Mechanical Properties of Drilling Defect Induced Glass Fiber Epoxy Composites Developed By Resin Infusion Technique

by

Izat Emir Bin Ismail

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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Mechanical Engineering Programme

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Approved by,

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CERTIFICATION OF ORIGINALITY

I declare that this thesis entitled “Mechanical Properties of Drilling Defect Induced Glass Fiber Epoxy Composites Developed By Resin Infusion Technique” is the result of my own research except as cited in the references.

IZAT EMIR BIN ISMAIL

ABSTRACT

Composite laminates such as Glass Fiber Reinforced Epoxy (GFRE), Carbon Fiber Reinforced Epoxy (CFRE) and other fiber metal composite laminates have been widely used in industries which include aerospace, aircraft structural components and oil and gas fields due to their superior mechanical properties. Drilling can be considered as an important machining operation for the assembling of laminates. By reason of hard-to-machine characteristics of the components, the drilling operation induced defects. This paper studies the mechanical properties that are affected from the induced defect. In this research, GFRE composite were used and fabricated using the vacuum assisted resin infusion method. The results of the drilled samples were tested for its tensile strength and structural analysis. This research is intended to help readers obtain a comprehensive view on mechanical properties of glass fiber reinforced epoxy.

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PROJECT BACKGROUND

1.1 Background of Study

During the past decades, the field of composite materials has developed tremendously in areas such as aircraft, spacecraft and even in oil and gas field. The fiber reinforced composites are being used to replace steel for certain parts in the industries due to its light weight, high strength, and resistance to corrosion [1]. Composite can be characterized as a material composed of two or more different materials, with the properties of the resultant material that make up the composites [2]. The traits of composite materials which include low density, high strength and stiffness, chemical and corrosion resistance make it as an alternative to metals and alloys.

Joining of smaller composite laminates parts into bigger structure is always the case due to limitation of transportation and fabrication. The superiority and efficiency of bolt joints crucially depend on the quality of the machined holes. The needs to improve the composite materials through manufacturing are the major affair of the industries nowadays. A range of drilling process is being used to produce bolted and riveted joints for the assembly of components which include composite laminates. The problems of drilling fiber composites are discussed in the next section.

1.2 Problem Statement

The main machining operation that has to be carried out to fasten the sub-components of a product is making holes. Out of all the approaches used for making holes in composite laminates, conventional drilling which uses twist drills is the most simple and widely acceptable machining operation [3]. However, the fiber reinforced composites, owing to their non-homogeneity, anisotropy and high abrasiveness of fibers, show a considerable problems in drilling process such as delamination, fiber pull-out, hole shrinkage, spalling, fuzzing and thermal degradation [4]. The damage resulted from the drilling severely reduce strength against fatigue, thus degrading the long-term performance of composite laminates and affect the mechanical properties [5].

1.3 Objectives

The aim of this project is to study the influences of drilling induced defect and changes in mechanical properties of the fiber composites.

- To fabricate fiber composites material ($0^o/90^o$ woven E-glass Fiber) using vacuum assisted resin infusion method by ensuring uniform process condition.
- To perform drilling process on the fiber composites material with various spindle speed and feed rate.
- To study the effect of drilling induced defect on the mechanical properties of the glass fiber composites.

1.4 Scope of Study

The study was carried out to fabricate fiber composite using vacuum assisted resin infusion method, glass fiber as the reinforcing material while epoxy resin as the matrix. The defects were induced by drilling operation which uses Mazak Variaxis 630-5X. The samples were then tested for tensile strength and structural analysis.

1.5 Significance of Study

There is a growing need in the use of the Glass Fiber Reinforced Epoxy (GFRE) especially in engineering application. However, effects of drilling operation from the resin infusion fabrication method and how it affects the mechanical properties of GFRE have not yet been fully examined. The lack of available data of these materials makes the findings of the study of potential importance towards understanding the microstructure and behavior of the glass fiber laminates. The output of the study can be informative in certain extent as the results of the study might provide important information and reference for further research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Composite materials are not new, since materials are known to have been used by the ancient Chinese, Israelites and Egyptians, all whom embedded straw in bricks to improve their structural capabilities [6]. Nowadays, the increment numbers in the usage of composite materials are greatly seen, as it has been used for airframes, automobile components and even in the oil and gas industries, for example oil and gas subsea production system are using GFRE pipe for firewater and cooling water system. In aerospace industry, GFRE are used in fairings, storage room doors, landing gear doors, and passenger compartment rather than using metal alloys permitting to weight reduction [7]. In this chapter, related theories and literature of previous work will be discussed.

2.2 Fiber Reinforcements

Fiber consists of thousands of filaments where each filament is having a diameter between 5 to 15 micrometers allowing them to be producible using textile machines [8]. Reinforcements can be continuous, woven or chopped fiber which can increase the mechanical properties of the composites. The fiber length is specified by the continuity of the composites.

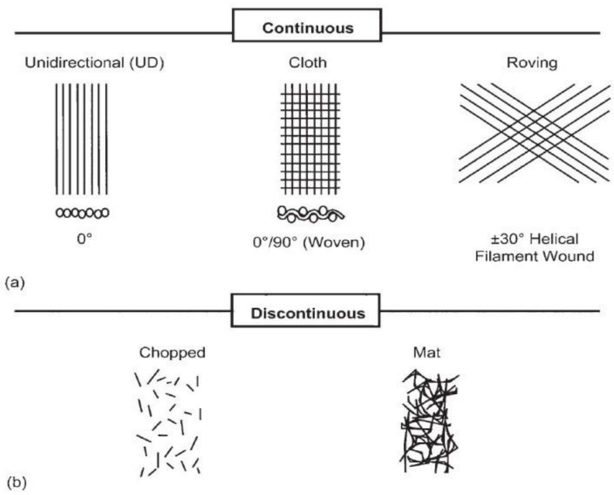


Figure 1: Group of fiber

Glass is by far the most widely used fiber due to its good characteristics which include high abundance, high strength and low cost compared to other composites. There are several different type of glass fiber with 4 different forms; roving, chopped strand, chopped strand mat and woven roving. There are several grades of glass fiber that are produced commercially for example E-glass, S-glass, R-glass, C-glass and Cemfil. The code “E” in E-glass fiber stands for electrical [9]. In this research, E-glass woven fiber was used as reinforcement material to produce fiber composites. According to Sims, 90% of the composites fabrication in aerospace industry used this fiber as reinforcements due to high resistant to corrosion, high strength-to-weight ratio, low thermal conductivity, longevity, adequate optical properties, low transportation costs, low installation costs, low resistance to flow, low electrical conductivity, dimensional stability, ease of installation, good energy savings and light in weight [10].

2.3 Matrix Material

The properties of fiber that limits its engineering application is fiber cannot transmit load from one to another. The composite which consist of fiber and matrix material that are embedded together where the matrix serves to bind and transfer load to the fiber and protect them again environmental attack and damage due to handling.

Polymers (commonly called plastics) have established themselves as matrix materials for composites in many applications and well established markets exist for them whereas most composites based on other classes of matrix materials are still primarily at the development stage. Their chief advantages are low cost, easy to process, good chemical resistance, and low specific gravity. On the other hand, low strength, low modulus, and low operating temperatures limit their use. They also degrade by prolonged exposure to ultraviolet light and some solvents [9]. Polymers can be classified as thermoplastics or thermosets. Thermoplastic soften or melt on heating whereas thermosetting do not soften but decompose upon heating. Epoxy is one of the thermosetting resins which are going to be used in this research to fabricate fiber composites. At room temperature, resin starts as a viscous liquid, which in the presence of the hardener to initiate the cross linking reaction and usually heating, changes to a rigid solid possessing a three-dimensional molecular network. Resin is a good resistance to most chemicals, good resistance to creep and fatigue, high strength and good electrical properties [11].

2.4 Induced Defect

For GFRE, usually the failure that happens occurred internally instead of any changes in its macroscopic appearance or behavior. The internal material failure can be seen from breaking of fibers, micro cracking of matrix, separation of fibers from matrix (debonding), and separation of laminae from each other in laminate composite (delamination) [9]. Drilling composite materials is more practical compared to placing holes during molding due to shrinkage problem during processing. Conventional drilling is widely used in industry due to easy handling and low cost compared to the other technique such as ultrasonic drilling, laser beam drilling and water jet drilling [8]. Unlike the machining of traditional materials, problems are encountered during the machining of GFRE. Delamination is a major damage encountered caused by machining operations of composite material [12].

