FINITE ELEMENT MODELING OF ARCAN TESTING METHOD FOR DUCTILE AND BRITTLE MATERIAL UNDER DIFFERENT LOADING CONFIGURATION

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ABSTRACT

Recently, many scientist use finite element analysis of Arcan test method to validate their experiment outcome as it provides several result which impossible to obtain by considering basic theoretical approach. This paper is based on the application of Arcan test method introduced by Arcan et al. to determine the shear strength and shear modulus of brittle and ductile materials. The aim of this research is to study the stress properties of both materials types under Arcan test method using Finite Element Analysis (FEA). The test method has been systematically run using ANSYS finite element analysis software involved CAD and finite element modeling of the butterfly shape sample that was subjected to tensile load with different loading configurations. The finite element model is validated geometrically by ANSYS element shape checking capability. Nine samples of butterfly shape were produced from each Selfix Carbofibre and Aluminium 6061 materials. Three samples from each group materials were tested for each loading configuration. Three samples of dumb-bell shape were prepared and tested to determine the tensile modulus of Selfix Carbofibre. Shear loading test for all epoxy and aluminium samples recorded the highest ultimate failure load of 1.1kN and 4.54kN respectively. Meanwhile, for tensile loading test for all epoxy and aluminium samples recorded the highest ultimate failure load of 0.827kN and 6.71kN respectively. From finite element analysis, it can be observed that different characteristic of stress in field based on different type of loading configuration. Arcan test method proven to be an effective to measure shear modulus for both materials types as the values were almost similar to the previous study and ASTM standard. The high stress located at the both end of significant section is due to effect of notch which generated stress concentration and leads to fracture. The effect of notch to the tensile stress for both materials types can be reduced by increasing the notch radius until it reaches the optimum values. The results obtained lead researchers in the reliability of the Arcan set up configurations in obtaining shear modulus of both ductile and brittle materials as it seen proven by finite element analysis done in this study and it is crucial to take account notch radius as it effect uniformity of stress in the material tested.

Keywords: Arcan Test Method, Finite Element Analysis, Structural Epoxy, Aluminium 6061, Tensile Shear

Introduction

Recently, many scientist use finite element analysis of Arcan test method to validate their experiment outcome as it provides several result which impossible to obtain by considering basic theoretical approach. Compared to conventional calculation approach analysis, finite element analysis is typically used for the design and optimization of a complex system by deconstructing the system into very small pieces called element. Systems that may fit into this category are too complex due to their geometry, scale, or governing equations.

Determination methods of mechanical properties such as tensile strength and particularly in-plane shear properties of materials have been investigated few decades back to date. Some researchers applied Iosipescu specimen geometry, rail shear method, and many other methods to obtain shear properties but had drawn to some problems dealing with additional stresses which disrupt the ‘pure shear’ state (Liu et al., 1999), (Standards, 2007). Arcan, et al., (1978) had proposed a method that had proven to obtain ‘pure shear’ condition. Eventually, experimental works need to be confirmed with finite element modelling to compare the results with the theory.

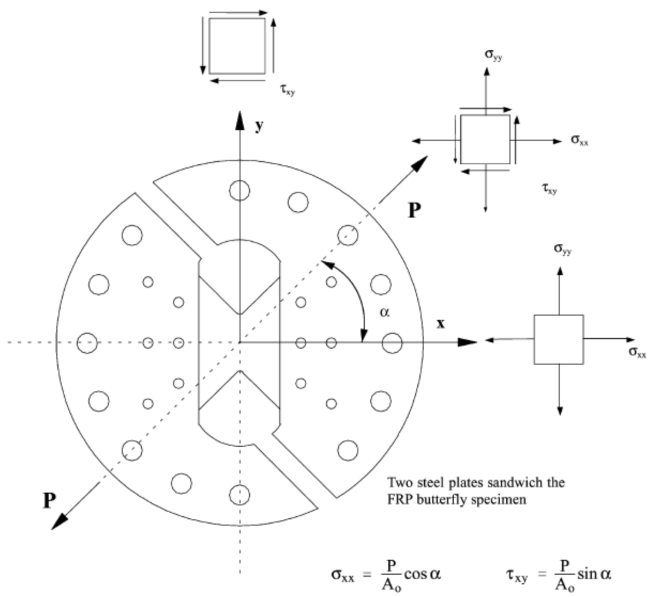
Finite Element Method was applied to nonlinear problems and large deformation in late 1960s and early 1970s (Ashok and Tirupathi, 2012). In Arcan test method, finite element analysis also has been considered by most scientists such as Mohr and Doyoyo (2002), Rinaldi et al. (2010), Rani El Hajjar et al. (2003) and David Delsart et al. (2008) in their research and experiment in order to confirm the prediction capability of Arcan test.

