Composite structures under ballistic impact

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Abstract

In the present study, investigations on the ballistic impact behaviour of two-dimensional woven fabric composites has been presented. Ballistic impact behaviour of plain weave E-glass/epoxy and twill weave T300 carbon/epoxy composites has been compared. The analytical method presented is based on our earlier work. Different damage and energy absorbing mechanisms during ballistic impact have been identified. These are: cone formation on the back face of the target, tensile failure of primary yarns, deformation of secondary yarns, delamination, matrix cracking, shear plugging and friction during penetration. Analytical formulation has been presented for each energy absorbing mechanism. Energy absorbed during each time interval and the corresponding reduction in velocity of the projectile has been determined. The solution is based on the target material properties at high strain rate and the geometry and the projectile parameters. Using the analytical formulation, ballistic limit, contact duration at ballistic limit, surface radius of the cone formed and the radius of the damaged zone have been predicted for typical woven fabric composites.

Keywords: Ballistic impact; Woven fabric composite; Energy absorbing mechanisms; E-glass/epoxy; T300 carbon/epoxy

1. Introduction

Composite structures undergo various loading conditions during the service life. For the effective utilization of composites as protective structures, the critical requirement is the resistance to foreign object ballistic impact loading. For such applications, the condition for the penetration of the projectile into the composite target and the associated damage mechanisms should be clearly understood. Post ballistic impact residual strength is also an important consideration. Impact loads can be classified into three categories: low velocity impact, high velocity impact and hyper velocity impact. The reason for this classification is that energy transfer between projectile and target, energy dissipation and damage propagation mechanisms undergo drastic changes as the velocity of the projectile changes. One of the possible ways of enhancing the ballistic limit is to utilize textile composites.

Kinetic energy of the projectile when impacted into the target is dissipated and absorbed in various ways by the target. The main energy absorbing mechanisms during ballistic impact are: kinetic energy absorbed by the moving cone formed on the back face of the target, shear plugging of the projectile into the target, energy absorbed due to tensile failure of the primary yarns, energy absorbed due to elastic deformation of the secondary yarns, energy absorbed due to matrix cracking and delamination and frictional energy absorbed during penetration.

An impact event is considered to be a low velocity impact if the contact period of impactor is longer than the time period of the lowest vibrational mode. In low velocity impact regime, the support conditions are crucial as the stress waves generated outward from the impact point have time to reach the edges of the structural element, causing its full-vibrational response. On the other hand, in high velocity or ballistic impact, the response of the structural element is governed by the ‘local’ behaviour of the material in the neighborhood of the impacted zone, the impact response of the element being generally independent of its support conditions. The contact period of the impactor is much smaller than the time period of lowest vibrational mode of the structure. Hyper velocity impact involves projectiles moving at extremely high velocities such that the local target materials behave like fluids and the stress induced by the impact is many times the material strength.
The composite structural applications which involve survivability of personnel and equipments against penetration by high velocity projectiles are of much import. Thus, it is important to have an understanding of the penetration process of the composites by a projectile under ballistic velocities. Considering the importance of this subject there are many experimental studies on the ballistic impact of composites. But the experimental studies are specific to certain types of composite materials under certain ballistic impact conditions. Based on these experimental studies the ballistic impact behaviour of a class of composite materials cannot be characterized. For complete understanding of a class of composite materials, analytical studies are necessary based only on mechanical/fracture and geometrical properties of target and ballistic impact parameters. But the analytical studies are very limited. The ballistic impact performance of composite laminates is dependent on the mechanical characteristics of the reinforcement/matrix and the physical characteristics of the impacting projectile and the target. Mechanical characteristics of the target include the elastic modulus, tensile strength, fracture strain and laminate configuration. Projectile characteristics include mass and shape. Thickness and size are the target parameters that affect the ballistic impact performance. Ballistic impact is generally a low-mass high-velocity impact caused by a propelling source. Ballistic limit of a target is defined as the maximum velocity of a projectile at which the complete perforation takes place with zero exit velocity.

