Shear Properties of Woven and Chopped Strand Mat Laminated Composite by Arcan Test Method

Mohd Sharizan Bin Mohd Sharif
sharizan539@yahoo.com
Department of Mechanical Engineering, Politeknik Sultan Salahuddin Abdul Aziz Shah, Selangor

Siti Khalijah Binti Jamal
khalijahjamal@yahoo.com
Department of Mechanical Engineering, Politeknik Sultan Salahuddin Abdul Aziz Shah, Selangor

Suaiza Binti Khairi
suaiza@psa.edu.my
Department of Mechanical Engineering, Politeknik Sultan Salahuddin Abdul Aziz Shah, Selangor

Abstract

The woven and chopped strand mat (CSM) are two types of GFRP (Glass-Fiber Reinforced Polymer) manufacture glass fabrics used in laminated composite. The main purpose when producing GFRP is to produce the materials that can process the best mechanical properties to suit with a certain condition. There are many tests which can be used in order to determine GFRP's mechanical properties. Arcan Test Method is the most suitable test for determining shear stress in GFRP. Based on the past experiment, the pure shear stresses occur at the significant area was proven and the test result is reliable. Factors that affected the GFRP shear stress are forms and orientation of the fibers. Besides that, volume fractions of fibers, Vf can also affect the shear stress in the materials. The stress will be higher when the load is being applied to the fiber direction and it will be lower at the transverse direction. Furthermore, the shear strength will be increased with the fiber volume fractions increment. Uniform shear strain, γ occur at the significant area where strain at (+45° and -45°) direction is uniform. Therefore, Arcan Test Method can be used to determine the shear stress of different fiber form s and fiber volume factions for GFRP materials.

Keywords: Glass-Fiber Reinforced Polymer, Arcan Test Method, shear strength, volume fraction

1.0 Introduction

The thermoset based composites are commonly use in engineering practice because they are simple to manufacture, low cost and high strength. Thermoset based composite is a composite material which use thermoset resins as the matrices. It can be categories in polymer matrix composites (PMC) because the composites consist of a polymer such as epoxy, polyester and urethane reinforced by thin-diameter fiber such as glass and carbon. Graphite-epoxy composite is approximately five times stronger than steel on a weight-for weight basis (TP Sathishkumar, S Satheeshkumar, 2014). Normally, most of the laminated continuous fiber composites contain planes weakness between the laminations along fiber and matrix interfaces. In shear, the composite strength will be dominated by these weaknesses unless the stress direction intersects the fiber (F.C. Campbell, 2010). Shear stress at the interfaces between the plies can seldom be avoided by lay-up design because of the anisotropies of neighbouring plies. In most engineering application, it is necessary to test the laminated composite plate to obtain the shear and stress properties and also determining the failure criteria (William D. Callister, Jr., 2007). In 1978, Arcan *et al.* introduced method of testing shear properties of material under uniform plane-stress conditions (M. Arcan, Z. Hashin & A Voloshin, 1978). Arcan *et al.* designed a special test fixture with a special shape of butterfly specimen. Using the photoelastic analysis, it shown that in the significant section of the specimen is possible to produced uniform plane stress with high degree of accuracy. The compact nature of the Arcan fixture offers advantages to obtain the shear properties in all in-plane directions in a relative simple manner. The Arcan fixture can be used to apply both shear and axial forces to the test specimen and this special case of loading produces pure shear on the significant section. In this case, the research that carries out is to obtain the shear stress of thermoset based composite with different fiber volume fractions and fiber forms. In general, typical shear test method used to determine the shear properties of most materials is the cylinder-torsion test (Aamir Muhammad Khokhar, 2011). However, this method has disadvantage which is unable to produced significant section on the sample and the grips strongly influence the state of stress. Therefore, the studies concentrated on the Arcan Test Method to determine the shear stress of thermoset based composite with different fiber volume fractions and fiber forms. The apparatus consist of specimen with butterfly shape and Arcan test fixture (test rig). The shear properties obtained due to the volume of the fiber usage and fiber forms.

2.0 Objective

The objective of this project is to determine the shear stress of thermoset based composite with different fiber volume fractions and fiber forms using the Arcan Test Method. The study focus on the following properties;

i. An average shear stress and shear modulus properties, τ and G of thermoset based composite with different fiber volume fractions and fiber forms.
ii. Analysis due to fiber volume fractions and fiber forms.
iii. The reliability of the test data.

