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МАТЕРИАЛИ ЗА БАЛИСТИЧНА ЗАЩИТА

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BALLISTIC PROTECTION MATERIALS

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Ballistic vests are composed of particular high performance clothing. They could be reinforced by one or two armor panels according to the protection level and are designed to resist to attacks intended to upper parts of the body to save lives of its wearers. The resistance behavior of ballistic body armor depends on several factors related to the ballistic fabric properties. The type of fabric, its thickness, its structure, its strength and strain, and the type of the employed resin are the most important factors. In this paper, the factors influencing the ballistic performances of soft armor panel and hard armor panel are presented. It also reports the various methods developed by the researchers to improve the performance of ballistic materials.

Keywords: Ballistic materials, Kevlar fiber, UHMWPE fiber, ballistic impact, shear thickening fluid

Introduction

A bulletproof vest or body armor vest is an equipment that avails absorbing the ball's impact and reduces or stops the projectile's penetration to the torso. According to the American National Institute of Justice (NIJ) standard body armor is extensively classified into two categories, namely, hard panel and soft panel. The soft panel should preserve the wearer against projectiles whose velocity could go up to 500 m/s. They are considered for lower NIJ levels (II-A, II, and III-A). The hard armor was constructed to resist projectile velocity of more than 500 m/s when worn in conjunction with a soft armor. It has to guarantee high protection NIJ levels (III and IV).

Different materials have been used to protect the user of the ballistic vest according to the threat degree of attacking weapons. These materials are made as layered composites. Hard panels are principally made of metal, composite or ceramic plates. Moreover, the hard panel could be made with various combinations such as ceramics/composites, ceramics/metal, composites/metal and ceramics/ composites/ metal. These combinations guarantee a considerable resistance to crushing against sharp forces and high degree of attacking weapons. However, the resulting body armors are heavy (more than 10 kg), prohibitive, and increase the thermophysiological discomfort on the wearer. Figure 1 illustrates an example of the combination of a hard panel. The projectile hitting a hard panel is remarkably deformed. This act causes the fragmentation of fragile hard protection and generates consequently a risk for the wearer. The function of the soft panel then is absorbing the remaining energy after the striking action.

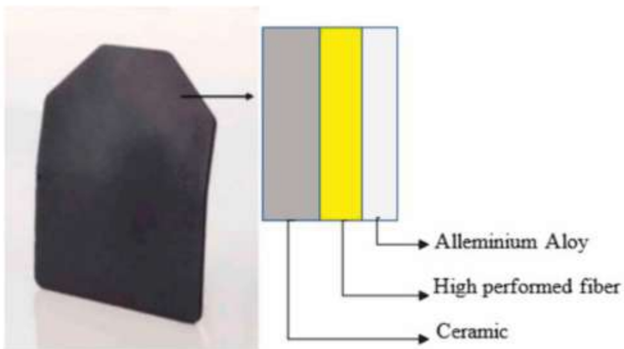

Figure 1. Example of hard panel composition (ceramic/ composite/metal)

The idea of using textile materials in bulletproof vests arose from the fact that some textiles can absorb large amounts of energy due to their high modulus of elasticity, low density, and high tenacity. Today, there is a growing interest in strong and lightweight materials for new developments of ballistic protection. To assure protecting effect, soft ballistic panels are composed of 20–50 layers of woven or unidirectional fabrics, made from high performance fibers. Nevertheless, the panels remain massive and heavy enough to restrict the wearer's movement.

Fibrous products for ballistic protection

There are different types of fibers used for ballistic applications such as mineral, organic, and natural fibers.

<u>Mineral fibers</u>

Carbon fiber

Carbon fibers are generally obtained by two types of precursors, namely, PAN precursors and pitch precursors. High resistance (HR) filaments of 7 μm of diameter, as well as intermediate modulus (IM) filaments, are thus obtained. To obtain high modulus (HM) or very high modulus (VHM) filaments (5.5 µm in diameter), an additional graphitization step around 3000°C under argon is necessary. This graphitization leads to a reorientation of the hexagonal networks and increases the stiffness of the fibers. Carbon fiber is used in ballistic material, thanks to its excellent mechanical properties (Table 1).

