The resistance to the high-velocity impact of the intra-layer hybrid plain weave composites

Hang Wu[1,2], Yang Bai[1,2], Shilin Fang[1,2], Zhenqiang Zhao[1,2]*, Chao Zhang[1,2,3]

[1]School of Aeronautics, Northwestern Polytechnical University, Xi'an, Shaanxi, China 710072
[2]Joint International Research Laboratory of Impact Dynamics and Its Engineering Applications, Xi'an, Shaanxi, China 710072
[3]School of Civil Aviation, Northwestern Polytechnical University, Xi'an, Shaanxi, China 710072

Abstract

Numerous studies have shown that hybridization is an effective way to modulate the properties of composites. For instance, hybrid composites of ductile and brittle fibers exhibit excellent impact resistance through rational design. This study investigates hybrid plain weave composites containing carbon fiber bundles and Kevlar fiber bundles in layered configurations. Composite panels with different hybrid proportions and configurations were fabricated and tested using a one-stage gas gun to assess their resistance to high-velocity impacts, as shown in Fig. 1. The test results indicate that the pure Kevlar panel, characterized by relatively high elongation and low modulus, exhibits a higher ballistic limit velocity than the pure carbon panel. Furthermore, replacing part of the carbon fiber bundles with Kevlar bundles effectively increases the ballistic limit velocity of the composite panel. As the proportion of Kevlar in the hybrid composite panels increases, the impact damage area becomes larger, with a greater tendency for cracks and delamination. Additionally, a finite element model was developed to simulate the high-velocity impact on the hybrid plain weave composite panel, and its validity was confirmed through comparison with experimental results.

Keywords: Hybrid composites; high-velocity impact; ballistic limit velocity; numerical simulation

1. Introduction

Fiber-reinforced composites are widely used in high-tech fields, particularly in the aerospace industry, due to their high specific strength and high specific modulus. In the case of carbon fiber-reinforced composites, which are commonly used in aviation, a key issue during service is impact resistance to external objects. Examples include ice collision and bird impact during aircraft take-off and landing, as well as various inclusiveness and non-inclusiveness issues encountered during flight [1-3]. High-speed impacts from external objects can significantly affect composite structures [4-6]and may even lead to catastrophic accidents.

The response of composites to high-velocity impacts is influenced by multiple factors, such as the material properties of the weave structure, fiber type, thickness of the composite, structural shape, constraints, and service temperatures [7-12]. Single-fiber reinforced composites typically do not simultaneously possess high strength, high modulus, and good toughness. Recently, hybrid tough and brittle fibers has emerged as a solution [13]. For instance, combining aramid fibers, which have relatively high elongation and low modulus, with carbon fibers, which have low elongation and high modulus, can enhance the impact resistance of composites [14]. Hybrid fiber composites can meet specific requirements that single composites cannot achieve [15-16] and represent an effective approach to regulating composite properties. In comparison to traditional reinforced materials, this composite material not only incorporates the advantages of individual materials but also possesses a distinctive advantage in terms of enhancing the designability of the material and realising the multifunctionality of the composite material at a reduced cost. Consequently, the study of the impact of intra-layer hybrid on the mechanical properties of composites holds significant theoretical importance and broad application prospects. Dehkordi et al. [21] conducted a study on five distinct blends, measuring the compressive strength before and after impact at varying energies of 15J/30J/40J. The findings of the study indicated that the impact resistance exhibited a rising correlation with the proportion of basalt and nylon present, as the impact energy increased. Zulkifli et al. [17] investigated the ballistic impact properties of carbon fiber/UHMWPE interlayer hybrid composites. Their results showed that the flexural strength of hybrid composites was high compared to single composites when carbon fibers were placed in the outer layer of the specimen. Additionally, the incorporation of UHMWPE into carbon fiber composites effectively increased the ballistic ultimate velocity. Zhao et al. [18] examined the impact properties and damage mechanisms of a novel carbon-Dyneema hybrid fabric-reinforced plastic composite using drop hammer and steel ball impact tests. They analyzed the force-displacement response, energy absorption, and damage mechanisms of the hybrid composites and compared them with woven carbon laminates. The experimental results indicated that the hybrid composites exhibited improved impact resistance, with Dyneema fibers inhibiting the splitting of the bottom surface during impact. Xu et al. [19] studied the ballistic limits, damage modes, and energy absorption characteristics of hybrid fiber-reinforced polymer target plates (HFRPT) consisting of carbon fiber-reinforced polymer (CFRP) and aramid fiber composites (AF). Their findings demonstrated that hybridization provided better ballistic impact resistance by influencing damage modes and energy absorption.

