Properties of Carbon/Epoxy and Glass/Epoxy Composite Produced From Prepreg as a Structure for Battery Pack in Electric Vehicle Applications

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Abstract:

A carbon/epoxy and glass/epoxy prepreg were utilized to manufacture composites sample by utilizing vacuum bagging and oven curing techniques. Composites offers lightweight, provides improved mechanical properties, and improves energy efficiency, making it ideal for the development of a backup structure for a battery pack. To prepare composite samples from carbon/epoxy and glass/epoxy prepreg, five various bagging technique were employed. The experiment showed that bagging technique affected interlaminar shear strength (ILSS) and tensile strength. A5 exhibited the highest tensile and ILSS strength among samples with the least void content which is from carbon/epoxy composite. This was identified as a suitable candidate for battery pack backup structure. Initially, the samples quality was tested non-destructively using an ultrasonic C-scan, which revealed wrinkles, dry spots, and porosity on the surfaces. Physical inspection and NDT aren't consistent with the results based on the quality of the fabricated samples. Due to the substantial differences between samples in void content, higher void content leads to lower mechanical properties. The quality of carbon/epoxy composites as a candidate material in the battery pack structure development greatly depends on sample preparation or fabrication technique in order to produce the better mechanical strength with low percentage of defects. Apart from having high strength and less defects, manufacturing and material costs as well as its thermal conductivity property also need to be considered. Glass/epoxy composite offers a more effective material cost when compared to carbon/epoxy composite.

Keywords: Vacuum bagging, ILSS, Mechanical properties, Ultrasonic C-Scan

1 Introduction and Background

The latest generation of prepreg out autoclave has been introduced by prepreg material producers, this latest development of prepregs has shown that it is possible to produce quality autoclave parts using vacuum bag assembly. Without the use of autoclave, the prepreg material developed can reduce the cost of acquisitions and operations, and is compatible with various types of low-cost curing process, including conventional ovens, heating blankets, and heated appliances [1][2][3]. The use of prepreg out of autoclave (OOA) does not accelerate the production process of advanced composite products. Due air trapped removing during processing, is it a time-dependent process. The curing cycle of OOA technique is usually longer. Typically, mpletely conducted debulking process, vacuum must be held for a longer period before starting the curing process. The duration of this vacuum holding depends on the size and complexity, from as low as 4 hours for 0.4 m^2 to 16 hours for 72 m^2 [4]. In addition, external factors such as relative humidity also play a very important role in controlling void content in the lamina. In general, epoxy resin tends to absorb moisture in the air and trapped humidity is very difficult to remove under vacuum bagging (VB) processing. The effect of relative humidity on empty content of processed laminate VB has been systematically studied [5].

Method of inspection using ultrasonic C-scan was identified as a primary screening technique for determining the quality of an advanced composite material before it can be used in the field. The principles of ultrasound and disability carbon/epoxy composite can occur during the fabrication process have been widely discussed[6][7][8][9][10]. Among the defects that often occur in polymer-based composite materials are voids

that exist in the laminate and a product during the manufacturing process. Defects such as voids and porosity often occur due to the manner and appropriateness occur during the manufacturing process. Defects such as may result in a reduction in interlaminar shear strength (ILSS) of 5 % to 7 % for every 1 % increase voids are detected [11][12][13][14][15][16]. With this reduction, it would lead to a reduce in strength. Generally, void exist in or between the layers of fibres used even in resin system itself. There are four mechanisms that can cause the formation of voids and porosity [17]

a. the air trapped during the accumulation layer.
b. a slowdown in the resin.
c. volatiles released from the curing process.
d. internal pressure build-up of resin cure shrinkage.

The research focuses on the integration of carbon fibre composite materials in battery pack backup structures and explores its limitations, advantages and potential applications. This work aims to contribute to the understanding of how carbon fibre composites can enhance the performance and reliability of battery pack structures in various industries especially in electric vehicle (EV) application. From materials selection, fabrication process, laminate design considerations and performance evaluation, this study aims to provide valuable insights for future developments and research in this field. The purpose of this work is to investigate the use of carbon fibre composites as battery pack backup structures by investigating the mechanical/physical properties and quality inspection by means of various fabrication strategies. The research aims to assess the benefits and challenges associated with incorporating carbon fibre composites in battery pack designs. By analysing the mechanical/physical properties, fabrication process and the quality inspection, this study seeks to provide valuable insights into the potential advantages, limitations, and performance evaluation of carbon fibre composites in battery pack backup structures. The scope of this work encompasses the examination of carbon fibre composites and their possibility integration as battery pack backup structures. It includes an analysis of the lightweight, high strength, and corrosion resistance properties of carbon fibre composites. The research also explores the manufacturing process, cost and manufacturing complexity associated with using carbon fibre composites in this context. Additionally, the scope of this work extends to case studies exploring the application of carbon fibre composites in electric vehicles, the aerospace industry, and renewable energy systems. Figure 1 is the structure of battery pack suggested to use carbon/epoxy composite material.

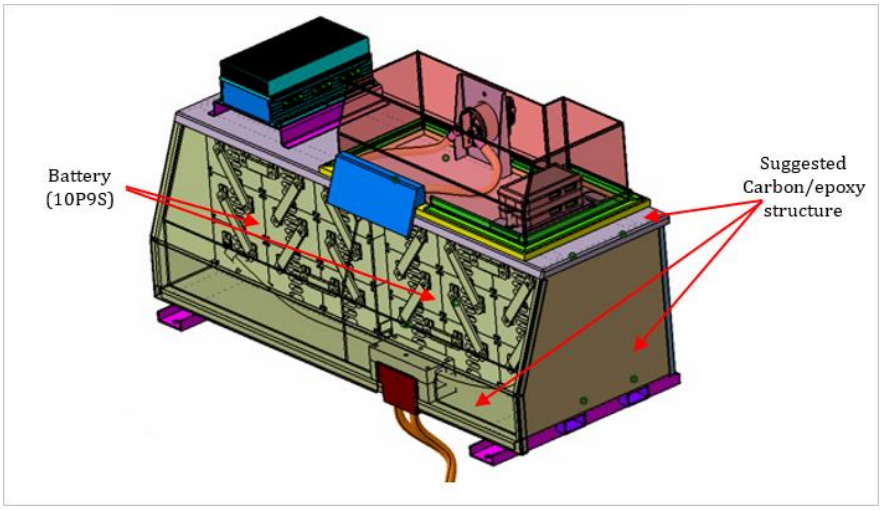


Fig. 1 Suggested structure to be made from carbon/epoxy composite material.

2 Experimental Procedure and Testing

2.1 Materials Selection

Five (5) samples were fabricated accordingly to this study as in Table 1, 2 and 3 for each sample (carbon/epoxy and glass/epoxy). Prepreg laminating was carried out using 600 mm x 300 mm composite mould which is

purposely for autoclave moulding. The prepreg material was used under tradename Cytec with code name Cycom 5320 and Cycom 7668 were identified as a main material. This particular material was developed by Cytec. At least three (3) specimens per sample will be fabricated using vacuum bagging and oven cure technique. The best specimen was investigated accordingly.

