Low Velocity Impact and Post Impact Tensile Properties of Plain Weave Woven GFRP Composite Laminates

M. A. Kounain, F. Al-Sulaiman, Z. Khan

Abstract*: Instrumented drop weight impact tests at different impact energies were performed to investigate the effect of ply stacking sequence and thickness in plain weave glass fiber reinforced composite laminates with 0º and 0/90º ply orientations. Post impact tensile tests were performed to predict the residual strength of the material. It was found that the stacking sequence did not significantly affect the impact behavior of the composite laminates. The peak load increased with increase in the number of plies. Residual tensile strength, strain at failure and elastic modulus of the laminates decreased with the increase in the impact energy due to increase in the impact damage area.

Keywords: GFRP laminates, Low velocity impact, post impact tensile properties

I. INTRODUCTION

Fiber reinforced composites are highly susceptible to impact loading [1-5]. Most often than not these composites are exposed to low velocity impacts either during assembling or in use which could result in serious degradation in the mechanical properties [6-8]. The damage under impact is often barely visible to the naked eye but can have a significantly deleterious effect on the strength, durability, and integrity of the composite structures and components. Low velocity impact in fiber reinforced composites can introduce various types of damages like delamination, fiber breakage, matrix cracking and fiber-matrix debonding. These types of damages are microscopic in nature and hence escape detection under visual inspection and frequently result in structural failures at loads well below the design level [**Error! Reference source not found.**]. It is thus necessary to fully understand and characterize the impact resistance of fiber reinforced composites to help the manufactures and design engineers in making sound decisions in material selection, manufacturing processes and structural designs. In recent past substantial amount of research has been undertaken to understand the impact behavior of Fiber Reinforced Polymer (FRP) composite laminates by tailoring the material layup sequence [11-17]. However, till date the impact behavior of woven composite laminates has not been well understood with respect to the stacking sequence of the laminate.

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While several researchers have investigated various aspects of stacking sequence related to non-woven composite laminates, no one was successful in developing a simple method of predicting the impact damage resistance for an arbitrary layup. In this present study, the effects of stacking sequence (ply orientation) on impact resistance of woven Glass Fiber reinforced Polymer (GFRP) composite laminates are evaluated.

II. MATERIALS AND METHODS

2.1. Materials

The plain weave woven GFRP composite laminates evaluated in this study were manufactured by Vacuum Bagging technique at room temperature under a vacuum pressure of 0.8. Glass fiber glue was used as the matrix material which accounted to 150% of fiber weight. Polyester stitch yarns were used in the weft direction to hold the glass fibers. 12 different specimens based on two ply orientations 0° and 0/90° with 8, 16, 24, 32, 40 and 48 plies were evaluated (see Table 1).

2.2. Impact Tests

Impact tests on each specimen was carried out using an instrumented drop weight test system (Dynatup 9250G, Instron Corp., USA) impact testing machine using a hemispherical steel tup. 150 mm x 150 mm laminates were clamped in the fixture (Figure 1) and impacted once at its center at three impact energy levels of 5, 7.5 and 10 J.

Table 1 Material configuration of Woven Composite laminates

Specimen	Average Thickness (cm)	Density (g/cm^3)
0^0 8 Ply	0.097	1.34
$0/90^0$ 8 Ply	0.0925	1.42
0^0 16 Ply	0.2045	1.22
$0/90^0$ 16 Ply	0.1885	1.37
0^0 24 Ply	0.271	1.25
$0/90^0$ 24 Ply	0.2615	1.32
0^0 32 Ply	0.3845	1.15
$0/90^0$ 32 Ply	0.393	1.23
0^0 40 Ply	0.342	1.9
$0/90^0$ 40 Ply	0.358	1.86
0^0 48 Ply	0.408	1.89
$0/90^0$ 48 Ply	0.429	1.86

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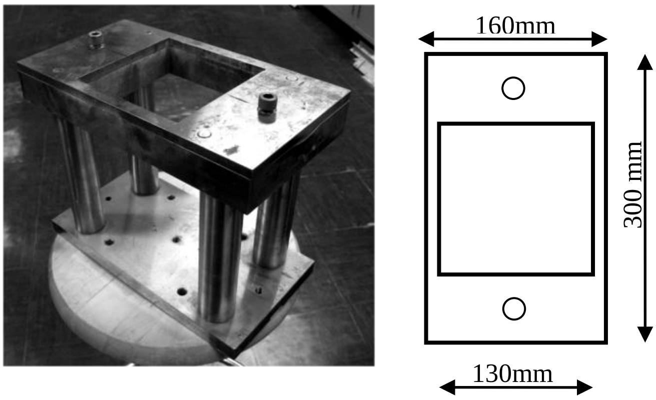


(a) **(b)**

Figure 1. Impact Test Fixture used for testing Woven Composites

2.3. Post Impact Tensile Test

Post impact tensile tests were performed on Instron 8801 servo-hydraulic testing system. Specimens were tested to failure at a cross-head speed of 1 mm/minute. Through computerized data acquisition software, test data like tensile stress (σ), tensile strain (ε), modulus (E), load and deflection were recorded.

