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Glass fibers for impact protection systems. A review

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Abstract. This paper is a review about glass fiber fabrics used for impact protection. The authors comment on types of fabrics, tests done for pointing out the impact resistance. Many of applications refer to ballistic protection but, as one may notice, experimental studies in open literature are disperse from the point of view of parameter ranges. Many articles on the subject do not have details on materials (fabrics and adhesives) used to manufacture the protection samples and on technology for obtaining the final system of protection. Few tests are done according to national, international or military standards because of difficulties in sample manufacturing at industrial scale or the costs related to sample producing. This review could be useful for the start of a research on ballistic panels based on or including glass fiber fabrics, for making the researchers familiar to their particular failure mechanisms.

1. Introduction

High-performance fibers have a history of only about 100 years, but they offer innovative solutions for protection against impact [1, 2]. Nylon and silk fibers had been used to make body armors, but with limited efficiency. Nylon, patented by DuPont got on the market in 1939. In the 1960s, the same firm developed polyparaphenylene terephthalamide (PPTA), now known as Kevlar, a much stiffer semirigid rod molecule and produced fibers of very high crystallinity. Today, these ones and similar fibers like Twaron are essential in manufacturing individual protection systems. Other polymeric fibers are particularly designated for ballistic protection, based on ultrahigh density polyethylene ultrahigh-molecular-weight polyethylene (UHMWPE) (trade names as Dyneema, Spectra), polybenzobisoxale (PBO), polybenzobisthiazole (PBT), polybenzenimidazole (PBI) [3]. Even if glass fibers have some shortcommings, they are used for vehicle and other systems protection against ballistic impact.

Fiber tensile strength increases with decreasing fiber diameter and is limited by defects, residual stresses, and structural inhomogeneities. The risk of finding defects decreases with decreasing fiber diameter for polymeric fibers, carbon fibers, ceramic and glass fibers. Nowadays, the commercial carbon fibers range from 4 µm to 10 µm in diameter; for polymeric and most ceramic and glass fibers, diameters are in the range of 10 µm to 15 µm. Fibers processed by chemical vapor deposition, such as boron fibers, tend to have much larger diameters, typically 100-150 µm [4].

2. A short presentation of glass fibers

The manufacturing of glass fibers and fabrics is still an energy consuming sector as the glass is melt-extruded and drawn into fibers typically at 1000°C to 1200°C.

Figure 1 presents the chemical composition of different grade of glass (symbols are explained under the figure). If one analyzes the graphs of their mechanical characteristics in Figure 2, it is obvious that grade S, including S2 is recommended for ballistic applications. One may notice that glass is based on SiO_2 and Al_2O_3, the highest sum of these two ceramics being of 90% for the grade S, a glass fiber that is especially used for its mechanical resistance.