3.0 Methodology

A special butterfly-shaped specimen has been designed to achieve a better test result especially in shear test (C. YenJ.N. CraddockK.T., 2008)(Matthieu Dunand and Dirk Mohr, 2017) (Figure 1). The method includes pure shear as a special case, when the angle equal to zero. The principle behind the geometry of the specimen is that in the pure shear zone, the isostatics will intersect the sheared cross-section at an angle of ± 45°.

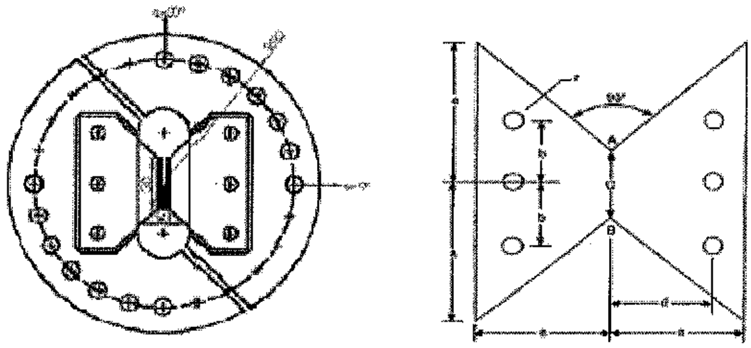
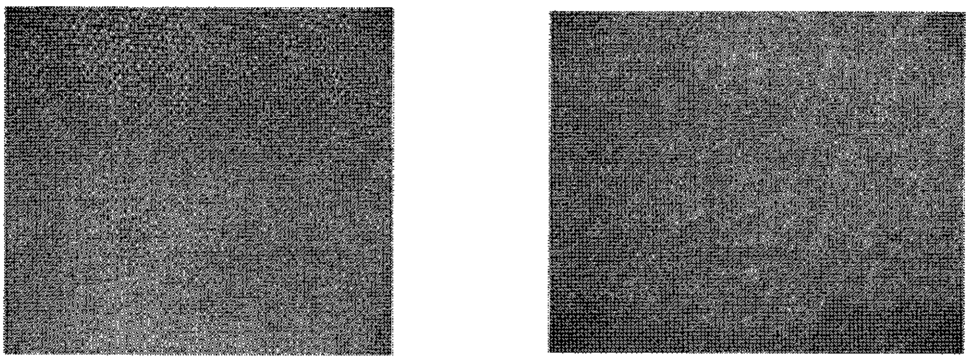


Figure 1: Test fixture set-up and shape of butterfly specimen

The composite strip was attached into aluminium plates using adhesive. Bonding was carried out using a special jig to ensure alignment of the specimen halves. After that, steel substrates were polished prior to bonding using sand paper. For composite surface, preparation method involved decreasing with methyl ethyl ketone (MEK), rinse and check for water break, hand abrasion with 320 grit aluminium oxide abrasive papers and clean for bonding. The specimens were pinned into the loading device in order to transmit the applied loads. With the application of the load P and by varying the loading angle, α from 0° to 90°, pure mode-I, pure mode-II and all mixed mode loading condition can be created and tested. By using an Instron testing machine, load-displacement curves generated by the test machine were used to determine maximum loads and displacement. Figure 2 represents the material used to make the specimen.



(a) Woven　　　(b) Chopped Strand Mat(CSM)

Figure 2: The materials that are used to make the specimens

4.0 Installation and specimen preparation

Hand lay–up technique has been done to make a fiber reinforced composite plate. Therefore, the plate must be cut using metal blade saw in order to produce a butterfly shape specimens due to the test rig size. The shear test was carried by using the Instron Universal Testing Machine

Model 5982 with Arcan test rig. The applied load to the rig was in tensile but the loading mode was transferred or imposed onto the specimen in the form of shear.

