BALLISTIC IMPACT BEHAVIOR OF CARBON NANOTUBE DISPERSIZED EPOXY RESIN: PARAMETRIC STUDIES

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1 Introduction

One of the most important requirements of modern structural components for high technology aerospace, marine, civil, automobile and defense applications is high impact resistance, in turn, high energy absorption capability. Protection against external high velocity projectiles is one of the critical requirements, particularly in the aerospace and defense industry. Recent advances at enhancing ballistic protection capability include dispersion of carbon nanotubes (CNTs), with high energy absorption characteristics, into resins. The small size and extraordinary stiffness of CNTs makes them an ideal reinforcement for resins. Studies available in literature on the various damage and energy absorbing mechanisms of carbon nanotube (CNT) dispersed resins under quasi-static loading \([1-4]\) indicate that reinforcing resins with CNTs enhances their mechanical properties, with an increase in fracture toughness being a major feature. This gives CNT dispersed resins strong potential applications in making ballistic impact resistant components.

When a ballistic impact event takes place, different types of stress waves propagate in the impacted bodies \([5]\). In order to study ballistic impact behavior of composite structures, a thorough understanding of stress wave propagation is essential.

Studies are available in literature on the ballistic impact behavior of CNT dispersed polymer matrix composites \([6-9]\). Pandya et al. \([6]\) investigated the effect of multi-walled carbon nanotube (MWCNT) dispersion on the ballistic impact behavior of unidirectional E-glass / epoxy. Laurenzi et al. \([7]\) studied the high velocity impact behavior of MWCNT dispersed Kevlar-29 / epoxy. Rahman et al. \([8]\) carried out experimental investigations on the ballistic impact behavior of MWCNT dispersed E-glass / epoxy. Tehrani et al. \([9]\) investigated the effect of MWCNT dispersion on the ballistic impact behavior of carbon / epoxy composites. These studies \([6-9]\) reported an enhancement in ballistic impact properties of composites on CNT dispersion. To our knowledge, there are no studies on the ballistic impact behavior of CNT dispersed resins.

In the present study, ballistic impact behavior of MWCNT dispersed epoxy resin is presented based on analytical investigations. The focus of the present work is on parametric studies. The analytical model is based on stress wave propagation \([5]\) and energy balance between the kinetic energy of the projectile and the energy absorbed by different mechanisms. During the ballistic impact event, the energy lost by the projectile is absorbed by the target through various damage and energy absorbing mechanisms such as compression of the target directly below the projectile, compression in the region surrounding the point of impact, formation of ring and radial cracks in the resin leading to tensile failure, shear plugging of the target and energy absorbed by CNTs. The inputs required for the analysis are: mass, shape and velocity of the projectile, thickness and mechanical properties of the target. Analytical predictions are compared with typical experimental results. Further, the effect of mass, diameter and incident impact velocity of the projectile, target thickness, and amount of MWCNT dispersion on ballistic limit velocity are studied.

2 Damage and energy absorbing mechanisms

2.1 Carbon nanotube

Various damage and energy absorbing mechanisms of CNTs under quasi-static loading \([10-15]\) include change in CNT morphology through Stone-Wales transformation, dislocations along helical paths within the nanotube wall due to intra-molecular plastic flow, ‘sword in sheath’ telescoping failure of multi-walled carbon nanotubes (MWCNTs),
progressive thinning of MWCNTs into single-walled carbon nanotubes (SWCNTs) and of SWCNTs into a single chain of carbon atoms before fracture, and formation of localized, permanent buckles along nanotube length.

Deformation and damage mechanisms of CNTs under high strain rate impact loading [16] are fracture at point of impact, curving of layers of MWCNTs at point of impact, ripple formation along length of MWCNTs, internal cap formation due to axial compressive deformation, formation of capped closed-shell MWCNTs with aspect ratio 1 referred to as carbon onions, plastic deformation in the form of necking followed by cup-and-cone type fracture, and peeling of MWCNTs due to shear loads.

2.2 Resin

Damage mechanisms of neat resins under ballistic impact include shear yielding, shear plugging and formation of ring and radial cracks.

