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Original article

Overview of polymer laminates applicable to elements of light-weight ballistic shields of special purpose transport means

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ABSTRACT

The paper reviews and evaluates the possibility of using polymer fibrous composites for lightweight passive bulletproof armors for application in special-purpose means of transport. The shielding properties of the composite ballistic plates manufactured based on fibers commonly used for such applications: aramid (Kevlar, Twaron) and polyethylene ones (Spectra, Dyneema) as well as ceramic-laminate systems built based on the both above-mentioned ones have been characterized. Examples of application of lightweight, polymer ballistic laminates in armors and supplementary armors of special-purpose transport vehicles, illustrated by aircraft constructions, have been presented in accordance with literature sources and manufacturers' information.

KEYWORDS

aramid fibers, polyethylene fibers, polymeric laminates, bulletproof armor, ballistic plates

Introduction

The puncture resistance, the so-called ballistic resistance, is one of the basic characteristics of equipment exposed to shelling or impact during explosions or by fragments [*Miedzynarodowe*… 1998]. Such equipment includes ground and air transport vehicles equipped with shields to protect the life or health of persons inside them as well as the property carried against projectiles, grenades, mines or improvised bursting charges that may occur directly under or near the vehicle [Berdak 2007]. Such charges, containing a certain number of explosives, have a thin or thick shell. At the time of detonation, this shell undergoes the specified fragmentation (intended fragment sizes and their number) or undefined fragmentation (any shape of fragments and the inestimable number of fragments) [Berdak 2007]. Such moving fragments can pierce the armor, and then the armor resistance is referred to as fragmented proof [*Ballistic Resistance*… 2008; *Ballistic Resistant*… 1985; PN-V-87000:1999].

Other criteria for the selection of ballistic shields relate to determining the conditions for the effect of the kinetic energy range on the armor [*Ballistic Resistance*… 2008; *Ballistic Resistant*… 1985; PN-V-87000:1999]. Kinetic energy is one of the main parameters determining the choice of material to be used in the construction of the shield. For insignificant impact energy, e.g. for projectiles imitating shrapnels or small-caliber ammunition (with a kinetic energy of less than 700 J), the use of loosely packed (packets) fabrics made of high-strength fiber is sufficient to stop the projectile [Starczewski 1999]. A small deformation of the rear side of the shield is maintained, which is important in the production of personal protective shields, e.g. in bulletproof vests, where the weight of the ballistic shield significantly affects the mobility of the person using it.

For high-strength fiber laminates [*High-Temp…* n.d.; French 2000], for low impact speeds, impact resistance increases with increasing fiber strength and warp strength, and inversely proportionally to the modulus of elasticity. For energy in the range of 700-3000 J, some researchers [Starczewski 1999] suggest the use of laminates made of fibers with high elastic modulus and strength, in the polymer warp. The properties of the shield at the macroscopic level are then similar to those of brittle materials, since the deformation of the laminate in the direction of impact is negligible. Other researchers [Wisniewski 2002; Wisniewski and Zurowski 2001] suggest the use of fibers with the low modulus of elasticity and high relative elongation in the polymer warp. Such laminates tend to deform before the perforation occurs, so that the impact or explosion energy is partially dispersed also by giving a kinetic energy to the shield.

Composite laminates are characterized by particularly high resistance to hard steel shrapnels from artillery shells, metal barriers and fragmentation projectiles. The advantages of composites have been applied in personal protection (bulletproof vests, helmets), as outer and inner cover panels of armored vehicle cabs. The field tests have shown that polymeric composite materials that form passive armor reduce the impact of cumulative projectiles (HEATs) more significantly than passive metal armors [Starczewski 1999; Wisniewski 2002; Wisniewski and Zurowski 2001].

1. Light (soft) passive panels

Armors can be classified by construction, structure and composition. However, the mass is the most important criterion for armors. Therefore, their main division is of mass character (Fig. 1).

Ballistic composites used in light passive armor constructions consist of a matrix and a warp. The warp is mostly polymeric resins (thermoplastic, chemically cured, thermoset) as well as metals or ceramics. The matrix, in the terminology of ballistic composites, is continuous fibers, including of *rowing* type (polyethylene, nylon, carbon, polypropylene, polyamide, glass) and(or) fabrics of different weaves and directions of the afore-mentioned fibers. The type of matrix affects the strength and rigidity of the laminate, while its form – the degree of anisotropic properties (strong, weak, quasi-anisotropic).

