Research progress in advanced polymer matrix composites for armor protection systems

J L Xu, Y W Chen, R H Wang, F Q Li, A Y Liu, H Z Wei, D Y Wang and S H Li
Shandong Non-metallic Materials Institute, JiNan 250031, China

Email: cywat53@sina.com

Abstract. With the changes of modern warfare modes and the development of missiles and weapons, the battlefield survivability of military vehicles is facing severe challenges. Vehicles must have high protection performance and better mobility. However, both of them are contradictory each other. The advanced resin-based composites has excellent mechanical properties and strong designability, and is one of the main technical means to solve the above problems, but it also encounters a bottleneck. In view of these situations, this paper summarizes the development of advanced composites in recent years, and discusses in detail the protection mechanism of advanced composite materials, material selection and manufacturing processes, and the latest developments and future application trends of advanced composite materials for armor protection systems.

1. Introduction
In recent years, advanced resin-based bullet-proof composite materials have been extensively used to meet the needs of modern high-tech wars. Bulletproof composite materials refer to a class of composite materials designed and manufactured mainly to block the penetration of bullets, shrapnel, and jets. Their functional characteristics are very different from structural composite materials. Its preparation process is simple, convenient, and low cost. This composite can achieve the purpose of reducing weight and greatly improving the bulletproof performance. With the dual functions of bearing capacity (structure) and bulletproof (function). It is the primary choice material for new bulletproof armors [1-3]. This article summarizes the development of advanced composite materials in recent years, and discusses in detail the protection mechanism, material selection and manufacturing process of innovative composite materials, and the latest progress and future application trends of advanced composite materials for armor protection systems.

2. Bulletproof Mechanism and Material Selection of Advanced Composites in Armor Protection System

2.1. Bulletproof mechanism of advanced composite materials
The projectile was passed through the following stages of destruction when advanced composite components was penetrated [4-7].

(1) Tensile failure stage. At this stage, the ballistic fiber was deformed by stretching, and part of the kinetic energy of the projectile was converted into the fiber's fracture energy.
(2) Shear failure stage. Laminated by the projectile's penetration, the laminate was cut into "push plugs" of fine particles along the thickness direction. This shear failure absorbed most of the kinetic energy of the projectile.

(3) Delamination. The impact load perpendicular to the surface of the laminate generated a stress wave. The stress wave is propagated along the axial and longitudinal directions of the impacted fiber, and then is propagated to the intersecting fiber at the fiber intersection. The composite material transmitted and absorbed energy in this way. But this process was inhibited to some extent by the matrix resin.

(4) Melt failure. For UHMWPE fibers, the melting temperature is low (about 138 °C). When the laminate was penetrated, heat was generated due to friction. When the temperature exceeded the melting point of the UHMWPE fibers, the fibers were begun to melt and caused fiber into breakage.

According to the above-mentioned several stages of destruction, the protection mechanism of the advanced composite material in the armor protection system is as follows. When the projectile penetrates, the panel is first strike, and the panel's high strength, high modulus, and high compression strength are used to destroy the projectile. It reduces the speed of the projectile, increasing the area of action between the projectile and the armor, and at the same time, the damaged ceramic and the projectile wear each other to prevent further penetration of the projectile; then the composite back plate with the good impact performance and deformation ability is used to absorb the projectile. The residual energy of the body and the broken ceramics to prevent the projectile from penetrating the back plate, thereby achieving the purpose of protection. Bulletproof composite material structure is shown in figure 1.

![Figure 1. Schematic diagram of armored composite structure protection.](image)

2.2. Materials selection and Molding processes of advanced composite materials
The ballistic fiber material used in armor protection system mainly includes glass fiber, aramide fiber, ultra-high molecular weight polyethylene fiber, carbon fiber, PBO and M5 fiber, and mixed fibers of the above-mentioned fibers. Various fibers are woven in 2D, 3D, and no Weft orthogonal and mixed fiber weaving. The basic materials used mainly include epoxy resin, polyest resin, modified phenolic resin and vinyl resin. The main molding methods include hot pressing and RTM. Due to the characteristics of large-scale arms weaponry, the molding process of armored composite materials is mainly low-pressure and mass-forming. The main molding processes include hot pressing, autoclave molding, and RTM process. Among them, the composite material RTM process is to place the fiber or fabric preforms / performed in a closed mold, and then directly inject the resin matrix, and finally obtain a near-net-size composite material parts/parted with excellent comprehensive properties.
Compared with the traditional hot press forming and autoclave forming technology, the RTM process can reduce the manufacturing cost by about 40%. In order to further increase production speed, improve product quality and reduce product manufacturing costs, a series of improvements have been made based on the RTM process, and vacuum-assisted transfer molding (VARTM or VARI), thermal expansion resin transfer molding (TERTM), and resin film have been developed. Infiltration molding (RFI), continuous resin transfer molding (CRTM), co-injection transfer molding (RIRM), and Seeman composite resin permeation molding (SCRIMP), etc. [8-11]. Vacuum-assisted transfer molds (VARTM or VARI) in these derivative technologies is particularly suitable for preparing armor composites. figure 2 displays the common materials and main molding methods of advanced composite materials for armor structures.

