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Energy absorption and ballistic limit of nanocomposite laminates subjected to impact loading

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ABSTRACT

Composite laminates made of glass/epoxy with and without nano fillers were subjected to projectile impact. The laminates of different thicknesses were prepared by hand lay-up and compression molding processes. Laminates were made from glass woven roving mats of 610 gsm, epoxy resin and nano clay of 1–5 wt.% of matrix. A piston type gas gun setup was used to impact a spherical nose projectile of diameter 9.5 mm and mass of 7.6 g, on the nanocomposite laminates at impact velocities in the range of their ballistic limit and above. The energy absorbed during penetration and ballistic limit of the nanocomposite laminates were studied both experimentally and analytically. The analytical model also predicts the energy absorbed in various failure modes due to tensile failure of primary fibers, deformation of secondary fibers, delamination and matrix crack. Mechanical properties like tensile modulus, stress–strain function, shear modulus, and strain energy release rate were used as input to the analytical model. Laminates of three, five and eight layers have been considered for the analysis. The effect of clay dispersion in the matrix for different failure modes is discussed. Ballistic limit obtained from the model is validated with experimental results and good agreement is found.

1. Introduction

Composites used for structural applications in aircraft and high performance land based vehicles must withstand impact loads apart from static and cyclic loads. Tool drops, debris striking, projectile hit in air vehicles are some of the examples of impact loading. In the aerospace industry, impact damage in laminated composite materials continues to be a major concern as it causes significant reduction in strength. Therefore, understanding of the influence of impact on vibration, energy absorption and subsequent damage mechanisms and assessing residual strengths are essential for the successful use of these materials. Polymer composites retard the projectile by absorbing the kinetic energy of projectiles during ballistic impact. To understand the ballistic impact of composite laminates, different energy absorbing mechanisms are to be considered. The energy absorbing mechanisms are moving cone formation on the back face of the target, elastic deformation of secondary fibers, tensile failure of primary fibers, delamination and matrix crack. Cantwell and Morton [1] studied the response of CFRP under low and high velocity impact and found that low velocity impact resulted in global deformation whereas high velocity impact resulted in a localized deformation. Nettles and Lance [2] modeled the low velocity impact response of a honeycomb sandwich structure with carbon fiber/epoxy facings using a simple spring mass model. They showed that agreement between predictions and experimental data was good at energy level that was required to initiate significant damage within the structure. Goldsmith et al. [3] studied experimentally the perforation of different types of honeycomb cores, metallic/plastic covers and sandwich combinations in the wide range of striking velocities. The concept of ballistic limit in relation to composites and sandwiches was discussed and the variation of residual velocities with initial velocities was examined. Lee et al. [4] performed tensile and compressive tests to measure the strength variation with respect to strain rate on glass/epoxy composites. Lim et al. [5] carried out experiments to investigate the impact phenomenon of double-ply systems that consists of Twarons CT 716 fabrics for projectiles of hemispherical, flat, ogival and conical nose. The ballistic limits for double ply laminates were 246, 125, 118 and 115 m/s for hemispherical, flat, ogival and conical nose projectiles respectively. Borvik et al. [6] carried out experimental, and theoretical studies of circular steel plates of different

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Notations

A_{delam}	area of delamination
$C_{plastic}$	plastic wave velocity
C_{trans}	transverse wave velocity
d	fibers failure width
E_{def}	energy absorbed due to deformation
E_{delam}	energy absorbed due to delamination
E_{frac}	energy absorbed due to tensile failure of fiber
E_L	energy lost during impact
$E_{matcrack}$	energy absorbed due to matrix crack
$e_{matcrack}$	energy absorbed by matrix cracking per unit volume
E_{cone}	energy absorbed due to moving cone
E_{total}	total energy absorbed by the laminate
f	transmission factor
G_{IIc}	critical strain energy release rate in mode-II
G_{23}	shear modulus
h_t	thickness of the laminate
KE_o	initial energy of the projectile
m	mass of projectile
M_{cone}	mass of moving cone
r_{tr_i}	distance traveled by transverse wave
r_{pl_i}	distance traveled by plastic wave
r_{d_i}	radius of damaged area
V	velocity of the projectile
V_m	volume fraction of the matrix
V_o	ballistic limit
Z_i	distance moved by the projectile
ε_o	failure strain at the point of impact
ρ	density of the laminate
σ	stress

thicknesses by a blunt projectile for velocities 70–500 m/s. Ulven et al. [7] studied the perforation of various projectile geometries in carbon/epoxy laminates. Sun et al. [8] reviewed relevant literature which dealt with various manifestations of energy absorption of composites from the nano to the macro-scale, with emphasis on the nano-scale. Aymerich et al. [9] investigated the impact response of standard and modified clay vacuum infused glass/epoxy laminates and showed up to 30% increase in energy absorption when compared to the standard laminates.