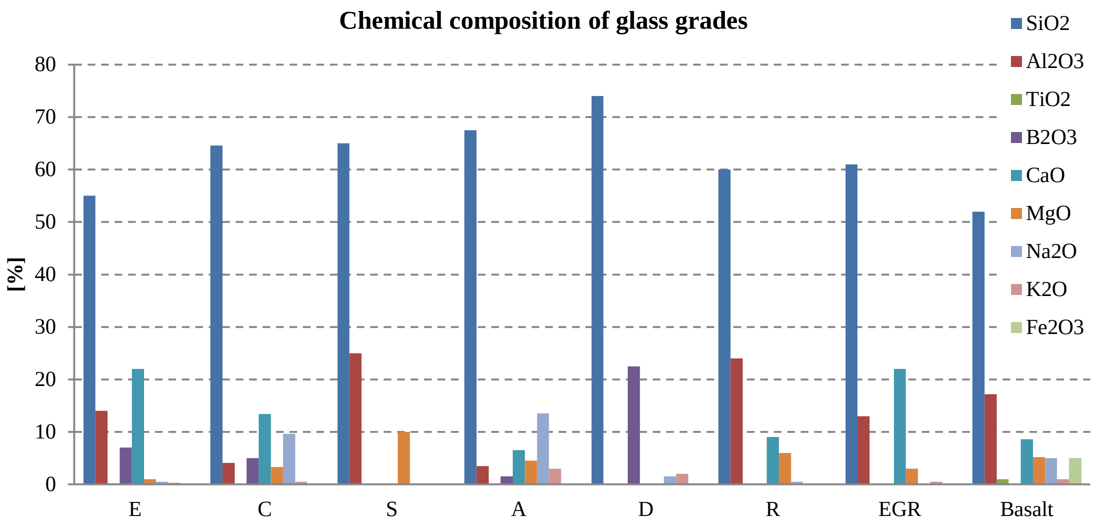


Figure 1. Chemical composition of glass grades: A - durability, high mechanical strength and high electric resistivity, C - high corrosion resistance, D - low dielectric constant, E - high mechanical strength and high electric resistivity, AR - alkali corrosion resistance, R- high strength and acid corrosion resistance S - highest tensile strength, S2- high strength, elasticity modulus and stability [5]

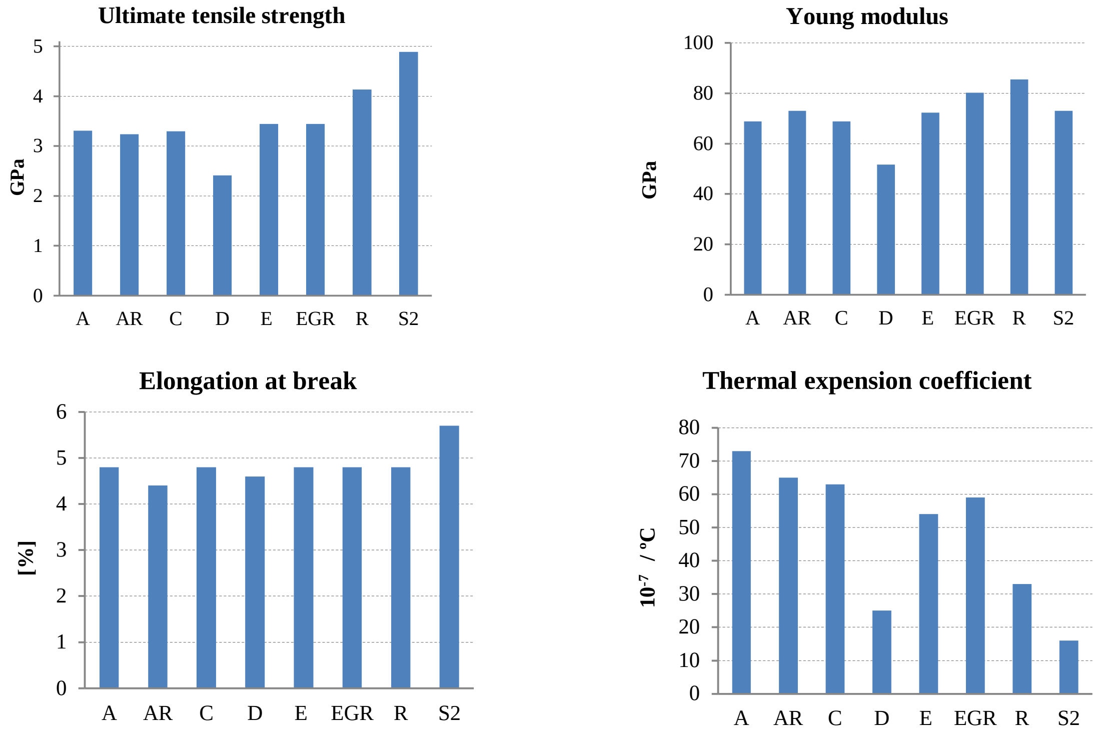


Figure 2. Characteristics of glass fibers (after [5])

Glass fibers fall into two categories: low-cost general-purpose fibers and special-purpose fibers. Over 90 % of glass fibers are general- purpose products. These fibers are known by the designation E-glass. Special-purpose fibers, which are of commercial significance in the market today, include glass fibers with high corrosion resistance (ECR-glass), high strength (S-, R-, and T E-glass), with low dielectric constants (D-glass), high-strength fibers, and pure silica or quartz fibers, which can be used at very high temperatures.