Limited number of semi-analytical and semi-numerical models, which require input details from a few experiments, are available [1–11]. But in these studies all
the energy absorbing mechanisms have not been considered. Also, complete details are not provided.

The objective of the present work is to present an analytical model for the ballistic impact analysis based only on dynamic mechanical and fracture properties of the target material, geometrical parameters of the target and the projectile parameters, such as mass, velocity, shape and size. The studies have been presented for typical woven fabric E-glass/epoxy and T300 carbon/epoxy composites impacted with flat ended cylindrical projectiles. The analytical method presented can be used for predicting the energy absorbed by different damage and energy absorbing mechanisms, ballistic limit, contact duration and the damage size. Ballistic impact behaviour of plain weave E-glass/epoxy and twill weave T300 carbon/epoxy composites has been compared. Energy absorbed by various mechanisms is calculated for a given mass and velocity of the projectile. By knowing the energy absorbed by various mechanisms, the total energy absorbed during impact event is calculated as the sum of the individual energies absorbed.

The energy absorbed at each time interval is calculated. Based on this, the velocity at the end of the corresponding time interval is calculated. This procedure is continued for the entire contact duration. At ballistic limit the target absorbs the entire energy of the projectile. So the energy absorbed by the target is made equal to the initial kinetic energy of the projectile. From this the velocity of the projectile, which is the ballistic limit of the target, is calculated.

The input to the present analytical model are: the dynamic mechanical properties of the target, target geometrical details and projectile shape, size, mass and incident ballistic impact velocity. The output that can be obtained are the ballistic limit of the target, contact duration and damage dimensions.

2. Damage mechanisms

For the complete understanding of the ballistic impact of composites, different damage and energy absorbing mechanisms should be clearly understood. Possible energy absorbing mechanisms are: cone formation on the back face of the target, deformation of secondary yarns, fracture of primary yarns/fibres, delamination, matrix cracking, shear plugging and friction between the projectile and the target. For different materials like carbon, glass or Kevlar, different mechanisms can dominate. Also, the reinforcement architecture can influence the energy absorbing mechanisms.

2.1. Cone formation on the back face of the target

Morye et al. [9] carried out ballistic impact tests on woven Nylon prepreg composites. They monitored the back face deformation behaviour using high speed photography. Their study showed that a cone was formed on the back face of the composite during the ballistic impact event. Experimental studies by Zhu et al. [12] on woven Kevlar/polyester laminates of varying thickness also showed the cone formation on the back face of the composites during ballistic impact event. The cone formation on the back face can be explained on the basis of transverse wave propagation during ballistic impact.

Figs. 1 and 2 show the deformation and cone formation on the back face of the composite during ballistic impact. Here, $d$ is the diameter of the projectile, $r_{ti}$ is the surface radius of the cone formed and $z_i$ is the distance traveled by the projectile. During the ballistic impact event, the distance traveled by the projectile and the depth of the cone formed are equal. Also, the velocities of the projectile and the cone would be equal.

The yarns directly below the projectile are called primary yarns. These yarns provide the resistive force to the projectile penetration into the target. The remaining yarns within the conical region are known as secondary yarns. These yarns deform and cause some energy absorption. The conical portion has a finite velocity equal to that of the projectile.

For the analysis of the ballistic impact event, the contact duration can be subdivided into certain number of time intervals of duration $\Delta t$. The damage mechanism and the energy absorption can be determined for each
time interval and this effect can be taken into account while proceeding with further time intervals. The surface radius of the cone formed can be calculated on the basis of transverse wave propagation. The transverse wave velocity depends on the stress-strain curve at high strain rates for the material.

During the second time interval the surface radius of the cone increases from \( r_{t1} \) to \( r_{t2} \). Surface radius \( r_{t2} \) is calculated based on how much additional transverse wave propagation has taken place during that time interval. As the transverse wave propagation continues, surface radius of the cone \( r_n \), cone depth \( z_i \), mass of the cone \( M_{CJ} \) and the strain in the fibres \( e_i \) increase. As the strain within the fibre exceeds the permissible dynamic tensile strain, the corresponding fibre fails. Increase in \( r_{n}, z_{i}, M_{CJ} \) and \( e_{i} \) continues until all the fibres are broken or the entire energy of the projectile is absorbed by the target. It may be noted that the strain within the primary yarns is not constant. At any moment, it is maximum at the point of impact and decreases as we move away from the point of impact.