Fiber	Density (g/cm3)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
HTA carbon	1,8	3400	238	1.4
IMS carbon	1,8	5400	295	1.7
S_2 glass	2,46	4890	86.9	5.7
E-glass	2,58	3445	72,3	4,8
C-glass	2,52	3310	68,9	4,8
Basalt	2,6–2,7	2800–3100	80–90	2,6–2,7

Table 1. Physical and mechanical properties of some mineral fibers.

Glass fiber

Glass fiber having low cost production is the most widely used reinforcement in fields such as construction, boating and non-structural aeronautical applications. In addition, it has an excellent ballistic performance. The principal advantages of glass fibers are high tensile strength, high chemical resistance, and excellent insulating properties. The disadvantages are relatively low tensile modulus and high density (among the commercial fibers), sensitivity to abrasion during handling, relatively low fatigue resistance, and high hardness. Table 2 presents physical and mechanical properties of different types of glass fibers. According to these characteristics, grade S2 is recommended for ballistic applications.

Basalt fiber

Basalt fiber is obtained from the fusion of the volcanic rock of the same name. The raw material is easily accessible and almost in unlimited quantities. Several publications have appeared in recent years documenting the importance of basalt fiber in protective clothes. Table 2 presents the physical and mechanical properties of this high performance fiber. In the armor protection field, basalt fiber has excellent performances. In addition, laminates reinforced with basalt fibers have indeed mechanical properties equivalent to those of composites reinforced with glass fibers or even superior.

Organic fiber

Aramid fiber

Aramid fiber is the most common material used for protective vests. It is an aromatic polyamide containing cyclic aromatic elements and amide group, namely, phenyl group, which is responsible for the high performance properties as shown in Figure 2. The linear structure of the polymer chains is also responsible for these properties because they can form easily strong intermolecular bonds. Aramid fibers have unique properties that set them apart from other fibers. Aramid fiber tensile strength and modulus are significantly higher than those of earlier organic fibers while fiber elongation is lower. They can be woven on fabric looms more easily than brittle fibers such as glass, carbon, or ceramic. First-generation aramids came as breakthrough materials with the Nomex® made by DuPont as early as 1961. A much higher tenacity and modulus fiber was developed and commercialized, also by DuPont, under the trade name Kevlar® in 1971. Another aramid Twaron®, similar to Kevlar®, appeared on the market toward the end of the 1980s by Teijin.

Polyethylene fiber

Polyethylene polymer requires gel spinning procedure for its formation as a ballistic-resistant material It is widely known as ultra-high molecular weight polyethylene (UHMWPE). This fiber has extremely linear molecular chains, resulting in very high parallel orientation and crystallinity. This family of fibers includes the Dyneema® products from DSM and the Spectra® products from Honeywell. The mechanical characteristics of the most common type of UHMWPE fibers are presented in Table 2.

PBO fiber

PBO is the abbreviation of the para-phenylene benzobis oxazole fiber. It is made by the Toyobo Company (Osaka, Japan) under the trademark Zylon®. It has interesting performance in both mechanical properties and resistance to environmental effects such as heat, moisture, abrasion, and seawater corrosion.

