ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

GLASS/EPOXY WOVEN COMPOSITE LAMINATE DESIGN BASED ON NONLINEAR RESULTS

Hazatul Nabila, Sanusi Hamat, Logeswaran Arumugam, Ain Umaira, Ibrahim M Alibe, Milad Golshan and Dayang Laila Majid
Department of Aerospace Engineering, Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia
E-Mail: dlaila@ upm.edu.my

ABSTRACT

The purpose of this case study is to analyse the effect of the stacking sequence and lay-up orientation of the fiber of laminated composite materials employing plain weave C-glass fibres with varying fibre densities. The study was divided into two parts which are simulation and experimental analysis. Through the simulation analysis, three designs were proposed and the best design with the highest UTS was chosen to be fabricated in order to validate the simulation results. All designs are symmetric in terms of angle of orientation which only utilized 00/900 and ±450 plies. The simulation analysis were performed using ABAQUS and the finite element model was simulated in a non-linear mode with displacement of 3mm. The second part of this study is to fabricate the best design with the highest UTS based on the ABAQUS analysis. The specimen was fabricated through hand lay-up method before being cut into a rectangular shaped coupon with standard dimensions according to ASTM D3039. The prepared coupons were then tested using the tensile testing machine in a standard room temperature to find the UTS. The experimental results were analysed to get the stress strain curve. The UTS values determined from both numerical and experimental analysis were compared. The percentage of error between the two values were calculated which determine the accuracy of the ABAQUS analysis to the real experimental result. The comparison showed that the percentage of error is 5% which is an acceptable value.

Keywords: composite materials, uts, fibre orientation, glass fibre, abaqus.

INTRODUCTION

In general terms, the word composite implies being constituted of multiple portions. In practice, the term composite material are used in a more restrictive sense; a material that constitute of two or more materials with differing natures and complementary features, leads to a material that possess superior properties to its original constituents. Composite material composed of two important constituents which are matrix, also known as a binder, and fibres which act as the reinforcement. Types of fibres such as carbon, Kevlar or fibreglass, sizes of fibres which are continuous, chopped, powder, or woven type, percentage of fibre loading, and angles of fibre orientation are among the factors that affect the properties of the composites [1, 2, 3, 4, 5, 6,7]. Each factor has a significant effect on the final application of the composite material [6]. In recent decades, composites are emerging as the most favourable raw materials used in many applications compared to metal and ceramics. Possess high strength to weight ratio, great impact and corrosion resistance, composites also offer their best flexibility in design where most of the composites can easily fixed the shape of the mold during fabrication process [1, 4,5,6,7, 8]. In aviation industry, the composite materials are widely used as primary components for aerospace, commercial, private and military aircraft. Doors, wings, elevator, as well as interior cabin of these aircraft are made of composites due to their great properties together with light weight advantage. C. Soutis [9] suggests that the utilization of fibre reinforced polymer especially carbon reinforced plastic will surely conquer 50% of the structural mass of an aircraft in the future. P. Feraboli *et al.* [10] also stated that there will be more opportunities for aircraft components to be made of composites when high-volume carbon fibre content combined with an aerospace-qualified epoxy resin. Nevertheless, the composite material is also used in automotive industry, infrastructural development, sports industry and recreational facilities.

As the application of composites arise in the industry, many research works were carried out to optimize their potential to suit the industrial demands. Researchers also interested in diversifying materials used in composites to ensure continuity in supply.

Composite materials are not necessarily reinforced by one type of fibre alone. Hybrid composite materials are composites consist of two or more constituents at the nanoscale or molecular level. The following are examples of research work in hybrid composites and their mechanical properties.