Failure of all the fibres indicates complete perforation of the projectile into the target. At this stage, if the projectile still has some kinetic energy, it would be exiting with certain velocity. If the exit velocity is zero, the corresponding incident ballistic impact velocity of the projectile is the ballistic limit. If the projectile velocity is zero during the contact event before all the fibres are broken, it indicates that only the partial penetration has occurred.

2.2. Energy absorbed due to deformation of secondary yarns

Possible cone formation on the back face of the target during ballistic impact event is shown in Fig. 1. The primary yarns take the direct force and ultimately fail if the strain exceeds the maximum strain limit. As a result the complete target perforation takes place. All the yarns apart from the primary yarns, i.e., the secondary yarns, shown in Fig. 1 deform and absorb some energy. The energy absorbed by secondary yarns depends on the strain distribution within the secondary yarns. Strain in the secondary yarns near the tip of the cone, i.e., at point A is the same as that in the primary yarns and it decreases linearly to zero as we move out radially to point B.

2.3. Energy absorbed due to tensile failure of primary yarns

Primary yarns/fibres provide the force to resist the penetration of the projectile into the target. The strain is maximum in these yarns/fibres. These yarns fail under tension when the strain of these yarns exceeds the ultimate strain in tension at high strain rate. Failure of these yarns/fibres results in absorption of some energy. Fig. 1 indicates the strain variation in primary yarns within a layer and in through the thickness direction.

During cone formation, the tensile strain would be maximum along the middle primary yarn, in each layer. Within the primary yarns in a layer strain reduces gradually, as we move away from the mid primary yarn. This is due to the fact that the middle yarn is pushed by complete projectile diameter, but other primary yarns face a projectile length which is lesser than projectile diameter.

The top layers of the laminate when impacted get compressed apart from the cone formation, which causes the strain in the top layers to be more than that in the bottom layers. The extent of compression is based on the stress at the point of impact. This stress causes an extra straining of the top layers. The variation of strain in through the thickness direction is shown in Fig. 1. The strain in the top layers is more than the strain in the bottom layers. Each primary yarn has different strain. As and when the strain of a particular yarn reaches the dynamic tensile failure strain, failure occurs to that particular yarn. As a result, there will be a sequential failure of yarns starting with the yarns in the top layer, then proceeding toward the bottom layer. It may be noted that the strain within the primary yarn is not constant. At any moment it is maximum at the point of impact and decreases as we move away from the point of impact.

2.4. Energy absorbed due to shear plugging

Cantwell and Morton [13] observed frustum-shaped shear cut-out zone on impacting carbon fibre reinforced angle ply laminates with steel spherical bullets. Lee and Sun [14] and Ellis [15] reported shear plugging to be one
of the major damage modes on impact of angle ply graphite/bismaleimide by blunt/flat projectiles. Fig. 3 shows schematic arrangement of plug formation during ballistic impact. Brittle nature of carbon based composites was responsible for change in damage mechanism. Shear plug formation is not observed for glass reinforced composites which have high failure strain at high strain rates.

2.5. Energy absorbed by other mechanisms

Delamination and matrix cracking would absorb some energy (Fig. 2). Additionally, friction between the projectile and the target would also absorb some energy.

3. Analytical formulation for woven fabric composites

On striking a target, energy of the projectile is absorbed by various mechanisms like kinetic energy of moving cone $E_{KE}$, shear plugging $E_{SP}$, deformation of secondary yarns $E_D$, tensile failure of primary yarns $E_{TF}$, delamination $E_{DL}$, matrix cracking $E_{MC}$, friction energy $E_F$ along with other energy dissipation mechanisms. An analytical model is presented for the above-mentioned mechanisms, which dominate during ballistic impact of two-dimensional woven fabric composites [16,17].

