Energy Absorption Characteristics and Crashing Parameters of Filament Glass Fiber/Epoxy Composite Tubes

Energy Absorption Capacity of Filament Fiber Glass-Epoxy Composite Tubes

Al-Qrimli, Haidar Fadhil Abbas

Published in:
The 2nd International Conference on Engineering and ICT, February 2010, Melaka, Malaysia

Publication date:
2010

Energy Absorption Capacity of Filament Fiber Glass-Epoxy Composite Tubes

Haidar Fadhil Abbas Al-Qrimli*[1], Fadhil Abbas M.[2], Hakim S. Sultan[1], Karam S. Khalid[3], Chong W. P[1], Ibraheem Ahmed[1], Laith Q. Saeed[1] and Dhafer Shnawah[1].

[1]Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[2]Department of Electrical Engineering, University of Baghdad, Baghdad, Iraq
[3]Department of Mechanical Engineering, University of Tenaga, 43009 Kuala Lumpur, Malaysia

*Corresponding author: dajla99@hotmail.com Tel: ++60123356795 Fax: ++603-79675317

Abstract— **The energy absorption capacity of a sequence of axially crushed composite tubes fabricated from high tow count filament glass fiber with different number of layers (4, 6, 8, and 10 layers), is to determine the viability of with considering the use of such fibers in automotive applications. To that end, glass-epoxy tubular specimens with circular cross-sectional geometry and 0/90° orientation fibers were fabricated and crushed statically to examine the energy absorption characteristics and to calculate the crushworthiness parameters. Three specimens were cut from each of these tubes. Twelve specimens were crushed statically by using INSTRON machine. In order to characterize the tubes and specimens, a number of measurements were taken. These measurements included wall thickness, cross-sectional dimensions, volume, and mass. Two important energy absorption measures were examined: the specific energy absorption (SEA) and the load ratio to the average load. The number of layers had a significant effect on the energy absorption.**

***Keywords*— Compression, Maximum load, Crashworthiness, Quasi-static axial loading.**

Nomenclature

FWG	Filament winding glass fiber
P_i	Initial Failure Load
P_{max}	Maximum Failure Load
P_{av}	Average Failure Load
D_i	Initial Displacement
D_f	Final Displacement
PR	Load Ratio
TEA	Total Energy Absorption
SEA	Specific Energy Absorption
VEA	Volumetric Energy Absorption
CFE	Crush Force Efficiency
C	Crush Strain Relation

I. INTRODUCTION

Composite materials are often used to reduce the weight of structures. In the automotive industry weight reduction is important because fuel consumption is directly related to vehicular weight. Federal regulations requiring increased fuel efficiency are forcing the industry to examine new light weight materials for major structural components. In addition, there is an increased concern for occupant safety during roadway accidents. Though active devices such as front, side, and knee airbags, and pop-out devices may be one solution, using the passive capacity of the structure is also as attractive. Metals are currently used in car frames and integrated frame-body structures, and these and other metallic components are designed to passively absorb energy during accidents. However, automotive manufacturers are moving toward nontraditional materials [1- 6] and any new structural material under consideration should be capable of participating in the energy absorption process associated with accidents. Recent work has shown that it is possible to use composite materials as both structural and energy absorbing members, and still pass federal safety standards [6-7]. [8-9] they found that the composite idea can be related to the macro scale. The major structural applications for fiber - reinforced composites are in the field of commercial aircrafts, for which weight reduction is critical for higher speeds and increased payloads. Currently a large variety of composite components are used in aircrafts. [10-11] found out that automotive parts represent an immense market for composites. Both the volume of the automotive market and the potential automotive uses for composite materials are very large. [12-13] Hand layup, a simple, old composite fabrication process, is a low-volume, labor-intensive methods suited especially for large components such as boat hulls. Glass or other reinforcement mat or woven roving is positioned manually in the open mold, and resin is poured, brushed, or sprayed over and into the glass. By hand lay-up process is possible to obtain smaller values of surface roughness than by filament winding process. Hand lay-up is the better process considering the smaller values of specific cutting pressure and surface roughness. Entrapped air in removed manually with squeegees or rollers. Room-temperature curing polyester and epoxies are the most commonly used matrix resins. Curing is initiated by a catalyst or accelerator in the resin system, which hardens the fiber-resin composite without external heat. [14] Proposed that there are several composite automobile parts are now in production, and many others are being planned. These parts include suspension springs, space frames, body panels, and entire assemblies. Elgalai et al [15] they make a quasi-static axial compressive load to examine the crushing behavior of composite corrugated tubes, and they used two types of composite material in the test, carbon fiber/epoxy in filament form and glass fiber/epoxy in woven roving. They studied the effect of corrugation angle and they found that the corrugated tubes very sensitive to the increase in corrugation angle, the results showed that CFRE-40 exhibited the highest energy absorption capability, so we can notice that the increase in angle have influence on the energy absorption capabilities. And for the glass fiber/epoxy composite tubes they found consistent trends with the variation in the specific crushing energy absorbed. They studied the effect of fiber type also and they found that carbon fiber/epoxy have the highest load-absorbing capacity. Jose et al. [16] They fabricated tubes of circular and square cross sections and they use polyester resin and plain weave E-glass with fibers oriented at 0/90° and they used steel molds for making the specimens they make a quasi-static compression test on the specimens and the results shows that among the conditions, tubes of circular cross- section is the best comparing to the other specimen. Giovanni et al. [17] they make impact tests by making a series of quasi-static tests to get information on the laminate strength characteristics, and they mentioned that the energy absorbed by the specimens can be calculated from the load–displacement curve.

