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Experimental and Numerical Study of Energy Absorption Behaviour of Glass and Carbon Epoxy Composite Tubes under Static Compressive Loading

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***Abstract**: Compression test on glass and carbon fiber epoxy composites tubes were conducted. Effect of tube thickness and fiber type on the load - displacement behavior as well as energy absorption of composites tubes has been investigated. All these parameters found to be effective on the load-displacement behavior and energy absorption capacity of composite tubes. Results obtained from the study shows that, carbon epoxy stands higher load and energy absorption capability than glass epoxy. To simulate the behavior of composite tubes ABAQUS Finite Element Software package was used. Elastic orthotropic material model along with a Hashin Damage model was employed to simulate the load-displacement relations of carbon and glass composite tubes. FE predicted and experimental load displacement curves matched well up to the first failure of the tubes. The FE predicted and experimentally obtained maximum loads were very close. However the FE predicted behavior after the first failure zone deviated from experimental results. The level of deviation was different for each case. Hence FE predicted and experimental energy absorption was not the same.*
***Keywords**: Energy absorption, carbon fiber, glass fiber, composite tubes, Finite element analysis*

I. Introduction

It is important to understand energy absorption behavior of materials especially composite materials because of it's advantages in many industries due to safety reasons. The most commonly used energy absorbers in the automotive industry are manufactured from steel, which are used as bumpers in the front of vehicles. Their aim is to absorb energy in the event of an accident. Though, the material fails in a folding manner.

Energy absorption has been a topic of great interest for engineers and scientists over the years, due to its advantages in improving vehicle crashworthiness and also used for high way safety. Crash worthiness defined as the resistance of vehicle to protect its occupants from serious injury or death in an accident; therefore it counts as essential parameters for vehicle and aircrafts due to its importance [1]. Crashworthiness can be significantly improved by the use of composite energy absorber. Extensive research about energy absorbing properties of composite tubes has shown that, under appropriate condition and with the correct design, composite material can offer substantial performance over the equivalent metallic structure. The way they absorb energy with a constant crush load is in line with the ideal deceleration curve while metals fail by plastic buckling which causes oscillation of the crush load [2].

Many researchers have been investigated crushing behavior and energy absorbing capability of composite tubes of circular, cylindrical, and rectangular shape. S. H. Lee and Anthony M. Waas [3] investigated the compressive response and fracture characteristics of glass fiber and carbon fiber reinforced unidirectional composite experimentally. The carbon fiber composite was seen to have a lower compressive strength than the glass fiber composites. The conclusion drawn from the studies is that, the carbon fiber composite demonstrated higher stiffness than the glass fiber composite. Stanislaw Ochelski and PawelGotowicki [4], in their experimental study, found that the higher energy absorption value is caused by mechanical properties of epoxy reinforced with carbon fibers. It is concluded that the parameters that influence the crushing and bending during the tests are reinforcing fiber, orientation angle of the fiber, fiber content in the composites, number of layers and stacking sequence. SivakumarPalanivelu*et al* [5] studied the energy absorption behavior of glass polyester composite tube with square, circular, and hexagonal cross sectional shapes with thickness of 2mm. The results obtained indicated that, circular tubes stand highest energy absorption and followed by hexagonal and then square tubes. However, finite element model was an effective and economic method for simulating damage and failure of composite materials. Very limited finite element analysis has been done regarding the energy absorption behavior of composite tubes. For instance, F. Mustapha and N. W. Sim [6] in their investigation concluded that, there is a good agreement between the experimental and FEA throughout the loading process and also observed that, one percent error is estimated for the peak load between the experiment and failure used to simulate progressive damage. Ping Zhang *et al* [7] the numerical results were in good agreement with quasi static axial crushing tests and also energy absorbing property and failure showed a similar trend with experimental. Rizal Zahari [8] he validated the reliability of numerical analysis against results obtained quasi static compression test, which confirms the accuracy of the progressive failure methodology. The present paper used ABAQUS as a numerical tools using progressive damage methodology based on Hashin's failure criterion in order to compared the results with experimental.