2.4. Optical and SEM Fractography

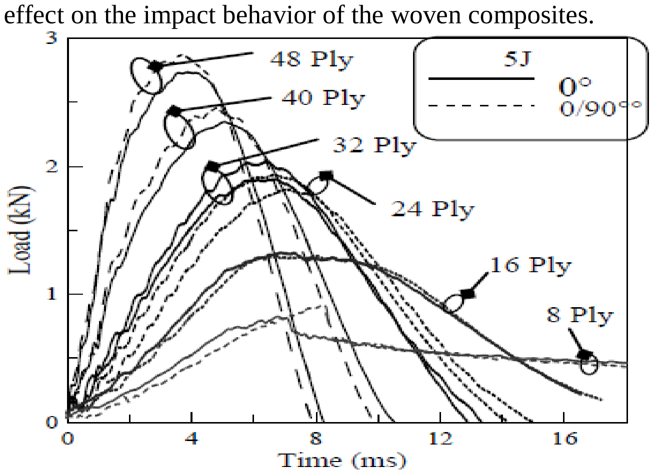
Optical examination of the front and back sides of the laminates were carried out using a low magnification metallographic microscope. The optical observations allowed determining the shape and extent and nature of the impact damage. In addition to the above, cross-sections of impact damage areas are also optically examined. For this, purpose specimens were sectioned perpendicularly through the center of the impact damage and polished down to 0.3 μm aluminum oxide. This examination was helpful in providing information with respect to damaged pattern and the progress of impact damage through the thickness of the composite laminates. The morphology of impact damaged surface was studied using Scanning Electron Microscope (SEM). To suppress charging and to increase electron emission, gold coating under vacuum was applied to the fracture surface using Coating Ion Sputter.

2.5. Delamination Area Calculation

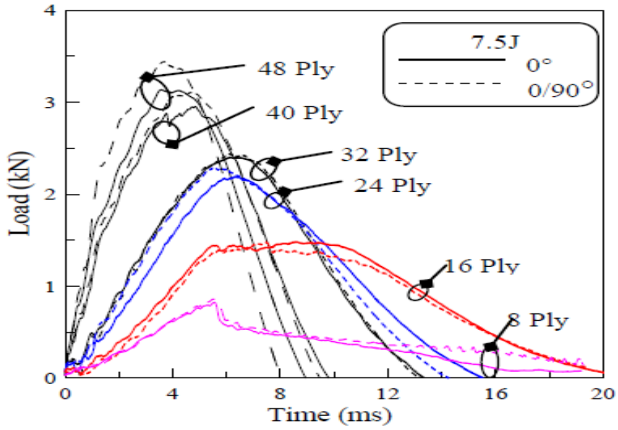
In this study, the term Damage area or Impact damage area or Delamination area refers to the projected internal delamination area (overlap area of delamination at each interface of the composite laminate) and not the calculated cumulative areas of superimposed delamination areas. This area was measured using visual manual method using backlight technique taking advantage of the transparency of this material to white light.

III. RESULTS AND DISCUSSION

Load-time curves plotted from the experimental data obtained from the force transducer of the impact machine are provided in Figures 3 (a, b, c) for impact energies of 5, 7.5 and 10J. The peak loads were not only dependent on the impact energy but also on the number of laminate plies and the stacking sequence. In the rising portion of load-time curve load oscillates as matrix cracking, fiber matrix de-bonding and ply delamination are initiated. Significant difference in peak load was noted at all impact energies with the increase in number of plies. For 8 ply specimens the load drops gradually to zero and thus the total displacement was higher for these specimens. The total contact duration and the time to reach peak load of the composites reduced with the increase in stiffness of the material which in turn increases with the increase in thickness of the material. Variation of Peak load with laminate layup and Impact Energy is shown in Figure 3. It was observed that for all specimens the peak load increased with the increase in incident impact energy from 5 to 10J. As number of plies of the material increased, the material thickness increased as shown in Table 1 which would increase the peak load. Variation of Energy to peak force with laminate layup and impact energy is shown in Figure 5. Energy at peak load (E_i) has also been reported as the critical parameter [xx]. Significant difference in E_i is observed with increase in impact energy and with the laminate ply numbers and stacking sequence. Along with the other impact parameters recorded, Table 2 enlists the total absorbed energy with respect to the laminate layup and impact energy. Variation of Total Absorbed Energy with respect to material layup and Impact Energy is also provided in Figure 6. Total energy includes energy to initiate damage as well as the energy required to propagate the damage. After the peak load, the material continues to absorb energy through fiber fracture, fiber pullout, matrix crack propagation, and delamination. Even after maximum load, the composite fails in the progressive manner continuing to absorb much impact energy. It is observed from Table 2, that varying the stacking sequence (0° and 0/90°) didn’t had any significant effect on the impact behavior of the woven composites.