2.4.1 Delamination Induced by Drilling

According to Liu et al., drilling-induced delamination is greatly shown at the entry and exit of drilled holes periphery. "Peel-up" and "Push-out" are two most observable damages related to drilling composite laminates [13]. Peel up delamination occurs around the drilled holes entry periphery while push-out at the hole exit periphery. The push-out delamination is somehow emerge at the hole exit if the thrust force applied go beyond the inter-ply bonding strength and researches show that it is more critical than peel-up delamination [13].

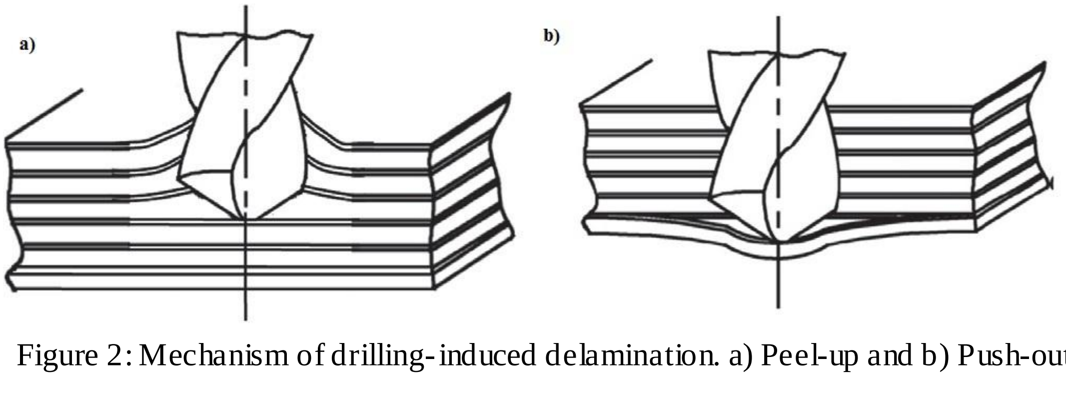


Figure 2: Mechanism of drilling-induced delamination. a) Peel-up and b) Push-out

2.4.2 Effects of Input Variables on Delamination

Factors such as feed rates, cutting parameters, end tool geometries/materials is an important consideration to be taken in obtaining the best performance on drilling operation. Liu et al. in their research stated that delamination increased with feed rate at any different cutting speed with a range of drill bits [13]. According to Davim et al. [14] and Sardinas et al. [15], whose research on drilling FRP manufactured by hand lay-up technique, delamination increase along with cutting speed during conventional drilling. In a research by Khashaba, cutting speed of 455 rpm to 1850 rpm and feed rate of 0.03 mm/rev to 0.3 mm/rev were used to drill woven/epoxy composites. The result showed that delamination decreased with increasing cutting speed. On the other hand, delamination increased with increasing feed rate, as the thrust force increase [16]. Based on the findings of most researchers, delamination occurred even at minimum feed, thus variation of feed technique from CNC drilling machine is recommended in avoiding delamination and at the same time increasing drilling efficiency.

2.5 Mechanical Properties

Glass fibers possess very high specific properties, in particular, stiffness and strength, which make them attractive as the reinforcing elements in the composite materials. To take full advantage of these properties, it is necessary to combine them with a matrix material, such as polymer, that bonds well with the fiber surface and transfers stress effectively between the fibers [17]. The matrix also stabilizes the fiber in compression, contributes to the resistance of damage due to impact by exhibiting plastic deformation, and provides out-of- plane properties to the laminates [18]. Epoxy has always been the preferred choice as the matrix for glass fibers due to its excellent properties and its suitability for various processing techniques [19]. Table shows the properties of commonly used reinforcements and matrix material.

Reinforcements	**Fiber Diameter, *d* (µm)**	**Density, ρ(kg/m3)**	**Young's Modulus, *E*(MPa)**	**Shear Modulus, *G*(MPa)**	**Poisson Ratio, *v***	**Tensile Strength, σ(MPa)**	**Elongationn (%)**
R-glass	10	2500	86000	-	0.2	3200	4
E-glass	16	2600	74000	30000	0.25	2500	3.5

Table 1: Properties of commonly used reinforcements [7]

Matrix	Density, ρ (g/cm3)	Young's modulus, E (GPa)	Poisson's Ratio, ν	Tensile Strength, σ (GPa)	Failure Strain, ε^* (%)
Thermosets					
Epoxy resins	1.1-1.4	3-6	0.38-0.40	0.035-0.1	1-6
Polyester	1.2-1.5	2.0-4.5	0.37-0.39	0.04-0.09	2

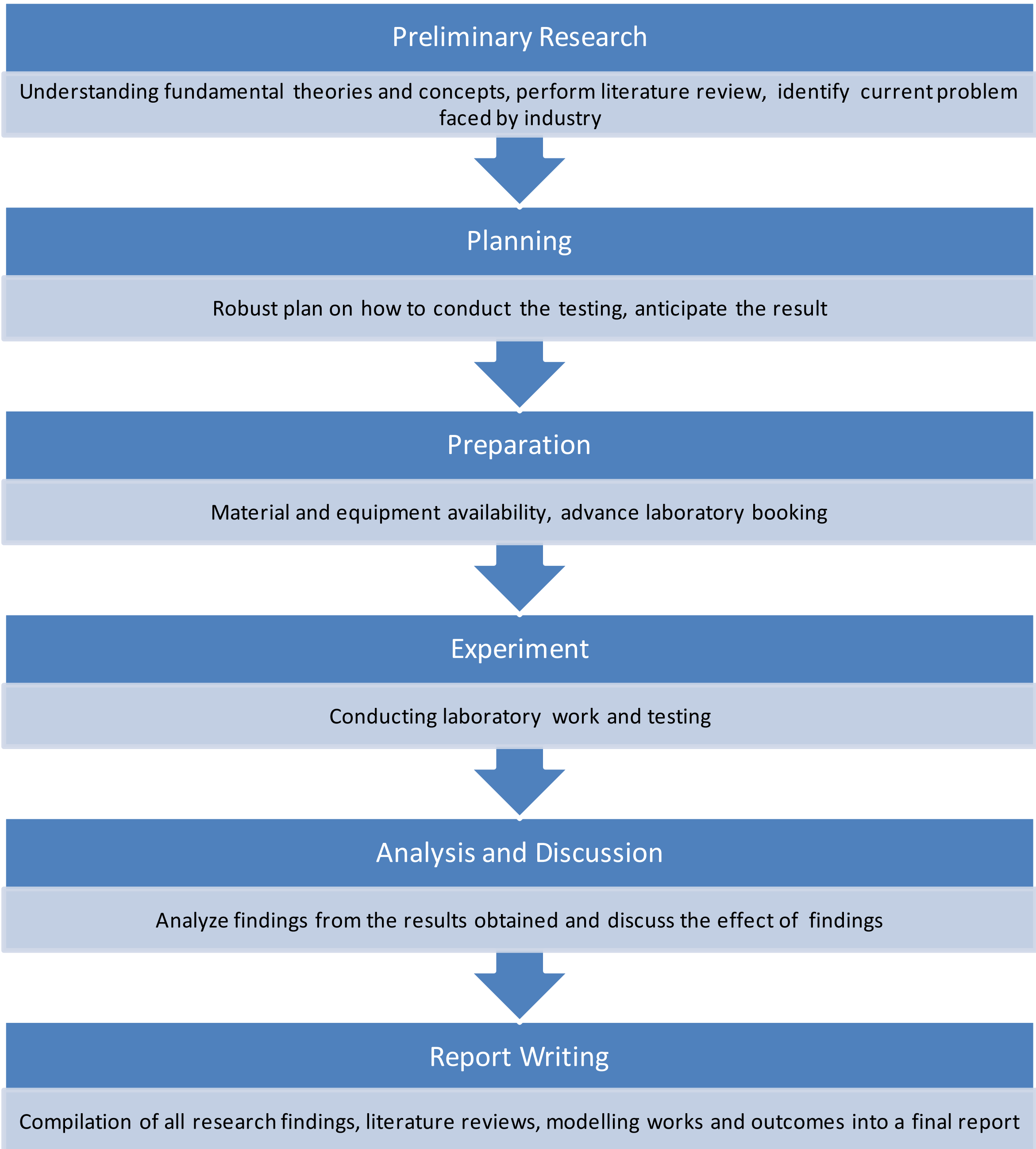
Table 2: Selected properties for different types of matrix [20]

The mechanical properties of fiber reinforced composites were very dependent on content of the reinforcing fiber, thus high fiber volume fraction is preferred. To fabricate the composites, assisted resin infusion method were used. Resin Infusion is part of the Liquid Composite Moulding (LCM) process family. The term LCM describes the closed mould process in which a liquid polymeric resin is impregnated through a fibrous reinforcement. The final fiber volume fraction (Vf) achieved can be higher and more consistent than that achieved with traditional open mould techniques. LCM processes also have the potential for automation, greatly reducing labour costs [21], where it can be widely used for many applications. The manufactured products have very low porosity and surface finish is good compared to the other techniques such as hand lay-up and spray-up molding [22]. Based on the research of Abraham et al., Interlaminar Shear Strength (ILSS), arising from the RTM technique was 70% higher than that from autoclave method [23]. According to Atas et al., The flexural strength of the repaired samples formed by infusion process is approximately 54% higher than that of hand lay-up [24].