Table 1 Sample Identification

Code	Description of laminating and bagging technique with oven cure
A1	Normal bagging with single vacuum source/port
A2	Normal bagging with two vacuum ports
A3	Debulk each 3 plies, single vacuum port with PTFE on top of mould surface
A4	Normal bagging with caul plate on top assisted by two vacuum ports
A5	Staggering layout, normal bagging with 2 vacuum ports

Table 2 Number of Ply Involved Reflect with Carbon Prepreg Used

Sample ID	Prepreg	Ply Thickness (mm)	No of ply
A1C/E	Cycom 5320	0.21	12
A2C/E	Cycom 5320	0.21	12
A3C/E	Cycom 5320	0.21	12
A4C/E	Cycom 5320	0.21	12
A5C/E	Cycom 5320	0.21	12

Table 3 Number of Ply Involved Reflect with Glass Cycom 7668/7781 Prepreg Used

Sample ID	Prepreg	Ply Thickness (mm)	No of ply
A1G/E	Cycom	0.24	12
A2G/E	Cycom	0.24	12
A3G/E	Cycom	0.24	12
A4G/E	Cycom	0.24	12
A5G/E	Cycom	0.24	12

In order to achieve 2.5 mm to 3.0 mm in thickness of carbon/epoxy composite panel, twelve (12) plies of prepreg were laminated accordingly (Table 1). Bagging construction was involved in usage of polytetrafluoroethylene (PTFE) film, intensifier (caul plate), peel ply, breather ply and bagging film. Debulking, staggering construction, single and double vacuum ports will be introduced in order to produce better composite panel. The prepared samples were cured into walk-in curing oven at 177^0C as a supplier recommendation. In order to produce the composite laminate, various of supporting tools have been used as in Table 3.

Table 3 List of Supporting Tools and Equipment Involved in Fabrication Process

No	Tools/Equipment	Details
1	High temperature vacuum bag	204^0C ST[1],Nylon material with 0.05 mm thickness

2	Breather cloth	204^{0}C ST[1], polyester material
3	Release fabric/peel ply	232^{0}C ST[1], nylon with silicone coated
4	Compaction roller	Plastic roller, a steel frame, and a wood handle
5	Straight shear (scissor)	Metal scissor with 20 mm length
6	Sealant	Synthetic rubber, 204^{0}C ST, 204^{0}C ST[1], 12 months SL[2]
7	Vacuum hose	9 bar max pressure, 0.91 cm ID[3], 1.91 cm OD[4],232^{0}C ST[1]
8	Vacuum port	63 mm round base diameter,260^{0}C ST[1], aluminium
9	Oven (walk-in type)	260^{0}C MT[5]
10	Vacuum pump	Absolute vacuum 0.5 mbar
11	Prepreg	Cycom 5320

Source: Manufacturer product data

[1]ST-Service temperature
[2]SL-Service life
[3]ID-Internal diameter
[4]OD-Outer diameter
[5]MT-Maximum temperature

Table 4 Cycom 5320 Prepreg Properties (Cytec Industries Inc)

Style	Plain Weave
Fibre areal weight (FAW)	193 gsm
Tack life at room temperature (RT)	20 days @ RT
Shop life	30+ days minimum @ RT
Cured resin density	1.31 g/cc
Wet glass transition temperature	163^{0}C

Table 4 Cycom 7668/7781 Prepreg Properties (Cytec Industries Inc)

Style	7781 (8HS)
Fibre areal weight (FAW)	Approx. 295 gsm
Handling life at room temperature (RT)	15 days @ 24 ^{0}C
Shop life	30+ days minimum @ 24 ^{0}C
Shelf life	270 days at -12 ^{0}C

2.2 Method

2.2.1 Mould Preparation

Composite mould was used to fabricate the required samples. Before conducting the fabrication process, mould preparation procedure was carried out in order to prevent any problem while moulding and demoulding process.

a. Mold Cleaning: Surface of the mould was thoroughly clean by using acetone as a cleaning agent. Any stuck resin from the previous molding was eliminated.

b. Waxing and Buffing: Once the mould clean, waxing, and buffing procedure was carried out. Waxing involves in wiping the surface of mold with wax material. The surface was left for approximately five (5) minutes to ensure the wax material dry and properly consolidated with mould surface. Then, buffing process was carried out. In buffing process, it involves in removing the dry wax at the surface of mold. It was done using clean cotton-based cloth to prevent any contamination. The process of waxing and buffing was carried out for three (3) times to ensure the proper coating on the mould surface.

2.2.2 Preparation of Prepreg Material

In preparation of the prepreg material, some of the established procedure was followed in order to extend the shelf life of the materials. Prepreg was stored in freezer with storage temperature of -180C as a requirement from material supplier. The following is the procedure in preparing prepreg material.

1. Defrost Process (thawing): Prepreg was removed from the freezer and located at the environmental control room for at least eight (8) hours before executing the next process. In the room, prepreg roll was thawed to eliminate the frost that occurred in storage freezer. Prepreg was thawed at 25^0C with humidity 55 %.

2. Prepreg Sectioning Process: The dry prepreg roll was then sectioned with dimension of 300 mm x 300 mm. In order to achieve at least 2.5 mm composite panel thickness, twelve (12) plies of prepreg were sectioned accordingly. Each sample consists of three (3) specimens where each specimen consists of twelve (12) plies of prepreg sheet. In order to produce five (5) construction, 180 plies of prepreg with 300 mm x 300 mm in dimension was sectioned. Based on ply thickness calculation as below equation, each ply has 0.21 mm thickness.

$$t_{ply} = FAW/\rho V_f \quad (1)$$

where:

t_{ply}	:	is the ply thickness.
FAW	:	is the fibre areal weight.
ρ	:	is the fibre density.
V_f	:	fibre volume fraction

2.2.3 Molding Process

The details sequence of molding process has been discussed further in the following section.

a. Prepreg Laminating (debulking): Prepreg was laminated onto the surface of mould. Backup film was properly removed and the prepreg was stuck onto the mould surface. For the 2nd ply, backup film was removed and stuck onto the laminated 1st ply. This procedure was repeated. At the 3rd ply, laminate was properly bagged and at the top of 3rd laminate, release film, breather and intensifier or caul plate was located to get maximum compaction. Debulking process was done for 3 minutes. After debulking, bag was removed, and the laminating process of 4th ply was executed. The same procedure was done until the 6th ply where the debulking process was executed again. The last debulking process was done at the 10th ply of laminating process.

b. Bagging Process: The established construction of vacuum bagging process was implemented in this research as per recommendation by Cytec Industries Inc. Vacuum bagging construction such as in Figure 2:

2.2.4 Summary of vacuum bagging process

Fabrication of carbon/epoxy composite panel using prepreg. The prepreg was supplied by Cytec Industries Inc. Existing vacuum bagging technique was implemented with various type of vacuum bagging construction followed by curing in oven (figure 3). The curing profile will be as per manufacturer recommendation. Vacuum bagging construction such as in Table 5 with 100 % vacuum integrity.

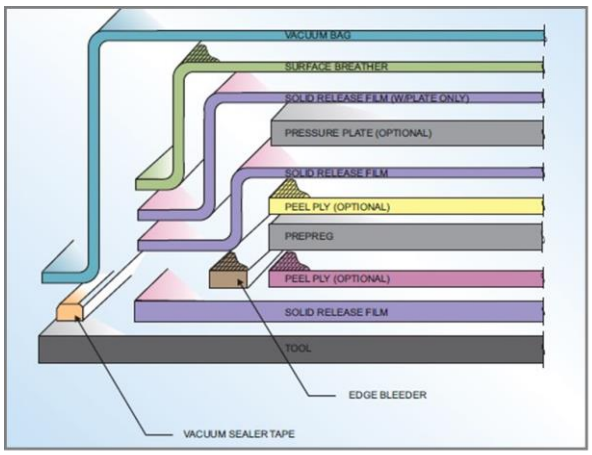


Fig. 2 Typical vacuum bagging construction by Cytec Industries Inc 2021

Fig. 3 Vacuum Bagging Oven Cure (walk-in oven)

Table 5 Bagging Construction for 12 Plies Laminate

Bagging technique	Details
Normal construction of vacuum bagging	no debulking, single vacuum port
Normal construction of vacuum bagging	no debulking, two vacuum ports
Vacuum bagging with two vacuum port	Debulk each 3 plies. Attach PTFE film on the mould surface.
Normal vacuum bagging	No debulking, with caul plate assisted by two vacuum ports.
Normal vacuum bagging	Staggering prepreg layout and assisted by two vacuum ports.