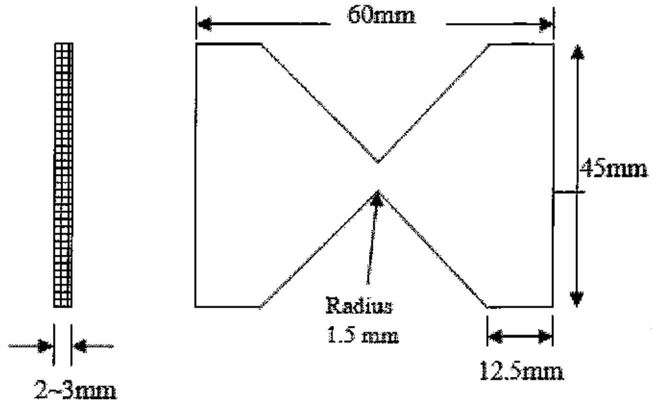


Figure 3: The butterfly specimen geometry

Figure 3 show the dimension of the specimens, which is 60 mm length, 45 mm width and average thickness in range of 2 ~ 3 mm. The 90° notches was formed at the centre of 60 mm length side by side such that the distances between notches was left about 10 mm at the middle to introduce shear field on the significant area. A radius of 1.5 mm was made in order to eliminate stress concentration point and produce a uniform shear stress distribution. A rosette type strain gauge, TML FCA-1-11 with 1 mm gauge length was installed onto the side of the butterfly specimen at the centre of the significant area (figure 4). The strain gauge was installed by referring to the manual of installation provided. The Arcan test fixture consists of a pair of male and female parts. The exact shape and size of specimen was mounted into the female part follows by the male part. Both parts were tightened by screws to ensure the specimen was tightly gripped between the fixtures to prevent from slippage and misalignment during loading. The complete assembly of fixtures (figure 5) was attached to the holder at lower and upper part accordingly prior attached to the Instron Universal Testing Machine. The tensile loads were applied through holder before loading configuration changed to shear mode that finally imposed onto the specimen (figure 6). The direction of principal shear then will act in the direction of ± 45° as referred to the horizontal axis of specimen significant section.

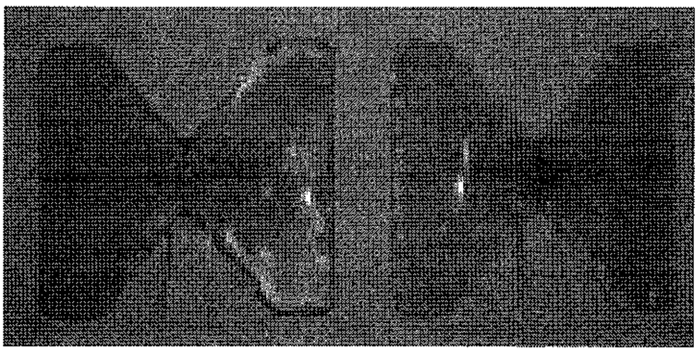


Fig 4: Complete gauge installation onto butterfly specimens

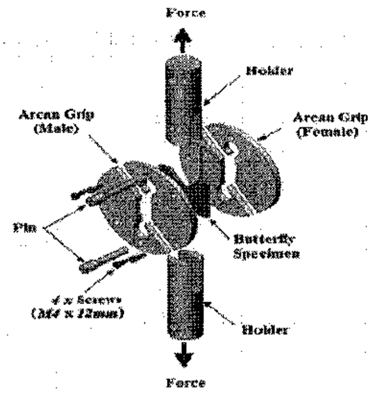


Figure 5: Assembly drawing of Test Rig

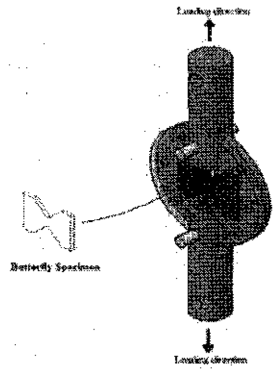


Figure 6: Set-up of Arcan fixture before testing

5.0 Testing procedure

Testing procedure was performed according to Oskui et. al 2016. By using an Instron Universal Testing Machine Model 5982, the 5 kN load cell was loading to the specimen. The loading rate was set-up to 1mm/min. The specimen was loaded up to failure specimen principal strains were measured at every 0.1 kN load increment and this was manually recorded by TDS 303 data logger until near to failure. The applied load and machine displacement were recorded automatically by the computer. Apart from that, a stopwatch was use to obtain time of failure for each specimen. Therefore, the relationship between the applied shear stress and shear strain in each gauge of the strains rosette can be established by dividing applied load on cross-sectional area of significant section. For every single specimen, maximum load, strain near to the failure and mode of failure were recorded. From the tests that have been carried out, the data were recorded such as load at/near to failure (kN), strain in ± 45° at significant area for every 0.1 kN load (με), failure mode (cracking or fracture pattern) and time to failure (s). After all the data has been recorded, the following equations were used to determine the shear stress (τ), average shear strength, average shear strain (γ) and shear modulus G at the significant area.

