 65° and loosely clamped sampled wrinkles at shear angle 70°. That means the loosely clamped samples get wrinkled earlier as compared to tightly clamped.

4.3 Bias extension test calculations

4.3.1 Introduction

Data collected during the bias extension test was used to calculate the theoretical values of the shear angle for the particular displacement. The following formula is used to calculate the value of shear angle [1].

$$\theta = \frac{\pi}{2} - 2\arccos\left[\frac{1}{\sqrt{2}} + \frac{d_1}{2L_1}\right]$$

Where θ is shear angle d_1 is the extension of the sample and L_1 is the side length of the central region before deformation and measured as to be 75 mm. We had done the calculation for d_1 = 43.414 mm. Putting these values in above equation to determine the theoretical shear θ.

$$\theta = (\pi/2) - 2 \text{ x } \cos^{-1}[(1/\sqrt{2}) + (29.667/340)]$$

Therefore, θ_1= 80.45°. (See appendix C)

The graphs of load versus theoretical shear angle and load versus extension are as shown in figure 20 and 21.

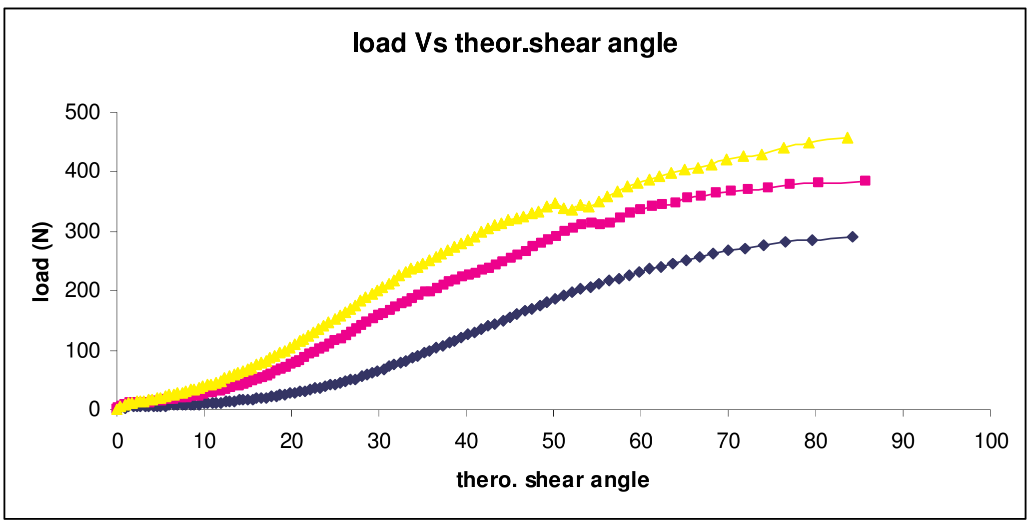

Figure 20 shows a graph of load versus theoretical shear angle obtained during bias extension tests.

The above shows comparison between loads applied on the crosshead and theoretical shear angle. Three colours represent three different samples which go under bias extension test. From graph we can see that approximately all lines follow the same path except the first sample which is represented in a blue colour in the above graph. Blue line gives smaller values of shear angle.