Several studies appeared in literature which concentrate on analytical studies of metallic and composite panels. Goldsmith and Finnegan [10] studied impact loading on aluminum and steel alloy targets by using hard steel sphere projectiles of diameters 3.18 mm–12.7 mm in the velocity range of 160–2700 m/s. Zhu et al. [11] studied the response of Kevlar/polyester laminates to quasi static and dynamic penetration by cylindro conical projectiles. Lee and Sun [12] carried out a combined experimental and numerical study of the dynamic penetration of clamped circular CFRP laminates. Sun and Potti [13,14] used a punch curve that was used as the structural constitutive model capturing the high nonlinear behavior of the laminate in the penetration process. Abrate [15] described an energy balance model in which the incident energy of the projectile was equated to the energy stored in bending, shear and contact effects. Velmurugan et al. [16] studied the response of sandwich panels (Glass/Epoxy/PU Foam) to projectile impact in the velocity range of 30–100 m/s. Naik et al. [17] formulated a time dependent analytical model based on wave theory to investigate the ballistic impact behavior of two dimensional woven fabric composites when subjected to impact loading. The analytical results were then compared with the experimental results. Garcia-Castillo et al. [18] studied the effect of a biaxial preload in the behavior of glass/polyester woven-laminate plates subjected to high-velocity impact. The analytical model was based on energy considerations of the in-plane preloaded laminates.

Literature review shows that there is not much work on energy absorbing mechanisms of projectile impact on nanocomposite laminates. In this study, a time dependent analytical model based on literature is developed to predict the energy absorption in various failure modes and ballistic limit of the nanocomposite laminates. The energy absorbed by the three, five and eight layer laminates, with and without clay subjected to impact loading, is discussed. Also the energy absorption in different failure modes and ballistic limit of the laminated composites are predicted using a mathematical model. The model results are validated with the experimental results.

2. Experimental setup and preparation of nanocomposite laminates

Experiments were performed by using a gas gun test setup which is shown in Fig. 1. Air pressure in the chamber was varied to get different velocities. Plates of required size were clamped at the edges and were subjected to impact by a cylindrical projectile. Incident velocity was measured by Laser diode system which is shown in Fig. 2.

The nanocomposite laminates were fabricated in two steps. Clay was mixed with epoxy resin using shear mixer at 750 RPM for 2 h and kept in the vacuum oven to remove the air bubbles at room temperature, for better dispersion. The hardener Triethylenetetramine (TETA) of 10% by weight was mixed with the epoxy - clay mixture. The laminates of 300 mm × 300 mm were prepared for testing by hand lay-up technique and then compressed in compression molding machine.

3. Mathematical model

Several analytical and numerical models are used to predict energy absorption and ballistic limit of the targets. Most of the analytical and FE models are for conventional composites.

In this study, a time dependent analytical model is developed to predict the energy absorption in various failure modes and ballistic

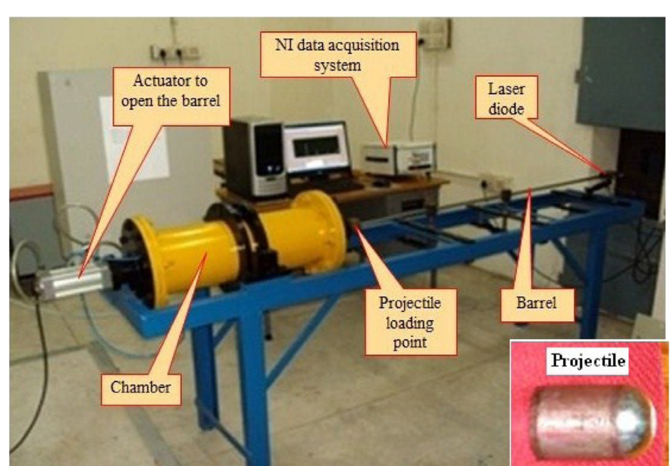

Fig. 1. Gas gun experimental set-up.