3.1. Analytical formulation

A cone is observed on the back face of the target as shown in Fig. 1 when struck by a projectile [9,12]. Shear plugging on the front face and cone formation on the back face start taking place depending on the target material properties during the ballistic impact event. The velocity of the cone is the same as the velocity of the projectile. Initially, the cone has velocity equal to that of the projectile and has zero mass. As time progresses, the mass of the cone increases and velocity of the cone decreases. As the cone formation takes place, the yarns/fibres deform and absorb some energy. The primary yarns which provide the resistive force to the projectile motion deform the most, thus leading to their failure. When all the primary yarns fail the projectile exits the target. Tensile failure of the yarns thus absorbs some energy of the projectile. During the ballistic impact event, delamination and matrix cracking take place in the laminate area which forms the cone. The total kinetic energy of the projectile that is lost during ballistic impact is the total energy that is absorbed by the target till that time interval and is given by

$$E_{TOTAL} = E_{KE} + E_{SP} + E_D + E_{TF} + E_{DL} + E_{MC} + E_F$$

(1)

An analytical model to predict the ballistic limit is presented below. Firstly, modelling of a single yarn is presented. The model is further extended to the woven fabric composites. The analytical model is for the case when the projectile impacts the target normally.

The following assumptions are made in the analytical model presented:

1. Projectile is perfectly rigid and remains un-deformed during the ballistic impact.
2. Projectile motion is uniform during penetration within each time interval.
3. Yarns/fibres in a layer act independently.
4. Energy absorption due to primary yarn/fibre breakage and deformation of the secondary yarns are treated independently.
5. Longitudinal and transverse wave velocities are the same in all the layers.

3.2. Modelling of a single yarn subjected to transverse ballistic impact

When a yarn is impacted by a projectile transversely, longitudinal strain wavelets propagate outward along the filament [4,18,19]. The outermost wavelet, called the elastic wave propagates at velocity

$$c_e = \sqrt{\frac{1}{\rho} \left( \frac{d\sigma}{d\varepsilon} \right)_{\varepsilon=0}}$$

(2)

The innermost longitudinal wavelet called the plastic wave propagates at velocity

$$c_p = \sqrt{\frac{1}{\rho} \left( \frac{d\sigma}{d\varepsilon} \right)_{\varepsilon={\varepsilon_p}}}$$

(3)

Here, $\varepsilon_p$ denotes the strain at which plastic region starts. As the strain wavelets pass a given point on the yarn, material of the filament flows inward toward the impact point. The material in the wake of the plastic wave front forms itself into a transverse wave, shaped like an inverted tent with the impact point at its vertex. In a fixed coordinate system, the base of the tent spreads outward with the transverse wave velocity. This is depicted in Fig. 4. The transverse wave velocity is given by
Fig. 4. Configuration of a yarn/fibre before and after transverse impact: (a) before impact; (b)–(d) after impact.

\[ c_i = \sqrt{\frac{(1 + \varepsilon_p)\sigma_p}{\rho}} - \int_0^{\tau_i} \frac{1}{\rho} \left( \frac{d\sigma}{dc} \right) dc \]  \hspace{1cm} (4)

If the complete impact event is divided into a number of small instants, then at \( i \)th instant, the time is given by \( t_i \). By that time the transverse wave has traveled to a distance \( r_{tu} \) and the plastic wave has traveled to a distance of \( r_{pi} \). The projectile has moved through a distance \( z_i \).

Radii \( r_{tu} \) and \( r_{pi} \) after time \( t_i = i\Delta t \) is given by

\[ r_{tu} = \sum_{n=0}^{n=i} c_{tu}\Delta t \]  \hspace{1cm} (5)

\[ r_{pi} = \sum_{n=0}^{n=i} c_{pe}\Delta t \]  \hspace{1cm} (6)

3.3. Modelling of woven fabric composite

Woven fabric composites consist of warp and fill yarns, interlaced in a regular sequence. As the projectile impacts on to the woven fabric composite, there can be many yarns beneath the projectile. In the present analysis, all the warp and fill yarns are treated separately. Behaviour of each yarn is analysed as explained in the previous section. Overall behaviour of the woven fabric composite is presented considering the combined effect of all the individual yarns within a layer.

