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A Numerical Study on Prediction of BFS in Composite Structures under Ballistic Impact

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ABSTRACT

Back Face Signature (BFS: maximum permanent displacement at the back face of the plate) is one of the important performance factors criteria laid down for the standardization of body armors. In the current work, BFS of a composite plate under ballistic impact are determined for Kevlar 29 and 129 composite panels. Numerical studies using explicit time domain approach has been carried out to determine the ballistic response of the target plate through direct impacts of two types of rigid projectiles. Tie–break interface is used to model inter-ply delamination and contact. Effects of various parameters such as material stiffness, impact or geometry are determined. The BFS is estimated for various cases considering different impact velocities (140m/s-500m/s). Validation study for the present FE model explained above and subsequent results of dynamic analysis are verified through the existing results reported in the literature.

Keywords: Impact response, Kevlar, Numerical analysis, Back Face Signature (BFS).

1. INTRODUCTION

Composite materials are extensively used in a variety of applications like aircraft and military, space, automotive, sporting goods, marine structures, medical equipments. Highly desirable characteristics of composite materials like high strength to weight ratio, high stiffness to weight ratio, resistance to corrosion, low coefficient of thermal expansion are the driving force behind these applications. Composites tend to damage, particularly under impact loading. Such impacts will significantly reduce the strength of a laminate without causing any visible damage. Laminated composites have great potential in producing lightweight body armors. Factors like type of fiber and matrix, laminate thickness, lay-up sequence, geometry, boundary conditions, type of projectile, velocity of projectile, size, shape and kinetic energy of the projectile affect the response of laminated composites under ballistic impact.

Maximum permanent displacement at the back face of the plate during impact is described as the back face signature (BFS). BFS is the one of the important performance factors for assessing body or vehicle armors [1]. BFS of different target materials was calculated with two different types of projectile [4]. Experimental and numerical results were compared. The striking velocity of the projectile in the experiment was between 130 and 250m/s. Investigation of ballistic impact behaviour of two-dimensional woven fabric E-glass/epoxy composites were presented as a function of projectile and target parameters in a study [3]. Gower et al. [4] investigated BFS of Kevlar 29 and Kevlar 129 materials impacting with two different types of projectile and experimental and numerical results were compared. The striking velocity of the projectile in the experiment was between 130 and 250m/s.

Ballistic impact response of plain weave E-glass/epoxy and twill weave T300 carbon/epoxy composites were compared analytically and different damage and energy absorbing mechanisms during ballistic impact have been described in [5]. The analytical method presented was based on wave theory. A finite element model was developed by [6] to simulate the high velocity impact response of Kevlar29/Phenolic plate. Contact was tie break and a surface-to-surface eroding contact algorithm was used to simulate the interaction between the projectile and target. Impact performance of woven fiber Kevlar-29 and Al2O3 powder/epoxy was studied both experimentally and theoretically, and established a relationship between ballistic limit with thickness of the target for the hybrid composite considered.

The objective of this study is to investigate the variation of the back face signature (BFS) with different parameters and dynamic response of composite plate under ballistic impact. Numerical studies have been carried out by using explicit time integration approach, to study the ballistic response of Kevlar 29 and Kevlar 129. Two rigid (7.5mm diameter hardened steel 120˚ cylindrical-conical shaped and 9mm hemispherical nosed) projectiles are used in the current study. BFS is calculated by considering different cases with variation in velocity between 140m/s-500m/s. The effect of projectile velocity on the behaviour of composite beam is determined. The variation of BFS with velocities and time histories are obtained. Obtained results are validated with the results existing in the literature.

2. MATHEMATICAL AND NUMERICAL MODEL

A. Explicit Time Integration

Finite element (FE) method is one of the most powerful computational methods for structural analysis of composites. For solving dynamic events an explicit time integration scheme is commonly used. The investigation has been carried out using explicit time integration approach. The considered integration method can be an effective tool for solving a wide variety of nonlinear solid and structural mechanics problems. Explicit methods require a small time increment that depends solely on the highest natural frequencies of the model and is independent of the type and duration of loading. The equations involved are given below. The general dynamic equation takes the form,