Singh and Bhatnagar stated that damage generated during drilling operation leads to decreasing of mechanical behavior of the product [25]. From the research of Durão et al. which experimented on drilling composite material with different type of drill bit, cutting speed and feed rate, it shows that larger delamination causes a decrement in the mechanical strength based from the result of Open-hole tensile test [26]. The mechanical properties on are affected by the induced defect from the drilling which will be discuss further on this paper.

CHAPTER 3: METHODOLOGY

3.1 Research Methodology



3.2 Experimental Procedure

The procedure to fabricate the specimens and testing out mechanical properties will be discussed further here. The project was based on one type of composite material which is glass fiber reinforced epoxy, using $0/90^0$ woven E-glass fiber. The technique that was being used is vacuum assisted Resin Infusion which is suitable for prototypes and give better surface finish then the hand lay-up method.

3.3 Sample Fabrication

The GFRE plates used in the experiment were produced by using vacuum assisted resin infusion technique. The materials that were used to fabricate the specimen were woven glass fiber and epoxy resin.

3.3.1 Vacuum Assisted Resin Infusion Technique

This technique uses vacuum pressure to drive resin into the laminate. The glass fibers were laid dry on the mold where the vacuum condition was achieved before resin is introduced. Once a complete vacuum is achieved, resin literally flowed into the laminate via carefully placed tubing. Instead of manually wetting the reinforcements using hand lay-up, this technique used a vacuum bag to extract the excess resin out from the laminate. Vacuum bagging greatly improves the fiber-to-resin ratio and results in a stronger and lighter product.

i. Prepare the mould surface
ii. Cut and position the reinforcement, 300x300 mm x 14 layers.
iii. Add the peel-ply layer and the infusion mesh
iv. Position the resin feed spiral. It is a spiral wrapped plastic tube that is used to improve the flow of resin from the feed tube into the laminate.
v. After that, the resin feed connector and the vacuum connector is carefully placed.
vi. Before applying the vacuum bagging tape (tacky-tape), ensure that the mould is clean so that the tape will tightly stick. The tape is used extensively in all vacuum bagging processes where its pliable nature makes it highly effective at providing an air tight seal
vii. Position and tape down the vacuum bag carefully.
viii. Connect and seal the resin feed hose and vacuum hose.

ix. Set up the resin feed pot and vacuum pump and catch-pot.

x. Clamp the resin feed line and switch on the vacuum pump.

xi. Evacuate the air and adjust the vacuum bag.

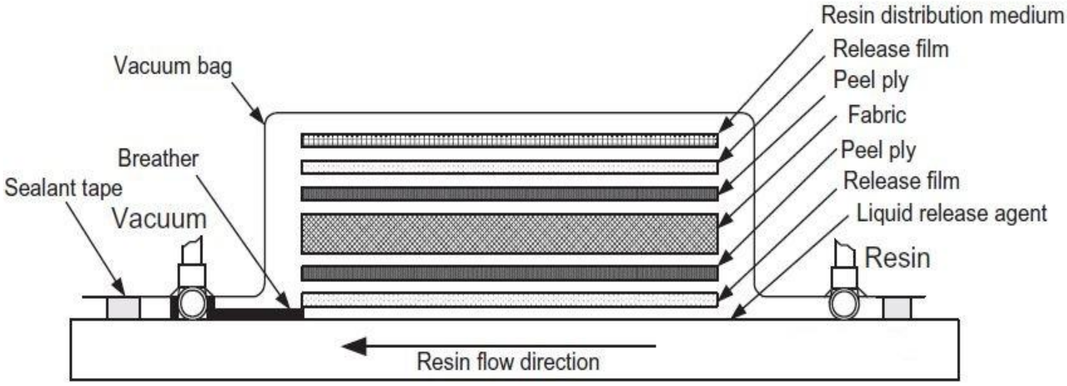


Figure 3: Vacuum infusion arrangement

xii. Gauge the correct amount of epoxy and hardener. The mixing ratio is 10:6 by mass for epoxy and hardener. The mixing is carefully done and later added to the fee pot.

xiii. Unclamp the resin feed line and monitor the infusion.

xiv. After it finish infused, clamp the hose and cut it. Ensure that it is air tight.

xv. The laminates are then inserted into a furnace to let it cure at 90 ^{o}C for two hours.

xvi. After the curing process, the specimen was cut out with dimension according to the standard that is going to be used for the testing.

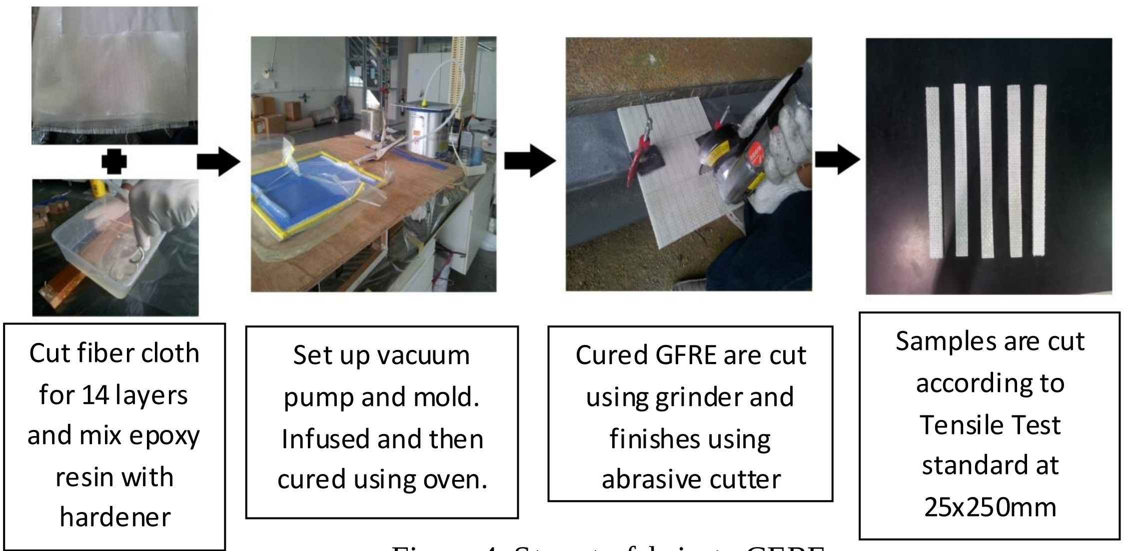


Figure 4: Steps to fabricate GFRE

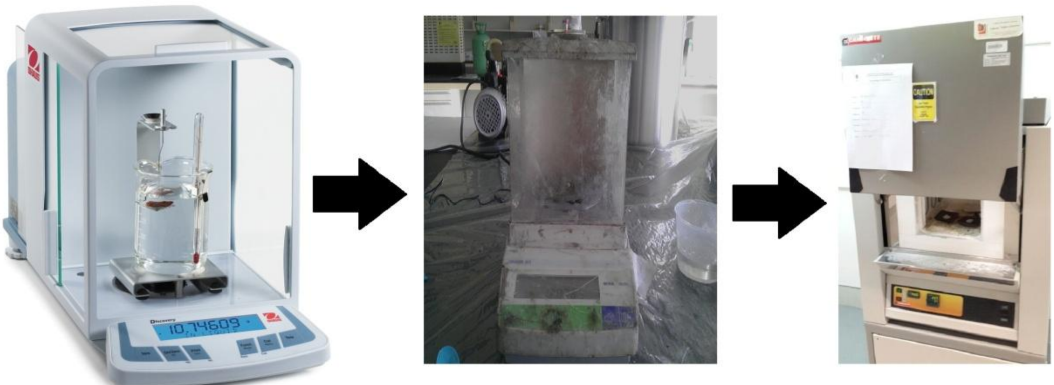
3.4 Burn-off Test

This test method covers the determination of the ignition loss of cure reinforced resins from which the weight of the resin in the composite can be found. This in turn, helps to determine the fiber volume fraction. The test was performed adhering to ASTM D 2584 which is the Standard Test Method for Ignition Loss of Cured Reinforced Resins.