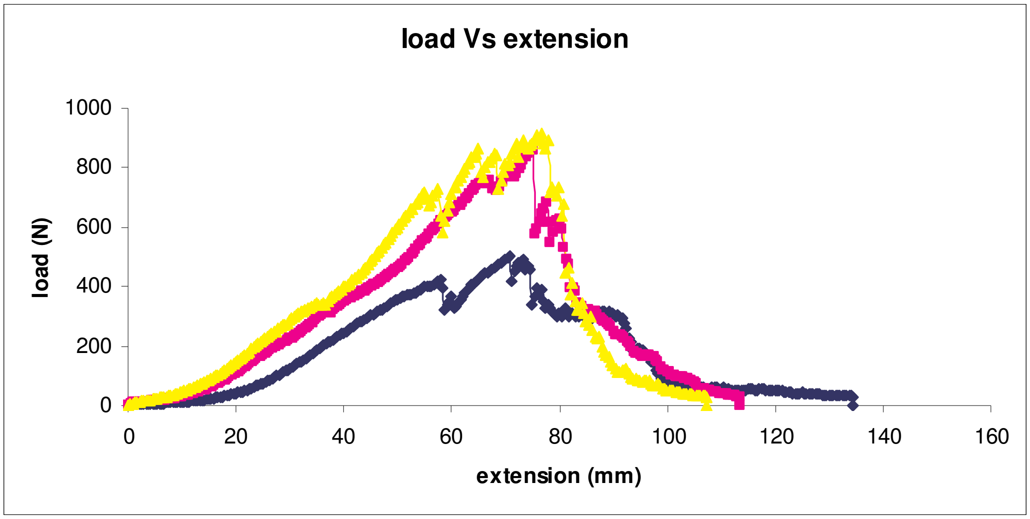

Figure 21 comparing load versus extension.

The above graph shows comparison between load and extension. Also we can see that the maximum load applied is 917.74 N at the extension of 76.60 mm. This graphs starts from zero load and goes on increasing with the extension up to the certain extent and after that when the destructive deformation occurs load falls down to zero again at hence the extension also stop.

According to Harrison *et al.* during bias extension test the sample got extended and inter-tow slip occurs. The slip distance is calculated by following formula [8].

$$s = \frac{W - 2L_o \sin(\phi/2)}{2\sin(\phi/2)}$$

Where s is slip, W is width of the mid-section deformed sample, L_o is the original side length of the central region and Φ is the inter fiber angle. Here it has been assumed that the sample remains flat without any wrinkling on that [8].

All these values are calculated through visual analysis. During analysing the videos we measured the right hand side parameters of the above equation and put them in to the above equation to determine the slip distance ‘s’. For first sample the slip distance (s) is equal to 108.060 mm, for second sample the slip distance (s) is equal to 108.060 mm and for third sample the slip distance is equal to 104.971 mm in appendix C its detail calculations is given.

Also total displacement of crosshead can be calculated by using following formula

$$d = 2\cos(\phi/2)(L_o + s) - \sqrt{2}L_o$$

Where *d* is the displacement of the crosshead, Φ is the inter fiber angle, *Lo* is the original side length of the central region and s is the slip distance [8].

With the help of visual analysis, we calculate the variables of the above equation and determine the crosshead displacement for the particular fiber angle. We had tested three samples and analysed the same. Hence, d_1 is equal to 256.033 mm, d_2 is equal to 256.033 mm and d_3 is equal to250.372 mm (in appendix C detail calculations is given).

4.4 Visual analysis

In this section with the help of visual analysis we can calculate the experimental shear angle. First of all we calibrate the camera and find out the calibration factor. After that we analyse all the tests and measure the required parameters and angles as well. Before using these values in the actual calculation we multiply the measured values with calibration factors.

Experimental shear angle can be determined by directly measuring the shear angle at particular time frame. The white cross marked at central region of the samples helps to measure the shear angle. As samples get deformed the white mark also get distort and by measuring the angle between these cross we can easily determine the experimental shear angle. With the help of visual analysis we can not only determine the deformation and shear angle but also the wrinkling phenomenon and when does it occurs. Following are the graphs for experimental shear angle.

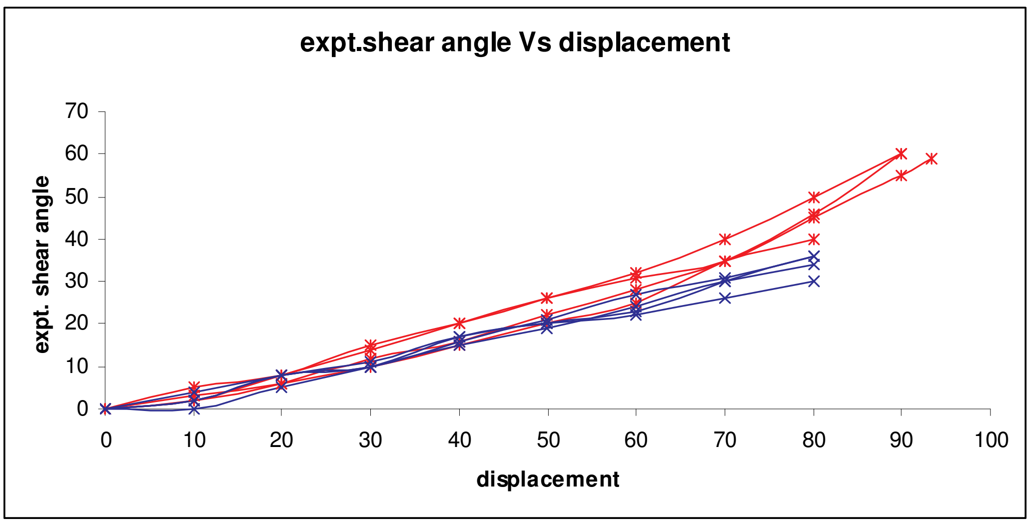

Figure 22 shows a graph of experimental shear angle versus displacement.