$$[M]\ddot{u}+[K]u=F \qquad (1)$$

where, [M] is the mass matrices, [K] is stiffness matrix for beam and *F* is the force applied and *u* is the nodal displacement in the global coordinates. The above equation tells that the applied force is resisted by the inertia force and the stiffness force. All the three quantities are a function of time in dynamic analysis. The equation of motion for the $(i+1)^{th}$ time increment can be calculated directly using the central difference method. In central difference method the displacement and acceleration are given by the relations,

$$u^{(i+1)} = u^{(i)} + \Delta t^{(i+1)} \dot{u}^{\left(i+\frac{1}{2}\right)}$$

$$\dot{u}^{\left(i+\frac{1}{2}\right)} = \dot{u}^{\left(i-\frac{1}{2}\right)} + \frac{\Delta t^{(i+1)} + \Delta t^{(i)}}{2} \ddot{u}^{(i)} \qquad (2)$$

Thus the values of $\dot{u}^{\left(i+\frac{1}{2}\right)}$ and $u^{(i+1)}$ are calculated from the values of $\dot{u}^{\left(i-\frac{1}{2}\right)}$ and $\ddot{u}^{(i)}$ of the previous step. The acceleration at the beginning of the increment is computed by

$$u^{(i)} = M^{-1}\left(F^{(i)} - Ku^{(i)}\right) \qquad (3)$$

The time increment Δt is limited by

$$\Delta t = \frac{L}{C_0} \qquad (4)$$

where, L is the characteristic length and C_0 is the wave speed.

B. Finite Element Model

Definitions of the material properties and development of a proper contact algorithm are the key issues for finite element analysis of a composite laminate under ballistic impact. The current numerical model is implemented into a latest version of ABAQUS (6.10) from Dassault Systems. This included automatic contact capability which facilitates the definition of complex contact conditions [7]. The plate geometry is partitioned to include a central target location that allowed a finer mesh to be applied near the impact zone. This finer mesh is transitioned to a coarse mesh at the outer edges of the plate using the sweep mesh technique. Figs. 2 a & b shows the details of the finite element mesh used for the problem considered.

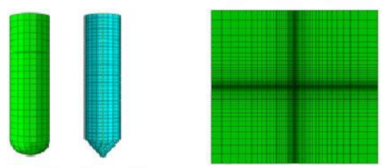

Fig 2. Details of finite element mesh (a) Projectile. (b) Target

Each lamina in the laminated panel is modeled as a separate entity with a tie break interface. The composite laminate meshed with C3D8 elements (Continuum three dimensional eight noded solid elements) and impactor with R3D4 elements (Three dimensional four noded rigid elements) is used. The general contact algorithm is used to prevent interpretation between the impactor and the plate. It greatly simplifies the definition of contact interactions where individual contact pairs are not required. A surface is defined that includes all interior faces of the plate mesh, to allow the projectile to interact with the internal plate material as elements erode. This surface is then included in the general contact definition. The coefficient of friction between the impactor and plate was taken as 0.2. The composite plate considered has 19 layers of mesh and 18 interfaces are created. Explicit time domain analysis is carried out to obtain the dynamic response.

3. NUMERICAL STUDY AND VALIDATION

A. Problem Definition

In current work, numerical studies have been carried out to determine the BFS of composite plate under ballistic impact. Explicit time integration technique has been implemented to determine the ballistic response. Improved finite element meshes and contact definitions are implemented. Each laminated panel is modeled as a separate entity with tie break interface.

The composite plate considered in present study is made of Kevlar 29 and Kevlar 129 with 19 plies. Scientific name of Kevlar is poly-paraphenylene terephthalamide. It is an aramid, a fibre similar to nylon but with very different properties. The composite plate material properties are given in Table I. The ballistic response of the target plate is investigated through direct impacts of two rigid projectiles (120˚ conical 7.5mm diameter and 9mm hemispherical nosed) made up of heat treated AISI 4340 steel are used to enhance the different failures. The dimensions of the composite plate are 25.4cm x 30.48cm and 19 plies with total thickness of 9.5mm. These are the typical measurements used for body armor [4]. Simply supported conditions are imposed.