3.4. Strain and deceleration history: single yarn of woven fabric composite

When a projectile impacts a woven fabric composite, a cone with quasi-lemniscate cross-section would be formed on the back face of the target. Quasi-lemniscate shape is because of difference in elastic properties and critical strain energy release rates along warp/fill directions and the other directions. For simplicity, the cone formed can be considered to be of circular cross-section, rather than quasi-lemniscate. The base of the cone spreads with a transverse wave velocity

\[ c_i = \sqrt{\frac{(1 + \varepsilon_p)\sigma_p}{\rho}} - \int_0^{\tau_i} \frac{1}{\rho} \left( \frac{d\sigma}{dc} \right) dc \]  \hspace{1cm} (7)

and the plastic wave velocity is given by

\[ c_{pi} = \sqrt{\frac{1}{\rho} \left( \frac{d\sigma}{dc} \right) z_{pi}} \]  \hspace{1cm} (8)

After time \( t_i \) the transverse wave has traveled to a distance \( r_{tu} \) and the plastic wave has traveled to a distance of \( r_{pi} \). The projectile has moved through a distance \( z_i \). Radii \( r_{tu} \) and \( r_{pi} \) after time \( t_i = i\Delta t \) are given by

\[ r_{tu} = \sum_{n=0}^{n=i} c_{tu}\Delta t \]  \hspace{1cm} (9)

\[ r_{pi} = \sum_{n=0}^{n=i} c_{pe}\Delta t \]  \hspace{1cm} (10)

Because of stress wave attenuation, the stress in the yarn and hence, the strain in the yarn varies with the distance from the point of impact. Stress and in turn strain is maximum at the point of impact and decreases as one moves away from the point of impact. At \( i \)th time interval, the strain at the point of impact is given by

\[ \varepsilon_i = \left\{ \frac{(d/2) + \sqrt{(r_{tu} - (d/2))^2 + z_i^2} + (r_{pi} - r_{tu}) - r_{pi}}{b(r_{pi}/a) - 1} \right\} \times \left\{ \ln b \right\} \]  \hspace{1cm} (11)

Once, the strain variation in a yarn/fibre is known, the energy absorbed by various mechanisms like kinetic energy of the moving cone, deformation energy absorbed by secondary yarns, tensile failure of primary yarns, delamination and matrix cracking can be calculated. The formulation for energy absorbed by various energy absorbing mechanisms is provided in the following sections.

At the beginning of the first time interval of impact, entire energy is in the form of kinetic energy of the projectile. Later, this energy is divided into energy absorbed by various damage mechanisms and the kinetic energy of moving cone and projectile. Considering the energy balance at the end of \( i \)th time interval, we obtain

\[ KE_{p0} = KE_{ke} + E_{SP(i-1)} + E_{DL(i-1)} + E_{TF(i-1)} \]

\[ + E_{DL(i-1)} + E_{MC(i-1)} + E_{Fi(i-1)} \]  \hspace{1cm} (12)

Rearranging the terms in the above equation, the following form is obtained:
\[
\frac{1}{2} m_p V_0^2 - E_{i-1} = \frac{1}{2} (m_p + M_C) V_i^2
\]

(13)

where

\[
E_{i-1} = E_{SP(i-1)} + E_{DL(i-1)} + E_{TF(i-1)} + E_{DL(i-1)} + E_{MC(i-1)} + E_{F(i-1)}
\]

(14)

Each of the contributing terms to \(E_i\) is explained in the succeeding sections. The terms on the right-hand side of Eq. (14) are known at \((i-1)\)th instant of time. From this, the velocity of the projectile at the end of \(i\)th time interval can be obtained and it is given by

\[
V_i = \sqrt{\frac{\frac{1}{2} m_p V_0^2 - E_{i-1}}{\frac{1}{2} (m_p + M_C)}}
\]

(15)

If the projectile velocity is known at the beginning and the end of \(i\)th time interval, then the deceleration of the projectile during that time interval can be found out. It is given by

\[
dc_i = \frac{V_{i-1} - V_i}{\Delta t}
\]