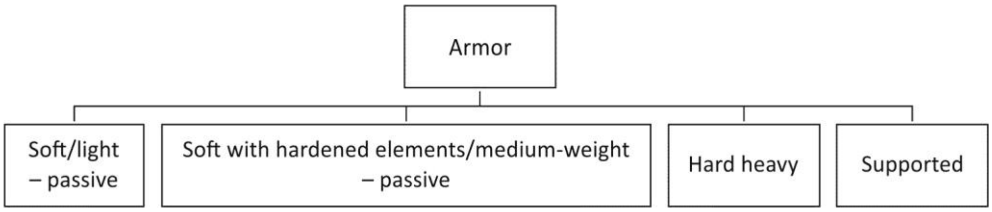


Fig. 1. Criterion for division of armors
Source: [Starczewski 1999; Wisniewski 2002; Wisniewski and Zurowski 2001].

The mechanical properties of composites depend on three basic factors: rigidity and strength of the matrix fibers; rigidity of the composite warp; adhesive strength between fibers and the warp. Selected properties of fibers applied on ballistic laminate matrices are presented in Table 1.

In the manufacture of soft (light) bulletproof armors the following types of reinforcing fibers are most commonly used (as the composite matrix):

1. Polyethylene fibers with ultra-high molecular weight produced by Allied Signal, Honeywell (Spectra fibers) and DSM (Dyneema fibers) are ultra high strength synthetic fibers that are resistant to moisture, chemicals, ultraviolet radiation, cuts and abrasions.
2. Aramid fibers produced by Du Pont (Kevlar fibers), Akzo (Twaron) and Teijin (Technora) are known for their high strength (five times the steel), flexibility and thermal resistance.

Moreover, both aramids and polyethylene fibers are used to make polymeric woven composites whose ballistic properties are obtained by the selection of fibers and weaving methods. Modern materials woven from Spectra fibers offer ballistic protection as well as “shock absorption” for protection against injury.

Advanced personal soft armor systems are also based on non-woven polymer fibrous composites, according to Shield technology (Honeywell Company), made of Spectra fibers, of Spectra Shield, Spectra Shield Plus and Spectra Flex series, as well as made of aramid fibers of Gold Shield and Gold Flex series. Compared to traditional woven ballistic materials, Shield technology offers the highest ballistic protection in the V_{50} comparative tests, higher protection against multiple impacts. Spectra light-fiber based composites also have high resistance to abrasion, chemicals and UV radiation.

Another example of the use of soft fibrous materials is the use of fullerene thread, which is several times stronger than steel. Its mono-crystalline, homogeneous structure causes that when braided it forms nets that are extremely resistant to rupture and impact. The denser the network, the more rigid it is and the greater its capability to halt projectiles. Its price and production difficulties only allow for its partial use in soft armor. Therefore, only leading companies use them in their vests.

