Effect of Impactor Mass on Dynamic Response and Retention Properties of Composite Plates under Successive Impacts

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Abstract

This study mainly focuses on the effect of mass of impactor upon dynamic response of laminated composites. For this purpose two different impactors with different masses were used. The impact velocities were selected so that impactors with different masses had the same kinetic energy. The experiments were performed on simply supported woven E-glass reinforced epoxy laminates which are made of 8 layers stacked symmetrically. The variation of impact force, impactor velocity and laminate displacement versus interaction time were obtained. The impulse and energy absorption characteristics and damage zones were also investigated. After low velocity impact, the test specimens were subjected to three-point bending testing in order to get retention mechanical properties.

Keywords: Polymer matrix, laminates, impact and ballistic

1 Introduction

Composite materials may be subjected to unexpected shocks and impacts which can form internal damage such as delamination and back-face splitting or bulging. It is reported that internal damage within composite materials can reduce the residual strength as much as 60% depending on the damage area and deformation mechanisms [1–4].

Low velocity impact response of laminated composites was theoretically investigated by some authors [5-7]. The retention mechanical properties of these materials were investigated by using compression after impact test [8-11]. Impact can produce delaminations and matrix cracks [12–14, 10] and change the internal strain distribution. The general failure modes that can arise within fiber reinforced composites are matrix damage, delamination, fiber damage and penetration [15, 16]. These types of damage are generally barely visible by naked eye. Visible damage occurs if impact has energy above impact energy threshold of the material which is laminate stiffness dependent. Transverse impact first initiates intraply matrix cracks within a lamina. The cracks within a lamina may appear as shear cracks or as bending cracks at the surface of the laminate. Shear cracks are generated by interlaminar shear stresses while bending cracks are generated by tensile stress [17, 18]. The formation and accumulation of these flaws can lead to failure of the apparently undamaged structure. The damage formation and progression can also result in oscillatory interactions of elastic waves created by impact, such as wave reflection at newly

created interfaces inside the material and wave interactions [19].

Belingardi et al. [20, 21] tested thick composite laminates under repeated impacts. The damage progression and energy dissipation of woven glass reinforced composite was investigated [22, 23] under repeated impacts until complete perforation. The resistance to repeated low energy impacts of different fabrics reinforced composites was investigated by Morais et al. [24]. Hosur et al. [25] investigated the repeated impact behaviors of woven carbon/epoxy and woven glass/epoxy composites. Mouritz et al. [26] studied the effect of increasing impact energy and increasing number of repeated impact upon flexural strength and interlaminar shear strength of stitched and non-stitched glass-reinforced plastic (GRP) laminates.

The literature review showed that studies on low velocity impact responses of laminated composites mainly focus on impact response under single impact or repeated impact. However, in practice an impact shows itself as successive impacts in which dropping mass continuously impacts and rebounds until initial impact energy fully consumed. During an impact event 12-15 successive impacts with decreasing intensity can be observed. The contact force is maximum at the first impact and the great majority of the damage occurs during that time. However, successive impacts expand the damage zones and involve the response of damaged material.

The aim of this study is to investigate the effect of impactor mass on the dynamic behaviors of composite laminates. The experiments were performed on a drop weight testing machine by using two different impactors with different masses. The experiments were performed on simply supported woven E-glass/epoxy laminates. The reason why this material has been selected is that its simple nature and well characterized properties. So, it is believed that the obtained results can easily be generalized and applied to different kinds of composite materials which are in complex nature.

The impact forces and laminate deflections versus interaction time have been obtained. Impulse force and kinetic energy absorption of the laminate subjected to different strike velocities have also been investigated. After the impact test, the damage formation on the laminates was assessed and effects of impact loading upon mechanical properties were obtained by using three point bending test.

2 Experimental Studies

2.1 Materials

The test specimens are 8 plied woven E-glass/epoxy. The dimensions of the test specimens are 90x25x3mm. Table 1 presents the mechanical properties of the matrix and reinforcement materials. Components were cured at 80 oC for 2 hours and were cut down to the specified dimensions of the test specimens by using high revolution speed circular saw under water coolant. Then, the materials inspected by naked eye in order to determine possible perforations such as interlaminar damage and edge delaminations which could form during cutting. However no noteworthy perforations were observed. The composite materials were then subjected to mechanical testing and burn off test. Table 2 shows the mechanical properties of composite plates.

Table 1 Mechanical property of the fiber and the matrix

	E (GPa)	σ_{TS} **(MPa)**	ρ **(g/cm³)**	ε_{max} **(%)**
E-glass	73	2400	2.6	4-5
Epoxy	3.4	50-60	1.2	1.5-2

Table 2 Properties of specimens

Strength (MPa) (longitudinal direction)	632	Fiber volume fraction (%)	80±0.6
Strength (MPa) (Transverse direction)	68	Longitudinal Elasticity Modulus (GPa)	43
Poisson's ratio	0,19	Transverse Elasticity Modulus (GPa)	12

2.2 Testing Set-up

An instrumented drop weight impact testing machine was used to perform tests. It consisted of a drop tower equipped with an impactor and a variable crosshead weight arrangement, a 22.24 kN force sensor and a data acquisition system to acquire the contact force-time history. The impactor has a semi-cylinderical tip with 12 mm diameter. The testing

machine and impactor assumed to be perfectly rigid. Fig.1 schematically shows the testing set up.