2.3 Testing Procedures

2.3.1 Mechanical testing

The specimens were prepared and tested accordingly to ASTM D3039 for tensile strength with length of 250 mm x 25 mm (width) x 2.5 mm (thickness), ASTM D2344 for ILSS. The ILSS was determined by using a short beam shear test. All of the mechanical tests were conducted by using twin column Universal Testing Machine from Instron (model 5582) with 100 kN load cell and 2 mm/min constant crosshead speed. The micro strain was measured using data logger with attachment of strain gauge specifically for composite materials

from Kyowa. The aluminium end tab was introduced at the tensile and compression test to avoid stress concentrations at the sample during testing was conducted as in figure 4.

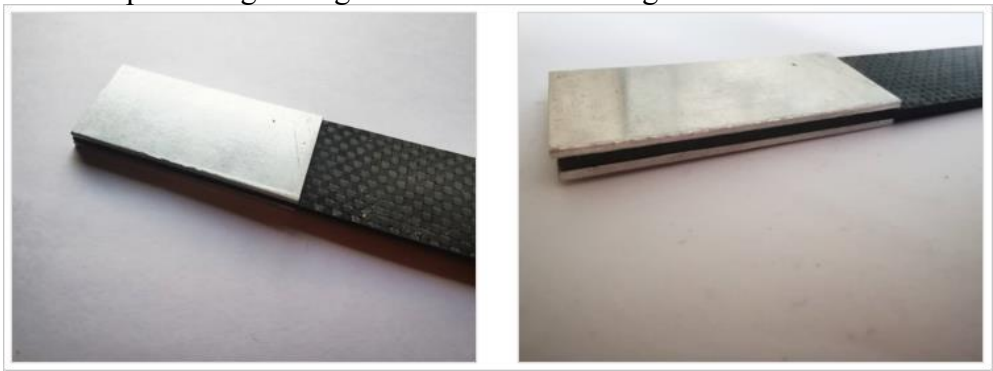


Fig. 4 Aluminium end tab for carbon/epoxy composite tensile test specimen

2.3.2 Interlaminar Shear Strength (ILSS)

ILSS is a measure of the shear strength between the layers of a composite material. Shear properties of composite materials are investigated using short beam shear tests, Similar to flexural testing methods (three-point bending), short beam shear tests bend a beam, but the beam is shorter than its thickness. According to ASTM D2344, the test involves placing a rectangular specimen on two fixed distance supports (span length). As a result of its geometry, the specimen has a low span-to-thickness ratio. The ILSS value is calculated by dividing the maximum load at failure by the cross-sectional area of the specimen. It is important to consider ILSS when designing composite structures to prevent delamination between layers.

$$ILSS = 0.75(\frac{P_m}{bh}) \quad (2)$$

where:

ILSS : interlaminar shear strength.

P_m : maximum load observed during the test,N.

b : measured specimen width, mm

h : measured specimen thickness, mm

2.3.3 Tensile Test

In summary, ASTM D3039 is a standard test method for determining the tensile properties of fibre-reinforced composites. Specimen is pulled and analysed for reaction to the force. The test requires specific equipment which known as universal testing machine with specimen geometry (figure 5) and test procedure according to ASTM D3039.

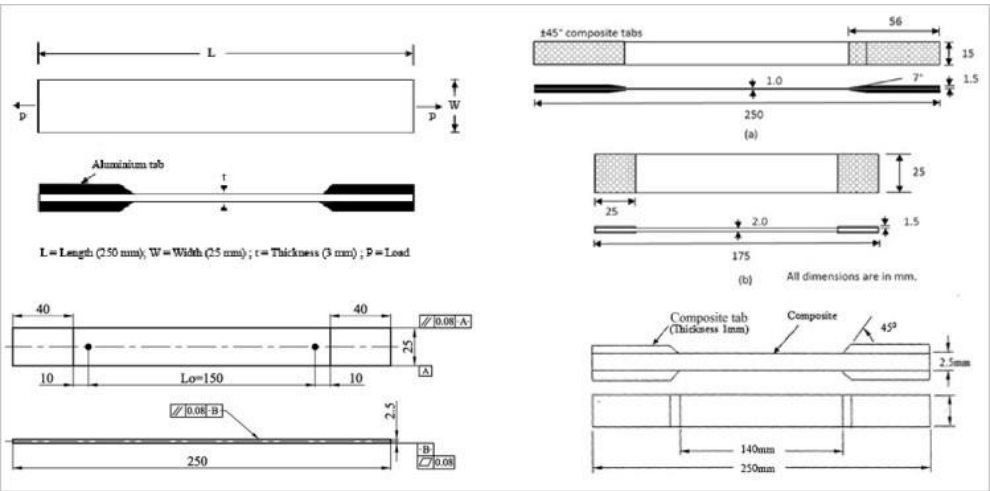


Fig. 5 Composite tensile test specimens according to ASTM D 3039

2.4 Physical testing

2.4.1 Void Volume

Void volume fraction describes how much empty space or voids are present in carbon/epoxy composites. This term refers to the number of voids in carbon/epoxy composites. The void volume fraction can be calculated using the Archimedes Theoretical versus Actual Density technique, which involves determining the actual density of the sample by weighing it in air and then while submerged in water [18]. It is worth noting that void content levels as high as 6% are often acceptable in some applications, such as ground vehicle components and secondary structural members [15]. However, the presence of voids can significantly affect the mechanical properties of the composite material [19]. In order to calculate void content, test method A in ASTM
D2734-94(2003) was used accordingly as below equation

$$V = 100(T_d - M_d)T_d, \quad (3)$$

Where:

V : is the void content, %.
T_d : is the theoretical density, g/cm^3.
M_d : is the measured density, g/cm^3.

Theoretical density was calculated using the following equation as per ASTM D2734-94(2003).

$$T_d = 100/(\frac{R}{D} + \frac{r}{d}), \quad (4)$$

Where:

V : is the void content, %.
R : is the weight of resin, %.
D : is the density of resin, g/cm^3.
r : is the weight of reinforcement, %.
d : is the density of reinforcement, g/cm^3.

2.5 Non-destructive testing (NDT)

The ultrasonic inspection of the panels was made by applying the Pulse-Echo method. A $\frac{1}{4}$" diameter single crystal pulse-receiver flat transducer of 2.25 MHz from Panametrics was used and the inspection was made with the specimens immersed in distilled water. The ultrasonic device used is Ultrapac II system (automated immersion system), in association with Ultrawin software for data acquisition, control and imaging. The distance between the transducer and the material (water path) was set at the end of the near field value of the transducer used (which is 33.2 mm), in order to avoid the fluctuation of the acoustic pressure which takes place into the near field zone. A glass plate, on which the specimens were placed, was used as a reflective plane, in order to distinguish the back wall echo from any other one.

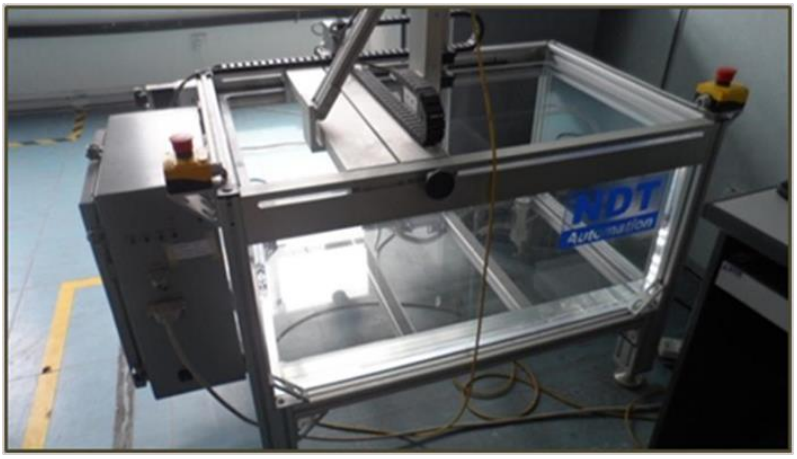


Fig. 6 Ultrasonic C-Scan System for NDT

3 Result and Discussion

The summary of the average tensile, ILSS and void properties determined for all of the tested carbon/epoxy composite materials are shown in the table below.

