AN EXPERIMENTAL INVESTIGATION OF PENETRATION FAILURE MODES IN COMPOSITE LAMINATES

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Abstract

The impact tests were conducted with a high-velocity gas cannon. Three kinds of stacking sequence composite laminates $[(45/-45)_4]_s$, $[(0/45/90/-45)_2]_s$ and $[(0/45/90/-45)_4]_s$ were impacted by a projectile with a velocity of 10-300 m/s. A laser velocity surveying apparatus was employed to measure the striking and residual velocities of the projectiles. The process of impact perforation was observed by taking photographs with a high-speed framing camera to those targets. And the impact fracture behavior and the energy absorption property were analyzed. The ballistic characteristics were represented by the experiential formulas which gave the relationship between the striking and residual velocities of the projectile. The experiential formulas can estimate the ballistic limit penetration velocities and the residual velocities.

1 Introduction

Fiber reinforced composite materials are used extensively in military and civil applications due to their excellent mechanical properties like high specific strength, specific stiffness, resistance to corrosion, increased fatigue life among others. However, they are susceptible to impact damage due to their low toughness properties. Composites that are used in aerospace and land based structural components are often subjected to high velocity impact threats like broken engine parts, turbine blades, fragments from bombs, shells, mortars, and grenades. There are many issues that determine the response of the composite materials to impact threats. These include: type and volume fraction of the fibers, laminate thickness, boundary conditions, the matrix system, the lay-up sequence, geometry, size and the kinetic energy of the impactor.

A study on impact response of composite laminates concluded that impact perforation is the most important damage stage in composite laminates subjected to impact loading. The reason is that impact characteristics and mechanical properties degradation of composite laminates reach critical values when perforation takes place [1-3]. In order to investigate impact perforation behavior of carbon fiber reinforced composite, the impact tests were conducted with a high-velocity gas cannon. The perforation behaviors were evaluated by absorbed energies during perforation, morphological in situ observations using high-speed framing cameras and postmortem observations. The ballistic characteristics were represented by a given experiential formula, which gave the relationship between the striking and residual velocities of the projectile.

2 Specimens and Projectile

T300 carbon fibers were used in making composite laminate specimens. The weight fraction of fibers was kept constant at 60%. The matrix of the specimens was from thermo-setting epoxy resin. The cure of all laminates was done at room temperature, 23^0C, and relative humidity 50%. Three kinds of stacking sequence, $[(45/-45)_4]_s$, $[(0/45/90/-45)_2]_s$ and

$[(0/45/90/-45)_4]_s$ were used in the test. The configuration of the specimens is 90mm×90mm in plane area and 2.4mm (4.8mm) in thickness (Fig. 1). A steel bullet of weight 19.99g was used as a projectile in the test. The size of the bullet is shown in Fig. 2.

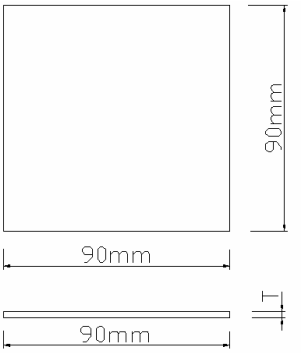


Fig. 1. **D**imensions of a specimen (T is the thickness)

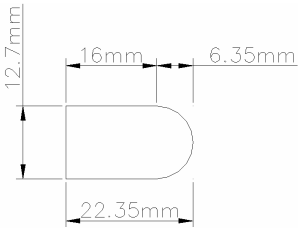


Fig. 2. Dimensions of a projectile

3 Experiments

The high velocity impact tests were made by using a gas cannon. The specimen was mounted in a clamp supported boundary condition along its four edges. Fig. 3 shows a schematic diagram of the impact perforation experimental setup. Varying the pressure of gas in the firing chamber varied the impact velocity. The impact tests were designed to investigate the damage evolution at the ballistic limit. The bullet accelerated from 10 to 300 m/s by a light gas cannon, was ejected from its launcher tube. It passed a velocity measurement device and vertically impacted the center of the front surface of the specimen. A laser velocity surveying apparatus was employed to measure the striking velocity v_s and residual velocities v_r of the projectile. A typical signal output from velocity measurement is shown in Fig. 4.