An experimental study was conducted by K.G Satish *et al.* [3] to determine the effect of hybrid composite specimen subject to in-plane tensile and compressive loading and showed laminated specimens with higher percentage of steel sustain greater loads irrespective of fibre orientations. Keshavamurthy *et al.* [11] conducted a study on the tensile properties of Glass/Epoxy laminate composite specimens with varying the fibre orientation. Glass/Epoxy with 0^{o} fibre orientation, which is parallel to the axial loading, yielded higher strength when compared with 30^{0} & 45^{0} for the same load, size & shape. P. Feraboli *et al.* [10] investigated inter laminar shear strength of carbon/ epoxy laminates and find out that discontinuous fibres offer performance similar to the continuous quasi-isotropic value. While Fumihiko *et al.* [12] identify the factors controlling the strength, flaw size and the fracture toughness of carbon fibres related to the fibre nanostructure. These indicate that the research works about composites were carried out in a huge area starting from the properties of the fibre itself to the process of fabrication that could be the factor that affect the strength of the composites.

Ultimate Tensile Strength (UTS) is one of the important properties of materials that indicate the ability of a material to sustain load. Most of researchers in the composites' area carried out the tensile testing to identify the strength properties of the new materials. Tran *et al.* [2] found that aligned carbon nanotube (CNT) reinforcement greatly enhanced tensile strength and elastic modulus of epoxy resin which then attributed to the reinforcement of aligned CNTs along the tensile direction. P. Feraboli *et al.* [10] studied the complex relationships between reinforcement aspect ratio to the tensile, compressive, and flexural moduli and strengths. From the tensile testing, UTS is shown to increase monotonically with chip length, but remains noticeably lower than the continuous quasi-isotropic (QI) value.

To minimize the experimental works so that time and materials used could be reduced, a numerical method would be a good alternative. Finite element analysis is one of the numerical method that can be used to obtain solutions to a large class of engineering problems involving stress analysis, heat transfer, electromagnetism and fluid flow. The finite element analyses were developed using ANSYS software which capable of performing static, dynamic, heat transfer, fluid flow and electromagnetism analyses. ANSYS is a comprehensive general-purpose finite element computer program that was first time released in 1971 and being used in many engineering fields, including aerospace, automotive, electronics and nuclear. Recently, the finite element analyses has been one of the researcher`s attention to validate any experimental results and to analyse any complex design before carry out the fabrication process.

To understand and explain the underlying failure mechanisms and test result, Linlin *et al.* [13] used the FE numerical simulation in their study of SiC_3D/Al interpenetrating phase composite material subjected to a three-point bending load. From the study, Linlin *et al.* indicate that the FE numerical simulation allowed the whole fracture process of the sample to be tracked while the experimental test could only tracked the rapid crack propagation with the increasing load and no crack generation was observed initially. However, both the experimental and numerical methods were consistent at the macroscopic scale, where crack propagation occurred predominantly in the SiC phase which also consistent with the general understanding.

Ana M. *et al.* [14] describe in detail the finite element guidelines for simulation of fibre-tension dominated failures in composite materials validated by case studies. Several examples of previous research works were expanded by using state-of-art solution techniques and composite modelling provided by ABAQUS. The paper also addresses common problems faced by analysis to give guidelines to the recent studies.

To validate the experimental results with the numerical analysis, E. Car *et al.* [15] carried out two procedures to simulate the constitutive behaviour of fibre reinforced composites materials. These procedures are based on two different concepts which are Mixing and Homogenization theories. Results from both procedures show a good agreement with the experimental values although they have different nature in both numerical procedures. The tests were carried out on specimens of carbon/epoxy composite that present a notch in the central area of the specimens. The angle orientation of the carbon fibres in all specimens are 0^o related to the longitudinal axis of the sample. The specimens are subjected to a tension load and the behaviour under tensional loading was observed. It was observed that the stress concentration was generated in the notched area of the specimens which firstly affect the matrix.