The force signals produced by the sensor are in milivolts and first amplified by a signal processor and then transmitted to the data acquisition card within a PC. The variations of interaction force between the impactor and the sample versus time were obtained by using NI Signal Express software.

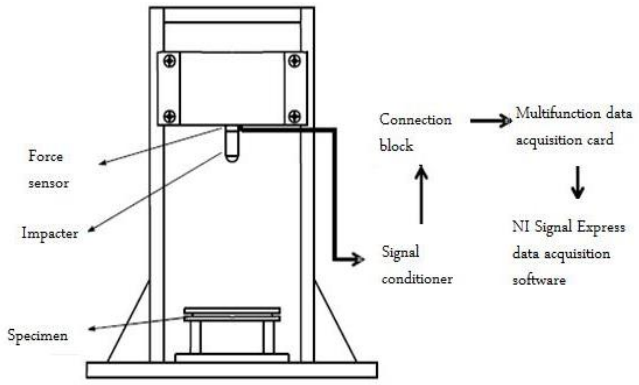


Figure 1 Impact test stand

2.3 Testing Procedure

The height and mass of the impactor was varied in order to obtain various impact energies. The tests were done by using two different masses as 13 kg and 6.5 kg in order to obtain the effect of dropping mass. The impact velocities were selected in such a way that different dropping masses result in same impact energies. So the effect of dropping mass and impact velocity become clear. The tests were conducted for three different velocities and separately repeated three times. The used test parameters are presented in Table 3.

Table 3 Test parameters

Dropping mass (kg)	Initial strike velocity (m/sec)		
13	1	1.25	1.5
6.35	1.44	1.8	2.16
Impact Energy (J)	6.5	10.2	14.6

The data acquisition system can transmit 10.000 data pairs per second. Newton's second law of motion can be used to express the acceleration as in Eq.(1). Here a, F and m represents acceleration, force and mass respectively while i represents each successive data points.

$$a_i = \frac{F_i}{m} \tag{1}$$

It is reported that the acceleration can be expressed as linear functions of time as follows [27].

$$a(t) = k.t + c \tag{2}$$

Where

$$k = \frac{a_i - a_{i-1}}{t_i - t_{i-1}} \tag{3}$$

$$c = \frac{t_i a_{i-1} - t_{i-1} a_i}{t_i - t_{i-1}} \tag{4}$$

in which the coefficients k and c should be determined for successive data points. The velocities and the displacements were obtained by the integration of the following equations over a time step which has been defined by successive data points.

$$dv = a(t)dt \Rightarrow \int_{v_{i-1}}^{v_i} dv = \int_{t_{i-1}}^{t_i} a(t)dt$$

$$ds = v(t)dt \Rightarrow \int_{s_{i-1}}^{s_i} ds = \int_{t_{i-1}}^{t_i} v(t)dt$$

The impulse force and absorbed energy can be defined as follows. Here, J, W and t_f represents impulse force, absorbed energy and interaction time.

$$J = \int_0^{t_f} F.dt$$

$$W = \frac{1}{2} m(v_{initial}^2 - v_{final}^2)$$

When the impactor first hits the material, the kinetic energy of the impactor is partly transferred to the material. The remaining kinetic energy is used for rebound which makes the impactor rise. This process continues until the kinetic energy of the impactor is fully consumed. During this process the material is subjected to 12-15 impacts. However it is concluded that first 5 impacts transfer great majority of the kinetic energy of the impactor to the material and damage forms at this period.

The specimens were tested under simply supported boundary condition in which two opposite sides are supported while the other two sides were free. So the

specimens can show free angular deformation and vertical deflection.

3 Results and Discussions

Figs. 2-4 show the variation of impact force versus interaction time. As seen in these figures as the impact velocity increased impact forces increase. When the first impact occurs some of the initial impact energy is transferred to the material and impactor rebounds. This process creates successive impacts and continues until initial energy of impactor is fully consumed. It is seen in Figs. 2-4 that forces at each successive impact decreases.

It is seen in Figs. 2-4 that the impact force increases with increasing impact energy. However, though the same impact energy applied the higher impact velocities resulted in higher impact forces. It is also seen in Figs. 2-4 that for the same impact energy, the interaction time for small dropping mass is smaller than that of bigger dropping mass. Besides it is concluded that the bigger mass creates some oscillations at force-time variation.