This study is based on the application of Arcan test method introduced by Arcan et al. (1978) to determine the shear strength and shear modulus of material. Arcan test method had been implemented and modified by many researchers such as Voloshin and Arcan (1980), Doyoyo and Wierzbicki (2003), Yen et al. (1988), Shukur (2007), Rani El-Hajjar at el. (2007), Abu Hassan et al. (2015) and Samuel et al (2006) to examine behaviour and mechanical performance of various brittle material.

The aim of this research is to study the behaviour of brittle and ductile materials samples under ARCAN test method using FEA. In this research, the objective has been systematically approached using ANSYS finite element analysis software. The approach involves investigation of the problem and analysis of the butterfly specimens subjected to a load with different loading configuration. The condition are simulated in ANSYS which involved CAD and finite element modelling of the butterfly shape specimen, and then the finite element model is validated geometrically by ANSYS element shape checking capability. The finite element model subjected to static structural analysis confirmed the stress concentration and crack initiation take place which indicated cause of the failure. The performance of tensile data of Arcan test affect by notch. Finally, this research concludes with a proposal to revised specimen model and recommendation for further analysis.

The modified Arcan fixture and its butterfly shape specimen capable to produce pure shear and biaxial stress conditions, as shown in Figure 1. The shear response from various biaxial stress states can be obtained in α relatively simple manner by varying the angle of α at which the load is applied. A special case of ‘pure shear’ can be produce at significant section AB when α = 90 degree as shown in Figure 2. The basic concept of configurations is that the Arcan test set-up has a well-defined as significant section AB, where the stresses are assumed to be uniform. This uniformity of stresses is a result of appropriate geometrical parameters of the butterfly specimen. Another outcome of the butterfly type geometry is the stresses at the significant section are the highest because of small cross-sectional area in segment and thus, initial yield or failure is more likely to occur within the section.

Figure 1: Arcan fixture for shear test with different loading configurations



Problems Formulation

The force applied to the rig will produced shear and normal stress at section AB. In order to determine the normal stress σ_x and the shearing stress τ_{xy} acting on the face perpendicular to the x-axis, an element in state of equilibrium to the x and y axes shall be considered. By assuming the uniform stresses on the significant section AB, the equilibrium analysis can be write as

$\rightarrow \Sigma F_x = 0;$ $P\cos\alpha - \sigma_{xx} A = 0$

$$\sigma_{yy} = \frac{P}{A}\cos\alpha \quad [2.1]$$

$\uparrow \Sigma F_y = 0;$ $P\sin\alpha - \tau_{xy} A = 0$

$$\tau_{xy} = \frac{P}{A}\sin\alpha \quad [2.2]$$

The rectilinear portions of the cut-outs element are oriented at ± 45 shows the principal stresses in the vicinity are also in these directions. It follows that τ_{xy} on AB as given by equation [2.5] is a principal shear stress. Therefore on AB,

$$\sigma_{xx} = \sigma_{yy} = \frac{P}{A}\cos\alpha \quad [2.3]$$

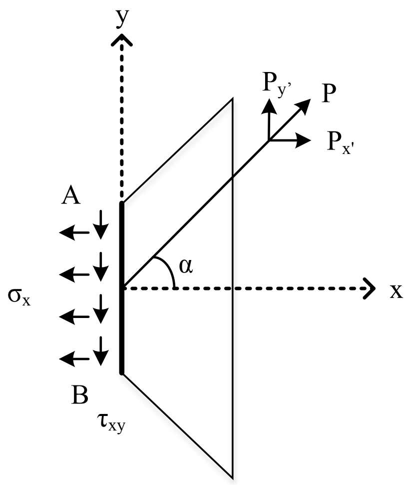
and the principal stresses are

$$\sigma_1 = \sigma_{xx} + \sigma_{xy} = \frac{P}{A}(\cos\alpha + \sin\alpha) \quad [2.4]$$

$$\sigma_2 = \sigma_{xx} - \sigma_{xy} = \frac{P}{A}(\cos\alpha - \sin\alpha) \quad [2.5]$$

Finite element analysis also has been considered by most scientists in their research and experiment. An error occur during experiment has made the finite element analysis are more relevant to produce accurate data. In Arcan test method, the result obtain still are not accurate even strong theoretical background. The problem become more complicated since orthotropic type of material was introduced.