2.3 CNT dispersed resin

In case of CNT dispersed resins, additional damage and energy absorbing mechanisms [1-4] are CNT pull-out, CNT rupture, CNT bridging, crack deflection and reduction in spherulite size.

To our knowledge, there are no studies on the ballistic impact behavior of CNT dispersed resins. However, additional damage and energy absorbing mechanisms would lead to enhancement in the ballistic impact performance of resins upon CNT dispersion.

3 Penetration and perforation process

The transverse ballistic impact by a projectile onto a target generates longitudinal compressive and shear stress waves along the thickness direction and longitudinal tensile and shear stress waves along the in-plane direction [5].

Fig. 1 presents different stages of penetration / perforation of a rigid cylindrical projectile with a flat end into neat epoxy and MWCNT dispersed epoxy target during ballistic impact. Fig. 1a indicates beginning of the ballistic impact event. The impact event can be sub-divided into two stages. During stage 1, longitudinal compressive and shear stress waves travel along the thickness direction. The target undergoes compression directly below the projectile and also in the surrounding region as shown in Fig. 1b. Compression of the target also produces tension along the radial and circumferential directions in the surrounding region. The shear wave follows the compressive wave. As the compressive and shear waves travel along the thickness direction, the target could fail under compression or shear plugging whenever the induced strains exceed the corresponding failure strains. The failed surface is uneven and characterized by the presence of a number of cracks of varying crack length in the radial direction.

Stage 2 starts when the tensile stress in the circumferential direction leads to crack propagation along the radial direction around the periphery of the projectile (Fig. 1c). Crack propagation is followed by brittle fracture in case of epoxy resin, with complete failure taking place without any plastic deformation. In other words, the crack, once initiated, propagates instantaneously along the radial direction and leads to complete failure of the target through shattering (Fig. 1d). Stage 2 ends when the target is completely failed due to brittle fracture and shattering of epoxy resin (Fig. 1e).

During the ballistic impact event, the target offers resistance to penetration / perforation of the projectile into itself. The incident kinetic energy of the projectile would be absorbed by the target through various damage and energy absorbing mechanisms. As a result of this, the kinetic energy of the projectile, in turn, the velocity of the projectile would decrease. Compression of the target directly below the projectile, compression in the region surrounding the impacted zone, shear plugging of the target, formation of ring and radial cracks in the resin leading to tensile failure and energy absorbed by CNTs are the energy absorbing mechanisms that are considered in the analysis.
When the projectile strikes onto the target, the planar view can be sub-divided into two regions as shown in Fig. 1f. The region directly below the projectile is referred to as region 1. The surrounding region up to which the transverse wave travels along the in-plane directions is referred to as region 2.

As the longitudinal compressive stress wave propagates in the thickness direction, compression of the target takes place in region 1 (Fig. 1f). The projectile displacement results in compressive strain in the target up to the distance travelled by the compressive wave. Region 2 also experiences compressive strain during projectile displacement along the thickness direction.

Immediately upon impact, the contact force between the projectile and the target results in

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**Fig. 1.** Penetration and perforation stages of neat epoxy and MWCNT dispersed epoxy target during ballistic impact.
through-the-thickness shear plugging stress within the target around the periphery of the projectile. If the induced shear plugging stress exceeds the permissible shear plugging strength, the resin would fail due to shear plugging.

As the compression of the target takes place along the thickness direction, the target would be under tension along the in-plane directions. This can lead to the formation of ring and radial cracks [17]. If the induced tensile stress in the circumferential direction overcomes the threshold target fracture toughness, given by the stress intensity factor $K_I$, the epoxy resin target would undergo catastrophic tensile failure through brittle fracture and shattering.

4 Analytical formulation

The main objective of the analysis is to predict the energy absorbed by various mechanisms, ballistic limit velocity and contact duration.

