Ballistic Performance of Kevlar/Epoxy Composite Laminates

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Kevlar/epoxy composite laminates, of different thicknesses and layup sequences, are prepared by hand layup technique followed by compression moulding. These laminates are subjected to the impact of the projectiles at velocities varying from 30 m/s to 380 m/s. The effect of projectile velocity on delamination and energy absorption is studied. The residual velocity and energy absorption capacity are obtained for the laminates of different thicknesses and layup sequences. Various failure modes were observed in the experiments, and considering these and based on energy principles an analytical model is developed to compute the energy absorption capacity of the laminates, the ballistic limit and the residual velocity. Results thus obtained are compared with experimental results, which show a good agreement. Numerical study (FEA through Abaqus) is carried out for velocities ranging from 200 m/s to 400 m/s and the effect of thickness and orientation is studied. The results are compared with analytical results and are found in good agreement.

Key Words: Ballistic Limit; Strain Rate; Angle-Ply Laminate; Residual Velocity; Energy Absorption

1. Introduction

The body armours that absorb the impact of the projectiles from a firearm or explosions should be light weight and be capable of absorbing kinetic energy of the impactor. Unidirectional and woven fabrics of Kevlar are commonly used material for the body armour due to their high failure strain, high modulus and higher strength-to-weight ratio. In high velocity impact, kinetic energy of the projectile is absorbed by several failure mechanisms of the laminate such as tensile failure of the primary fibers, deformation of the secondary fibers, delamination, matrix cracking, friction between the projectile and laminate, shear plugging and kinetic energy of the moving cone formed on the back side of the laminate. Knowing the failure modes involved in the impact events, analytical model can be developed to determine the energy required for penetration, which can be used to predict the ballistic limit and residual velocity of the projectile after the impact.

Several analytical [1-7] and numerical studies [8-14] have been carried out in the recent past. Morye et al. [1] have presented a simple analytical model to determine the energy absorbed by composites under impact loading and also carry out ballistic impact tests on woven nylon, aramid and Dyneema composites to verify the results obtained from analytical study in projectile strike velocity range of 500m/s to 600m/s. Chocron-Benloulo et al. [2] have developed a simple analytical model for ballistic impact against ceramic/composite armors and verified the results experimentally and numerically. The velocities of the projectile considered were above 1000 m/s. Bohong Gu [3] has developed analytical model to calculate the decrease in kinetic energy as well as residual velocity of the projectile on woven fabric of Twaron and Kuralon. Naik et al. [4] have formulated analytical expressions for each energy absorbing mechanism during impact, energy absorbed at different time interval during impact and the corresponding

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reduction in velocity of the projectile. Experimental and analytical studies were carried for the response of sandwich panels, subjected to impact of heavy mass projectiles at low velocities [5]. Zhu et al. [6, 7] have also presented an analytical model for normal impact and perforation of conical nose cylindrical projectile on laminated kevlar-29/polyester targets, and compared analytical results with experiments for velocity up to 200 m/s. Tham et al. [8] have performed impact experiments on helmet at velocity 205 m/s, which is below the ballistic limit of the helmet and the results have been validated with FE analysis. Further simulation has been performed for higher velocities to determine the ballistic limit of the helmet. For numerical simulations AUTODYN-3D has been used. Silva et al. [9] have conducted experiments and numerical study of ballistic impact on thin kevlar-29 laminates of different thicknesses. AUTODYN-3D has been used to estimate the ballistic limit and damage area. Deka et al. [10] have analyzed the E-Glass/ Polyprolene composites of different thickness values. For simulation of damage phenomenon explicit 3D code, LS-DYNA, has been used. Experiments have been performed for the velocity range of 150 m/s to 270 m/s. Sevkat et al. [11] have performed combined experimental and finite element study of angle-ply glass/epoxy composites subjected to impact by deformable projectile. For simulation of ballistic limit, LS-DYNA 3D code has been used. The velocity ranges considered are at ballistic limit and above. Gama et al. [12] have presented a full 3D finite element model of ballistic impact on thick composite sections. They have used LS-Dyna and progressive composite damage model MAT162 which is linear elastic up to the initiation of damage and nonlinear softening thereafter. They have also validated the model with the ballistic experiments on glass/epoxy composites over a wide range of impact velocities from 50 to 1000 m/s. Garcia-Castillo et al. [13] have proposed nondimensional parameters, namely, geometric ratio and density ratio, to estimate the projectile velocity and displacement during the perforation of thin plates made from woven glass/ polyester laminates. The results have been verified with experimental results of residual velocities, contact time and ballistic limit by these two parameters.