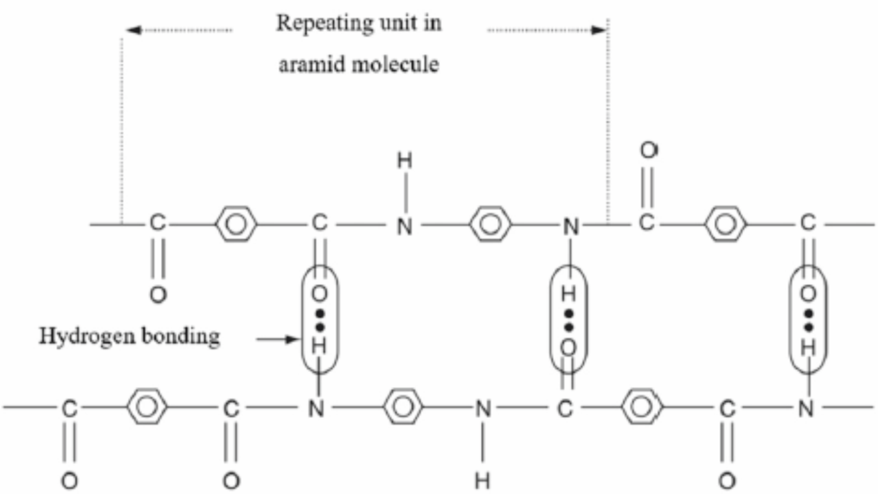

Figure 2. Molecular structure of aramid fiber (Kevlar 49)

Table 2. Physical and mechanical properties of some organic fibers

Fiber	Density (g/m^3)	Tensile strength (MPa)	Young's modulus (GPa)	Strain to failure (%)
Kevlar	1.43–1.47	2965–3300	70–113	2.6–4.2
Nomex	1.38	330–630	140	22
Technora	1.39	3400	72	4.3
Twaron	1.44	2400–3600	70–110	3.6
Dyneema	0,97	3600	110	3.5
Spectra	0,97	3400	117	2.7–3.6
PBO	1.54–1.65	5800	180–270	2.5–3.5

It is promised to replace today's aramids and can absorb nearly twice the energy per unit areal density than both Kevlar and Spectra fibers but costs several times as much as aramid or polyethylene. Moreover, PBOs provide a vest with equivalent protection to aramid vests at half the thickness. However, PBO has been faced problem from vest manufacturing market due to performance decline at aging.

Natural fibers

Lately, natural fibers have gained interest in the ballistic application for several reasons. First, they are environment friendly, which means that they are biodegradable. The modulus– weight ratio of some natural fibers is greater than that of E-glass fibers, which means that they can be very competitive with E-glass fibers in stiffnesscritical designs.

Jute fiber

The jute fiber is extracted from the stem of the jute plant. This natural fiber presents a range of density 1.30– 1.45 g.cm3 and tensile strength between 393 and 800 MPa, which makes it suitable to replace synthetic fibers in polymer composites. The ballistic tests revealed that the jute fabric composite has a relatively similar performance to the Kevlar.

Curaua fiber

Curaua fibers are extracted from the leaves of the curaua plant. The mechanical tests showed that the curaua/ epoxy composite present good ballistic performance with a depth penetration lower than that of aramid fabric.

Ramie fiber

Ramie is a natural fiber that exhibits a high strength when wet. They present ballistic similar performance comparing to Kevlar but at high temperatures, natural fibers start to degrade. The degradation leads to deterioration of mechanical properties.

Fabric structures used in ballistic applications

Soft ballistic panels are made from numerous layers of the unidirectional fabrics (UD), bidirectional fabrics (2D), triaxial fabrics (3D), braided fabrics, and nonwoven fabrics.

Unidirectional fabric (UD)

The unidirectional fabric is the extensively used structure for the ballistic applications. It is a non-woven structure composed of unidirectional bonded layers. The UD fabrics are produced by placing warp and weft fibers at right angles (at 0° and 90°) on the top of each other and then sticking them by using polyethylene film as shown in Figure 3.