Procedure:

According to the testing procedure a clean crucible was heated for about 15 minutes at about 550ºC in a muffle furnace. The crucible was then cooled to room temperature (20°C) and its weight was found to the nearest 1.0 mg. The specimens prepared as per the standards were weighed in the crucible to the nearest 1.0 mg and then placed inside the furnace. A temperature of around 500ºC was maintained in the oven such that the specimen burned uniformly and moderately. This was continued until only ash and carbon remained and the burning ceased. The crucible was taken out of the furnace, cooled to room temperature and its weight along with the contents of the crucible was measured to the nearest 1.0 mg.

When only glass fabric or filament was used as the reinforcement of an organic resin that was completely decomposed to volatile materials under the conditions of this test and the small amount of volatiles (residual solvent, water) that may be present is ignored, the ignition loss can be considered to be the resin content of the sample. A minimum of 3 samples were prepared for the specimen.



Small piece of GFRE 10x10 mm is cut and weight to get the density

GFRE is weight together with crucible before and after

GFRE was burnt at 500 ºC for 60 minutes

Figure 5: Steps for burn-off test

3.5 Parameters of Drilling

The defect was induced by drilling GFRE using CNC drilling machine where its feedrate and spindle speed was controlled. **Mazak Variaxis 630-5X** CNC machine was used due to its capability to drill at high speed. A **6 mm diameter High Speed Steel** drill bit is being used throughout the experiment. The specimen size for the drilling process was 250x25x9 mm.

Sample	**A1**	**A2**	**A3**	**A4**	**A5**
Spindle Speed, n (rpm)	15000	12000	9000	6000	3000
Feedrate, V_f (mm/min)	300	300	300	300	300

Table 3: Drilling parameters of sample with constant feedrate

Sample	**B1**	**B2**	**B3**	**B4**	**B5**
Spindle Speed, n (rpm)	9000	9000	9000	9000	9000
Feedrate, V_f (mm/min)	900	700	500	300	100

Table 4: Drilling parameters of sample with constant spindle speed

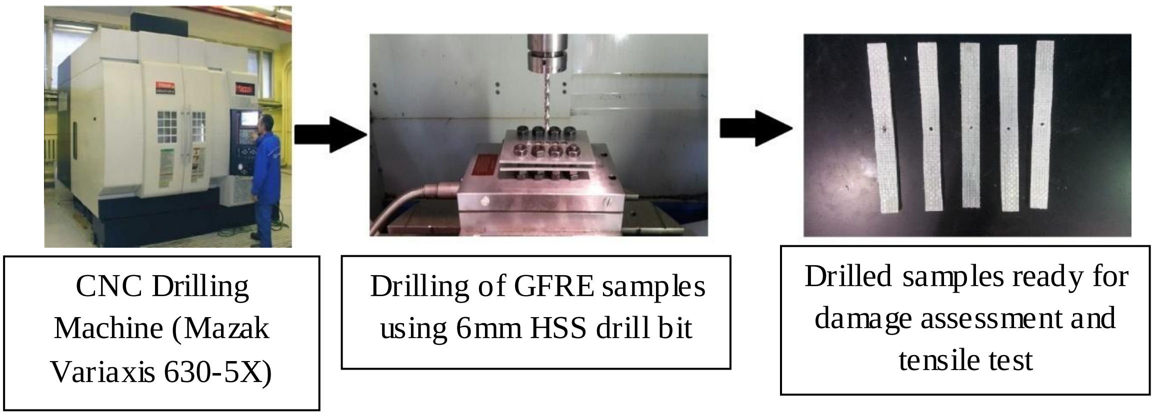


Figure 6: Drilling process using CNC machine

3.6 Measurement of Damage Factor

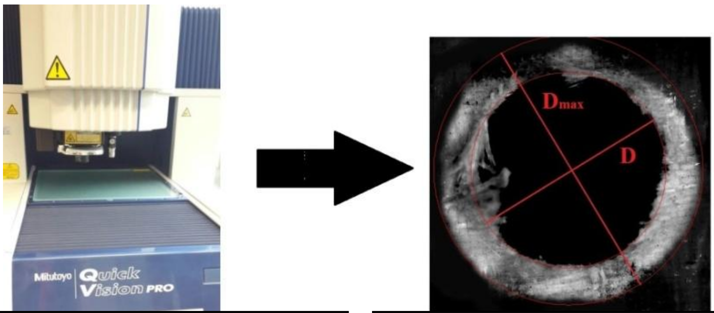
The delamination around the drilled holes was used to find the damage factor. In order to determine the damage factor, F_d, measurement method is used. Mitutoyo 3D Non Contact Measuring System was used together with QVPAK software to measure the damage. The machine works on non-contact principle which eventually prevent any type of damage to the hole surfaces. Damage factor, Fd is obtained using;

$$F_d = \frac{D_{max}}{D}$$

Where; F_d = Damage Factor

D_{max} = Maximum diameter of damage zone

D = Diameter of drilled hole



Surface of drilled holes were cleaned and hanged between two bars for sufficient lighting from top and bottom part of samples. Lenses were adjusted using joystick	Sufficient light was supplied onto sample and damage observed around the sample was captured and analyzed.

Figure 7: 3D non contact damage measurement

3.7 Tensile Test

The mechanical properties of fiber composite were measured using Universal Testing Machine (UTM 100 kN), Zwick Roell H100 with workshop Release Software at room temperature. Dimensions and standard used for samples are from ASTM 3039 and D5766.

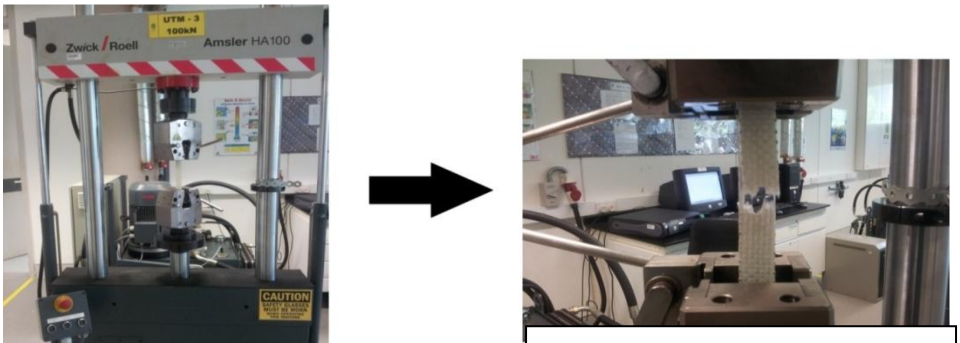
I. Abrasive cutter is used to cut the specimen to dimension of 25 mm wide x 250 mm long.

II. Grip the specimen 10mm from the top and 10 mm from the bottom of the specimen.

III. Emery cloth is attached at the gripped part of the specimen to avoid slippage.

IV. Test is run at the speed of 0.02 mm/sec.

One directional force is applied at both ends of the specimen. Gradually increase of load will results to increase deformation. When fracture occurred, the load will be recorded as ultimate tensile strength. Stress versus strain curve will be plotted and thus data are going to be obtained.



Sample is gripped apart on the marked line

Fractured sample, load at the breakage point is recorded as ultimate tensile strength

Figure 8: Tensile test using universal testing machine

3.8 Field Emission Scanning Electron Microscope

Field Emission Scanning Electron Microscope (FESEM) SUPRA 40VP is used to analyzed the microstructures of samples by visualizing very little topographic details on the surface or entire of the object. For GFRE, gold vapor deposition was applied onto samples to let it have a conductive layer over the sample. Micrograph observation of the internal surface of drilled holes are observed and captured to be analyzed.