Table 6 Summary of overall results

Sample ID	Void, %	Tensile σ (MPa)	Tensile Modulus (GPa)	ILSS(MPa)
A1 (C/E & G/E)	6.5/12.1	227.01/179.34	66.78/28.68	18.76/10.14
A2 (C/E & G/E)	13.4/18.4	209.13/163.24	55.17/26.17	14.17/7.65
A3 (C/E & G/E)	4.3/10.9	324.91/187.42	57.12/31.22	28.02/20.67
A4 (C/E & G/E)	19.7/23.1	217.07/160.19	63.27/27.58	17.76/8.77
A5 (C/E & G/E)	8.6/15.3	231.64/178.64	67.34/28.96	22.57/12.81

*C/E is Carbon/Epoxy and G/E is Glass/Epoxy

3.1 Tensile properties

Figure 7 and 8 clearly illustrates the tensile properties in terms of tensile strength and modulus for the various carbon/epoxy composite fabricated using different bagging construction as stated previously in table 1 and 5. Sample A3 which implemented the bagging technique of debulking each 3 plies with introduction of single vacuum port and the presence of polytetrafluoroethylene (PTFE) at mould surface has recorded the highest tensile strength with the value of 324.91 MPa and 187.42 MPa for glass/epoxy sample.

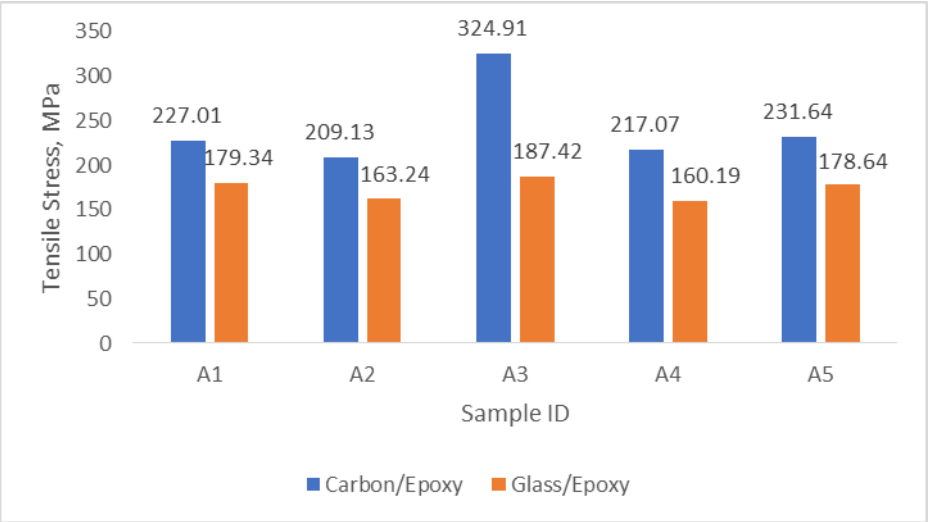


Fig. 7 Comparison of tensile strength

The presence of PTFE is believed to improve the quality of composite products especially in enhancing the surface quality [20]. The void content recorded for this sample is the lowest among others which is 4.3 % for carbon/epoxy and 10.9 % for glass/epoxy sample. A void in carbon/epoxy composites can reduce the ultimate fibre failure force, the dissipated energy, and the interlaminar shear strength and flexural strength [21][22][23][24][25][26]. To accurately analyze the effect of voids on composite performance, researchers use various techniques, including X-ray micro-computed tomography (micro-CT) and the Archimedes technique [18][27]. Studies have shown that the effect of voids is more severe in the transverse direction of carbon/epoxy composites [28]. The mechanical properties of carbon fibre epoxy composites are influenced by the presence of voids due to the method of manufacturing of the composite itself. Voids also affected the result of tensile modulus as well where A5 recorded the highest of tensile modulus at 67.34 GPa for carbon/epoxy and 31.22 GPa for glass/epoxy which occurred at sample A3. Referring to the results of tensile testing, there are significant changes in terms of stress and modulus involving samples A1 and A5 due to different vacuum bagging methods. In A4 sample, introduction of intensifier (caul plate) and assisted by two (2) vacuum source (ports). This kind of bagging construction produced porous surface as in figure 9 and 10. Without presence of PTFE film on the mold surface, it clearly effected the surface of the composite sample as shown in figure 9 and 10. Besides that, the effect of prepreg fibre architecture to explore the possibility that surface porosity might stem from air trapped at the tool-prepreg interface during layup [29]. The effect of surface porosity also affects the overall strength of the sample. There are no significant changes among carbon/epoxy sample where the Chord modulus is ranging from 55 GPa to 67 GPa, while glass/epoxy is between 26 GPa to 31 GPa. Sample A1 and A5 have significant differences in terms of tensile strength and modulus compared to the samples that prepared with the presence of single vacuum port and staggering assisted by two vacuum ports. For sample A2 and A4, the introduction of two vacuum source strategy and assisted by caul plate was not successful in producing high quality sample.

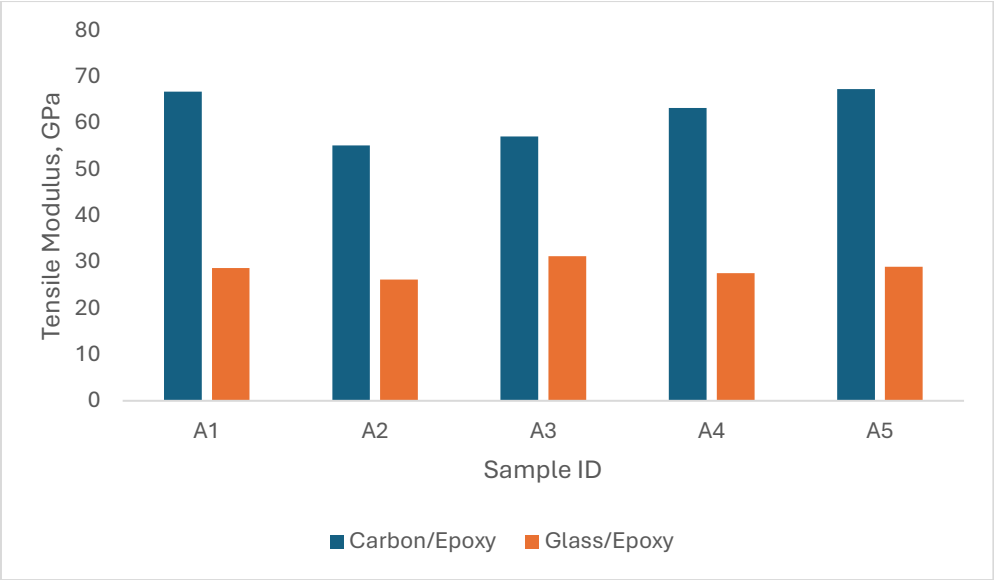


Fig. 8 Comparison of tensile modulus (Chord Modulus)

