DAMAGE ASSESSMENT OF CFRP AND GFRP LAMINATES SUBJECTED TO LOW VELOCITY IMPACT

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Abstract - *Polymer Composite laminates are fast replacing structural heavy metals such as Cast Iron and steel because of their high strength to weight ratio, higher stiffness to weight ratio, improved fatigue resistance, improved corrosion resistance, higher resistance to thermal expansion and simplicity of manufacture. It is a common knowledge that due to high heterogeneity, these laminates have very poor low velocity impact behavior. To enable design of critical components of aerospace and automotive parts, it is necessary to thoroughly understand the mechanism of damage and suitably arrive at the constituents of the laminate layers.*

This paper presents the experimental study of damage behavior on glass fiber reinforced polymer and carbon fiber reinforced polymer of varied thickness (1 mm and 2 mm) subjected to low velocity impact test at different impact energy levels. Drop/falling weight impact method is conducted as per ASTM D7136 and the incident impact energy is varied by varying the height of the indenter and keeping the mass of the indenter constant. Composite laminates are prepared using Vacuum bagging process and is cured at room temperature. Bi-Woven cloth of 20 GSM is used as the fiber phase and Epoxy resin is used as the Matrix phase. For each level of impact energy, parameters such as absorbed energy, initial and degraded stiffness, peak-absorbed load, deflection at peak load, damage area and maximum damage diameter were determined. For characterizing and understanding the damage process of the impacted specimen, various Non-Destructive testing methods such as Visual Inspection, Radiography and Ultrasonic A-Scan tests are conducted.

Key Words: Glass Fiber Reinforced Polymer, Carbon Fiber Reinforced Polymer, Low Velocity Impact, Drop weight Impact Method, Damage Assessment Non-Destructive Technique (NDT) Testing

INTRODUCTION

Glass Fiber reinforced polymers (GFRP)

Glass Fiber reinforced polymers is a fiber strengthened plastic made from glass fibers**.** GFRP is cheaper and more flexible than CFRP. GFRP are used in boats, automobiles, bathtubs, and enclosures [1].

Carbon Fiber reinforced polymers (CFRP)

Carbon fiber reinforced polymer (CFRP) is a fiber reinforced plastic made from carbon fibers. Carbon fiber reinforced polymer (CFRP) is extremely strong and have high strength to weight ratio. Properties of CFRP rely upon the formats of the carbon fiber and the extent of carbon fiber with respect to polymer matrix [1].

Fabrication of Laminates

The laminates of glass fiber reinforced polymer (GFRP) and Carbon fiber reinforced polymer (CFRP) of 1mm and 2mm thickness were set up by Hand Lay-Up process, following by vacuum bagging method to remove the entrapped air and overabundance resin. The resin used is epoxy resin with fiber orientation in 0 and 90 degrees.

In the Hand Lay-Up process, liquid resin is poured into the mold and the reinforcement is placed on the top. A roller is used to impregnate the fibers with resin. Similarly, different layers of resin and reinforcement layer is applied to make a laminate of required thickness. The laminates prepared by Hand Lay-Up process are further processed by vacuum bagging technique and are cured at room temperature. The laminates sheets once cured are cut into dimension of 150X150 mm with the help of diamond cutter.

Low velocity Impact loading

Impact is defined as a high force or shock applied over a short period of time. The best example for impact is the collision of two bodies. When the two bodies encounter each other, they develop a contact force. In the case of drop weight impact test, when the indenter is impacted on the target, contact force is developed[7]. Impact is classified as low, intermediate, high and hyper velocity. Low velocity impact is one of the causes of damage in composite structures [3]. Low velocity impact may be because of a tool fall, bird hit, striking of foreign objects, debris etc [3]. Because of low velocity impact damage, strength of composite laminatesis reduced to 50% of their initial strength. The residual strength in tension, compression, bending and fatigue will be lessened to differing degrees relying upon the damage mode.

Effects of Impact loading on composite laminates

Composite laminates used in different applications are inescapably subjected to impact damage during manufacturing, maintenance or in-service because of some foreign objects. These impacts result in various damage forms such as Matrix cracking, delamination and fiber cracking which may be overlooked during visual inspection. This unnoticed category of damage is referred to as Barely Visible Impact Damage (BVID), which cannot be seen just through a look by our naked eye, and it causes degradation of structural properties. BVID is observed under low levels of Impact energy and as the Impact energy levels increases, Clearly Visible Impact Damage is observed [5]. According to Fawcett and Oakes from Boeing [6], BVID is characterized as ‘‘small damages which may not be found in general during heavy maintenance general visual inspections using typical lighting conditions from a distance of five (5) feet’’.