(a)



(b)

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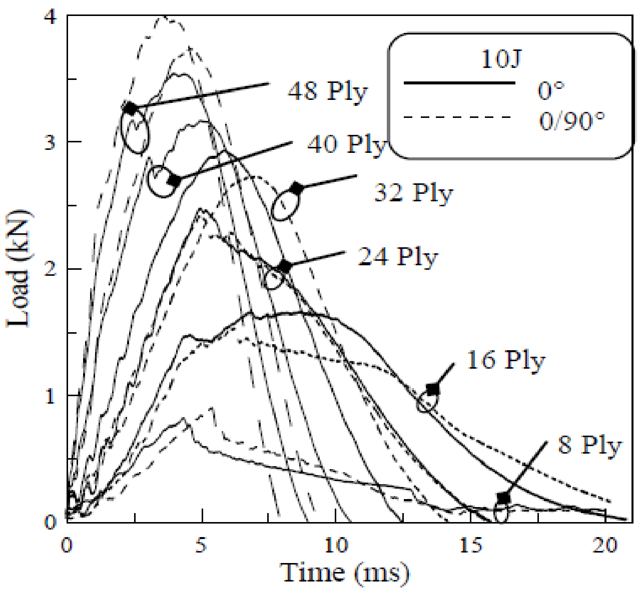

(c)

Figure 2. Load v/s Time plot for specimens impacted at (a) 5J (b) 7.5J (c) 10J.

All composite laminates except the 40 and 48 ply, were impacted at various energies to find the *perforation threshold*, at which the dart penetrates the material and protrudes completely from the back of the laminate. This was obtained by impacting each material by increasing the impact energy until complete perforation of the material took place. Table 2 also provides the values of perforation threshold for each of these woven composite laminates. It is obvious that the resistance to perforate the composite laminate should increase with the increase in its thickness, which is indeed the case. Variation of projected internal delamination area with respect to impact energy and material layup is shown in Figure 6. In this study, it is observed that delamination area increases with the increase in impact energy due to the linear relationship between them as reported in previous studies [6]. Effect of thickness of the material on delamination area is such that the delamination area decreases with the increase of thickness of the composite material until 24 ply and thereafter it was found to increase which lead to the optimal material configuration of 0° 24 ply.

Table 2. Impact test results of all Glass fiber Woven composites

Specimen ID	Perforation Energy (J)	Impacted Energy	Peak Load (kN)	Deflection at Peak Load, mm	Energy to Peak Load, J	Total Energy (J)
0^0 8 Ply	15	5	0.83 ± 0.01	7.7 ± 0.12	3.22 ± 0.05	4.80 ± 0.35
		7.5	0.84 ± 0.02	7.65 ± 0.32	3.22 ± 0.07	7.79 ± 0.87
		10	0.88 ± 0.07	7.93 ± 1.24	3.24 ± 0.47	9.21 ± 1.29
$0/90^0$ 8 Ply	15	5	0.85 ± 0.09	9.03 ± 1.96	4.16 ± 0.45	6.35 ± 0.00
		7.5	0.89 ± 0.02	8.75 ± 1.06	3.50 ± 0.26	7.51 ± 0.62
		10	0.93 ± 0.02	9.26 ± 0.64	3.63 ± 0.14	8.69 ± 0.38
0^0 16 Ply	25	5	1.58 ± 0.00	7.93 ± 0.04	4.84 ± 0.15	5.75 ± 0.07
		7.5	1.66 ± 0.00	8.72 ± 0.98	6.98 ± 0.88	7.90 ± 0.87
		10	1.61 ± 0.08	8.54 ± 0.93	8.38 ± 2.24	10.40 ± 0.75
$0/90^0$ 16 Ply	15	5	1.50 ± 0.03	8.69 ± 0.24	4.71 ± 0.32	5.78 ± 0.03
		7.5	1.49 ± 0.12	8.53 ± 1.33	6.25 ± 1.17	7.84 ± 0.26
		10	1.59 ± 0.06	8.99 ± 0.5	7.42 ± 1.21	10.61 ± 0.36
0^0 24 Ply	30	5	2.00 ± 0.06	6.77 ± 0.34	5.38 ± 0.1	4.02 ± 0.1
		7.5	2.24 ± 0.05	7.14 ± 0.12	7.35 ± 0.07	6.54 ± 0.17
		10	2.40 ± 0.11	8.08 ± 0.66	9.04 ± 1.5	8.96 ± 0.07
$0/90^0$ 24 Ply	20	5	1.90 ± 0.05	6.57 ± 0.34	5.36 ± 0.00	4.33 ± 0.16
		7.5	2.35 ± 0.07	7.94 ± 0.3	7.30 ± 0.62	6.59 ± .15
		10	2.33 ± 0.12	7.98 ± 0.42	8.48 ± 0.32	9.43 ± 0.21
0^0 32 Ply	45	5	1.92 ± 0.02	4.82 ± 0.03	6.04 ± 0.00	5.00 ± 0.00
		7.5	2.41 ± 0.01	6 ± 0.3	8.64 ± 0.04	7.07 ± 0.11
		10	2.91 ± 0.03	6.54 ± 0.03	11.09 ± 0.00	8.83 ± 0.08
$0/90^0$ 32 Ply	40	5	1.89 ± 0.09	4.62 ± 0.67	5.02 ± 0.08	5.07 ± 0.02
		7.5	2.41 ± 0.04	5.7 ± 0.07	8.65 ± 0.00	7.08 ± 0.11
		10	2.78 ± 0.07	6.32 ± 0.27	11.09 ± 0.04	8.92 ± 0.01
0^0 40 Ply	--	5	2.43 ± 0.11	3.92 ± 0.3	5.17 ± 0.04	3.25 ± 0.03
		7.5	2.97 ± 0.02	4.48 ± 0.2	7.43 ± 0.42	4.98 ± 0.05
		10	3.35 ± 0.26	5.25 ± 0.36	9.71 ± 0.36	6.54 ± 0.26
$0/90^0$ 40 Ply	--	5	2.44 ± 0.02	4.05 ± 0.2	5.18 ± 0.02	3.18 ± 0.08

