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Ballistic Impact on Glass/Epoxy Composite Laminates

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ABSTRACT

Glass/epoxy composite laminates are subjected to impact loading and the energy absorbing capacity of the laminates is studied. In the present study, laminates with four different orientations and thickness values are considered. Analytical study is carried out based on energy method and results are compared with FE results obtained from Abaqus/Explicit software. Results obtained from the analytical methods are showing good agreement with the FE results. It is found that cross-ply laminates are most efficient in ballistic resistance when compared with the laminates of other orientations. It is also noticed that the energy absorbing capacity is decreasing with increase in velocity of the projectile for a given lay-up and thickness value.

Keywords: Ballistic Limit, strain rate, angle-ply laminate, residual velocity, energy absorbed

NOMENCLATURE

Δt	Impact duration
$\Delta\varepsilon$	Failure strain
$\dot{\varepsilon}$	Strain rate
V_0	Projectile initial velocity
V_r	Projectile residual velocity
L_{gauge}	Length of the plate
R_{cx}	Radius of cone in X-direction
R_{cy}	Radius of cone in Y-direction
C_{tx}	Transverse velocity in X-direction
C_{ty}	Transverse velocity in Y-direction
d	Diameter of projectile
h	Thickness of the laminate
E_x	Young's modulus in X-direction
E_y	Young's modulus in Y-direction
ε_{px}	Plastic strain in X-direction
ε_{py}	Plastic strain in Y-direction
E_{ca}	Area under stress-strain diagram
E_{TF}	Energy absorbed by primary yarns
E_{ED}	Energy absorbed by secondary yarns
E_{DL}	Energy absorbed in delamination
G_{IIcd}	Fracture toughness in mode-II
n	Number of layers
E_{MC}	Energy absorbed in matrix cracking
ν_m	Matrix volume ratio
m_c	Mass of moving cone
E_{KE}	Energy absorbed by moving cone
E_0	Total energy absorbed

1. INTRODUCTION

Because of light weight and high specific strength, fibrous composite materials are increasingly used in marine, aircraft and structural applications. Glass fibers are commonly used in structural applications because of its easier availability and low cost. Structures made from these fibers sometimes are subjected to low to high velocity impact of the projectiles hence these structures and structural elements should be designed to withstand the impact loading.

In the past several analytical and numerical studies have been carried out to investigate the impact on composite laminates. There are several models to predict the perforation of composite laminates. There are methods based on elasticity approach[1-4]. Zhu[1], *et al.* have determined the force acting on conical projectile using laminate plate theory. They divided the impact event in three phases namely indentation, perforation and exit. Resisting forces in all three phases are determined and using Newton's laws velocity and deceleration is determined. Sun[2], *et al.* have proposed simple spring model to predict the residual velocity and ballistic limit of the projectile. Different criteria for damage initiation, progression and plug formation are considered. Wen[3-4] *et al.* have investigated the perforation and penetration of FRP laminates struck normally by projectiles of different shapes.

The alternative method to quantify the damage in composite is the energy method[5-11]. In this method the energy absorbed in different damage mechanisms have been quantified and based on the energy calculations the residual velocity and ballistic limit have been calculated. Morye[5-6], *et al.* have studied that in addition to the two major energy absorbing mechanisms namely tensile failure of fibers and elastic deformation of the composites, the energy absorption in the form of kinetic energy of the moving cone also plays a major role. Zhu[7], *et al.* have considered delamination energy but neglected the energy absorbed in matrix cracking. Naik[8], *et al.* have

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considered all the damage mechanisms during perforation of the composite plates and verified with experimental results. Goldsmith[9], *et al*. Calculated energy absorbed in global plate deflection, fiber breakage, delamination, formation and bending of petals, hole enlargement and friction between striker and sample. Lee[10-11], *et al*. have proposed penetration model based on quasi-static punch test and used the results for computational analysis of high velocity impact. Velmurugan[12], *et al*. have performed experimental and analytical studies for the response of sandwich panel, which are subjected to projectile impact. Ganesh Babu[13], *et al*. have done impact test using heavy mass projectile using round, conical and flat nose shape projectiles on unidirectional glass/epoxy composite plates.