(16)

Note that the velocity at the beginning of the \(i\)th time interval is the same as the velocity at the end of \((i-1)\)th time interval. Distance traveled by the projectile \(z_i\) up to \(i\)th time interval is given by

\[
z_i = \sum_{n=0}^{n-1} \Delta z_n
\]

(17)

\[
\Delta z_i = V_{i-1} \Delta t - \frac{1}{2} dc_i (\Delta t)^2
\]

(18)

Utilizing \(dc_i\), the deceleration of the projectile during \(i\)th time interval, the force resisting the projectile motion can be calculated. It is given by

\[
F_i = m_p dc_i
\]

(19)

The magnitude of the force on the projectile is the same as the magnitude of the force applied on the target, by the projectile. Hence, this force can be used to determine whether shear plugging takes place or not.

The above process is repeated until all the primary yarns in the target fail, i.e., the complete perforation takes place. The velocity at the end of time interval, during which all the yarns are broken, is the residual velocity of the projectile. On the other hand, if the numerator in Eq. (15) becomes zero, then the projectile does not penetrate the target completely with the given initial velocity. Thus by repetition of above procedure with various velocities so as to get complete perforation with zero residual velocity, the ballistic limit of the target laminate can be obtained.

3.5. Kinetic energy of cone formed

The cone formed on the back face of the target absorbs some energy. By the end of \(i\)th time interval the radius of the cone formed is

\[
r_{ti} = \sum_{n=0}^{n-1} c_{nt} \Delta t
\]

(20)

Mass of the cone formed is

\[
M_C = \pi r_{ti}^2 h \rho
\]

(21)

The velocity of the cone formed is equal to \(V_s\), the velocity of the projectile at the end of \(i\)th time interval. So the energy of the cone formed at the end of \(i\)th time interval is

\[
E_{K_{\text{CN}}} = \frac{1}{2} M_C V_s^2
\]

(22)

3.6. Energy absorbed due to shear plugging

When the target material is impacted by the projectile, shear plugging stress in the material near projectile periphery rises. As and when the shear plugging stress exceeds shear plugging strength, shear plugging failure occurs. As a result, plug formation takes place. This phenomenon is observed for carbon/epoxy composites (Fig. 3). If at the beginning of the \(i\)th time interval, shear plugging stress exceeds shear plugging strength, then the energy absorbed by shear plugging during that time interval is given by the product of distance sheared, shear plugging strength and the area over which shear plugging stress is applied. It is given by

\[
\Delta E_{SP} = Nh_S \rho \pi dh
\]

(23)

where \(N\) indicates the number of layers shear plugged during \(i\)th time interval and \(S_{SP}\) denotes shear plugging strength. The energy absorbed by shear plugging by the end of \(i\)th time interval is given by

\[
E_{SP} = \sum_{n=0}^{n-1} \Delta E_{SPn}
\]

(24)

3.7. Energy absorbed due to deformation of secondary yarns

The secondary yarns experience different strains depending on their position. The yarns which are close to the point of impact experience a strain equal to the strain in the outermost primary yarn, whereas those yarns which are away from the impact point experience less strain. The strain variation is assumed to be linear from \(A\) to \(B\) (Fig. 1). This imposes the following boundary conditions for the variation in strain at time \(t_i\):

- \(\varepsilon_{sy} = \varepsilon_{py}\) at \(r = d/\sqrt{2}\), i.e., at point \(A\)
- \(\varepsilon_{sy} = 0\) at \(r = r_u\), i.e., at point \(B\)
Here, \( e_y \) is the strain in the outermost primary yarn in that layer. The energy absorbed in the deformation of all the secondary yarns can be obtained by the following integration:

\[
E_{Di} = \int_{d_i/\sqrt{2}}^{r_y} \left( \int_0^{e_{\max}} \sigma_y(e_y) \, de_y \right) \, d\theta 
\times \left\{ 2\pi \sigma - 8\pi \sin^{-1}(d/2r) \right\} dr 
\]  

(25)