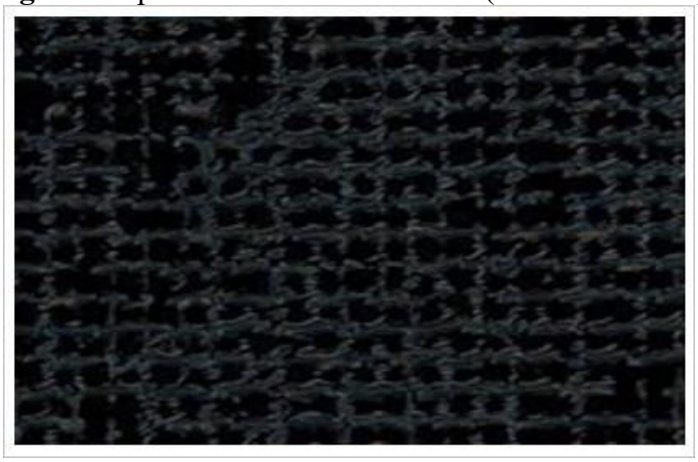


Fig. 9 Surface appearance of sample A3

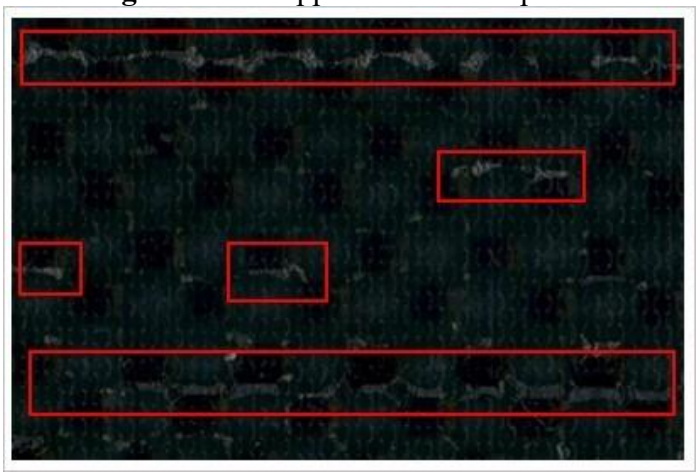


Fig. 10 Surface appearance of sample A4

Using this particular laminate construction (staggering), it produced a wrinkle resin area on top of the sample as in figure 8. From tensile test, it recorded the lowest stress which is about 209.13 MPa while modulus is 55.17 GPa for carbon/epoxy sample and sample A2 and A4 for glass/epoxy sample recorded the similar (low) and without significant changes in stress and modulus. The formation of ply wrinkles due to shear between plies and normally, the presence of wrinkles also coincides with in-plane misalignment in 0^0 plies of up to 50^0 [30]. Defects, such as in-plane waviness and out-of-plane tow wrinkles, cause significant reductions in the mechanical performance of RTM manufactured composite parts based on woven preforms as highlighted by

Lightfoot J. et al. [30]. If layers can slip over one another the additional length can be accommodated by producing so called 'bookends', but if the resistance to slip is too high, layers may form wrinkles [31]. Introduction of staggering laminating technique with no debulking was done and assisted by two (2) vacuum source as for A5 sample was not also producing a good sample [32][33][34][35][36] compared to A3 sample. It recorded the stress which is 231.64 MPa and 67.34 GPa tensile modulus for carbon/epoxy and 178.64 MPa, 28.96 GPa for glass/epoxy sample. Figure 9 clearly shows the dry spots on the surface occurred transversely along the A1, A2 and A4 sample. Since the tensile test was conducted longitudinally along the sample, the dry spot was considered as a significant defect which led in weaken the overall strength for sample A2 for both samples. Thus, it produced a non-comparable result to A1, A2 and A5 samples. Dependency of the location initiation either from interface of fiber/matrix or voids on strain rate as well as temperature, higher macroscopic fracture strain for model with voids [22]. As reported by Olivier P. et al., a reduction in longitudinal tensile strength with voids will decrease approximately 10 % with 10% increment in void content [26]. Another study from Sergio Frascino et al. stated that if 2.5 % increment in void content, the overall tensile strength will reduce approximately up to 15 % [37]. From the overall tensile strength result, there is about 25 % strength reduction compared to A5 (highest) and A3 (lowest) sample. The chord modulus is the slope of the chord drawn between any two specified points on the stress-strain curve in figure 11 as an example. In this measurement, strain gauge with 6 mm gauge length (figure 13) was used to produce the micro strain data (figure 11). From the equation y=65.392x0.0181, the slope, '**m**' with value of 65.392 is the chord modulus of elasticity. The chord modulus of this particular specimen is 65.39 GPa

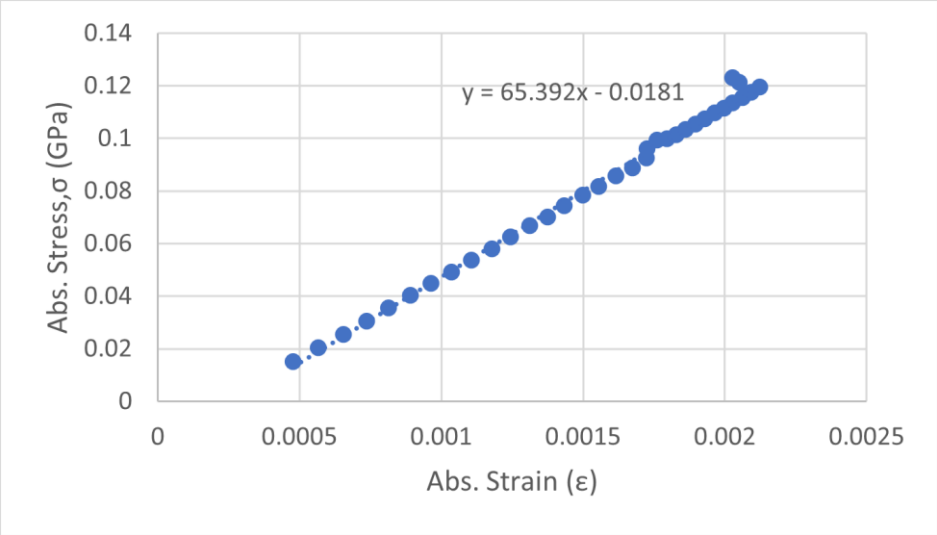


Fig. 11 Example of chord modulus determination for specimen A1

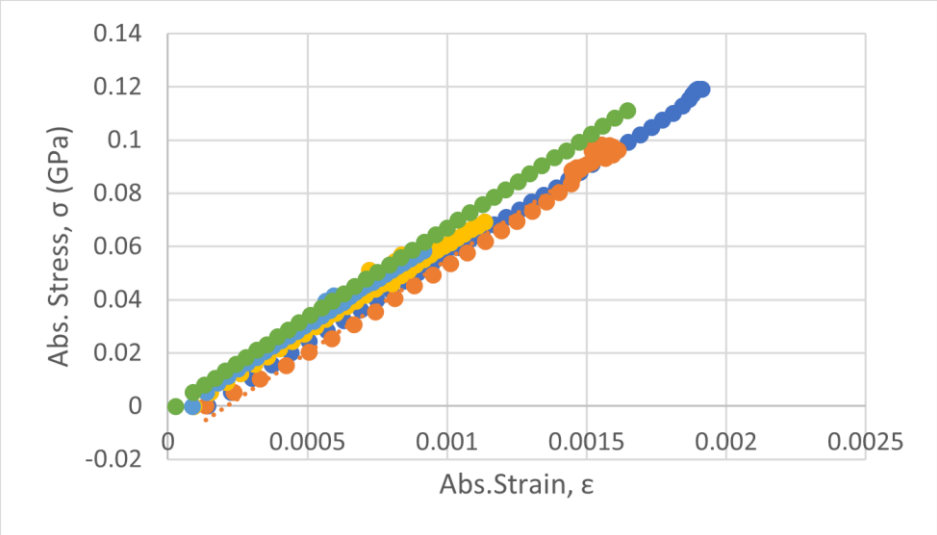


Fig. 12 abs. stress vs abs. strain graph for sample A

Fig. 13 Tensile test specimen with strain gauge attachment

The chord modulus of elasticity was calculated using stress-strain data using the below equation as in ASTM D3039.

$$E^{chord} = \triangle\sigma/\triangle\epsilon, \quad (5)$$

Where:

E^{chord} : is the tensile Chord modulus of elasticity, GPa.
$\triangle\sigma$: is the difference in applied stress between two strain points, MPa.
$\triangle\epsilon$: is the difference between two strain points.