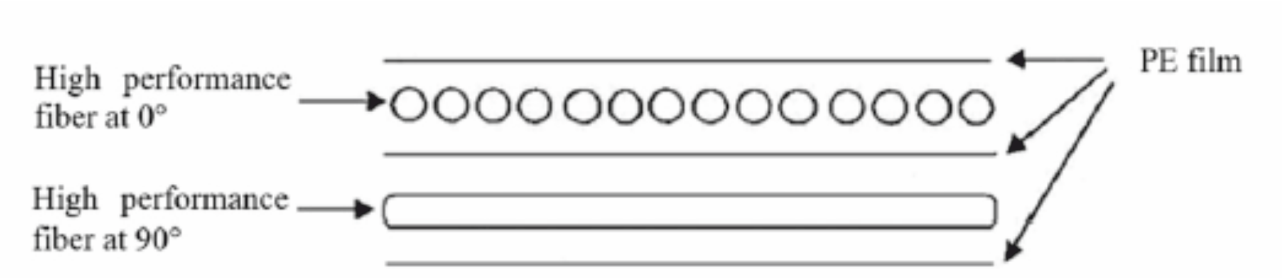

Figure 3. UD fabric structure formed by placing the yarns at 0° and 90° and sticking them using polyethylene (PE) film

A UD layer of fabric could contain two and even more layers of fibers. The obtained layers are laminated into a soft or a hard panel. Compared to woven fabrics, in the UD ones the fibers are totally straight without interlacement points. After bullet impact, the fibers respond directly to absorb and to propagate the weave stress. The unidirectional structure absorbs around 12.5–16.5% more energy than woven fabric panels for the unit panel weight [1]. Moreover, because of the intersection point in woven fabrics, the projectile energy is restricted to be dissipated fast. In fact, because of the absence of crimped yarn in UD fabrics, the longitudinal strain wave travels more faster.

Bidirectional fabrics (2D)

Bidirectional woven fabric is the traditional and most used structure for soft body armor. In addition to material characteristics, the weave structure has a significant influence on ballistic performance. The plain weave presents the highest impact resistance followed by 3/1 Twill, 2/2 Twill and Satin as shown in Figure 4. In fact, the bullet passes more easily through more fabric layer as the bullet does not spend its energy breaking the yarns.

Triaxial fabric (3D)

Triaxial woven fabrics (3D) have been widely applied in ballistic protection. Interlock angle and orthogonal weave architectures shown in Figure 5 are the most widely used weave structures in ballistic protection.

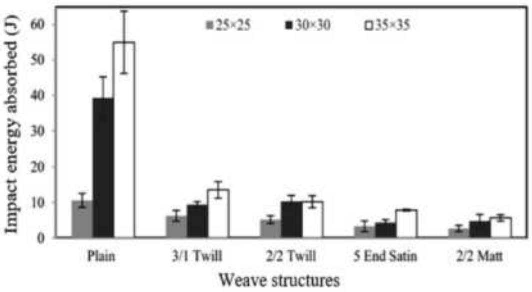

Figure 4. Impact of weave on energy absorption

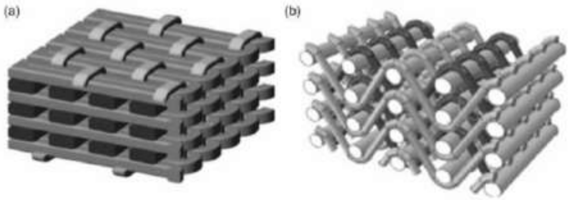

Figure 5. 3D woven structures: (a) orthogonal weave and (b) interlock angle weave

In the literature, it was proven that 3D woven fabrics have high impact resistance and high damage tolerance under low-velocity impact. Another advantage of the use of 3D woven fabrics their formability and moldability without the need of cutting or sewing. Moreover, the presence of Z-oriented yarns in 3D fabrics enhances in-plane properties due to the bias yarn layers so that could be the solution for the delamination problem in 2D and UD fabrics.

Polymer-matrix used in ballistic applications

Because of their lightweight, flexibility, and mechanical performance, the cited high-performance fibers are exploited as reinforcement in polymer–matrix composites for body armor application. To more enhance the protection level of the ballistic body armor, the choice of the appropriate matrix is crucial. In a composite material, the main role of the matrix is to distribute the forces between the fibers. However, it also governs its thermal and chemical resistance and plays an important role in its impact resistance. The matrix consists of a polymer resin to which fillers and additives are added. Two main categories of resins can be distinguished: thermosets and thermoplastics.