In the present study, the analytical model, which is based on energy balance, is used to verify the results obtained from Abaqus/Explicit code for the glass/epoxy composites. The analytical model is presented by the authors[14] and validated with experimental results for the Kevlar/epoxy composites. It is observed[15,8] that there is no shear plug formation in the glass/epoxy composite laminates so developed formulation is verified for the glass/epoxy laminates. For validation of analytical studies, results obtained from finite element simulation using Abaqus/Explicit are used. The results obtained from analytical and FE studies are showing good agreement.

2. ANALYTICAL MODEL

For the development of analytical model it is assumed that the projectile is rigid. Friction between projectile and plate during penetration is negligible. Strain rate does not change during perforation. Damage mechanism of failure is uniform across the thickness of the plate.

The energy of the projectile is absorbed by different damage mechanisms such as tensile failure of the primary yarns (Fig. 1), elastic deformation of the secondary yarns, delamination, matrix cracking and energy absorbed by the moving cone on the back side of the laminate.

The radius of the cone formed[6] on the back side of the plate depends upon the time *Δt*, during which the bullet remains in contact with laminate. This time duration is also the time required for the failure of the laminate. This can be calculated by the expression;

$$\Delta t = \frac{\Delta \varepsilon}{\dot{\varepsilon}} \tag{1}$$

where

$$\dot{\varepsilon} = \frac{2V_0}{L_{gauge}} \tag{2}$$

$$R_{cx} = C_{tx} \Delta t \tag{3(a)}$$

$$R_{cy} = C_{ty} \Delta t \tag{3(b)}$$

where expressions for C_{tx} and C_{ty} are given by,

$$C_{tx} = C_{ex} \sqrt{\varepsilon_{px}(1+\varepsilon_{px})} - \varepsilon_{px} C_{ex} \tag{4(a)}$$

$$C_{ty} = C_{ey} \sqrt{\varepsilon_{py}(1+\varepsilon_{py})} - \varepsilon_{py} C_{ey} \tag{4(b)}$$

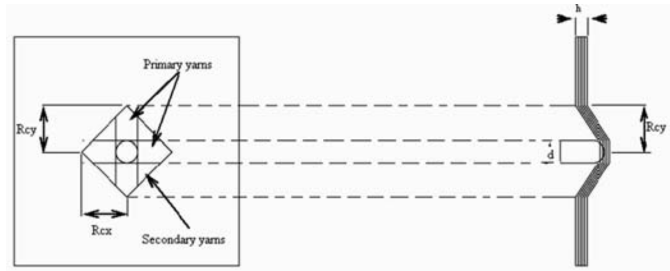

Figure 1. Primary and secondary yarns.

Primary yarns are those, which are directly under the impact of the projectile and fail under tension. Energy absorption by tensile failure of the yarns in terms of Young's modulus in X and Y directions as shown in Fig. 2, is given by

$$E_{TF} = \frac{\pi d^2 h}{4} E_{ca} + \left(\frac{1}{2} (R_{cx} E_x (\varepsilon_{px})^2 + R_{cy} E_y (\varepsilon_{py})^2) hd \right) \tag{5}$$

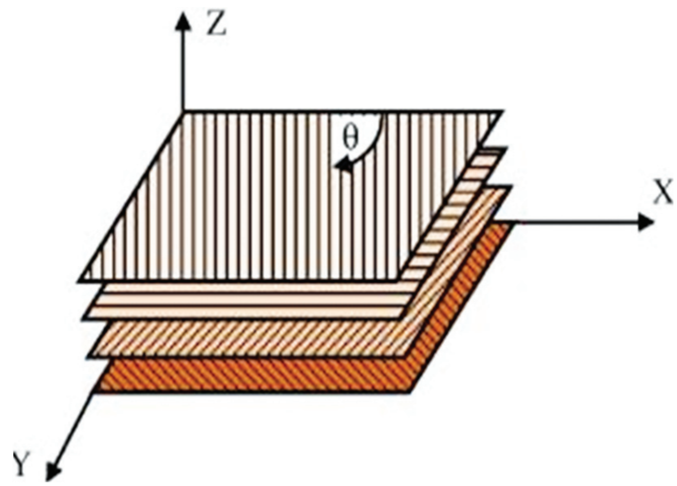

Figure 2. Principal directions of the laminate.