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		7.5	3.02 ± 0.12	4.66 ± 0.26	7.72 ± 0.03	4.60 ± 0.02
		10	3.69 ± 0.06	5.18 ± 0.07	10.07 ± 0.07	6.11 ± 0.12
0^0 48 Ply	--	5	2.69 ± 0.06	3.15 ± 0.01	4.98 ± 0.01	3.22 ± 0.04
		7.5	3.16 ± 0.03	3.95 ± 0.12	7.2 ± 0.6	4.98 ± 0.15
		10	3.68 ± 0.21	4.52 ± 0.00	9.78 ± 0.1	6.34 ± 0.54
$0/90^0$ 48 Ply	--	5	2.77 ± 0.14	3.14 ± 0.22	4.98 ± 0.05	3.19 ± 0.13
		7.5	3.37 ± 0.1	3.75 ± 0.12	7.26 ± 0.14	4.95 ± 0.17
		10	3.94 ± 0.07	4.38 ± 0.40	9.72 ± 0.33	6.15 ± 0.03

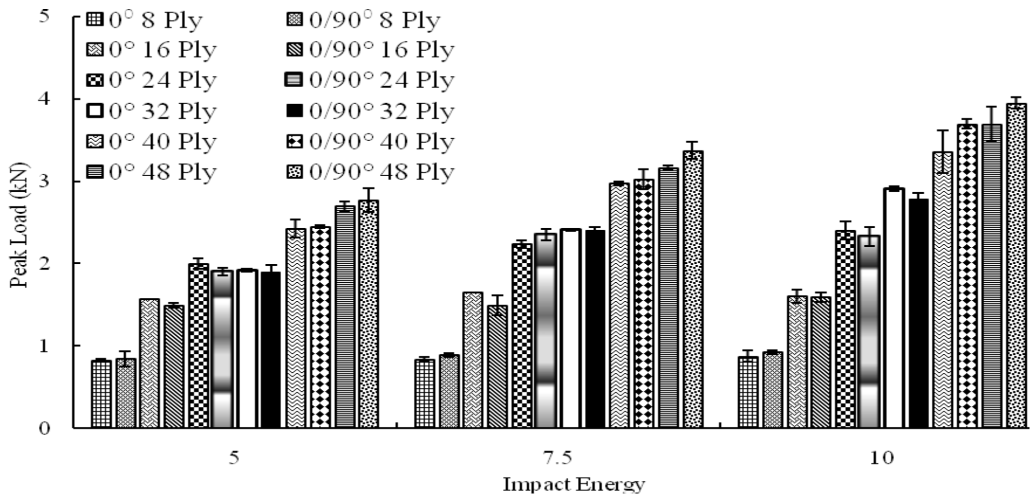

Figure 3. Variation of Peak Load with respect to laminate ply numbers and Impact Energy

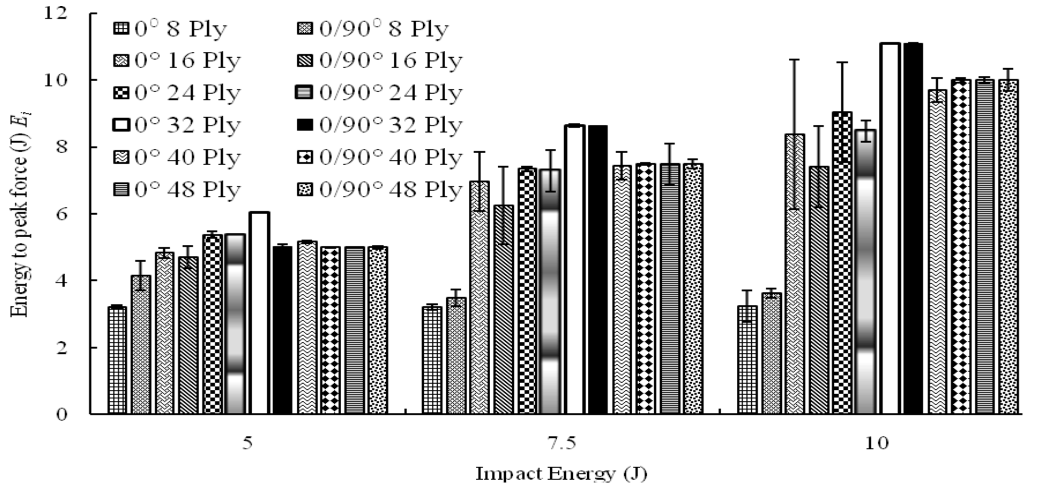

Figure 4. Variation of Energy to Peak load with respect to laminate layup and Impact Energy

