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Analysis of Composite Laminate Under Ballistic Impact by Bullets of Different Types

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Abstract: Today, composites are expansively used in almost every field like in aerospace, automobile, military, industries, construction and many more. In these fields, they may be exposed to impact loads at times, ballistic loads to be precise. Therefore, it is very important to be aware of the response, damage evolution and the behavior of the material to such loads. Impact load is a rate-dependent load and acts for a short time but does the damage. This study intends to optimize the existing Kevlar epoxy material for the ballistic helmets. An effort is made to suggest a suitable replacement for the same. The material considered here is a carbon fiber epoxy composite. A finite element model of three dimensions is developed for the composite laminate. The ballistic impact of two bullets on this composite is simulated employing finite element method using ANSYS workbench 15 explicit dynamics and the same is validated analytically. The energy absorbed upon impact is checked for different thicknesses and for different kinds of laminate. At the end, a suitable kind of laminate with a suitable thickness is suggested for the replacement.

Key words: Composite laminate, ballistic impact, finite element modeling, analytical validation, suggested, efforts

INTRODUCTION

Composites are a class of materials who have been used in more or less every field. They find applications in aerospace-in making of airplane body parts, fuselage and other parts as well; in military-bulletproof jackets, ballistic helmets for soldiers, lightweight guns, etc., industries-making of boilers, other accessories; construction-road bridges, bathroom fixtures, etc. Composite materials undergo various impact loadings during their life span. Impact loads include low velocity and high velocity loads. Low velocity include dropping of tool on the surface or punching of dye, high velocity include effect of bird strike, ballistic impact, terminal ballistics and many more. The composites to be used in military or marine applications where the probability of impact loads are much higher compared to other applications, the material has to be first checked whether it can tolerate such high load or not. Investigations on the projectile impact behavior such as impact due to a bullet and the subsequent damage initiation and propagation are the foundation of the ballistic analysis that help checking the survivability of the material. The support conditions play a very important role in these tests. In low velocity tests, these influence the energy absorption unlike the high velocity tests which is independent of supports. It solely depends upon the constraints that we assign and the complete energy is transferred to the material being impacted upon. Many investigations have been carried out in this field and they say that the stress rate and strain rate of a polymer composite plate increase considerably with the impact velocity and the deformation is sudden at the time of impact.

There have been several models on this analysis. Long (2015) presented a rate-dependent material model of a polymer composite and showed the damage progression through finite element modeling and subsequent graphs. The material considered was a T300/NY9200GA or carbon fiber/epoxy material. A round conical steel projectile was impacted upon the plate and the subsequent deformation and the changes in the contact force were analyzed and summarized in a graph. Team of Bandaru *et al.* (2016) have experimentally investigated a Kevlar fabric for the ballistic test and have found that thermoplastic based composite laminates were able to sustain bullet impact and the ballistic limit increased with increase in adhesion between Kevlar and polypropylene matrix. Apart from experiments and analytics simulation was also carried out and the results were tabulated and compared. There was close resemblance among the results. Puente *et al.* (2007) have

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done experimental and simulation experiments on ballistic impact on CFRP laminates. The energy absorption mechanism was plotted and an analytical model was presented based on the theory that the kinetic energy lost by the projectile is equal to the sum of crushing energy and energy transfer due to momentum and the tensile fiber failure energy of the composite laminate. Morye *et al.* (2000) developed a simple analytical model for the calculation of energy absorption mechanism for the ballistic impact on the laminate. The determined value of ballistic limit was compared with three different composite models and the results were compared with the experimentally determined ones.