Figure 2: Internal mean shear and normal stress along the 'significant section'



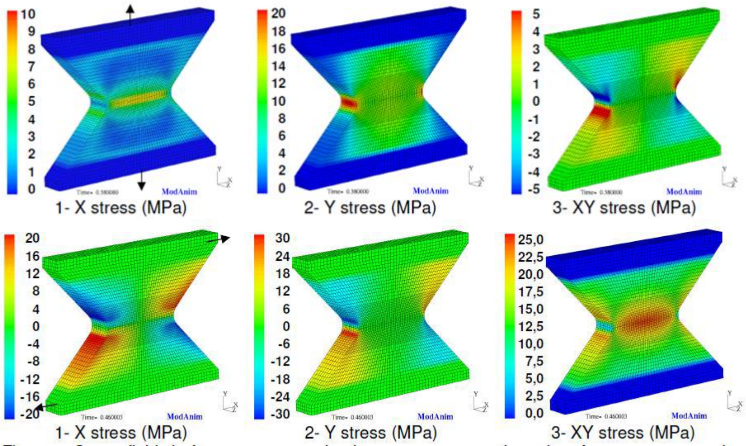
1. Previous Studies 1

In year 2008, David Delsart *et al* used finite element method to study the material through thickness and out- of-plane shear properties identified of Fibre Reinforced Composite from Arcan test method. The stress concentration generated at the mid-section of the specimen was observed until fracture occurs as shown in Figure 3. From the result, max tensile and shear load of numerical was found less than experiment with -40% and -24% respectively. Simulation results which the parameter based on Arcan tests properties were shown in Table 1.

Table 1: Simulation results – parameter based on Arcan tests properties

Load configuration	Experimental Max. Force (N)	Numerical Max. Force (N)
0°	1904	1146
90°	2535	1928

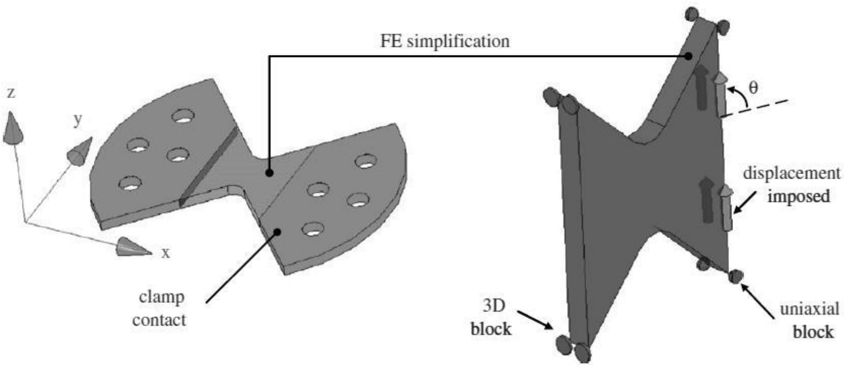
Figure 3: Stress field of tensile loading before rupture



2. Previous Studies 2

In year 2010, R. Rinaldi et al (2010) conducted a research on modelling structure polycarbonate. A finite element method is used in order to confirm the prediction capability of Arcan test in various loading condition. Analysis for "pure shear" loading show boundary condition proposed for the shear test was set to be fixed at left segment of specimen with the direction of load are based on Arcan test practice (α=90°) at right segment as shown in Figure 4. Roller condition at right segment of specimen only applied at "pure shear" loading.