Characteristics of glass fiber fabrics (woven or not) are: higher mechanical properties in flexural strengths, a specific density between polymeric and steel fabrics, impact resistance, good mold conformability, very good wet out, low consumption of resins when producing layered composites.

3. Fabrics for protection systems

A criterion that is of high importance for impact protection structure including glass fibers is the glass fiber architecture. Studies on systems including stratified composites are done at different level: from micro level for the fibers and yarns, meso level that deal with fabrics and layers, to macro level when the simulation and experimental results are given for the entire protection structure. Recent advances in computer hardware make possible the simulation of panels under ballistic impact considering yarns and several layers [6].

Properties of composites reinforced by long fibers significantly depend on fiber nature, yarn architecture and matrix and the technology to put these together, fiber volume fraction, fiber orientation, laminate thickness. Glass fibers have high strength at low costs; carbon fibers have very high strength, stiffness and low density, aramid fibers have high strength and low density, preventing the fire spread and they are penetrable by radio waves. Polyesters are the most often matrices because they offer good properties at relatively low costs. Epoxies and polyamides have better properties, but they are expensive. Strength of composites increases by higher fiber volume fraction and fiber orientation parallel to load direction. Although glass and carbon fibers are relatively common, polymer, metal and ceramic fibers are used in specific applications, including military ones.

Rao and Farris [7] investigated the influence of twist on strength and modulus and found that fiber yarns exhibit the best tensile strength at an optimum twist angle of about 7°. In ballistics, the most common weave patterns are plain and basket weaves. Fabrics are also produced with unidirectional yarns, with a single orientation or more (two, three and four), for the latest, the angle between plies varying from [0°, 90°], [-45°, 45°] to [0°, 90°, -45°, 45°]. Cunniff [8] observed that loosely woven fabric or unbalanced weave led to poor ballistic performance.

Faur-Csukat [9] manufactured fabric composites with 55%wt fibers by manual lay-up, followed by compression. The ballistic performance of carbon-, glass-, aramid-, and polyethylene- fiber fabrics used to manufacture protection panels showed that their efficiency was as following: glass is better than aramid, which is better than or equal to ultrahigh-molecular-weight polyethylene (UHMWPE), which is better than carbon fibers.

Generally, fibers with large strain at high strain rate are better energy absorbers than those with low strain at break. [10], [11]. The fiber-matrix interface plays a critical role in managing the impact resistance. It was observed that weaker interfacial interaction resulted in higher energy absorption [12], [13] [14], but each matrix has to pass the experimental proof for being accepted, Composites with fabrics exhibit particular failure mechanisms as fiber-matrix debonding, delamination (between layers), slippage, cracking net, but also friction, favor for energy absorption.

Weave architecture also influences the ballistic performance of composites. Under the conditions investigated, the performance of basket-weave fabrics was better by about 10% than that of plain-weave fabrics. [9]. Satin and twill weaves also tended to absorb more energy than the plain weaves [15], possibly because the fiber are not loosing their strength to face the characteristic crimping in weaving. The architecture of the fabric is more important in thicker composites than in thinner composites, as the small crimp angle decreases stress concentration.

Improved ballistic performance may be obtained by using 3D woven fabrics instead of 2D woven fabrics [16] but this new architecture by 3D stitching is prone to loosen the yarns. Walter et al. [17]

analyzed results from 3D woven glass-fiber composites and observed that delamination along the weak layer is a severe shortcoming for these composites under impact at high strain rates. In general, Z-stitching increased the resistance to failure and it restricted damage to a smaller total area than that in unstitched samples. Hosur et al. [15] reported a decrease in ballistic limit in Z-stitched targets, although no explanation of this decrease was provided but it could be the fact that yarns seems to be have more space among them when stitching in such way.