The main objective within this study was to validate the numerical analysis with the experimental results of glass/epoxy woven composite laminate design which showed the highest UTS. Three designs with different angle of fibre orientation but same stacking sequence of medium and high densities of woven type glass fibre which believe to give the best UTS were analysed using the Finite Element model. The design with the highest UTS was selected to be fabricated and analysed through the experimental works. The UTS value from the Finite Element Analysis was validate with the value from the tensile testing through the experimental procedure.

O.Velecela *et al.* [6] studied steady state quasi static compression of GFRP monolithic laminates & sandwich panels made of randomly oriented continuous filament mat. The effect of face laminate thickness on impact energy absorption is studied. The experimental data showed, high value of energy absorbed per unit mass were predominant failure of the thickest monolithic laminates. Momchil Dimchev *et al.* [7] investigate the effect of carbon nanofibres on the tensile and compression properties of hollow particles filled composites. The result of this study showed, the addition of 0.25wt. % carbon nanofibres result in improvement in tensile modulus and strength compared to similar syntactic foam compositions without nanofibres. R Velmurugan *et al.* [8] studied tensile, flexural, shear and impact properties of glass/palmyra fibre waste sandwich composites and found 58-65 wt% fibres showed good flexural strength. S. Channabasavaraju *et al.* [9] evaluated tensile and flexural properties of glass, graphite and kevlar fibre reinforced polymer matrix composites. The results have showed the variation in the fibre types has significant effect on the tensile and flexural properties of composite materials. Vinod B *et al.* [10] studied the effect of fibre orientation on the flexural properties of PALF reinforced bisphenol composites. The results revealed that, fibre orientation have great effect on the flexural properties of fibre reinforced polymer matrix composites.

METHODOLOGY

Numerical analysis using ABAQUS

In this study, the materials used are C-glass woven fibre with different densities which are medium 400gsm and high 600 gsm as the reinforcement to the matrix of epoxy. In order to place the C-glass woven fibre, there are thousands combinations of angle orientation with different stacking sequence of the medium and high densities fibre could be proposed in each design.

As the main objective of this study is to validate the numerical analysis with the experimental results, three random designs were proposed. One of the design was specifically prepared with all 0^o angle of fibre orientation in order to verify briefly that the tensile strength of a composite depends more on the fibre than the matrix. The other two designs were distinguished with 45^o angle of orientation that were predicted to have a good value of UTS based on the previous work analysis compared to other value of angle orientation [16]. Therefore, these 2 designs were proposed to see the effect of placing 45^o angle of fibre orientation to the value of UTS and compared to the first design that was theoretically concluded to have the highest UTS.

All the proposed designs were analysed using ABAQUS. From this method, the ability of each proposed design to achieve highest UTS could be defined. Haidar F. *et al.* [17] previously concluded that with an acceptable percentage of error, the finite element models of composite were selected as the most similar representation of the actual composite materials. Thus, only the best design from the ABAQUS analysis which shows the highest UTS will be selected to be fabricated and analysed experimentally.

During the ABAQUS analysis, all three finite element models is a composite consist of 8 plies of woven C-glass fibre reinforced with epoxy. The thickness of each ply was fixed to be 0.20mm for the medium density and 0.30mm for the high density plain weave glass fibres. Therefore an approximately 3mm thickness of the finite element models of glass/epoxy composite could be achieved. All models were designed to be a symmetric composite in terms of angle orientation .
All the three designs proposed for the finite element models were shown below.

Table-1. Ply orientation of glass fibre for design A, B, and C.