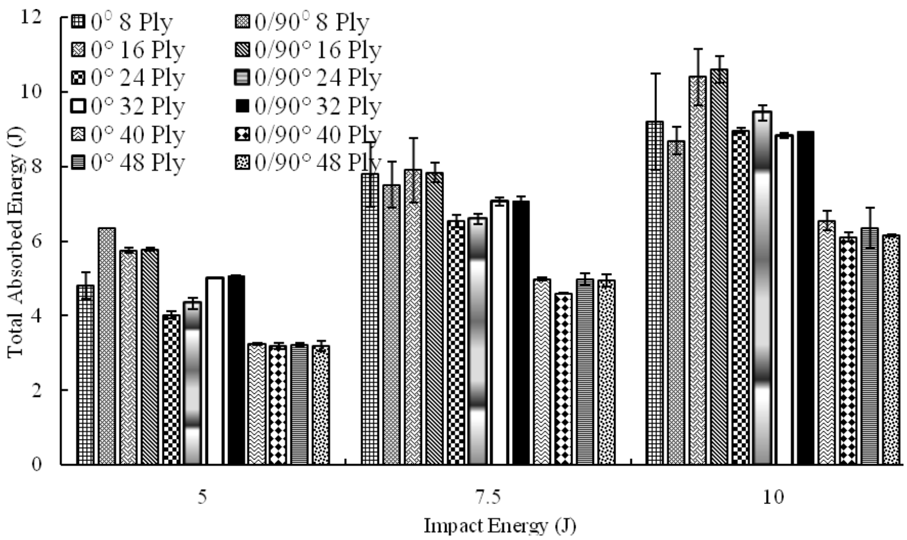

Figure 5. Variation of Total Absorbed Energy with respect to material layup and Impact Energy

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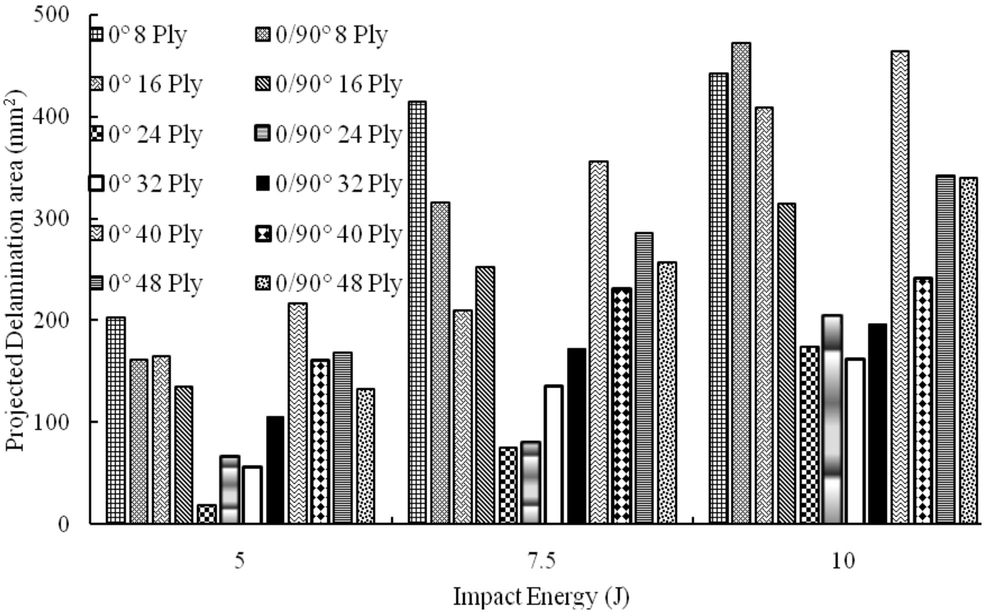

Figure 6. Variation of Delamination area with respect to material layup and Impact Energy

3.1. Residual Strength of Woven Composites

In this study the effect of stacking sequence, thickness, impact energy and damage area on the residual tensile strength of the composite is investigated. Initially data for the specimens which failed at grips were rejected and the gripping pressure was rectified. Most baseline specimens failed laterally in the middle as shown in Figure 8 (a) and the impacted specimens failed at the damage zone perpendicular to the direction of loading as shown in Figure 7 (b).

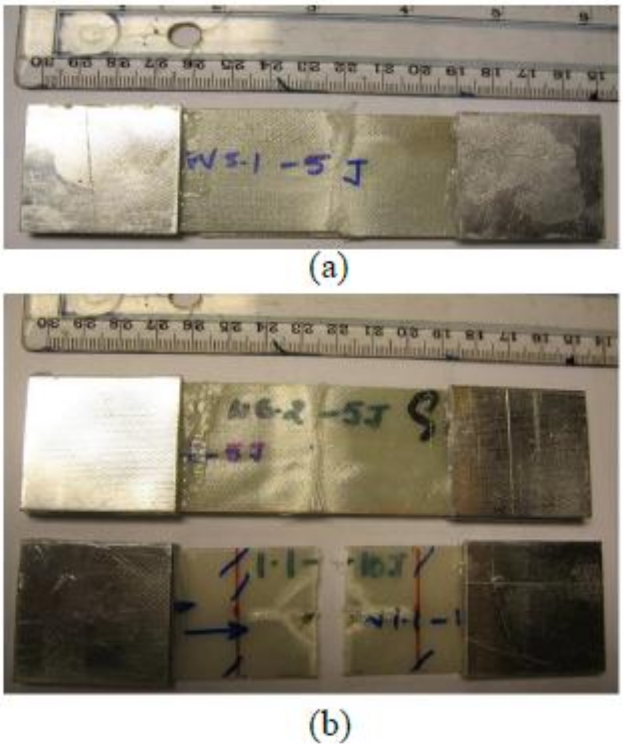

Figure 7. Typical tensile specimen failure (a) Baseline specimen (b) Impacted specimen