Shockey et al. [18] studied single-ply Zylon fabrics and observed that absorbed energy was proportional to fabric areal density, but that ballistic effectiveness was not strongly dependent on mesh density or weave tightness. Chitrangad [19] recommended a range of 0.60 to 0.95 for the cover factor (the ratio of the area covered by the yarns to the whole area of the fabric) of fabrics for ballistic applications. Lower value characterizes fabrics too loose, but higher value induces too much bending stress in yarns, during weaving. The V_{50} of composite fabrics with higher elongation in weft yarns and lower elongation-to-break in warp yarns was greater than that of fabrics made from a single material, which may be due to the lesser influence of yarn crimp. By considering yarn crimp in modeling, Tan et al. [20] obtained more accurate results. The number of fabric plies also affects the ballistic performance (typically, there may be 18-56 plies). Shockey et al. [18] noticed an increase of the specific energy absorbed by stratified targets due to friction between layers. Also, a model designed by Ionescu et al. [41] estimated that friction reduce the residual velocity. The influence of interply distance on ballistic performance has also been investigated [8], [21]. The influence of projectile geometry becomes less important with the increased number of plies. [22] A 3D woven structure was studied in a fabric composite [23] designed to provide greater through-thickness direction reinforcement than in conventional 2D woven fabrics; this structure showed higher ballistic performance and led to fewer penetrated layers under impact.

Kolopp et al. [24] did an experimental impact study has been conducted on sandwich structures to identify and improve armor solutions for aeronautical applications: a non-perforated panel with minimal weight and back deformations. Medium-velocity impacts (120 m/s) have been conducted using a 127 g spherical projectile. Two potential choices of front skin have been identified for the sandwich structure: 3 mm thick AA5086-H111 aluminium plates and aramid stitched fabrics (8 to 18 plies). Impact tests indicate that aluminium honeycomb core associated with aluminium skins show mitigated results. However, the combination of dry fabric front skin and aluminium honeycomb show better performances than aluminium sandwiches, with a global weight decrease.

Applications of glass fiber fabrics and their composites include automotive, shipbuilding, energy generation, construction, chemical/petrochemical, nuclear, manufacturing and ballistic protection [4].

In automotive industry, the glass fiber ratio by weight is between 31% for pan floor (with polyesther matrix, firm Das, 2011) to 55% for body and door (with epoxy resin, Rocky Mountain Institute) and 69% for chassis (with epoxy resin Suzuki & Takahashi, 2005). For impact protection panels, this percentage could be higher as the end-users want a low surface density and a small thickness [25].

4. Issues related to protection system design

Figure 3 presents a flow chart in designing a new protection system, pointing out a closer coupling of researches for both material development, modeling and simulating community, resulting in significantly reduced time for development of new armor. Restricted information issues make the solutions to be punctual or only partially effective [26]. The elements of an impact protection system are not themselves new (Figure 4 presents a theoretical and general structure. [27], a similar one being also detailed in Figure 5 [16]), but the emphasis shifts from design−produce−shoot test−re-design to simulation iterations, and from designing with materials on the market to designing with materials proved to have impact resistance. The feedback loop between protection system design and material design contrasts with current practice, in which a one-way flow puts new materials on the shelf to be tried in the produce-shoot test-analysis process [26] (Figure 3).