The yarns, which deform elastically due to cone formation on the back side of the plate and absorb some amount of the projectile energy, are known as secondary yarns. The energy absorbed by elastic deformation of the secondary yarns is obtained by the following expression.

$$E_{ED} = \left(\pi E\, \varepsilon_p^2\right) \int_0^{R_c} rhdr = \frac{1}{4} (E_x \varepsilon_{px}{}^2 + E_x \varepsilon_{px}{}^2) R_{cx} R_{cy} h \tag{6}$$

The energy absorbed in delamination, which is in the shape of a parallelogram (For glass/epoxy laminates), is given by,

$$E_{DL} = 2(n-1) R_{cx} R_{cy} G_{IIcd} \tag{7}$$

Energy absorbed by matrix cracking is given by,

$$E_{MC} = 2 R_{cx} R_{cy} E_{mt} h \nu_m \tag{8}$$

During the impact event, when the projectile penetrates the plate, cone is formed on the back side of the plate. The total kinetic energy absorbed by the moving cone is given by the expression.

$$E_{KE} = \frac{1}{16} m_c (V_0 + V_r)^2 \tag{9}$$

By using the above equations, total energy absorbed in damage mechanisms is calculated as:

$$E_0' = E_{TF} + E_{ED} + E_{DL} + E_{SP} + E_{MC} + E_{KE} \quad (10)$$

From the energy conservation laws:

$$\frac{1}{2} m_p V_0^2 = E_0' + \frac{1}{2} m_p V_r^2 \quad (11)$$

Using Eqns. (1)-(11) following expression is obtained, for residual velocity

$$V_r = \frac{-2m_c V_0 + \sqrt{4M_c^2 V_0^2 - 4(m_c + 8m_p)\left[\left(m_c - 8m_p\right)V_0^2 + E_0'\right]}}{2\left(m_c + 8m_p\right)} \quad (12)$$

3. NUMERICAL SIMULATION OF IMPACT

Abaqus/CAE is used as a preprocessor to model the glass/epoxy plates and bullet assembly while Abaqus/Explicit code is used to analyze the failure initiation and damage evaluation during high-velocity projectile impact of the composite laminates.

In Abaqus/CAE, the composite plate is modeled as a 3D deformable solid while the projectile is modeled as discrete rigid to reduce the computational effort because element label calculations are not performed for rigid body elements. The dimension of the plate modelled is 300 mm x 300 mm having 8 layers, 12 layers, 15 layers and 19 layers, wherein each layer thickness is 0.3 mm. Each layer of the plate is meshed with 3D 8 noded linear brick solid element C3D8R available in Abaqus/Explicit element library. C3D8R elements offer the reduced integration and hourglass control. Each layer is having a single element through thickness. The projectile is meshed with 3 node 3D triangular facet R3D3 discrete rigid elements. Fine meshing in the impact region when compared to boundary of the plate has been used to obtain the smooth stress variation in the impact region. Size of the mesh is increased gradually from impact region to outer edges of the plate as shown in Fig. 3(c). Four lay-up sequences namely, 0/90, 0/90/30/-60, 0/90/45/-45 and 30/-60/60/-30, of the glass/epoxy composite plate have been considered for analysis. Material properties assigned for the plate have been given in Table 1 while for the bullet 7.5 g mass has been assigned on the reference point of the bullet at the tip of projectile. Hashin 3D Damage material model which is available in VUMAT is used to define the onset of damage while Matzenmiller model[16] is used to define damage evolution of composites. This will define the material behavior after the onset of damage initiation. VUMAT is a FORTRAN code which allows the user to implement any general constitutive equation. The plate and the projectile are assembled with a gap 0f 0.5 mm between projectile tip and the plate upper surface as shown in Figs. 3(a) and 3(b). Bullet is assigned to move in the positive Z-direction of the coordinate systems. Total duration of 0.0003 s is assigned for each simulation during which projectile could have moved at least 60 mm and impact phenomenon is completed by this time. During perforation, some elements of the plate in impact region underwent deformations beyond failure strain and hence element deletion is incorporated in the analysis. Contact between the plate and bullet is defined as a general contact which defines the contact in initial and subsequent steps also. In general contact during perforation elements deform beyond limit is deleted from the plate surface and new surface is formed and interaction between new surfaces and projectile is redefined during the perforation. Interaction properties between the plate and bullet are defined as the tangential behavior with penalty of coefficient of friction value of 0.5 to stop the movement of the projectile in horizontal direction during impact. The plates analyzed are having all four edges fixed while the projectile velocity is varied between 200 m/s to 350 m/s in steps of 50 m/s.