In this graph red lines indicates results obtained from picture frame test which are carried out with tightly clamped samples. These values of shear angle are calculated by using visual analysis. Blue lines represents results obtained from picture frame test which are carried out with loosely clamped samples. For tightly clamped picture frame test and bias extension tests the graph of experimental shear angle versus displacement does not vary much, the lines obtained from the results of these two tests are close to each other as shown in the graph 10.

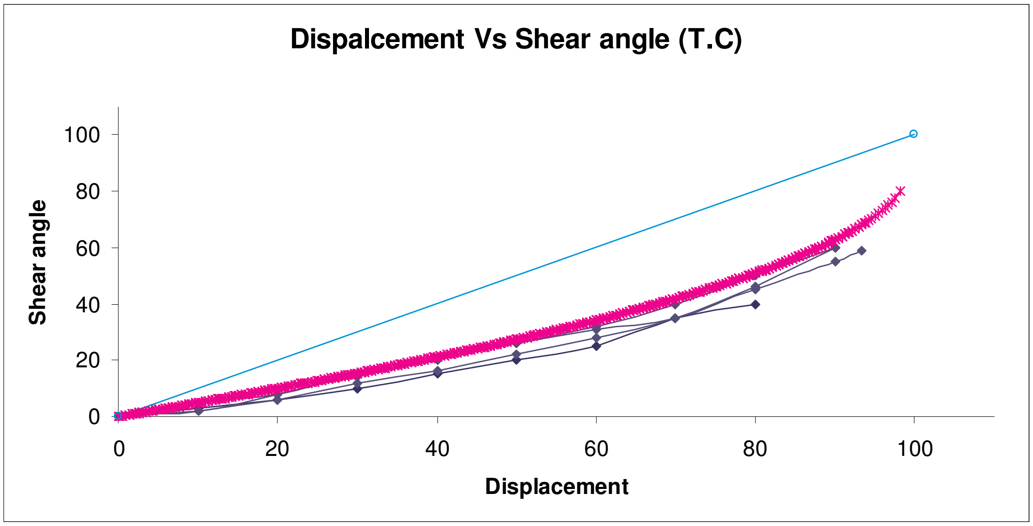

Figure 23 shows a graph of displacement or extension versus shear angle (θ) for tightly clamped samples.

Figure 23 compares displacement or extension of samples to the both shear angles calculated theoretically or calculated experimentally. During picture frame tests, the theoretically calculated values of shear angle for tightly clamped sample are represented by pink coloured lines and blue lines are experimentally calculated shear angles. From graph we can see that a thick pink line but actually it is four thin lines so aligned that it looks like one thick pink line that means the values of shear angle obtained from theoretical calculations are very close to each other as compared to the values obtained from experimental calculations.

Also the green line in the above graph which is at 45° to X – axis, assumed to be an ideal line and this line is drawn to just get an idea of how far is the ideal values of the shear angle as compared to the theoretical and experimental values of shear angle. In case of tightly clamped condition the theoretical shear angles are close to experimental shear angles.