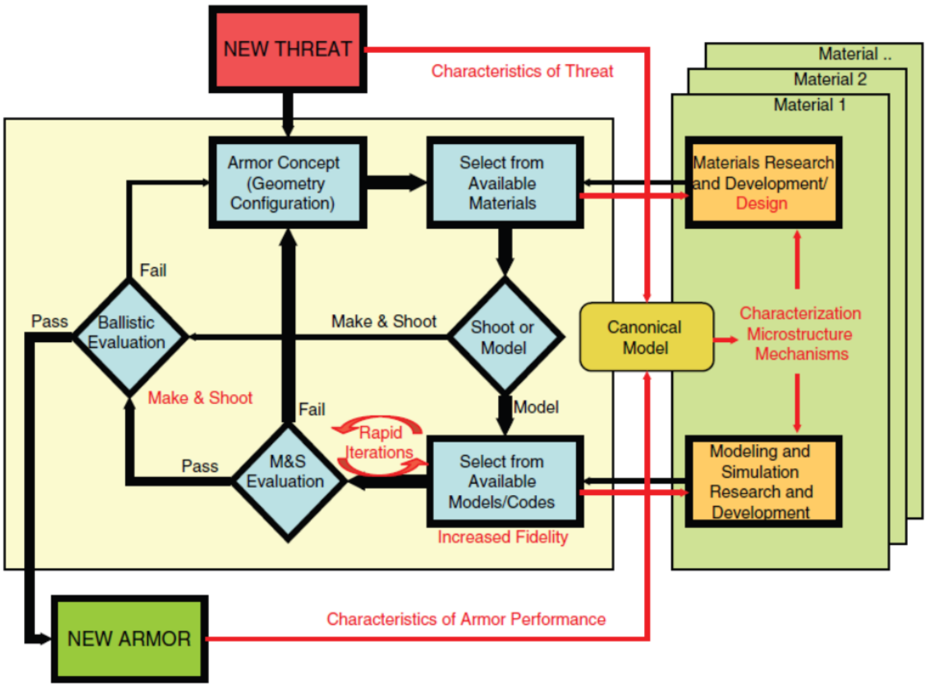


Figure 3. Flow chart for (re-)designing an armor [26]

Figure 4 presents a typical impact protection system. Medvedovski [28] pointed out that a ballistic protecting system consists of a monolithic ceramic or composite ceramic-metal plate, covered by ballistic polymeric fabrics with a high tensile strength (such as Kevlar, Twaron, Spectra, Dyneema), lining or laminated in polyethylene, placed on the back of ceramic or ceramic–metal composite, aluminum thin sheets may be as backing material. In some cases, a spall shield is attached on the front of armor.

	Material	Functions
1	Composite	Low velocity, impact abrasion protection
2	Ceramic tile	
3	Elastomer	Ballistic protection, structural integrity
4	Composite	
5	Metal mesh/Plate	Displacement attenuation
6	Fiber composite (glass, polymeric)	Fire, smoke and toxicity protection

Figure 4. An impact protection system (after [26])

Under the impact of the projectile (velocity of 700–1000 m s^{-1}), the hard ceramic pack is cracked and the residual energy is absorbed by the soft reinforced backing material that must support the post-impact fracturing of the ceramic pack and the defeated bullet. Soft covering also protects the system against possible damage associated with vibrations. Figure 5 presents a system with several of the elements from Figure 4, tested by [16].

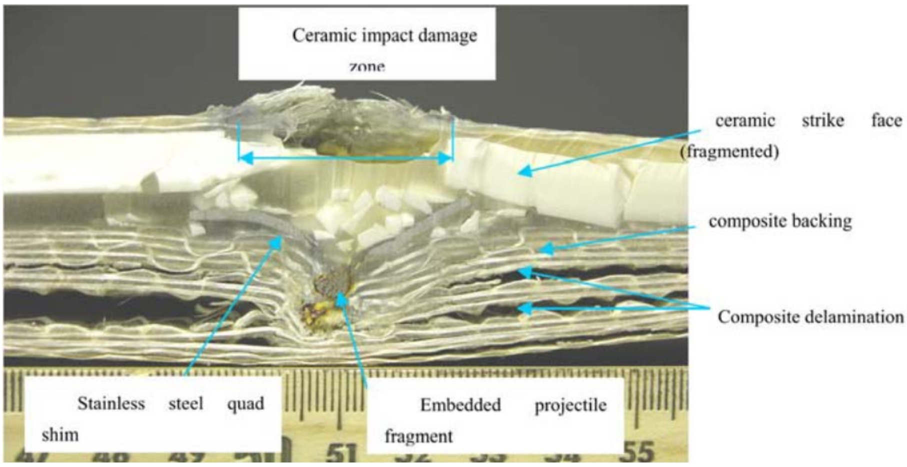


Figure 5. Water jet cross section of a vehicle armor panel, with 3D woven backing. [16] Fabric type, thickness, impact velocity projectile