Stress vs Strain graphs of all tensile tests performed on 8, 16, 24 and 32 ply specimens impacted at 5, 7.5 and 10J along with the baseline specimens are listed in Table 3 and graphically shown as the stress-strain curves **Error! Reference source not found.**. Figure 9 (a) shows an almost linear behavior up to failure. 0°, 0/90° layup baseline specimens and specimens impacted at 5J showed similar slope i.e. similar modulus. The 8-ply laminates with 0° orientation impacted at 10J exhibited the lowest post impact residual tensile strength, lowest strain at break and lowest modulus of all the laminates tested. This is expected because the 8-ply laminates experience the highest impact energy per unit thickness. As the number of plies increase, the laminates exhibit more of a non-linear stress-strain relationship as observed from Figure 9 **Error! Reference source not found.**At the beginning of the test, stress increases linearly with strain up to an initial leveling off point which signifies initial matrix failure in the laminate, which occurs at 1 % strain in the case of 32 ply laminates. The stress after this point then increases very gradually due to fiber reorientation until failure.

3.2. Factors Effecting Residual Strength

Stacking sequence: As observed from Table 3, the variation in the stacking sequence had no significant effect on the post impact residual strength of the woven composites.

Impact Damage area: Impact damage or Projected internal delamination area increases with the increase in impact energy and there lies a direct relation between the residual tensile strength and

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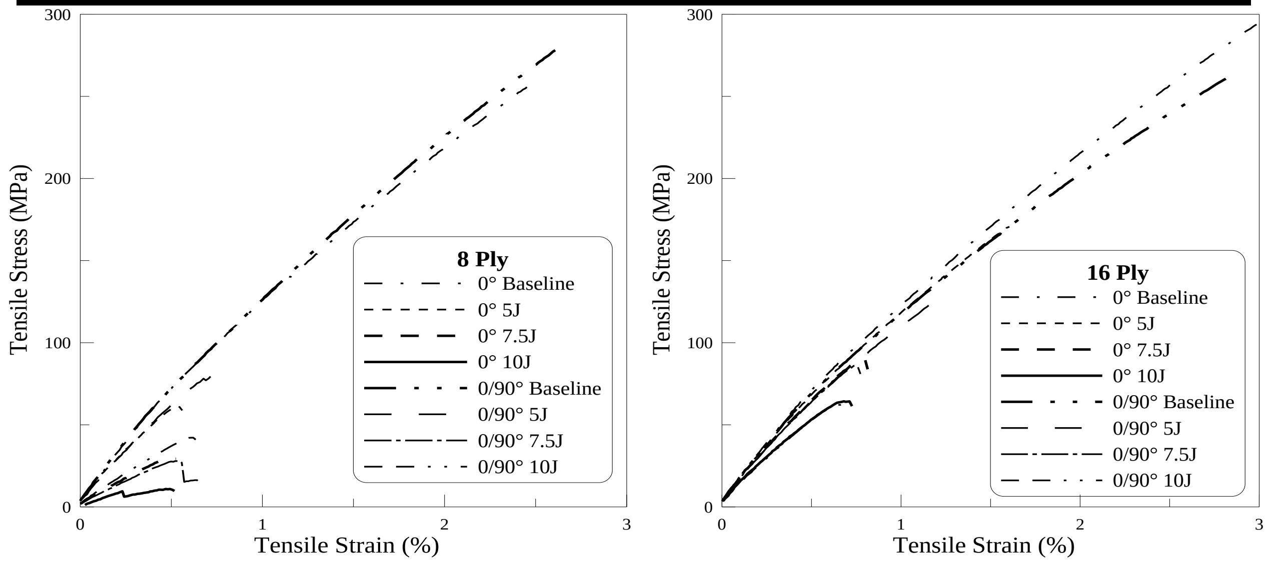
Table 3. Post Impact Tensile test data of woven composites