Types of resin

Thermosetting resin

Thermosetting resins are the most widely used in structural composites. Generally associated with long fibers, they are liquid or viscous liquids and crosslink under the thermally activated action of a catalyst and a hardener. The transformation is irreversible and forms an infusible and insoluble product. Currently, the main thermosetting resins are polyesters, phenolics, and epoxies. The most used matrix is epoxy for its high stiffness, high stress at break, and low elongation at break. This has the effect of promoting the transfer of load on the fibers leading to high mechanical properties. For the same type of fiber, the higher the toughness of the resin, the more difficult it is for delamination to propagate and the higher the residual strength of the material after the impact as shown in Table 3. However, the high rigidity of this resin makes it very little tenacious and therefore sensitive to crack propagation during

Table 3. Properties of the epoxy resins

Property	922 resin	914 resin	924 resin	920 resin
Tensile strength (MPa)	56	47.7	65	34.9
Young's modulus (GPa)	4.05	3.9	3.8	3.76
Tensile strain (%)	1.7	1.4	2.4	8.41
Poisson ratio	0.38	0.41	0.41	0.39
Compression strength (MPa)	196	180	175	290
Toughness (J/m^2)	51	103	150	541
T_g (°C)	—	190	190	107

impact. To overcome this problem, other types of resins have been considered like thermoplastic resins.

Thermoplastic resins

Thermoplastic resins are polymers with linear or branched chains (monodirectional or bidirectional). They are generally fusible and soluble, and this gives them the great advantage of being able to be alternately softened by heating and hardened by cooling and facilitates their molding by viscoplasticity. This transformation is also reversible, making it possible to recycle thermoplastic polymer materials. Among the thermoplastic resins used in aeronautical composites, the most common are polyether ether ketone (PEEK), polyphenyl sulfide (PPS), polyetherimide (PEI), and polyethylene (PE). PEEK is a semi-crystalline thermoplastic with very good mechanical and physical properties, making it the ultimate structural thermoplastic.

Polymer matrix fillers

Polymer nanocomposites are advanced engineering materials in which nanoparticle fillers are incorporated in a polymer matrix. The role of fillers is to modify the mechanical, physicochemical, and electrical properties of the pure matrix.

Elastomeric particles

To improve the impact resistance of organic composites, the inclusion of a ductile phase within the matrix is necessary. These are generally elastomeric particles. These particles allow energy dissipation because they present the area of stress concentrations that will boot the apparition of micro-cracks.

Nanosilica

The nanosilica particles are defined by their high specific surface area, and due to their collective agglomeration, silane coupling agents modify nanosilica surface for their successful dispersion and deagglomeration causing the formation of chemical bonds between them and organic components. The addition of nanosilica highly improves the impact damage resistance of the carbon/epoxy composite based on less damaged area and higher residual shear strength with nanosilica versus no nanosilica [2].

Carbon Nanotubes

Carbon nanotubes are considered as one of the strongest materials with a tensile strength varying from 11–63 GPa and an ultra-high Young's modulus which is more than 1 TPa. In addition, the strength of CNT/polymer interfacial bonding increases with an increase in the aspect ratio of CNT fibers, which in turn leads to a high composite stiffness. Besides, carbon nanotubes have a relative low density that guarantees better movability for the wearer of the ballistic vest.

Graphene

Graphene is material kind of carbon nanotechnology. It is known as one of the strongest materials. The monolayer graphene has a theoretical Young's modulus of 1 TPa and a strength of 125 GPa. The addition of graphene nanoplatelets improves the energy absorption by 12.88% [3].

Multilayer ballistic systems

Most armor panels are manufactured using multilayered assemblies of fabric. In a multilayer ballistic system (MBS), each layer absorbs part of the kinetic energy resulting from the ball's hitting. The goal of the multilayered system is to stop the projectile before damaging the final layer. Moreover, the multilayered system has been proven in several research studies to be effective in minimizing the effects of blunt trauma that can result in non-penetrative injuries such as bruising and bone breakage [4]. Multilayer ballistic systems are used in hard panels as well as soft panels.