The three categories of Impact Damage are

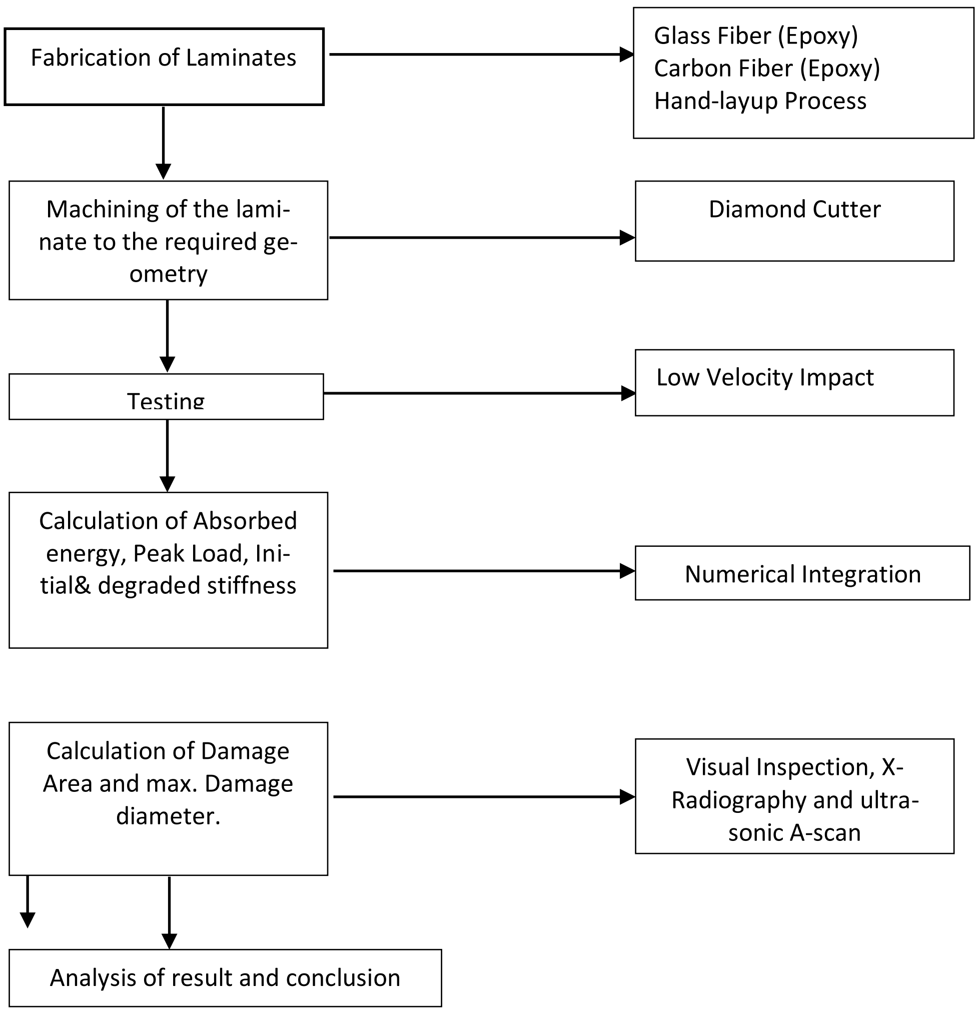
1.Clearly Visible Impact Damage (CVID)

2. Visible Impact Damage (VID)

3. Barely Visible Impact Damage (BVID)

METHODOLOGY

Objective: Damage characterization of laminates subjected to low velocity Impact loading



Damage Assessment

Damage due to impact loading can be assessed by various non-destructive inspection techniques. Researches have used Scanning Electron microscope (SEM) to identify the microscopic damage [2]. Ultrasonic A-Scan, C-scan and X- radiography, thermogram, tomography and various other methods are also conducted for identifying the surface defects and calculation of damage diameter, width, length and area.

Non-destructive Inspection

Composite laminates subjected to impact loading are damaged in different modes and it is not easy to predict the damage mode and calculate the damage. Non-destructive inspection is one of the best methods to do a qualitative and quantitative assessment of damage. NDI is used to understand the properties of the surface and subsurface of the material without causing any damage to the material. [4].

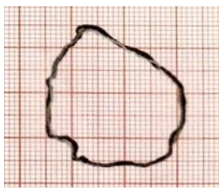
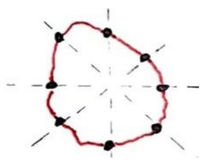
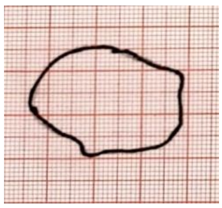
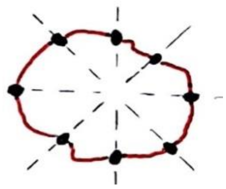
We have used 3 NDI techniques which are:-

Visual inspection

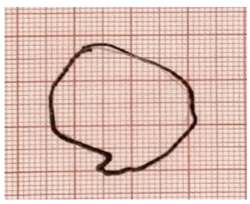
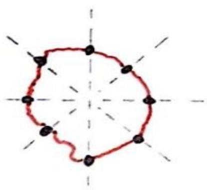
Radiography

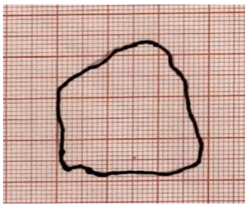
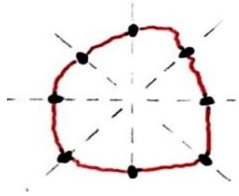
Ultrasonic Testing A-Scan

Damage assessment of Post Low velocity Impact Tested specimens-CFRP-1mm

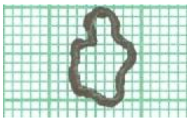
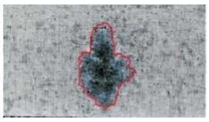
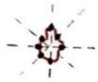
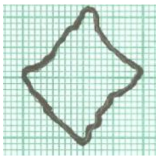
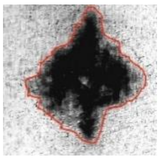
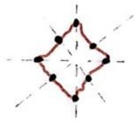
Specimen Designation	Impact Energy (J)	Damage UT 'A' Scan	
E-LVI-04	1.8	**No Damage**	**No Damage**
		Damage area = 0 mm^2 : Max. damage dia. = 0 mm	
E-LVI-05	2.6		
		Damage area = 574 mm^2 : Max. damage dia. = 33 mm	
E-LVI-03	3.5		
		Damage area = 595 mm^2 ; Max damage dia.= 32 mm	

Damage assessment of Post Low velocity Impact Tested specimens-CFRP-2mm

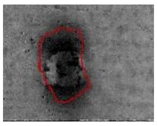
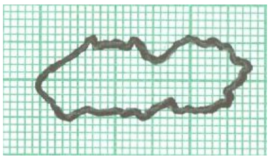
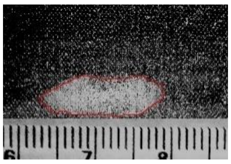
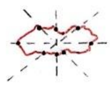
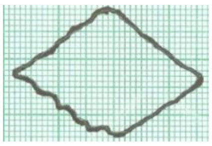
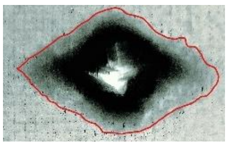
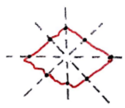
Specimen Designation	Impact Energy (J)	Damage UT 'A' Scan	
F-LVI-03	10.6		
		Damage area = 501 mm^2 ; Max. damage dia.= 29 mm	