Table 1. Properties of high strength fibers

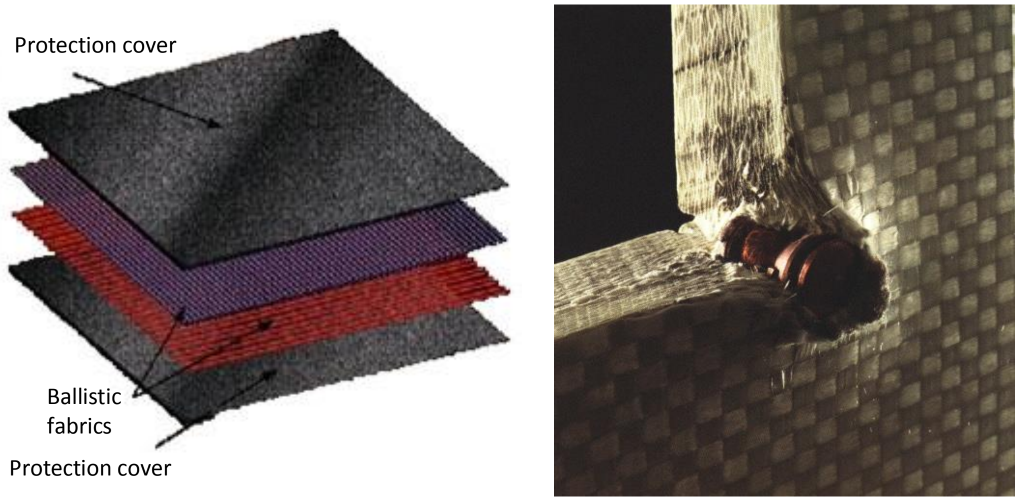
Fibers	Density ρ [g/cm^3]	Modulus of elasticity E [GPa]	Tensile strength R_m [GPa]
T700 (carbon)	1.80	228	4.83
T1000G (carbon)	1.80	297	6.38
E (glass)	2.58	72	3.45
R (glass)	2.55	85	4.33
S2 (glass)	2.49	87	4.59
Hollex (glass)	1.80	67	3.45
Kevlar 49 (aramid)	1.45	120	3.62
Kevlar 29 (aramid)	1.44	58	3.62
Twaron (aramid)	1.44	80	3.15
Twaron CT Microfilament (aramid)	1.45	124	3.15
Spectra 900 (PE)	0.97	62 ÷ 97	2.18 ÷ 2.61
Spectra 1000 (PE)	0.97	98 ÷ 113	2.95 ÷ 3.25
Spectra 2000 (PE)	0.97	113 ÷ 124	3.21 ÷ 3.51
Dyneema (PE)	0.97	87	2.70

Source: [Starczewski 1999].

In the manufacture of soft bulletproof armor, other materials are also used to a lesser extent:

1. Ceramics – hard silica baked at very high temperatures, it perfectly disperses the impact of projectiles. Its disadvantage is that its strength declines quickly after multiple hits – it crumbles and breaks. CeramTech®, GlassTech and Ceramit belong to the most popular technologies;
2. Steel – its disadvantage is the high density that limits movement and speed. Metal Gear and CarbonGear are typical examples of this type of technology;
3. Duralumin – the light alloy that is resistant to impact and tearing, slightly worse than steel and ceramics, but with significantly lower density. Duralex is the leading company that uses this alloy in its products;
4. Titanium – light metal, very tough but extremely difficult to process.

The reinforcing fiber layers, most commonly in the form of fabrics, are combined by means of a polymer warp into packets of ballistic planes (Fig. 2a). These planes offer structural consistency and strength, with the possibility of multiple impacts. The mechanism to halt the projectile consists in controlling delamination and absorption of energy (Fig. 2b). These planes also eliminate the occurrence of ricochets [PN-V-87000:1999].



a b

Fig. 2. Design (a) and idea of operation (b) of ballistic laminate

1.1. Ballistic plates made of Kevlar fibers

Du Pont's Kevlar is the best-known fiber used in personal protection systems. For the past 25 years, nearly one million Kevlar ballistic vests have been put into service and no case has been reported where such a vest has failed to satisfy a wearer.

Table 2. Ballistic tests of High-Temp plates made of Kevlar fiber

High-Temp ballistic plates made of Kevlar fiber tested as inserts for bulletproof vests according to NIJ Standard 0108.01 – Level III (the plate weight of 1.86 kg, dimensions 250 × 300 mm, ammunition 7.62 × 51 mm M80 NATO ball (7.62 × 54 R LPS))			
Shot number	Velocity [m/s]	Puncture	Deformation [mm]
1	852	no	less than 29 mm
2	854	no	
3	857	no	
4	852	no	
5	852	no	
6	846	no	
High-Temp ballistic plates made of Kevlar fiber tested as inserts for bulletproof vests accordiong to PSBD Standard – Level RF1 (the plate weight of 1.86 kg, dimensions 250 × 300 mm, ammunition 7.62 × 51 mm NATO Ball L2A2 (7.62 × 54R LPS))			
Shot number	Velocity [m/s]	Puncture	Deformation [mm]
1	849	no	13
2	843	no	6
3	845	no	11

Source: [Starczewski 1999].

To stop the high-energy rifle bullets, the vest is traditionally reinforced with a rigid insert – a ceramic plate based on a composite laminate with several layers of Kevlar material.