![Figure 2. Common materials and main molding methods of advanced composite materials for armored structures.](image)

3. Application progress of advanced composite materials for armor protection systems

This article reviews the research on advanced composite materials for armor protection systems in recent years including the simulation analysis, fiber fabric form and ply design, fiber characteristics and mechanical properties, target plate thickness and boundary effects. The armor system is summarized with composite materials.

3.1. Ballistic simulation designs and analysis

GU X et al. [12] Derived a unidirectional composite viscoelastic damage constitutive relationship and established a finite element analysis model for high-speed impact damage of composite laminates based on the macro-microscopic structure of fiber-reinforced composite materials. Using this model, the ballistic performance and damage characteristics of composite laminates under high-speed impact of different shapes of projectiles are deeply studied, and the influence of related parameters on impact damage is discussed.

Hu N et al. [13] studied the damage characteristics of composite laminates under high-speed impact, and analyzed the impact of three different thicknesses of Kevlar fiber laminates and UHMWPE
laminates on three types of projectiles: cylinder, sphere, and cube through finite element simulation. Deformation and failure under the action, three main modes of overall deformation and failure of the laminated plate were obtained, and the results were compared with the experimental phenomena to clarify the relationship between the initial kinetic energy of the projectile and the overall mode of deformation and failure of the laminated plate. The results show that for UHMWPE materials, the energy absorption when the projectile velocity is at the boundary between the overall bending deformation zone and the tensile layered damage is about half the energy absorption at the ballistic limit, and the energy absorption of the Kevlar fiber will exceed half of the ballistic limit energy absorption. When the laminate is impacted by a cylinder or cube, the maximum energy absorption will occur at the ballistic limit, and the maximum energy absorption of the sphere occurs when the projectile speed is greater than the ballistic limit.

Zhang J et al. [14] designed a new type of explosive reaction armor intercepting high-speed long-barreled armor-piercing projectile (referred to as long-barreled ammunition) with a ring-shaped charge structure as the basic structure. The simulation of the ring-shaped explosive forming structure disturbing the penetration process of the tungsten alloy long rod projectile is also analyzed. The results show that the explosive shaped penetrating body of the ring shaped charge structure has higher defensive performance, the effective penetration depth of the long-barrel bullet is reduced by 32.5%, and the crater length is increased by 10.4% compared with the linear charge structure. Fracture and yaw of the long-barreled elastic rod under complete interference; the simulation results agree well with the experimental results.

Jia B et al. [15] simulated the forward impact of cone-shaped projectiles on fiber-reinforced composite laminates, and analyzed the relationship between the initial velocity and the residual velocity of the laminates under different impact velocities at different impact speeds, and the equivalent stress contour and failure of the laminate Feature clouds. The results show that when the thickness of the single-layer board is kept constant, increasing the number of layers of the laminate can significantly enhance the elastic properties of the laminate; the composite laminates undergo shear failure directly under high-speed impact, and reach first under low-speed impact. A certain degree of deflection then occurs, and the failure mode is fiber tensile failure.

Xin S [16] conducted a systematic numerical simulation of the ballistic performance of fiber-reinforced resin-based composites. A dynamic progressive damage constitutive model for fiber-reinforced resin-based composites is proposed.

Xu Y et al. [17] studied the effect of sandwich materials on the anti-elastic properties of 'sandwich' composite armor by using the Lagrange algorithm in the explicit nonlinear dynamic analysis software LS-DYNA using numerical simulation methods. The process of composite armor plates combined different sandwich materials penetrated by an armored cylindrical projectile were simulated using Three-dimensional numerical simulation. The results demonstrate that the sandwich material can greatly reduce the mass of armor plates of the same volume, and at the same time greatly improve the anti-elastic performance of the composite armor. Among the 9 target plate combinations designed, the titanium alloy sandwich composite armor shows superior anti-elastic performance.

