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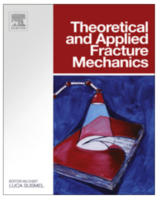

Studies on ballistic impact of the composite panels

Sudhir Sastry Y.B. [a,*], Pattabhi R. Budarapu [b], Y. Krishna [c], S. Devaraj [d]

[a] *Dept. of Aeronautical Engineering, Institute of Aeronautical Engineering, Hyderabad, India*
[b] *Institute of Structural Mechanics, Bauhaus University of Weimar, 99423 Weimar, Germany*
[c] *Scientist G, Head, Structural Test Facility, DRDL, Hyderabad, India*
[d] *Dept. of Aeronautical Engineering, Vignan Institute of Technology, Hyderabad, India*

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ABSTRACT

The ballistic impact of the composite materials is studied using the numerical models. Individual impact studies are conducted on the composite plate made-up of woven fabric CFRP, E-glass/epoxy and the Kevlar/epoxy composites. The plate is fabricated with 8 layers of equal thickness arranged in different orientations. A spherical steel projectile is considered for the high velocity impact. The projectile is placed very close to the plate, at the center and impacted with a velocity of 100 m/s. The displacement and the stress distribution in each layer are studied for the layup sequence [+45/−45/+45/−45/−45/+45/−45/+45]. The variation of the kinetic energy, the increase in the internal energy of the laminate and the decrease in velocity of the projectile with time are also studied. Based on the results, the best layup sequence for the ballistic impact of each material is suggested.

1. Introduction

The design of composite materials is aimed at achieving superior performance with unique thermo-mechanical properties and specific strengths, which are not possible with the traditional materials [1]. Composite materials used in the aircraft structures [2,3], armoured vehicles [4] and soft armours [5] must withstand impact loads like: fan blade impacting engine containment, tool drops, debris striking and projectile/bird impact, apart from the static, fatigue and buckling [6,7] loads. Based on the energy transfer between the projectile and the target, energy dissipation and damage propagation mechanisms, the impact loads are classified into three categories, (i) low velocity impact, (ii) high velocity impact and (iii) hyper velocity impact.

The composites used in the design of structures involving personnel, like: the aircrafts, the space crafts and the defense vehicles against the penetration by high velocity projectiles are of much importance. Therefore, it is important to understand the penetration of a projectile at ballistic velocities into the composite panels. The ballistic impact of a composite material [8] is defined as an impact resulting in complete penetration of the laminate. The non-penetrating impact is referred as low velocity impact. As the projectile touches the target, compression and shear waves propagate away from the impact point and reflects back after reaching the back face. The target motion is generated as a result of the motion of the compression and shear waves. The contact period of the impactor is ‘longer’ than the time period of the lowest mode of vibration of the structure, in the low velocity impact and is ‘smaller’ in the high velocity impact. Therefore, in the low velocity impact the structural response is influenced by the boundary conditions. Whereas, the response of the high velocity impact structure is localized on the impacted area and does not dependent on the boundary conditions [9]. A threshold velocity of 20 m/s [10] is accepted as a transition between the low and high velocity impact. Hyper velocities refer to velocities more than 3 km/s, which usually occurs on the outer surfaces of satellites with the large population of space debris [11]. The hypervelocity impact (HVI) characteristics of nano-composites of ultra-high molecular weight polyethylene fabrics with single-walled carbon nanotubes in epoxy matrix [12] are studied in [13].

The kinetic energy of the impacted projectile is dissipated and absorbed by the target in several ways. The main energy absorbing mechanisms are: the kinetic energy absorbed by the moving cone formed on the back face of the target, the shear plugging of the projectile into the target, the energy absorbed due to tensile failure of the primary yarns, the energy absorbed due to elastic deformation of the secondary yarns, the energy absorbed due to matrix cracking and delamination and the frictional energy absorbed during penetration. The fiber orientation, ply thickness and the fiber volume fraction will influence the strength of fiber reinforced laminates [14]. The specific energy absorption capacity of thin laminates is

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[*] Corresponding author.
E-mail address: sudhirsastry@gmail.com (Y.B. Sudhir Sastry).

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more than the thick laminates [15]. Moreover, when multiple thin laminates are separated by air gaps, their specific energy absorption capacity is significantly weaker than the sum of their specific energy absorption capacities. This is due to small laminate particles propelled ahead of the projectile and causing the damage to the next plate before the projectile impacts [15].

Techniques based on the continuum mechanics principles [3,16] are frequently used for a wide range of composite applications to formulate the basic governing equations. However, continuum mechanics is restricted to laminates with simple geometries and behavior. More sophisticated models [17,18] have been developed by adopting contact interaction [19] algorithms [20] within a finite element (FE) procedure for simulation of the debonding behavior. There are several advanced techniques to model the crack in the continuum, like: meshfree methods [21–34], reproducing kernel particle method (RKPM) [35,36], radial point interpolation method (RPIM) [23,37], Meshless Local Petrov–Galerkin (MLPG) [38,39], or partition-of-unity enriched methods such as the eXtended Finite Element Method (XFEM) [40–46], the Generalized Finite Element Method (GFEM) [47–54], the Smooth Finite Element Method (SFEM) [55–58], the Partition of Unity Finite Element Method (PUFEM) [59,60], the eXtended Element Free Galerkin method (XEFG) [61–67], the Cracking Particles Method [68–74], the phantom node method [75–81] or the Numerical Manifold Method (NMM) [82,83], the phase-field methods [84,85], to name a few.