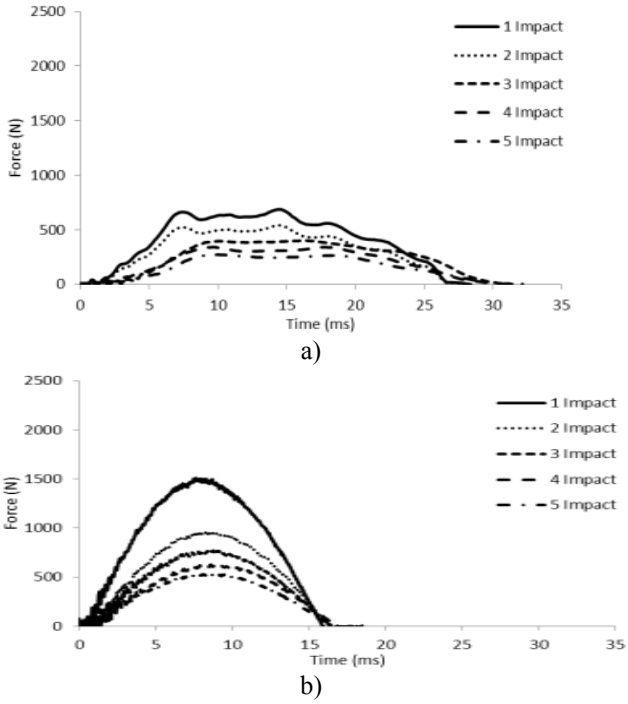


Figure 2 Variation of impact force with interaction time for impact energy of 6.5 J a) dropping mass=13kg, initial impact velocity= 1m/s, b) dropping mass=6.35kg, initial impact velocity=1.44 m/s

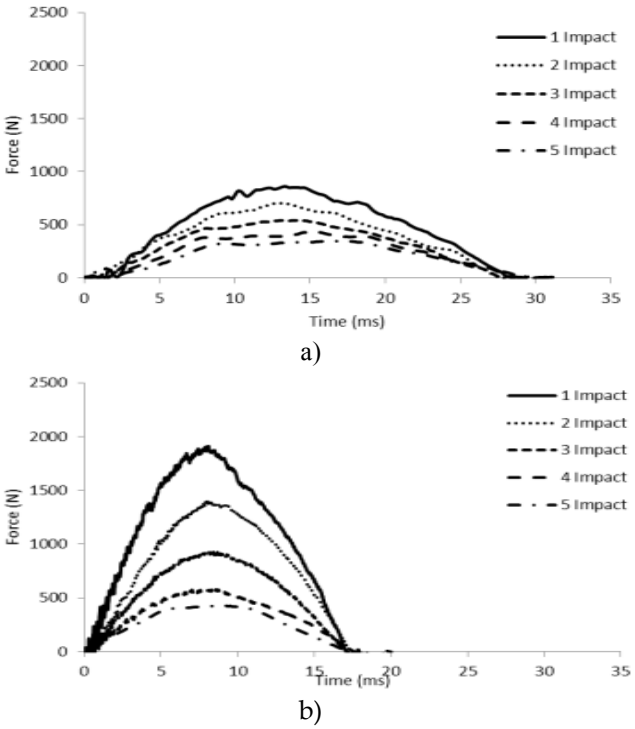


Figure 3 Variation of impact force with interaction time for impact energy of 10.2 J a) dropping mass=13kg, initial impact velocity= 1.25m/s, b) dropping mass=6.35kg, initial impact velocity=1.8 m/s

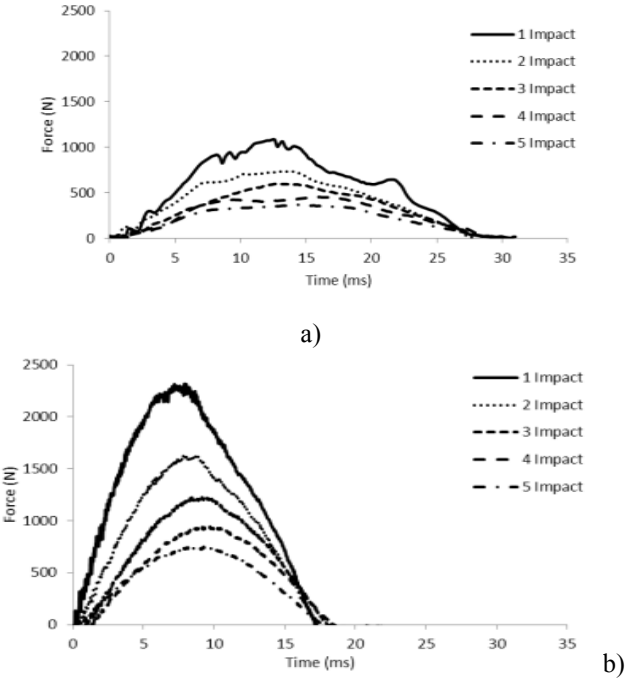
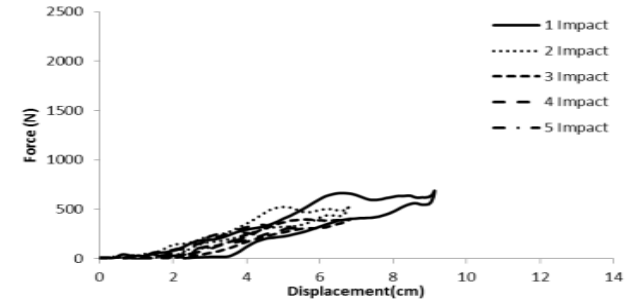