The most important factor should be taken into account when designing an automobile is the safety of the passengers when a crush or collision of the vehicle occurs. When evaluating the crashworthiness performance of energy absorber devices, attention should be directed to the instantaneous crush behavior such as crush force efficiency (CFE), crushed strain (CS), failure modes in different stages of the crushing process and energy absorption capabilities [18-20].

II. FABRICATION OF TUBES

A number of fiberglass tubes were fabricated with a circular shape. Three specimens were fabricated for each layer, and they have been fabricated in the same way.

There are several steps of tube fabrication. Preparing the mandrel is an easy way to shape the fiberglass/epoxy into desired shape. For circular shape, the circumference of each mandrel is calculated in order to know the exact length of fiberglass that needs to provide, where the width is fixed for all the specimens is 300 mm as shown in Figure 1. Then the length of specimen can be defined as the circumference x N Where N is number of layers.

After the desired length of fiberglass is ready, then the hand lay-up process is started. Then the mandrel is used to roll the fiberglass through the length by putting the mixture epoxy/hardener simultaneously. The mixture must be followed the ratio 4:1 by weight. By rolling the fiberglass with the exact length which is calculated before, it can be produced the desired layers of laminated tube. After the solidation process for the epoxy/hardener, the mandrel is removed apart from the fiberglass tube. Not to mention that the mandrel should be covered with a couple of layers of thin flexible plastic to prevent the epoxy resin from touching the mandrel directly. Finally the specimens leaved more than 8 hours to make sure that the epoxy/ hardener dry. The fiberglass tube is ready for finishing into the desired geometry by using the cutting machine. (See Figure 2 and Figure 3)

The crushing test had been performed on to all the specimens by using an electrical computer-controlled servo-hydraulic INSTRON machine type 4469. The speed was set at constant 15 mm/min. The specimens were axially crushed between two steel flat platens; one is static and the other one moving with constant speed. The type of failure modes has been observed such as debonding, delamination, fiber pullout and matrix cracking. The INSTRON machine used is shown in Figure 4.

III. RESULTS AND DISCUSSION

A. Load Displacement Curves

Load-displacement curve can be classified into two main zones the first zone represent the elastic behavior stage which is called the pre-crushing stage of the specimen then the initial failure will observed (P_i), after the initial failure the plastic zone starts and it's the second zone of the load displacement curve and it's called the post-crushing stage. The load displacement curve shows the maximum load (P_{max}), average load (P_{av}) and the displacement of the failure.

From here, the other crashworthiness parameters can be also calculated.