Most studies on intraply hybrids have focused on quasi-static and low-velocity impacts, with fewer investigations addressing high-velocity impacts. This paper examines the mechanical properties of woven composites comprising carbon fibre tows and Kevlar fibre tows in intraply. The findings are presented for typical woven composites. The impact resistance of pure carbon fibre, pure Kevlar and composite plate with different hybrid modes was evaluated through experimental methods. This enabled the mechanical response of composite flat plate with different hybrid modes under high-speed impact load to be compared and analysed. The objective was to clarify the high-speed impact failure mechanism of the blended woven composites and to provide technical references and experimental bases for the design of the intraply hybrid composites.

In this study, we designed composite plates using carbon fiber, Kevlar, and three different blends for typical woven composites. High-speed impact tests were conducted to determine the ballistic limiting velocities. Non-destructive testing techniques, such as ultrasonic C-scan, were employed to assess the damage and evaluate the effect of different blends on impact resistance.

2. Material and experiment

2.1 Material design

The composite plates were molded using carbon fiber and Kevlar, supplied by Shandong Weihai Expansion and Shandong Taihe New Material, respectively. Both fibers utilized the same epoxy resin matrix (LT5078). Table 1 presents the fundamental material parameters.

Table 1 –Basic material parameters

Material	Density(g/cm^3)	Tensile Modulus (GPa)	Tensile Strength (MPa)	Tensile failure strain
TZ700S	1.81	237	5351	2.26
529S	1.45	80	2905.92	4.00
LT-5078	1.1	3.2	75	8.00

Three composite panels were designed and fabricated with different in-layer hybridizations: CK, C1V1K, and C1V2K. Additionally, to facilitate performance comparisons, non-hybridized composite panels made solely of carbon fibers (C) and Kevlar (K) were prepared as a control group. The specific hybrid configurations are illustrated in Figure 1. All composite plate thicknesses were uniformly designed to be 4.5 mm.

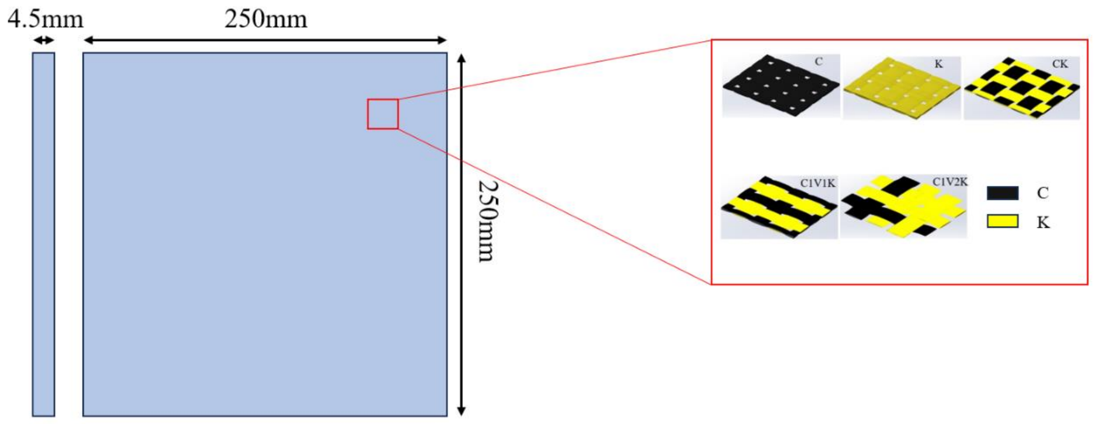

Figure 1 –Schematic diagram of the five different hybrid methods.