Table 1 Properties of Kevlar 29 and Kevlar 129

Properties	Woven Kevlar-29 [2]	Woven Kevlar-129 [4]
E1 (GPa)	18.5	22
E2 (GPa)	18.5	22
E3 (GPa)	6.0	9
G12(GPa)	0.77	0.77
G13(GPa)	5.43	2.715
G23 (GPa)	5.43	2.715
υ12	0.25	0.25
υ13	0.33	0.33
υ 23	0.33	0.33
• (g/cm^3)	1.23	1.23

B. Results and Discussions

The ballistic performance of composite plate in the current study was performed using explicit time domain approach in which time increment can be calculated directly using the central difference method. The obtained results are validated with the experimental and numerical simulations reported in the literature [4].

Displacement (BFS) Time Plot

Numerical predictions of BFS-time variations are validated for 9mm diameter cylindrical-hemispherical ended projectile impacting a 19-ply Kevlar29 composite plate at 146m/s and 120^o cylindrical-conical projectile impacting Kevlar 129 at 244m/s.

Fig. 5a shows the BFS-time plot for Kevlar 29 impacting with 9mm diameter cylindrical-hemispherical ended projectile with velocity of 146m/s. This Fig. shows the dynamic response of the composite plate. The BFS-time variation obtained from current study agrees fairly with the experimental and numerical predictions [4]. BFS obtained from the current study is within the 5.2194% of the experimental value. This percentage is very close to the numerical work reported. Fig. 5b presents the BFS-time variation for Kevlar 129 impacted with 120o cylindrical-conical projectile at 244m/s. The variation of BFS with time in current study is 7.012% more than the experimental predictions. The predicted BFS-time variation is in good agreement with the literature although the values are slightly higher. To assess the accuracy of the numerical simulation the initial slope of the BFS-time graph can be used.

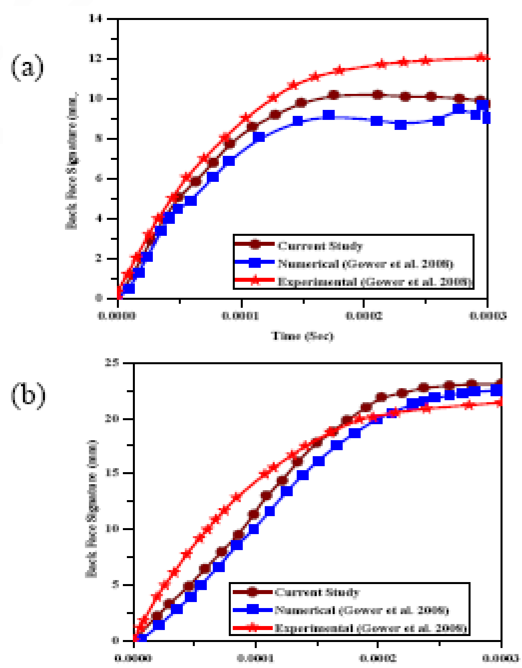

Fig. 5. Back Face Signature-Time histories plot (a) Kevlar29-Hemispherical at 146 m/s (b) Kevlar129-Conical at 244 m/s

A good agreement can be observed for the initial slopes of numerical and experimental predictions for hemispherical projectiles as shown in Fig. 5a. There is a slight increase in the slope of the numerical simulation for conical projectile compared to the experimental work from literature (Fig. 5b). A little effect can be predicted on initial slope by changing the material properties such as compressive strength through thickness, membrane strain, membrane modulus or modulus in fiber direction (*E1*), tensile strength and shear strength along the thickness [4].

BFS-Velocity Variation

Figs. 7(a-b) present the results for maximum displacement of both Kevlar plates impacted with various velocities by conical nose projectile. Predictions for the Kevlar 29 and Kevlar129 impacting with conical projectile (Fig. 7a, 7b) show the capability of the numerical model developed. In the current study, simulations with the hemispherical projectile gave BFS value in consistent with the numerical study reported in the literature (Fig. 7a).