Zhang M [18] carried out researches on the influence of fragment speed, fragment shape, and target plate thickness on its elastic performance based on the finite element simulation. The effects of initial fragmentation velocity, aspect ratio and the incident angle on the effective penetration depth and ballistic depth of the composite target were also studied. At the same time, the incident angle of the shape of the crater and the target surface stress distribution were also analyzed.

The Clemson University Joint Army Research Laboratory and other institutions used traditional finite element methods to perform numerical analysis of the Kevlar KM2 ballistic fiber felt to determine the material's penetration resistance and the overall flexural deformation failure response to impact. The team's Grujicic [19] and others further optimized and upgraded the ballistic impact / explosion protection calculation analysis model of plain woven Kevlar fiber-reinforced polymer matrix composites.
Italy Cassino and University of South Lazio Sorrentino et al. [20] made Kevlar29 plain weave felt and thermosetting resin into laminates, and carried out Walker numerical model prediction and ballistic performance test on the prepared composite armor.

Sabadin G et al. [21] Studied the composite armor structure of a new type of ceramic and ultra-high molecular weight polyethylene composites, and used ANSYS-Autody to use both mesh and meshless methods for the projectile characteristics, deformation, debris and The fracture of the anti-ballistic armor was compared with the test. The results show that the theoretical predictions agree well with the experimental results.

3.2. Fiber fabric forms and ply design
He Y [22] used S-glass fiber, UHMWPE fiber, para-aramid 1414 fiber and heterocyclic ammid fiber as reinforcement materials, and used hot pressing to prepare high-performance fiber-reinforced resin-based composite armor plate including orthogonal UD structure and woven structure (2D plain weave and 3D angular connection Lock). The results show that the UD structure has the best bulletproof performance, followed by the 3D angle interlock structure and the 2D plain weave structure.

The results of Zhang D T et al. [23] showed that UHMWPE fiber composites using orthogonal unidirectional weftless (UD) structures have higher ballistic ultimate speed and energy absorption capabilities than 2D plain weave and 3D orthogonal structural composites.

The results of research by Aswani et al. [24] shows that the composite armor using 3D woven aramid fiber is superior to the composite armor plate with 2D plain weave.

Boyd S [25] of Sandia National Laboratory in the United States studied the effect of twisting on impact resistance of elastic aramid fiber yarns and measured the Euler shear wave velocity induced by the impact using a high-speed camera. The results show that the Euler shear wave speed increases with the number of twisted fiber yarn, which means higher ballistic performance. Therefore, the use of twisted fiber yarn in the ballistic fiber felt can improve the ballistic performance of the material.

Research by Karthikey-an K et al. [26] found that [0/90] orthogonal laminate structure has better ballistic performance in UD structure laminate design.

3.3. Fiber properties and mechanical properties
Jiao Y et al. [27] studied the ballistic performance of UHMWPE fibers, S glass fibers, aramid 1414 fibers, and heterocyclic aramid fibers reinforced polyolefin and water-based polyurethane resins, which were prepared by hot pressing using orthogonal unidirectional weft-free composite armor plates. The results show that the ballistic performance of UHMWPE is positively related to the strength and modulus of the fiber. The ballistic performance of the four fibers from high to low is UHMWPE, heterocyclic aramid fiber, aramid 1414 fiber and S-glass fiber.

Tuan L C et al. [28] Studied the effect of yarn fineness and Young's modulus on ballistic woven fabric's ballistic performance. The results of the study show that the yarn fineness had no significant effect on plain weave fabric, and Young's modulus had a complex effect on the ballistic performance of the fabric. Zhou Y et al. [29] also studied the effect of yarn grip on the ballistic performance of ultra-high molecular weight polyethylene felts, and clarified the feasibility of effectively enhancing friction between yarns by creating a new type of felt structure.