II. Material and Experimental Procedure

In this study materials required were: E-Glass FWR6-1200 glass fiber and A-38 carbon fiber as reinforcing fibers. Hexion L285 Epoxy and H287 Hardener are used as matrix materials. Peel-ply material between composite and bleeder was used. The removal of excess resin was done using bleeder. Aluminum 6063 tubes with different diameters were used as mandrel. Ren mold-release agent between mandrel and composite was applied before manufacturing. Cylindrical tubes of composite are manufactured using filament winding method. There were six composite tubes in total. The size of the tubes has been selected with a length of 1000 mm and diameters of 25 mm, 30 mm and 35 mm respectively. The tubes were manufactured at a two axial computer controlled filament winding machine which required the use of software to generate a machine path. Maximum winding diameter of the machine was 610 mm and the maximum winding length was 4000 mm. The system was capable of utilizing winding angles from 0° to 90° and it's carriages receives a fiber from one creels. The machine can carry a mandrel of maximum 227 kg. The filament winding machine is given in Fig.2**.** Cylindrical tubes of composite are manufacture using filament winding method. Initially ren release was rubbed on the Aluminum 6063 surface three times at the interval of 20 min, for easy removal of manufactured composite tubes. Then the Aluminum tubes were placed and gripped on the filament winding machine.

Figure 1: Filament Winding Machine

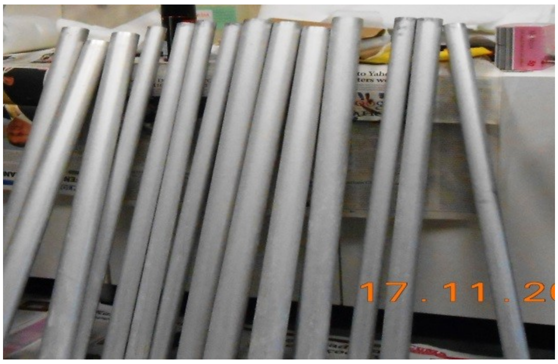
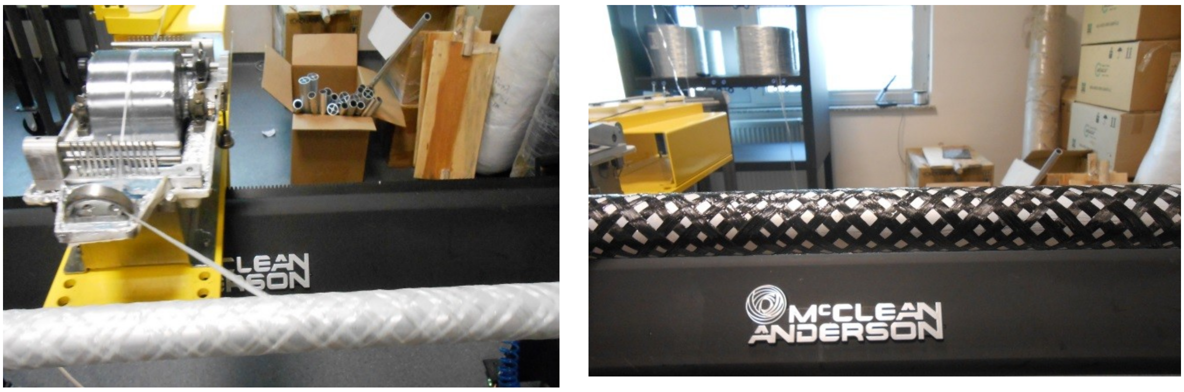


Figure 2: Treated Aluminum Surfaces

2.1 Fabrication of Composite Test Specimen

The tubes were manufactured by using an epoxy resin system with two different fiber types of glass and carbon. For both glass and carbon three different mandrel diameters (25 mm, 30 mmand 35 mm) and the winding angle of 45° were selected. The mandrel is supported horizontally between a head and a tail stroke. The tail stroke is driven by required angle and speed using computer program. As the mandrel rotates, a carriage moves along the mandrel and give a fiber with a given position and tension. Carriage motion is controlled by the computer. Fig. 2 (a) and (b), represent the process of manufacturing composite tubes using filament winding process.



(a) Glass epoxy (b) Carbon epoxy

Figure 3: Manufacturing Process of Glass Epoxy and Carbon Epoxy

Fiber passed through a resin bath and get wet before winding operation. The amount of resin was reduced with a blade which was attached on the resin bath. Once the composite tubes are manufactured, a blanket and Teflon were wrapped on the tubes and tighten it with the plastic tape in order to absorb the excess resin. Manufactured tubes were kept in room temperature for 48 hours and then placed in the furnace for curing. Curing operation was carried out at 60℃ for 15 hours.