F-LVI-05	8.9		
		Damage area = 712 mm^2 ; Max. damage dia. = 35 mm	

Damage assessment of Post Low velocity Impact Tested specimens - GFRP-1mm

Specimen Designa-tion	Impact Energy (J)	Damage		
B-LVI-03	1.8	 Visual	 Radiography	 UT 'A' Scan
		Damage area = 42mm^2 ; Max. damage dia. = 9.5mm		
B-LVI-02	3.5	 Visual	 Radiography	 UT 'A' Scan
		Damage area = 200 mm^2 ; Max. damage dia. = 22 mm		

Damage assessment of Post Low velocity Impact Tested specimens - GFRP-2mm

Specimen Designation	Impact Energy (J)	Damage		
C-LVI-06	3.5	 Visual	 Radiography	 UT 'A' Scan
		Damage area = 37mm^2 : Max. damage dia. = 8mm		
C-LVI-02	7.0	 Visual	 Radiography	 UT 'A' Scan
		Damage area = 211 mm^2 : Max. damage dia. = 28 mm		
C-LVI-05	17.6	 Visual	 Radiography	 UT 'A' Scan
		Damage area = 383 mm^2 ; Max. damage dia. = 35 mm		

UT-'A-Scan', X-radiography and visual inspection clearly collaborate each other both with respect to damage diameter and damage area in the case of GFRP laminates. However, in the case of CFRP laminates visual inspection and X-radiography do not recognize the damage areas and lead to spurious results. In such cases, UT-'A-Scan' is the only method to discern damage. Damage area increases up to fracture point (perforation) and thereafter the area does not increase with increase in impact energy.

EXPERIMENTATION

Low velocity Impact Test

Low Velocity impact test was led on glass fiber reinforced polymer (GFRP) and Carbon fiber reinforced polymer (CFRP) of 1mm and 2mm thickness at different energy levels using Low velocity impact test equipment, which has been designed for carrying impact tests as per ASTM standard.

Figure 8: Low Velocity Impact test equipment.

The specification of the Low-velocity impact test equipment used is as follows:

Table 1: Specifications of Low-velocity impact test equipment.

Height of fall	1.5m (maximum)
Impactor mass	3.6 Kg
Impactor Tip	12.6 mm diameter Hemispherical tip.
Impactor velocity	2 – 6 m/s
Impactor energy	53 J
Load Cell	5000N
Specimen Size	150X150 mm

Geometry and Boundary conditions

The specimen is cut into 150X150 mm with the help of a diamond cutter and is placed inside the fixture with all the sides fixed.

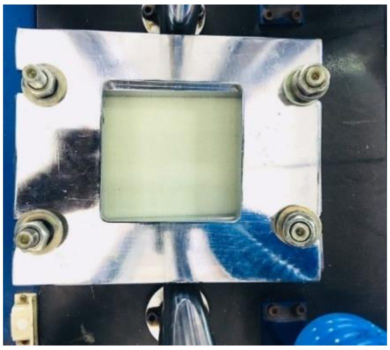


Figure 9 : Fixture set-up with all the sides fixed.

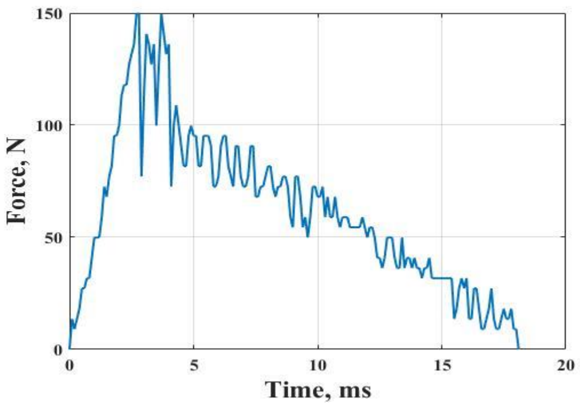
Calculation

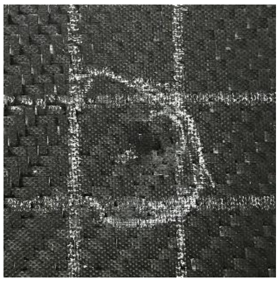
In the Drop-weight impact test, the indenter is dropped from a height under free fall. This free fall has an initial impactor velocity of 'v_i', which is equal to $\sqrt{2gh}$. where h is the height of the impactor from the reference. The potential energy at this height is 'mgh' and this cause formation of kinetic energy from potential energy of $\frac{1}{2}mv^2$ during free fall of the impactor. The impact energy I.E. acting on the specimen is equal to 'mgh' or $\frac{1}{2}mv^2$.

The impactor consists of a load cell; this load cell monitors the contact force, time duration of impact. This data is recorded by the system through data acquisition card, and Force vs time plot is generated.

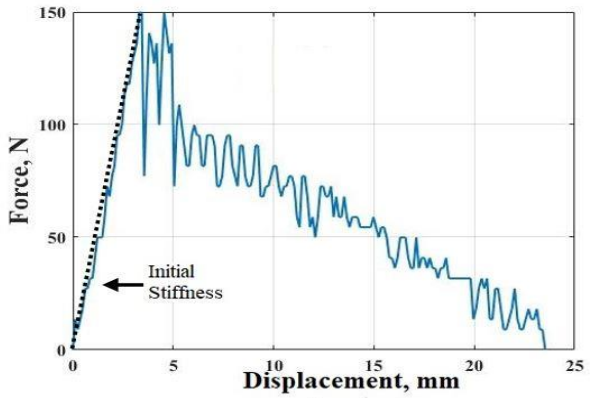
The equations mentioned in ASTM D-7136 [9] are used to find out the velocity at any instant of time, displacement of the impactor and Energy absorbed by the specimen.