3.4. Composite target thickness
Chen C et al. [30] established a theoretical calculation model for the ballistic limit and residual velocity of a medium-thickness UHMWPE fiber-reinforced composite laminate based on a three-stage penetration mechanism. Reddy P R S et al. [31] used E-glass fiber reinforced phenolic resin as the back plate of armored composite structure. The study finds that energy absorption and laminate thickness have a non-linear relationship, and the deformation of the projectile mainly depends on the thickness of the target plate. Nguyen L H et al. [32] studied the ballistic performance of ultra-high molecular weight polyethylene composite boards of different thicknesses against two caliber fragments. Studies show that as the thickness of the target increases, the sample exhibits two stages of
penetration. The first stage is the initial shear punching, the penetration occurs during fiber shear, and the target does not flex. The second stage is the projection, and the sublayer breaks off the target plate and undergoes large flexion and penetration during the fiber is stretched.

Impact of boundary effects

Zhang C et al. [33] established a model for predicting equivalent elastic and strength properties of braided composites, quasi-static tensile and compression damage behaviors of two-dimensional and triaxial braided composites, and a meso-scale finite element simulation method, and studied the boundary effects of braided composites including formation mechanism and its effect on equivalent elastic properties and strength.

Luo S et al. [34] established a finite element analysis model of high-speed impact damage of fiber reinforced composite laminates based on the three-dimensional viscoelastic constitutive relationship of composites. The following conclusions were obtained. The damage area of the laminate without stress on the four sides of the boundary is the largest. The damage area of the laminate is the second with two opposite surfaces having stress, and the damage area of the one-sided and three-sided laminates with stress is the smallest. When the boundary stress increases and the impact velocity does not change, the residual velocity is basically unchanged, and the damage area increases first and then decreases; when the impact velocity increases and the boundary stress is constant, the residual velocity increases linearly and the damage area increases first and then decreases.

4. Research on the application trend of advanced composite materials in armor protection systems

4.1. Application of Shear Thickening Fluid in high-speed ballistic resistance

Shear Thickening Fluid (STF) is currently used in the field of human protection, but its high-speed ballistic resistance has also attracted researchers' attention. Recently, researchers have researched STF in the field of high-speed ballistic resistance. Wang T et al. [35,36] prepared STF, and then combined it with two-dimensional ultra-high molecular weight polyethylene (UHMWPE) fabric by padding to prepare STF/UHMWPE composites. The results show that the UD cloth STF composite two-dimensional UHMWPE fabric target sample has a maximum diameter reduction of 37.68% and a depression depth reduction of 10.13% compared to the pure UD cloth target sample. The UD cloth STF/UHMWPE composite target sample has the best high-speed impact resistance. Then it explored the effect of 2D and 3D fabric structure on the high-speed impact properties of STF/ultra-high molecular weight polyethylene (UHMWPE) composites, and used 2D UHMWPE fabric and 3D UHMWPE fabric to STF to prepare STF/UHMWPE composite materials were combined with UD cloth to prepare three sets of target samples. The experimental results show that STF/UHMWPE (2D) composites perform better in high-speed impact experiments, and the ability of the composites to absorb energy in the radial direction is stronger than in the longitudinal direction. The results of research by Shukgai Y et al. [37] shows that the use of STF infiltration of multilayer Kevlar composites can also improve high-speed impact performance. Sen S et al. [38] used a coupled Eulerian–Lagrangian (CEL) method to simulate STF-Kevlar for the problem that the existing numerical simulation of STF aramid fiber composites could not be further studied in terms of deformation and failure. For composite materials, Kevlar yarn uses a Lagrangian membrane element, and STF is embedded in the Eulerian grid. Simulations consider different projectiles, impact speeds, and shear rate and viscosity changes of STF. The projectile response characteristics of STF have been well demonstrated during the research. The above simulations and studies on high-speed resistance have shown that if the thickening liquid can be combined with materials or structural forms that produce high shear strain such as fibers, flexible porous materials, ceramic particles, etc., it can be expected to be used in armor protection system.
4.2. Application of nanomaterials in advanced composite materials for armor protection systems

The application of nanocomposites in armor protection systems has been further studied in recent years. For example, nano-modification of aramid fiber or nano-filling in its composite material will also improve the ballistic resistance. Sodano H A et al. [39] enhanced interfacial strength by growing vertical ZnO nanowires on the surface of Kevlar fibers. The interfacial strength of the fiber is 96.9% higher than that of bare fiber, and the peak load of the pull-out test is increased by 6.5 times. Nanowires strengthen the pull-out performance of Kevlar fibers, which in turn improves the ballistic impact protection level of the material. Manero A et al. [40] studied the effect of nanoparticle fillers on Kevlar 29 impact-resistant composites, and performed V50 ballistics on abrasive carbon fibers and Kevlar 29 fiber composites filled with carbon nanotubes and core-shell rubber particles test. The results show that the nano-core-shell rubber particle filler is effective for energy absorption during impact due to cavitation, and also significantly improves ballistic performance.