From Figure 6 the structure of the specimen generates the elastic zone at the beginning as shown in the load displacement curve in Figure 5 then the structure started folding, causing a dramatic drop in the curve as shown in same Figure then the curve starts going up again due to the recovery of the structure to the failure. Then the curve starts to rise due to the cumulative materials of the specimen after crushing and from Table 2 the initial failure load is 10.92 kN at 1.59 mm crushing displacement and the maximum failure load is 12.51 kN which is the lowest values comparing to the other specimens shown in the same Table. FWG-6L-0/90° From the Figure 5 the curve obviously can be divided into two main zones, the first zone ends at 24.85 kN crushing load, the next stage is the plastic zone as shown in the same Figure the curve drops dramatically due to the radial cracking in the structure of the specimen due to absence of the vertical fiber because this specimen has been made using filament fiber, then the crushing accedes the failure area as shown in Figure 7. The curve rises again due to that as shown in Figure then the curve drops down again because of the cracking in the structure in the bottom and the top of the specimen. After that the curve disappears and the crushing stops due to acceding the 0 kN limit of the machine before finishing the whole crushing. (FWG-8L-0/90°) Increasing the number of layers improves the behavior of the structure by increasing the initial crushing load, the load can be divided into two main zones as mentioned before, the elastic zones ends at 35.81 kN initial load, the plastic zone explain the multi failure mode that is generated due to proceeding in the crushing, then the curve starts increasing again due to the recovering of the structure, then the curve grows again up due to cumulative materials of the specimen**.** (See Figure 8)

The load displacement curve of the specimen with the circular geometry with 10 layers and 0/90° orientation angle by using filament fiber and as shown in Figure 9, the curve is divided into two main zones, the elastic part which ends at 41.39 kN initial failure load at 0.79 mm crushing displacement and then after that the plastic zone begin. The curve drops sharply due to the wall cracking of the specimen, then the curve increases with fluctuation because of the specimen recovering structure then the curve starts fluctuation until the end of this because of the separation of the laminate then the curve increases until a specific point to start decreasing again until the end of the crushing and this fluctuation is due to the failure modes occur to the specimen: fiber breakage and fiber debonding as shown in the Figure 9, Table 2 shows the maximum load which occurs and the average load with their displacements.

IV. CRASHWORTHINESS PARAMETERS

C. Average failure load (P_{av})

P_{av} is a very important factor of the crashworthiness parameters to the crushing energy absorbed by the structure. The equation of the average load is that take the sum of all the results for each specimen then divide it on their number. It is clear that the lowest average load is produced by the specimen FWG-4L-0/90º and the highest average load is produced by the FWG-10L-0/90º as illustrated in Table 2. This means that the thickness or the number of the specimen layers effect on the average load.

D. Load Ratio (PR)

The main purpose for using the load ratio parameter because it's very important to study the failure modes along the crushing failure and the load ratio (PR) is the ratio between the initial failure load (P_i) and the maximum failure load (P_{max}) and this can be show in the equation PR= P_i / P_{max}. When the initial failure load is the same value of the maximum failure load that's mean the load ratio will equal to 1 and this means that the structure initially crushed in a limited catastrophic failure mode. In addition, if the load ratio (PR) is less than 1, that's mean a matrix failure mode will observed in the initial crushing stage of the specimen. FWG-4L- 0/90º shows the lowest value of PR (0.87) and the other specimens have the same value which is 1 as shown in Table 3.

E. Total Energy absorbed (TEA) (KJ)

The area under the load-displacement curve represents the total energy absorbed (TEA) and it can be calculated from the equation: TEA = $\int P_{av}\, D_s \equiv P_{av} (D_f - D_i)$. Where the P_{av} is the mean crushing load, D_f is the final crushing distance and D_i is the initial crushing distance. The SI units for the TEA are kJ. To explain the calculations of the TEA, the area under the load-displacement cure divided into two regions. The first one is the pre-crushing and it can be calculated by finding the area under the triangle, so the area will be the ½ multiplied by the P_i and D_i where the SI units is kN .m (kJ). The energy absorbed in the second (post-crushing) region can be calculated from the equation, then after that TEA can be calculated by finding the simulation of energy absorbed in the two regions (pre and post crushing).