Hard MBS

The hard panel is generally composed of a ceramic front layer followed by a composite material usually composed of plies of synthetic fabric made from high performance fiber (UHMWPE, Kevlar, etc.). Other kinds of hard panels use only a ductile composite material using the low-density high-performance fiber as reinforcement. Multilayered fabrics are combined together with a thermoset resin binder. After projectile impact, the ceramic plate abides the incident stresses, and this shatters the ceramic. This allows absorbing a large amount of the incident energy and spreading of the hitting load to a larger area.

It is important to mention that the choice of the suitable resin highly influences the hard panel's ballistic performance. In fact, the resin presenting high ductility absorbs more energy. A multilayered hard armor system composed of ceramic front layer followed by a PALF-reinforced epoxy composite can be made. Layers are joined by a thin layer of polyurethane (PU)-based adhesive as shown in Figure 6. Ballistic performances meet the NIJ standard for ballistic protection against a rifle with 7.62 mm caliber.

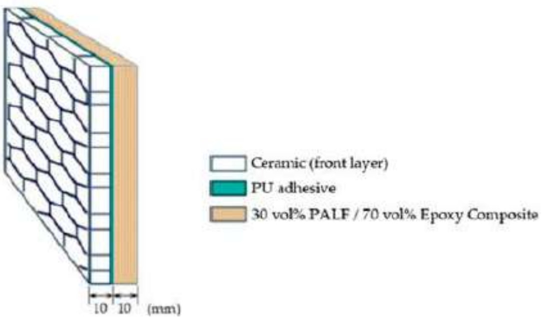

Figure 6. A schematic presentation of the hard armor system proposed in reference

Soft MBS

The soft body armor is composed of many layers of ballistic fabric joined together using different types of sewing seam without the use of a resin binder. The performance of the soft body armor is related to several parameters. The most important factors that have a noticeable influence of the soft MBS ballistic performance are the number of layers, the orientation of layers, and the hybrid composition of those layers.

Number of fabric layers and stitching

The soft ballistic panel is generally composed of a number of layers of high performance fabrics. When hitting by the projectile, the front layers are pushed because the striking velocity is beyond the ballistic limit of each of these layers.

Layer orientation

The superposing of ballistic layers to obtain a single soft panel could be done in various ways. The ply orientations highly affect the capacity of energy absorption of the multilayered soft panel. In fact, the energy absorption using oriented layers was 15% greater, depending on the number of the plies [5]. They found that the mechanical strengths of hybrid panels decrease with the increase in the orientation angle of aramid layers (Figure 6).

Failure mode of MBS under ballistic impact

The failure modes are defined as the reaction or the response of an armor panel after the ballistic impact. When a ballistic fabric is hitted