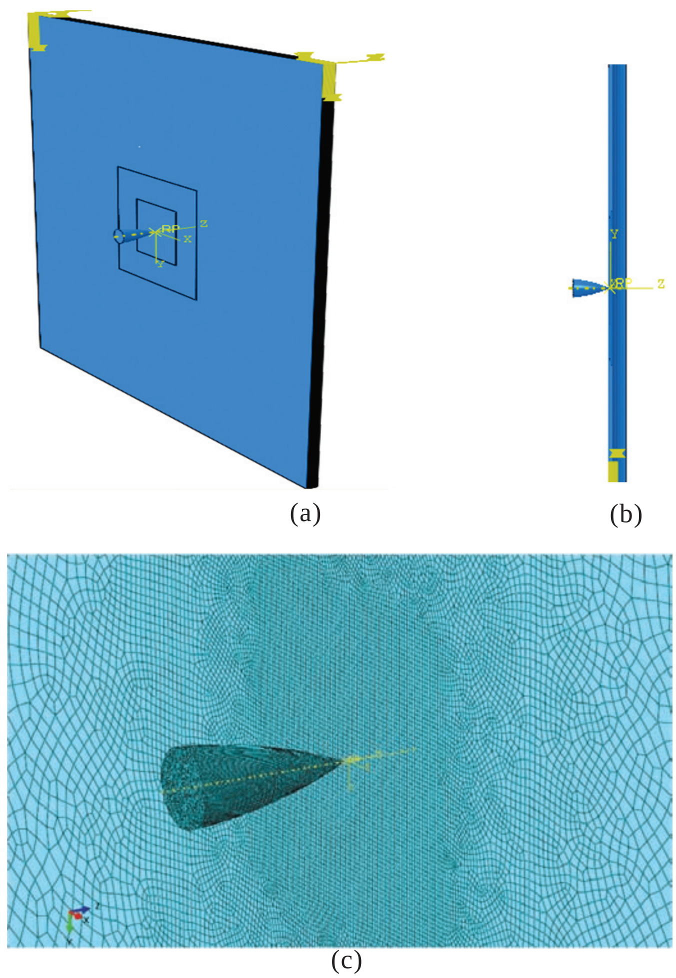

Figure 3. (a) Isometric view of bullet and plate initially (b) Side view of plate and bullet assembly (c) Meshed plate and bullet.

3.1 Material Data

Experimental tests are conducted to determine the material properties (Tables 1 and 2) of the glass/epoxy laminates. These properties (Table 1) are achieved by conducting tensile test according to ASTM Standard D3039 for tensile moduli E_1 and E_2, compression test according to ASTM standard D3410 M, test for Mode-II Interlaminar fracture toughness using end notched test

Table 1. Material properties of glass/epoxy composites determined experimentally. [Mpa]

E_1	E_2	ν_{12}	ε_0	X_{1t}	X_{1c}	X_{2t}	X_{2c}	G_{IIcd} (J/m^3)
2700	2700	0.327	0.02	250	183	250	183	1000

Table 2. Material properties of glass/epoxy composites obtained from Naik & Meduri[17]. [MPa]