High-Temp ballistic plates [*High-Temp…* n.d.] are a group of lightweight composite panels made of Kevlar fiber, protecting against high-energy rifle bullets. They can be used as ballistic inserts for vests as well as vehicle armor plates in all cases where reliability is required in high temperature conditions. Table 2 shows the results of tests performed on the High-Temp ballistic plates.

1.2. Ballistic plates made of Twaron fibers [*Twaron*… n.d.]

German ballistic plates are based on para-aramid fibers with the trade name Twaron. The properties of plates forming ballistic shields depend on the parameters of the fabric from which the plate is made and on the number of fabric layers in the matrix. Depending on the required puncture resistance, the fabrics with different diameters of fibers forming the yarn and the ratio of yarn in the weft and warp are used.

Twaron CT marketed in 1991 is a high strength aramid fiber, primarily intended for impact protection. Impact resistance has been improved with respect to Twaron Standard by increasing the tensile strength and the modulus of elasticity.

Twaron CT Microfilament is a fiber with even better properties, especially energy absorption, obtained by twisting a large amount of fibers (about 1000) into yarns, which are about 50% more fibers in the yarn in relation to traditional products. An example of the effect of the increased strength on the performance may be the ballistic boundary for military helmets. In 1980, the Bundeswehr helmets had a ballistic barrier of 550 m/s (according to the V_{50} test). At the beginning of 1990, the requirements rose to 600 m/s. These were met due to the use of Twaron CT Microfilament (Fig. 3) [*Twaron*… n.d.; *Processing*… n.d.].

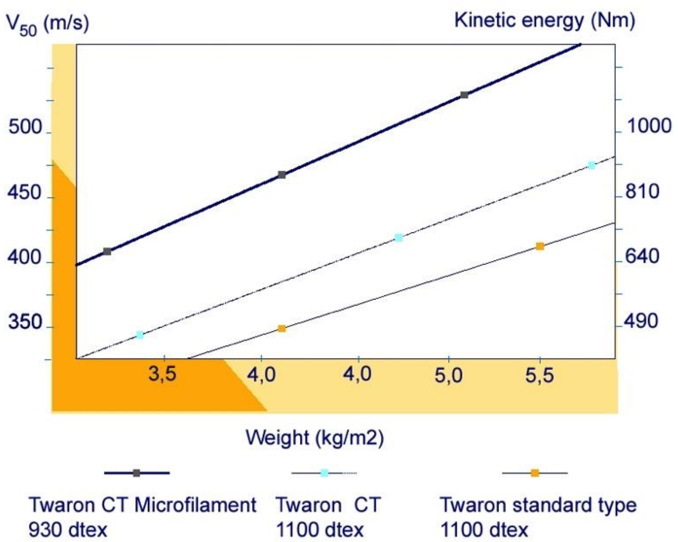


Fig. 3. Influence of change in strength on ballistic properties of Twaron fiber

Source: [Twaron… n.d.; Processing… n.d.].

Types of Twaron yarns allow for making fabrics of different weaving styles. Each of these styles is attributed to specific ballistic applications, giving the possibility of choosing the most suitable product for a threat, due to its properties, weight and cost.

High strength is associated with a unique mechanism of damaging aramid fibers. Cracking of aramid fibers does not take place via brittle fracture, as it does for glass fibers and carbon fibers. Instead, aramid fibers break through a series of micro cracking of single filaments. Such many micro cracks absorb a large portion of energy and thereby very high strength is received.

In some applications, aramid fibers can be used as surface coating of components with a core made of carbon or glass fibers. These hybrid composites combine not only the good protective properties of aramids but also the high strength and stiffness of the remaining fibers.

1.3. Polyethylene fibers Spectra [Honeywell… n.d.]

The molecular formula of this polymer is the same as ordinary polyethylene but varies in molecular weight that is from 10 to 100 times higher than of ordinary polyethylene. Ordinary polyethylene is made up of ductile hydrocarbon molecules forming short chains. While in the high-strength polyethylene, these molecules are several times longer.