Gold vapor deposition was applied onto sample to provide conductive

After the samples are vacuum to ensure air tight, scanning starts

Figure 9: Steps for FESEM

3.7 Gantt Chart and Key Milestones

Semester January 2013

Activities / No. of Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Literature Review														
Planning of experiment and setup					1									
Fabrication of composite laminates										2				
Testing of mechanical properties (1)														3

Table 5: Gantt chart for semester January 2013

Semester May 2013

Activities / No. of Week	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Testing of mechanical properties (2)						4								
Report writing														5

Table 6: Gantt chart for semester May 2013

	Project Progress
1	Key Milestone 1: Experiment and setup identified
2	Key Milestone 2: Vacuum Assisted Resin Infusion laminates fabricated
3	Key Milestone 3: Resized, booked lab, tested properties.
4	Key Milestone 4: Mechanical testing completed
5	Key Milestone 5: Report writing completed

CHAPTER 4: RESULTS AND CONCLUSION

4.1 Fiber Volume Fraction

In order to determine properties of a composite material, relative proportions of the matrix and reinforcing materials is importantly be referred from fiber volume fraction, V_f which is more significant and used significantly in theoretical analysis of composite materials. Rule of mixtures used to define V_f where it is the method to approximate estimation of the properties from assumption that volume weighed average of the phase's properties. The expressions below used to determine weight fraction of the phase's [27]:

$$Vc = Vm + Vf \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where Vf can be expressed as;

$$V_f = \frac{\rho_m W_f}{\rho_f W_m + \rho_m W_f} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

Where;

V_f = volume fraction of fiber

W_f = weight of fiber

W_m = weight of matrix

ρ_f = density of fiber (2.56 g/cm^3)

ρ_m = density of matrix (1.4 g/cm^3)

4.1.1 Density Measurement

The density of the fiber composites was measured using Mettler Toledo AX405 based on Test Method A in ASTM D0792. The specimens were cut to the dimension of 1x1x1 cm^3. Averages of 3 readings were taken to get the accuracy of the data.

Density,

$$\rho = \frac{A}{A-B}(\rho_0 - \rho_l) + \rho_l$$

Where;

ρ_0 = Density of auxiliary liquid (0.99752)

ρ_l = Density of air (0.0012)

A, B = Mass of specimen according to Test Method A

	Sample 1	**Sample 2**	**Sample 3**
A (mass of GFRE in air, g)	6.051	5.841	6.530
B (mass of GFRE in water, g)	2.805	2.705	3.026
Density of GFRE (g/cm^3)	1.803	1.855	1.892
W_f **(g)**	4.158	4.120	4.773
W_m **(g)**	1.893	1.721	1.757
V_f **(%)**	58.24	59.64	62.18

Table 7: Fiber volume fraction

The volume fraction resulted from the fabrication was between ($0.58 < Vf < 0.62$). It is categorize under intermediate fiber volume fraction and exhibit brittle failure with fiber pullout. These ranges are applicable if the void content in the composite is negligible [9].

4.2 Effect of Drilling Parameters on Damage Factor, F_d

It can be seen that during the drilling operation, there is a significant difference in torque and thrust force at different drilling parameter. It leads to damage in the form of delamination, fiber pull out and matrix burning around the drilled holes which somehow affect the properties of the GFRE. Damage factor obtained from 10 drilled samples with different in spindle speed (rpm) and feed rate (mm/rev) are measured.

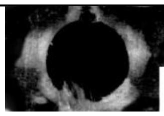
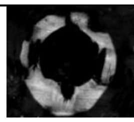
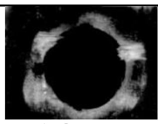
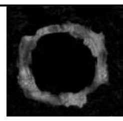
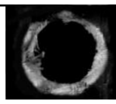
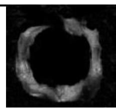
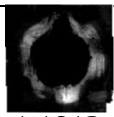
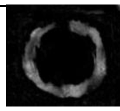
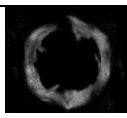
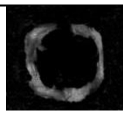
F_d / n (rpm)	Entering Damage Factor	Exiting Damage Factor
15000	 1.3018	 1.2644
12000	 1.2775	 1.1392
9000	 1.1998	 1.1214
6000	 1.1813	 1.0919
3000	 1.1273	 1.0863

Table 8: Damage factor, Fd for constant feed rate of 0.03 mm/rev

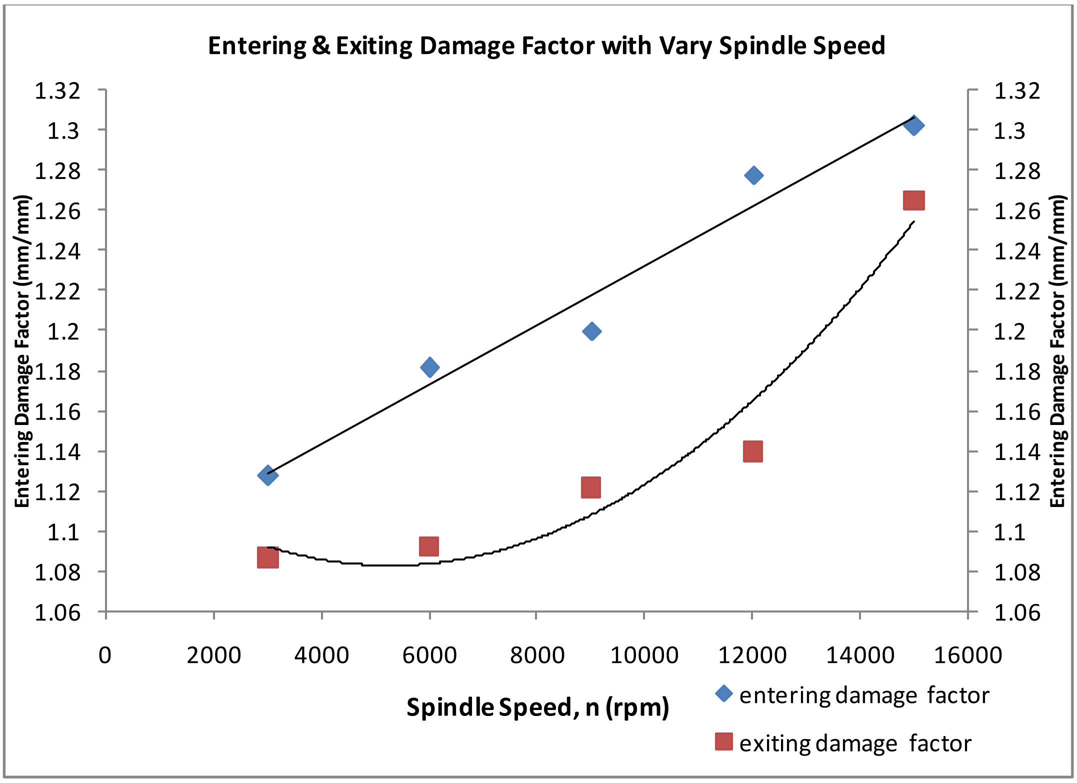


Figure 10: Graph of damage factor against spindle speed for a constant feed rate

From the results, it can be seen that for a constant feed rate of 0.03 mm/rev, the damage factor increase as the spindle speed increase. The damage factor is as high as 1.3 at the entering and 1.26 at the exiting for a spindle speed of 15000 rpm. Based on the report of Gaitonde et al., delamination induced by drilling operation reduces in line with cutting speed during high speed drilling of thin woven-ply CFRP [28].