### 3.8. Energy absorbed due to tensile failure of primary yarns

The yarns directly below the projectile, known as the primary yarns, fail in direct tension. All the primary yarns within one layer do not fail at one instant of time. As and when the strain in a particular yarn reaches the dynamic failure strain in tension, the yarn fails. It may be noted that the length of yarns/fibres failing in tension is twice the distance covered by the longitudinal wave. Also, the complete length of a primary yarn is not strained to the same extent as explained earlier. The reason for this phenomenon is stress wave attenuation. When the strain in yarns/fibres exceeds failure strain, it fails and some energy is absorbed due to tensile failure. For a yarn/ fibre of cross-section area \( A \) it is given by

\[
E_{TF} = A \int_{e_0}^{e_{\max}} \sigma(e) \, de 
\]  

(26)

where \( e_0 \) is the ultimate strain limit. If during \( n \)th time interval \( N \) numbers of yarns/fibres are failing, then the right-hand side of the above expression is multiplied by \( N \).

### 3.9. Energy absorbed due to delamination and matrix cracking

Delamination and matrix cracking absorb some part of the initial kinetic energy of the projectile. A part of the conical area undergoes delamination and matrix cracking (Fig. 2). The extent to which composite has delaminated and the matrix has cracked till \( i \)th time instant can be calculated on the basis of strain profile in the composite at that time interval. From the results derived in the earlier section it can be observed that the strain at the impact point is the highest and it decreases as one moves away from the point of impact. The area in which strain is more than the damage initiation threshold strain \( e_d \), will undergo damage in the form of matrix cracking and delamination. However, complete matrix cracking may not take place. Evidence for this phenomenon is provided by the fact that after ballistic impact, matrix is still attached to the fibres and does not separate from the reinforcement completely. Due to matrix cracking, the interlaminar strength of the composite decreases. As a result, further loading and deformation causes delamination. This delamination is of mode II type. Again, delamination may not occur at all the lamina interfaces. Towards the end of ballistic impact event, when only a few non-delaminated layers are left, these non-delaminated layers are more likely to bend rather than delaminate.

The area undergoing delamination and matrix cracking in the conical region is of quasi-lemniscate shape, which is taken to be \( A_{qd} \) percent of the corresponding circular area. During \( (i + 1) \)th time interval the area of delamination and matrix cracking is given by

\[
\pi (r_d^2 - r_{di}^2) A_{qd} 
\]  

(27)

where \( r_d \) indicates the radius up to which the damage has propagated until \( i \)th time interval. So the respective energies absorbed by delamination and matrix cracking during this time interval are given by

\[
\Delta E_{DLi} = P_d \pi (r_d^2 - r_{di}^2) A_{qd} G_{Icd} 
\]

(28)

\[
\Delta E_{MCl} = P_m \pi (r_d^2 - r_{di}^2) A_{qd} G_{Icd} 
\]

(29)

The factors \( P_d \) and \( P_m \) stand for percentage delamination and percentage matrix cracking. Energy absorbed till the \( i \)th time interval is given by

\[
E_{DLi} = \sum_{n=1}^{i} \Delta E_{DLn} 
\]

(30)

\[
E_{MCl} = \sum_{n=1}^{i} \Delta E_{MCl} 
\]  

(31)

### 3.10. Calculation of contact duration

The impact event starts when the projectile touches the front face of the target. End of the event is taken to be when all the primary yarns fail or when the velocity of the projectile becomes zero. Total time from the start of the impact event till the end of the event is called as contact duration. If the end of the event occurs during \( n \)th time interval, then the contact duration is obtained as

\[
t_c = n\Delta t 
\]  

(32)

### 4. Results and discussion

Ballistic impact behaviour of woven fabric composites when impacted by a flat ended projectile has been presented. This behaviour is based on the analytical method presented in the previous section. Specifically, ballistic limit, contact duration at ballistic limit and surface radius of the cone formed at the ballistic limit have been determined. These results have been compared with the experimental results. Behaviour of plain weave E-glass/epoxy and twill weave T300 carbon/epoxy composite structures under ballistic impact has been compared. Input data necessary for the analytical prediction of ballistic impact behaviour in the present study has been provided in Table 1.
4.1. Calculation of ballistic limit, contact duration and surface radius of the cone formed during ballistic impact