Figure 4 Variation of impact force with interaction time for impact energy of 14.6 J a) dropping mass=13kg, initial impact velocity= 1.5m/s, b) dropping mass=6.35kg, initial impact velocity=2.16 m/s

Figs. 5-7 show the variation of vertical displacement versus impact load for different levels of impact en-

ergy. As seen in these figures considerable energy consumption occurs at each successive impact. However latter impacts consume less energy than former impacts do. It is also seen that as the level of impact energy increased the vertical displacement of material increased. It is also worth noting that the same energy levels obtained by different parameters created similar vertical displacements.



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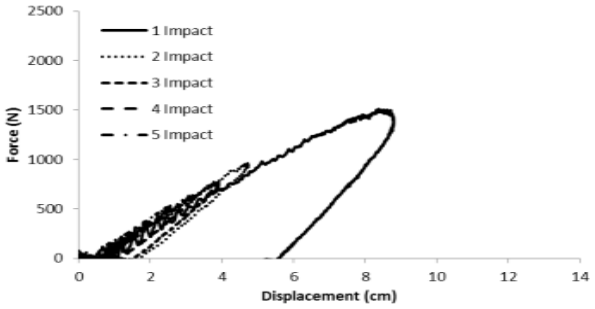

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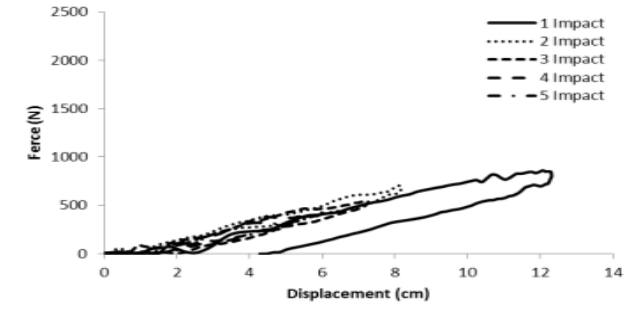
Figure 5 Variation of impact force with deflection for impact energy of 6.5 J a) dropping mass=13kg, initial impact velocity= 1m/s, b) dropping mass=6.35kg, initial impact velocity=1.44 m/s



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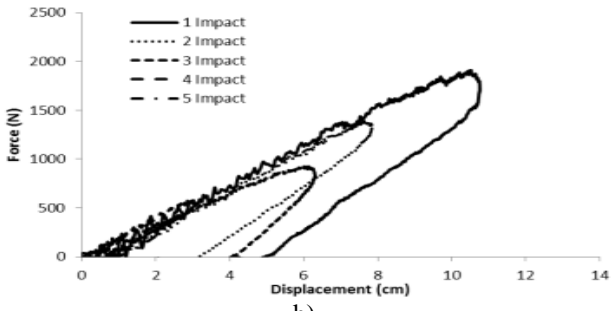

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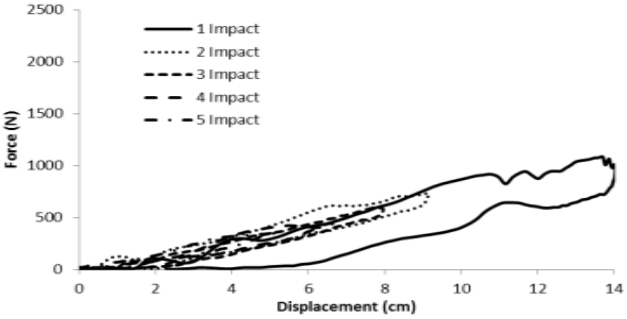
Figure 6 Variation of impact force with deflection for impact energy of 10.2 J a) dropping mass=13kg, initial impact velocity= 1.25m/s, b) dropping mass=6.35kg, initial impact velocity=1.8 m/s



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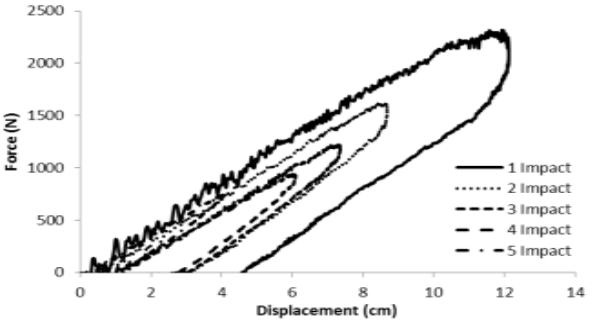