Calculation of Low Velocity Impact test of CFRP 1mm (E-LVI-05).

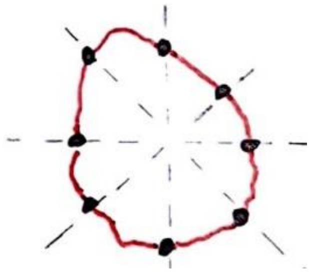




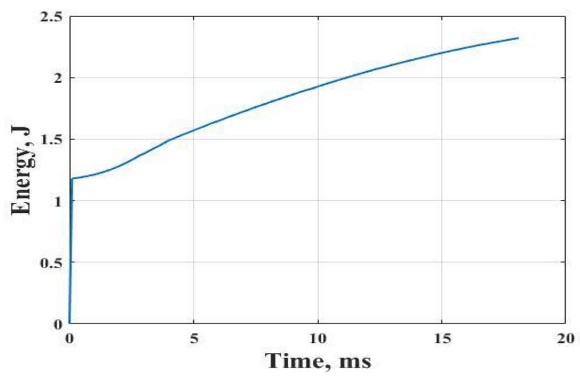
Top view



Bottom view



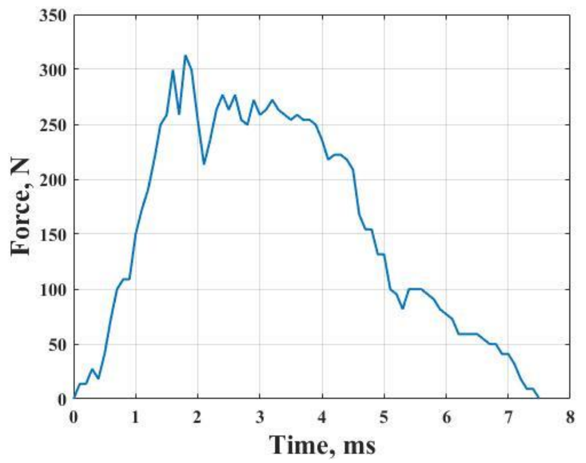
Area of damage at top surface



Impact Energy = 2.6 J
Maximum absorbed energy: 2.3 J
Peak absorbed Load: 150 N
Deflection at Peak load: 4.5 mm
Damage area:574 mm^2 (UT 'A'-Scan)
Max. Damage dia. = 33 mm
Damage mode: Dent, splits

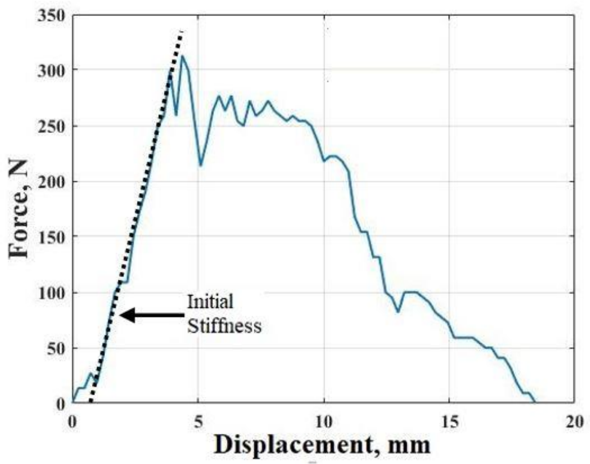
Calculation of Low Velocity Impact test of CFRP 2mm (F-LVI-03).

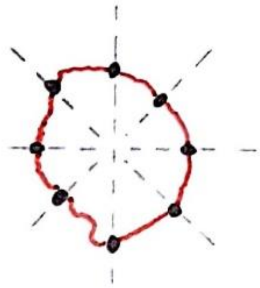
Specimen designation: F– LVI – 03 Dimensions of test specimen: 150 x 150 mm Thickness: 2 mm ASTM Standard: D7136	Mass of the Indenter: 3.6 Kg Indenter type: 12.6 mm Dia. Hemispherical tip Height of Fall: 0.3 m Boundary condition : All edges fixed



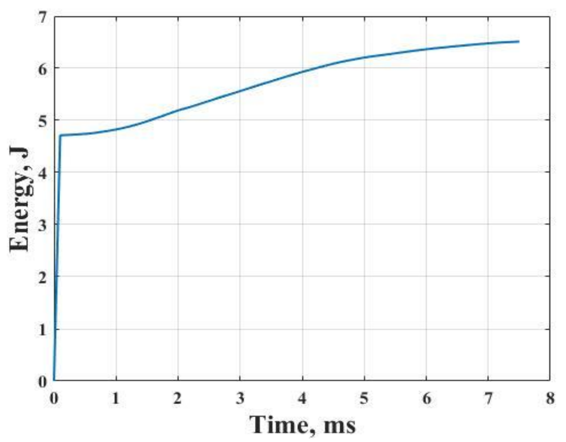
Top view

Bottom view



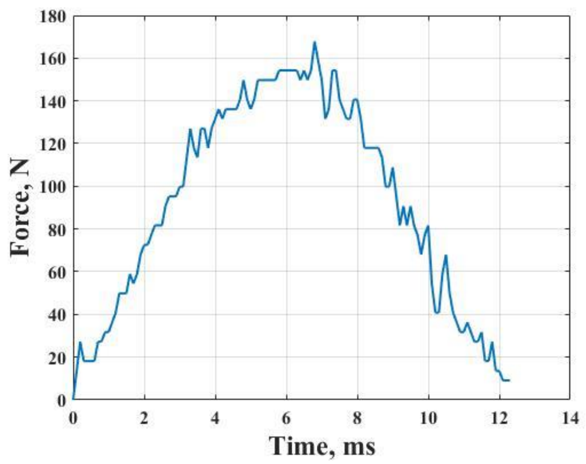


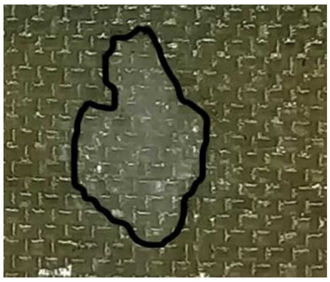
Area of damage at top surface
Impact Energy = 10.6 J
Maximum absorbed energy: 6.5 J
Peak absorbed Load: 325 N
Deflection at Peak load: 4.1 mm
Damage area:501 mm² (UT 'A'-Scan)
Max. Damage dia. = 29 mm
Damage mode: Fiber breakage