2.2Test Procedure

Computer controlled Instron-43 Universal testing machine was used for compression test with a load capacity of 50 KN. The test rate was adjusted to 0.1mm/s. The tests were conducted in room temperature. Composite tubes were compressed between two parallel grips. While the upper grip was moving the lower one was stationary. The fixed grip was fitted with a load cell from which the load signal, crosshead displacement and time were stored in the computer. In each test the load was assigned as the Y-axis and the crosshead displacement as X-axis. For all composites compression tests, progressive crushing occurred.

III. Finite Element Analysis

The 3-D finite element analyses of compression behavior of composite tubes weremodeled using Abaqus, a commercial finite element modeling (FEM) software. The computer models developed for this study consisted of multiple unidirectional fiber lamina stacked in various orientations.The element chosen was S4R, 4 nodes doubly curve thin or thick shell, with reduced integration, hourglass control, and finite membrane strains. The numerical analysis was performed by considering the experimental test parameters. The material properties of the composites were obtained from previous research study conducted by our research team [9]. During finite element modeling; strength values obtained from previous research were reduced match experimental results. This could be due to the fact that strength values of flat tensile specimens reported in previous study does not well represent the strength values of filament wound composite tubes. However elastic constants were the same. The geometric irregularities observed on the surface of the tubes may result in strength reduction.The composite tube was meshed with approximate global size of 2.5 mm, element deletion turned on and maximum degradation was selected as 0.99. The mesh and boundary condition are presented in Fig. (4) and (5) respectively.

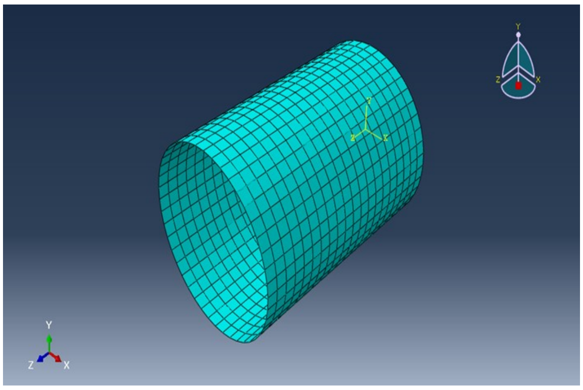


Figure 4: Mesh and geometry of glass epoxy tubes

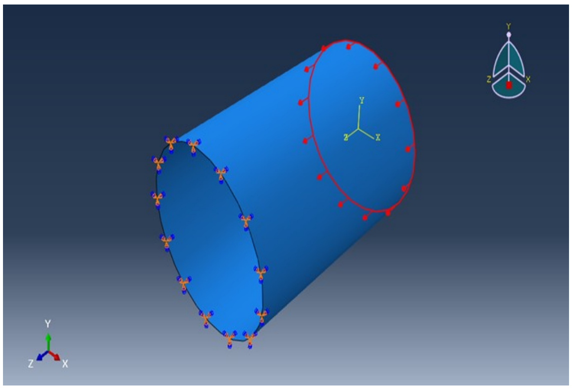


Figure 5: Boundary condition applied to glass/epoxy

Table 1: Glass/epoxy and Carbon/epoxy material properties

Symbol	Meaning	Glass/epoxy	Carbon/epoxy
E_1	Young's modulus along fiber direction 1 (MPa)	21040	34770
E_2	Young's modulus along fiber direction 2 (MPa)	6680	6680
γ_{12}	Poisson's ratio	0.33	0.33
G_{12}	Shear modulus in 1 – 2 plane (MPa)	900	850
G_{13}	Shear modulus in 1 – 3 plane (MPa)	850	800
G_{23}	Shear modulus in 2 – 3 plane (MPa)	850	800
α	Coefficient that determine contribution of shear stress to the fiber tensile initiation criterion	0.1	0.1
X^T	Longitudinal tensile failure stress in fiber direction (direction 1) (MPa)	800	900
X^C	Longitudinal compressive failure stress in fiber direction (direction 1) (MPa)	358	450
Y^T	Transverse tensile failure stress in direction 2 (transverse to fiber) (MPa)	125	120
Y^C	Transverse compressive failure stress in direction 2 (transverse to fiber) (MPa)	90	70
S^L	Longitudinal shear strength	38	33
S^T	Compressive shear strength	65	60