a) Shear stress, $\tau = \dfrac{P}{B_s\, h_s}$

Where; P – Load (N);
b_s – Length of significant section (mm)
h_s – Thickness of significant section (mm)

b) Shear Strain, $\gamma = 2(\varepsilon_x)_{\theta=45^\circ}$

Where; $(\varepsilon)_{\theta=45^\circ}$ - Strain at 45° angle

c) Shear modulus, G = $\Delta\tau / \Delta\varepsilon$

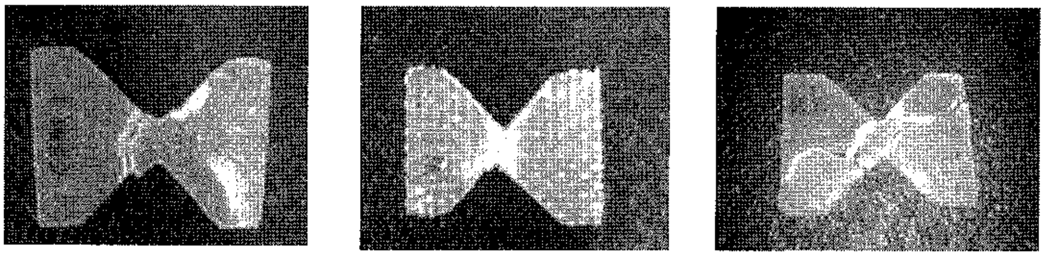
Where; $\Delta\tau/\Delta\varepsilon$– Slope of the plot of shear stress as a function of shear strain within the linear portion of the curve (N/mm2)

6.0 Result

Referring to the table 1, maximum load for CSM is 2.21 kN where maximum shear stress is 69.89 MPa. At the elastic level, the shear modulus for CSM is 2.16 GPa. For Woven, the maximum load is 0.57 kN and shear modulus is 0.27 GPa. The last sample is resin where the maximum loading is 2 kN and shear modulus is 0.6 GPa. Figure 7 show the fracture surface for every specimen.

Table 1: Experiment result for each sample

Sample	Maximum yield load	Strain approach yield limit		Shear stress at yield load	Shear Modulus	Shear strain at yield load
	P(kN)	45°	-45	τ (MPa)	G (GPa)	γ (με)
CSM	2.21	11214	-10684	69.89	2.16	21898
Woven	0.57	48266	-48169	25.09	0.27	96435
Resin	2.00	23245	-23185	38.90	0.60	46430



(a) CSM specimen (b) Woven (c) Resin

Figure 7: Specimen fracture surface

For each specimen, the principal strains in the +45° and -45° angle were used in order to calculate the shear strain. Then, the shear stresses versus shear strains graph can be obtained (figure 8). Therefore, the elastic shear modulus was determined using the curve gradient of the earlier stage of the shear-strains curve.