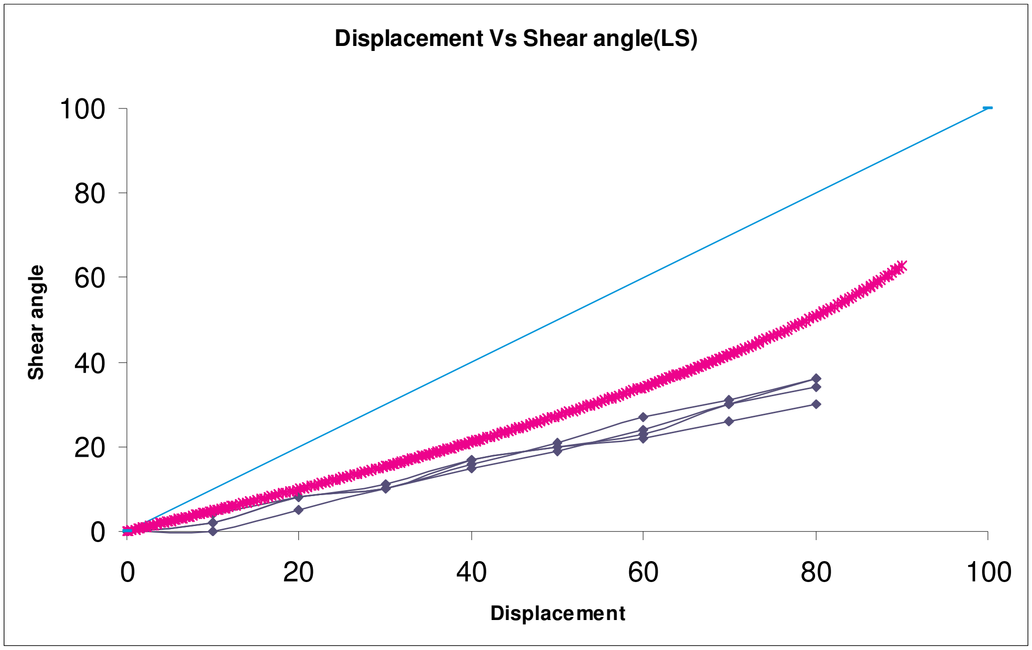

Figure 24 shows a graph of displacement or extension versus shear angle (θ) for loosely clamped samples.

The above graph shows comparison between displacement or extension of the sample and shear angle obtained during picture frame test with loosely clamped samples. Theoretical analysis gives the values of shear angle are presented by pink coloured lines; these four thin lines are so close to each other and that its look like a one thick pink line. Experimentally analysed shear angles are represented by blue coloured lines which are little bit distinct from each other as compare to pink lines. Green line is assumed to be an ideal line and at 45° to the X – axis; this line is drawn to just get an idea of how far is the ideal values of the shear angle as compared to the theoretical and experimental values of shear angle. We can also see that the lines for theoretical shear angles and the lines for experimental shear angle are not as close as the same lines appeared in graph 11.

Now for bias extension test we had done three tests and gather the relevant data, calculate the inter fiber angle (Φ), theoretical and experimental shear angles (θ). At last we plot the graphs of inter fiber angle (Φ) versus displacement and experimental shear angle (θ) versus displacement as shown in graph 13 and 14.

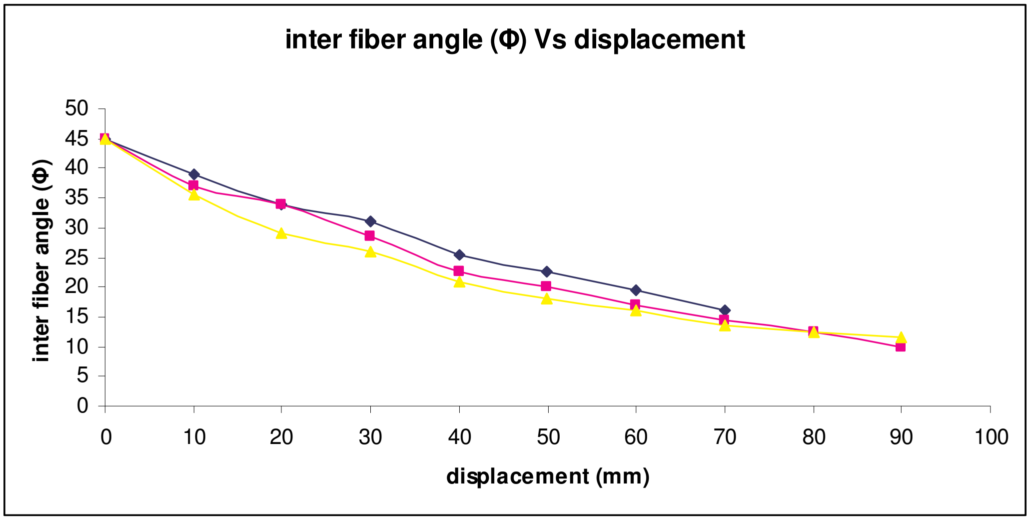

Figure 25 shows a graph of inter fiber angle (Φ) versus displacement

From the figure 25 we can see that the graph starts from displacement equal to zero at the time inter fiber angle is 45° and the graph ends at displacement equal to 90 mm when inter fiber angle is 10°.