In the present study, experimental and analytical studies have been carried out on the kevlar/epoxy laminates subjected to impact at velocities ranging from 30 m/s to 380 m/s and their deformation mechanism is studied for different velocities, fiber orientations and different thicknesses. FE analysis is also carried out for velocities ranging from 200 m/s to 400 m/s. The residual velocities and energy absorption obtained by experiments and FE analysis are compared with analytical results, which are in good agreement.

2. Experiments

Experiments have been performed on the kevlar/epoxy laminates, made of (0/90) layup sequence with 8 layers, for the velocity range of 30 m/s to 170 m/s and residual velocities have been measured. The residual velocities are calculated using analytical studies and compared with experimental values. Experiments were also performed at 380 m/s and residual velocities obtained experimentally are compared with analytical results. The values obtained from experiments and analysis are in good agreement.

3. Specimen Preparation

The kevlar/epoxy laminates have been fabricated using kevlar fabric (Areal density 165 gsm) and epoxy resin (LY 556 with 10% HY 951) by hand layup technique, followed by compression moulding. Average thickness of each layer is 0.3 mm. The size of the specimens is 300 mm X 300 mm.

4. Material Data

The input data for analytical study and FE analysis has been obtained from experiments, and the values are given in Table 1. The tensile properties such as Young’s modulus, strength and failure strain have been obtained by performing tensile test according to ASTM Standard D3039 for 0° and 90° directions. Tensile specimen dimensions are 300 mm x 15mm and thickness around 5.4 mm. Poisson’s ratios ν_{12} (= ν_{13}) have been obtained by fixing strain gauges in two perpendicular directions on the gauge surface of the tensile specimen. In FE analysis, E_1 (= E_{13}) and X_{12} (= X_{13}), for the unidirectional composites are used. To determine the compressive strength in two
Table 1: Material properties of the kevlar/epoxy composites

<table>
<thead>
<tr>
<th>$E_1$(MPa)</th>
<th>$E_2$(MPa)</th>
<th>$E_3$(MPa)</th>
<th>$v_{12}$</th>
<th>$v_{13}$</th>
<th>$v_{23}$</th>
<th>$G_{12}$(MPa)</th>
<th>$G_{23}$(MPa)</th>
<th>$G_{13}$(MPa)</th>
<th>$\varepsilon_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>33500</td>
<td>8000</td>
<td>8000</td>
<td>0.35</td>
<td>0.35</td>
<td>0.33</td>
<td>2260</td>
<td>3000</td>
<td>2260</td>
<td>0.029</td>
</tr>
<tr>
<td>$X_{11}$(MPa)</td>
<td>$X_{12}$(MPa)</td>
<td>$X_{22}$(MPa)</td>
<td>$X_{23}$(MPa)</td>
<td>$X_{33}$(MPa)</td>
<td>$S_{12}$(MPa)</td>
<td>$S_{23}$(MPa)</td>
<td>$S_{13}$(MPa)</td>
<td>$E_{m1}$(MJ)</td>
<td></td>
</tr>
<tr>
<td>358</td>
<td>260</td>
<td>21</td>
<td>130</td>
<td>21</td>
<td>130</td>
<td>44</td>
<td>34</td>
<td>44</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Experiments have been performed according to ASTM standard D3410 M. To obtain shear strain and in-plane shear modulus of the composites, stress-strain curves have been obtained from tensile tests specimens with $\pm45^\circ$ fiber orientations, as per ASTM Standard D-3518. The corresponding shear stress and in-plane shear modulus [14] have been calculated by using the relations $S_{12} = \frac{\sigma_x}{2}$ and $G_{12} = \frac{E_1}{2(1+\nu_{12})}$, respectively, where $\sigma_x$ is maximum stress obtained in $\pm45^\circ$ tensile test and $S_{23}$ is shear strength of the epoxy. In the present analysis $G_{12} = (G_{13})$. $G_{23}$ is calculated by relation $G_{23} = \frac{E_2}{2(1+\nu_{23})}$. $G_{\text{HC}}$ has been obtained by using end notched specimen. Values of matrix cracking ($E_{m1}$) have been obtained from reference [4]. Tensile tests have been performed for different orientations and thicknesses and results obtained have been used in analysis for energy calculations. The tensile stress-strain curves are shown in Fig. 1. The Young’s modulus and failure strain are given in Table 2.