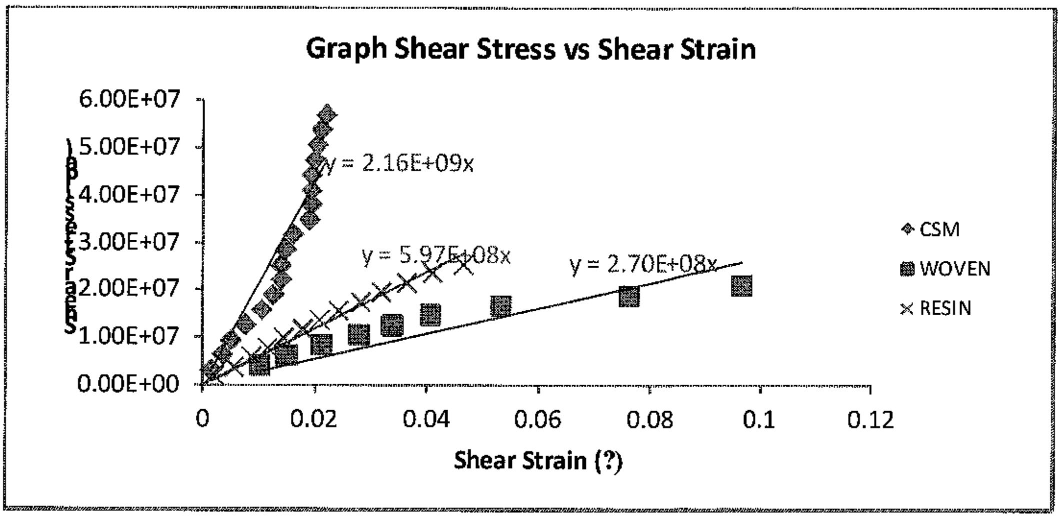


Figure 8: Relationship between shear stress and shear strain for each sample

Generally, the result shows the changes of element of shear stress is directly proportional with shear strain when shear force is increase. This is occurring because composite material is brittle in nature (Ban, H., Im, S., Kim, Y., 2015). Value of shear modulus for all specimens is evaluating base on slope of the curve. The resulting of strain profile +45 and -45 is same with theory and literature where the profile always symmetry at both side even though a small inconsistency can be seen on the slope of the graph. This inconsistency occurs due to specimens with Arcan rig during the test run.

Figure 9 and 10 shows relationship between shear stress and shear modulus. The result shows when shear stress is increase, the shear modulus is also increased.

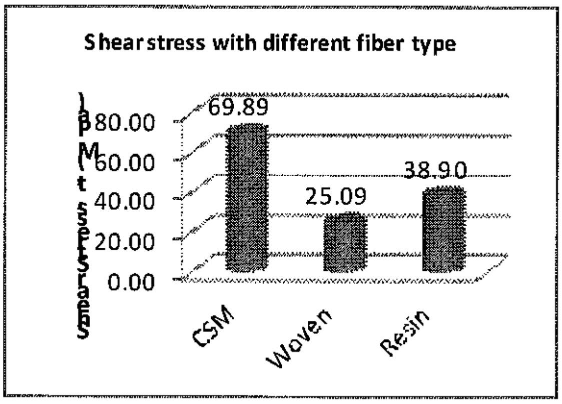


Figure 9: Shear Stress bar chart

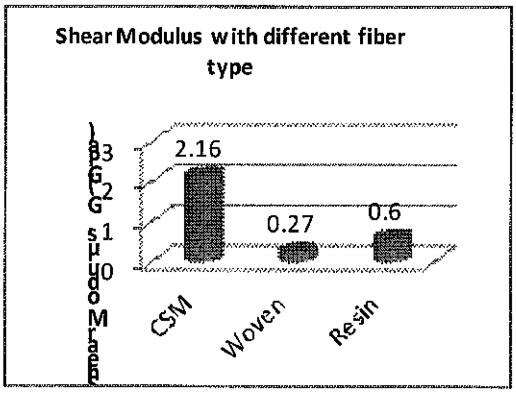


Fig 10: Shear Modulus bar chart

Burn-Off test results – relationship between shear stress and fiber Volume Fraction, V_f

Burn-off test has done to obtain the fibre volume fractions, Vf contain in the specimen. The fibre volume fractions will be determine based on the fibre weight left in the furnace $V_f = (W_f / \rho_f) / (W_f / \rho_f + W_m / \rho_m)$ which is the result shows at table 2.

Table 2: Burn-off test result for CSM and Woven

Specimen	Fibre Density g/m^3	Resin Density	Fibre Weight (g)	Initial weigh t (g)	Resin Weight (g)	Volume Fractions, Vf
CSM	2.53	1.4	5.1825	12.6039	7.4214	0.2787
Woven	2.53	1.4	8.3999	13.5051	5.1052	0.4766

From the shear stress value for each specimen that has been shown before, the shear stress was clearly influenced by the volume fractions of fibre consists in the specimens. For woven specimen, Vf value in the specimens almost two times larger compared to the CSM specimens. The relationship between shear stress and Vf for woven specimens as shown below (figure 11).