Sample A	Sample B	Sample C
HIGH (0^0)	HIGH (0^0)	HIGH (0^0)
MEDIUM (0^0)	MEDIUM (-45^0)	MEDIUM (0^0)
HIGH (0^0)	HIGH (45^0)	HIGH (45^0)
HIGH (0^0)	HIGH (0^0)	HIGH (0^0)
HIGH (0^0)	HIGH (0^0)	HIGH (0^0)
HIGH (0^0)	HIGH (45^0)	HIGH (-45^0)
HIGH (0^0)	MEDIUM (-45^0)	HIGH (0^0)
HIGH (0^0)	HIGH (0^0)	HIGH (0^0)

Designs A and C are having 12.5:87.5 medium-high density ratio whereas for design B it is 25:75 density ratio. Each woven ply is modelled as two uni-directional lamina resulting in total of 16 plies. The 16 plies consist of 8 plies C-glass woven fibre while the other 8 plies represent the epoxy layers which will be applied before each layer of fibre lamina during the fabrication process. Before a solid section for the coupons used in the simulation was assigned and created, the mechanical properties of the materials in the finite element models were obtained from a published study [18]. The specimen was meshed using solid elements possessing layer capability in ABAQUS. A non-linear static analysis has been performed using ABAQUS in the X - direction of the samples.

To get the most realistic outcomes in terms of material behaviour, the dimension used also based on the ASTM D3039. It was aligned to the experimental analysis that later the testing being conducted according to the same standard [19]. The simulation was carried out in a non-linear mode with a displacement of 3mm being applied to one end of the finite element coupon model. The other end of the coupon model was set as boundary condition represent the fix grip section in the universal tensile test machine. The simulation was carried out until the coupon model became fracture. The results through the simulation method were analysed using ABAQUS.

Table-2. Mechanical properties of glass/epoxy unidirectional lamina[18] [16].

PROPERTY	SYMBOL	UNIT	GLASS/ EPOXY
Fiber volume fraction	V_f	-	0.45
Longitudinal elastic modulus	E_1	GPa	38.6
Transverse elastic modulus	E_2	GPa	8.27
Major Poisson`s ratio	ν_{12}	-	0.26
Shear modulus	G_{12}	GPa	4.14
Ultimate longitudinal tensile strength	$(\sigma_1^T)_{ult}$	MPa	1062
Ultimate longitudinal compressive strength	$(\sigma_1^C)_{ult}$	MPa	610
Ultimate transverse tensile strength	$(\sigma_2^T)_{ult}$	MPa	31
Ultimate transverse compressive strength	$(\sigma_2^C)_{ult}$	MPa	118
Ultimate in-plane shear strength	$(\tau_{12})_{ult}$	MPa	72
Longitudinal coefficient of thermal expansion	α_1	μm/m /°C	8.6
Transverse coefficient of thermal expansion	α_2	μm/m /°C	22.1
Longitudinal coefficient of moisture expansion	β_1	m/m/ kg/kg	0.00
Transverse coefficient of moisture expansion	β_2	m/m/ kg/kg	0.60

VOL. 10, NO. 21, NOVEMBER 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Experimental model

From the ABAQUS analysis, the best design which has the highest UTS was defined. There are several techniques to fabricate a composite material. In this experiment, the traditional hand lay-up method was used. This method gave good benefits in terms of minimized surface roughness and specified cutting pressure [20, 21]. It also allows to produce wide variety complex items with limited apparatus in low cost. However, this method requires a good skilled operator to manually positioning the reinforcement plain weave glass fibre mat in the open mould and poured resin. It also needs a longer curing time compared to other methods. All these factors influenced the mechanical properties of the composites fabricated [22].

In this experiment, the same materials with same properties as the finite element model were used to give the nearest similar representation of the model. A basic sample of 40mm x 40mm glass fibre reinforced composite was fabricated using ratio 40:60 of fibre to resin based on previous literature review [23]. The resin composed of hardener and epoxy with ratio 2:1. After cured, the sample was cut into a rectangular coupon size of 250mm x 25mm according to the ASTM D3039 before being tested using the universal tensile test machine. An extra precaution step has been carried out to avoid slippage of sample during testing by sanding both sides of the end part of all coupons by sand paper and glued a piece of 25mm x 50mm of emery cloth on top of the sanded part to give a rough surface for the gripping area. The slippage problem gave a big influenced to the result of testing and behaviour of sample during failure. This step also being suggested in the ASTM D3039 [19]. The tensile test was carried out in a room temperature of 27° with a constant cross head speed of 2mm/min up to fracture stage. Ten samples were being tested and only four samples with consistent data were chosen to be analysed. The raw data of stress and displacement of the four chosen samples were recorded and collected for further analysis. The behaviour of the samples during fracture was observed and analysed.

