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Simulation on a Composite Laminate Subjected to Ballistic Impact

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Abstract. A finite element model was developed to study the damage mechanisms of composite laminates under high velocity impact conditions. Modified Hashin failure criteria were used for the fiber breakage prediction. Cohesive elements were defined between two adjacent layers in the target laminate for the prediction of delamination initiation and propagation during the impact. The strain rate effects were also considered for the composite stiffness and strength. By using the developed finite element model, the ballistic limit, $V_{L,}$ for a composite laminated target can be calculated, which was validated by the test data in the public literature.

Introduction

The glass fiber reinforced composites are widely used in some engineering applications where the high velocity impact is a big concern. Composite laminate made of E-glass/plastic possesses an excellent impact resistance capability due to its significant increase in both stiffness and strength under a high strain rate condition. A lot more kinetic energy from the impactor is absorbed by the glass reinforced composite than normal metallic materials. Therefore, it is quite important to study and understand the structure behavior of glass reinforced composite laminates subject to high velocity impact during the development of some products like composite helmet, shield, airplane canopy and armor.

A term that is used to describe impact resistance of a laminate is called *ballistic limit*[1], $V_{L,}$, which provides a quantitative measurement for the maximum amount of kinetic energy that the target can absorb before it is perforated by the projectile. It is defined as the minimum velocity at which a particular projectile is expected to consistently, completely penetrate an armor of given thickness and physical properties at a specified angle of obliquity.

To determine the ballistic limit of a composite laminate is very important for the design of a composite armor. There were substantial studies on the ballistic impact behaviour of composite laminates made by glass/fiber and some other composite materials using analytical and numerical method, as well as experimental tests [2-16].

Duan[5] used LS-DYNA to investigate the effect on the energy absorption of friction and boundary conditions. Results showed that both the yarn strain energy and the yarn kinetic energy are increased when there exists friction, and the boundary conditions significantly affect the fabric deformation, stress distribution, and time history of energy absorption.

Deka[6] et al using an explicit three-dimensional finite element code LS-DYNA to analyse the perforation mechanisms, ballistic limit and damage evolution. A progressive failure model MAT162, based on modified Hashin’s criteria was assigned to analyse failure of the laminate.

Heimbs[13] et al developed a numerical approach using ABAQUS to predict the impact damage of preloaded composite plates under bird strike loading. In order to validate the model, bird impact tests were performed at the DLR Stuttgart gas cannon test facility using a specially designed test rig that allows for uniaxial tensile of compressive preloading. The standard composite material model in the commercial FEA code ABAQUS was used, which is based on an orthotropic linear elastic formulation and Hashin failure criteria for damage initiation.

This paper investigates the deformation and failure mechanisms of the composites laminates subjected to high velocity impact by using finite element method. Ballistic limits and damage characteristics obtained in the analysis are compared to the publically reported test results.

Finite Element Model

Problem Description and Finite Element Model

The following configuration shown in

Fig. 1 is used to study the penetration of a clamped laminated square plate by a cylinder rigid rod. The in-plane dimensions of the target plate are 100mm ×100mm and the thickness is 4.5mm. The steel cylindrical rod is 4.76mm in diameter and 3.33g in mass. The impact velocities are 170m/s, 175m/s, 180m/s and 188m/s respectively.

Fig. 2 shows the finite element model generated in ABAQUS. The target laminated plate was meshed by solid elements C3D8R layer by layer. The interfaces between the adjacent layers were meshed by cohesive elements COH3D8 to simulate the delamination initiation and propagation. It has been shown that the more the delamination interfaces are used, the more realistic the results[13]. There are totally 10 plies cohesive elements with zero initial thickness defined in this model. The target was clamped on the left and right sides. The projectile was assumed to be a rigid body with a given impact velocity. Eroding contact was defined between the projectile and the target. Strain-rate effect and failure mechanisms of the composite laminated target were considered and incorporated in the user defined subroutine material model VUMAT. Table 1 gives the static elastic and strength properties of an E-glass/plastic lamina in the plate. It was assumed that there was no friction between the projectile and the target during the impact.