A high-speed framing camera was used for the in situ observation of the impact perforation behavior. The kinetic energy of a projectile was changed from the impact energy E_s to the residual energy E_r after perforating a specimen. The energy absorbed by the specimen was E_s-E_r=0.5$m(v_s^2$-$v_r^2)$, where m is the mass of a bullet. After the experiments, postmortem morphological observations were carried out on the specimens to investigate their failure modes. A serial of high-speed photographs of thick-0 specimen impacted at the velocity of 161 m/s are shown in Fig. 5.

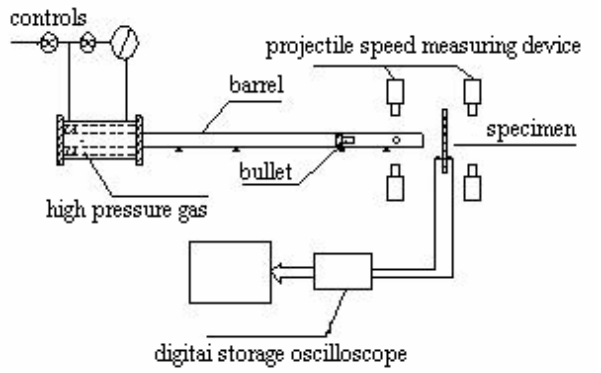


Fig. 3. Schematic diagram of impact testing

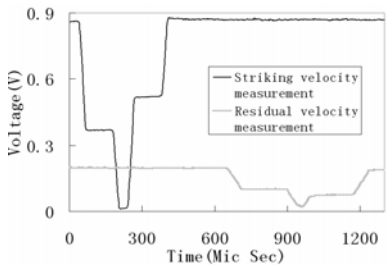


Fig. 4. Typical signal output from velocity measurement

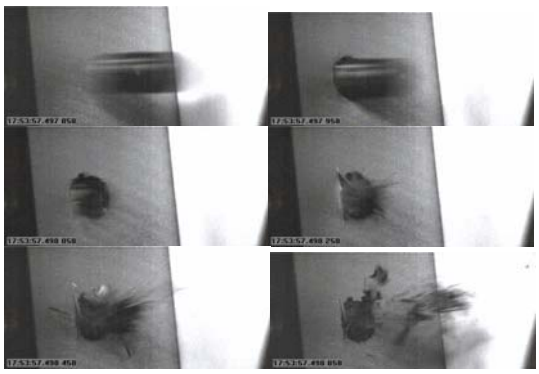


Fig. 5. High-speed photographs of thick-0 impacted at the velocity of 161 m/s

4 Results and Discussion

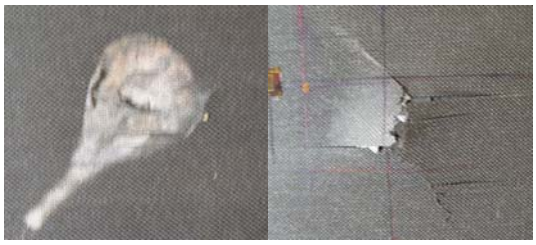
4.1 Failure Mode

Figs. 6-14 show typical images for the front and rear surfaces of the specimens impacted. For specimen notations, the first word, i.e. thin (thick), represented the thickness of 2.4mm (4.8mm) specimens. The second number 0 stood for stacking sequence $[(0/45/90/-45)_2]_s$ ($[(0/45/90/-45)_4]_s$) and 45 for $[(45/-45)_4]_s$ while the last number was a serial number of the specimens. The ballistic limit velocity denoted by v_{50} is the threshold velocity at which 50% of the projectiles penetrate, and 50% are arrested within the bounds of the specimens. We have considered v_{50} as the velocity at which the projectile has almost emerged from the rear surface of the specimen. Under this condition, the projectile remains embedded within the specimen, yet visible when viewed from the rear surface. Figs.6-8 are "rebound" cases for three kinds of stacking sequence specimens impacted. This means the bullet did not penetrate the specimens and return to the front of the specimens after impact due to the impact velocity is less than ballistic limit speed. Figs.9-11 are "insert" or "partial penetration" cases. The bullet velocity is at critical velocity of penetrations. And Figs 12-14 are "complete penetration". In this case, residual velocity of the bullet can be measured by the laser velocity surveying apparatus.