5. Impact Experiments

Impact experiments for velocities up to 170 m/s have been performed on the kevlar/epoxy laminates using a gas gun set up, consisting of a barrel and a gas chamber. The projectile velocities are changed by varying gas pressure in the gas chamber. The conical projectile used had the diameter of 9 mm, length 15 mm and weight is 7.5g. Samples are mounted on a target holder with all edges fixed. To measure the initial and residual velocities laser diode and aluminum foils have been used, respectively. Digital counter and oscilloscope have been used to determine the time difference in interruption of the two laser diodes and breaking the aluminum foil circuits by the projectile. To calculate the initial velocity and residual velocity the distance between laser diodes and aluminum foils, which is 60 mm, has been divided by time difference

Fig. 1: Stress-strain diagram for 19 layers and different layup sequences

Table 2: Young’s Modulus and failure strains for the laminates of different fiber orientations and thickness values

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Thickness (layers) (E=E_1=E_2) (GPa)</th>
<th>Failure strain (%)</th>
<th>Shear plug strength $S_w$ (N/m²)</th>
<th>Mode II fracture toughness $G_{\text{IIc}}$ (J/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0/90/30/-60)</td>
<td>19</td>
<td>24.57</td>
<td>2.96</td>
<td>9.7</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>24.73</td>
<td>2.7</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>23.81</td>
<td>3.1</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>23.61</td>
<td>2.86</td>
<td>9.5</td>
</tr>
<tr>
<td>(0/90/45/-45)</td>
<td>19</td>
<td>23.48</td>
<td>3.1</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>23.65</td>
<td>2.86</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>22.66</td>
<td>2.8</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>22.44</td>
<td>3.133</td>
<td>9.0</td>
</tr>
<tr>
<td>(30/-60/60/-30)</td>
<td>19</td>
<td>16.16</td>
<td>3.03</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>16.15</td>
<td>3.12</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>16.06</td>
<td>3.0</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>15.91</td>
<td>3.3</td>
<td>8.8</td>
</tr>
</tbody>
</table>
obtained from digital counter and oscilloscope. The values thus obtained and the energy absorption, are given in Table 3. High velocity experiments have been performed at 380 m/s using sterling submachine gun with 9 x 19 mm parabellum bullet. Initial and residual velocities have been measured by using infrared sensors and values are given in Table 3. There is no perforation observed in the 8 layers laminates for velocity up to 80 m/s. It is seen in experiments that the plug is formed for the impact velocity of 380m/s and none up to 180m/s. It is observed from Table 4 that delamination area increases with increase in the velocity of the projectile up to perforation and after that it decreases. The delamination area at velocity 170 m/s is minimum.