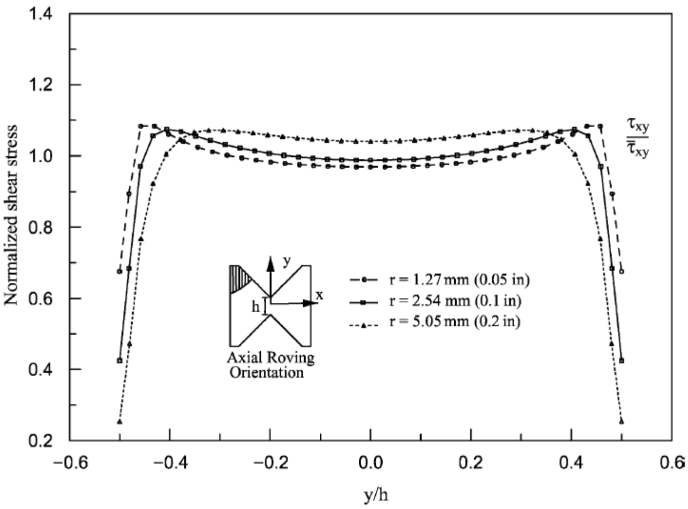
Figure 4: Original experimental shape and boundary condition



3 Previous Studies 3

In year 2003, Rani El-Hajjar at el. used finite element analyses of to stimulate the effect of notch radius and material orthotropic on the uniformity and distribution of stresses in the significant section of the butterfly specimen of Arcan test method under shear loading. There were three notch radii selected to determine the most appropriate radius of 1.27mm, 2.54mm and 5.05mm. Figure 5 shows the shear stress profile along the gauge section for FRP axial orientation. A normalised stress profile near to 1 was found near the centre for the specimen with a notch radius of 2.54 mm.

Figure 5: Effect of notch radius on shear stress profile along gauge section



In this study, therefore, Selfix Carbofibre epoxy and aluminium material chosen for sampling specimen and modelling consist isotropic characteristic. The investigation was focused on the characteristic Selfix Carbofibre epoxy which indicates the brittle behaviour. The mechanical properties of Selfix Carbofibre epoxy list on Table 2 In addition, the investigation of material behaviour on variety of notch radius was conducted in this study.

Table 2: Typical mechanical and physical properties of Selfix Carbofibre epoxy adhesive

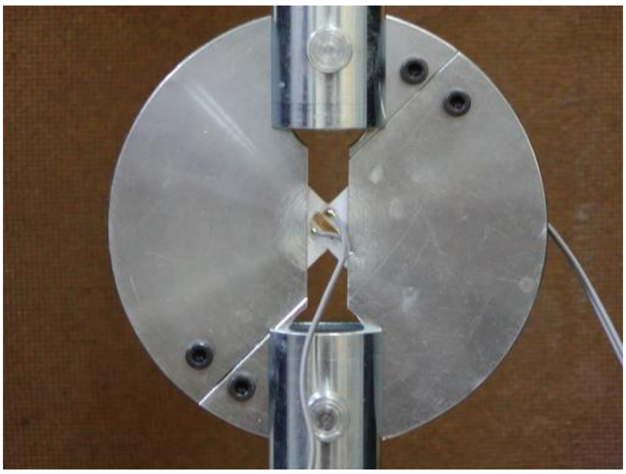
Property	Value
Compressive strength (MPa) aged of 7 days at 20 °C	90
Tensile strength (MPa)	27.7
Thermal expansion /°C	33×10^{-6}
Shear modulus (GPa)	2.67
Tensile Modulus(GPa)	7.79
Shear strength (MPa)	21.8
Glass transition temperature (DMTA) °C	> 65
Water absorption	0.4%

Methodology

1. Load Test

The tests were performed using an Instron Universal test machine with a 5kN load cell for Selfix Carbofibre epoxy and aluminium. The maximum load applied before rupture was recorded for finite element analysis. The Arcan fixture set-up at α = 0°, α = 45°, and α = 90° for tensile, tensile shear and shear loading configuration respectively. Arcan fixture set-up configuration was shown in Figure 6.

Figure 6: Arcan fixture set-up configuration



2. Finite Element Software Package
ANSYS Workbench was used to investigate the stress distribution of the butterfly specimen. The maximum stress and stress profile along significant section AB was obtained by finite element analysis

Results And Discussion

1. Shear Test
From load test, it could observe that the fracture line of epoxy specimen occurred at about 45° angle measured from the specimen principal axis to the line of significant section AB. as shown in Figure 7. This situation confirmed that the specimen failed in the direction of principal stresses which was the direction of the tensile principle stress corresponding to the state of pure shear.