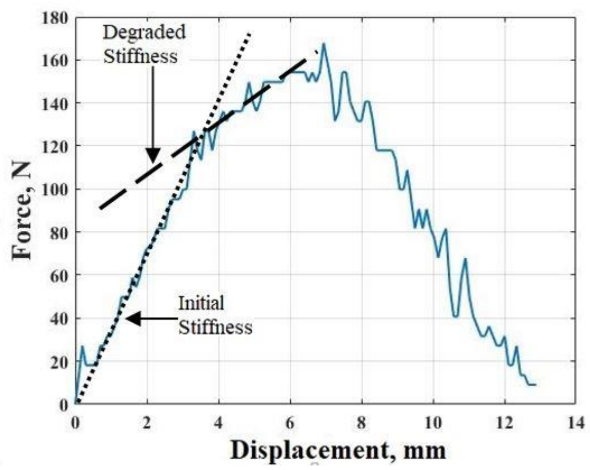
Calculation of Low Velocity Impact test of GFRP 1mm (B-LVI-03).

Specimen designation: B– LVI – 03	Mass of the Indenter: 3.6 Kg
Dimensions of test specimen: 150 x 150 mm	Indenter type: 12.6 mm Dia. Hemispherical tip
Thickness: 1 mm	Height of Fall: 0.05 m
ASTM Standard: D7136	Boundary condition : All edges fixed

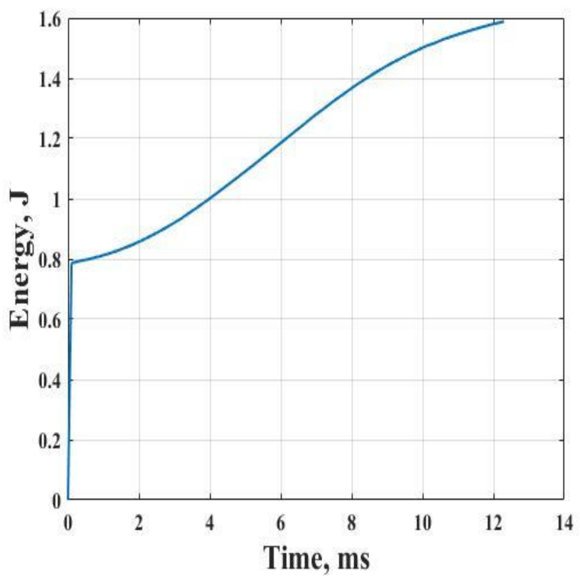




Top view



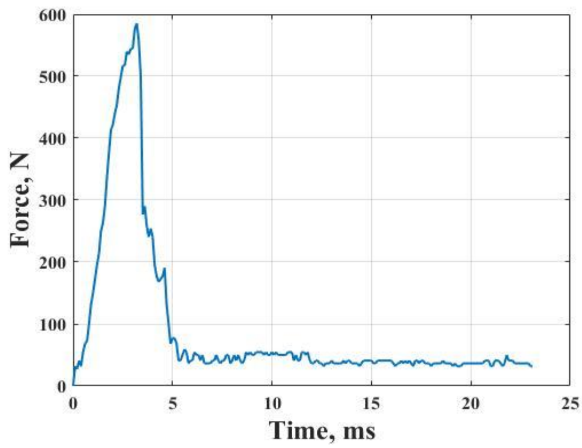
Bottom view



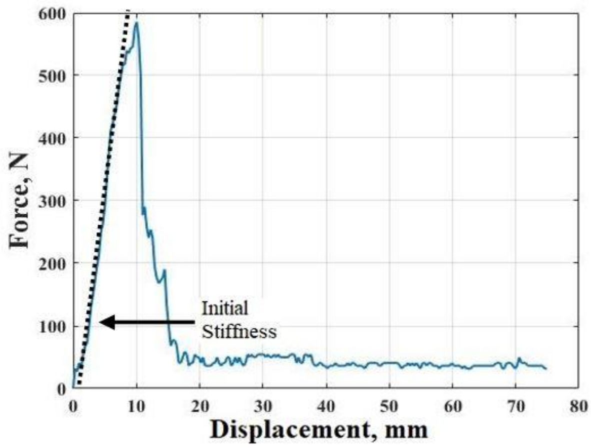
Area of damage at top surface
Impact Energy = 1.8 J
Maximum absorbed energy:1.6 J
Peak absorbed Load: 168 N
Deflection at Peak load: 6.9 mm
Damage area: 42 mm^2 (UT 'A'-Scan)
Max. Damage dia. = 9.5 mm
Damage mode: Delamination

Calculation of Low Velocity Impact test of GFRP 2mm (C-LVI-05).