3.1 Damage and Failure Prediction

The procedures for predicting the growth of the damage path are developed using the progressive failure analysis methodology implemented within the Abaqus/standard static finite analysis code [10]. The Hashin damage criterion has been used in this study to predict intra-lamina damage modes such as fiber failures and matrix failures. The intra-lamina failures mode considered were

- Fiber failure in tension and compression,
- Matrix cracking in tension and compression

The Hashin failure criteria are quadratic in nature due to curve fitting not physical reasoning of material behavior [11]. To account for the observed phenomenon of the multi-mode failure of fiber reinforced composites, Hashin introduced four damage initiation criteria for fiber and matrix, tension and compression. The input data for Hashin criteria are the longitudinal tensile and compressive strengths, the transverse tensile and compressive strengths, and the longitudinal and transverse shear strengths. All the strength values are assumed to be positive [12]

The initiation criteria have the following general forms.

Fiber tension ($\hat{\sigma}_{11} \geq 0$):

$$F^t = \left(\frac{\hat{\sigma}_{11}}{X^T}\right)^2 + \alpha\left(\frac{\hat{\gamma}_{12}}{S^L}\right)^2 \quad (1)$$

Fiber compression ($\hat{\sigma}_{11} < 0$)

$$F^c = \left(\frac{\hat{\sigma}_{11}}{X^C}\right)^2 4 \quad (2)$$

Matrix tension $\hat{\sigma}_{22} \geq 0$)

$$M^t = \left(\frac{\hat{\sigma}_{22}}{Y^T}\right)^2 + \left(\frac{\hat{\gamma}_{12}}{S^L}\right)^2 \quad (3)$$

Matrix compression ($\hat{\sigma}_{22} < 0$)

$$M^c = \left(\frac{\hat{\sigma}_{22}}{2S^T}\right)^2 + \left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right]\frac{\hat{\sigma}_{22}}{Y^C} + \left(\frac{\hat{\gamma}_{12}}{S^L}\right)^2 \quad (4)$$

Where

X^T : Longitudinal tensile strength

X^C : Longitudinal compressive strength

Y^T: Transverse tensile strength

Y^C: Transverse compressive strength

S^L : Longitudinal shear strength

S^T: Transverse shear strength

$\alpha$is the coefficient that determine contribution of shear stress to the fiber tensile initiation criterion

$\hat{\sigma}_{11}$, $\hat{\sigma}_{22}$,$\hat{\gamma}_{12}$ are components of the effective tensor $\hat{\sigma}$ that is used to evaluate initiation criteria.

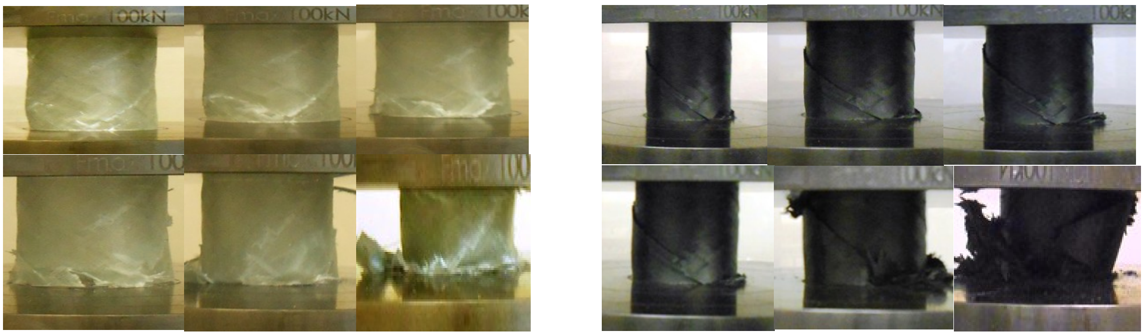
The material properties are degraded based upon the damage mode. In the current work, the fiber failure damage mode is assigned to the DELETE parameter. Hence the damage path prediction is achieved by deleting (or eroding) an element when all of the material points within the element have failed in the fiber failure mode. The maximum degradation used was 0.99. The output variable STATUS will indicate if an element is active or not. A value of 1.0 for the STATUS output variable indicates an active element, and a value of zero indicates a deactivated or deleted element.