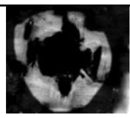
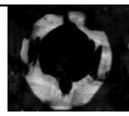
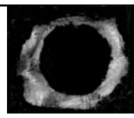
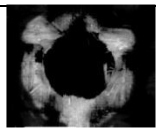
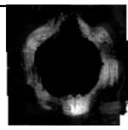
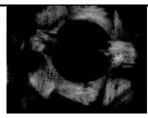
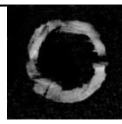
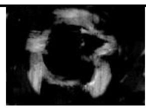
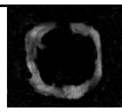
F_d / f (mm/rev)	Entering Damage Factor	Exiting Damage Factor
0.1	 1.3912	 1.4746
0.08	 1.3104	 1.4189
0.06	 1.2714	 1.3466
0.03	 1.2495	 1.3067
0.01	 1.2180	 1.2008

Table 9: Damage factor, Fd for constant spindle speed of 9000 rpm

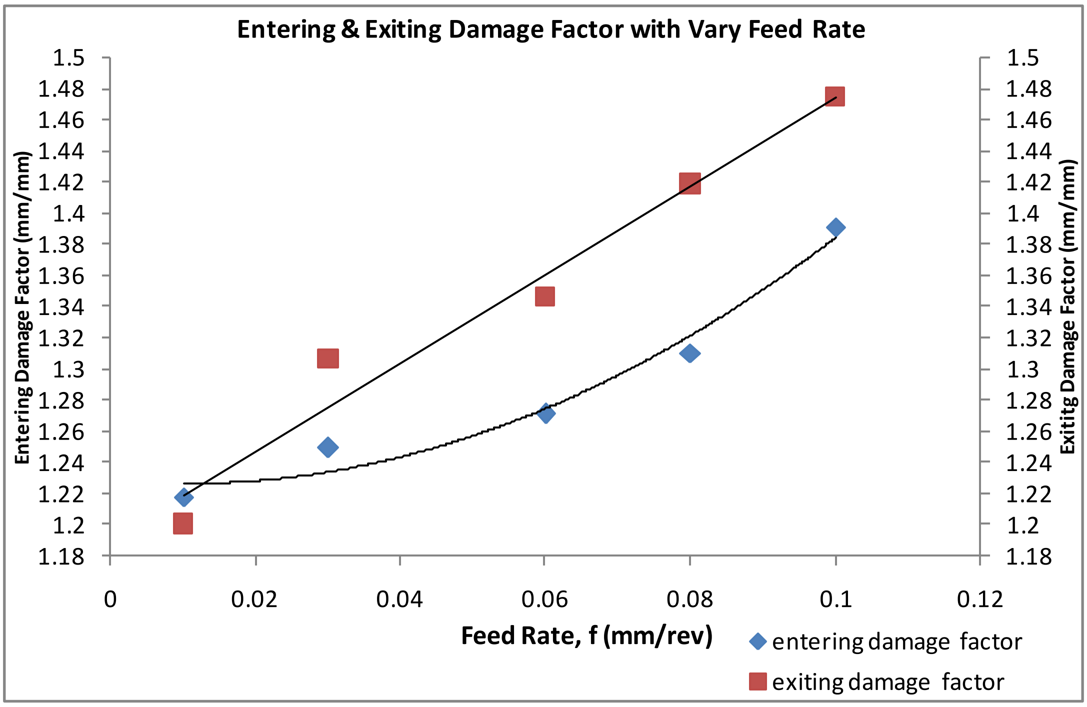


Figure 11: Graph of damage factor against feed rate for a constant spindle speed 9000rpm

From the results of constant spindle speed, 9000 rpm, it can be seen that the damage is more significant as the feed rate increases. From the research of Khashaba which used variation of cutting speed and feed rate, it showed that the damage decreased with increasing cutting speed and damage increased with higher feed rate [16]. Thrust force increased as feed rate increased, but it is applied at low fix spindle speed. Higher thrust force lead to higher damage around drilled holes due to tool's vibration. However the thrust force and torque could not be studied due to limitation of equipment. Karnik et al. reported that when feed rate is kept at lower value, minimum delamination attained at higher speed range which lead to matrix softening at high temperatures [30]. Damages are also resulted from poor cutting action. The increment in cutting speed increase the risk of thermal damage as it leads to softening of matrix material which in this experiment is epoxy. It will eventually lead to loss of mechanical strength of uncut plies of the laminate.

Damage may also take place due to poor surface finish of GFRE. The wax that has been used to provide a layer which supposedly eases the removal of GFRE from the mold might not be sufficient enough which somehow affect the surface finish.

This shows that drilling parameters are crucial in controlling the damage around the holes, namely a high rpm and a high feed rate. Adequate time used to grind the GFRE in line with the correct arrangement of drilling parameters will inhibit splintering that cause the damage. The use of CNC machine with variation of feed rate and spindle speed is vital when drilling composites material.

4.3 Tensile Test

The specimens were successfully tested for the drilled and non-drilled GFRE. Based on the result of non-drilled sample, it shows that the tensile strength is 137.262 Mpa. Figure 12 shows a sample which has undergone tensile test at its Ultimate Tensile Strength and the graph generated by the computer which connected to the UTM.

Figure 12: Non-drilled sample after tensile test

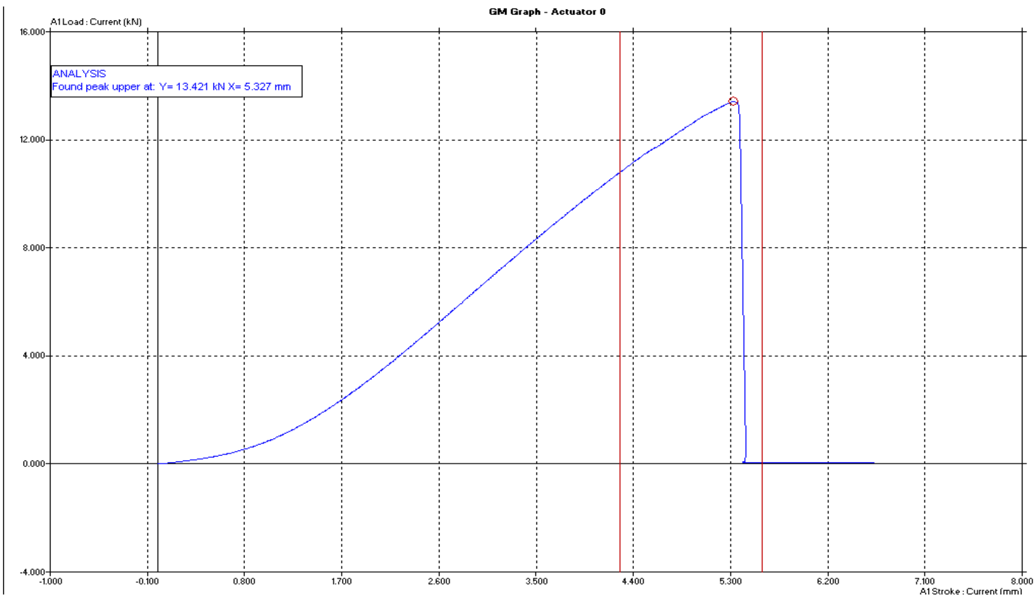


Figure 13: Graph of Stress Vs Strain

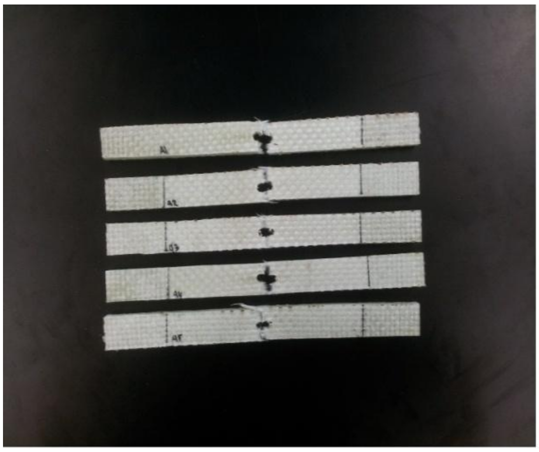
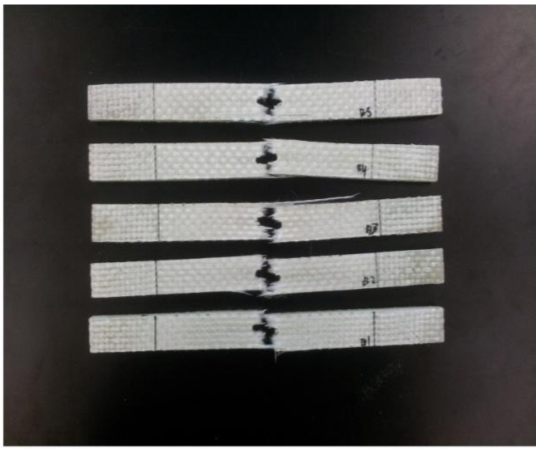



Figure 14: Drilled Samples after Tensile Test

A)