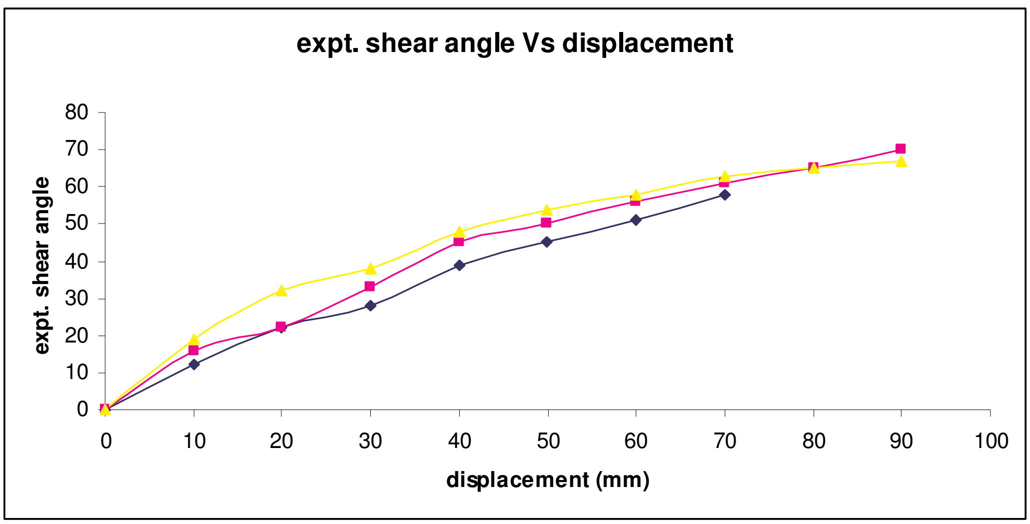

Figure 26 shows a graph of experimental shear angle (θ) versus displacement.

We can calculate the shear angle if we know inter fiber angle (Φ), using following equation,

$$\theta = \pi / 2 - 2\Phi$$

The figure 26 shows comparison between experiment shear angles versus displacement. The three samples are represented by three different colours. We can see that shear angle goes on increasing as displacement goes on increasing.

4.5 Comparison of the theoretical shear angle to the experimental shear angle

In this section, for both picture frame and bias extension tests the theoretical shear angle and experimental shear angle are calculated, compared and graphs of theoretical shear angle versus experimental shear angle are plotted.

4.5.1 For picture frame test

(A) tightly clamped

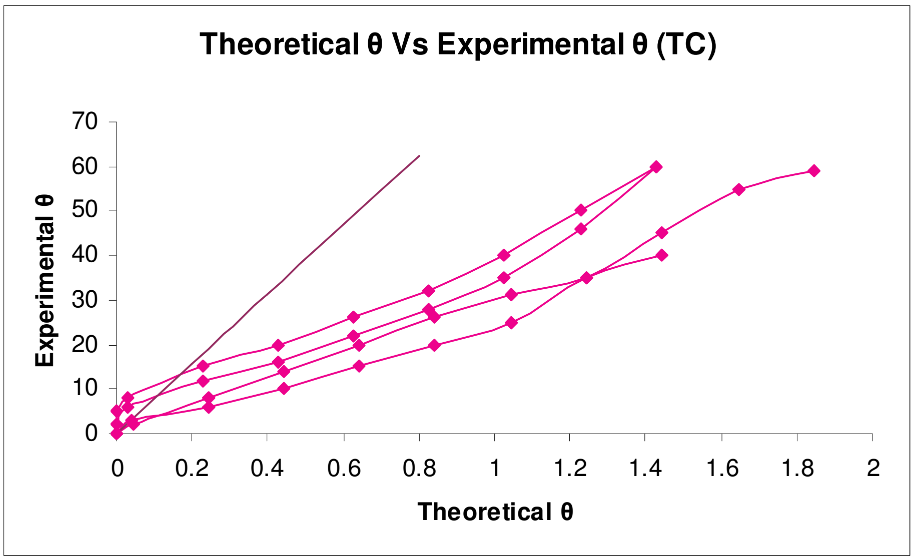

Figure 27 shows a graph of theoretical shear angle versus experimental shear angle for picture frame clamped tightly.