IV. Results and Discussion

Compression tests were carried out oneach cylindrical composite tube. The load-displacement response and energy absorption capability of cylindrical composite tubes were recorded and calculated respectively. The effects of using different fibers and thickness were studied. The energy absorbed during progressive crushing of composite tube is the area under load-displacement curve. Energy absorption of glass/epoxy and carbon/epoxy of composite tubes were calculated from load-displacement curves with graphical method.

4.1 Effects of Thickness on Energy Absorption Capability of Glass/Epoxy and Carbon/Epoxy Composite Tubes

The specimens with one, two and three layers with 50mm length and 35 mm diameter were considered. The load- displacement curves behaves linearly first and then specimen cracked since the absorbed energy exceeds the threshold of material properties at the crush zone due to the crack, instant drop in the load was observed. Initial load for 1 layer glass/epoxy specimen was 2.01 KN, and then load dropped to 0.66 KN, and increased to 0.94 KN at the end of 32 mm axial displacement. For 2 layer glass/epoxy, maximum load was 7.94 KN, then the load dropped to 1.91 KN, and then increased to 4.39 KN at the end of 32 mm axial displacement. The maximum load for 3 layer glass/epoxy was obtained as 12.01 KN, then load dropped to 2.60 KN, and then increased to 5.21 KN at the end of 33 mm of axial displacement. During the static test of glass epoxy composite tube, damage was observed as white line forming along the fiber/matrix. The crack formation in the matrixand fiber/matrix debonding was presented in Fig. 5 (a).



(a) Glass/epoxy (b) Carbon/epoxy

Figure 5: Crushing sequence of glass/epoxy and carbon/epoxy composite tubes snapped at 5mm interval.

In the case of carbon/epoxy, maximum load for 1 layer was 2.65 KN then dropped to 0.75 KN and then increased to 0.95 KN at the end of 33 mm axial displacementload. For 2 layer maximum load was 8.34 KN, then the load dropped to 2.11 KN, and then increased to 4.63 KN at the end of 32 mm axial displacement. The maximum load for 3 layer carbon/epoxy was obtained as 11.37 KN, then load dropped to 2.02 KN, and then increased to 6.42 KN and then dropped to 5.21 KN at the end of 33 mm of axial displacement. During the compression test, crack noise failure could be heard in the initial stages of the experiment, this noise arose as damage mechanism which attributed to delamination and fiber fracture. Fig. 5 (b) shows the growth and accumulation of damage within the composite tubes. However it was observed during the experiment that, after initial crack, progressive damage initiated at the bottom and collapse more significantly at the bottom of the tubes.