What limits the use of polyethylene fibers is their tendency to creep and lose strength at high temperatures. These fibers should not be used above 150°C or in applications where the load will be applied for an extended period, even at room temperature. Polyethylene begins to lose its internal strength (about 40%) at temperatures of about 70°C. As a result, when used at elevated temperatures, polyethylene laminate should be 25% heavier than at room temperature to maintain the adequate level of strength. Their high impact resistance, however, was the cause of their increased utilization, often in combination with glass fibers. The strength of polyethylene fibers makes them easily applicable as protection against impact, e.g. helmets for motorcyclists and soldiers, aircraft covering materials.

In the case of he Spectra Shield composite technology, a thermoplastic elastomer is the composite warp. It prevents the fiber from moving and gives a high flexibility to each plate. Typically, two pre-preg layers are used, one oriented at the angle of 90° to the other, they are joined together and covered with thin sheets of polyethylene. The whole forms a single element that is produced as the basic material for the construction of shields. Honeywell proposes the following forms of ballistic polymer laminates with Spectra fibers:

1. Spectra Shield LCR – in the form of so-called “soft ballistics” for personal protection;
2. Crossing straps are protected from moisture by laminating them into thin polyethylene sheets;
3. Spectra Shield PCR – this is the pre-preg, ready for molding by pressing. It is used for hard ballistics to protect vehicles, vessels and aircrafts at a level comparable to structural armoring;

4. Spectra Shield VE – especially formed Spectra Shield LCR. This product provides ballistic protection while remaining plastic and soft. Applications primarily in personal protection.

Hard armoring, such as used for protecting the bottom of helicopters or the sides of armored personnel carriers, is made by arranging a great number of layers of crossing pre-pregs. The rigid shields are made of fibers in combination with various resins, usually thermosetting ones. In addition, they can be vulcanized, which makes them more rigid and can be used as construction elements, for example as the sides of conveyors (DERA ACAVP vehicle). More efficient armor is obtained by combining fiber-based composites with ceramic plates. They are resistant to piercing by anti-tank missiles. Table 3 shows the ballistic properties of laminates made of Spectra fibers.

Table 3. Ballistic properties of laminates made of Spectra fibers

Areal density [kg/m^2]	**Thickness [mm]**	**Level of protection according to NIJ 0108.01**	**Weapons and ammunition (caliber)**	**Projectile velocity [m/s]**
0.29	3.55	I	.22 LRVH .38 RN Lead	320 259
0.36	3.96	II	9 mm FMJ .357 Mag. JSP	358 381
0.45	5.55	IIIA	.44 Mag. SWC 9 mm FMJ	426 426
2.14	26.9	III	5.56 mm ball 30 cal sp 308 NATO FMJ	938 774 838
2.38	28.1	III+	AK47 7.62 × 39 sc 5.56 mm SS109	746 914
1.13 (1/8” armor steel)	13.4	III+	AK47 7.62 × 39 sc 5.56 mm SS109	746 914

Source: [Starczewski 1999].

1.4. Polyethylene fibers Dyneema [*High Performance*… n.d.]

Depending on the tensile strength, modulus of elasticity, laminate construction and the binder used, DSM offers the following types of ballast laminates based on Dyneema24 fibers:

1. UD-SB21, for use in bulletproof vests against ballistic ammunition, the surface density of 145 g/m^2;
2. UD-SB31, specially designed laminates against 9 mm FMJ and Magnum ammunition, the surface density of 132 g/m^2;
3. UD75-HB2, for personal protection, meeting the NIJ level III protection, and for the so-called “hard ballistic” as supplementary armor for military vehicles, the surface density of 258 g/m^2;

4. UD-HB25, designed for use in armored vehicles and helmets, the surface density of 130 g/m^2.

Special attention is paid to the properties of UD-HB25 laminates that are recommended for applications where high levels of protection and mechanical properties are required – as "hard" protection for military vehicles, helicopters and vessels (Fig. 4, Table 4).