The highest value is produced by the FWG-10L-0/90º (2.56 kJ) and the lowest value is produced by FWG-4L- 0/90º. Table 3 shows the exact values of TEA for specimens.

F. Specific Energy Absorption (SEA)

The specific energy absorption (SEA) is the most important factor in the design of the parts that are needed to reduce their weight, such as cars, airplanes and motorcycles, etc. The SEA is the energy absorbed per the mass of the specimen and the SI units of the SEA is kJ/kg. It can be calculated from the equation: (SEA= TEA/Mass). FWG-8L- 0/90º produced the highest specific energy absorption and even the energy absorbed (TEA) of FWG-10L-0/90º is higher than the FWG-8L- 0/90º, but the weight of FWG-8L- 0/90º is less than FWG-10L- 0/90º because the layers are less. By applying the equation to find the SEA, the result of FWG-8L- 0/90º will be higher than FWG-10L- 0/90º, and the FWG-8L- 0/90º produced the highest energy absorption comparing with all the specimens that fabricate in this study. This mean that the weight is an effective factor that effect on the SEA, so reducing the weight of the specimen to get more SEA that will give more reliability to the parts by increasing the safety and reducing the fuel consumption of the engine. The weight of the specimens is shown in Table 1.

Figure 10 show the SEA for the specimens made by using the filament winding method with circular geometry and 90° orientation angle of the glass fiber as shown in the Figure the highest value of SEA is produced by FWG-8L-90° which is 12.16 kJ/kg compared to the other specimens in the same Figure and the lowest SEA is produced by FWG-4L-90°. Table 3 shows the exact values of the filament winding specimens.

G. Volumetric Energy Absorption (VEA)

The Volumetric Energy Absorption (VEA) in an essential parameter for the energy absorbing system design. The VEA is the ratio between the total energy absorption to the volume of the specimen. The SI unit is kg/m^3 and VEA can be obtained from the equation (VEA = TEA / V). Where TEA is the total energy absorption and V is the volume of the specimens. The volume of the circular specimens can be calculated $(V = (\pi \times (t + D)^2 / 4) \times H)$ Where t, is the wall thickness of the specimen wall, the average thickness for all the specimens considered being similar for all the specimens and D is the inner diameter of the tubes 100 mm. The VEA increase gradually from the lower to the highest thickness this is because the volumes of the specimens are equal. Thus, the amount of VEA will depend on the TEA, since the FWG-10L- 0/90º produced the highest.

H. Crush Force Efficiency (CFE)

This is a very important parameter to evaluate the performance of the structure during the crushing process. Crush force efficiency (CFE) is the ratio between the average crushing load (P_{av}) and the maximum crushing load (P_{max}), and it can be obtained from the equation: (CFE= P_{av} / P_{max}). The performance of FWG-10L- 0/90º is more efficient than other specimens, which proved that this specimen is the best choice in the energy absorbing system design that deals with circular tubes structures, circular geometry tubes can be used in any structure.

I. Crush Strain Relation (C)

The crushing strain relation (C) allows a homogeneous comparison of the structural response independently from the material elastic properties. The higher the value of the C parameter, the higher the magnitude of energy absorbed by the structure and the more optimum the design of the structure. Crushing strain relation is the ratio between the crushing lengths to the total length of the specimens ($C = (D_f-D_i) / H$), where (D_f-D_i) are the final and the beginning of the crushing distance respectively, and H is the crushing distance. The lowest C is produced by FWG-10L- 0/90º then the specimen with 8 and 6 layers have the same value of C. But as shown in Table 3 there is a very slight difference between the values and it's closed to 1. This means that the crushing distances between the specimens are closed to each other.