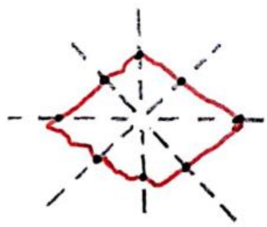
Specimen designation: C– LVI – 05 Dimensions of test specimen: 150 x 150 mm Thickness: 1 mm ASTM Standard: D7136	Mass of the Indenter: 3.6 Kg Indenter type: 12.6 mm Dia. Hemispherical tip Height of Fall: 0.5m Boundary condition : All edges fixed



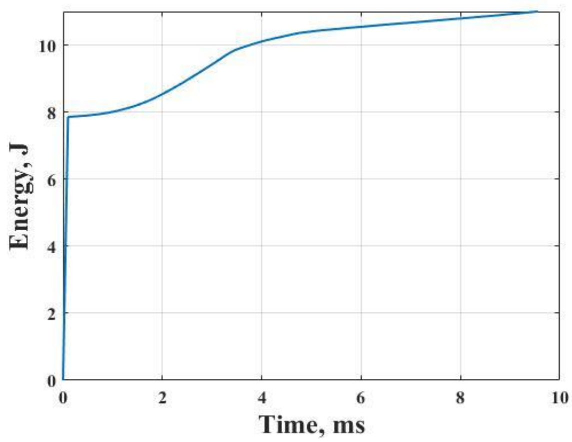
Top view



Bottom view



Area of damage at top surface



Impact Energy = 17.6 J
Maximum absorbed energy: 11 J
Peak absorbed Load: 585 N
Deflection at Peak load: 9.7 mm
Damage area:383 mm^2 (UT 'A'-Scan)
Max. Damage dia. = 35 mm
Damage mode: Fiber breakage.

Like this we done the calculation of the all other specimens CFRP(1mm& 2mm) and GFRP(1mm& 2mm) for which we have made the Tables 2, 3, 4 and 5

RESULTS AND CONCLUSION

Drop weight impact test was directed on laminates of glass fiber reinforced polymer (GFRP) and Carbon fiber reinforced polymer (CFRP) of 1mm and 2mm thickness with varying levels of impact energy. The parameters such as Energy absorbed by the specimen, percentage of energy absorbed, Initial stiffness, degraded stiffness, peak load, damage area and maximum damage diameter were computed and analyzed.

Results of Carbon fiber reinforced polymer

Table2: Results of Low Velocity Impact Test (CFRP – 1mm)

Specimen	Impact Energy (J)	Absorbed Energy (J)	Peak Load (N)	Max. Deflection (mm)	Damage area (mm^2)	Damage dia. (max) (mm)	Initial stiffness (N/mm)
E-LVI-04	1.8	1.7	154	4.4	-	-	38
E-LVI-05	2.6	2.3	150	4.5	574	33	39
E-LVI-03	3.5	2.1	150	3.6	595	32	41
E-LVI-02	5.3	3.6	154	4.0	689	32	40
E-LVI-01	7.0	3.6	168	3.7	681	33	40

Table3: Results of Low Velocity Impact Test (CFRP – 2mm)

Specimen	Impact Energy (J)	Absorbed Energy (J)	Peak Load (N)	Max. deflection (mm)	Damage area (mm^2)	Damage dia. (max) (mm)	Initial stiffness (N/mm)
F-LVI-04	7.1	5.9	360	3.8	450	33	81
F-LVI-05	8.9	7.1	335	4.0	712	35	76
F-LVI-03	10.6	6.5	330	4.1	501	29	80
F-LVI-02	14.1	7.4	381	5.3	730	37	83
F-LVI-01	17.6	8.7	350	3.8	970	39	80

Table 0: Absorbed Energy Results of Low Velocity Impact Test (CFRP – 1mm)

Specimen	Height of fall (m)	Peak Load (N)	Impact Energy (J)	Absorbed Energy (J)	$\frac{E_{absored}}{E_{impact}} \times 100$ (%)
E-LVI-04	0.05	154	1.8	1.7	94.4
E-LVI-05	0.075	150	2.6	2.3	88.4
E-LVI-03	0.1	150	3.5	2.1	60
E-LVI-02	0.15	154	5.3	3.6	68
E-LVI-01	0.2	168	7.0	3.6	51.4

Table5: Absorbed Energy Results of Low Velocity Impact Test (CFRP – 2mm)

Specimen	Height of fall (m)	Peak Load (N)	Impact Energy (J)	Absorbed Energy (J)	$\frac{E_{absored}}{E_{impact}} \times 100$ (%)
F-LVI-04	0.20	360	7.1	5.9	83.0
F-LVI-05	0.25	335	8.9	7.1	79.7
F-LVI-03	0.30	330	10.6	6.5	61.3
F-LVI-02	0.40	381	14.1	7.4	52.4
F-LVI-01	0.50	350	17.6	8.7	49.4

Results of Glass fiber reinforced polymer (GFRP)

Table6: Results of Low Velocity Impact Test (GFRP – 1mm)

Specimen	Impact Energy (J)	Absorbed Energy (J)	Peak Load (N)	Deflection at Peak load (mm)	Damage area (mm^2)	Damage dia. (max) (mm)	Initial / Degraded Stiffness (N/mm)
B-LVI-03	1.8	1.6	168	6.9	42	9.5	34.0 (11)
B-LVI-02	3.5	2.7	182	5.5	200	22	35.0 (0)
B-LVI-07	4.4	2.8	200	5.7	222	24	36.0 (0)
B-LVI-04	5.3	3.0	192	5.0	429	35	37.0 (0)
B-LVI-01	7.0	3.9	195	5.2	472	35	38.0 (0)
B-LVI-05	8.8	4.7	231	6.4	464	45	37.0 (0)

Table7: Results of Low Velocity Impact Test (GFRP – 2mm)

Specimen	Impact Energy (J)	Absorbed Energy (J)	Peak Load (N)	Deflection at Peak load (mm)	Damage area (mm^2)	Damage dia. (max) (mm)	Initial / Degraded Stiffness (N/mm)
C-LVI-06	3.5	3.3	363	7.1	37	8	60.0 (37)
C-LVI-02	7.0	6.0	445	9.7	211	28	60.0 (34)
C-LVI-03	10.6	8.3	517	7.2	316	32	61.3 (0)
C-LVI-08	12.4	8.7	558	12.6	331	34	64.0 (0)
C-LVI-01	14.1	8.9	540	9.2	331	33	62.2 (0)
C-LVI-05	17.6	11.0	585	9.7	383	35	63.0 (0)