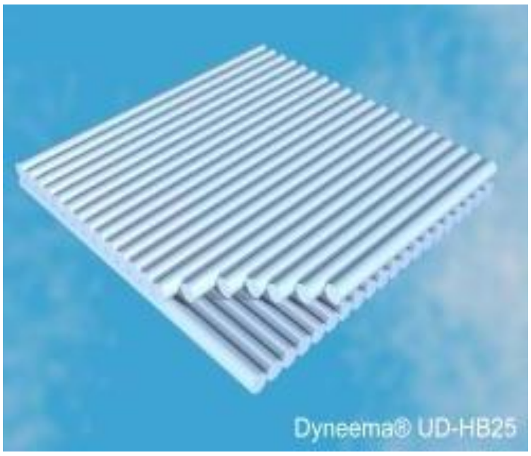


Fig. 4. Dyneema fiber laminate, surface density 130 g/m^2, protection level: steel core ammunition pistols 62 × 39 AK47 MSC; 7.62 mm NATO Ball and Dragunov rifle ammunition

Source: [High Performance… n.d.].

Table 4. Ballistic properties of laminates made of Dyneema UD-HB25 fibers

Level of protection according to NIJ 0108.01	Ammunition	Projectile weight [g]	Projectile velocity [m/s]	Required surface density [kg/m^2] / [number of layers]
II	.357 Magnum JSP	10.2	425	4.1 / 31
	9 mm FMJ	8.0	358	3.2 / 25
III-A	.44 Magnum Lead SWC Gas Checked	15.55	426	4.7 / 36
	9 mm FMJ	8.0	426	3.9 / 30
III	7.62 mm FMJ (308 Winchester)	9.7	838	18.2 / 140

Source: [High Performance… n.d.].

1.5. Ceramic-laminate systems

The compliance by the armor with he certain level of protection requirements is conditioned by its constituent elements. Armors made of laminates or combinations thereof have limited protective capabilities, i.e. max. to level III + according to NIJ or FB 6 class according to PN-EN 1522:2000.

In case of the protection above level 1 according to STANAG 4569 (against effects of anti-armor projectiles) armors are made of steel or a combination of armored steel and laminate. However, they are heavy systems. Mixed (hybrid) systems: ceramic-laminate (Fig. 5); ceramic-metal (thin armored steel or alloys of aluminum or titanium) constitute alternatives for ceramic-metal laminates. Armored steel or ceramic takes over destroying a projectile with a hard core (anti-armor projectile) by crushing the projectile (Fig. 6), while the laminate absorbs fragments and crushes.

a b

Fig. 5. Ceramic-laminate systems: a) the substrate from combination of polyethylene-aramid laminates and the ceramic cartridge in modular system; b) the substrate from combination of glass and carbon fabric laminates with the ceramic cartridge

Source: [Twaron… n.d.; High Performance… n.d.].

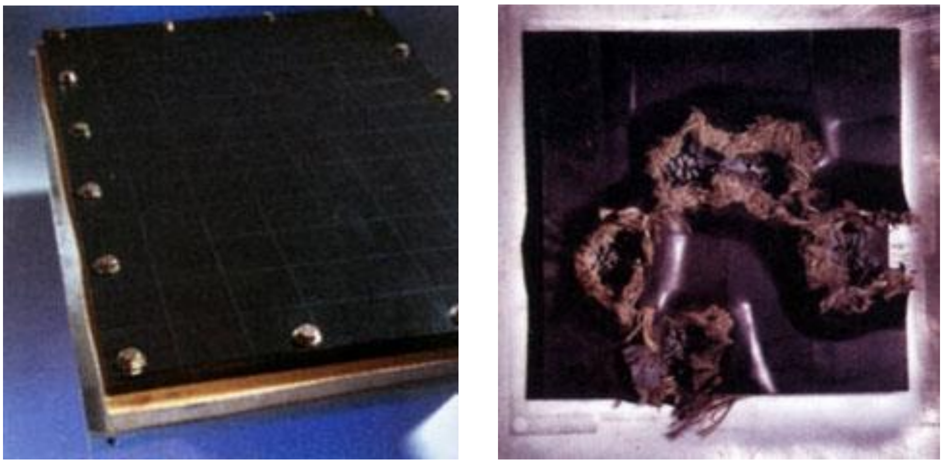


Fig. 6. Effects of firing at ceramic-laminate system with 7.62 × 51 AP bullet. The system meets the requirements of multi-point fire. Producer: Ceradyne (the USA)

Source: [Honeywell… n.d.].