RESULTS AND DISCUSSION

Figures-1, 2 and 3 showed the stress contours on the model. As expected, the tip showed higher stress distribution compared to the root where it is fixed. Similarly, the strain contours are shown in Figures-4, 5 and 6 and all displayed similar trends as stress contours since strain is proportionate to stress. Stress and strain were concentrated more on the tip as the displacement was applied there while the bottom part of the coupon model was set as boundary condition which is fixed.

From the load displacement results obtained from the finite element analysis, the resultant stress strain curves are plotted as shown in Figure-7. Design A showed the highest stress as compared to B and C. This indicate that design A has the highest UTS among the 3 designs. The results also explained that placing the 45º angle of fibre orientation in the composite laminate did not improve the tensile strength of that laminate. Therefore, design A which possess only 0º angle of fibre orientation was chosen to be fabricated and analysed through the experimental procedures.

Stress strain curve for design A that was fabricated and tested in tension is given in Figure 8. All four samples displayed almost linear behaviour up to the maximum stress level followed by immediate fracture. This behaviour is typical for brittle material. The maximum stress and strain for all 4 samples of design A that were tested in the universal tensile testing machine were recorded in Table-3. The results of all samples showed a consistent value. Therefore, an average value of the Ultimate Tensile Strength of the experimental result was taken to be compared with the value from the numerical analysis.

A comparison of the finite element results with the experimental results is given in Table-4. This comparison helps to determine if the simulation results are reasonable, and that the properties analyzed were precisely based on true principles of experimental results. The FEA result is validated by the experimental work and showed an excellent agreement with 5% error.

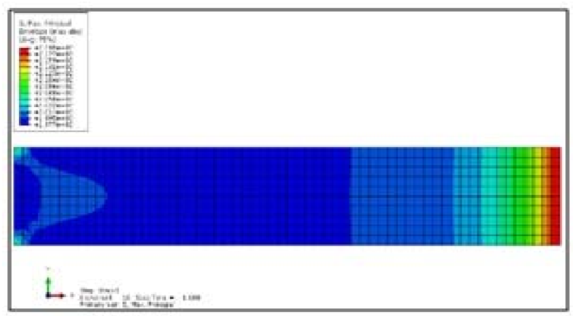

Figure-1. Stress contours for sample A.

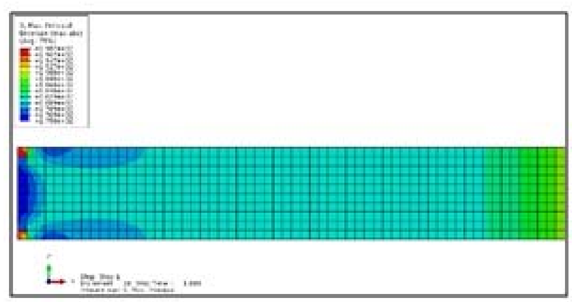

Figure-2. Stress contours for sample B.

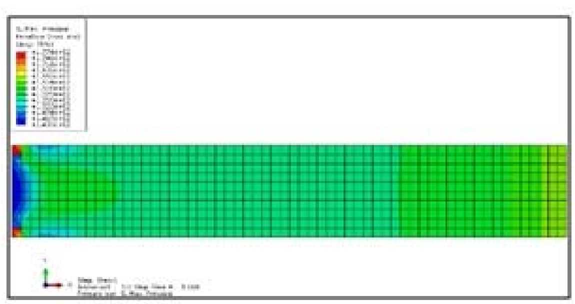

Figure-3. Stress contours for sample C.