From the tensile test conducted, A5 has the highest modulus among others sample. Due to defect occurred in sample A2, there is significant impact on the chord modulus of elasticity for both samples with range of 55.17 GPa (carbon/epoxy) to 26.17 GPa (glass/epoxy) as stated in table 6 as well as it reflects the result of ILSS. During testing, crack was initiated from long voids in high void content specimens [38][39]. The most significant difference between the tested samples is the use of PTFE as the initiator layer located on top of mold surface for sample A3. Sample preparation A1, A2, A4 and A5 does not use a PTFE layer on the surface of the mould which produces a porous surface (wrinkle and dry spot) as in figure 10a and 10b which resulted in a significant decrease in its overall modulus value. D.V. Bachurin stated that the elastic modulus and yield strength are decreased by voids [40]. Tensile, shear, flexural and compressive properties have also been proven to decrease with increasing void content [41]. Therefore, composite materials should be manufactured towards minimum void content by optimizing manufacturing techniques

3.2 Interlaminar Shear Strength (ILSS)

Carbon/epoxy composites can have significantly different interlaminar shear strength when voids are present. According to studies done by Hong-Yan Zhu et al. 2009, carbon/epoxy fabric laminates with a high void content have decreased interlaminar shear strength by about 34 % [39]. The effect of voids on the mechanical properties of composite laminates is influenced by many factors, such as void shape, size, and location [39]. Studies of unidirectional graphite-fibre-reinforced composites have shown that voids have a significant impact on interlaminar shear strength of polyimide matrix composites [42][43]. In addition, the study revealed that accurately quantifying the strength drop-off proved difficult, and the strength drop-off recorded for interlaminar shear was 9.7 % [15]. With a two (2) percent increase in void content, interlaminar shear strength and flexural strength will decrease by approximately 20 percent. Flexural modulus will decrease by approximately 10 percent as mentioned by Ghiorse, S.R. [15]. Increasing void content decreases interlaminar shear fatigue life, and static failure is more affected by voids than fatigue [44]. From the ILSS results, it clearly shows that the presence of void significantly affects the interlaminar shear strength. Sample A2 recorded the

lowest ILSS for both samples at 14.17 MPa – carbon/epoxy and 7.65 MPa – glass/epoxy. The interlaminar shear strength values for A4 lower as the higher void content occurred at 19.7 % for carbon/epoxy and 23.1 % for glass/epoxy. In the presence of voids, interlaminar shear strengths may be reduced, and it is difficult to quantify this strength loss accurately [45]. Interlaminar failure in carbon/epoxy composites can occur due to various mechanisms, including:

1. Fiber/matrix interface debonding: Essentially, this occurs when the bond between fibers and matrix is broken, resulting in the separation of the two materials [46]. The result of ILSS shows that with less void content inside the specimens, it will produce a high ILSS. Sample A3 has the highest ILSS as value of 28.02 MPa for carbon/epoxy and 20.67 MPa for glass/epoxy has been recorded.

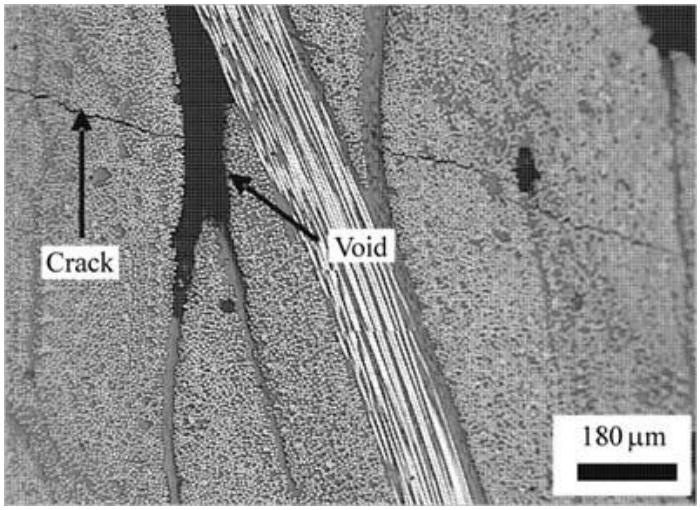


Fig. 14 Micrograph of failure of carbon/epoxy composite laminate [44]

Figure 14 clearly shows the air trapped (void) in the composite laminate as studied by Zhu Hongyan et al. The presence of void, naturally provide fibre and matrix debonding zone before testing was conducted.

2. Matrix cracking: Impact loading in composite panels can lead to matrix cracking, which can eventually lead to interlaminar failure [47]. The ILSS result arrangement from the lowest to highest value of ILSS shown in figure 15. It clearly shows that with the application of 2 vacuum ports and introduction of the intensifier (caul plate) produced a high void content sample/specimen for sample A4. If PTFE film is present for both samples, the vacuum bagging process can be improved by reducing friction between the composite and the vacuum bagging film [48][49] and it has been proved in sample A3. Consequently, the resin can flow more easily and uniformly throughout the composite because of the reduction in friction. In this experiment, the strategy of debulking, normal bagging construction (figure 2), two vacuum source and the addition of PTFE film on the mold surface can reduce/produce carbon/epoxy composite laminates that have the lowest void content and produce high mechanical strength compared to other samples.

3. Fiber breakage: For higher impact energies, interlaminar failure can occur due to fiber breakage [47]. Void content determines the strength of the bond between fibre and matrix. If the void content is high, there is no solid contact between the fiber and the matrix. Load cannot be transferred to the entire fiber length which eventually results in matrix crack followed by the phenomenon of fiber breakage.

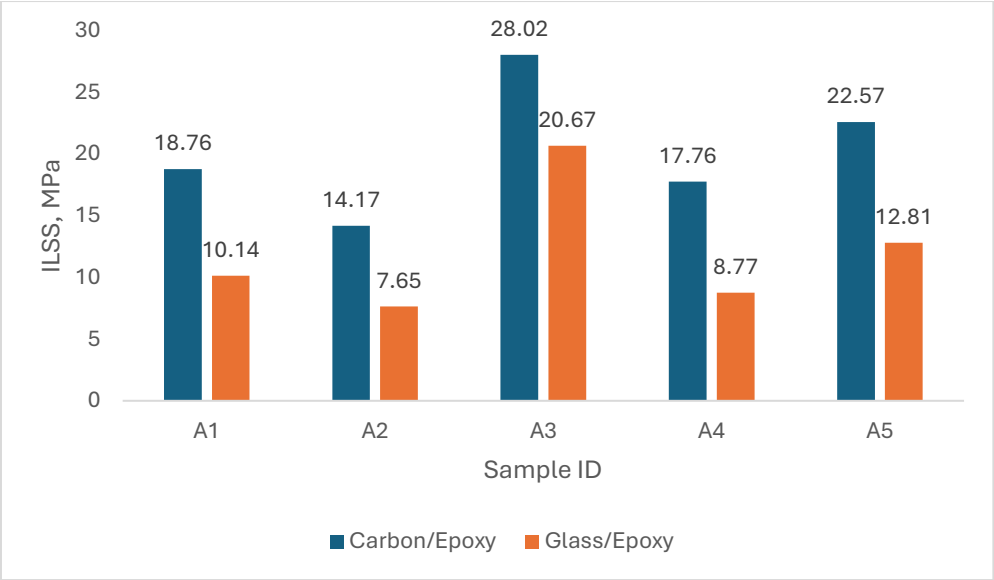


Fig. 15 Comparison of ILSS

Sample A3 was prepared by using PTFE on the mould surface with debulking for each 3 plies. As shown in table 6, PTFE film is believed to help produce samples with less void content (less than 7 %). In addition, this low void content has improved the results of other mechanical tests including the ILSS. The techniques of debulking, assisted by two (2) vacuum source produced a specimen/sample with high void content as in A2 and A4 for both carbon and glass/epoxy samples. Since the location of the vacuum ports were located on top of the bagged specimen, it believed that higher resistant for matrix to flow during vacuum bagging process which causes air to be trapped during the process.