Table8: Absorbed Energy Results of Low Velocity Impact Test (GFRP – 1mm)

Specimen	Height of fall (m)	Peak Load (N)	Impact Energy (J)	Absorbed Energy (J)	$\frac{E_{absored}}{E_{impact}} \times \mathbf{100}$ **(%)**
B-LVI-03	0.05	168	1.8	1.6	88.8
B-LVI-02	0.1	182	3.5	2.7	77.1
B-LVI-07	0.125	200	4.4	2.8	63.6
B-LVI-04	0.15	192	5.3	3.0	56.6
B-LVI-01	0.20	195	7.0	3.9	55.7
B-LVI-05	0.25	231	8.8	4.7	53.4

Table9: Absorbed Energy Results of Low Velocity Impact Test (GFRP – 2mm)

Specimen	Height of fall (m)	Peak Load (N)	Impact Energy (J)	Absorbed Energy (J)	$\frac{E_{absored}}{E_{impact}} \times \mathbf{100}$ **(%)**
C-LVI-06	0.1	363	3.5	3.3	94.2
C-LVI-02	0.2	445	7.0	6.0	85.7
C-LVI-03	0.3	517	10.6	8.3	78.3
C-LVI-08	0.35	558	12.4	8.7	70.1
C-LVI-01	0.4	540	14.1	8.9	63.1
C-LVI-05	0.5	585	17.6	11.0	62.5

Note:

1. Damage area and maximum damage diameter obtained from Ultrasonic “A” Scan
2. Initial and degraded stiffness obtained from force – displacement graph

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Graphs:

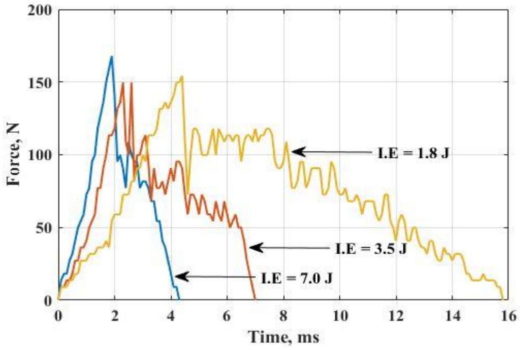

Figure 1:(CFRP 1 mm)

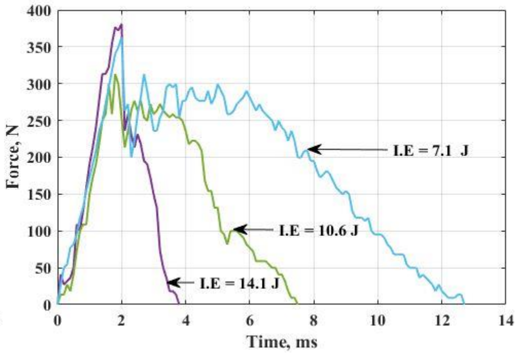

Figure 2: (CFRP 2 mm)

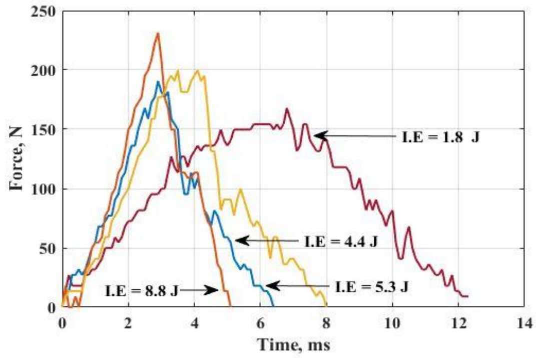

Figure13:(GFRP 1 mm)

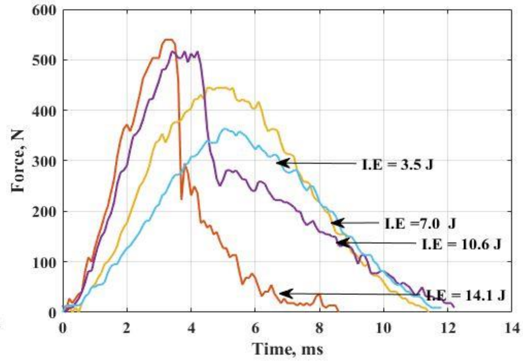

Figure14: (GFRP 2 mm)

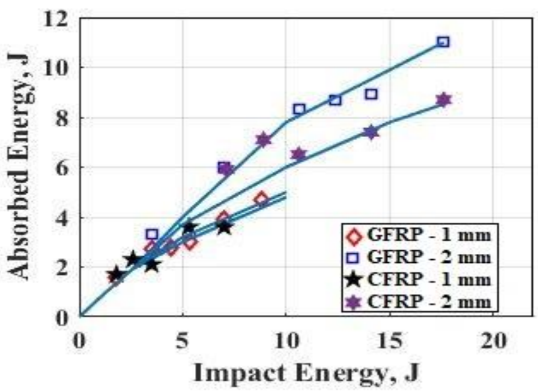

Figure15(a)

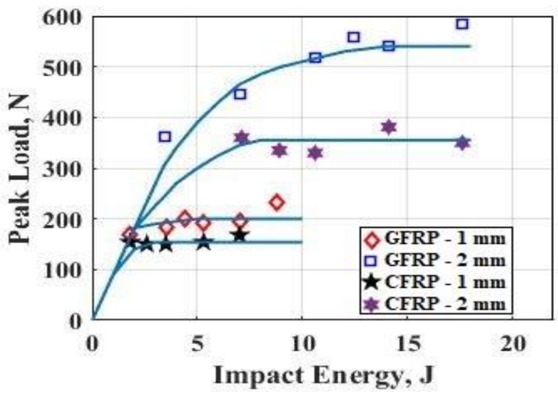

Figure15(b)