2.2 High-velocity impact experiment

The high-velocity impact test was conducted using a one-stage light air cannon. Four specimens of each intraply hybrid mode were subjected to impacts from wedge-shaped titanium alloy bullets, each measuring 50 mm in length, 50 mm in width, and 6 mm in height, at various velocities. The ballistic limits were identified within intervals where the difference between the rebound and penetration velocities was approximately 10 m/s. Specimens measuring 250 mm x 250 mm were cut from the original 500 mm x 500 mm plates using waterjet cutting. The test pieces were clamped in place using two steel base plates, and bolts were tightened with a torque wrench set to 25 Nm. During the test, the cartridge is propelled by high-pressure gas along the guide rail, reaching the exit of the gun barrel where it is obstructed by the device. The slice-shaped bullet is then detached from the cartridge due to inertia and continues to fly forward, colliding with the fixed composite material target plate at high speed and ultimately being arranged in the rear of the target plate of the sandbags to block, as shown in Fig. 2.

In the course of the test process, it is necessary to ascertain the speed of the bullet, the deformation of the target plate and other physical quantities. Four high-speed cameras were utilised in the test, with one positioned above the front of the target plate to capture the initial impact of the bullet on the target plate. Another was placed on the side of the vertical impact direction to document the flight process and velocity of the projectile as it exited the chamber. The remaining two cameras were employed to obtain the deformation of the target plate after impact. Prior to the test, a spray of scattering material was applied to the dorsal surface of the target plate. During the test, the two cameras located on the left and right sides of the target plate were used to record the deformation of the dorsal surface of the target plate during the impact process. During the test, the two cameras positioned at the left and right sides of the target plate recorded the deformation of the target plate's dorsal surface during the impact process. This was combined with the use of three-dimensional DIC technology to calculate the displacement and deformation field of the target plate's dorsal surface. The velocity of the impact was recorded, and the interval between the penetration and non-penetration velocities was defined as the ballistic limiting velocity interval of 10 m/s. The velocity of the impact was measured by the two cameras positioned on either side of the target plate. A high-speed impact failure analysis of hybrid woven composite flat plates was conducted in order to facilitate a comparison and analysis of the damage modes exhibited by composite flat plates with different hybrid modes.