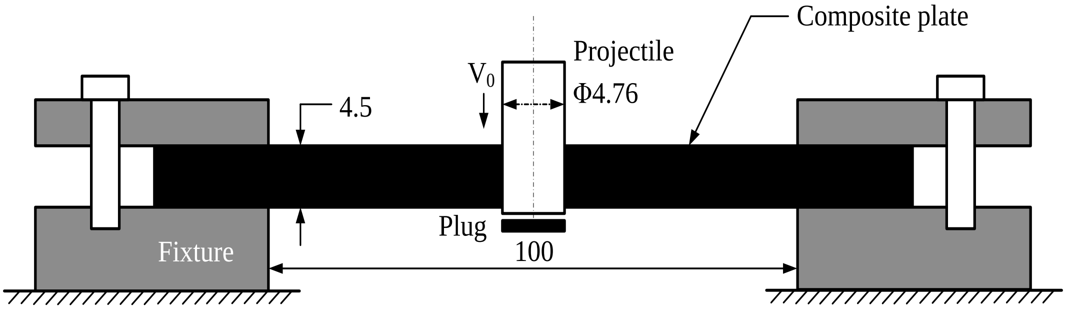


Fig. 1 Ballistic impact specimen configuration

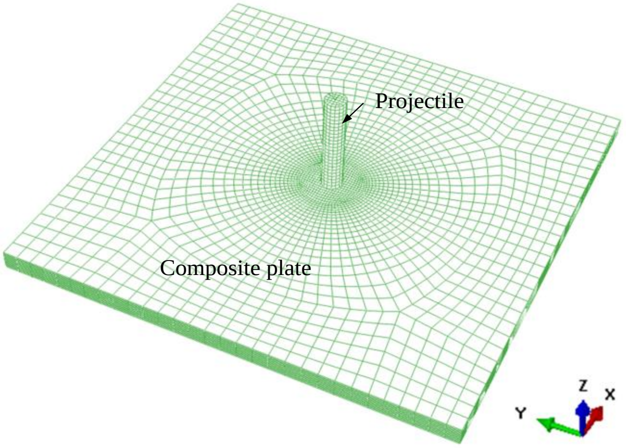


Fig. 2 Finite element model

Tab. 1 Lamina material properties of the target plate

Elastic Modulus		Strength	
$E_{11}=E_{22}$[MPa]	38600	X_T[MPa]	1062
E_{33}[MPa]	8300	X_C[MPa]	610
υ_{12}	0.279	Y_T[MPa]	1062
$\upsilon_{13}=\upsilon_{23}$	0.3	Y_C[MPa]	610
G_{12}[MPa]	4200	S_{12}[MPa]	72
$G_{13}=G_{23}$[MPa]	3400	$S_{13}=S_{23}$[MPa]	58.36

Failure Models

Modified Hashin failure criteria[12] were adopted in the failure prediction during the impact. It is assumed that:

Tensile Fiber Mode in 1-direction ($\sigma_{11}>0$)

$$r_1^2=\left(\frac{\sigma_{11}}{X_T}\right)^2+\alpha\left(\frac{\sigma_{12}+\sigma_{13}}{S_{12}}\right)^2 \tag{1}$$

Compressive Fiber Mode in 1-direction ($\sigma_{11}<0$)

$$r_1^2=\left(\frac{\sigma_{11}}{X_\mathrm{C}}\right)^2 \tag{2}$$

Tensile Fiber Mode in 2-direction ($\sigma_{22}>0$)

$$r_2^2=\left(\frac{\sigma_{22}}{Y_T}\right)^2+\alpha\left(\frac{\sigma_{21}^2+\sigma_{23}^2}{S_{21}^2}\right) \tag{3}$$

Compressive Fiber Mode in 2-direction

$$r_2^2=\left(\frac{\sigma_{22}}{Y_\mathrm{C}}\right)^2 \tag{4}$$

In the above equations, X_T, X_C, Y_T and Y_C denote the tensile and compressive strengths in fiber and its transverse direction. S_{12}, S_{13} and S_{23} represent the shear strengths in the plane and transverse directions and $S_{13}=S_{23}$. α is the shear stress interaction coefficient and $\alpha=0.2$. The element would be deleted from the model if the damage variables $r_1\geq 1$ and $r_2\geq 1$.

Inter-layer delamination was simulated using cohesive elements[14] and the delamination initiation was assumed to happen when the quadratic nominal stress ratio in Eq.(5) reaches 1.0.

$$\left(\frac{\langle t_n\rangle}{t_n^o}\right)^2+\left(\frac{\langle t_s\rangle}{t_s^o}\right)^2+\left(\frac{\langle t_t\rangle}{t_t^o}\right)^2=1 \tag{5}$$

where $\langle\ \rangle$ is Macaulay brackets. When the damage initiated in the cohesive element, the material stiffness was degraded according to the damage evolution law as following

$$\{t\} = (1 - D)\{\bar{t}\} \tag{6}$$

where $\{\bar{t}\}$ are the stress components predicted by the elastic behaviour for the current strains without damage and D is damage variable.

Strain Rate Dependent Response

Under the ballistic impact, the influence of strain rate effect of an E-glass/plastic material quite significant and must be considered in the analysis. Some previous research has focused on this effect[10, 16]. The strain-rate effect on the elastic modulus E_{RT} and strength values S_{RT} is modeled as follows.

$$\{S_{RT}\} = \{S_0\}\left(1 + C_1 \ln \frac{|\dot{\varepsilon}|}{\dot{\varepsilon}_0}\right) \tag{7}$$

$$\{E_{RT}\} = \{E_0\}\left(1 + C_2 \ln \frac{|\dot{\varepsilon}|}{\dot{\varepsilon}_0}\right) \tag{8}$$

In the above equations, C_1 and C_2 are the strain rate constants. E_0 and S_0 are the modulus and strength values of E_{RT} and S_{RT} at the reference strain-rate $\dot{\varepsilon}_0 = 1\text{s}^{-1}$, respectively[15]. Strain-rates can be computed internally while strain-rate constants can be only obtained from test data. However, as these test data are currently not available, the strain rate constants will be determined according to the reported results. In [16], the strain rate constant $C_1 = 0.1$ was used to analyse the impact process. Here, the strain rate effect was magnified and chosen as $C_1 = 0.12$. The stiffness strain rate constant $C_2 = 0.02$.