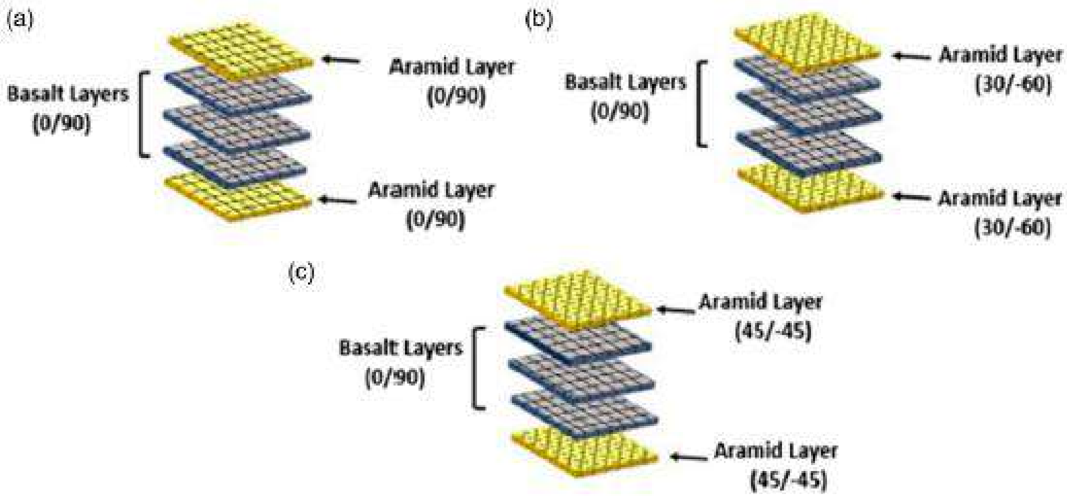

Figure 6. Schematic presentation of interply hybrid composites

by a projectile, the energy is absorbed through various mechanisms, depending on both material and projectile parameters. Generally, the MBS fails in two different ways. The first one is related to the intralayer damage. At this stage, the failure could occur at the level of fiber, yarns, the matrix, or the interface between the fiber and the matrix. The second one is related to the interlayer damage. In this stage, the failure could be defined as a delamination between the consecutive layers. These failure mode mechanisms explain the deceleration of the projectile. As shown in Figure 7, when the projectile punches the fiber, longitudinal and transverse waves propagate from the point of impact. These waves added to the displacement of the projectile lead to the progressive deformation of the target, in the form of a cone. The fibers located in the axis of the projectile are called primary fibers. They provide the direct resistance to penetration. All the other fibers inside the cone are the secondary fibers. They absorb part of the incident energy by elastic deformation

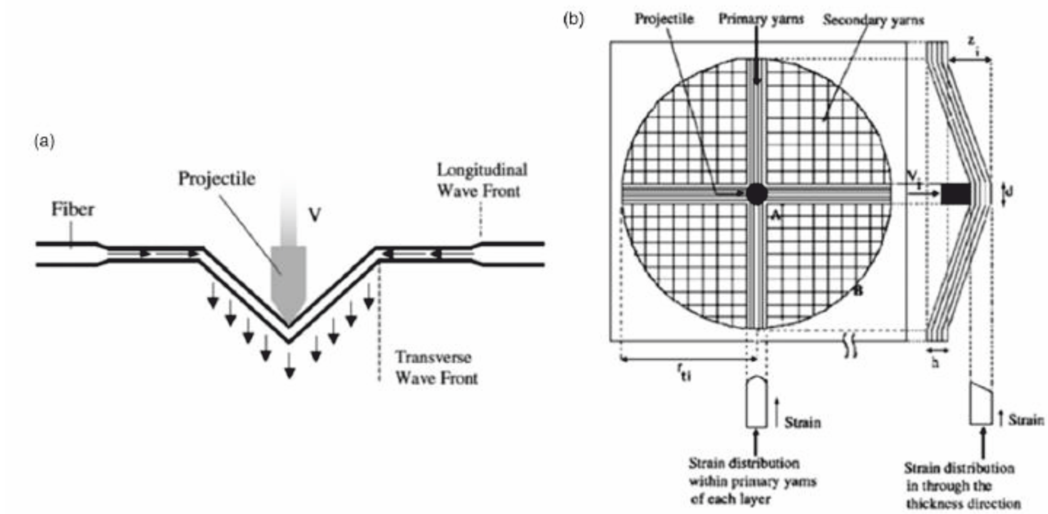

Figure 7. Longitudinal and transverse energy propagation: (a) yarn level and (b) multilayered panel level

The failure mode was identified as punching, fiber breakage, and delamination as shown in Figure 8.