2. Tensile Test
From load test, it could observe that the fracture line of ET2 specimen occurred at about 90° angle measured from the specimen principal axis to the line of significant section AB as shown in Figure 8. This situation confirmed that the specimen failed in the direction of principal stresses which was the direction of the tensile principle stress corresponding to the state of pure tensile.

3. Tensile Shear Test
From load test, it could observe that the fracture line of ETS3 specimen occurred at about 30° angle measured from the specimen principal axis to the line of significant section AB as shown in Figure 9. This situation confirmed that the specimen failed in the direction of principal stresses which was the direction of the tensile principle stress corresponding to combination tensile and shear loading.

Figure 7: Brittle failure of ES1 occurred at ±45°

Figure 8: Brittle failure of ET2 specimen occurred at ±90°

Figure 9: Brittle failure of ETS3 occurred at ±30°

4. Finite Element Analysis

By observing the stress field in Figure 10, the maximum principle stress about 64.97MPa was located at the notch of the significant section AB. The stress field also show almost similar shape of fracture line specimen that can be seen during experiment

By observing the stress field in Figure 11, the maximum principle stress about 52.4MPa was located at the notch of the significant section AB. The stress concentrates at the significant section which indicates as the location of failure.

By observing the stress field in Figure 12, the maximum principle stress about 326MPa was located at the notch of the significant section AB. This situation clearly describe that the fracture initiated at the notch of the significant section AB. In addition, the high stress generated due to existence of bending moment.