The process of optimization of ceramic-laminate systems results primarily from the requirements of aviation. An ineffective increase in armor weight limits combat capabilities of helicopters and aircrafts. Moreover, the thickness of armor plates due to the existing subsystems and mechanisms is the problem in the modernized and armored constructions.

Silicon carbide (SiC) or boron carbide (B_4C) systems – the aramid or polyethylene laminate – are the most commonly used laminated-ceramic composites in the protection of helicopters exposed to anti-tank firing. Systems with corundum ceramics are 20% heavier than those with carbide ceramics. However, the cost of the former is much lower.

2. Application of ballistic laminates in transportation means

In recent years, due to the ever-increasing level of threats to crews of military transport assets, modernization has begun, in particular with regard to ground vehicles and aircrafts that participate in overseas missions. When it comes to armoring, modernization was carried out by: armoring of the existing (increasing their level of protection) and acquisition of new armored vehicles (of a certain level of protection). On the one hand, due to the high requirements for ballistic resistance [*Ballistic Resistance*… 2008; *Ballistic Resistant*… 1985; PN-V-87000:1999], on the other hand, due to the limited load capacity of the transportation means, some of them were equipped with composite armors (polymer-fibrous), mainly in the form of additional plates. The greatest advantage of such composite armors is their higher value of mass efficiency [Wisniewski 2002; Wisniewski and Zurowski 2001] in relation to steel armors. But their production and operation are more expensive than metal armor.

The analysis of helicopter armor design solutions shows that, depending on the engine power and allowable takeoff mass, larger areas or only parts of the cabin are protected. In small helicopters principally pilots' positions are protected (Fig. 7) [*High-Temp…* n.d.].

a b

Fig. 7. Ceramic-laminate modules covering seats: a) high protection level against the impact of projectiles in the range 7.62 × 51 ÷ 12.7 AP M2; b) lower protection level up to 7.62 × 51 AP
Source: [High-Temp… n.d.].

The interiors of Bell 205 (Fig. 8) and Bell 212 (Fig. 9) helicopters are protected by light laminated and ceramic modules.

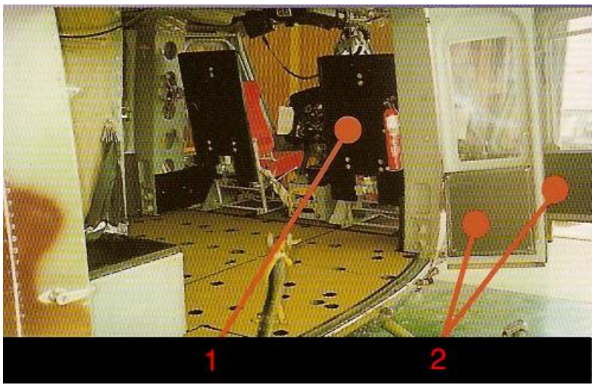


Fig. 8. The interior of the Bell 205 armored helicopter: 1 – ceramic cover of the pilot's seat; 2 – ceramic door covers. The floor is covered with laminate composite
Source: [Twaron… n.d.].

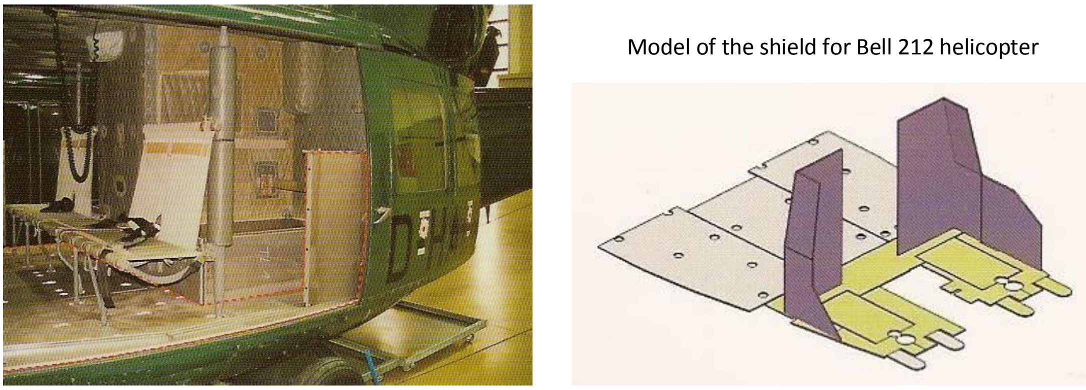


Fig. 9. Design solution for the Bell 212 helicopter against the effects of firing with 7.62 × 51 AP projectiles. A similar solution was used for Eurocopter NH 90
Source: [Twaron… n.d.].