The above graph show comparison between the values of theoretical shear angle and experimental shear angle obtained during picture frame test with tightly clamped samples. A plain straight line is at 45° to X – axis and assumed to be an ideal line giving ideal values for theoretical and experimental shear angles.

(B) loosely clamped

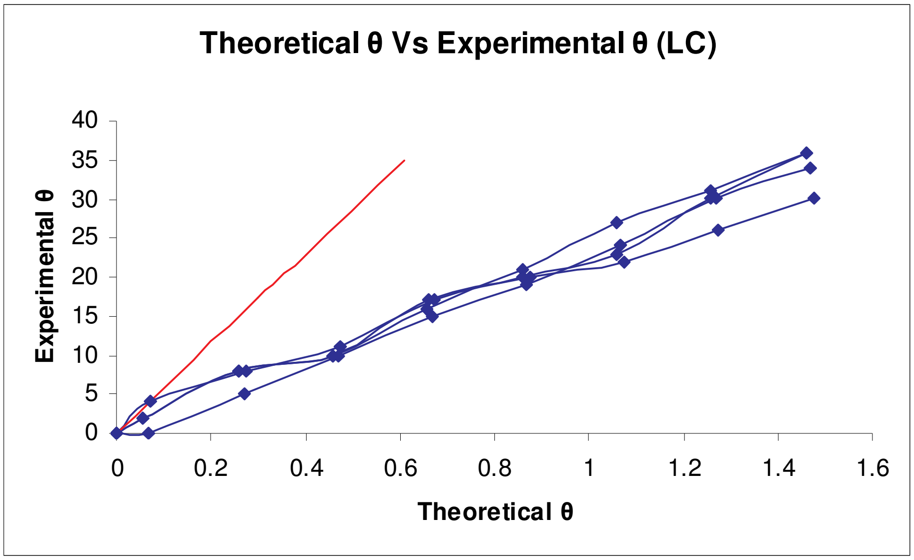

Figure 28 shows a graph of theoretical shear angle versus experimental shear angle for the picture frame clamped loosely.

In picture frame test with loosely clamped samples, we calculate and gathered all values of theoretical and experimental shear angle. From this data we plot the graph of theoretical shear angle versus experimental shear angle as shown in the figure 28.

4.5.2 For bias extension test

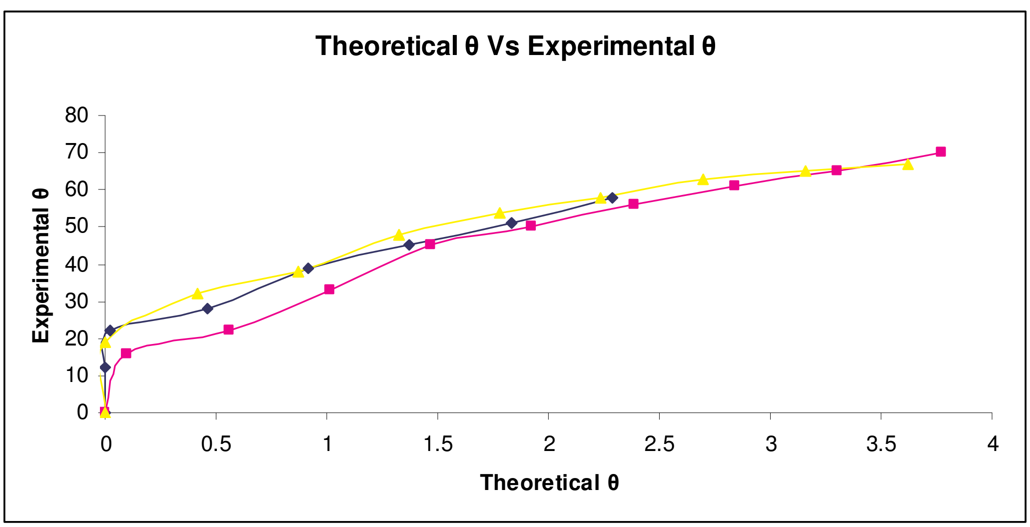

Figure 29 shows a graph of theoretical shear angle versus experimental shear angle for the bias extension test.