Sample	Spindle Speed, n (rpm)	Feed Rate, f (mm/rev)	Entering Damage Factor, Fd	Exiting Damage Factor, Fd	Ultimate Tensile Strength, σ
A1	15000	0.03	1.3018	1.2644	71.22
A2	12000	0.03	1.2775	1.1392	79.679
A3	9000	0.03	1.1998	1.1214	82.679
A4	6000	0.03	1.1813	1.0919	90.016
A5	3000	0.03	1.1273	1.0863	99.305

B)

Sample	Spindle Speed, n (rpm)	Feed Rate, f (mm/rev)	Entering Damage Factor, Fd	Exiting Damage Factor, Fd	Ultimate Tensile Strength, σ
B1	9000	0.10	1.3912	1.4746	101.353
B2	9000	0.08	1.3104	1.4189	101.005
B3	9000	0.06	1.2714	1.3466	98.636
B4	9000	0.03	1.2495	1.3067	104.652
B5	9000	0.01	1.2180	1.2008	101.834

Table 10: A & B) Drilling parameters, damage factor from drilling and ultimate tensile strength

Figure show drilled samples which have undergone tensile test to determine the ultimate tensile strength. The results of the test together with the parameter of drilling are recorded on table. Table A (sample A) shows the UTS for the samples with fix feed rate of 0.03 mm/rev. The UTS can be seen as decreasing as the spindle speed increase. Table B (sample B) represent the UTS for sample with constant spindle speed of 9000 rpm. The UTS is more or less the same as the feed rate increased. Graph of Stress Vs Strain for variation in spindle speed and variation in feed rate are shown in Figure 15 and 16. The relation of UTS with the damage factor will be discussed further on this chapter.