Specimen	Impact Energy (J)	Energy per unit thickness (J/cm)	Impact Damage area (cm^2)	Tensile Strength (MPa) σ	Strain at break (%) ε	Modulus (GPa) E
0^0 8 Ply	0	0.00	0.00	234.94	2.21	13.71
	5	51.55	2.03	61.30	0.55	14.02
	7.5	77.32	4.15	29.54	0.53	6.71
	10	103.09	4.42	10.92	0.49	4.18
$0/90^0$ 8 Ply	0	0.00	0.00	255.70	2.29	14.69
	5	54.05	1.62	81.50	0.76	13.39
	7.5	81.08	3.16	28.21	0.55	6.17
	10	108.11	4.72	42.17	0.62	8.07
0^0 16 Ply	0	0.00	0.00	289.55	3.14	13.1
	5	24.45	1.66	159.46	1.59	12.97
	7.5	36.67	2.10	88.85	0.81	13.67
	10	48.90	4.09	64.25	0.69	12.38
$0/90^0$ 16 Ply	0	0.00	0.00	273.70	2.80	13.73
	5	26.53	1.36	143.08	1.31	13.54
	7.5	39.79	2.52	86.19	0.75	13.71
	10	53.05	3.15	69.10	0.66	13.27
0^0 24 Ply	0	0.00	0.00	305.66	3.61	13.11
	5	18.45	0.20	269.03	4.17	12.14
	7.5	27.68	0.76	234.20	2.71	12.88
	10	36.90	1.75	104.49	0.98	13.48
$0/90^0$ 24 Ply	0	0.00	0.00	283.07	2.81	14.35
	5	19.12	0.66	283.45	3.40	12.92
	7.5	28.68	0.80	230.60	2.58	12.99
	10	38.24	2.04	111.2	1.11	13.56
0^0 32 Ply	0	0.00	0.00	259.21	4.51	11.76
	5	13.00	0.56	245.43	4.03	11.42
	7.5	19.51	1.35	236.89	4.28	11.17
	10	26.01	1.62	240.72	4.18	11.67
$0/90^0$ 32 Ply	0	0.00	0.00	252.23	4.24	11.46
	5	12.72	1.06	232.38	3.55	11.47
	7.5	19.08	1.72	228.38	3.36	11.21
	10	25.45	1.97	227.57	3.15	11.58



(a) **(b)**

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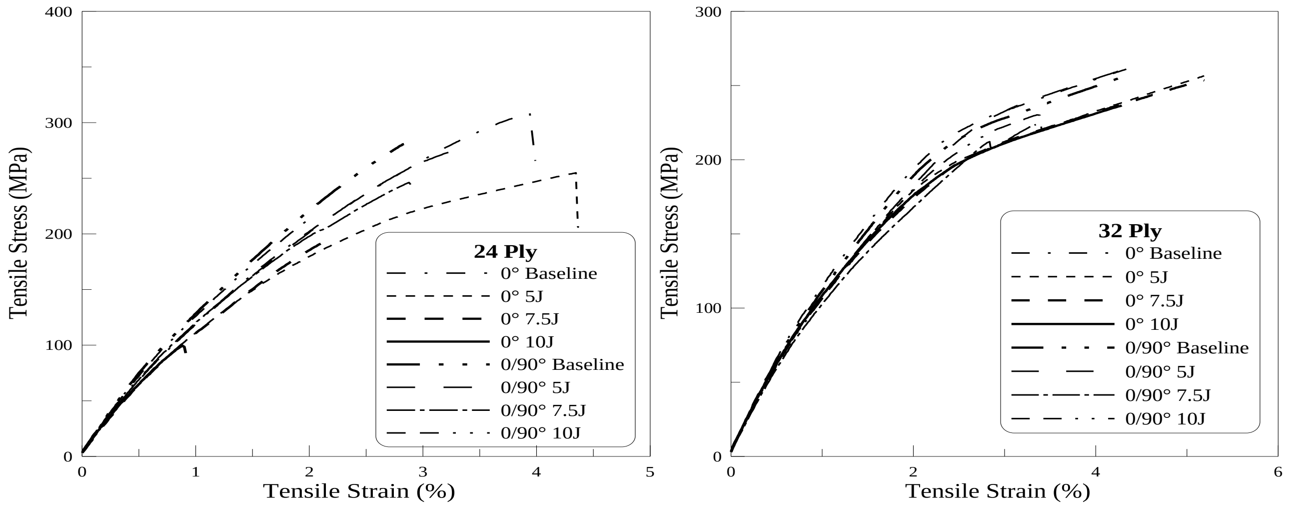

(b) **(d)**

Figure 9. Stress-Strain curve of (a) 8 Ply (b) 16 Ply (c) 24 Ply (d) 32 Ply Woven Composite specimens

The damage area, such that higher the impact energy, higher would be the damage area and lower would be the residual tensile strength. In woven composites, fiber breakage is the common mode of failure as matrix cracks are limited to matrix micro cracks, since the interlaced fibers prevent matrix cracks from excessive propagation and there are less matrix rich regions in woven fiber laminates. Hence delamination in woven composites is associated more with fiber breakage than matrix failure [19]. **Impact Energy:** The residual tensile strength, the strain at failure and the modulus of the composite laminates decreased with the increase in impact energy. But the increase in impact energy had no significant effect on the stiffness and as well as the strength of 32 ply specimen. This behavior can be attributed to the fact that tensile properties in a fiber reinforced composites are influenced predominantly by the integrity of the main load bearing constituent which are fibers and it is possible that the volume of broken fibers could be small in comparison with the sample volume. Delamination and matrix cracks are less susceptible to affect the overall tensile performance of the composite provided that the fibers inside the laminate are undamaged [13,**Error! Reference source not found.**]. Thus it is apparent from the data, that the presence of delamination areas had a negligible effect on the stiffness of 32 ply specimen and hence only specimens with broken fibers showed a decrease in the values of tensile properties. Inverse relationship between impact energy and tensile strength for individual specimens is shown in Figure 8. At 10J impact energy $[0°]_8$ specimen loses highest amount of its tensile strength i.e. by 95**.**35% and at the same energy $[0°]_{32}$ ply specimen loses the lowest amount i.e. by 7**.**13% which is also evident by the steeper negative slope of the trend line for $[0°]_8$ specimen as seen in Figure 8. This is due to the higher impact energy per unit thickness and higher damage area of $[0°]_8$ specimen which leads to its brittle failure also evident by its lowest strain at failure as observed from Table 3.