MATERIALS AND METHODS

Materials and properties: The composite material considered in this work is a T700/epoxy or carbon fiber/epoxy composite. It is used in the structural applications. Two kinds of the laminate was investigated, one is the symmetric angle ply type and the other is the cross ply type. It is assumed that both the fiber and matrix are linearly elastic. The material was developed in the CAD Software Fusion 360. The physical properties of the material are given as follows in Table 1. The density is equal to 1549.79 kg/m^3. The thickness of each ply was kept as 0.15 mm. The orientation for the angle ply laminate was taken as (0, 60) (0, 60, -60) and (0, 60, -60, 45). The laminate is symmetric in nature. The projectile considered here are two bullets. First bullet is a standard 7.62×39 mm Full Metal Jacket (FMJ). It was developed by soviet union and is in use since then. This bullet is used in an AKM rifle. It has a copper plated steel jacket in the core, it has a soft steel core and lead filling the gap between core and the jacket. The second bullet is a 5.56×45 mm Full Metal Jacket (FMJ). This bullet is currently being used in M16 assault rifles. The details of the bullets are given as follows in Table 2.

Development of damage model: A damage model is prepared and the mechanisms were investigated. Certain assumptions had to be assumed while conducting the analysis. The assumptions are:

- The projectile is rigid and has no deformation in any direction
- The friction between the projectile and material is neglected and the heat generated is negligible
- The failure of composite is uniform across the thickness
- The fibers in each layer act independently
- There is no change in the strain rate

Table 1: Properties of the composite material

Properties	Values
E_1 [Pa]	4.77E+10
E_2 [Pa]	4.77E+10
E_3 [Pa]	1.0E+10
G_{12} [Pa]	1.83E+10
G_{13} [Pa]	3.82E+09
G_{23} [Pa]	3.82E+09
μ_{12}	0.304
μ_{13}	0.316
μ_{23}	0.316

Table 2: Different parameters of the bullets

Bullet (mm)	Bullet diameter (mm)	Maximum velocity (m/sec)	Maximum pressure (MPa)	Mass of the bullet (g)
7.62×39	7.92	739	355	7.9
5.56×45	5.70	940	430	0.4

These assumptions stand raised during the energy transferred to the composite. The damage in the composite occurs mainly in four different stages:

- The tensile fiber failure of primary yarns
- The failure of secondary yarns
- The cracking of the matrix material
- Delamination of the laminate

The first layer of fiber coming in contact with the bullet tear out absorbing ample amount of energy. Next the secondary yarns which provide the maximum resistance to impact absorb the maximum energy and are dependent upon the number of ply layers and the tensile strength of the lamina. During the damage occurrence a cone is formed at the back face of the laminate symbolizing the frontal cone shape of the bullet. Delamination of the composite takes place and after all these stages the laminate finally fails and the bullet penetrates completely through the laminate. Different types of damage like delamination, fiber and matrix damage in a CFRP composite panel is shown by Long (2015) (Fig. 1).

Analytical model: The analytical model for the laminate includes the calculation of material matrices and the different varieties of energies the composite laminate absorbs. The analytical model for calculation of material matrices includes for a symmetric angle ply lamina in the 1-2 plane, stress-strain relation are given by:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} \tag{1}$$

Where $[Q_{ij}]$is the stiffness matrix:

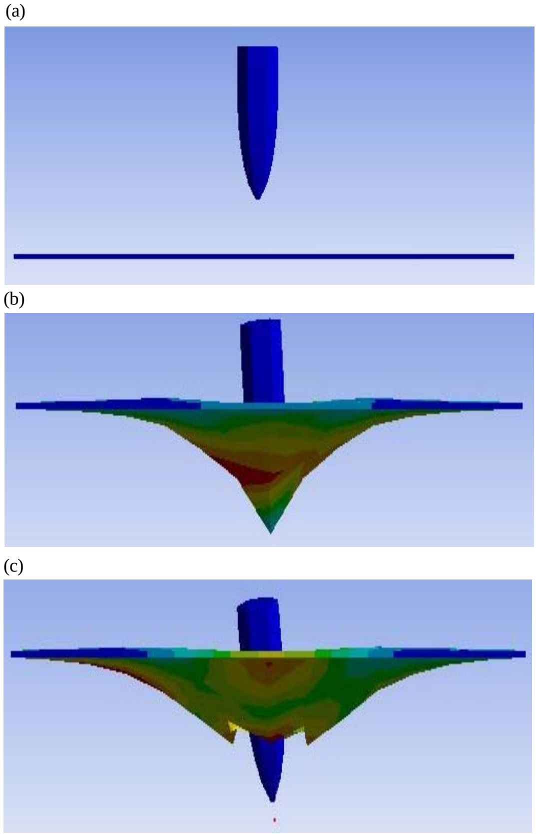

Fig. 1: A damage model of 5.56×45 mm bullet impacting on 4 layer thick composite material: a) The bullet is about to impact the material; b) The bullet has impacted and is perforating through the material and c) The bullet has penetrated through the material

$$Q_{11} = \frac{E_1}{1-\mu_{12}\mu_{21}}; Q_{22} = \frac{E_2}{1-\mu_{12}\mu_{21}}; Q_{12} = \frac{\mu_{12}E_2}{1-\mu_{12}\mu_{21}}; Q_{66} = G_{12} \tag{2}$$

where E_1, E_2, μ_{12}, μ_{21}, G_{12} are the Young's modulus, Poisson's ratio and Shear modulus of the lamina. For angle ply lamina:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{3}$$

where $[\bar{Q}_{ij}]$ is a reduced stiffness matrix. The midplane strains are given by the relation:

$$\{\varepsilon_0\} = [N][A]^{-1} \tag{4}$$

Where:

[N] = The resultant stress over the entire laminate

[A] = The extensional stiffness matrix

$$[N] = \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = \sum_{k=1}^{n} \int_{Z_{k-1}}^{Z_k} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} d_z \tag{5}$$

$$[A] = A_{ij} = \sum Q_{ij}^{k} (z_k - z_{k-1}) \tag{6}$$

The other extensional stiffness matrices are: [B] = [0] for symmetric laminate and:

$$[D] = D_{ij} = \sum_{k=1}^{n} Q_{ij} \left(d_k \bar{z}^2 + \frac{d_k^{\,3}}{12} \right) \tag{7}$$

Similar kind of analytical model is proposed by Liaghat *et al.* (2013), Naik and Shrirao (2004). The energy model is based on the assumption that the velocity of the bullet at the point of impact is the same applied velocity and the air resistance is neglected. Similar model was also suggested by Puente *et al.* (2007) and Varas *et al.* (2013). The Mathematical formulation of energy balance equation is:

Kinetic energy lost bythe bullet = The energy absorbed by the laminate

This is expressed analytically as:

$$KE_{Pro} = E_C + E_M + E_{TF} + KE_{Vr} \tag{8}$$

Where:

KE_{Pro} = The Kinetic Energy of the bullet: it is given by $1/2 mp\, V_i^2$

m_p = The mass of projectile

V_i = The initial velocity of the projectile

Before the calculation of the energies, the radius of the cone formed at the back face should be calculated. It can be calculated as: the velocity of elastic wave C_e is given as:

$$Ce = \sqrt{\frac{1}{\rho}\frac{d\sigma}{d\varepsilon}} \tag{9}$$

Where:

ρ = The density of the composite material

$d\sigma$ and $d\varepsilon$ = Elastic stress and strains on the laminate after impact

The velocity of transverse wave C_t is given as:

$$C_t = C_e \times \sqrt{\varepsilon_p (1+\varepsilon_p)} \times \varepsilon_p \tag{10}$$

where, ε_p is the plastic strain of the composite. The minimum time required for the damage to be done is given by:

$$\Delta t = \frac{\Delta\varepsilon}{\dot{\varepsilon}} \tag{11}$$

Where:

$\dot{\varepsilon}$ = $2v_i/L_{guage}$

L_{guage} = The length of the material

Radius of the cone R_c is given as:

$$R_c = C_t \times \Delta t \tag{12}$$

E_C is the energy absorbed by laminate crushing. When the projectile comes in contact with laminate, it crushes the laminate by compression. It is given by:

$$E_c = \sigma_c \pi R^2 h$$

Where:

σ_c = The out-of-plane compressive stress

R = The radius of the projectile

h = The thickness of the laminate

E_M is the Energy absorbed by linear momentum transfer from the bullet to the laminate. This happens when the laminate volume has fallen from the composite due to previous mechanism, it is assumed to accelerate from rest and proceed with initial velocity. It is given by:

$$E_m = \frac{1}{2}\pi R^2 h_\rho V_r^2$$

Where:

ρ = The density of the laminate

V_r = The residual velocity of the bullet

This mechanism is observed at the ballistic limit where the projectile just perforates thus breaking the fibers by tension. It is given as:

$$E_{tf} = X_t \varepsilon_f 4R_c dh$$

Where:

E_{TF} = The energy absorbed by tensile fiber failure

R_c and d = The radius of the cone and diameter of the projectile

X_t = The tensile stress in X direction (and Y direction for woven laminates)

ε_f = The correspond to ultimate strain

The kinetic energy because of residual velocity is given by 1/2 $m_pV_r^2$. The energy balance Eq. 13:

$$\frac{1}{2}m_p V_i^2 = \sigma_c \pi R^2 h + \frac{1}{2}\pi R^2 h\rho V_r^2 + X_t^{\varepsilon} f 4R_c dh + \frac{1}{2}m_p V_r^2 \tag{13}$$

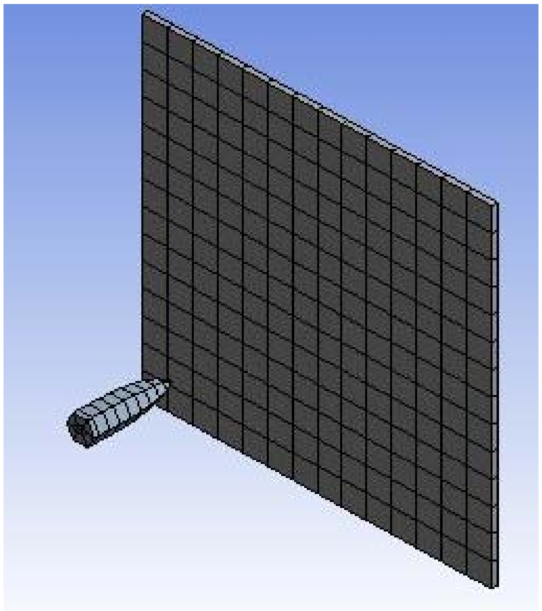

Fig. 2: Meshed assembly of the bullet and composite material

From Eq. 13 the residual velocity is given as:

$$\frac{V_r^2 = m_p V_i^2 - 2\sigma_c \pi R^2 h - Xt\varepsilon_f 4Rcdh}{m_p + \pi h\rho R^2} \tag{14}$$

From this model, the energy absorbed by the laminate is computed and verified with the simulation results.

The simulation model: A three dimensional finite element model was developed for both composite plate and the bullet in ansys workbench 15 (Lim *et al*., 2003; Silva *et al*., 2005). The length and breadth of composite model are 70×70 mm and the bullet was modeled according to standard dimensions. Meshing was done using quad/triangular elements. The number of elements for the 5.56×45 mm bullet and plate assembly is 286 and for 7.62×39 mm bullet and plate assembly is 296 elements. Figure 2 shows an assembly of 5.56×45 mm bullet and the composite plate.

The material assigned for the bullet is structural steel with 7,850 kg/m^3 as density. The bullet is modeled as rigid in all the directions because our main concentration is on the composite and the changes occurring in it. The nodes along the four faces of the laminate were fixed in X-Z directions and are the boundary conditions. An explicit dynamic analysis with Autodyn as solver is used to simulate the ballistic impact behavior of the composite panel (Fig. 3). The results are categorized according to the bullet and are obtained as follows.