TABLE 1
DIMENSIONS

ID	Mass (g)	Volumetric (m^3)	Thickness (mm)
FWG-4L-0/90º	100.67	0.08	2.17
FWG-6L-0/90º	192.65	0.08	3.5
FWG-8L-0/90º	202.82	0.08	4.22
FWG-10L-0/90º	218.11	0.08	4.76

TABLE 2
LOADS AND DISPLACEMENTS

ID	P_i	P_{max}	P_{av}	D_i	D_f
	kN			mm	
FWG-4L-0/90º	10.92	12.51	7.46	1.59	73.00
FWG-6L-0/90º	24.85	24.85	8.08	3.43	72.46
FWG-8L-0/90º	35.81	35.81	19.51	2.80	71.64
FWG-10L-0/90º	41.39	41.39	32.90	0.79	62.60

TABLE 3
CRASHWORTHINESS PARAMETERS

ID	PR kN/kN	TEA kJ	SEA kJ/Kg	VEA kJ/m^3	CFE kN/kN	C mm/mm
FWG-4L-0/90º	0.87	0.78	7.75	9.93	0.60	0.71
FWG-6L-0/90º	1.00	1.72	8.90	21.85	0.33	0.69
FWG-8L-0/90º	1.00	2.47	12.16	31.41	0.54	0.69
FWG-10L-0/90º	1.00	2.56	11.73	32.59	0.79	0.62

V. CONCLUSION

In a filament winding process, a band of continuous resin impregnated roving's or monofilaments is wrapped around a rotating mandrel and then cured either at room temperature or in an oven to produce the final product. The technique offers high-speed and accurate method for placing many composite layers. The mandrel can be cylindrical, round or any shape that does not have re-entrant curvature. Mechanical strength of the filament wound parts not only depends on the composition of component material but also on process parameters like fiber tension, resin chemistry, curing cycle and the number of layers.

The specimens with the FWG-8L- 0/90º had higher specific energy absorption than the specimens with the FWG-10L-0/90º.
The specimen number of layers (tube thickness) played a major role in determining the energy absorption characteristics. The FWG-10L-0/90º specimens have higher SEAs than the other specimens.

FIGURE CAPTIONS

Figure 1: Schematic shows the top and front view of specimens.
Figure 2: E-600 woven roving fiber glass mixed with epoxy resin.
Figure 3: Wooden mandrels and cutting process.
Figure 4: INSTRON machine used in this study.
Figure 5: Load displacement curve of the specimens.
Figure 6: Progress of Crashing FWG-4L-90°
Figure 7: Progress of Crashing FWG-6L-90°
Figure 8: Progress of Crashing FWG-8L-90°
Figure 9: Progress of Crashing FWG-10L-90°
Figure 10: SEA of different number of layers.
Table 1: Dimensions.
Table 2: Loads and displacements
Table 3: Crashworthiness parameters

ACKNOWLEDGMENTS

The authors would like to thank University Malaysia and staff for the financial support for this research and thank Hayder A. Dohee .

REFERENCES

[1] V. P. ed. McConnell. "*Automotive Composites: A Design and Manufacturing Guide*", Ray Publishing, Wheat Ridge, CO, Vol. 1, 1997, pp. 6-7.
[2] Piellisch, Richard. "Beyond Gasoline: Autos Remain Elusive for Carbon Composite Structures, but Alternative Cars Still Hold a Great Market Potential," SAMPE Journal, Vol. 32, No. 5. 1996, pp. 14-17.
[3] M. Karbhari, Vistasp, Falzon, Paul J., and Herzberg, Israel "Energy Absorption Characteristics of Hybrid Braided Composite Tubes," *Journal of Composite Materials*, Vol. 31, No. 12.1997, pp. 1165-1186.
[4] H. Hamada, A. Nakai, K. Kameo, and , N. Takeda. "Crushing Performance of Braided Composites," *Proceedings of the Eighth Japan-U. S. Conference on Composite Materials,* September 24-25, 1998, pp. 467-475.
[5] Mallick, 2007, "*Fiber reinforced Composites Materials, Manufacturing, and Design".* By Taylor & Francis Group, LLC CRC Press is an imprint of Taylor & Francis Group, (third edition, by LLC revised and expanded. 10987654321 university of Michigan, Dearborn. Printed in United State of America)
[6] Peter Morgan, "*Carbon Fibers and Their Composites"*, CRC press is an imprint of Taylor and Francis Group LCC, no. 10: 0-8247-0983-7, printed in united state America on acid-free paper 10987654321. (2005).
[7] Giovanni Belingardi, Maria Pia Cavatorta, Davide Salvatore Paolino,*"Repeated impact response of hand lay-up and vacuum infusion thick glass reinforced laminates".* Mechanical Engineering Department, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy, International Journal of Impact Engineering 35 (2008) 609–619.
[6] Derek Hull, prof. R. W. Cahn, Professor E. A. Davis, professor I. M. Ward, (1990), "*an introduction to composite materials (Cambridge solid state science series)"*, printed in great Britain at the university press, Cambridge. ISBN 0 521 239911111 5.
[7] Tao Yin, Min Zhi Rong, Jingshen Wu, Haibin Chen and Ming Qiu Zhang. "Healing of impact damage in woven glass fabric reinforced epoxy composites", J Applied Science and Manufacturing 2008; 39: 1479-1487
[8] Denial Gay, Suong V. Hoa, Stephen W. Tsai, (2003), "*composite materials design and applications"*. CRC Press printed in united state of America. No. 1-58716-084-6.