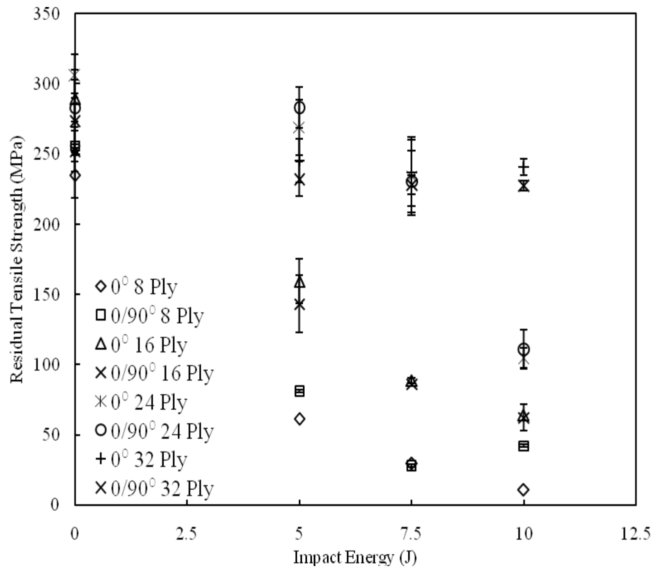

Figure 8. Residual Tensile Strength data vs Impact Energy

Thickness: Effect of thickness on residual tensile strength of each specimen is understood well by bar chart shown in Figure 9 where specimens are arranged in an increasing order of their thickness. With the increase in no. of plies in the specimen the thickness increases and with it increases the resistance to tensile load and hence it is seen from the chart that the residual strength of specimens increase with the increase of thickness and reaches a peak value of 283 Mpa at 24 ply and thereafter even with the increase in thickness to 32 plies, the residual strength drops, which is related to the increase in impact damage area for 32 ply. Thus 24 ply composite was found to be the optimum woven composite material which is in correlation to the findings observed in Figure 2.

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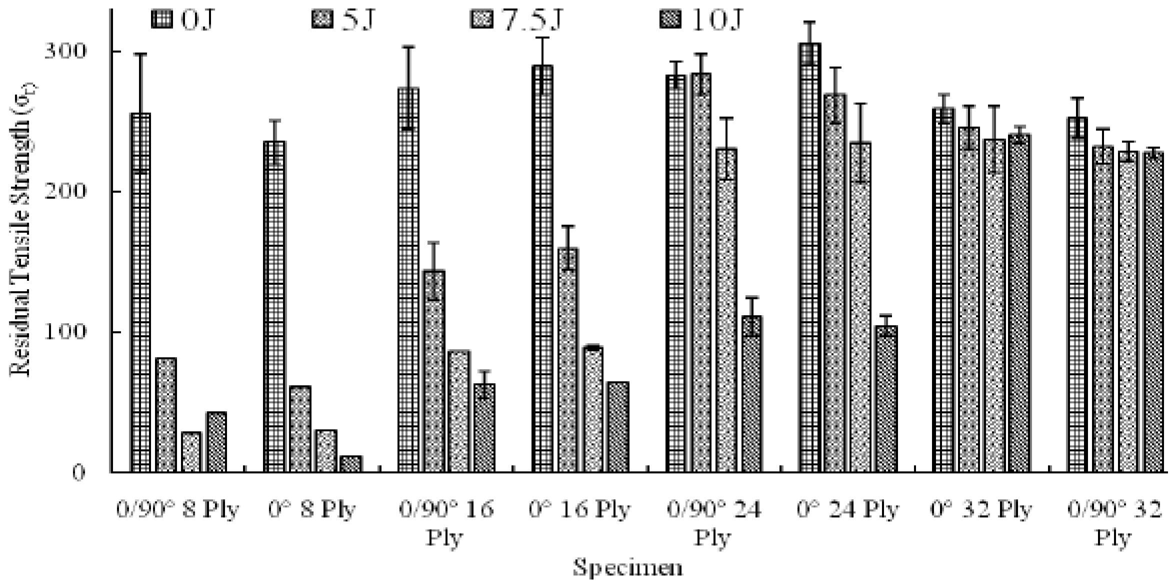

Figure 9. Residual Tensile Strength of all specimens arranged in ascending order of their thickness

IV. CONCLUSIONS

With the aim to investigate the effect of stacking sequence on the impact behavior of GFR woven composite material, drop weight impact tests were performed on the material. Following conclusions were drawn from the results:

- It was observed that the peak load was not only dependent on impact energy but also on the thickness.
- Effect of stacking sequence on the impact behavior was not significant; on other hand the thickness had a significant in improving the impact resistance.
- An optimum material configuration was found based on the impact damage area and post-impact strength of the material.

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