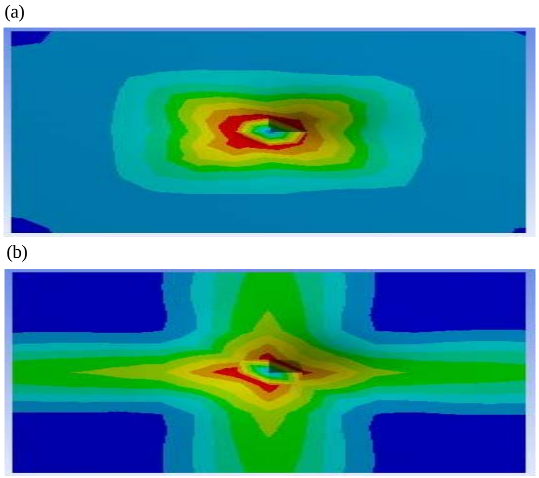

Fig. 3: Stress distribution of: a) Symmetric angle ply and b) Cross ply laminate of 8 layers impacted with a 5.56×45 mm bullet

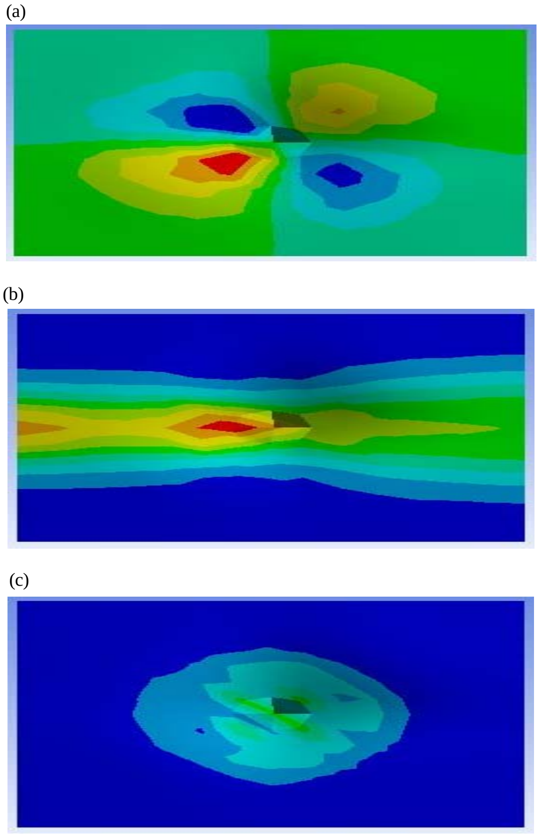

Fig. 4: Energy distribution: a) Energy absorbed due to crushing; b) Energy absorbed because of tensile fiber failure and c) Energy absorbed during momentum transfer of a 7.62×39 mm bullet impacting on the composite

Bullet of size 7.62×39 mm: Analysis was conceded by impacting the bullet at 700 m sec just below its maximum velocity. The different energies absorbed during impact were calculated and verified with simulation results.

Bullet of size 5.56×45 mm: Similar analysis was carried out for this bullet and the values for the energies was obtained. The results obtained were validated with simulation results. A sample of the results is shown in Fig. 4. From Fig. 4, the distribution of all the three energies upon impact can be seen. For a unidirectional laminate, the damage is not constrained within the point of contact and it spreads to the neighboring fibers. In woven laminate, the damage is limited to the point of impact only and does not spread as in the case of unidirectional laminate. Therefore, laminates with woven configuration prove to be more effective than the unidirectional ones. Naik and Shrirao (2004), Cheeseman and Bogetti (2003) have conducted experiments on woven laminates of both glass/epoxy and CFRP laminates.

When the bullet impacts the material an elastic wave and a transverse wave propagate through the thickness of the material and return back to the bullet. The velocity of the elastic wave is very high than that of the transverse wave. These waves form the dent like shape or the cone shape with the vertex as point of impact. The concluding radius of the cone relies upon the time Δt. This time interval can be accurately determined by experimental methods. The exact residual velocity can be experimentally determined by equipping high speed photography into the experimental setup as done by Bandaru *et al*. (2016) and Gower *et al*. (2008) with Kevlar® fabric.