The complexities of armor systems make the assessment of weight depending on the event they are designed for. What is lightweight for vehicles is extremely heavy for personnel. Thus, in assessing whether an armor system is sufficiently lightweight, one cannot look at the absolute weight of the system. Because protection systems are designated to protect a particular area [26], their weight is better described by its areal density, $\mathbf{A_d}$:

$$\mathrm{A_d} = \frac{\text{system weight}}{\text{area to be protected}} \quad \left[\mathrm{kg/m^2}\right] \tag{1}$$

But this characteristic of the system does not indicate its effectiveness. The effectiveness of two protecting systems is only assessed by comparing their performance against the same threat. The effectiveness of a given protection system is called its mass effectiveness, $\mathbf{E_m}$, the ratio of the areal density of rolled homogeneous armor (RHA), a common steel for tank armor that will stop a particular threat, to the areal density of the given protection system that will stop that same threat:

$$\mathrm{E_{m(protection\ system)}} = \frac{\mathrm{A_{d(RHA)}}}{\mathrm{A_{d(protection\ system)}}} \tag{2}$$

The mass effectiveness of the protection system indicates how effective it is against a specific threat and generally suggests whether the system may be considered lightweight— that is, the higher $\mathbf{E_m}$ value, the lighter is the weight of the system. One of the issues of any system is that $\mathbf{E_m}$ does not translate from one threat to another and only tests done.

5. Tests and failure mechanisms in glass fiber composites for ballistic protection

The densities of B_4C (2.52 g/cm^3) and SiC (3.29 g/cm^3) are less than that of Al_2O_3 (3.98 g/cm^3), but due to its easy sinterability and lower cost of raw powders, alumina is still preferred in vehicle protection, where the extra weight can be tolerated, while the lighter ceramics are now used in body armor [26].

When a projectile hits the individual fiber or yarn longitudinal and transverse waves propagate from the impact point. Most of the kinetic energy transfers from the projectile to the principal yarns (those coming directly in contact with the projectile); the orthogonal yarns, which intersect the principal yarns, absorb less energy [29] [30] [31]. The transverse deflection continuously increases until it reaches the breaking strain of fibers and causes failure. Glass fiber composites have specific failure mechanisms that could be investigated by simulation [32], [33] and post-mortem investigations: breakage of fiber bonds and yarns, yarn pull-out, remote yarn failure, wedge-through effects (hole smaller than the diameter of projectile), fibrillation and splitting of the fiber, and effects of friction between the projectile and the fabric, resin, yarns and fibers (Figure 6).

In Figure 7, the panel made of glass fibers and epoxy resign arrested the bullet well, the fiber ratio, calculated for the cross section of structure being about 20%, but technology parameters are quite severe [34].

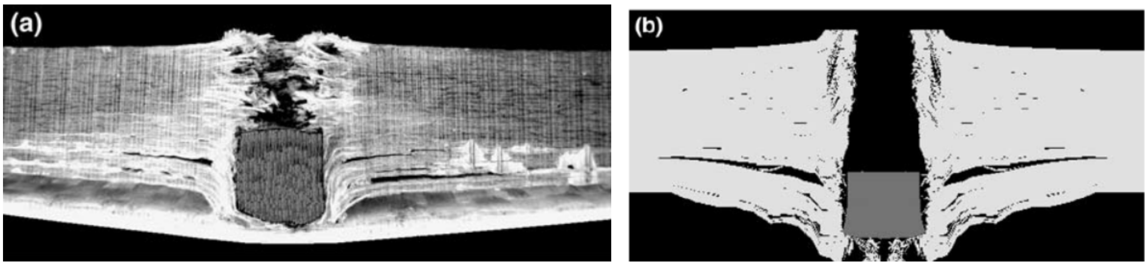


Figure 6. Experimental (a) and computational (b) results for an impact of 0.50 caliber FSP with a 25.4 mm, E-glass fiber reinforced poly-vinylester-epoxy matrix. Initial projectile velocity, 605 m/s [32]