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

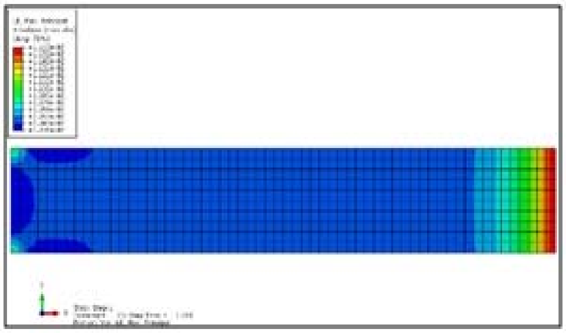

Figure-4. Strain contours for sample A.

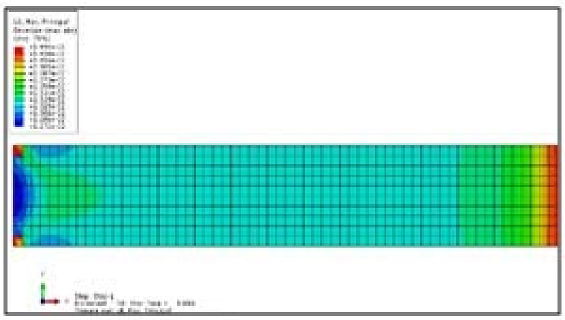

Figure-5. Strain contours for sample B.

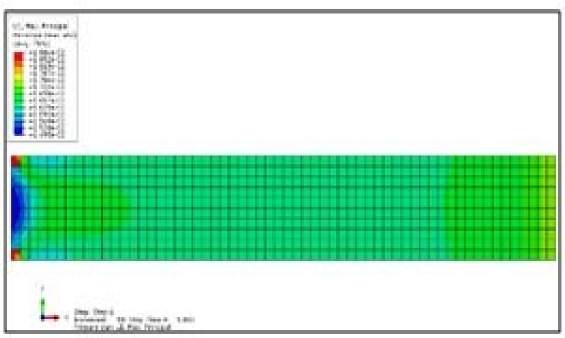

Figure-6. Strain contours for sample C.

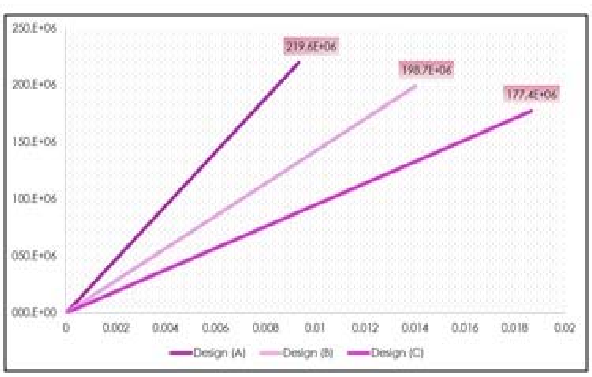

Figure-7. Stress-strain curve based on simulation results of design A, B and C.

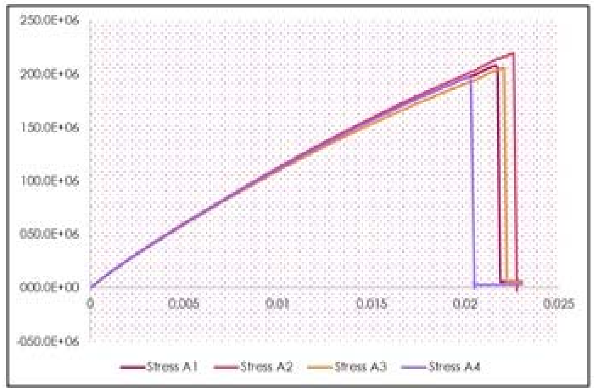

Figure-8. Stress-strain curve based on experimental result for Sample A.

Table-3. Experimental results for sample A.