In spite of similar impact energies, those fractured in significantly different failure modes. In both laminates Thin-45-14 (Fig. 12) and Thin-0-14 (Fig. 13), clear square and circular hole were observed on the front surface, respectively. For both laminates, however, delamination all occurred on the rear surface in fiber directions, i.e., in horizontal direction for Thin-0-14 and in 45^0 direction for Thin-45-14.

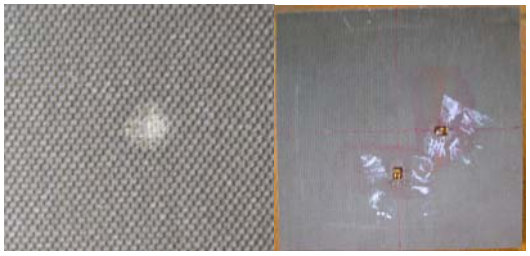
(a) Front surface (b) Rear surface

Fig. 6. Postmortem observations on Thin-45-3



(a) Front surface (b) Rear surface

Fig. 7. Postmortem observations on Thin-0-3

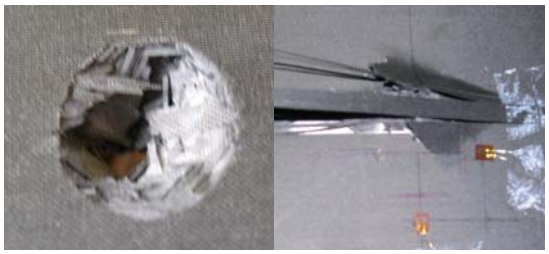


(a) Front surface (b) Rear surface

Fig. 8. Postmortem observations on Thick-0-1

(a) Front surface (b) Rear surface

Fig.9. Postmortem observations on Thin-45-4



(a) Front surface (b) Rear surface

Fig. 10. Postmortem observations on Thin-0-6

(a) Front surface (b) Rear surface

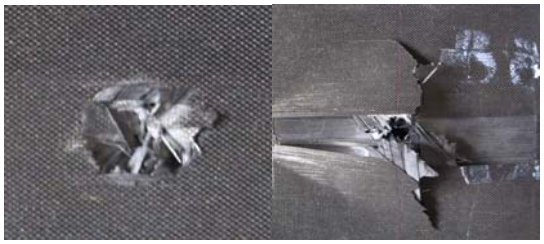
Fig. 11. Postmortem observations on Thick-0-3

(a) Front surface (b) Rear surface

Fig. 12. Postmortem observations on Thin-45-14

(a) Front surface (b) Rear surface

Fig. 13. Postmortem observations on Thin-0-14



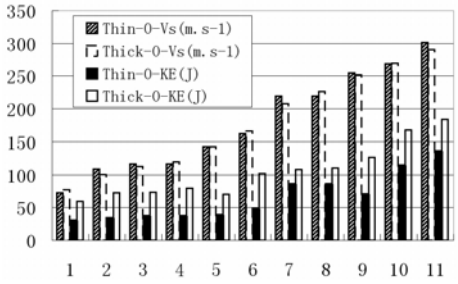
(a) Front surface (b) Rear surface

Fig. 14. Postmortem observations on Thick-0-8

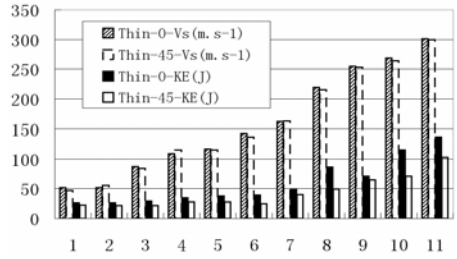
4.2 Absorbed Energy

Once a composite laminate was perforated, any excess impact energy would be retained as kinetic energy in the impactor except that an insignificant amount would be converted into additional damage. The energy absorption and projected damage were maximized at this condition. Hence, perforation threshold was an important parameter in characterizing the impact response of composite laminates. The incident velocity, v_s, was measured using a chronoscope. This method was not acceptable for measuring the exit velocity, v_r, as the projectiles exited the laminates at different angles and did not always pass through the narrow aperture of the chronoscope. A high speed camera was also used to measure the dynamic delamination areas and to investigate the path of the missile through the laminate.