The US Army Engineering Research and Development Center [41] studied the energy dissipation and high strain rate dynamic response of carbon nanotube-loaded E-GF composites. They grew carbon nanotubes on E-GF felts, then combined them with resin to form composite materials. Tests on the mechanical and ballistic properties of the composites show that the carbon nanotube-loaded composites have a 106% increase in specific absorption energy at high strain rates, a 64.3% increase in energy density dissipation after 5 cycles at a quasi-static strain rate, and a V50 value Increased 11.1%.

4.3. Research on Bulletproof Application of Negative Poisson's Ratio Honeycomb Sandwich

Negative Poisson's ratio materials and structures have special mechanical properties, and they undergo lateral contraction (expansion) under uniaxial pressure (tension). It has advantages over traditional materials in terms of shear bearing capacity, fracture resistance, energy absorption capacity, and crush resistance, so negative Poisson's ratio materials have been widely used in protective equipment, aviation, navigation, and defense engineering fields.

Jiang X [42] studied the process of the bullet penetrating the double-arrow honeycomb sandwich panel and the hexagonal honeycomb sandwich panel, and determined that the core of the sandwich panel played a major energy absorption role in the bullet penetration process. The results show that the anti-penetration performance of the double-arrow honeycomb sandwich panel is significantly better than that of the hexagonal honeycomb sandwich panel. The reason may be that the double-arrow honeycomb sandwich panel can better transfer the bullet force to the part away from the contact with the bullet when it is subjected to the tensile deformation of the hole wall. And the double arrow honeycomb cell has a negative Poisson's ratio effect, which makes the double arrow honeycomb cell material gather near the contact part with the bullet, which effectively reduces the bullet force. Yin G et al. [43] established a recessed hexagonal negative Poisson's ratio honeycomb material model with density gradient. Analyzed and compared the uniform negative Poisson's ratio honeycomb material and gradient negative Poisson's ratio honeycomb material under different in-plane impact velocities, deformation mode, dynamic response and energy absorption characteristics. Studies have shown that the dynamic response and energy absorption capacity of gradient negative Poisson's ratio honeycomb materials are affected by gradients, cell concave angles, and impact velocities. Negative Poisson's ratio honeycomb with density gradient Materials has good application prospects for structural protection. Qin W [44] carried out a detailed parameterization study of a concave honeycomb sandwich structure with negative Poisson's ratio properties. Through a large number of numerical calculations, the panel thickness, relative core density, and core thickness of the sandwich structure were systematically analyzed, Cell internal angle, cell size, and horizontal and vertical placement of the intermediate core affect the anti-penetration performance of the sandwich structure. The concave honeycomb sandwich structure shows more obvious negative Poisson feature in the bullet impact area, and its anti-penetration ability is higher than that of regular hexagonal honeycomb and square honeycomb sandwich structures.
5. Conclusions
In the application progress of advanced composite materials in armor protection systems, the following studies have been carried out in recent years.

1) The effects of projectile shape, target plate thickness, and material properties on elastic performance are studied using simulation design methods. Simulation design has become an indispensable research method for composite armor protection systems.

2) Further deepening the fiber fabric form and ply design in ballistic resistant composites, fiber characteristics and mechanical properties, composite target thickness, boundary effects and other influencing factors on the anti-elastic performance of armored system composites, some in Influential factors that are difficult to consider under test conditions are increasingly aided by simulation or virtual test methods.

Research on the application of advanced composite materials in armor protection systems has shown the following new trends, and will soon be applied in armor protection systems.

1) The Shear Thickening Fluid is expected to be applied to armor protection systems through further technological development.

2) Further application of the nano-materials is studied deeply in ballistic resistance. The application forms of nano-composites are mainly nano-modification of fibers or nano-filling in composite materials.

3) According to the energy absorption characteristics of negative Poisson's ratio honeycomb, some researchers have carried out research on the energy absorption effect of honeycomb sandwiches with negative Poisson's ratio structure in armor protection systems, which is expected to be gradually applied to armor protection systems.

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