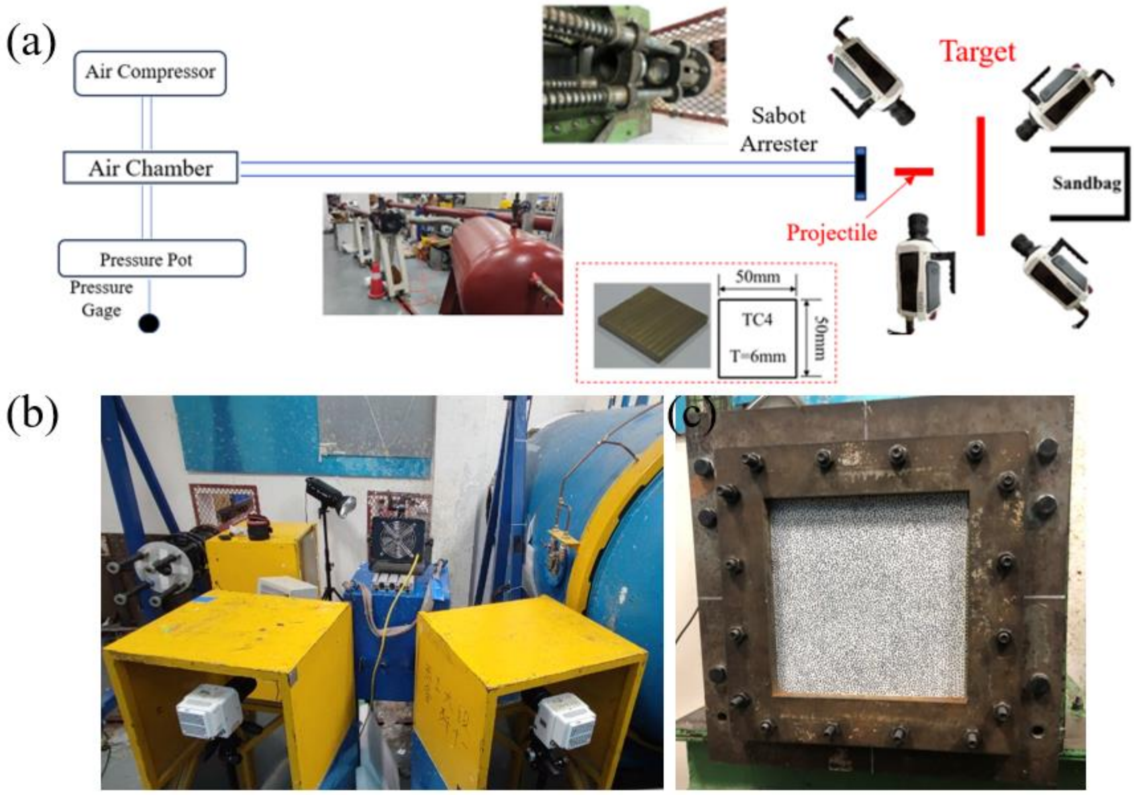

Figure 2 –Schematic diagram of the impact test device((a) a schematic diagram of the impact device;(b) camera layout; (c) composite plate fixing diagram).

3. Result and discussion

3.1 High-velocity impact experiment result

For the five composite panels with different hybrid modes, tests were conducted at speed intervals ranging from 99 m/s to 160 m/s. The number of tests, test speeds, and experimental results for each group are summarized in Table 1.

Table 1 –Impact experiment result.

Material	Speed(m/s)	Result
C	122.7	Penetrated
	100.5	Rebounded
	117.2	Penetrated
	107.2	Rebounded
K	137.4	Rebounded
	152.4	Penetrated
	124.7	Rebounded
	151.0	Penetrated
CK	114.5	Rebounded
	110.0	Rebounded
	126.2	Penetrated
	100.3	Rebounded

C1V1K	110.8	Rebounded
	121.2	Penetrated
C1V2K	99.7	Rebounded
	111.7	Penetrated
	128.1	Penetrated

Through the results of three-dimensional Digital Image Correlation (DIC), the out-of-plane deformation of composite plates with different hybrid modes during the impact process can be analyzed. The out-of-plane displacement contour diagrams for the rebound case of three typical hybrid modes are provided below, as shown in Figure 3.