SAMPLE	Maximum stress (MPa)	Maximum strain
A1	207.7	0.021
A2	219.6	0.023
A3	205.8	0.022
A4	197.3	0.020
AVERAGE	207.6	0.022

Table-4. Comparison UTS value between simulation and experiment method.

	Simulation	Experimental (average)
Ultimate tensile strength (MPa)	219.6	207.6
Percentage of error	5%	

Figure-9 shows all four samples of design A after being tested using the Universal Tensile Test Machine. All samples experienced same mode of failure which are Lateral Gage Middle (LGM) [19]. This mode shows that the samples break at the middle part of the rectangular coupon and the breaking section was perpendicular to the tensile load. The LGM mode was a good sign of fracture for brittle material instead of Lateral At grip Top (LAT) mode which indicate a certain error with the gripping section. The LGM mode of fracture behaviour clearly shows the characteristic of the materials are brittle which differs from the ductile characteristic that experienced angled fracture (AGM). It is equivalent by the linear line of the stress-strain curve which drop drastically at a certain maximum point of stress and strain without undergo plastic deformation.

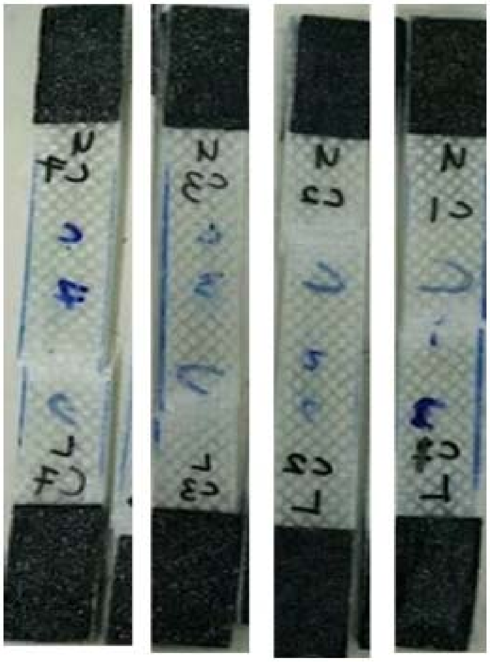

Figure-9. Failure mode for all samples design A.

CONCLUSIONS

In the current work, non-linear static analysis using ABAQUS was used to obtain the load and displacement as a means to gauge the maximum stress. The tensile strength obtained via FEA was validated with experimental tensile test conducted using design A with 5% error which was an acceptable percentage of error. This percentage value shows that Finite Element Analysis using ABAQUS is the most similar representation of the experimental analysis. The result from the numerical analysis is in a good agreement with the experimental results.

In the same time, this study also demonstrate the effect of density ratio and the fibre orientation on the strength of the composite. It is observed from the result that fibreglass /epoxy composite with 0° fibre orientation yields high strength when compared to 45° of orientations for the same load, size & shape. In addition, having higher dense fibres will increase the strength of the composite laminate.

REFERENCES

[1] Kamal M.M. *et al.* 2013. Behavior and strength of beams cast with ultra high strength concrete containing different types of fibers. HBRC Journal, Vol. 10, No. 1, pp. 55-63.

[2] Nam T.H. *et al.* 2015. Effects of CNT diameter on mechanical properties of aligned CNT sheets and composites. Composites Part A: Applied Science and Manufacturing, Vol. 76, pp. 289-298.

[3] Wang L. *et al.* 2014. Flexural properties of epoxy syntactic foams reinforced by fiberglass mesh and/or short glass fiber. Materials and Design, Vol. 55, pp. 929-936.

[4] Huang Y.J., Vaikhanski L. and Nutt S.R. 2006. 3D long fiber-reinforced syntactic foam based on hollow polymeric microspheres. Composites Part A: Applied Science and Manufacturing, Vol. 37, No. 3, pp.488-496.