E_3	ν_{13}	ν_{23}	G_{12}	G_{23}	G_{13}
8000	0.4	0.4	3900	4200	4200
X_{3t}	X_{3c}	S_{12}	S_{23}	S_{13}	$E_{mt}(MJ)$
27.1	140	28	28	28	0.9

method. Some more data (Table 2) are taken from the Naik & Meduri[17], in which the modulus and strength properties almost match with the experimental results. where E_1, E_2, and E_3 are Young's moduli , X_{1t}, X_{2t}, and X_{3t} are tensile strengths, X_{1c}, X_{2c}, and X_{3c} are compressive strengths in x, y, and z directions. G_{12}, G_{23}, G_{13} are shear moduli, ν_{12} , ν_{23} , and ν_{13} are Poisons ratios and S_{12}, S_{23}, and S_{13} are shear strength values in xy, yz, and zx plane respectively.

The modulus values for the laminates of different orientations are obtained[14] by using Eqn. (13) and are given in Table 3.

$$E_x = E_y = \frac{1}{t}\frac{\left(A_{11}^2 - A_{12}^2\right)}{A_{11}} \qquad (13)$$

4. RESULTS AND DISCUSSION

4.1 Analytical Results

Using the analytical formulation residual velocities of the projectile are calculated for four projectile initial velocities i.e. 200m/s, 250m/s, 300m/s, and 350m/s for the lay-up sequences considered . The results are shown in Table 4.

Table 3. Young's modulus and failure strains for different fiber orientations and thickness values.

Lay-up sequence	Thickness (mm)	Young's modulus (E_1) (GPa)	Failure strain ε_o (%)
0/90	8	27	5
	12	27	5
	15	27	5
	19	27	5
0/90/30/-60	8	21.6	5.2
	12	22.4	5.2
	15	22.56	5.4
	19	23.43	5.4
0/90/45/-45	8	21.66	5.5
	12	22.4	5.5
	15	22.5	5.7
	19	23.4	5.7
30/-60/60/-30	8	19.5	5.2
	12	20.1	5.2
	15	20.17	5.2
	19	20.2	5.2

From Table 4 it is observed that for all initial velocities the corresponding residual velocities are decreasing with increasing the thickness and for the same thickness laminates residual velocity is minimum for (0/90) laminate and maximum for (30/-60/60/-30) lay-up sequences which indicates that (0/90) lay-up laminate is absorbing maximum energy while (30/-60/60/-30) lay-up laminates are absorbing minimum energy.

4.2 FE Simulation Results

Ballistic performance of the glass/epoxy laminates is simulated for different thickness values, lay-up sequences and different initial velocities of the projectile. Total number of elements in the bullet is 21000 elements while in the plate it is 430000 elements.