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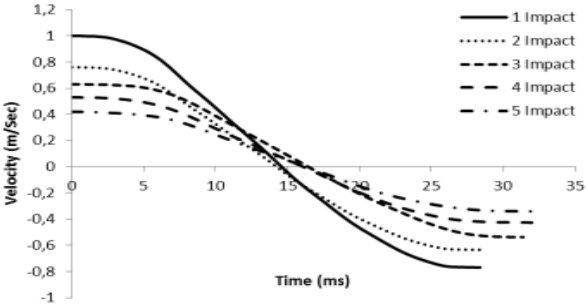
Figure 7 Variation of impact force with deflection for impact energy of 14.6 J a) dropping mass=13kg, initial impact velocity= 1.5m/s, b) dropping mass=6.35kg, initial impact velocity=2.16 m/s

Figs. 8-10 show the variation of impactor's velocity during interaction for different levels of impact energy. As seen in this figure each impact starts from a specific velocity and decreases to zero. After that point the impactor reverses and has a negative velocity and creates rebound. The initial velocity of next impact is the final velocity of previous impact. This situation continues until initial kinetic energy of the impactor fully consumed.



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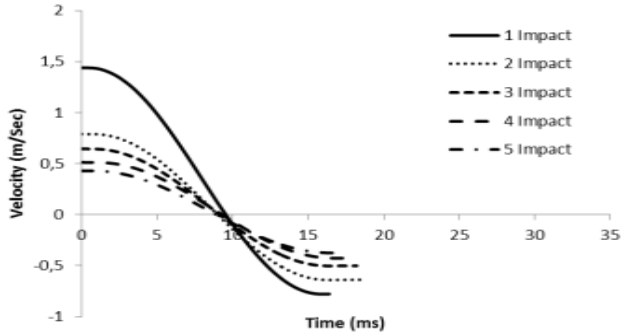

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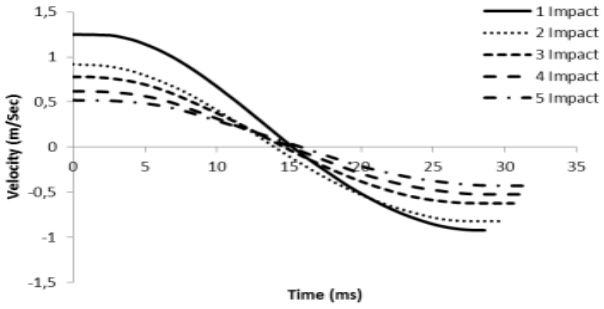
Figure 8 Variation of velocity with time for impact energy of 6.5 J a) dropping mass=13kg, initial impact velocity= 1m/s, b) dropping mass=6.35kg, initial impact velocity=1.44 m/s



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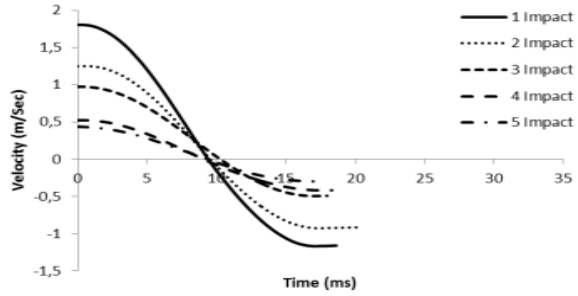

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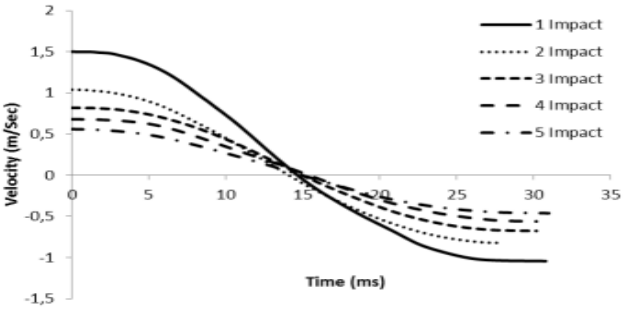
Figure 9 Variation of velocity with time for impact energy of 10.2 J a) dropping mass=13kg, initial impact velocity=1.25m/s, b) dropping mass=6.35kg, initial impact velocity=1.8 m/s



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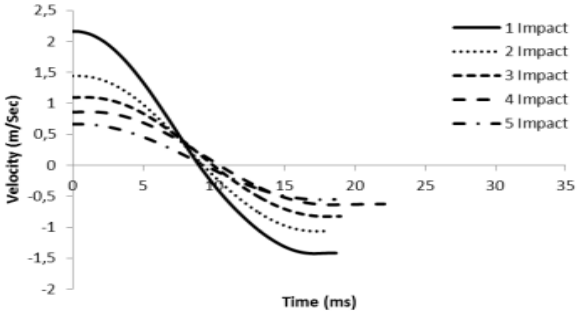

