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Analytical and experimental studies on ballistic impact behavior of carbon nanotube dispersed resin

Kedar S. Pandya, N.K. Naik*

Aerospace Engineering Department, Indian Institute of Technology Bombay, Powai, Mumbai, 400 076, India

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ABSTRACT

An analytical formulation is presented for the prediction of ballistic impact behavior of multi-walled carbon nanotube (MWCNT) dispersed epoxy resin. The formulation is based on stress wave propagation and energy balance between the projectile and the target. 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 impacted zone, shear plugging, formation of ring and radial cracks in the resin leading to tensile failure and energy absorbed due to the presence of carbon nanotubes. Complete failure of the target was due to catastrophic brittle fracture and shattering. Experimental studies are carried out on ballistic impact behavior of neat epoxy and MWCNT dispersed epoxy. Typical results on ballistic limit velocity and energy absorbed by various mechanisms are presented. Ballistic impact behavior of neat epoxy resin and MWCNT dispersed epoxy resin are compared. A good match is observed between the analytical and experimental results.

1. Introduction

High performance structural components undergo various loading conditions during their service life. Energy absorption capability, in turn, resistance to penetration/perforation of structural components subjected to impact loading is an important requirement for high technology aerospace, marine, civil, automobile and defense applications.

Ballistic impact is an impact caused by a propelling source, generally of low mass and high velocity. Different types of stress waves propagate in the impacted bodies during a ballistic impact event [1].

Carbon nanotubes (CNTs), with their remarkable mechanical properties, offer great promise in the development of high energy absorbing materials and structures. Recent advances at enhancing ballistic protection capability include dispersion of CNTs into resins. Studies in literature on carbon nanotube (CNT) dispersed resins under quasi-static loading [2–5] indicate that reinforcing resins with CNTs enhances their mechanical properties.

Studies are available in literature on high strain rate behavior of CNT dispersed resins and composites [6–9]. Mantena et al. [6] studied high strain rate compressive behavior of multi-walled carbon nanotube (MWCNT) dispersed nylon composites. Lim et al. [7] studied high strain rate compressive characteristics of CNT dispersed woven fiberglass/epoxy composites. An improvement in strength and energy absorption of composites due to CNT dispersion was observed. Rafiee and Moghadam [8] simulated the impact behavior of CNT dispersed polymer using multi-scale finite element modeling. Jindal et al. [9] investigated high strain rate compressive behavior of MWCNT-polycarbonate composites.

Studies are available in literature on the ballistic impact behavior of CNT dispersed composites [10–13]. Pandya et al. [10] investigated the effect of MWCNT dispersion on the ballistic impact behavior of unidirectional E-glass/epoxy. Laurenzi et al. [11] studied the high velocity impact behavior of MWCNT dispersed Kevlar-29/epoxy. Rahman et al. [12] carried out experimental investigations on the ballistic impact behavior of MWCNT dispersed E-glass/epoxy. Tehrani et al. [13] investigated the effect of MWCNT dispersion on the ballistic impact behavior of carbon/epoxy composites. These studies [10–13] reported an enhancement in ballistic impact resistance of composites on CNT dispersion. To our knowledge, there are no studies on ballistic impact behavior of CNT dispersed resins.

* Corresponding author. Tel.: +91 22 25767114; fax: +91 22 25722602.
E-mail address: nknaik@aero.iitb.ac.in (N.K. Naik).

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In the present study, an analytical formulation is presented for the prediction of ballistic impact behavior of MWCNT dispersed epoxy resin. Possible enhancement in ballistic impact resistance of the resin target through CNT dispersion is investigated. The formulation is based on stress wave propagation and energy balance between the projectile and the target. The projectile is assumed to be rigid and the energy is absorbed only by the target through various damage and energy absorbing mechanisms. Experimental studies are carried out on ballistic impact behavior of neat epoxy and MWCNT dispersed epoxy. Typical results on ballistic limit velocity and energy absorbed by various mechanisms are presented.

2. Damage and energy absorbing mechanisms

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 [1].

Different stages of penetration/perforation of a rigid cylindrical projectile with a flat end into neat epoxy and MWCNT dispersed epoxy target are presented schematically in Fig. 1. When the projectile strikes onto the target, the planar view can be sub-divided into two regions. The region directly below the projectile is referred to as Region 1. The surrounding region up to which the transverse stress wave travels along the in-plane directions is referred to as Region 2.

Fig. 1(a) 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. 1(b). 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.

Stage 2 starts when the tensile stress in the circumferential direction leads to initiation of crack formation around the periphery of the projectile as shown in Fig. 1(c). Crack initiation is followed by brittle fracture and shattering 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. 1(d)). Stage 2 ends when the target is completely failed due to brittle fracture and shattering of epoxy resin. Fig. 2 shows the failed surface of neat epoxy resin under quasi-static transverse loading after shear plugging. The failed surface is uneven and characterized by the presence of a number of cracks of varying crack length in the radial direction.

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, formation of ring and radial cracks in the resin leading to tensile failure and energy absorbed due to the presence of CNTs are the energy absorbing mechanisms that are considered in the present formulation.

As the longitudinal compressive stress wave propagates in the thickness direction, compression of the target takes place in Region 1. The projectile displacement results in compressive strain in the target up to the distance traveled 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 through-the-thickness shear plugging stress within the target around the periphery of the projectile. If the induced shear plugging stress exceeds the

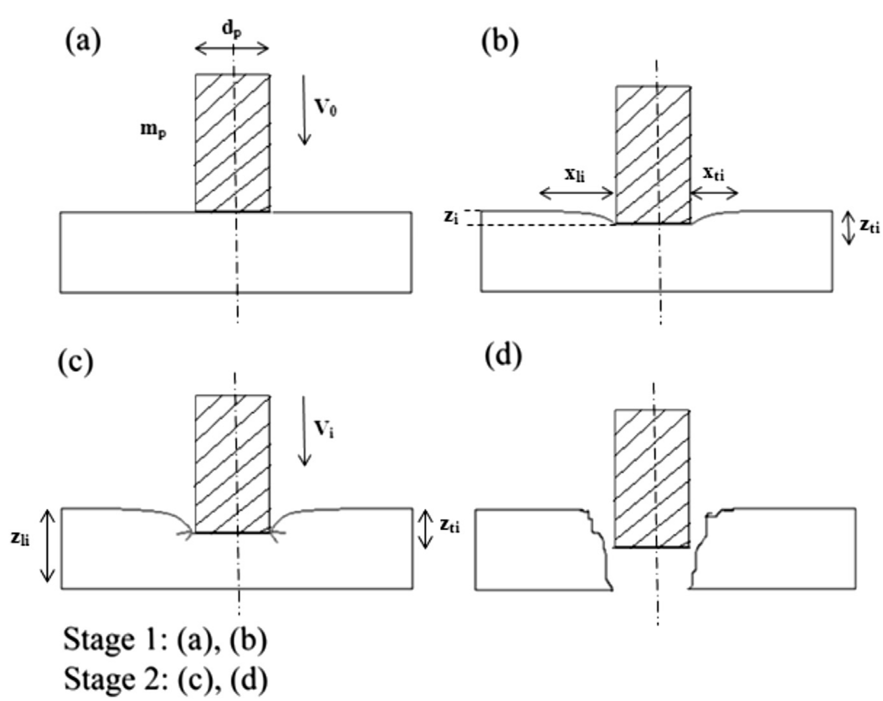

Fig. 1. Penetration and perforation stages of neat epoxy and MWCNT dispersed epoxy target during ballistic impact.