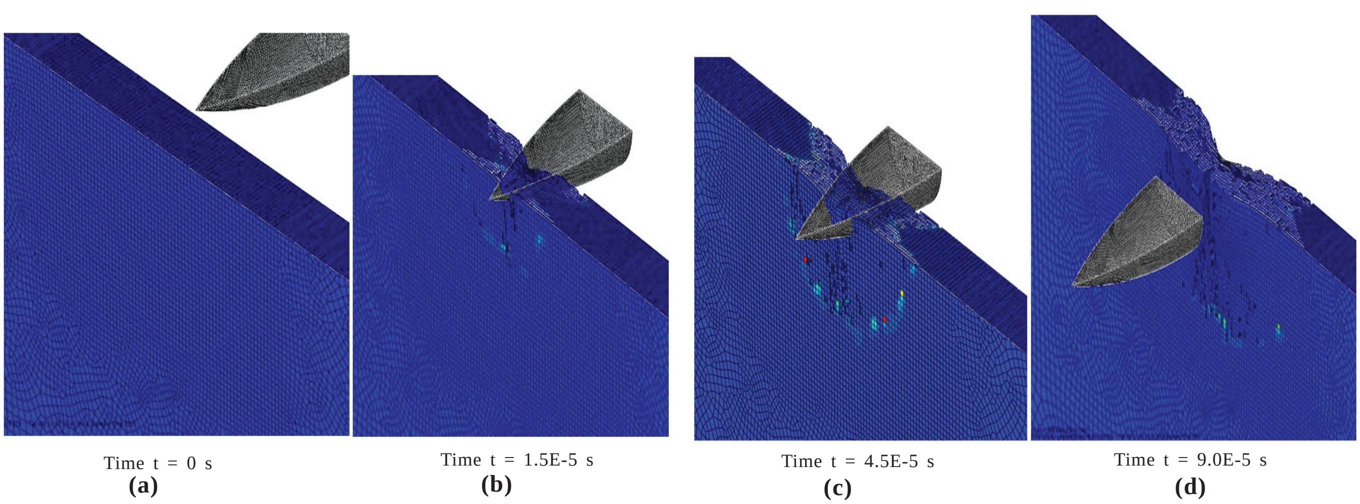

Figure 4. Damage propagation in (0/90) lay-up 19 layer glass/epoxy plate.

Table 4. Residual velocity with thickness and orientation for different initial velocities.

Initial velocity (m/s)	Lay-up sequence	8 Layers	12 Layers	15 Layers	19 Layers
200	0/90	195.9	193.9	192.5	191.2
	0/90/30/-60	196.78	195.21	193.93	192.769
	0/90/45/-45	196.95	195.45	194.2	193.1
	30/-60/60/-30	197.47	196.23	195.33	194.4
250	0/90	246.57	245.3	244.2	243.09
	0/90/30/-60	247.48	246.23	245.22	244.3
	0/90/45/-45	247.61	246.42	245.43	244.56
	30/-60/60/-30	248.02	247.04	246.29	245.56
300	0/90	297.5	296.2	295.3	294.3
	0/90/30/-60	297.92	296.89	296.05	295.29
	0/90/45/-45	298.03	297.05	296.22	295.5
	30/-60/60/-30	298.37	297.56	296.94	296.34
350	0/90	347.7	346.8	346	345.21
	0/90/30/-60	348.24	347.35	346.63	345.98
	0/90/45/-45	348.32	347.48	346.79	346.16
	30/-60/60/-30	348.61	347.9	347.49	346.87

Figure 4 (a) to 4(c) are showing the damage propagation in (0/90),19 layer glass/epoxy plate at different time of impact. From the figure it can be seen that the duration of impact of (0/90) lay-up, 19 layers, plate is around 0.9 µs. White lines are showing the delamination between the layers. It can be observed from Fig. 4(d) that the delamination on the back side of the plate is maximum. Stress wave propagates radially outwards during perforation which is seen in Fig. 4.

5. COMPARISON OF ANALYTICAL AND FE RESULTS

Results obtained for residual velocities and energy absorption from FE analysis and analytical study are compared. The results obtained for different layup sequences, thickness values and projectile initial velocities are shown in Table 5.

From the Table 5 it is observed that for all the initial velocities of the projectiles the residual velocity is minimum for (0/90) layup laminates hence (0/90)

Table 5. Comparison of residual velocities obtained numerically and analytically for different projectile initial velocities

Velocity (m/s)	Lay-up	Thickness							
		8 Layers		12 Layers		15 Layers		19 Layers	
		Anal	FE	Anal	FE	Anal	FE	Anal	FE
200	0/90	195.9	197	193.9	195.3	192.5	194.2	191.2	193.4
	0/90/30/-60	196.7	197.2	195.2	197.1	193.9	196.7	192.7	196.5
	0/90/45/-45	196.9	197.3	195.45	196.7	194.2	196.8	193.1	197.2
	30/-60/60/-30	197.4	198.7	196.23	196.3	195.33	196.27	194.4	195.7
250	0/90	246.57	247.3	245.3	246.5	244.2	246.4	243.0	246.2
	0/90/30/-60	247.4	247.7	246.23	246.5	245.22	246.4	244.3	246.1
	0/90/45/-45	247.6	247.4	246.42	246.3	245.43	246.5	244.56	246.4
	30/-60/60/-30	248.0	248.2	247.04	246.7	246.29	246.6	245.5	246.5
300	0/90	297.5	297.5	296.2	296.3	295.3	296.9	294.3	295.8
	0/90/30/-60	297.9	297.6	296.8	297.5	296.0	297	295.2	295
	0/90/45/-45	298.0	297.7	297.0	297.8	296.2	297.2	295.5	297.1
	30/-60/60/-30	298.3	297.6	297.5	296.1	296.9	295.6	296.34	296.3
350	0/90	347.7	347	346.8	346.7	346	346.4	345.1	346.7
	0/90/30/-60	348.4	347.8	347.3	348.3	346.3	346.9	345.8	345.4
	0/90/45/-45	348.2	348.2	347.48	348.1	346.9	346.9	346.6	347.8
	30/-60/60/-30	348.1	349.2	347.9	347.8	347.9	346.9	346.7	347.5