Results and Discussion

The ballistic impact of an E-glass/plastic composite laminate was studied by the developed finite element model with various impact velocities.

Fig.3 shows the time histories of ballistic velocities of the projectile with four different initial impact velocities. It can be seen that when the initial impact velocity is 175m/s or higher, the projectile would perforate the target, but if the initial impact velocity is 170m/s or lower, the projectile couldn’t perforate the target. By averaging these two values, the ballistic limit V_L of the laminate is estimated to be 172.5m/s, which is only 1.42% lower than the experimental value of 175m/s.

A cone-shape delamination pattern can be seen on the section area of the composite laminate as shown in Fig. 4, which is similar to the reality[11]. Fig. 5 shows the stress distribution and damage mechanisms during ballistic impact for the initial impact velocity of 188m/s. The typical failure modes , including fiber breakage and delamination , of the composite laminate target are clearly shown in Fig. 5 also.

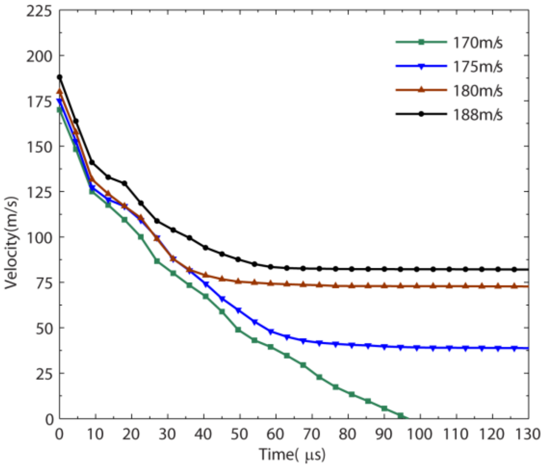


Fig. 3 Simulated time histories of projectile's velocities

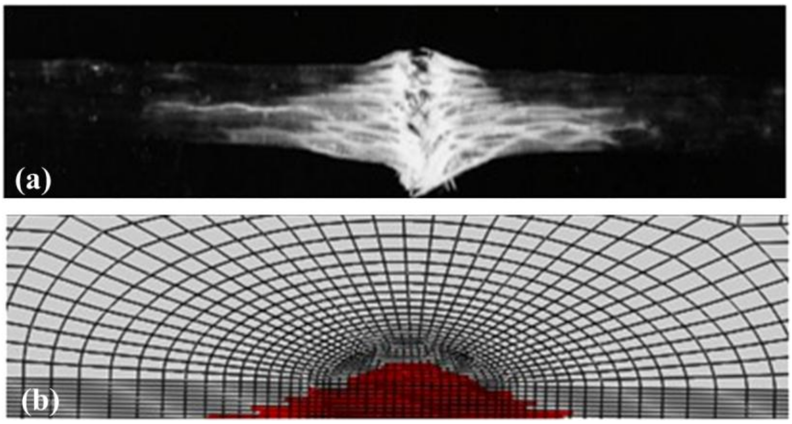
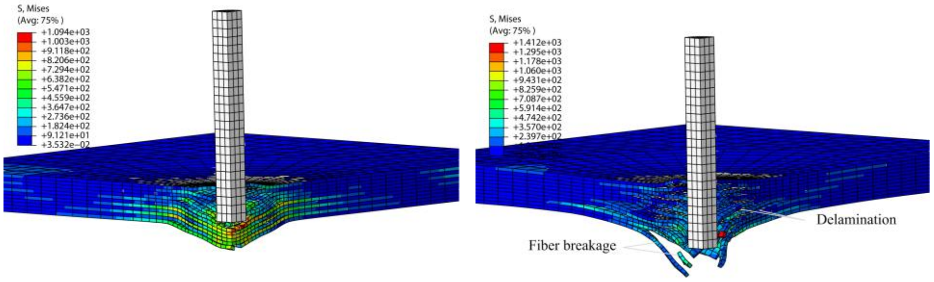


Fig. 4 Delamination shape compared with previous results0, (a) previous results in [11], (b) results calculated by using the present finite element model



(a) (b)

Fig. 5 Stress distribution and damage mechanisms during ballistic impact (1/4 view), $V_0 = 188\,\mathrm{m/s}$, (a) $t = 30\mu s$, (b) $t = 100\mu s$

Summary

A finite element model has been developed to investigate the failure behavior of fabric composites subjected to ballistic impact. By using the finite element model, ballistic limit and residual velocity of projectile under high velocity impact could be calculated. The results are compared with previous experimental data and have a good agreement with them. In this method, strain-rate sensitivity properties has been accounted, but the strain rate effect will need further investigation by experimentally characterizing the rate dependent behavior of various strain rates and composite materials.

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