### Table 3: Residual velocity and energy absorption of (0/90) kevlar/epoxy laminates at different initial velocities (t=2.4 mm)

<table>
<thead>
<tr>
<th>Initial velocity of projectile (m/s)</th>
<th>Residual velocity of projectile (m/s)</th>
<th>Energy absorbed (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>21</td>
<td>35.8</td>
</tr>
<tr>
<td>120</td>
<td>71</td>
<td>35</td>
</tr>
<tr>
<td>150</td>
<td>118</td>
<td>32.1</td>
</tr>
<tr>
<td>170</td>
<td>144</td>
<td>30.6</td>
</tr>
<tr>
<td>380</td>
<td>374</td>
<td>11.2</td>
</tr>
</tbody>
</table>

### Table 4: Delamination area at the back side of (0/90) kevlar/epoxy laminates at different velocities (t=2.4 mm)

<table>
<thead>
<tr>
<th>Initial velocity of projectile (m/s)</th>
<th>Projectile diameter (mm)</th>
<th>Damage area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>7.5</td>
<td>50</td>
</tr>
<tr>
<td>50</td>
<td>7.5</td>
<td>112.5</td>
</tr>
<tr>
<td>80</td>
<td>7.5</td>
<td>648</td>
</tr>
<tr>
<td>100</td>
<td>7.5</td>
<td>578</td>
</tr>
<tr>
<td>120</td>
<td>7.5</td>
<td>450</td>
</tr>
<tr>
<td>150</td>
<td>7.5</td>
<td>208</td>
</tr>
<tr>
<td>170</td>
<td>7.5</td>
<td>200</td>
</tr>
<tr>
<td>380</td>
<td>9.5</td>
<td>200</td>
</tr>
</tbody>
</table>

### 6. Analysis

Over the years many analytical models have been presented for impact analysis. Many of them are based on energy criteria [1-4] while some are based on elasticity [5, 6, 12, 13]. Among the energy based criteria, Morye et al. [1] have used high speed camera to get duration of impact. Bohong Gu [3] has used strain rates in the fabric to calculate the duration of impact. To calculate the duration of impact, time dependent model is used by Naik et al. [4] which is an iterative and lengthy procedure for the flat ended projectiles.

Based on the above studies [1-4] the present model has been developed with the following assumptions, that, (a) projectile is rigid and remains undeformed during the impact; (b) there is no friction between the projectile and plate; (c) mechanisms of failure of the laminate are uniform across the thickness, (d) laminates are thin, so strain rate is not changed during perforation and (e) material properties remain unchanged during perforation.

If $m_p$ is the mass of the projectile and $V_0$ is initial velocity of the projectile than the total kinetic energy of the projectile is

$$ KE_{po} = \frac{1}{2} m_p V_0^2 \quad (1) $$

Some amount of initial kinetic energy of the projectile is absorbed by the laminates by deforming into various failure modes. Thus from energy balance

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

$E_0$ is the total energy absorbed by the laminate in different failure mechanisms.

For single yarn subjected to impact, elastic and plastic waves propagate outwards from the impact point [15]. The velocity of elastic wave propagation, which is along the length of fibers, is given as

$$ C_e = \sqrt{\frac{1}{\rho} \left( \frac{d\sigma}{d\varepsilon} \right)_{\varepsilon=0}} = \sqrt{\frac{E}{\rho}} \quad (3) $$
Transverse waves travel direction

Fig. 2: Formation of elastic, plastic, transverse waves and cone formation on back side of the laminate

Transverse wave is formed during perforation, which is responsible for the cone formation on the back side of the laminate. The velocity of transverse wave is given by

$$C_t = (1 + \varepsilon_p) \sqrt{\frac{\sigma_p}{\rho(1 + \varepsilon_p)}} - \int_0^{\varepsilon_p} C(\varepsilon) d\varepsilon$$

$$= C_e \sqrt{\varepsilon_p(1 + \varepsilon_p)} - \varepsilon_p C_e$$

(4)