[9] N.A. Warrior, T.A. Turner, F. Robitaille, C.D. Rudd (2003), "*Effect of resin properties and processing parameters on crash energy absorbing composite structures made by RTM",* School of Mechanical, Materials, Manufacturing Engineering and Management, University of Nottingham, Nottingham NG7 2RD, UK

[10] Bank, L.C. and Gentry, T.R. (2001). "Development of a pultruded composite material highway guardrail" *Composites Part A: Applied Science and Manufacturing* 32, 1329-1338.

[11] Saiphon Charoenphan (2002) a thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Engineering Mechanics), "*Computer Methods for Modeling the Progressive Damage of Composite Material Plates and Tubes"*, At the University Of Wisconsin-Madison.

[12] Brent Strong A. (1991), "*composites in manufacturing"*, published by the society of manufacturing engineers in composites manufacturing association of SME in the united states of America, international standard book Number: 0-87263-406-x.

[13] E. Mahdi, A.M.S. Hamouda, B.B. Sahari, and Khalid, Y.A., (2003), "*Effect of Hybridization on Crushing Behavior of Carbon/Glass Fibre/Epoxy Circular Cylindrical Shells"*, Journal Of Materials Processing Technology, vol. 132, pp. 49-57.

[14] K. O. Mertens, L.C. Bank, and M. E. Plesha, "*Experimental studies of the progressive tearing failure of pultruded FRP composite tubes in flexure"*. American Society of 160 Composites, Proceedings of the 16th Annual Technical Conference, Virginia Tech, VA, (2001).

[15] Elgalai, E. Mahdi, A.M.S. Hamoudo, B.S. Sahari,(2004) "*Crushing response of composite corrugated tubes to quasi-static axial loading"*, Department of Aerospace Engineering, Faculty of Engineering, Institute of Advanced Technology, University Putra Malaysia, 43400UPM, Serdang, Selangor, Malaysia

[16] Jose´ Daniel D. Melo, Andre´ Luiz S. Silva, John Edward N. Villena, (2007), "*The effect of processing conditions on the energy absorption capability of composite tubes"*. (Department of Materials Engineering, Universidade Federal do Rio Grande do Norte, 59072-970, Brazil).

[17] Giovanni Belingardi, Maria Pia Cavatorta *, Davide Salvatore Paolino, "A *new damage index to monitor the range of the penetration process in thick laminates"* (Mechanical Engineering Department, Politecnico di Torino, Corso Duca degli Abruzzi, 24 – 10129 Torino, Italy), (2008),

[18] Hakim S. Sultan, Irfan Anjum and A. Badarudin (2008), *"Experimental Study of Composite Structures in Automotive Applications"*. Mechanical Engineering Department, Faculty of Engineering, University Malaya, 50603 Kuala Lumpur, Malaysia.