[5] Yuanjian T. and Isaac D.H. 2008. Combined impact and fatigue of glass fiber reinforced composites. Composites Part B: Engineering Vol. 39, No. 3, pp. 505-512.

[6] Kostopoulos V. *et al.* 2002. Finite element analysis of impact damage response of composite motorcycle safety helmets. Composites Part B: Engineering, Vol. 33, No. 2, pp. 99-107.

[7] Song J.H. 2015. Pairing effect and tensile properties of laminated high-performance hybrid composites prepared using carbon/glass and carbon/aramid fibers. Composites Part B: Engineering, Vol. 79, pp. 61-66.

[8] Datta J. *et al.* 2004. Beneficial effect of scandium addition on the corrosion behavior of Al-Si-Mg-SiCp metal matrix composites. Composites Part A: Applied Science and Manufacturing, Vol. 35, No. 9, pp. 1003-1008.

[9] Soutis C. 2005. Carbon fiber reinforced plastics in aircraft construction. Materials Science and Engineering A, Vol. 412, No. 1-2, pp. 171-176.

[10] Feraboli P. *et al.* 2009. Characterization of Prepreg-Based Discontinuous Carbon Fiber/Epoxy Systems. Journal of Reinforced Plastics and Composites, Vol. 28, No. 10, pp. 1191-1214.

[11] Keshavamurthy Y.C. *et al.* 2012. Investigation of Tensile Properties of Fiber Reinforced Angle Ply laminated composites. Vol. 2, No. 4, pp. 700-703.

[12] Tanaka F. *et al.* 2014. Factors controlling the strength of carbon fibres in tension. Composites Part A: Applied Science and Manufacturing, Vol. 57, pp. 88-94.

[13] Wang L. *et al.* 2014. Experimental observation and numerical simulation of SiC3D/Al interpenetrating phasecomposite material subjected to a three-point bending load. Computational Materials Science, Vol. 95, pp. 408-413.

[14] Girão Coelho A.M., Toby Mottram J. and Harries K. a., 2015. Finite element guidelines for simulation of

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

fibre-tension dominated failures in composite materials validated by case studies. Composite Structures, Vol. 126, pp. 299-313.

[15] Car E. *et al.* 2002. Numerical simulation of fiber reinforced composite materials—two procedures. International Journal of Solids and Structures, Vol. 39, No. 7, pp. 1967-1986.

[16] Mortazavian, S. & Fatemi, A., 2015. Effects of fiber orientation and anisotropy on tensile strength and elastic modulus of short fiber reinforced polymer composites. Composites Part B: Engineering, Vol. 72, pp. 116-129.

[17] AL-Qrimli H.F., Mahdi F. a. and Ismail F.B. 2015. Carbon/Epoxy Woven Composite Experimental and Numerical Simulation to Predict Tensile Performance. Advances in Materials Science and Applications, Vol. 4, No. 2, pp. 33-41.

[18] Tsai S.W. and Hahn H.T. Introduction to Composite Materials. Technomic Publishing Co., Table 1.7 p. 19; Table 7.1 p. 292; Table 8.3 p. 344.

[19] ASTM Standard D3039, 2008. "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials." , 03.

[20] Hassan A.R., 2009. Contact stress analysis of spur gear teeth pair. World Academy of Science, Engineering and Technology, Vol. 58, No. 4, pp. 611-616.

[21] Paulo J. Davim and Francisco M. 2012. A New Machinability Index in Turning Fiber Reinforced Plastics. Journal of Materials Processing Technology, 170, pp. 436-440.

[22] Avila A.F. and Morais D.T.S. 2005. A multiscale investigation based on variance analysis for hand lay-up composite manufacturing. Composites Science and Technology, Vol. 65, No. 6, pp. 827-838.

[23] Bakir B. and Hashem H. 2013. Effect of Fiber Orientation for Fiber Glass Reinforced Composite Material on Mechanical Properties. , Vol. 1, No. 5, pp. 341-345.