Examples of other applications of ballistic laminates in aviation, including the Polish solution for the Sokół helicopter (Fig. 11), are shown in Figures 10-12.

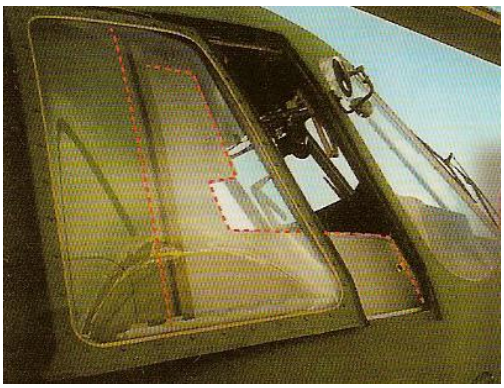


Fig. 10. Mi 8/17 helicopter, the dashed line indicates the position of the armored cover of the pilot's seat
Source: [Twaron… n.d.].

Fig. 11. Polish solution of light armor for the Sokół helicopter. Aramid laminate Lim M1 with corundum ceramics SiC
Source: [Grula 1992].

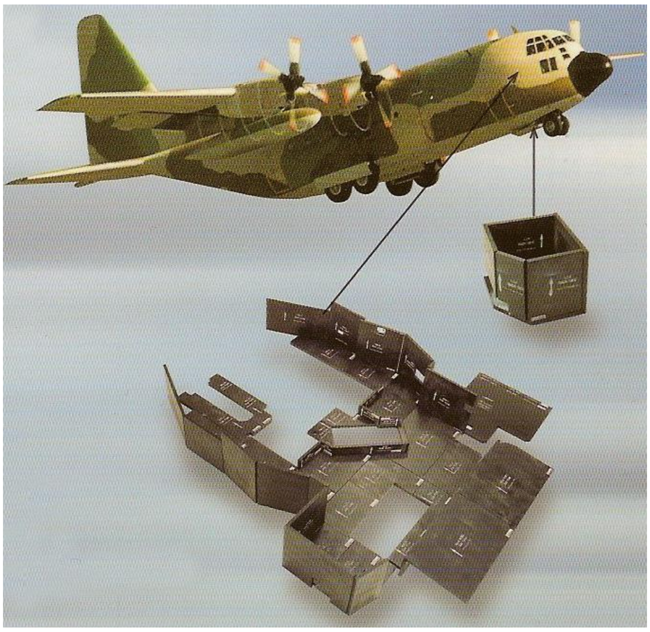


Fig. 12. View of the system of protection modules for the C-130 aircraft.
Protection level against 12.7 AP projectile. Shields against multi-point impact.
The cockpit-floor, seats and the logistic space – floor, doors, cargo space are protected
Source: [Processing… n.d.].

Conclusion

The characteristics of polymer-fibrous ballistic laminates presented in the paper constitute the guidelines for their selection on protective shield panels. These composites can serve as autonomous armor protection in their protection ranges. More often, however, they form complex systems, the so-called structural armors with gradient resistant properties to projectile impacts. Such compositions provide higher levels of protection, with a significantly reduced weight.

Most frequently light protection is designed in a mixed system. This means that ceramic-laminate plates are used wherever absolute requirements for the safety of the crews are to be satisfied. Where there is less risk, laminate systems are used, mainly to limit the effects of fragments and small arms projectiles.

The introduction of modular shielding systems reduces the cost of armoring and enables the use of the mixed protection system, easier maintenance and logistics related to transport and replacement.

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Conflict of interests

The author declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

ORCID

Michal Sliwinski – The author declared that he has no ORCID ID's

Wojciech Kucharczyk – The author declared that he has no ORCID ID's

Robert Guminski – The author declared that he has no ORCID ID's

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Biographical notes

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