During the ballistic impact on the laminate, longitudinal (elastic) waves followed by plastic waves travel along the fiber direction and transverse waves travel perpendicular to it from the point of impact as shown in Fig. 2. Morye et al. [1] have shown experimentally that there is a cone formation on the exit side of the laminate because of the transverse waves. The strain in the fibers due to transverse waves is plastic in nature. The cone radius depends upon the duration of impact $\Delta t$, which is from the beginning of the impact to the instant when the yarn is broken or the projectile is stopped. $\Delta t$ is calculated based on the strain rate. The strain rate depends on the gauge length and the velocity of the impact. The time required for failure can be calculated by using the expression

$$\Delta t = \frac{\varepsilon_0}{\dot{\varepsilon}}$$

(5)

where

$$\dot{\varepsilon} = \frac{2V_0}{L}$$

(6)

$V_0$ is velocity of the projectile during impact and $L$ is the length of the laminate.

Fig. 3: Primary and secondary fibers in cone area formed at the back side of the laminate

$\Delta t$, so obtained from the above expressions, is used to calculate the radius of cone and is given by the expression:

$$R_c = C_t \Delta t$$

(7)

The value of $C_t$ is obtained from Eqn. (4).

In the cone formation zone, the primary yarns are those which are directly under the impact of the projectile and fails in tensile mode as shown in Fig. 3. The total energy absorbed by primary yarns is the sum of the energy absorbed by the crushing of the composites portion which is directly under the bullet impact and the energy absorbed in plastic deformation of the primary yarns. Hence the energy absorption by these yarns is given by

$$E_{ty} = \frac{\pi d^2 h}{4} E_c + \left(4R_chd - \frac{\pi d^2 h}{4}\right)E\varepsilon_p^2$$

(8)

Fig. 4: Variation of strain in secondary fibers with radius of cone
where, $E_c$ is the area under the stress-strain curve in uniaxial tensile testing. In equation (8) first term is energy absorbed due to crushing of the laminate under the bullet impact while the second term is energy absorbed due to tensile stress in the primary yarns.

All yarns except primary yarns in the deformed cone area are considered to be secondary yarns (Fig. 3). Secondary yarns also elongate and absorb some amount of kinetic energy of the projectile. The energy absorbed by secondary yarns depends upon the strain distribution in these yarns. In the present study, a linear variation of strain from plastic strain to zero is assumed in the secondary yarns (Fig. 4). This imposes the following boundary conditions:

$$
\varepsilon = \varepsilon_p \text{ at } r = d \text{ and } \varepsilon = 0 \text{ at } r = R_c \text{ where } \varepsilon_p \text{ is the plastic strain of the composite.}
$$

For calculation of energy absorbed by secondary yarns average value of plastic strains has been considered.

The total energy absorbed by the deformation of the secondary yarns can be obtained by the expression

$$
E_{ED} = \left( \pi E \varepsilon_p^2 \right) rhdr = \frac{\pi E \varepsilon_p^2 (R_c^2 - d^2)}{4} \tag{9}
$$

At high velocity impact on the kevlar/epoxy composites shear plug formation [16] occurs and the kinetic energy of the projectile is obtained by the expression

$$
E_{SP} = \pi dh S_{sp} \tag{10}
$$

where $S_{sp}$ is shear plug strength of the composite.

Delamination and matrix cracking also absorb some amount of kinetic energy of the projectile. The delamination and matrix crack zones are normally in rhombus shape for the kevlar/epoxy laminates, which are formed on the back side of the laminate during impact. Hence the expression for the energy absorbed by delamination is given by

$$
E_{DL} = 2(n - 1)R_c^2 G_{lcd} \tag{11}
$$

where $n$ is number of layers in the laminate.

Energy absorbed by matrix cracking is expressed as

$$
E_{MC} = 2R_c^2 E_m h V_m \tag{12}
$$

where, $V_m$ is matrix volume fraction of the laminate.

Energy absorbed by moving cone on the back side of the laminate is given by:

$$
E_{KE} = \frac{1}{16} m_c (V_0 + V_r)^2. \tag{13}
$$

The above expression is obtained by considering average value of the mass of the cone and average projectile velocity which varied from $V_0$ to $V_r$.