4. Large scale fiber bridging: This acts as an important toughening mechanism in carbon fibre reinforced polymers (CFRPs) and can dominate the fracture of CFRPs [50]. The presence of void influence the fibre/matrix interface. The higher void volume, the more fiber bridging occurs.

5. Multiaxial states of stress: Matrix failure in carbon/epoxy composites is influenced by multi axial states of stress [45].

In summary, interlaminar failure in carbon/epoxy composites can occur due to various mechanisms, including fiber/matrix interface debonding, matrix cracking, fibre breakage, large scale fiber bridging, cohesive failure, and multi axial states of stress. The toughening mechanisms in CFRPs, such as large-scale fiber bridging, can play an important role in preventing interlaminar failure. In the presence of voids, interlaminar shear strength values can decrease, and it can be challenging to quantify the strength loss. Regardless of the loading method, the void content of composite materials is an important aspect of quality control.

3.3 Void content

From void measurement as in figure 16 and Table 6, it shows that sample A3 has the lowest void content for both carbon and glass/epoxy sample. The maximum value of void was occurred at sample A4. As stated by Ghiorse,1991, void content levels as high as 6% are often acceptable in some applications, such as ground vehicle components and secondary structural members which is non highly structural applications. According to ASTM D2734-94 [51], the void content should not be above 1 % which is suitable for highly structural applications such as in the aerospace industry. From figure 16, A4 contributes highest void content among others with value of 19.7 % for carbon/epoxy and 23.1 % for glass/epoxy followed by samples A2 at 13.4 % for carbon/epoxy and 18.4 % for glass/epoxy. The minimum void content recorded is for sample A3 with value of 4.3 % for carbon/epoxy and 10.9 % for glass/epoxy, A1 at 6.5 % - carbon/epoxy and 12.1 % - glass/epoxy and A2 contributes second highest about 13.4 % for carbon/epoxy and 18.4 % for glass/epoxy. It can be concluded that none of the samples meet the requirements for highly structural applications as enforced by ASTM D2734-94 which requires less than 1 % void content. In summary, air entrapment during vacuum bagging of carbon/epoxy composites can occur due to various reasons, including high viscosity of the resin,

insufficient vacuum pressure [51], poor compaction of the composite [52][53], bubble elongation, and high fibre volume fraction where prepreg with initially high states of resin impregnation will often fail to draw bubbles into air pathways through the centre of fibre tow cross-sections as shown in previous figure 10 and leading to air entrapment [54]. To prevent air entrapment, it is essential to ensure that the vacuum pressure is sufficient, the composite is properly compacted, and the resin viscosity is appropriate for the process. In this work, it can be discussed that with excess resin will produce a lower percentage of void inside the laminate. There are two reasons that promotes the formation of void as the pressure decreases the resin can outgas during cure. In addition, if some voids are already present in the laminate, their size will increase as the local resin pressure decreases as stated by S. Bickerton et.al, 2011. Referring to Ghiorse,1991 statement, sample A3 carbon/epoxy is meeting the requirements for specific use as stated with void content below 6 %, while all of the glass/epoxy samples are not meeting the requirement. Therefore, it is also very suitable (A3 Carbon/Epoxy) to be used as a backing plate in the manufacture of battery packs. However, for its use as a battery pack, it needs to be referred to the relevant standard for that purpose. Additional characterization related to the suitability of carbon/epoxy composite as a backup structure for battery pack should be carried out such as its conductivity rate (carbon is conductive) without leaving its strength quality.

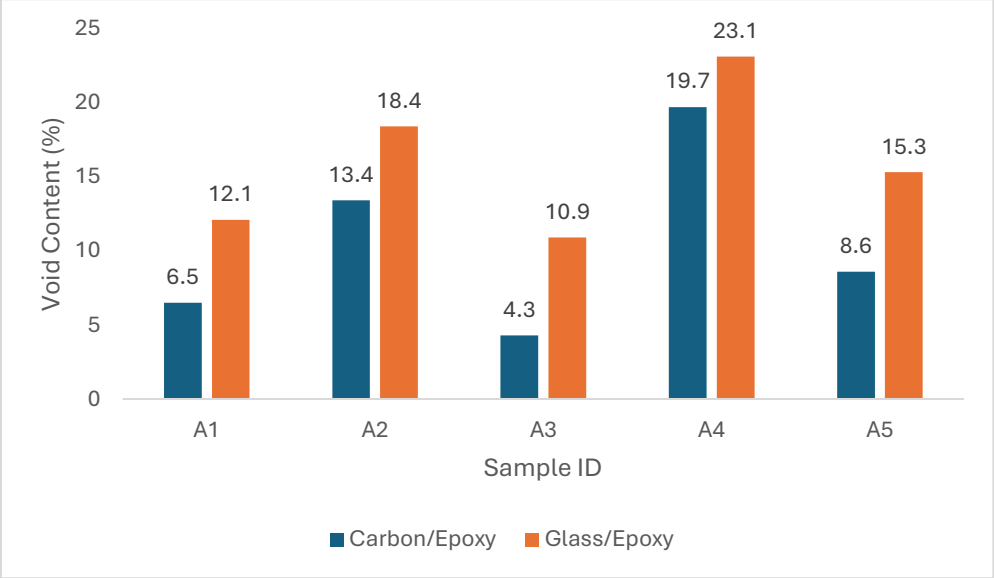


Fig. 16 Comparison of void content

3.4 Ultrasonic C-Scan

From the analysis done it is found that these colour changes in C-scan images correspond to real defects mainly surface porosity, voids (macro void which resulting from entrapped air in dry region), region of fiber kinking which produced high resin flow activities and resulted in producing dry spots or resin-rich region that normally occurred at the top of final ply for all samples and become worst without the use of PTFE film on the mold surface during fabrication process. In this experiment, it has been found that, traditional bagging methods are still relevant in producing a good quality samples as shown in the results of sample A1, A3 and A5. The staggering layup construction purposely is to help resin to flow with any obstacle from each ply of the laminate as well as to minimize/eliminate the formation of void that will result in delamination of the sample as for sample A5. Sample A4 was not subjected to the debulking process. It only involved in the application of intensifier (caul plate) on top of the laminate (after release/peel ply) and consolidated using 2 vacuum system. As a result, it consistently produces a dry spot where signal penetration is zero (figure 9) for both carbon/epoxy and glass/epoxy samples. Refer to figure 17 and 18, sample A3 was subjected to debulking, and the presence of PTFE film on top of mould surface to improve the resin flow during curing process. There is improvement in the signal penetration where most of the area in carbon/epoxy produced 100 % penetration as indicates in red colour. While for glass/epoxy samples, all samples show the same results (almost same) with signal penetration rates between 60 – 100 % as depicted in yellow to red. Using this bagging technique, the resin did not have time to flow to the breather ply and resulted in the formation of wrinkles from the cured resin between the woven (0^0 and 90^0) as in figure 10a. Most of the glass/epoxy samples as in figure 18

produced similar C-scan image where the signal penetration occurred between 60 % to 100 %. Although imaging using ultrasonic C-scan for carbon/epoxy samples A1, A2 and A4 as well as glass/epoxy samples was carried out and produced an unclean image, by performing supporting tests such as mechanical evaluation and void measurement it can prove that defects mostly occur on the surface of the sample.