4.1 Assumptions

The following assumptions are made in the analysis:
- Projectile impact is normal to the surface of the target.
- Projectile is considered to be rigid and cylindrical with a flat end.
- The region of the target up to which the shear stress wave reaches in the in-plane direction around the point of impact offers resistance to penetration.
- The impact event is sub-divided into smaller time intervals for the analysis.
- During any time interval, the velocity of the projectile remains constant.
- Compressive strain is uniform in the region of the target up to which compressive wave has traveled.
- Shear plugging stress is uniform in the region of the target up to which shear wave has traveled.
- The induced strain in the CNTs is the same as that in the resin target.

4.2 Solution procedure

At any instant during the ballistic impact event, incident kinetic energy of the projectile can be expressed as the sum of residual kinetic energy of the projectile at that instant and the total energy absorbed by the target till that instant. The energy balance at the end of $i^{th}$ time interval,

$$KE_{p0} = KE_{p1} + \{E_{CR1i} + E_{CR2i} + E_{SPI} + E_{RTi} + E_{BTi} + E_{CNI}\}$$  \hspace{1cm} (1)

Here, $KE_{p0}$ refers to incident kinetic energy of the projectile, $KE_{p1}$ refers to residual kinetic energy of the projectile at the end of $i^{th}$ time interval and $E$ refers to energy absorbed.

Suffixes $CR1$, $CR2$, $SP$, $RT$, $BT$ and $CNT$ refer to compression in region 1, compression in region 2, shear plugging, tension in the radial direction, tension in the circumferential direction and carbon nanotube, respectively. Suffix $i$ refers to up to $i^{th}$ time interval.

Expanding kinetic energy terms and rearranging other energy terms for simplification,

$$\frac{1}{2}m_pV_0^2 - \sum_{i=1}^{\infty} E_i = \frac{1}{2}m_pV_i^2$$ \hspace{1cm} (2)

Here, $m_p$ and $V_0$ refer to mass and incident impact velocity of the projectile, respectively. $V_i$ refers to projectile velocity at the end of $i^{th}$ time interval.

Hence, velocity of the projectile at any instant during the ballistic impact event,

$$V_i = \sqrt{\left(\frac{\frac{1}{2}m_pV_0^2 - E_i}{2m_p}\right)}$$ \hspace{1cm} (3)

Projectile velocity as a function of time as given in Eq. (3) can be determined if energy absorbed by various mechanisms during each time interval is known. Energy absorbed by various mechanisms during each interval can be evaluated if incident contact force is known.

The forces acting on the projectile during the first time interval are inertial force and compressive force. The methodology to evaluate the total contact force is given by [18,19].

Starting with the obtained incident total contact force, energy absorbed by various mechanisms during each time interval can be obtained. In turn, contact force profile, deceleration, projectile tip displacement and energy absorbed by various mechanisms can be calculated. This procedure can be continued till the end of the ballistic impact event.

Evaluation of energy absorbed by compression of the target directly below the projectile, compression in the region surrounding the impacted zone, shear plugging of the target and formation of
ring and radial cracks leading to tensile failure is performed based on the method given in [17,18]. Energy absorbed by CNTs is evaluated based on compressive and tensile quasi-static stress-strain curves of individual MWCNTs given in [20].

5 Experimental

Experimental ballistic impact studies were carried out on a single stage gas gun operated ballistic impact test apparatus [6]. Flat specimens of dimension 125 mm x 125 mm and thickness of 4.3 mm were used for the studies. The mass of the projectile made of hardened steel was 7.61 g and its diameter was 6.36 mm. Experimental studies were carried out on at least 6 specimens for each impact condition.

Two types of specimens were fabricated: neat epoxy resin and epoxy resin dispersed with 0.5 % by weight MWCNT. Amino functionalized MWCNTs with an average outer diameter of 10 nm and average length of 3 μm were used for the studies.

6 Results and discussion

Ballistic impact performance of neat epoxy and MWCNT dispersed epoxy resin target with thickness in the range of 2.0-10.0 mm is evaluated using the analytical method presented. Specifically, energy absorbed by different mechanisms, kinetic energy of the projectile, contact force, projectile velocity and projectile tip displacement are evaluated as a function of time. The input data necessary is given in Table 1.