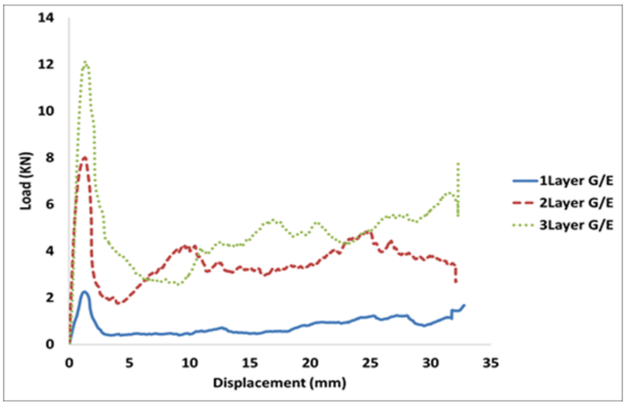


Figure 6: Load – displacement curves for glass/epoxy

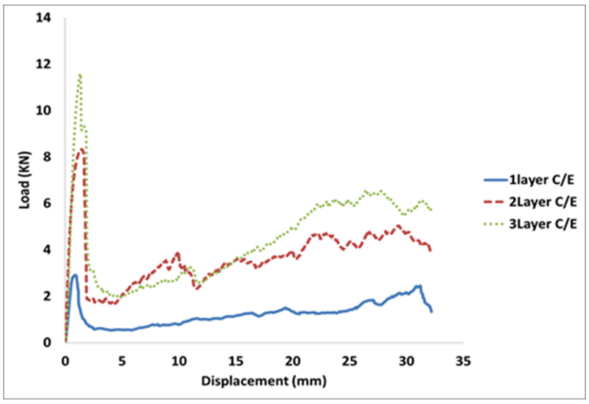


Figure 7: Load – displacement curves for carbon/epoxy

` Table 2: Showed summary of energy absorption for glass/epoxy and carbon/epoxy composite tubes. It is clearly indicates that, the energy absorption of glass/epoxy and carbon/epoxy composite tubes were directly affected by the number of layers. Consequently, composite tubes with higher number of layer give greater value of average crushing load which indicated greater value of energy absorption. The energy absorption for 1 layer, 2 layer and 3 layer glass/epoxy and carbon/epoxy were (26.60 KN and 43.70 KN), (115.6 KN and 132.3 KN) and (155.1 KNand 159.2 KN) respectively. It is also observe that composite reinforced with carbon fibers stands much energy absorption as presented in Fig. 8. In the case of FE simulated energy absorption almost similar trend was observed in comparison with experimental results as indicated in fig. 9.

Table 2: Energy absorption for glass and carbon epoxies

Number of Layers	Energy absorption (KN-mm)	
	Glass/epoxy	Carbon/epoxy
1 Layer	26.60	43.70
2 Layer	115.6	132.3
3 Layer	155.1	159.2

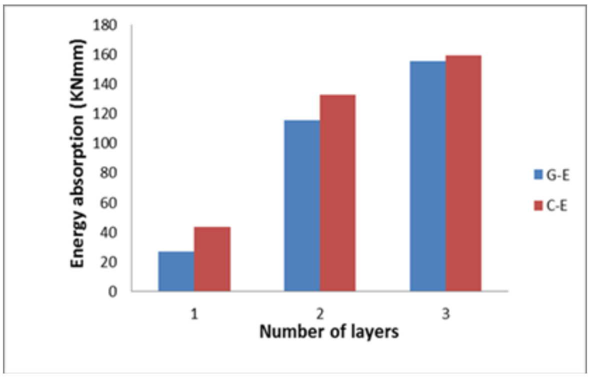


Figure 8: Total absorbed crash energy of glass/epoxy and carbon/epoxy with different number of layers

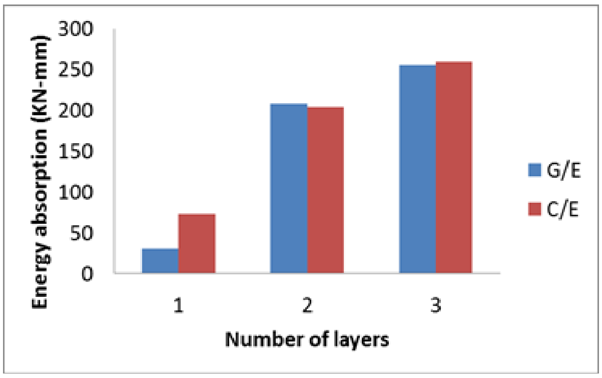


Figure 9: FE simulated energy absorption capability of glass epoxy and carbon epoxy with different thickness

4.2 FE Simulated Energy Absorption Capability of Glass/Epoxy and Carbon/Epoxy Tubes with Different Thickness

FEA results of glass epoxy and carbon epoxy obtained using Abaqus/Standard for the deformation modes and load displacement curve are shown in Fig. 10 and 11 respectively. It is clearly seen that in fig. 10, at the beginning of the loading operation, the applied load rises linearly up to a maximum load is obtained. The maximum load for 1 layer, 2 layers, and 3 layers glass epoxy were recorded as 2.11 KN, 7.95 KN and 11.99 KN respectively. In case of carbon epoxy, maximum recorded load were observe as 2.70 KN, 7.98 KN and 10.50 KN for different thickness as presented in Fig. 11.

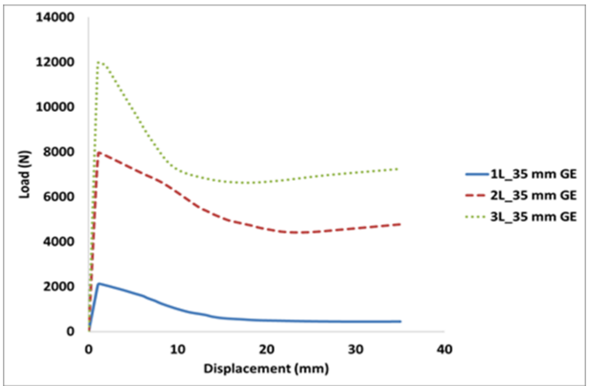


Figure 10: Load – Displacement curves for glass epoxy with different thickness.