RESULTS AND DISCUSSION

Bullet of size 7.62×39 mm: The results obtained analytically and by simulation for different thicknesses of 4, 6 and 8 layers are tabulated as follows:

- The Kinetic energy of the bullet is 1935.5 J
- For symmetric angle ply laminate (Table 3 and 4)
- For cross ply laminate

The graphical plot for the same is as follows in Fig. 5. From Fig. 5, it can be clearly seen that the energy distribution for the cross ply laminate is better than that for the angle ply laminate. The tensile fiber failure energy for symmetric angle ply laminate is seen decreasing but whereas for cross ply is seen increasing considerably. This shows that for 4 layers angle ply laminate the fibers in the first ply are broken due to high energy absorption.

Table 3: Results of symmetric angle ply laminate for different energy absorbed

	Energy absorbed by laminate crushing (J)		Energy absorbed by tensile fiber failure (J)		Energy absorbed by linear momentum transfer (J)		Total energy (J)	
No. of layers	Analytical	Simulation	Analytical	Simulation	Analytical	Simulation	Analytical	Simulation
04	25.71	25.67	85.16	84.81	10.52	11.99	1936.81	1937.89
06	51.56	51.59	43.54	43.54	15.88	16.35	1937.49	1937.99
08	70.23	70.26	47.85	47.66	20.84	20.69	1935.85	1935.54

Table 4: Results of cross ply laminate for different energy absorbed

	Energy absorbed by laminate crushing (J)		Energy absorbed by tensile fiber failure (J)		Energy absorbed by linear momentum transfer (J)		Total energy (J)	
No. of layers	Analytical	Simulation	Analytical	Simulation	Analytical	Simulation	Analytical	Simulation
04	13.30	13.29	27.05	27.07	10.93	18.45	1936.87	1944.38
06	24.51	24.54	63.08	63.00	15.95	18.21	1937.49	1939.69
08	33.87	33.87	82.76	82.90	20.85	22.60	1935.83	1937.72

Table 5: Results of symmetric angle ply laminate for different energy absorbed

	Energy absorbed by laminate crushing (J)		Energy absorbed by tensile fiber failure (J)		Energy absorbed by linear momentum transfer (J)		Total energy (J)	
No. of layers	Analytical	Simulation	Analytical	Simulation	Analytical	Simulation	Analytical	Simulation
04	13.25	13.26	31.82	31.84	9.46	9.51	1621.47	1650.19
06	28.71	28.71	15.3	15.28	13.92	16.94	1622.17	1625.17
08	35.82	35.84	17.23	17.26	18.59	21.02	1638.58	1641.06

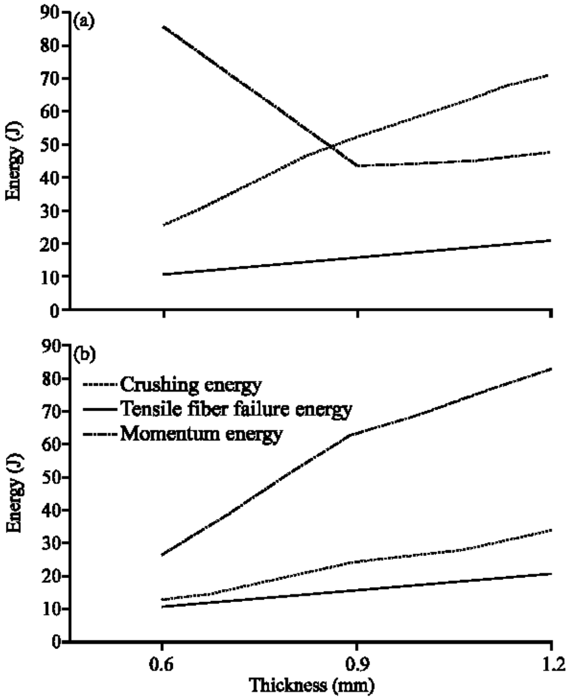

Fig. 5: Graphical plot of energy absorbed by: a) SAPL and b) Cross ply laminate for the bullet size of 7.62×39 mm