6.1 Analytical vs. experimental studies

Experimental ballistic limit velocity, \( V_{50} \) [6,21] was obtained for two types of specimens considered in the present study. The projectile diameter was 6.36 mm and the projectile mass was 7.61 g for all the cases. Fig. 2 presents damage patterns during ballistic impact for neat epoxy and MWCNT dispersed epoxy.

Analytical ballistic limit velocity, \( V_{BL} \) was obtained for both neat epoxy and MWCNT dispersed epoxy targets. For target thickness of 4.3 mm, \( V_{BL} \) for neat epoxy and MWCNT dispersed epoxy is 40 m/s and 44 m/s, respectively. This is in good agreement with experimentally obtained \( V_{50} \) values of 41 m/s and 43 m/s for neat epoxy and MWCNT dispersed epoxy, respectively for the same target thickness.

6.2 Energy absorbed by different mechanisms

Fig. 3 presents energy absorbed by different mechanisms and kinetic energy of the projectile as a function of time for MWCNT dispersed epoxy. The plots are at ballistic limit velocity, \( V_{BL} \). At any given instant of time, sum of residual kinetic energy of the projectile and energy absorbed by the target would be equal to the incident impact kinetic energy of the projectile.

For target thickness of 6.5 mm and projectile mass of 7.61 g, \( V_{BL} \) is 62 m/s and contact duration is 2.6 μs for MWCNT dispersed epoxy target. For this case, incident impact kinetic energy of the projectile is 14.6 J. The major energy absorbing mechanism is

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Diameter, ( d_p )</th>
<th>3.0-8.0 mm</th>
</tr>
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<tr>
<td></td>
<td>Mass, ( m_p )</td>
<td>4.0-8.0 g</td>
</tr>
<tr>
<td></td>
<td>Shape</td>
<td>Cylindrical flat ended</td>
</tr>
<tr>
<td>Target</td>
<td>Material</td>
<td>MWCNT dispersed epoxy</td>
</tr>
<tr>
<td></td>
<td>Target thickness, ( h )</td>
<td>2.0-10.0 mm</td>
</tr>
<tr>
<td></td>
<td>Percentage of MWCNT dispersion by weight</td>
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</tr>
<tr>
<td></td>
<td>Density, ( \rho )</td>
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</tr>
<tr>
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<td>Young’s modulus, ( E )</td>
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<td>Compressive failure strain, ( \varepsilon_{cf} )</td>
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<tr>
<td></td>
<td>Shear plugging strength, ( S_{sp} )</td>
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</tr>
<tr>
<td></td>
<td>Dynamic stress-strain curves</td>
<td>[22,23]</td>
</tr>
</tbody>
</table>

Table 1. Input parameters required for the evaluation of ballistic impact performance.
shear plugging of the target. MWCNTs dispersed in epoxy target and compression in regions 1 and 2 also absorb some energy. Energy absorbed by the other mechanisms is not significant.

6.3 Projectile velocity, contact force and displacement

Fig. 4 presents ballistic impact behavior of MWCNT dispersed epoxy target with $V_{BL} = 62$ m/s. Projectile velocity as a function of time is presented in Fig. 4a for target thickness of 6.5 mm with an incident impact velocity of 62 m/s. Initially, there is a gradual decrease in projectile velocity from point A to point B followed by a sudden decrease in projectile velocity from point B to point C. The sudden decrease in velocity is because, during the time interval from point B to point C, in addition to shear plugging, significant amount of energy is absorbed by MWCNTs and compression in regions 1 and 2 (Fig. 3). However, it should be noted that even during this time interval, shear plugging is the dominant energy absorbing mechanism. Point C corresponds to peak contact force. At the end of the ballistic impact event, projectile velocity becomes zero (Point D).
Fig. 4. Ballistic impact behavior of MWCNT dispersed epoxy, $h = 6.5$ mm, $m_p = 7.61$ g, $d_p = 6.36$ mm, $V_i = 62$ m/s, (a) velocity vs. time, (b) contact force vs. time, (c) projectile tip displacement vs. time.