The mass of moving cone is given by expression:

$$
m_c = \pi R_c^2 h \rho \tag{14}
$$

where $R_c$ radius of cone, $h$ is thickness of the laminate and $\rho$ is density of the composite.

The total energy absorbed by the laminate is given by the expression:

$$
E_0' = E_{TF} + E_{ED} + E_{DL} + E_{MC} + E_{KE} \tag{15}
$$

Using this in the energy conservation Eq. (2), a quadratic equation will be obtained in terms of the unknown residual velocity $V_r$. By solving the equation for $V_r$, we obtain the residual velocity of the projectile which is written as:

$$
V_r = \frac{-2m_c V_0 + \sqrt{4m_c^2 V_0^2 - 4(m_c + 8m_p) [m_c - 8m_p] V_0^2 + E_0'}}{2(m_c + 8m_p)} \tag{16}
$$

For ballistic limit, residual velocity $V_r = 0$, hence

$$
V_b = \frac{16E_0'}{\sqrt{8m_p - M_c}} \tag{17}
$$

Using classical laminate theory of composites [17], the Young’s modulus of the composites is obtained by the relation

$$
E_x = E_y = \frac{1}{t} \left( \frac{A_{x_1}^2 - A_{x_2}^2}{A_{x_1}} \right) \tag{18}
$$
where

$$A_{ij} = \sum_{k=1}^{N} \bar{Q}_{ij} (h_k - h_{k-1})$$  \hspace{1cm} (19)$$

$\bar{Q}_{ij}$ are components of transformed stiffness matrix of the composites and $h_k - h_{k-1}$ is the thickness of $k$th layer.

7. Numerical Simulation for Higher Velocities Under Impact Loading

To evaluate the ballistic response of the kevlar/epoxy laminates for different velocities, thicknesses and orientations, FE analysis has been performed. The velocity considered in the analysis is 200 m/s to 400 m/s. To study the effect of layup sequences and thicknesses, layup sequences, namely, (0/90), (0/90/30/-60), (0/90/45/-45) and (30/-60/60/-30) and thicknesses of 2.4 mm, 3.6 mm, 4.5 mm and 5.7 mm are considered. To simulate the impact problem, Abaqus/Explicit code has been used with available VUMAT user subroutine for Hashin-3D material model. Some details of the material model have been presented below.

8. Modelling Using Abaqus/CAE

Abaqus/CAE has been used for modelling of the laminate and the bullet. After making the model using different modules, an input file is generated. This input file is submitted to Abaqus/Explicit solver to carry out the analysis. In CAE ‘Part Module’, the plate is modeled as 3D deformable solid and the bullet is modeled as 3D Discrete rigid. The dimensions of the laminates are 300mm x 300mm. Numbers of layers considered are 8, 12, 15 and 19 with the corresponding thickness values of 2.4, 3.6, 4.5 and 5.7 mm, respectively. The orientation of layers considered for each laminate include (0/90), (0/90/30/-60), (0/90/45/-45) and (30/-60/60/-30). The projectile is made of steel with density of 7800 Kg/m$^3$ and weight of 7.5 g. The shape of the projectile is conical, which has a diameter of 9 mm.

The orientation angle has been assigned to each lamina of the laminate, in CAE ‘Property Module’. Density and mechanical constants are also defined in the same module. The properties of the kevlar/epoxy are considered as user material and these properties are assigned to the laminate while rigid bullet has been assigned with inertia/mass at the tip of the bullet. In ‘Assembly Module’, plate and bullet have been assembled relative to each other and a gap of 0.5 mm is maintained to apply general contact between the projectile and plate surface. The duration of impact is considered to be 0.0003 sec in all the cases. So, if the velocity of projectile is 200 m/sec, the distance travelled by the projectile will be 60 mm. Since maximum plate thickness considered for our analysis is around 6 mm, during this impact period, the impact phenomenon must have been completed. In ‘Step Module’ Dynamic/Explicit solver has been chosen to solve the problem. In the same module the field and history output required from analysis are specified. The contact between the bullet and plate has been defined in the ‘Interaction Module’ and a general contact is considered. The general contact algorithm generates contact forces to resist node-into-face, node-into-analytical rigid surface, and edge-into-edge contact penetrations.