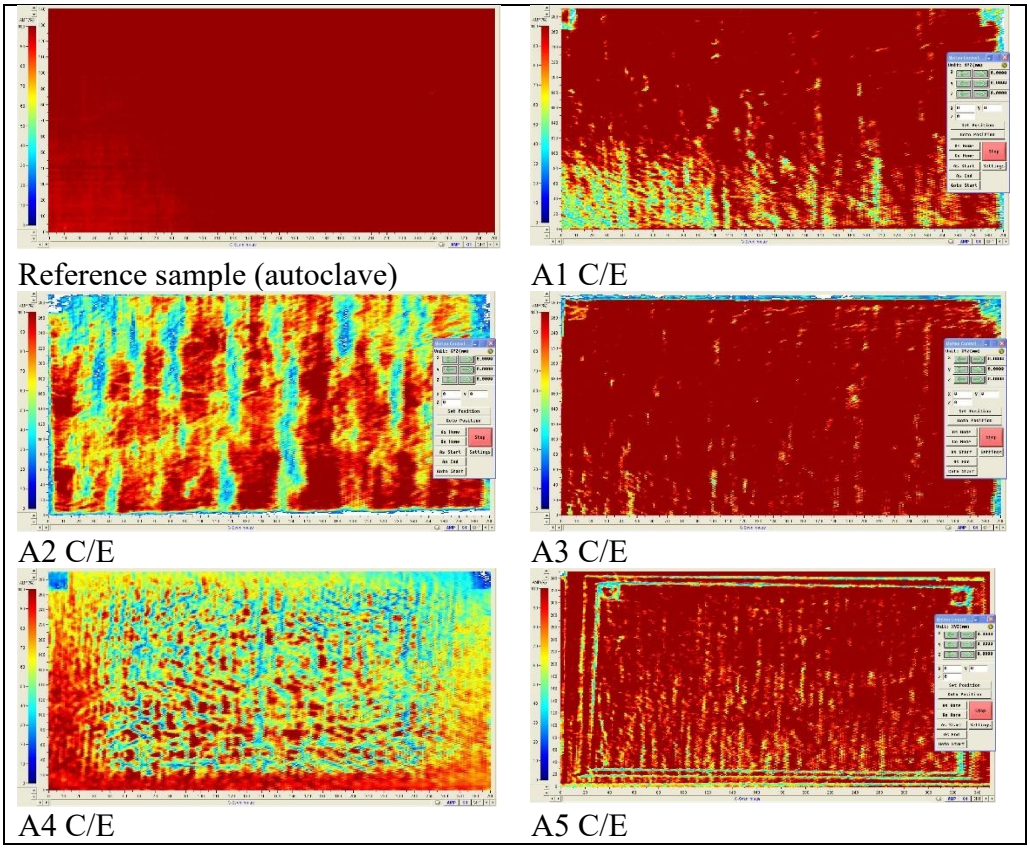
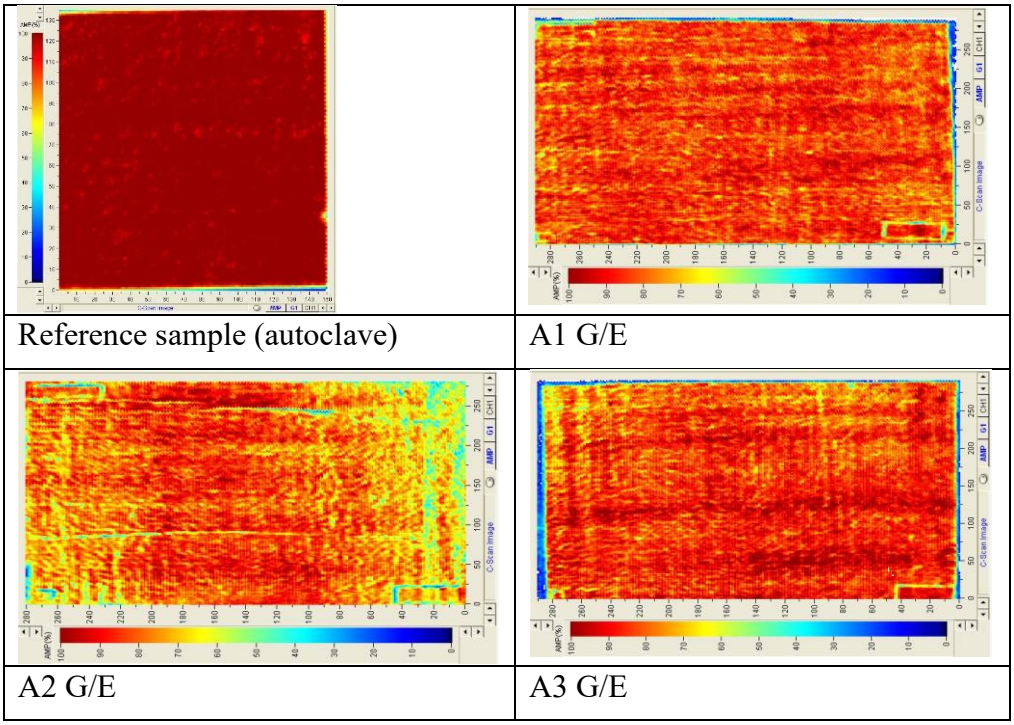
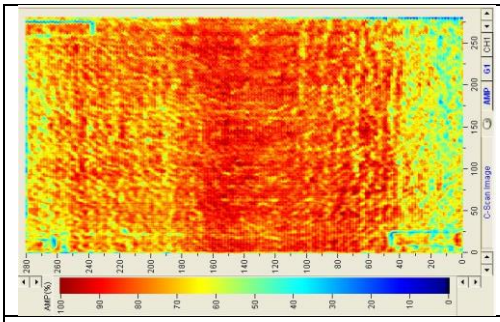
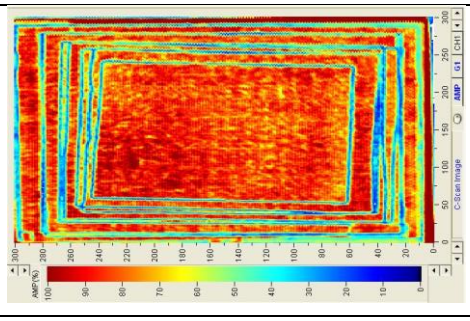


Fig. 17 C-Scan images for carbon/epoxy sample





A4 G/E



A5 G/E

Fig. 17 C-scan images for each sample

4 Conclusion

Samples A3 from carbon/epoxy sample is meeting the requirements for specific use as stated with void content below 6 %. Therefore, it is also very suitable to be used as a structure in the manufacture of battery packs compartment for EV application. A non-destructive inspection may not be sufficient to identify the defect type. The usage of 2 vacuum ports are not promising in enhancing the overall quality of the composite panel. Most of the sample subjected to 2 vacuum sources tend to produce dry spots and resin wrinkle in composite laminate where it will definitely reduce the properties of the composite, especially in strength. Debulking procedure in prepreg material can enhance the flow of resin during fabrication in order to produce a better quality of the composite product. Usage of PTFE film on top of mould surface also will assist in resin flow that resulted in producing a smooth surface composite product without porous surface. Most of the porosity on surface occurred at the junction of weaving which is at the junction of 0^0 and 90^0. In conclusion, it appears that for this particular materials, pulse echo ultrasonic inspection and defect classification for part acceptance may not be applied without any destructive test. It requires further study especially involving the construction method of vacuum bagging or additional requirements (supporting tools, materials and etc) needed during the manufacturing process. Further, it is necessary to study the effectiveness of the epoxy resin used in this prepreg system, particularly its rheological properties against temperature as a method of simulating composite manufacturing. For time being, glass/epoxy is not suitable for making a structure for the battery pack due to its properties which are highly insulative materials and low thermal conductivity compared to carbon/epoxy which is not an ideal environment for battery storage medium.

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