Fig. 4b presents contact force history of the ballistic impact event. It can be seen that there is a gradual increase in contact force initially from point A to point B because of the resistance offered by the target. A gradual increase in contact force during this time interval corresponds to a gradual decrease in projectile velocity (Fig. 4a). It should be noted that shear plugging is the only significant energy absorbing mechanism during this time interval (Fig. 3). There is a sudden increase in contact force from point B to point C, corresponding to a sudden decrease in projectile velocity. During this time interval, other damage and energy absorbing mechanisms such as energy absorbed by MWCNTs and energy absorbed due to compression in regions 1 and 2 become significant (Fig. 3). However, it should be noted that even during this time interval, shear plugging is the dominant energy absorbing mechanism. Point C represents peak contact force reached (385 kN), corresponding to peak deceleration of the projectile.

Crack propagation takes place around the periphery of the projectile along the radial direction when peak contact force is reached. Crack propagation is followed by catastrophic brittle fracture, accompanied by the instantaneous formation of radial cracks, which causes complete failure of the target. As the target fails due to brittle fracture, contact force starts decreasing. The contact force reaches zero at point D indicating end of ballistic impact event. This corresponds to time interval of 2.6 µs.

Fig. 4c presents displacement of projectile tip as a function of time. The maximum tip displacement is 0.13 mm (Point D). The shear wave reaches a distance of 4.8 mm along the thickness direction at the end of the ballistic impact event. It should be noted that the maximum projectile tip displacement is significantly less than the target thickness of 6.5 mm. This is because crack propagation takes place around the periphery of the projectile along the radial direction when tip displacement is 0.12 mm.

6.4 Effect of target thickness

Ballistic impact behavior of MWCNT dispersed epoxy target with thickness in the range of 2.0-10.0 mm is evaluated using the analytical method presented keeping other impact parameters constant. Ballistic limit velocity as a function of target thickness is presented in Fig. 5. It is seen that in the range of parameters considered, $V_{BL}$ increases with increase in target thickness. However, this increase is not exactly proportional to the increase in target thickness. Specifically, $V_{BL}$ is 23 m/s, 62 m/s and 84 m/s for target thickness of 2.0 mm, 6.5 mm and 10.0 mm, respectively in case of MWCNT dispersed epoxy target.

6.5 Effect of projectile mass

Effect of projectile mass on ballistic impact behavior of MWCNT dispersed epoxy target is evaluated. Projectile mass is varied in the range of 4.0-8.0 g, keeping other impact parameters constant. Fig. 6 presents ballistic limit velocity as a function of projectile mass. It is seen that in the range of
parameters considered, $V_{BL}$ decreases with increase in projectile mass. However, this decrease is not exactly proportional to the increase in projectile mass. Specifically, $V_{BL}$ is 85 m/s, 69 m/s and 61 m/s for projectile mass of 4.0 g, 6.0 g and 8.0 g, respectively in case of MWCNT dispersed epoxy target.

An increase in projectile mass leads to an increase in incident projectile kinetic energy for the same incident projectile velocity. As a result, ballistic limit velocity decreases with an increase in projectile mass.

### 6.6 Effect of projectile diameter

Effect of projectile diameter on ballistic impact behavior of MWCNT dispersed epoxy target is evaluated. Projectile diameter is varied in the range of 3.0-8.0 mm, keeping other impact parameters constant. Ballistic limit velocity as a function of projectile diameter is presented in Fig. 7. It is seen that in the range of parameters considered, $V_{BL}$ increases with increase in projectile diameter. Specifically, $V_{BL}$ is 48 m/s, 59 m/s and 69 m/s for projectile diameter of 4.0 mm, 6.0 mm and 8.0 mm, respectively in case of MWCNT dispersed epoxy target.

Shear plugging of the target is the main energy absorbing mechanism during ballistic impact. Energy absorbed due to shear plugging of the target increases with an increase in projectile diameter. Thus, for the same incident projectile impact velocity, ballistic limit velocity increases with an increase in projectile diameter.