Figure 7. Composite glass fiber + resin, thickness of 13 mm, after the impact with 9 mm FMJ at 420 m/s [34]

Ansari and Chakrabarti [35] presented experimental and numerical analysis of perforation behaviour of laminated composite reinforced with unidirectional glass fiber have been presented due to impact by 52 g blunt projectile. The influence of oblique impact on the ballistic performance of laminated target has been studied by considering four impact angles (0°, 30°, 45° and 60°) and impact velocities in between 50-500 m/s. The experimental impact tests on laminated target with fiber orientation (0°/90°/90°/0°) is performed with pneumatic gun. In general, delamination is the major cause of damage in the target plate struck by blunt projectile, normal to the target the amount of damage decreases as the impact angle increases. The delamination in the target plate occurs mostly due to matrix failure in tension or excessive stress along the thickness direction in case of normal impact whereas inter laminar stress causes maximum delamination in the target under oblique impact.

Another research of these authors remarks that for different sandwich composite plates made of glass fiber and Kevlar/epoxy laminate, sandwich composite having glass fiber laminate sandwiched in between Kevlar/epoxy offer good penetration resistance even better than that offered by single Kevlar/epoxy composite plate. The energy absorption in glass fiber composite plate is found to be more than the Kevlar/epoxy composite plate for all the incidence velocities. The energy absorption in sandwich composite plate KGK is found to be more than the other two combinations GKK and KKG and even more than that in case of Kevlar/epoxy plate of same thickness for all impact velocities. The differences in the energy absorption by sandwich composite plates KGK and KKG are 20.64 J and 138.33 J for incidence velocity of 100 m/s and 500 m/s, respectively, showing that the KGK sandwich composite serves better than the Kevlar/ epoxy as an energy absorber (here, K - Kevlar, G - glass fiber) [36].

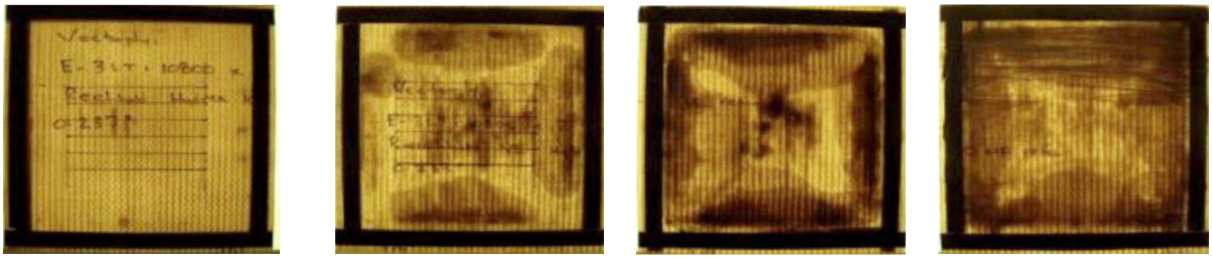
Table 1 presents several experimental works in order to point out the diversity of glass fabrics and matrixes, but also the variety of projectiles.

Table 1. Protection plate based on glass fibers.

Author(s) **Years**	Plate / pannel / Basic materials Resin	test
Herbert et al. 2007 [37]	E-glass: E_3LTi 10800, E_2LTi 7200, E_2LTi3600 vinyl ester resins and urethane	testing range of 3.08–7.53 MPa peak incident pressure
Sabet 2011 [38]	E-glass fiber reinforcement • chopped strand mat of 400 g/m^2, • plain weave, 400 g/m^2, • satin weave, 300 g/m^2, • unidirectional 300 g/m^2, • cross-ply unidirectional fiber [0°, 90°]. specimen areal density 0.4...0.9 g/cm^2	80...160 m/s 3 and 6 mm thickness smooth barrel gas gun plate 15 cm x 15 cm **projectile**: sharp tipped (30° conical head, total length of 30 mm, shank length of 15 mm, weight of 9.74 g)
Ansari 2017 [35]	unidirectional glass fiber target plate of size 140 mm × 140 mm × 3.3 mm and (0°/90°/90°/0°) by hand layup	52 g blunt projectile of diameter 19 mm fully clamped boundary condition 150-300 m/s
Armenakas 1973 [39]	glass-fiber-reinforced epoxy plates 316 S-glass fibers with 0.177 m as length, Φ123 μm; matrix epoxy was then prepared by mixing 10 g of Epon 828, 10 g of Epon 871 and 2.6 g of Epon curing agent D.	high rates of strain (30,000 in/in/min) and low rates of strain (0.0265 in./in./min to 26.5 in/in/min) The stress-strain relation of composites is linear up to failure.