In bias extension tests, after the test is complete; we calculate theoretical shear angles and determine experimental shear angles from visual analysis. After that a graph of theoretical shear angle versus experimental shear angle is plotted. Every set of data is close to each other. As shown in figure 29.

4.5.3 Conclusion

We calculate theoretical shear angle and by visual analysis we determine the experimental shear angle. After that a graph of theoretical shear angle versus experimental shear angle for both picture frame tests and bias extension tests. From all three graphs we can conclude that results obtained during picture frame test with tightly clamped samples are closer to results obtained during bias extension tests. Although the samples get deformed during picture frame tests with loosely clamped samples earlier as compared to any of the remaining two tests. Also the samples clamped loosely got wrinkled earlier as compared to tightly clamped samples. We can also observed wrinkling in bias extension tests and after the wrinkling of the sample it is hard to measure inter fiber angle and to calculate the shear angles. If we want to deform the sample at small load, picture frame with loosely clamped sample is used.

5. Conclusion

5.1 Introduction

In this project, first we have to investigate working of the picture frame rig and came to the conclusion that it is working correctly although there is small friction. But this friction is so small and could be neglect. After that, conducting sensitivity test we conformed that picture frame is working correctly.

During this project, we successfully designed and manufactured a rectangular bar which helps to maintain the square position of the picture frame while loading the picture frame rig in to the tensile testing machine.

Two test methods, picture frame test and bias extension test were used to characterise the shear behaviour of the composite material and the deformation of the material could be found by analysing test data or by visual analysis.

As we conduct the picture frame tests at room temperature but with two different clamping conditions. We performed four tests for each clamping condition. First condition was tightly clamped and we calculate both theoretical and experimental shear angles. We compared theoretical shear angle with the experimental shear angle and it can be concluded that lines plotted gives approximately constant slopes up to certain limit. The lines of theoretical shear angles and experimental shear angles are closer to each other.

Second clamping condition was loosely clamped; again we calculate and determine the theoretical and experimental shear angles. After that we plot a graph of theoretical shear angle versus experimental shear angle. From this graph we conclude that the lines which were plotted can not able to give constant slopes and also the lines plotted were interfering with each other. The lines of theoretical shear angles and experimental shear angles are not so close to each other.

From bias extension tests we get the results which were closer to the picture frame tests with tightly clamped condition. Also according to Harrison *et al.* combination of pin joint net (PJN) kinematics and intra-ply slip kinematics has been observed and distance of slip has been calculated accordingly. Also destructive deformation has been observed at the end of the testing.

Comparing all these tests and their results with each other we can conclude that the loosely clamping condition could be preferred condition to perform picture frame tests. Also the sample was secured in this clamping condition.

5.2 Limitation

There are some limitations which are introduced in this project because of time factor. If we have more time; we might be able to,

1. Test the samples at different or varying environmental conditions like temperature.

2. Conduct these test using different size or shape for example in case of bias extension test we could use samples which are broad at clamping section.
3. Compared the results obtained in this report with those developed within a Finite Element Analysis. Also simulation of model would be possible.
4. As samples get wrinkled during the tests its little hard to determine the shear angle or to determine shearing of the samples.

5.3 Future work

To achieve better results we have to take some steps in future.

1. To conduct these test with same clamping conditions but at different environmental conditions or varying temperature conditions.
2. To develop simulations of these tests and to compare the results obtained in this report to the results obtain with these simulations.
3. To avoid wrinkling some arrangement should be made or designed such as a sheet of transparent plastic glass closely attached to the central region of the sample which is to be tested.
4. Picture frame rig have 12 bolts on its arms and take considerable amount of time to load a sample and to unload the same. If we are working to some high temperatures say above 80°C it is very difficult to remove the bolts from the rig. To save time in picture frame tests during loading and unloading of the samples we could use automated and wireless drilling machine. Thus, this drill machine will help to loose or tight those 12 bolts in to the picture frame rig with less effort and investing less time.

6. Reference

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[12] Appendix A, containing detail information of the textile composites - Curv™, MFT, PURE and Armourdon.