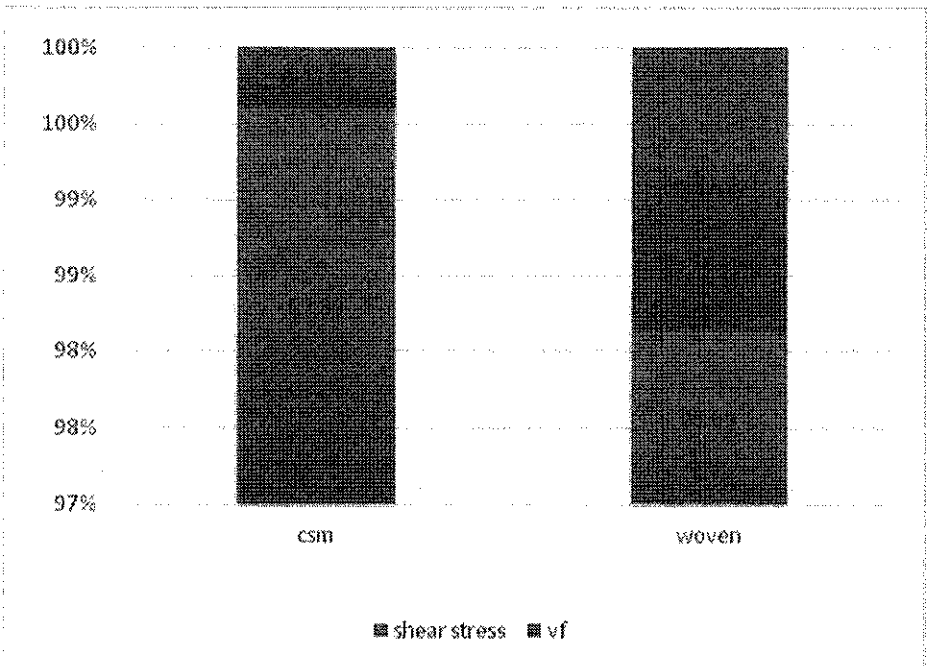


Figure 11: Relationship between shear stress and fibre volume fractions for woven and CSM specimens.

Theoretically, the materials strength increases with the content of fibers but the resin should not be neglected (Valery V. Vasiliev, Evgeny V. Morozov, 2013). Shear stress for CSM composite exhibit higher by 64% compared to woven. Even though, the fiber volume in woven composite is higher measured at 47.6%. This is due to low fiber resin bounding of woven composite. From the result, it can be conclude that shear strength increased invert to fiber volume fraction.

7.0 Conclusion

From the results that have been obtained, this project objective can be considered achieved by using Arcan test method in order to determine the shear stress of thermoset based composite with different fibre volume fractions and fibre forms. Due to the high value of fibre volume fractions, V_f into the specimens, the shear stress values for the specimens are exactly different. Besides that, the different fibre forms was also influent the strength and the failure mode of the specimens. The range of fibre volume fraction in the woven specimens is 0.4648 up to 0.4853, means the percentage of the fibre consists in the specimens is 46.48% to 48.53%. Because the resin content in the specimens is small compared to the other specimen types, woven specimen can only produce the shear stress between 16.89 MPa to 26.12 MPa. But for the Chopped Strand Mat (CSM) specimens, the specimens can absorb more resins into the fibre layers. It can be proven based on the range of fibre volume fractions in the specimen which is about 0.2132 to 0.2787. The shear stress value for CSM specimens is 57.97 MPa and up to 69.89 MPa depends on the resin or fibre content in the specimens. For the result, resin plays an important role if compared to the fibre in shear testing.

The significant section of the butterfly specimen had proved that the Arcan Test Method is reliable, as the shear stress strain relation is linear by propagated. Main factor that influenced the test data is the production method of the specimens (hand lay-up) resulting the porosity inside the specimens (i.e. air bubbles). Therefore, the specimens failed much faster when so much porosity occurred. The error of the test results happened perhaps because of some reasons such as using hand lay-up method. The method used to cut the specimens to the butterfly shape, porosity occurred in the specimens due to improper and misalignment occurred when the tightening of the butterfly specimen onto the housing resulting the shifting of the Mohr's circle therefore the pure shear condition did not happened. But the misalignment was hard to detect by visual inspection.

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