Composites Part B 76 (2015) 300–319

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

The effect of hybridization on the ballistic impact behavior of hybrid composite armors

Aswani Kumar Bandaru*, Lakshmi Vetiyatil, Suhail Ahmad

Department of Applied Mechanics, Indian Institute of Technology Delhi, New Delhi, India

ARTICLE INFO

Article history:
Received 6 December 2014
Received in revised form
3 February 2015
Accepted 3 March 2015
Available online 11 March 2015

Keywords:
Kevlar fiber
B. Delamination
B. Impact behaviour
B. Hybridization
C. Finite element analysis (FEA)

ABSTRACT

In the present study, effect of hybridization on the hybrid composite armors under ballistic impact is investigated using hydrocode simulations. The hybrid composite armor is constructed using various combinations and stacking sequences of fiber reinforced composites having woven form of fibers specifically high specific-modulus/high specific-strength Kevlar fiber (KF), tough, high strain-to-failure fiber Glass fiber (GF) and high strength/high stiffness Carbon fiber (CF). Different combinations of composite armors studied are KF layer in GF laminate, GF layer in KF laminate, KF layer in CF laminate and CF layer in KF laminate at various positions of hybridized layers for a fixed thickness of the target. In this article the results obtained from the finite element model are validated for the case of KF layer in a GF laminate with experimental predictions reported in the literature in terms of energy absorption and residual velocity and good agreement is observed. Further, the effect of stacking sequence, projectile geometry and target thickness on the ballistic limit velocity, energy absorbed by the target and the residual velocity are presented for different combinations of hybrid composite armors. The simulations show that, at a fixed thickness of the hybrid composite armor, stacking sequence of hybridized layer shows significant effect on the ballistic performance. The results also indicate energy absorption and ballistic limit velocity are sensitive to projectile geometry. Specifically, it is found that arranging the KF layer at the rear side, GF layer in the exterior and CF layer on the front side offers good ballistic impact resistance. The hybrid composite armor consisting of a CF layer in KF laminate acquires maximum impact resistance and is the best choice for the design compared to that of other combinations studied.

1. Introduction

The use of composite materials is advantageous to achieve light weight body armors. These composite armors may be subjected to various ballistic impact loadings depending on the type of the impactor, impactor velocity, lay up of laminas and design requirements [1,2]. The ability of an armor depends upon the hardness of the material, which is critical in blunting projectile and its ability to absorb kinetic energy of the projectile through different energy absorbing mechanisms majorly back face signature (BFS), energy absorbed due to tensile failure of the primary yarns, elastic deformation of the secondary yarns, matrix cracking, delamination and shear plugging of the projectile into the target [3,4]. Several authors have been studying the ballistic impact response of non-hybrid composite laminates through experimental and numerical simulations. The ballistic response was estimated using, (a) number of composite laminates with different stacking sequence [5,6]; (b) predicting the ballistic limit (V_{50}) at which probability of an armor penetration is 50% or velocity time histories; (c) the results obtained are further verified through experiments and numerical simulations [7–10].

Bunsell and Harris [11] showed that the failure due to impact and the flexural modulus of glass fiber reinforced (GF)/carbon fiber reinforced (CF) hybrid composites are dependent on the matrix rule based on the GF and CF properties. Jang et al. [12] performed low velocity impact tests by hybridizing graphite composites with fibers such as Glass, Polyethylene, Nylon and Polyester. They concluded that the addition of high strength fibers to base composite provides better energy absorbing capacity and good damage resistance against impact loading. The stacking sequence also plays an important role in controlling the delamination and plastic deformation. Grujicic et al. [13] studied the ballistic performance of light weight hybrid armor of CF and Kevlar fiber reinforced (KF)

* Corresponding author. Tel.: +91 11 26596412.
E-mail address: aswani006@gmail.com (A.K. Bandaru).