Figure 10 Maximum principal stress about 64.97MPa

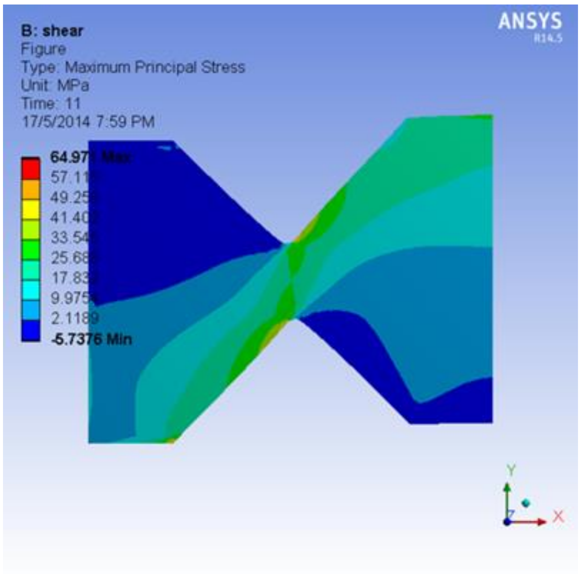


Figure 11 Maximum principal stress about 52.4MPa

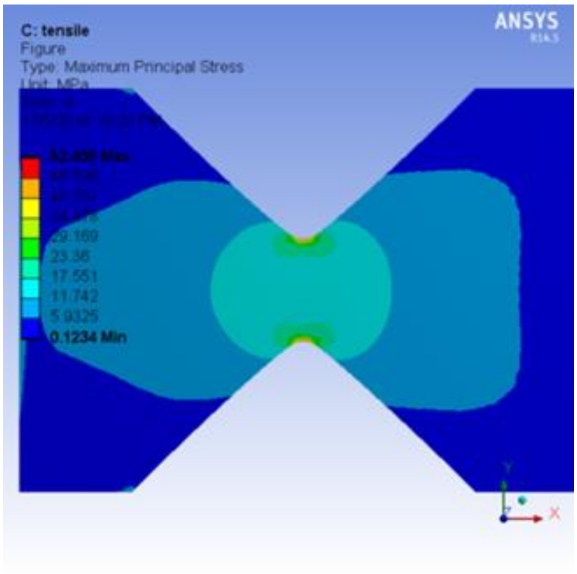
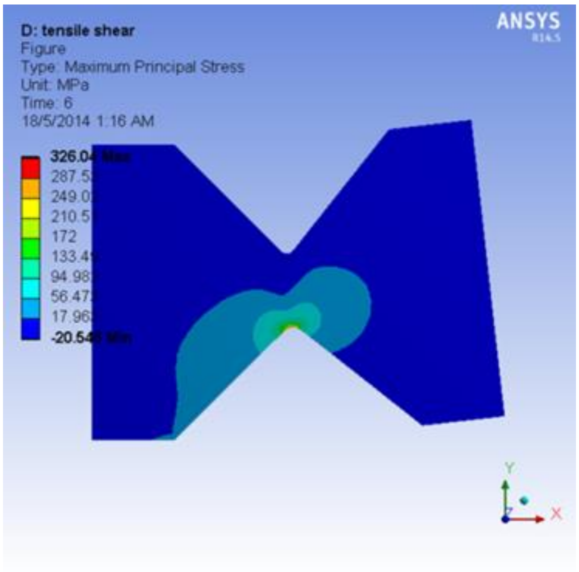
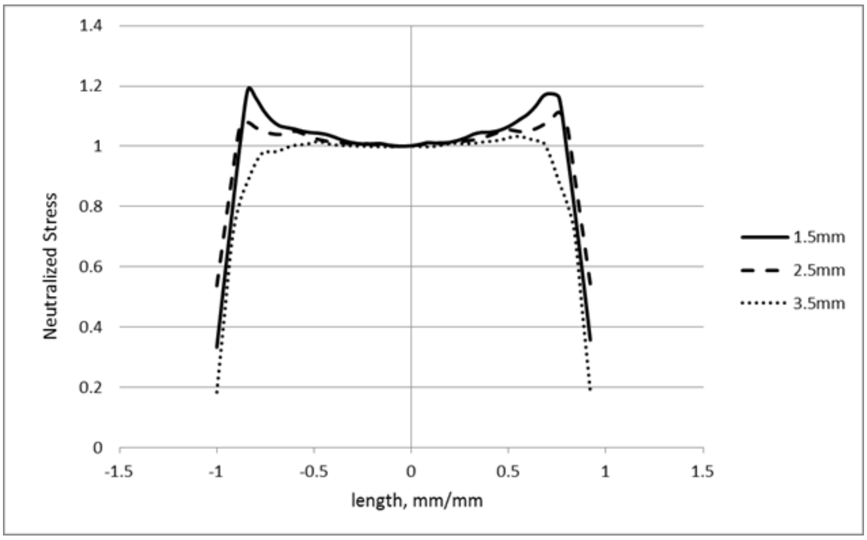


Figure 12 Maximum principal stress about 326MPa



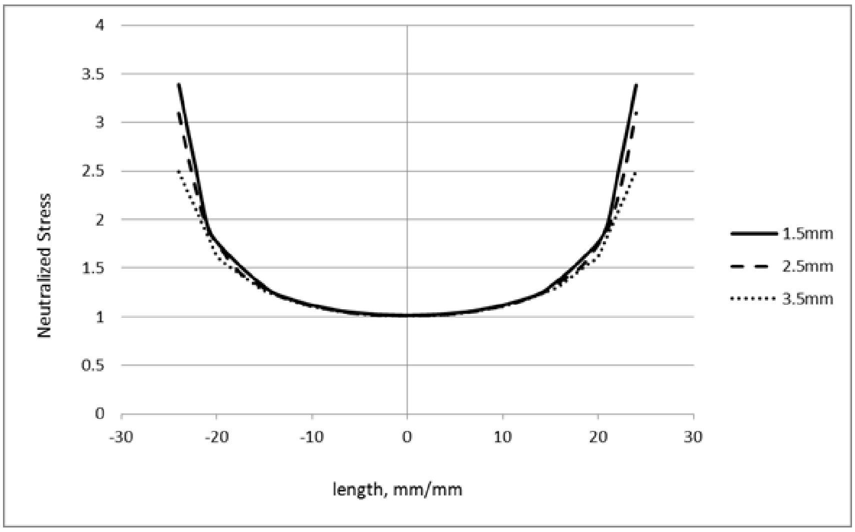
5. Notch Sensitivity Analysis

Figure 13: Effect of notch on stress distribution of Selfix Carbofibre due to shear load.



From Figure 13, the effect of notch was found higher when 1.5 mm radius on Selfix Carbofibre, which resulting about 20% high of stress than average value 1. The notch effect reduced as an increase of notch radius. Therefore, the most optimum notch was 3.5 mm as it provides most uniform stress along significant section AB.

Figure 14: Effect of notch on stress distribution of Selfix Carbofibre due to tensile load.



From Figure 14, it can be seen that the effect of notch to tensile stress of Selfix Carbofibre epoxy reduce as increase of notch radius. Therefore, the uniformity of stress can be improved by increasing the notch radius until it reaches optimum value.