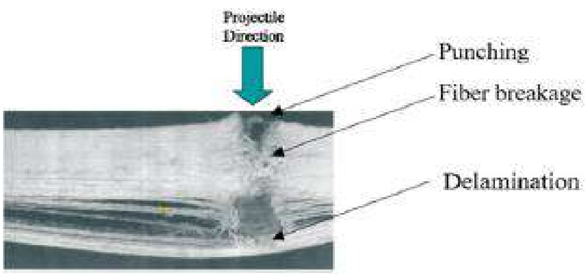

Figure 8. Failure mode in glass-reinforced polyester composite after ballistic impact

The initial penetration zone is dominated by transverse shear failure followed by ply tensile failure and then delamination. In order to enhance the MBS performance, researchers have employed the shear thickening fluid (STF) in combination with the ballistic fabrics. This method has shown promising results against low- and high-velocity impact as well as against stab and puncture [6]. Figure 9 shows that for the neat fabric, after the ballistic impact, the deterioration of the fibers is more accentuated compared to the STF-impregnated fabrics. This fiber breakage induces fiber pull-out and as a result a faster damage of ballistic panel composed by neat fabric comparing to the STF-treated samples occurs. Moreover, this phenomenon means that the force required to pull the fiber out from the STF-impregnated fabric rises and as a result the ballistic performance of Kevlar fabric is highly enhanced due to the use of STF.

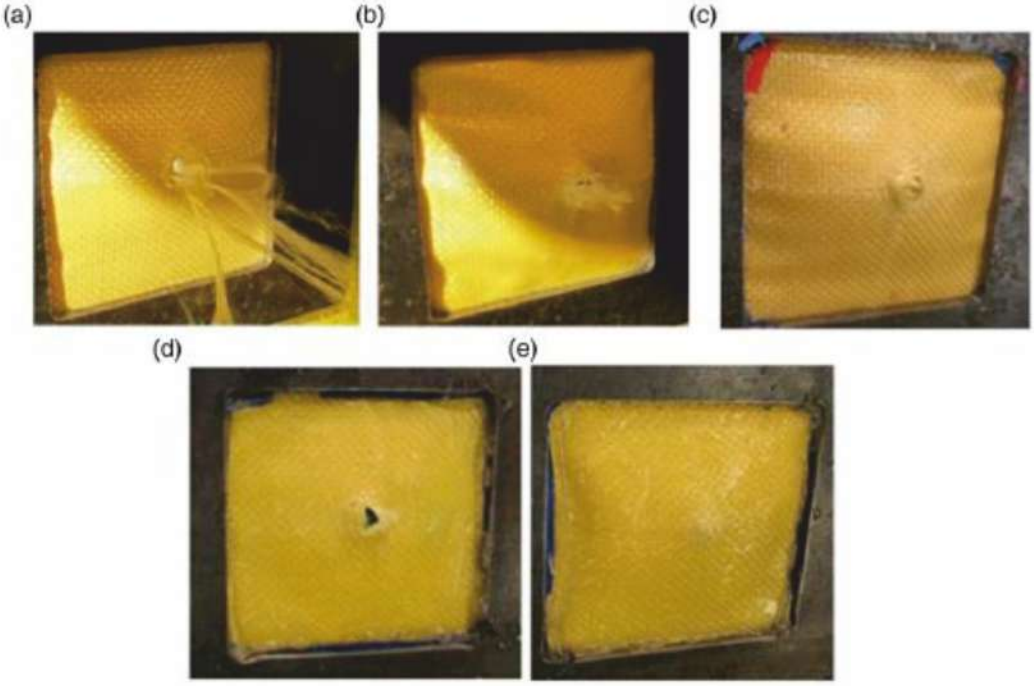

Figure 9. Ballistic test under high-velocity impact: (a) neat fabric, (b) impregnated fabric with 15 wt. % STF, (c) impregnated fabric with 25 wt. % STF, (d) impregnated fabric with 35 wt. % STF, and (e) impregnated fabric with 45 wt. % STF

Conclusion

This paper presents materials deployed in ballistic applications. Because of the absence of crimped yarns, UD fabrics are considered as the most efficient in terms of impact energy dissipation and stress weave propagation. For this reason, UD fabrics are commonly used for the design of ballistic panels. Composite material offers high protection level. Thermoset resins are used to produce hard panels while thermoplastic resin is suitable to obtain flexible and soft ballistic panel. Nanomaterials such graphene or carbon nanotubes used as fillers enhance the mechanical properties of the composite ballistic material.

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