### 6.7 Effect of average crack length

During stage 1 of the ballistic impact event, the target could fail under compression or shear plugging whenever the induced strains exceed the corresponding failure strains. The failed surface is uneven and characterized by the presence of a number of cracks of varying crack length in the range of 1.0-2.0 mm in the radial direction. This behavior is typical of brittle targets such as epoxy. It can be inferred that during the ballistic impact event, shear plugging of the target leads to radial crack initiation around the periphery of the projectile.

In the present studies, average crack length of 1.5 mm is considered. For this value of average crack length, crack propagation takes place around the periphery of the projectile along the radial direction as and when the induced tensile stress overcomes the threshold value of target fracture toughness. Analytical predictions of ballistic limit velocity obtained considering average crack length of 1.5 mm are in good agreement with experimental ballistic limit velocities.

Fig. 8 presents ballistic limit velocity as a function of average crack length for MWCNT dispersed epoxy target. In the range of parameters considered, it is seen that $V_{BL}$ decreases with increase in average crack length. Specifically, $V_{BL}$ is
69 m/s, 62 m/s and 58 m/s for average crack length of 4.0 mm, 6.0 mm and 8.0 mm, respectively.

6.9 Effect of incident projectile impact velocity

Projectile exit velocity as a function of incident impact velocity for target thickness of 6.5 mm is presented in Fig. 10. Ballistic limit velocity for target thickness of 6.5 mm is 62 m/s. The projectile does not exit the target at incident impact velocities below the ballistic limit velocity. There is a sudden rise in exit velocity at incident impact velocities just above the ballistic limit velocity. It can be seen that the rise in exit velocity becomes less steep at incident impact velocities much higher than ballistic limit velocity.

6.8 Effect of amount of MWCNT dispersion

Ballistic impact behavior of MWCNT dispersed epoxy target with amount of MWCNT dispersion in the range of 0-3.0 % by weight is evaluated keeping other impact parameters constant.

Ballistic limit velocity as a function of amount of MWCNT dispersion is presented in Fig. 9. It is seen that in the range of parameters considered, $V_{BL}$ increases with increase in amount of MWCNT dispersion. However, this increase is not exactly proportional to the increase in amount of MWCNT dispersion. Specifically, $V_{BL}$ is 57 m/s, 68 m/s and 72 m/s for neat epoxy, 1.5 % by weight MWCNT dispersed epoxy and 3.0 % by weight dispersed epoxy, respectively.

Fig. 7. Ballistic limit velocity as a function of projectile diameter for MWCNT dispersed epoxy, $h = 6.5$ mm, $m_p = 7.61$ g.

![Fig. 7](image1)

Fig. 8. Ballistic limit velocity as a function of average crack length for MWCNT dispersed epoxy, $h = 6.5$ mm, $m_p = 7.61$ g, $d_p = 6.36$ mm.

![Fig. 8](image2)

Fig. 9. Ballistic limit velocity as a function of amount of MWCNT dispersion by weight for MWCNT dispersed epoxy, $h = 6.5$ mm, $m_p = 7.61$ g, $d_p = 6.36$ mm.

![Fig. 9](image3)

Fig. 10. Projectile exit velocity as a function of incident impact velocity for MWCNT dispersed epoxy, $h = 4.3$ mm, $m_p = 7.61$ g, $d_p = 6.36$ mm.

![Fig. 10](image4)
7 Conclusions
Ballistic impact behavior of MWCNT dispersed epoxy resin is presented based on analytical investigations. The focus of the present work is on parametric studies. The analytical model is based on stress wave propagation and energy balance between the kinetic energy of the projectile and the energy absorbed by different mechanisms. The specific observations are:

- There is a good match between the experimental and analytical ballistic limit velocities.
- Shear plugging of the target is the major energy absorbing mechanism during ballistic impact for neat epoxy and MWCNT dispersed epoxy in the range of parameters considered.
- $V_{BL}$ increases with an increase in target thickness. However, this increase is not exactly proportional to the increase in target thickness.
- $V_{BL}$ decreases with an increase in projectile mass. $V_{BL}$ increases with an increase in projectile diameter.
- $V_{BL}$ increases with an increase in amount of MWCNT dispersion in neat epoxy target.

References