http://dx.doi.org/10.1016/j.compositesb.2015.03.012

epoxy composite laminates having equal thickness values. The work was performed using non-linear dynamic computational analysis using Autodyn 2D v5.0, a commercial hydrocode. Different combinations and stacking sequences of hybrid laminate for various thickness values were considered and the results obtained indicates that at a fixed thickness of the armor both the stacking sequence and the number of CF/KF laminates had a significant effect on the ballistic performance of the armor. However, no validation study was performed for the simulation presented. The ballistic impact response of a hybrid composite armor made of S2 Glass with a ceramic front face was analyzed by Grujicic et al. [14] using hydrocode simulations (Autodyn). It was concluded that the areal density of the composite laminates in the hybrid composite plays an important role in the evaluation of the ballistic performance. Feli and Asgari [15] presented a numerical code using LS-Dyna to estimate the ballistic perforation of ceramic/composite targets (made of Alumina 99.5% and composite back plate composed of Twaron fibers). Lagrangian model was used for the simulation. Residual velocity, perforation time and velocity time histories were obtained from the simulation and compared with the analytical models available in the literature. Hazell and Thomas [16] studied the ballistic impact response of hybrid composite comprising of carbon fiber reinforced plastic (CFRP) and plain weave Kevlar 29 fabric impacting with steel spherical projectile. Different combinations of hybrid composites were studied, among which CFRP at front face of the laminate backed by layers of Kevlar showed good energy absorption. Pandya et al. [17] conducted experimental studies on hybrid composites made of 8H satin weave T300 Carbon fabric and plain weave E-Glass fabric with epoxy resin. Damage patterns and ballistic limit were estimated and it was concluded that E-Glass layers in the exterior and Carbon layers in the interior provides higher ballistic limit. Zhu et al. [18] presented a material model for the simulation of dry fabrics under ballistic impact. Single and multiple FE layers were modeled to simulate the ballistic impact and found that single layer model is computationally efficient, gives accurate results equivalent to multilayer models. Chen et al. [19] experimentally investigated the ballistic performance of ultra-high-molecular-weight polyethylene (UHMWPE) woven and unidirectional UHMWPE. It was observed that placing woven fabrics on the impact side and unidirectional fabrics on rear side showed good ballistic impact resistance. The effect of hybridization on the ballistic response was studied experimentally by Tawfiq et al. [20] by placing a Kevlar layer in Glass/Polyester laminate at different positions. The total number of layers considered were eleven, including one layer of Kevlar. The higher ballistic limit was observed when Kevlar layer is placed at the back of the laminate. Muhi et al. [21] experimentally and analytically studied the behavior of E-glass/epoxy laminate hybridized with a layer of Kevlar 29 fiber under high velocity impact. Four layer GF composite laminates (thickness = 1.8 mm) were considered with one layer of KF at different positions. Position of Kevlar at the back of the laminate showed maximum energy absorption and found that the absorbed energy, decreased from blunt to hemispherical and then from hemispherical to conical projectiles.

The arrangement of composite layer in hybrid composite armor plays an important role in their ballistic impact performance. Investigating the impact response of several combinations of hybrid composites with different stacking sequences through experiments is time consuming, requires more manpower and is not economic. Numerical simulations can lighten the expenses incurred during the development of hybrid composite armors. Through numerical simulations, armor designers may explore and investigate the ballistic performance of hybrid composite armors with different combinations of light weight and strong composite laminates. Substantial research has been carried out to estimate the ballistic impact response of composite structures. However, research on more combination of hybrid composite armors and the effect of the hybridization with different stacking sequences subjected to ballistic impact is still in infancy.

In the present study, nonlinear dynamic response of hybrid composite armors subjected to ballistic impact is represented using a material model developed for large deformation and high strain rate conditions by Clegg et al. [22] based on the model developed by Anderson et al. [23]. This model couples the anisotropy of the material with the non-linear material response (shock). A finite element (FE) model has been developed using ANSYS-Autodyn (commercial FE software for hydrocode simulations) to study the effect of stacking sequence on the ballistic impact response of hybrid composite armors. The present FE model is validated with experimental results initially by considering the combination of KF layer in GF laminate impacting with cylindrical flat nosed (blunt) projectile and cylindrical hemispherical nosed (hemispherical) projectile. The crucial parameters such as energy absorbed by the target and the residual velocity are predicted. It is observed that the predicted values are comparable with that of the experimental results reported in the literature [21]. In addition, ballistic limit velocity, which is an important impact response parameter, has also been predicted from the present FE model. With the confidence gained from the validation, the present FE model is further extended to assess the ballistic impact response of hybrid composite armors with different combinations of composite laminates. Four different combination of hybrid composite armors with three types of composite laminate are considered for the current study (Table 1). The base laminate is called as master laminate and the layer added as slave laminate. The ballistic performance of all the four hybrid composite armors impacting with blunt and hemispherical projectiles is studied and the best possible combination showing better impact resistance is obtained.

2. Computational procedure

2.1. Ballistic impact phenomenon

Ballistic impact is a high velocity impact where low mass high velocity projectile impacts the target by a source such as a gun. As the ballistic impact phenomenon is of localized nature, the impact phenomenon (mechanics) near the impact zone is crucial for the design of body armors. As a result of the impact, stress waves are generated within the body armor along the thickness and radial direction. Since the direction of the projectile impact is normal to the target, a compressive wave propagated along the thickness of the armor, tensile and shear waves along the radial direction. The total event can be divided into two stages.

The first stage is the early stage of perforation governed by compression and deformation of the target material ahead of the projectile. The compressive wave reflects as tensile wave as it propagates through the inner surface of the armor, resulting in tensile failure at the interface of the plies leading to delamination. During this process, shear stresses are also generated within the target that can lead to failure. The compression of layers and failure

Table 1
Description of composite laminates.

Case	Base laminate	Slave laminate	Notation in text
1	GF	KF	K/G
2	KF	GF	G/K
3	CF	KF	K/C
4	KF	CF	C/K