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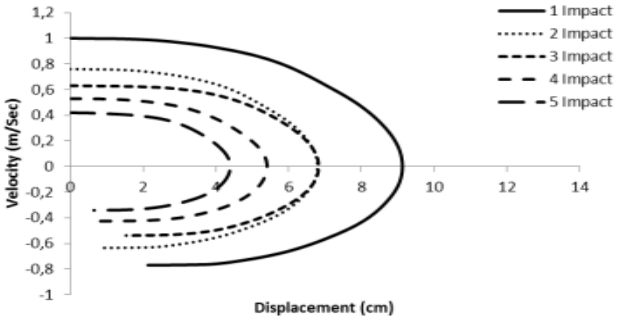
Figure 10 Variation of velocity with time for impact energy of 14.6 J a) dropping mass=13kg, initial impact velocity=1.5m/s, b) dropping mass=6.35kg, initial impact velocity=2.16 m/s

Figs. 11-13 show the variation of impactor velocity versus vertical displacement of material for different levels of impact energy. As seen in these figures as the impactor moves down the velocity decreases and then the displacement reaches its maximum when the velocity reaches to zero. After that point the velocity started to increase in negative direction while the displacement decreases and rebound starts. This situation is similar for all impacts. At the first impact some of initial kinetic energy is transferred to the material. So the impactor never reaches its initial height at the latter impacts. So velocities of each successive impact are lower than former impacts as seen in Figs. 11-13. It is also seen in these figures that as the initial impact energy increased the vertical displacements increases.



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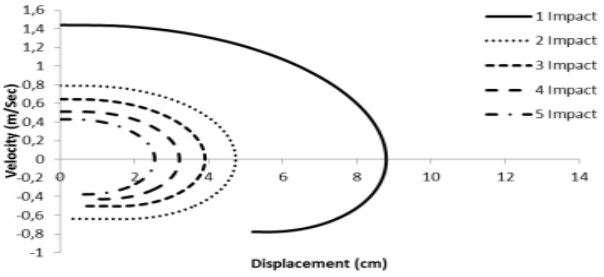

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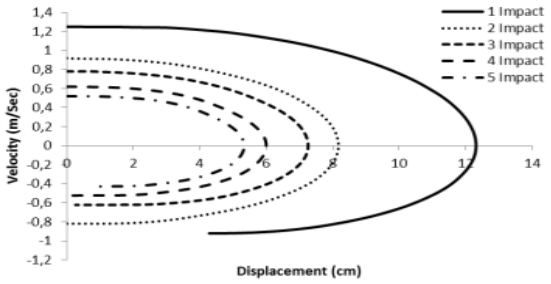
Figure 11 Variation of velocity with deflection for impact energy of 6.5 J a) dropping mass=13kg, initial impact velocity=1m/s, b) dropping mass=6.35kg, initial impact velocity=1.44 m/s



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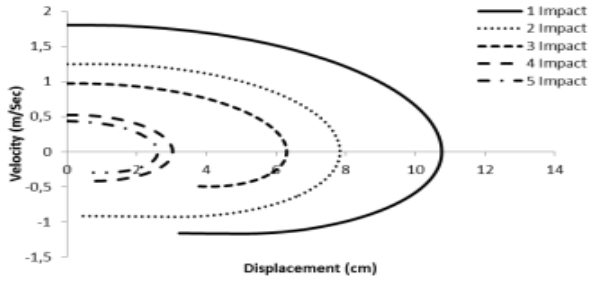

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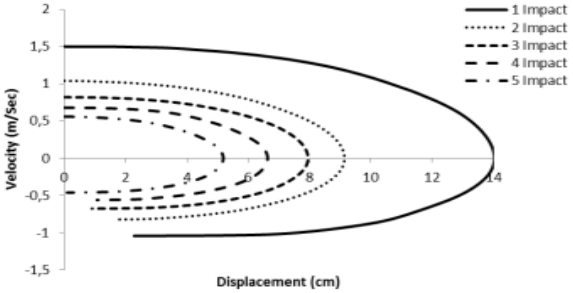
Figure 12 Variation of velocity with deflection for impact energy of 10.2 J a) dropping mass=13kg, initial impact velocity=1.25m/s, b) dropping mass=6.35kg, initial impact velocity=1.8 m/s



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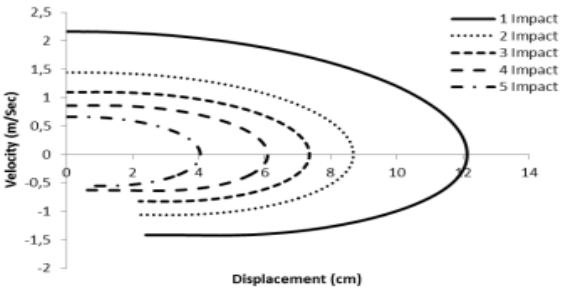

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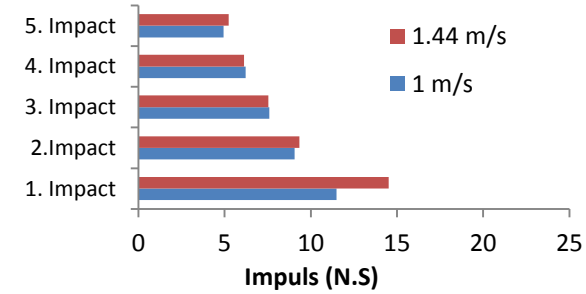
Figure 13 Variation of velocity with deflection for impact energy of 14.6 J a) dropping mass=13kg, initial impact velocity=1.5m/s, b) dropping mass=6.35kg, initial impact velocity=2.16 m/s

Figure 14 shows the variation of impulse force for first 5 impacts under different dropping masses. It is seen in this figure that as the impact energy level increased the impulse force increases. Besides it is seen that as the energy level increased the effect of impact velocity upon impulse force become effective at the first three impacts.