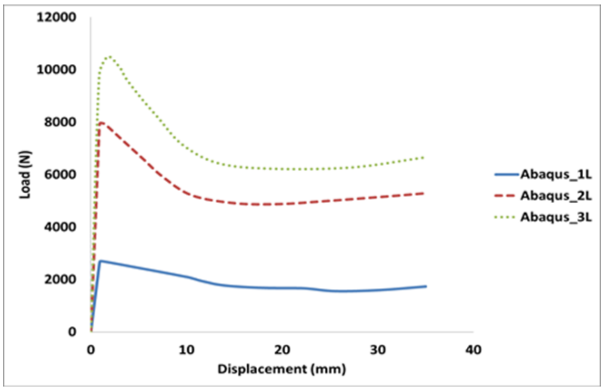
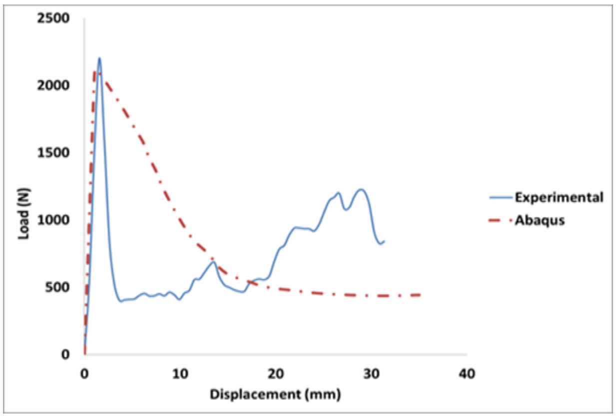


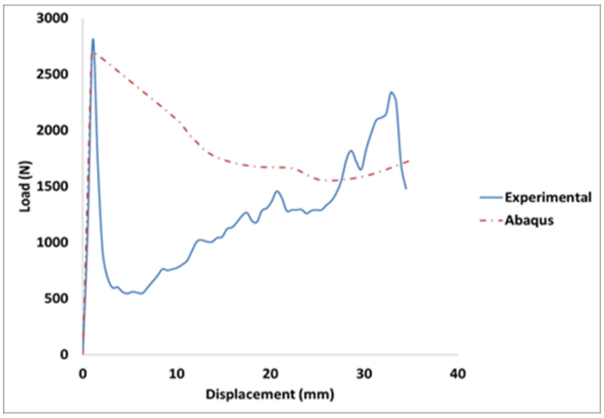
Figure 11: Load – Displacement curves for carbon epoxy with different thickness.

4.3 Comparison of Experimentally Obtained and FE Simulated Results

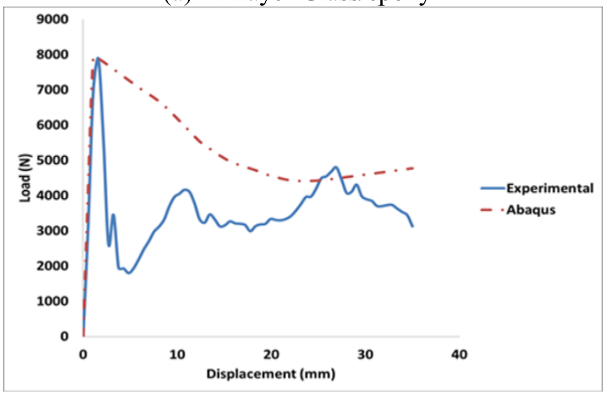
Fig. 12: (a) – (e) shows graph of load - displacement curves for experimental and numerical glass/epoxy and carbon/epoxy for 1 layer, 2 layer and 3 layer composite tubes with orientation angle of45°. The behavior of Load – Displacement graphs for the numerical composite tubes relates well with experimental results. Comparison of results showed that FE models successfully simulated the linear behavior and maximum load of the composite tubes, However Hashin failure model could not exactly predicted the behavior of composite tubes after the initial damage. The stress interactions proposed by Hashin do not always fit the experimental results, particularly in the case of matrix or fiber compression. It is well known that the moderate transverse compression ($\sigma_{22} < 0$) increase the apparent shear strength which is not predicted by Hashin's criterion. It is clearly seen that, from the visual comparison, the maximum load value obtained for both experimental and Abaqus, there is a good agreement in the results throughout the loading process. For both experimental and Abaqus, the linear portion up to the point where maximum load is reached is very close. It is also observe that, after the maximum loading step, the experimental and Abaqus load displacement curves drop off sharply at nearly the same maximum load.