Fig. 15 shows striking velocities and absorbed kinetic energies histogram. In Fig. 15, V_s is striking velocity and KE is kinetic energy absorbed. We could recognize clear differences in the absorbed energy among specimens. The thickness (Fig.16a) and stacking sequence (Fig.16b) of laminated composites are of important roles that affected impact perforation behavior of the carbon fiber reinforced composites.



(a) $[(0/45/90/-45)_2]_s$ and $[(0/45/90/-45)_4]_s$



(b) $[(0/45/90/-45)_2]_s$ and $[(45/-45)_4]_s$

Fig. 15. Striking velocities and absorbed kinetic energies

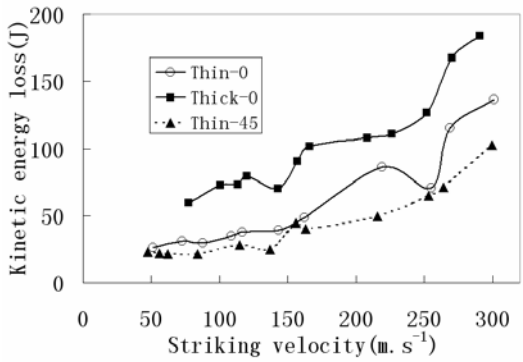


Fig.16. Kinetic energy absorbed by the composites

A comparison of the effect of impact velocity on the kinetic energy absorbed by Thin-45, Thin-0 and Thick-0 composites is presented in Fig. 16. It is clear from the experimental results that Thick-0 composites exhibit better projectile energy absorption capability than the Thin-45 and Thin-0 composites.

The absorbed kinetic energy, E_a, the impact and the residual kinetic energies are linked by the equation,

$$E_a = \frac{1}{2}mv_s^2 - \frac{1}{2}mv_r^2 \qquad (1)$$

For the target, when the shape and material of the projectile are unchanged the ballistic limit velocity is a constant. In other words, when a bullet impacts a target at the ballistic limit velocity v_{50}, the kinetic energy of the bullet is absorbed entirely by the target.

$$E_{a1} = \frac{1}{2}mv_{50}^2 \qquad (2)$$

Beyond the ballistic limit, the absorbed kinetic energy increases with increasing impact velocity. The difference between E_a and E_{a1} is assumed to be a function of striking velocities of the bullet as following.

$$E_a - E_{a1} = f\left(v_s\right) \qquad (3)$$

Based on the experimental results, the expression of $f(v_s)$ can be obtained experientially as

$$E_a - E_{a1} = f\left(v_s\right) = amv_s^2 + c \qquad (4)$$

where a and c are constants. Different targets have different a and c. The formulation described the relation of E_a和v_s can be expressed by statistical data from experiments.

$$E_a = 0.0421mv_s^2 + 16.778 \qquad (5a)$$

$$E_a = 0.0648mv_s^2 + 19.838 \qquad (5b)$$

$$E_a = 0.07125mv_s^2 + 52.548 \qquad (5c)$$

Eqs.(5a), (5b) and (5c) are formulas of energy absorption for composite laminates Thin-45, Thin-0 and Thick-0, respectively. Inserting Eqs. (5a), (5b) and (5c) into Eq. (1), an experiential formula predicting residual velocity can be expressed as Eq.(6) for the laminated composites Thin-45, Thin-0 and Thick-0, respectively.

$$v_r = \sqrt{0.9158v_s^2 - \frac{33.556}{m}} \qquad (6a)$$

$$v_r = \sqrt{0.8704v_s^2 - \frac{39.676}{m}} \qquad (6b)$$

$$v_r = \sqrt{0.8575v_s^2 - \frac{105.096}{m}} \qquad (6c)$$

5 Summary

Failure mechanisms and modes of the carbon/epoxy composite laminates were observed experimentally during high velocity impact. The thickness and stacking sequence of laminated composites are of important roles that affected impact perforation behavior of the carbon fiber reinforced composites. In spite of similar impact energies, composite laminates fractured in significantly different failure modes. In stacking sequence $[(0/45/90/-45)_2]_s$ ($[(0/45/90/-45)_4]_s$) and $[(45/-45)_4]_s$, clear circular and square hole were observed on the front surface, respectively. The velocity of ballistic limits for the carbon/epoxy laminates impacted by the projectiles was predicted using current experiential formula (6) by setting v_r equal to zero.

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