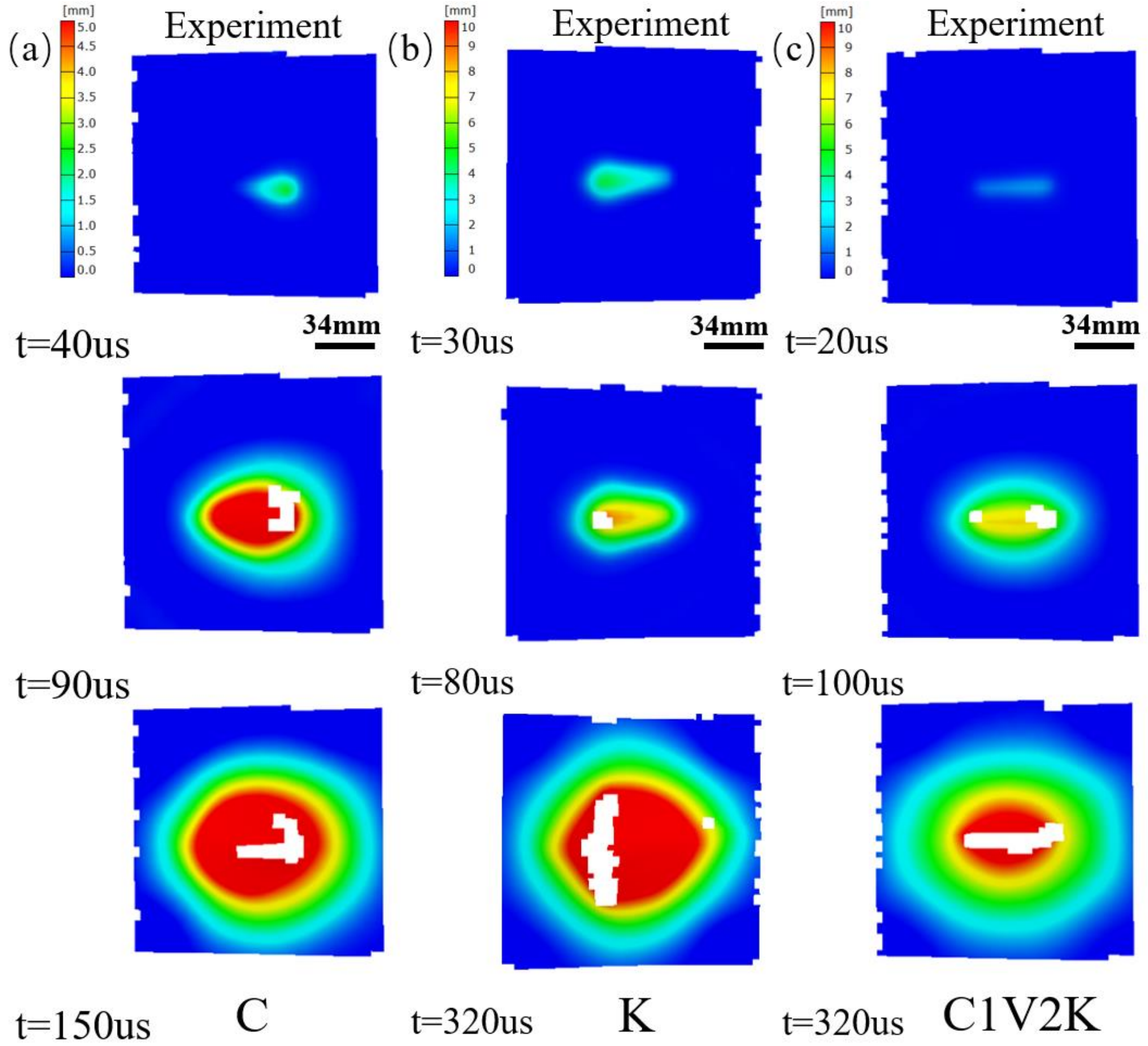

Figure 3 –Contour diagrams of out-of-plane displacements for three sets of typical hybrid modes under rebound conditions((a) C;(b) K;(c) C1V2K).

To investigate the failure modes of composite plates under different hybrid configurations during high-velocity impact, the impact region was observed at the ballistic terminal velocity. The damage morphology of the impact region for the five hybrid modes are presented in Figure 4.

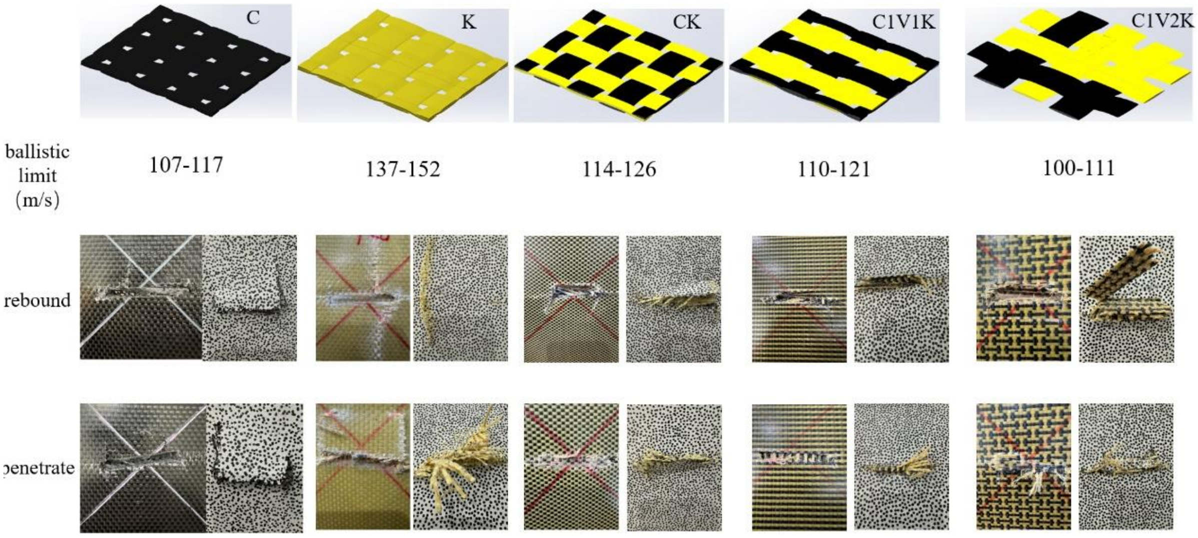

Figure 4 –The damage morphology of the impact region for the five hybrid modes.