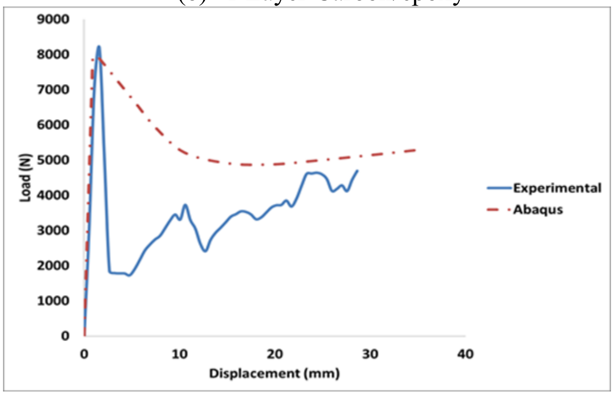
(a) 1 Layer Glass/epoxy



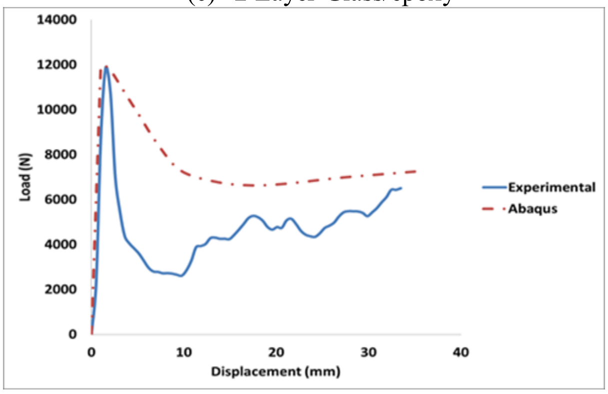
(b) 1 Layer Carbon/epoxy



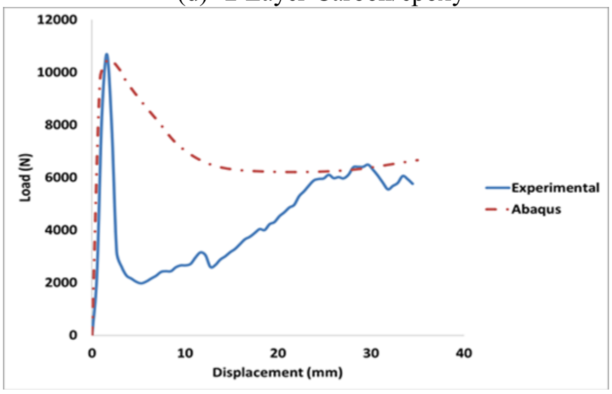
(c) 2 Layer Glass/epoxy



(d) 2 Layer Carbon/epoxy



(e) 3 Layer Glass/epoxy



(c) 3 Layer Carbon/epoxy

Figure 12: Comparing experimental and FEA results for glass/epoxy and carbon/epoxy with different thickness

V. Conclusions

Composite tubes were manufactured by process of filament winding. Glass and carbon fibers were selected as the reinforcement materials while epoxy resin and hardener have been used to form the matrix required for the fabrication of composite tubes. Six composite tubes were fabricated.Static compression test and energy absorption behavior of glass/epoxy and carbon/epoxy composite tubes were studied. During compression test, composite tubes experienced sudden breakdown mechanisms, which lead to progressive fluctuation within the vicinity of load displacement curves.Load-displacement curves deduced from this study show the same result when compared to other investigation from the literature. The parameters were studied include wall thickness and different fiber. Their effects on energy absorption were obtained, the specimen with thick layer absorb much energy absorption.ABAQUS is used as a numerical tools using progressive damage methodology based on Hashin failure to compared the results with experimental. The Load – Displacement behavior of the simulated composite tubes correlates reasonably well with experimental results. It is interesting to note that all the experimental results behave in a similar way with simulated composite tubes where, their linear portion is almost similar up to maximum loads. Of all simulated results, Hashin failure does not give reasonable fact on brittle failure type obtained from the experiment. Also it is observed that the maximum load values obtained from the experiment correspond to the results obtained from the simulation. This validates the capability of

Hashin's progressive failure in simulating damage with material linearityfor composite tube with reasonable accuracy.

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