The other two energies in the two kinds of laminates are seen increasing substantially. So, from the graphs we can infer that the cross ply laminate with 0° and 90° orientation absorbs energy better than the angle ply laminate for the same thicknesses. Similar results were obtained for Velmurugan and Sikarwar (2014) and Menna *et al*. (2011) who carried investigations on impact of bullet on glass/epoxy laminate. Atapek and Karagoz (2011) have also done impact tests using the same bullet on a tempered bainitic steel and found that main failure occurred because of plastic deformation and cleavage after the shot.

Bullet of size 5.56×45 mm: The results obtained analytically and by simulation for different thicknesses of 4, 6 and 8 layers are tabulated as follows:

- The kinetic energy of the bullet is 1620 J
- For symmetric angle ply laminate in Table 5 and 6
- For cross ply laminate

The graphical plot for the same is as follows in Fig. 6. From Fig. 6, 5.56×45 mm bullet, the crushing energy for angle ply laminate is greater than that for cross ply. This shows that upon impact the angle ply laminate takes more damage due to crushing and fiber failure occurs readily. This same does not occur for cross ply. This means that cross ply laminate is resisting more to the crushing by the bullet. Morye *et al*. (2000) also carried out experimental investigations on ballistic impact on nylon composites and obtained similar results.

Residual velocity: Residual velocity is the velocity left after impact. The bullet after impacting changes its direction of travel and this travel velocity is defined as the

Table 6: Results of cross ply laminate for different energy absorbed

	Energy absorbed by laminate crushing (J)		Energy absorbed by tensile fiber failure (J)		Energy absorbed by linear momentum transfer (J)		Total energy (J)	
No. of layers	Analytical	Simulation	Analytical	Simulation	Analytical	Simulation	Analytical	Simulation
04	9.93	9.94	28.24	28.27	9.33	9.840	1621.46	1622.01
06	13.36	13.39	29.61	29.62	13.92	16.015	1622.17	1624.31
08	17.79	17.81	35.71	35.71	18.58	19.490	1638.58	1639.51

Table 7: Residual velocity for different kinds of laminate and for different No. of layers

Kinds of laminate	No. of layers	Residual velocity (m sec)
Symmetric angle ply laminate	04	893.19
	06	884.38
	08	885.14
Cross ply	04	887.00
	06	884.67
	08	885.00

Table 8: Residual velocity for different kinds of laminate and for different No. of layers

Kind of laminate	No. of layers	Residual velocity (m sec)
Symmetric angle ply laminate	04	677.94
	06	680.00
	08	674.48
Cross ply	04	690.91
	06	681.39
	08	674.74

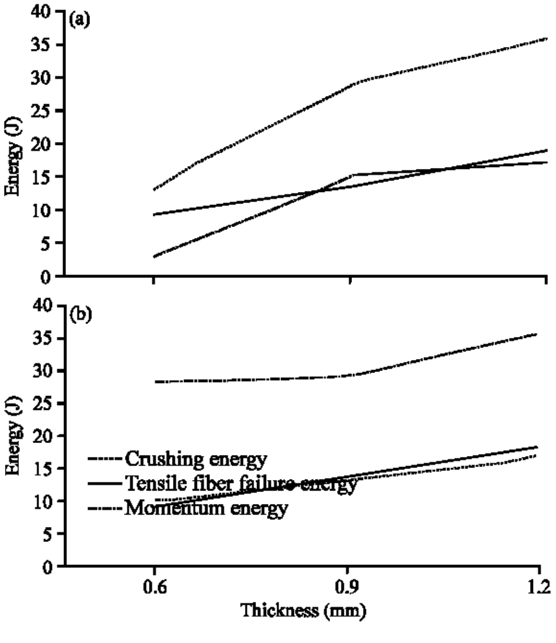

Fig. 6 Graphical plot of energy absorbed by: a) SAPL and b) Cross ply laminate for the bullet size of 5.56×45 mm

residual velocity. This depends on the impact resistance of the laminate and the radius of the cone formed at the back face of the composite laminate in Table 7 and 8. The residual velocities for both the bullets are given as follows in Fig. 7:

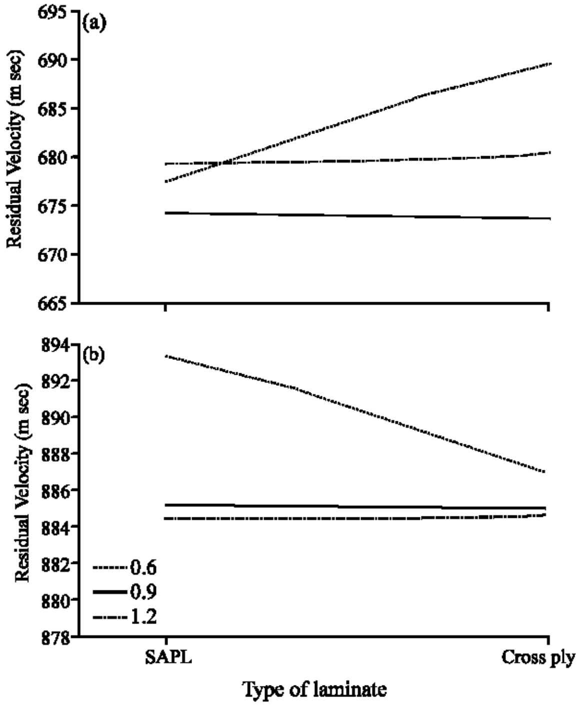

Fig. 7: Graphical plot of residual velocities of SAPL and cross ply laminate for bullet of size: a) 7.62×39 and b) 5.56×45 mm

- For 5.56×45 mm bullet
- For 7.62×39 mm bullet

The graphical plot for the same is as follows in Fig. 7. Figgure 7 shows that the residual velocity for bullet of size 7.62×39 mm impacting on cross ply laminate is higher than that for angle ply laminate. This says that the cross ply laminate resists the bullet and deflects it giving it good amount of residual velocity. As for the 5.56×45 mm bullet is concerned the angle ply laminate is proven to be good at deflecting the bullet giving the highest residual velocity. Velmurugan *et al.* (2010) showed similar analytical model and calculated the energy absorbed and residual velocity for different impact velocities for Kevlar/Epoxy laminate. Kulkarni *et al.* (2013), Aare and Leiven (2007) have done significant work on materials for combat helmets and traumatic brain injury and Asl (2015) have investigated on how different shell stiffness affect the load during ballistic impact on a combat helmet. Millan *et al*. (2016) has done experimental and numerical investigations on a combat helmet to predict its failure against the ballistic impact by a bullet.

CONCLUSION

In the present study, the analysis of ballistic impact of bullets of different sizes on a composite laminate with various energies absorbed, damage propagation and optimum impact withstanding capacity. The analysis was done on a composite laminate made of T700/epoxy carbon fiber. Verification has been done by both analytical modelling and finite element modelling using ANSYS workbench with Autodyn solver. The analysis is carried out on laminates of two different kinds viz. Cross ply and symmetric angle ply laminate for three different thicknesses. When the bullet of size 7.62×39 mm was made to impact on composite laminate of both 4 and 8 layers, it was observed that more tensile fiber failure energy was absorbed by the 4 layer cross ply laminate causing complete failure when compared to 8 layer cross ply laminate where complete failure does not occur. Both momentum energy and crushing energy found to increase exponentially as thickness increases. Ultimately, the energy absorption capacity of cross ply laminate is found to be higher than symmetric angle ply laminate. On similar lines when second bullet of size 5.56×45 mm was impacted on the above two laminates there was no much difference in the amount of energy a bsorption. Hence, from the point of view of results obtained by both analytical and simulation the impact resistance to impact of bullet 8 layered cross ply laminate was found to be more recommendable for applications like bulletproof jackets and combat helmets.

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