Conclusion

The study objective to finite element modelling of the butterfly specimen was achieved. The significant section of butterfly specimen has proven that Arcan test was reliable, as the shear stress and strain relationship was linearly propagated. The existences of normal strain indicate that pure shear loading are not perfectly produce by Arcan test. But the result can be accepted since the value was too small if compared to others method in obtaining pure shear condition.

From the results of finite element analysis, it can be observed that the maximum principle stress and strain for ductile and brittle materials was concentrated at the notch of the significant section which indicates as the location of failure. The stress field also show almost similar shape of fracture line specimen that can be seen during experiment. This situation clearly describe that the fracture initiated at the notch of the significant section AB due to existence of bending moment that generates high stress at the significant section.

The uniformity of stress along significant section AB affected by notch. A notch with 1.5 mm radius still not sufficient to overcome stress concentration especially for brittle and ductile material. The most optimum notch was 3.5 mm as it provides most uniform stress along significant section AB for shear load testing. Meanwhile, it can be seen that the effect of notch to tensile stress of epoxy reduce as increase of notch radius. Therefore, the uniformity of stress can be improved by increasing the notch radius until it reaches optimum value.

The tensile test from Arcan test method capable to perform reliable tensile data. The
present of notch affected the performance of tensile test. The performance of improve as increasing the notch radius in order to reduce stress concentration.

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References

Abu Hassan, S., Gholami, M., Ismail, Y. S., and Mohd Sam, A. R. (2015). Characteristics of Concrete / CFRP Bonding System Under Natural Tropical Climate. *Construction and Building Materials*, *77*(July), 297–306.

Arcan, M., Hashin, Z., and Voloshin, a. (1978). A method to produce uniform plane-stress states with applications to fiber-reinforced materials. *Experimental Mechanics*, *18*(4), 141–146

Arcan, M. A. New Method for Analyzing of Mechanical Properties of Composites Materials. 3rd International Congress on Experimental Mechanics, Los Angeles, California, 1973

Ashok D. B and Tirupathi R. C Introduction to Finite Elements in Engineering. Fourth Edition, Pearson International, Inc., 2012, pp. 17

David DELSART and Jean Michel MORTIER, Identification of the Interface Properties of Fibre Reinforced Composite Materials, June 2008

Doyoyo, M., and Wierzbicki, T. (2003). Experimental studies on the yield behavior of ductile and brittle aluminum foams. *International Journal of Plasticity*, *19*(8), 1195–1214

Liu, J. Y., Flach, D. D., Ross, R. J., and Lichtenberg, G. J. (1999). An improved shear test fixture using the {I}osipescu specimen. *ASME Mechanical of Cellulosic Materials*, *85*(1957), 139–147.

Mohr, D.and Doyoyo, M. (2002). Analysis of the Arcan Apparatus in the Clamped Configuration. Journal of Composite Materials, 36(22), pp.2583–2594.

Rani El-Hajjar and Rami Haj-Ali. In Plane Shear Testing of Thick Pultruded FRP Composites using Modified Arcan Fixture. Composites Part B, Volume (35):2004, pp. 421-428

R. Rinaldi, Modelling of the mechanical behaviour of amorphous glassy polymer based on the quasi-point defect theory—Part II:3D formulation and finite element modelling of polycarbonate , December 2010

Shukur, A.H., Mechanical Performance of Carbon Fibre Reinforced Vinyl Ester Composite Plate Bonded Concrete Exposed to Tropical Climate. PhD Thesis, UTM, 2007

Samuel. B. and Bertrand. L. Arcan test and strain field measurement to study material properties behaviour in 6056T78 FSW specimens, 6thInternational FSW Symposium, Saint-Sauveur, Canada. 10-13 October 2006

Standards, A. (2007). D4255/D4255M - 01 Standard Test Method for In-Plane Shear Properties of Polymer Matrix Composite Materials by the Rail Shear Method, *1*, 1–13.

Voloshin, A and Arcan, M. (1980). Failure of Unidirectional Fiber-Reinforced Materials—New Methodology and Results. Experimental Mechanics, 20(8), pp.280–284.

Yen, S.C., Craddock J.N. and Teh, K.T. Evaluation of a Modified Arcan Fixture for In-Plane Shear Test of Materials. Experimental Techniques, December, 1988