The primary mechanism for enforcing contact is node-to-face contact. The boundary conditions are defined in the ‘Load Module’ and it is assumed that all the four edges of the laminates are fixed and the initial velocity is assigned to the bullet in the predefined field condition. Each lamina of the laminate is meshed with 8 node linear brick 3D solid element C3D8R in the ‘Mesh Module’. Laminate is partitioned at the center, where bullet is supposed to impact, to create fine meshing around impact zone. The size of mesh is 0.5 mm in the central area and it increases gradually towards outer edge while bullet is meshed uniformly by 3 node 3D triangular facet R3D3 descret rigid elements.

9. Material Model

Abaqus offers a damage model enabling to predict the onset of damage and to model the damage evolution of composite material. The damage model is based on the work of Matzenmiller et al. [18], Hashin et al. [19, 20] and Camanho et al. [21]. Six different failure modes have been considered, which include fiber failure in tension, fiber failure in compression, matrix cracking under transverse tension
and shearing and interlaminar tensile and compression failure. The onset of damage is determined by damage initiation criteria of 3D Hashin model where damage is referred as the degradation of material property. The details of the initiation (Hashin’s) criterion is available in [19, 20].

The effective stress tensor $\tilde{\sigma}$, which is used to evaluate the initiation criteria, is computed from

$$\tilde{\sigma} = M\sigma$$  \hspace{1cm} (20)

where $\sigma$ is the true stress and $M$ is the damage operator.

Prior to any damage initiation and evolution the damage operator, $M$, is equal to the identity matrix, and hence $\tilde{\sigma} = \sigma$. Once damage initiation and evolution have occurred for at least one mode, the damage operator becomes significant in the criteria for damage initiation of other modes. The effective stress $\tilde{\sigma}$ is intended to represent the stress acting over the damaged area that effectively resists the internal forces.

An output variable is associated with each initiation criterion (fiber tension, fiber compression, matrix tension, matrix compression, interlaminar tensile and interlaminar compression) to indicate whether the criterion has been met. A value of 1.0 or higher indicates that the initiation criterion has been met.

10. Damage Evolution

After the onset of damage initiation, the behavior of material is defined by damage evolution. The damage evolution capability for fiber-reinforced materials [22] in Abaqus assumes that damage is characterized by progressive degradation of material stiffness, leading to material failure. Prior to damage initiation material is linearly elastic and beyond that there is a degradation in material properties. The stress-strain relation becomes:

$$\sigma = C_d \varepsilon$$  \hspace{1cm} (21)

where, $\varepsilon$ is the strain matrix and $C_d$ is the damaged elasticity matrix.

Abaqus [22] assumes a linear damage evolution law which is shown in Fig. 5. The positive slope of the stress-displacement curve prior to damage initiation corresponds to linear behaviour of the material; the negative slope after damage initiation is achieved by evolution of the respective damage variable. Fig. 5 shows the unloading path from a partially damaged state, such as point B, which follows linearly towards the origin. The same path is traced back to point B upon reloading.

Abaqus has interface that allows the user to implement general constitutive equations. In Abaqus/Explicit code the user-defined material model is implemented in the user subroutine VUMAT. This interface makes it possible to define any constitutive model of arbitrary complexity. The 2D Hashin’s damage criterion for shell elements is already available in Abaqus/explicit. In the present analysis, available VUMAT user subroutine for 3D Hashin damage model has been used. By using 3D Hashin damage model, it is possible to use 8 noded C3D8R solid elements to mesh the laminates that considers delamination energy between layers and gives more realistic results.