[19] F. Elfetori Abdewi, Shamsuddeen Sulaiman, A.M.S. Hamouda, E. Mahdia ,(2007), "*Quasi-static axial and lateral crushing of radial corrugated composite tubes",* Mechanical and Manufacturing Engineering Department, Faculty of Engineering, University Putra Malaysia, UPM, Serdang, Selangor 43400, Malaysia,; accepted 4 July 2007.

[20] Hakim S. Sultan Aljibori, Rahezar Ramle, Haidar Al-qrimli, Chong W. P, (2009), "Quasi-Static Axial Crushing of a ±45° Fiber Orientation Angle with a Different Number of Layers: Part 1", Experimental Study. American Journal of Scientific Research ISSN 1450-223X Issue 4 (2009), pp72-84 © EuroJournals Publishing, Inc. 2009 http://www.eurojournals.com/ajsr.htm.

APPENDIX

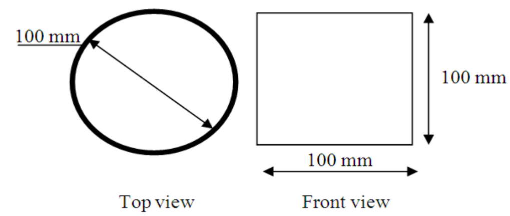

Figure1. Schematic shows the top and front view of specimens.

Figure2. E-600 woven roving fiber glass mixed with epoxy resin.

Figure3. Wooden mandrels and cutting process

Figure4. INSTRON machine used in this study

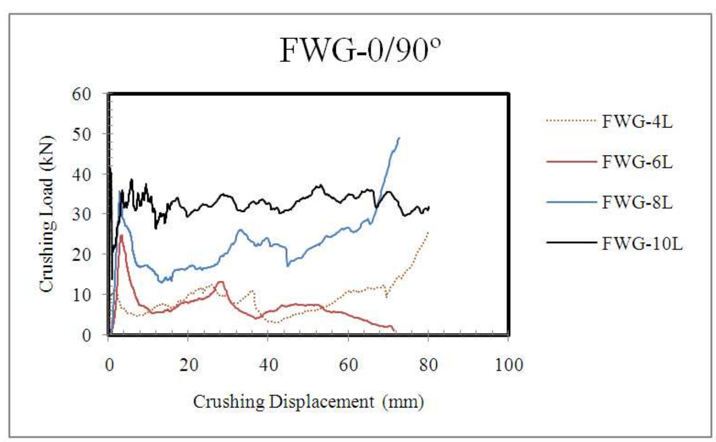

Figure5. Load displacement curve of the specimens.

Figure6. Progress of Crashing FWG-4L-90°

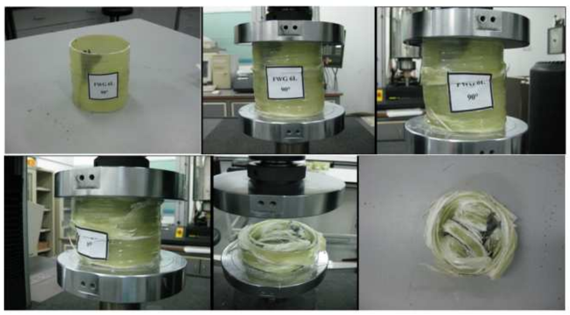

Figure7. Progress of Crashing FWG-6L-90°

Figure8. Progress of Crashing FWG-8L-90°

Figure9. Progress of Crashing FWG-10L-90°

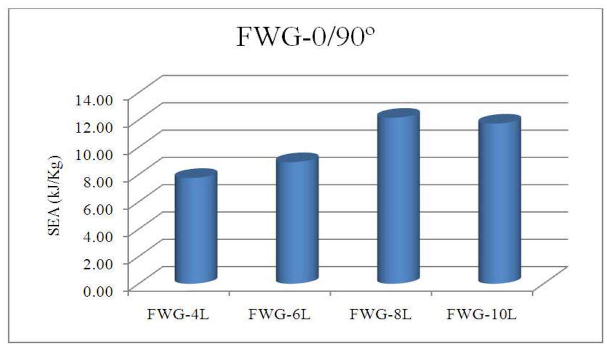

Figure10. SEA of different number of layers