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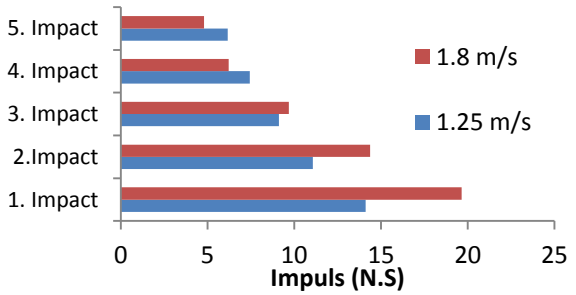

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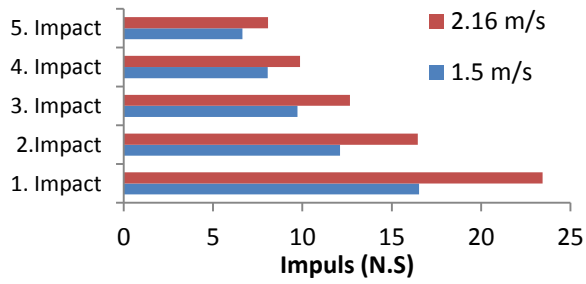
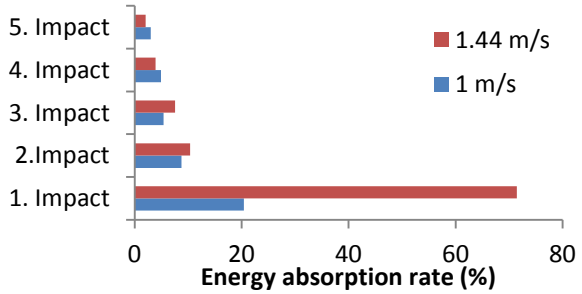


c)

Figure 14 Variation of impulse force at the successive

impacts a) Impact energy level: 6.5 J, b) Impact energy level: 10.2J c) Impact energy level: 14.6 J

Figure 15 shows the variation of energy absorption rate at each successive impact for different impact energy levels. As seen in this figure, the kinetic energy of small mass is absorbed more than that of big mass. It is seen that approximately 55-70% of initial kinetic energy of small dropping mass is absorbed at the first impact while 20% of initial kinetic energy of big dropping mass is absorbed. The energy absorption rate decreases dramatically at the successive impacts.



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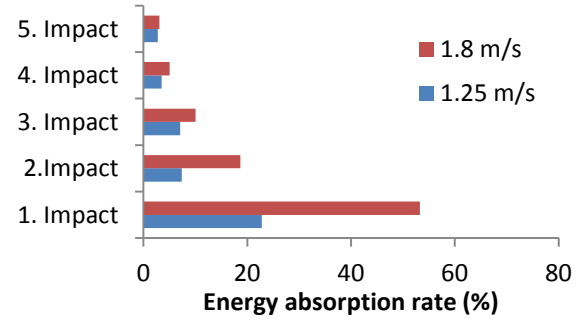

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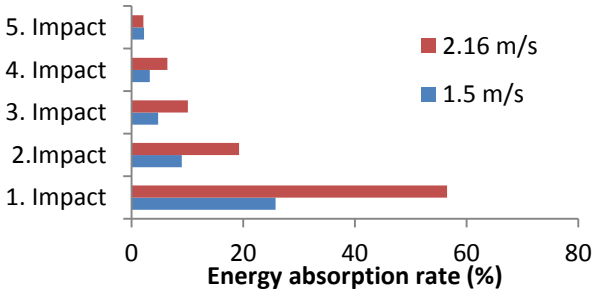


c)

Figure 15 Variation of energy absorption rate at the successive impacts a) Initial impact energy level: 6.5 J, b) Initial impact energy level: 10.2J c) Initial impact energy level: 14.6 J

Table 4 summarizes the peak forces, maximum vertical displacements and interaction times for impacts test performed under different dropping masses and impact velocities. As seen in this table small dropping mass results in small interaction times. So the peak impact forces of small mass are bigger than that of big mass. On the other hand big mass results in larger displacements. It is also seen that as the impact velocity increased peak vertical displacements increase.

Table 4 The peak force, peak displacement and interaction time for different strike velocities

The retention mechanical properties of impacted composite materials were obtained by three point bending test with feed rate of 5 mm/min. Table 5 shows the retention properties. As seen in this table, both retention bending strength and retention bending elasticity modulus decreased with increasing strike velocity. The retention bending strength and flexural modulus show the same behavior in case of dropping mass of 6.35 kg. However this decrease is small in comparison with decrease observed in specimens tested by 13 kg.