Firstly, under all test conditions, the impact surfaces showed varying degrees of matrix collapse and fiber shear damage, with surface markings resembling the end face of the titanium alloy bullet. Tensile damage to the fiber bundles was observed on the impact side, where fibers were pulled out and delamination occurred. During the impact process, when the bullet contacts the composite plate, a compressive shear coupling failure mode occurs around the contact surface and extends through the thickness of the plate. Tensile failure, dominated by a tensile shear coupling failure mode, occurs around the impact area on the impact side, leading to delamination.

Compared to the K-plate, the C-plate better maintained its braided structure post-impact, without exhibiting a looser state, and the other hybrid configurations also demonstrated attributes similar to the C-plate. Due to the introduction of Kevlar, longer matrix damage cracks appeared on both the front and back of the impact surfaces of the plates, except for the C-plates.

3.2 C-scan result

To compare the internal damage of the five series of plates after impact, delamination within the plates was detected using the ultrasonic C-scan technique. The C-scan results of the composite plates under rebound conditions are shown in Figure 5. Different colors in the center area represent delamination at various depths within the plates. Due to the complex weave structure and interfaces within the woven composites, which can interfere with ultrasonic detection, the results are used for qualitative comparative analyses.

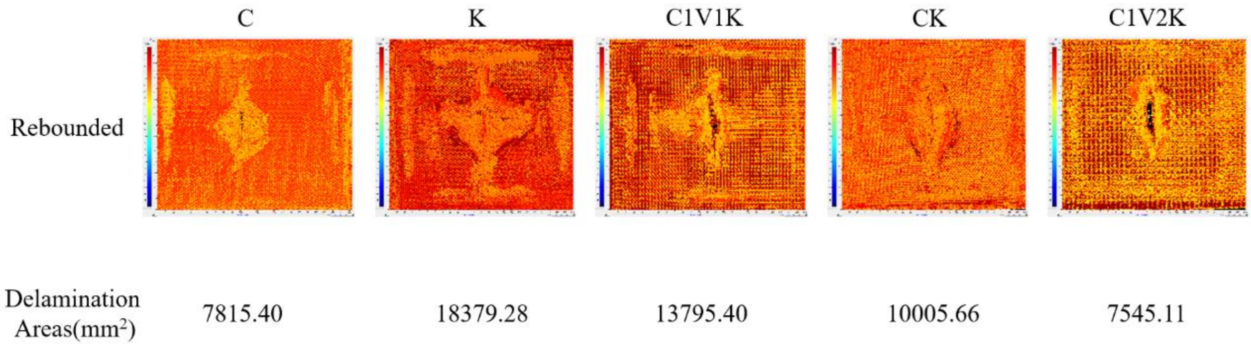

Figure 5 –C-scan results and delamination area under rebound conditions.

The results indicate that the damage area within the target plates not penetrated by the bullet is larger compared to those penetrated by the bullet. This is due to the greater magnitude and longer duration of deformation in the non-penetrated plates, allowing damage to propagate more extensively from the center towards the periphery. When the bullet penetrates the target plate, it carries residual kinetic energy through the plate, converting a significant portion of this energy into the necessary force for fiber fracture, resulting in a more concentrated damage area within the penetrated plates.

Furthermore, higher Kevlar content in the material leads to larger delamination areas. This is attributed to the lower axial modulus of elasticity of Kevlar, which induces greater deformation. According to Dang et al. [20], the introduction of Kevlar enhances mode-I interlaminar fracture toughness. Under rebound conditions, a majority of impact energy is absorbed by delamination and fiber fracture damages.

Contact Author Email Address

E-mail: 949940498wh@mail.nwpu.edu.cn

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