Table 6. Variation of energy absorption with thickness values and initial projectile velocity for different lay-up

Velocity (m/s)	Lay-up	Thickness							
		8 Layers		12 Layers		15 Layers		19 Layers	
		Anal	FE	Anal	FE	Anal	FE	Anal	FE
200	0/90	0.59	0.57	0.66	0.69	0.67	0.67	0.73	0.68
	0/90/30/-60	0.55	0.53	0.56	0.59	0.58	0.54	0.62	0.58
	0/90/45/-45	0.52	0.50	0.52	0.49	0.55	0.53	0.57	0.58
	30/-60/60/-30	0.45	0.39	0.46	0.39	0.47	0.43	0.47	0.43
250	0/90	0.57	0.54	0.67	0.65	0.63	0.66	0.73	0.67
	0/90/30/-60	0.54	0.49	0.55	0.57	0.54	0.47	0.58	0.56
	0/90/45/-45	0.51	0.49	0.51	0.47	0.55	0.52	0.56	0.57
	30/-60/60/-30	0.44	0.38	0.46	0.38	0.46	0.41	0.46	0.42
300	0/90	0.54	0.51	0.66	0.59	0.61	0.65	0.72	0.67
	0/90/30/-60	0.53	0.48	0.55	0.56	0.54	0.46	0.57	0.52
	0/90/45/-45	0.50	0.47	0.49	0.44	0.54	0.49	0.55	0.53
	30/-60/60/-30	0.42	0.37	0.45	0.38	0.46	0.40	0.45	0.42
350	0/90	0.52	0.51	0.66	0.58	0.59	0.65	0.71	0.66
	0/90/30/-60	0.53	0.47	0.52	0.54	0.46	0.41	0.56	0.51
	0/90/45/-45	0.49	0.47	0.47	0.42	0.50	0.49	0.52	0.52
	30/-60/60/-30	0.40	0.36	0.45	0.35	0.45	0.50	0.45	0.41

lay-up laminates are most effective laminates for all the velocities of the projectiles. Impact resistance properties of the glass/epoxy laminates have decreased with increase in projectile velocity as well as with decrease in thickness of the laminates.

Energy absorbing capacity of each layer is obtained by dividing the total energy absorbed by the laminates with the number of layers. The values are determined analytically as well as by FE analysis and values are given in Table 6**.**

From Table 6 it is concluded that (0/90) lay-up laminate is absorbing more energy while (30/-60/60/-30) lay-up laminates are absorbing less energy for a given impact velocity. This is because the effective in-plane modulus of the (0/90) laminates in longitudinal and perpendicular directions are higher compared to other lay-up laminates for a given thickness value.

6. CONCLUSION

A simple analytical model has been used to predict the residual velocity and energy absorbing capacity. The analytical results obtained are compared with results obtained from abaqus/explicit for the glass/epoxy laminates for different fiber orientations and thickness values. The results obtained from analysis match well with FE results. The results indicates that with increasing the velocity of the projectile damage extent as well as energy absorbing capacity is decreasing for a given lay-up orientation and thickness value. Lay-up (0/90) laminate is a most effective when compared to other orientations considered in the study for all velocity ranges and thickness values.

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