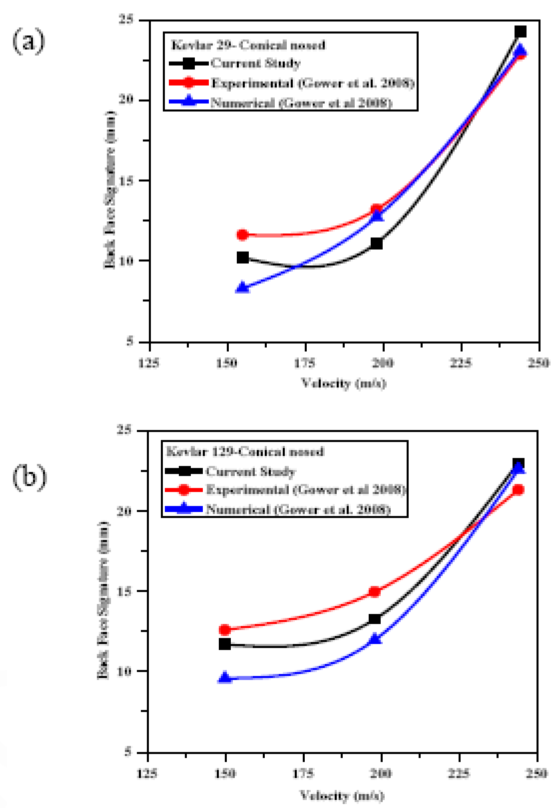

Fig 7 BFS-Velocity relationships (Conical nose) (a) Kevlar 29 (b) Kevlar 129

These low BFS values of hemispherical projectile ascribed to the influence of delamination and in-plane failure modes. The predictions in the current study are in good agreement with literature for conical projectile whereas for hemispherical projectile it is slightly low. When both Kevlar29 and Kevlar129 are impacted with hemispherical projectile (Figs. 8a&b), the variation of BFS with velocity is qualitatively in good agreement with the experimental results. In the current numerical study, BFS-velocity relationships for both Kevlar29 and Kevlar129 impacting with different projectiles are shown in Figs. 7 & 8. These Figs. depict that, although both the panels showed almost same BFS values when impacted with conical projectile at low speeds, there is a drastic increase for high velocities. In case of hemispherical projectile, both the panels have almost same BFS values at all velocities. The predicted values for BFS in the present study are in good agreement with the experimental and numerical studies reported.

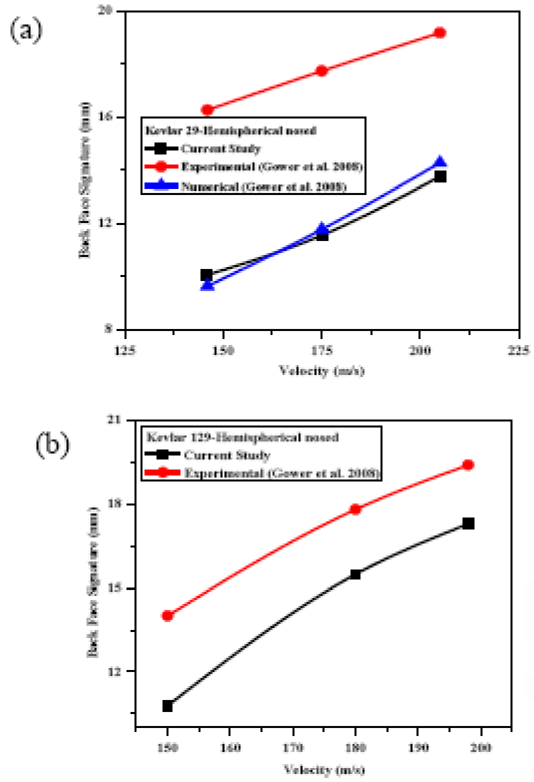

Fig 8 BFS-Velocity relationships (Hemispherical Nose) (a) Kevlar 29 (b) Kevlar129

4. CONCLUSIONS

The dynamic response of Kevlar29 and Kevlar129 composite plates impacted at ballistic velocities were investigated numerically. Based on this study, the following conclusions can be drawn:

- BFS-time plot for Kevlar 29 impacting with 9mm diameter cylindrical-hemispherical ended projectile with velocity of 146m/s showed the variation within the 5.2194% of the experimental value reported in the literature and it is very close with the numerical study as well.
- BFS-time variation from current study for Kevlar 129 impacted with 120° cylindrical-conical projectile at 244m/s given the variation is 7.012% more than the experimental predictions. But the nature of the variation is in good agreement.
- The predicted BFS variation from present numerical simulation showed excellent agreement for conical projectile impacting both the composite plates, while for hemispherical projectile was slightly low.

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