11. Results and Discussion

Analytical Results

The residual velocities and energy absorbed by the different failure mechanisms in the laminates have been obtained by analysis. Energy absorbed by different damage mechanisms at different initial velocities, has been calculated and is given in Table 5. Table 5 shows that for the (0/90) laminates energy absorbed in each damage mechanism is decreasing with increase in velocity of the projectile and decrease
Table 5: Energy absorbed by different damage mechanisms of the (0/90) laminate for different initial velocities and thicknesses

<table>
<thead>
<tr>
<th>No of layers</th>
<th>Velocity of projectile (m/sec)</th>
<th>( E_d ) (J)</th>
<th>( E_{cd} ) (J)</th>
<th>( E_{sp} ) (J)</th>
<th>( E_{ap} ) (J)</th>
<th>( E_{sc} ) (J)</th>
<th>( E_{ap} ) (J)</th>
<th>Residual velocity (m/sec)</th>
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</table>

in thickness of the laminates. Laminates of other lay-up sequences are following same trend. (0/90) lay-up laminates absorb maximum energy while (30/-60/60/-30) lay-up laminates absorb minimum energy.

It is observed from Fig. 6 that residual velocity corresponding to impact velocity of 350 m/s is the lowest for the (0/90) lay-up laminates while it is maximum for the (30/-60/60/-30) lay-up laminates. Same trend is following for other velocities also.

12. Analysis of FE Results

From Fig. 7, it is seen that there is cone formation on the back side of the laminate. Figs. 8(a) and (b) show the damaged top and bottom surfaces of the laminate.

Fig. 7: Cone formation on the back side of (0/90) laminate after perforation (t=5.7 mm)

Fig. 8(a): Top view of failed laminate of (0/90) lay-up orientation (t=5.7 mm)
having 19 layers thickness and (0/90) lay-up sequences at 350 m/s. On the top surface there is a small hole, which is equal to the diameter of the projectile while on the back side the damage area is high. The back side shows the crack propagation in two perpendicular directions.

13. Comparison of Analytical and Experimental Results

The residual velocity of the laminates is obtained through experiments as well as through analysis and the results are presented in Table 6 for velocities below 200 m/s and 380 m/s. From experimental study it is observed that the laminates with velocity up to 200 m/s there is no shear plug formation and at velocity 380 m/s there is shear plug formation. By considering this effect of plug formation in analysis at high velocity, the results are compared with experiments. Good agreement is found with experimental results.

14. Comparison of Analytical and FE Results

The ability of Abaqus to predict the behaviour of the laminate during impact phenomenon depends mainly on the input data. FE analysis using Abaqus has been performed for the projectile velocity in the range of 200 m/s to 400 m/s. Residual velocities for the given initial velocities are obtained numerically and compared with the results obtained from analytical model. These values are given in Table 7, and good agreement is found.

15. Conclusion

Response of Kevlar/epoxy laminates has been studied for different projectile velocities, fiber orientations and thicknesses by experimental, analytical and numerical methods. Theoretical expressions are obtained to predict the ballistic limit, residual velocity and energy absorption of the laminates. Experiments have been performed on (0/90) layup sequence and 2.4 mm
thickness laminates at) low and high velocities to investigate the effect of velocities on different failure mechanisms. It is seen that at lower velocities, shear plug is not formed, while at higher velocities there is shear plug formation. The residual velocities obtained from experiments and analytical formulations are compared and these show good agreement. With increase in velocity of the projectile delamination area at the back side of the laminates increases for velocities up to ballistic limit and after that it decreases.

FE analysis is performed for high velocities for different layup sequences and thicknesses. Results obtained from FE analysis are in good agreement with analytical results. The studies reveal that with increase in velocity of the projectile energy absorbing capacity decreases. Cross-ply laminates gives minimum residual velocity for the given initial velocity when compared to other orientations. Hence cross-ply laminates absorb more energy when compared with other lay-up laminates.

References

19. Hashin Z and Rotem A J Compos Mater 7 (1973) 448-464