Using the analytical method presented earlier ballistic impact behaviour of typical plain weave E-glass/epoxy and twill weave T300 carbon/epoxy composites has been evaluated. The results are presented in Table 2 and Figs. 5–8. For the case of E-glass/epoxy, complete perforation did not take place at $V_1 = 158$ m/s whereas with $V_1 = 159$ m/s, complete perforation took place with exit velocity of 54 m/s. The experimentally obtained ballistic limit is $V_{50} = 150$ m/s. Analytically predicted ballistic limit is between 158 and 159 m/s. For the case of T300 carbon/epoxy, complete perforation did not take place with $V_1 = 82$ m/s whereas with $V_1 = 83$ m/s, complete perforation took place with exit velocity of 18 m/s. The above results are with $m_p = 2.8$ g, $d = 5$ mm and $h = 2$ mm.

For T300 carbon/epoxy the studies were also carried out with $m_p = 1.8$ g, $h = 2$ mm and $d = 5$ mm. For this case the experimentally obtained ballistic limit, $V_{50} = 105$ m/s. The analytically predicted ballistic limit $V_{BL} = 99$ m/s (Table 2). It is generally observed that there is a good co-relation between the experimental results and the predicted results for both E-glass/epoxy and T300 carbon/epoxy.

From Figs. 5 and 7 it can be seen that the ballistic limit is much higher for E-glass/epoxy than for T300 carbon/epoxy. This is because of higher energy absorbed by E-glass/epoxy than by T300 carbon/epoxy (Fig. 9). Fig. 9 is for high strain rate loading. Also, shear plugging strength for E-glass/epoxy is much higher than that for T300 carbon/epoxy.

For E-glass/epoxy, energy absorbed by secondary yarn deformation and tensile failure of yarns are the main energy absorbing mechanisms. Shear plugging does not take place in this case. On the other hand, for T300 carbon/epoxy, the ultimate failure is because of shear plugging. Energy absorbed by secondary yarn deformation and shear plugging are the main energy absorbing mechanisms (Figs. 6 and 8). In this case, tensile failure of the yarns does not take place.
Fig. 5. Energy absorbed by different mechanisms during ballistic impact event, $m_p = 2.8 \text{ g}$, $h = 2 \text{ mm}$, $d = 5 \text{ mm}$: (a) twill weave T300 carbon/epoxy laminate, $V_I = 82 \text{ m/s}$; (b) plain weave E-glass/epoxy laminate, $V_I = 158 \text{ m/s}$.

Fig. 6. Projectile velocity, strain, contact force and shear plugging stress variation during ballistic impact event, $m_p = 2.8 \text{ g}$, $h = 2 \text{ mm}$, $d = 5 \text{ mm}$: (a) twill weave T300 carbon/epoxy laminate, $V_I = 82 \text{ m/s}$; (b) plain weave E-glass/epoxy laminate, $V_I = 158 \text{ m/s}$.

Fig. 7. Energy absorbed by different mechanisms during ballistic impact event, $m_p = 2.8 \text{ g}$, $h = 2 \text{ mm}$, $d = 5 \text{ mm}$: (a) twill weave T300 carbon/epoxy laminate, $V_I = 83 \text{ m/s}$; (b) plain weave E-glass/epoxy laminate, $V_I = 159 \text{ m/s}$.
It is generally observed that the energy absorbed by delamination and matrix cracking is of small magnitude.

5. Conclusions

Ballistic impact behaviour of typical plain weave E-glass/epoxy and twill weave T300 carbon/epoxy composites has been studied. It has been observed that, for identical ballistic impact conditions, ballistic limit is higher for E-glass/epoxy than for T300 carbon/epoxy. For E-glass/epoxy, energy absorbed by secondary yarn deformation and tensile failure of primary yarn are the main energy absorbing mechanisms. For T300 carbon/epoxy, the main energy absorbing mechanisms are the secondary yarn deformation and shear plugging.

References