Due to the non-linear and the non-homogeneous behavior of the material at the core of the defects, the continuum techniques fail to simulate the propagating defects accurately. Therefore, multiscale methods are developed, where the core of the defect(s) is captured in the atomistic region and the rest of the domain is modeled as continuum. The overlapping domains are coupled based on several techniques like: the Quasi-continuum method [86,87], the Bridging Domain Method (BDM) [25,88], the Arlequin method [89–91], the Bridging Scale Method (BSM) [92–96]. The multiscale methods are further extended to model the propagating defect, like: the extended the bridging domain method (XBDM) [97–100] and the Adaptive Multiscale Method (AMM) [101–103].

In the present work, we study the impact strength of the multilayered composite panels against the ballistic impact. Ballistic impact is a low-mass, high-velocity impact caused by a propelling source. The 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. The ballistic impact performance of the composite laminates depends on the mechanical characteristics (elastic modulus, tensile strength, fracture strain and laminate configuration) of the reinforcement/matrix and the physical characteristics of the impacting projectile (mass and shape) and the target (thickness and size) [9]. The arrangement of the article is as follows: The ballistic impact is introduced in Section 1. Details of the numerical model, failure modes of the composites and the numerical model are explained in Section 2. The ballistic impact studies on the composite panels made-up of the Carbon Fiber Reinforced Polymer (CFRP) in epoxy, the E-glass in epoxy and the Kevlar in epoxy are presented as three examples in Section 3. Section 4 concludes the article.

2. Modeling aspects of the composites

Composite materials are fabricated by binding the fibers [104,105] with resins like epoxy. For superior mechanical properties the fibers are arranged in several layers at different orientations, as shown in Fig. 1. The diameter of the fibers varies from 0.1–100 μm. Fig. 1(a) shows the individual plies at various orientations. The stacking sequence along with the coordinate system is shown in Fig. 1(b). The fibers act as reinforcement and they are bonded using a matrix material like polymers, ceramics and metals. Polymers are low in strength and Young's moduli, ceramics are strong, stiff and brittle, and metals possess good ductility and are intermediate in strength and Young's moduli. Due to its low density and very low coefficient of thermal expansion, epoxy is commonly used as the matrix material.

2.1. Stress–strain law

Composite materials are anisotropic and heterogeneous in nature, which results in the complex equations of motion. However, the equations of motion can be simplified by assuming the linear elastic behavior of the stress–strain relationship, as given below

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{31} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ \epsilon_{23} \\ \epsilon_{31} \\ \epsilon_{12} \end{Bmatrix} \tag{1}$$

where the subscripts 1, 2 and 3 are denote the coordinate axes (refer to Fig. 1(b)), σ denote the stress, ϵ denote the strain and the material constants are denoted by C. Eq. (1) can be written in simple as

$$\{\sigma\} = [C]\{\epsilon\}. \tag{2}$$

The material constant matrix (C) will become symmetric after invoking the compatibility conditions. Hence, after considering the compatibility and the orthotropic nature [106] of the composite materials, Eq. (1) can be reduced to

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{31} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ & C_{22} & C_{23} & 0 & 0 & 0 \\ & & C_{33} & 0 & 0 & 0 \\ & & & C_{44} & 0 & 0 \\ & \text{sym} & & & C_{55} & 0 \\ & & & & & C_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ \epsilon_{23} \\ \epsilon_{31} \\ \epsilon_{12} \end{Bmatrix} \tag{3}$$

where the total number of material constants are reduced to nine. Therefore, for a linear orthotropic composite material in a three-dimensional stress state, the material constants matrix will reduce to

$$[C] = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} (1-\nu) & \nu & \nu & 0 & 0 & 0 \\ & (1-\nu) & \nu & 0 & 0 & 0 \\ & & (1-\nu) & 0 & 0 & 0 \\ & & & \frac{(1-2\nu)}{2} & 0 & 0 \\ & \text{sym} & & & \frac{(1-2\nu)}{2} & 0 \\ & & & & & \frac{(1-2\nu)}{2} \end{bmatrix} \tag{4}$$

where E is the Young's modulus and ν is the Poisson's ratio. The strain energy stored in the body per unit volume can be calculated from

$$W = \frac{1}{2}[\sigma_{11}\epsilon_{11} + \sigma_{11}\epsilon_{11} + \sigma_{22}\epsilon_{22} + \sigma_{33}\epsilon_{33} + \sigma_{12}\epsilon_{12} + \sigma_{13}\epsilon_{13} + \sigma_{23}\epsilon_{23}]. \tag{5}$$

2.2. Failure modes of ballistic impact

Laminated composite structures fails mainly in two modes; (i) intra-ply failure mode, where the damage happens at the fibers,