	Dropping mass=13 kg			Dropping mass=6.35 kg		
	Initial strike velocity			Initial strike velocity		
	1m/s	1.25m/s	1.5m/s	1.44m/s	1.8m/s	2.16m/s
Retention bending strength	89±4	76±6	52±7	95±3	92±2	90±4
Retention flexural elasticity modulus	81±6	72±5	47±5	90±3	87±4	83±4

Table 5 Retention mechanical properties after low velocity impact

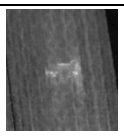
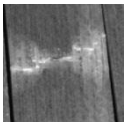
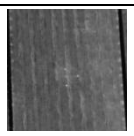
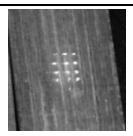
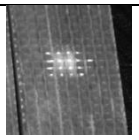
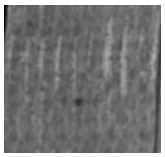
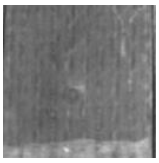
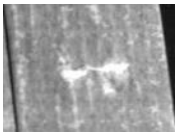
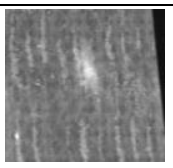
Dropping Mass (kg)	Initial strike velocity (m/s)	Peak force (N)	Interaction time (sec)	Peak displacement (m)
13	1	712±5	0.0284±7	0.015835±4
	1.25	734±6	0.0284±5	0.022092±3
	1.50	915±8	0.0290±3	0.027441±5
6.35	1.44	1509±5	0.0175±6	0.009853±5
	1.8	1910±5	0.0192±5	0.014116±4
	2.16	2317±6	0.0190±6	0.014676±6

4 Damage Assessments

The kinetic energy of the impactor is used for formation of damage types such as fiber/matrix breakage, fiber pull-out, fiber breakage and delamination. Depending on kinetic energy of the impactor one or more types of damages can form within composite material.

Table 6 contains images captured by laser scanner and shows the damage formed at the front and back surfaces of the material. As seen in this figure, for the dropping mass of 13 kg, as the strike velocity increases the damage on both front and back surfaces increases and the debonded regions increases in size. It is also seen that strike velocity of 1 m/s creates only matrix cracking. However, as the strike velocity increased the damage forms not only as matrix cracking but also as delamination and fiber debonding. The material still keeps its structural integrity and keeps some load carrying capacity, since the fibers have not broken. It is concluded that the damage formed on the front surfaces are mainly as a result of impact force induced indentation and bending effect while the damage formed on the back surface is as a result of indentation.

Table 6 Front and back surfaces of the material after impact under different strike velocities (1.6X)

Dropping mass=13 kg	Initial strike velocity	1 m/sec	1.25 m/sec	1.5 m/sec
	Front surface			
		a)	b)	c)
	Back surface			
		d)	e)	f)
Dropping mass=6.35 kg	Initial strike Velocity	1.44 m/sec	1.8 m/sec	2.16 m/sec
	Front surface			
		a)	b)	c)
	Back surface	No visible damage	No visible damage	
		d)	e)	f)

The impactors with different masses produce the same impact energy. However, the dropping mass of 6.35 kg created much less damage. The impact with strike velocities of 1.44 m/s and 1.8 m/s created only matrix cracking on the front surface and a small indentation while almost no damage has formed on the back surface. The impact with strike velocity of 2.16 m/s created a small delaminated zone in addition with matrix cracking on the front surface. However, debonding of a fiber bundle is seen on the back surface of the specimen.

5 Conclusions

The low velocity impact behavior and retention mechanical properties of E-glass reinforced epoxy lami-

nates under successive impacts have been investigated. Two different dropping masses were used. The retention mechanical properties were determined by three point bending test performed after low velocity impact.

The kinetic energy of the impactor is consumed by successive impacts. It is observed that the latter impacts absorb lower energy than the former impacts do.

It is concluded that for the dropping mass of 6.35 kg, great majority of impact energy is consumed at the first impact. However, for the dropping mass of 13 kg this situation is not true.

The damage increases with increased strike velocity. It is concluded that damage preliminarily occurs as a combination of matrix cracking and fiber debonding and while the strike velocity increased matrix cracking and debonding is followed by delamination.

Considerable mechanical degradation was observed after impact testing. The mechanical tests showed that increased strike velocity resulted in more decrease in mechanical properties which is mainly due to the formation of fiber debonding and delamination. However, small dropping mass created much less damage on both surfaces of the specimens which causes much less mechanical degradation.

It is concluded that, when the test specimens were impacted by a heavy mass damage within specimens mainly consists of heavy forms of damage such as fiber breakage and delamination. As a result of these damage formations a great loss in load bearing capasity and bending stiffness can be encountered. However, as a result of impact by a small mass, the contact forces are generally not high enough to breake the fibers and/or create delamination and the whole kinetic energy consumed mainly by matrix cracking which does not result in greate decrease in mechanical properties since these properties controlled by fibers.

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