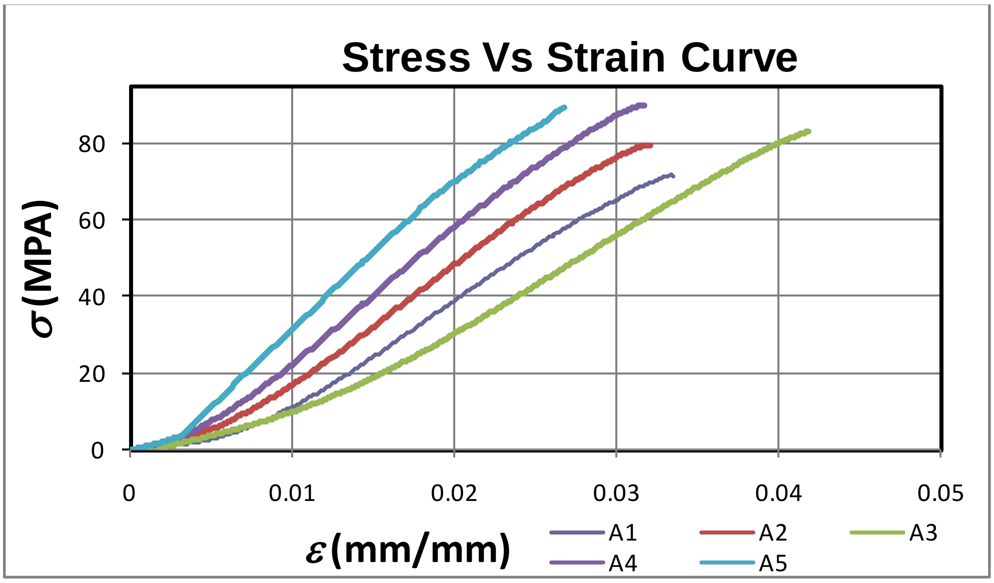


Figure 15: Stress vs strain curve for increasing spindle speed

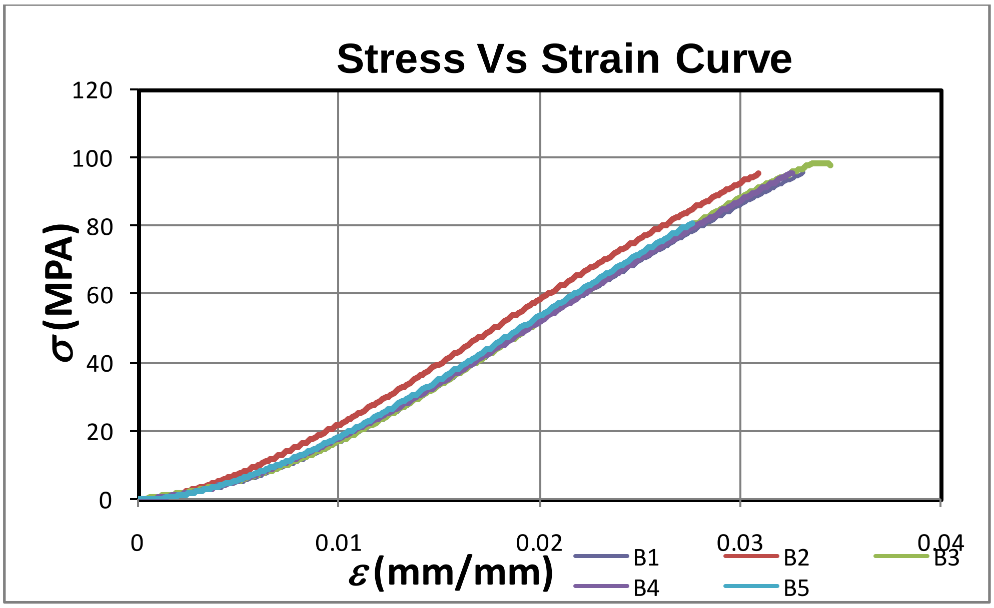


Figure 16: Stress vs strain curve for increasing feed rate

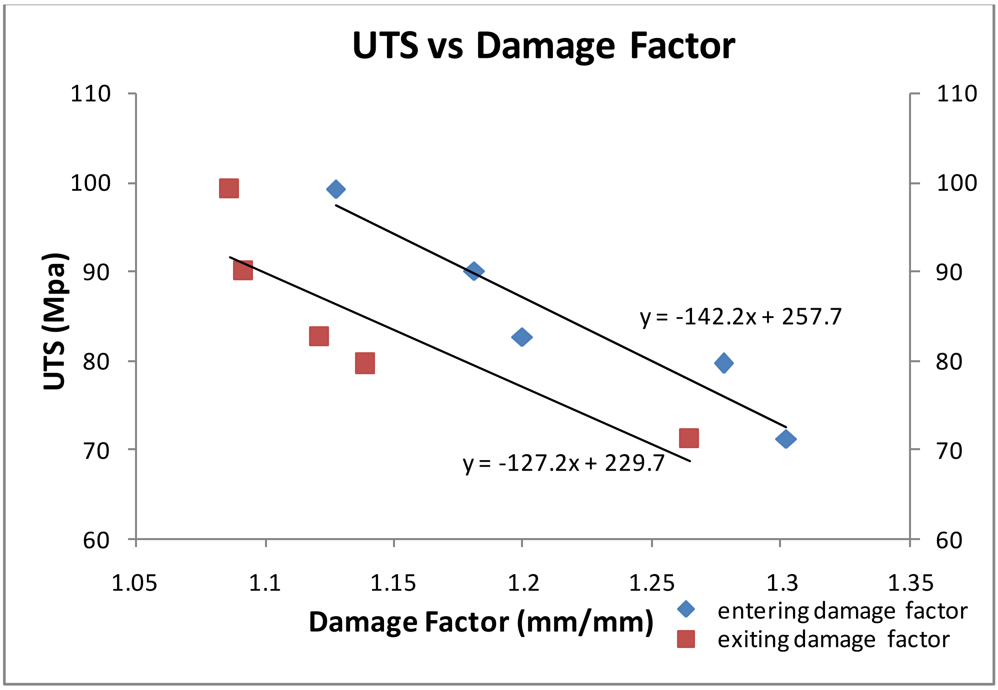


Figure 17: Graph of UTS vs damage factor for increasing spindle speed

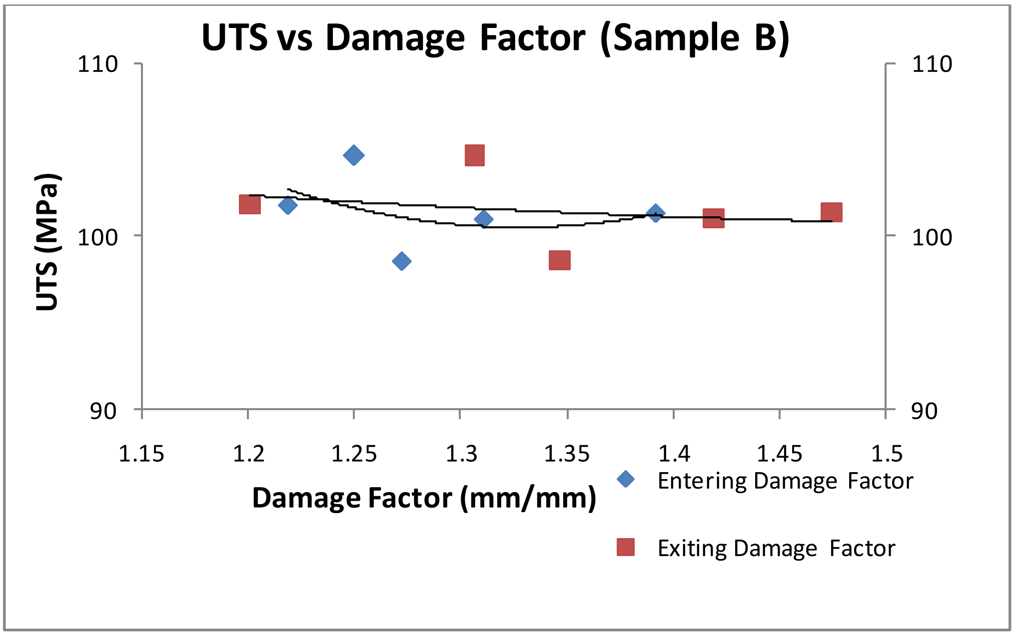


Figure 18: Graph of UTS vs damage factor for increasing feed rate

Figure shows the UTS vs Damage Factor for the sample with increasing spindle speed. The UTS decreased as the damage factor increased. The UTS for sample with increasing feed rate does not significantly affected by the damage factor as it increased. From the linear equation of sample A for UTS against exiting damage factor, $y = -142x + 257.7$, the calculated value shows that as the damage factor increase by 0.1 (assuming 1 to be perfect drill), the rate of decrement for UTS is at 12% of the original value. Thus, as the damage factor increase even by 0.1, there will be significant effect on the tensile strength.

Kishore et al. looked into the effect of the cutting speed, feed rate and drill point geometry on the tensile strength of GFRP composite. Based on the report, drilling operation which induced damage at higher cutting speeds, consequently have an effect on the tensile strength of the GFRP [29]. "Open Hole Test" showed that the relation between delamination and mechanical strength, where the increment in damage factor will results in reduction in mechanical strength of the plate around the connecting region supposedly screws, rivets or bolts which are used for assembly of components.

4.4 Microstructural Analysis

In depth study regarding the mechanical properties of GFRE leads to the usage of Field Emission Scanning Electron Microscope (FESEM) which allow the microstructure of the drilled holes to be examine in order to analyze delamination, fiber pull-out and matrix cracking of the drilled hole walls.

Only two samples were able to be sent for FESEM analysis due to limited use of the machine. There are two samples, one of it was cut from drilled part of GFRE and the other one is the drilled powder from the cutting.

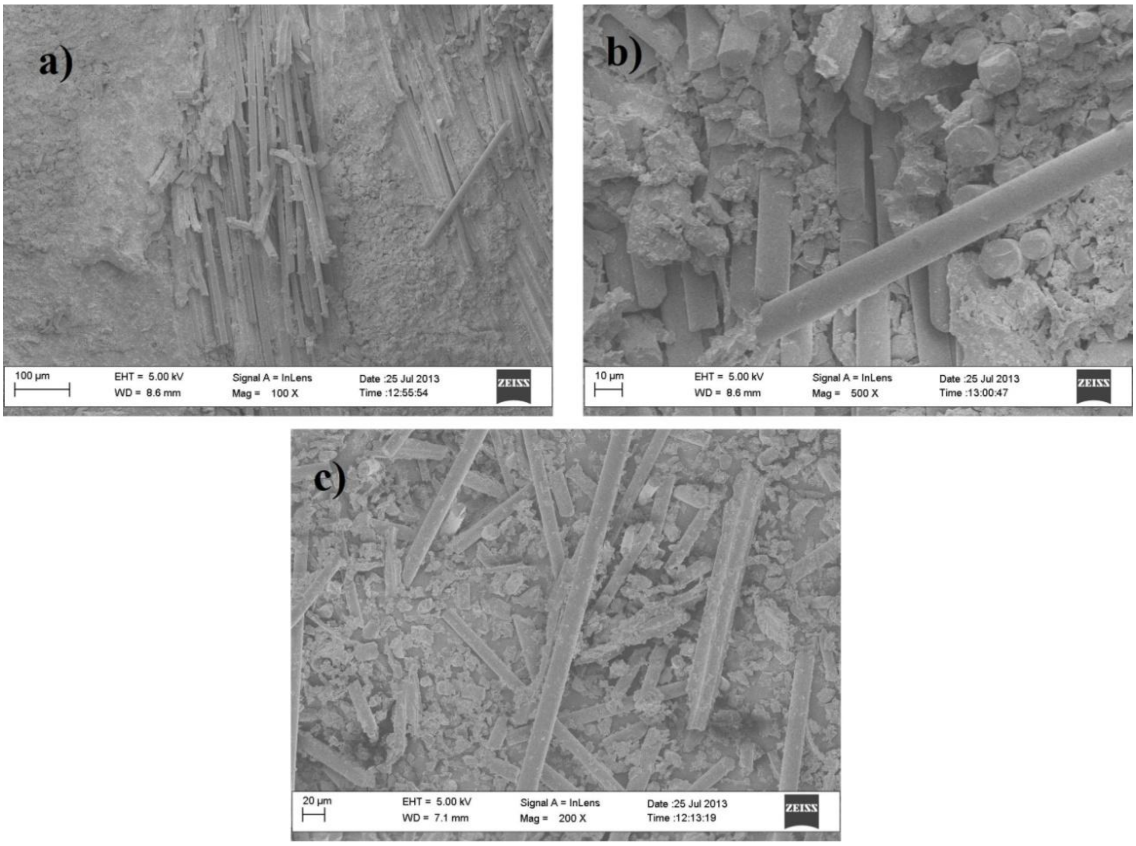


Figure 19: FESEM images of wear damage observation during drilling GFRE: (a) & (b) Drilled sides, (c) Powder from drilling.

Figure a & b are from the drilled sides of the GFRE at a magnification of 100X – 500X on the other hand, c is from drilled dust of GFRE taken aside after the drilling operation at magnification of 200X. The micrograph images from the FESEM showed defect such as fiber-matrix debonding. Figure a and b show defect at the wall's hole where separation of fiber from matrix can be seen.

Figure c showed the residual powder from the drilling operation. It can be seen that the fiber fracture and fiber pull-out due to weak interface between fiber and matrix. This happens when parts of fractured composite separate as the fibers debonded.

CHAPTER 5: CONCLUSION & RECOMMENDATIONS

The aim of the research is to investigate the influence of drilling process on the mechanical properties of GFRE.

The composite laminates of $0^o/90^o$ woven E-glass Fiber were successfully fabricated using vacuum assisted resin infusion method. The Fiber Volume Fraction of the GFRE resulted from the fabrication is between $0.58 < Vf < 0.62$ which falls under the category of intermediate FVF. The failure mode of the GFRE is brittle fracture of fibers with pull-out.

The fabrication process is followed by drilling process as to induce defect on the GFRE. Measurement of the damage factor, Fd are done using Mitutoyo 3D Non Contact Measuring System and microstructural observation using Field Emission Scanning Electron Microscope (FESEM). Low feed rates are appropriate for composite laminate drilling due to its decrement of thrust force, whereby low spindle speed will inhibit splintering which eventually decrease the delamination around the hole.

The effect of induced defect on mechanical properties of GFRE were tested using Tensile Test. Open Hole Tensile Test was used to describe mechanical loss due to delamination damage which the test procedures are very simple to execute. The feed rates does not significantly affect the UTS while the low spindle speed minimize the lost of mechanical strength.

Due to limitation of experiment, where the bending machine, dynamometer and x-ray is not available to be used, the Interlaminar Shear Strength (ILSS) of the GFRE and in depth review of the damage factor can't be done. The measurement of torque and thrust components of the drilling force associated with delamination are viable to expand the study. Further research on this area will help to determine how far is the mechanical properties are affected by drilling operation.

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