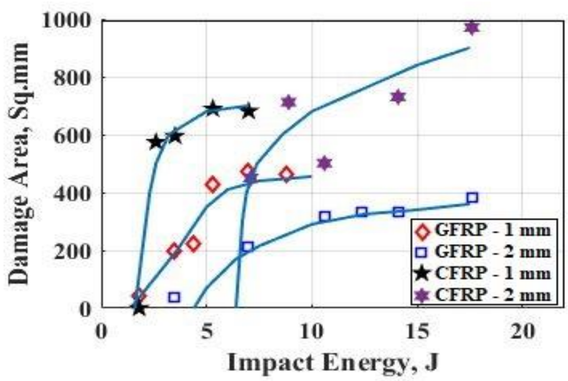

Figure15:.(c)

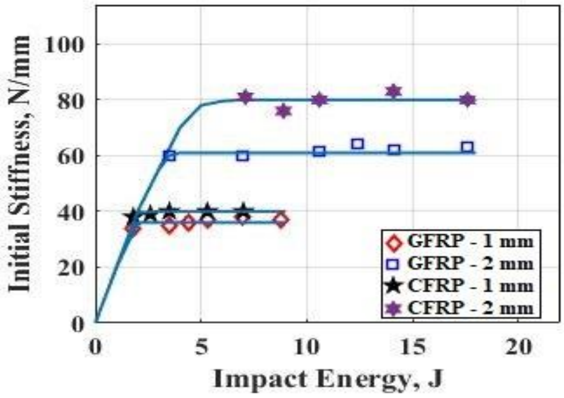

Figure15.(d)

DISCUSSION

Figure 11, 12, 13 and 14 shows the plot of Force vs Time for different levels of incident impact energy(I.E.) on CFRP (1, 2 mm) and GFRP (1, 2 mm). The time duration of impact decreases with increase in incident impact energy and the peak contact force is found to be almost constant as the incident impact energy is increased.

Figure 15(a), (b), (c), (d) shows plot of absorbed energy vs impact energy, peak load vs impact energy, damage area vs impact energy and initial stiffness vs impact energy for CFRP (1, 2 mm) and GFRP (1, 2 mm) laminates. Plot of Absorbed energy vs Impact energy shows the energy absorption behavior of laminates. At low levels of impact energy, the specimen absorbs around 90% of the incident energy and as the incident energy increases, the energy absorbed by the specimen starts decreasing. The specimen at higher values of incident energy absorbs around 50-80% of energy. This is because at low energy levels, the total input energy is absorbed in the form of elastic deformation energy by the specimen and very little amount of energy is dispersed in the form of sound, heat and other forms of energy. As the incident energy is increased, the energy absorption is in the form of plastic deformation and fracture energy, this absorbed energy leads to damage propagation and failure. The energy absorbed is around 50-80% and the rest of the energy dissipated largely in the form of sound, heat and kinetic energy of flying particles. The percentage of absorbed energy for CFRP (1, 2 mm) and GFRP (1, 2 mm) laminates with different levels of incident impact energy is shown in thetables4-3, 4-4, 4-9 and 4-10.

Plot of Peak load vs Impact energy shows the peak load absorbed by CFRP (1, 2 mm) and GFRP (1, 2 mm) laminates. The load absorbed by GFRP laminates is found to be more than that of CFRP laminates. This is because more energy is absorbed by GFRP laminates compared to CFRP laminates for a given incident impact energy since GFRP has more toughness and less stiffness compared to CFRP.

Plot of Damage area vs Impact energy gives understanding of damage in specimen with increasing levels of impact energy. It can be observed that damage propagation takes place in the linear section and material failure takes place at the end of linear section, as a result of perforation, and further increase in impact energy levels will not increase the damage area as saturation levels have been achieved.

From the plot of Initial stiffness vs, Impact energy it is seen that stiffness is not dependent on the incident impact energy and is completely dependent on the material elastic properties and thickness.

CONCLUSION

From the investigation, following conclusions have been made:

Polymer laminates absorb only 50-80% of the incident impact energy and the remaining energy is dispersed in the form of sound, heat, kinetic energy of flying particles and other forms of energy.

Initial stiffness is found to be independent of impact energy and found to be dependent on material elastic properties and thickness. The contact force also remains constant irrespective of the incident impact energy.

The Initial stiffness of 2 mm GFRP laminate (62N/mm) is found to be almost twice that of GFRP 1 mm laminate (35N/mm). Likewise, in the case of CFRP laminates, the initial stiffness of 2mm thickness (80N/mm) sheets is twice that of 1mm CFRP laminates (40N/mm). The trend is in the expected lines as the young's modulus of CFRP laminates (12.6 GPa) is slightly higher compared to GFRP laminates (11 GPa).

The peak-absorbed load of 2 mm GFRP laminate (540N) is found to be more than twice that of GFRP 1 mm laminate (200N). Likewise, in the case of CFRP laminates, the peak-absorbed load of 2mm thickness (350N) sheets is more than twice that of 1mm CFRP laminates (168N). Since more energy is absorbed by GFRP laminates for a given incident impact energy, the peak load is higher in GFRP laminates as compared to CFRP laminates.

The incident impact energy required for complete perforation of GFRP 1 and 2 mm laminates is respectively 2.4 and 7.1 joules. Similarly, the incident impact energy required for complete perforation of CFRP 1 and 2 mm laminates is respectively 3.5 and 14.1 J. Higher impact energy required for complete perforation in the case of CFRP as compared to GFRP is because of higher tensile strength and higher young's modulus of CFRP laminates when compared to GFRP laminates.

Damage modes such as Matrix cracking, fiber cracking and delamination were observed in CFRP (1, 2 mm) and GFRP (1, 2 mm) laminates subjected to low-velocity impact loading.

From the ultrasonic, X-radiography and visual inspection tests (on both CFRP and GFRP),the damage inflicted was found to be 'barely visible impact damage' (BVID) and 'visible impact damage' (VID) at low levels of impact energy and as the energy levels increased, the damages that occur are easily recognized and these come under the category of 'Clearly visible damage' (CVID).

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