Yuan [40] presented results of impact experiments for studying strength against spall and delamination in glass–fiber + epoxy resin composites. Two architectures are investigated—S2 glass woven fabrics in Cycom 4102 polyester resin matrix and a balanced 5-harness satin weave E-glass in a Ciba epoxy (LY564) matrix. The samples were impacted using an 82.5 mm bore gas-gun. The delamination strength of the plates was given as a function of the normal component of impact stress and applied shear-strain by subjecting samples to normal impact compression and combined shock compression and shear loading, respectively. The spall strengths of the two composites decreased with increasing levels of normal impact compression. Superposition of shear-strain on the normal impact compression was found to be detrimental to the spall strength. The E-glass reinforced composite was found to have higher spall strength under both normal impact compression and combined compression and shear loading as compared to the S2-glass composite. These relatively low spall strength levels of the S2-glass and the E-glass fiber reinforced composites have important implications in designing glass fiber light-weight integral armor.

Herbert et al. [37] evaluated the response of E-glass reinforced vinyl ester and urethane panels of varying structures subjected to shock loading and drop weight impact. Shock waves are created using a shock tube with a testing range of 3.08–7.53 MPa peak incident pressure (Figure 8). Drop weight impact performance was measured by energy absorbed by the samples, depth of penetration, and extent of internal damage. Glass preforms having total areal weights (4.88 and 7.32 kg/m^2) were infused with one of three types of vinyl ester and one urethane resin. Urethane panels having areal weight of 7:32 kg/m^2 performed better than similar vinyl ester resin panels. It was also found that of two materials with identical vinyl ester resins having an areal weight of 88 kg/m^2, the one with a finer glass structure consistently performed better under shock wave and drop weight impact testing.



3.08 MPa 4.54 MPa 5.72 MPa 7.12 MPa

Figure 8. Delamination of panels – 2 x 108 vinyl ester, 5.59 mm thickness [37]

Sabet et al. [38] investigated composites based on glass reinforced polyester under impact velocity of 80...160 m/s. Five different types of E-glass fiber reinforcement were used, including chopped strand mat, plain weave, satin weave, unidirectional and cross-ply unidirectional fiber reinforcements. The projectile used was a sharp tipped (30°) conical head with total length of 30 mm and shank length of 15 mm, with weight of 9.74 g. Composite plates of 150 mm x 150 mm were prepared with 3 and 6 mm thickness. Results showed higher ballistic limit velocity for 3 mm plates with cross-ply chopped strand mat reinforcement followed by unidirectional reinforcement and plain weave. Plates with satin weave and bi-directional fibers were almost at same level. The thicker specimens (6 mm), with plain weave fabrics showed better ballistic performance, followed by cross-ply unidirectional, satin weave, unidirectional and CSM reinforced plates. Dominant failure modes were: fiber tension, fiber shear failure for thin-walled and severe delamination for thick-walled plates. Plates with plain weave and cross-ply unidirectional reinforcements showed relatively higher ballistic limit velocity as compared to the other type of reinforcement. Energy absorption associated with plain weave and cross-ply unidirectional reinforcement plates has higher values (Figure 9). The overall damage area in all specimens increased towards the exit side, in the shape of a cone, some specimens showing four petals on the distal side together with sever delamination (Figure 10).

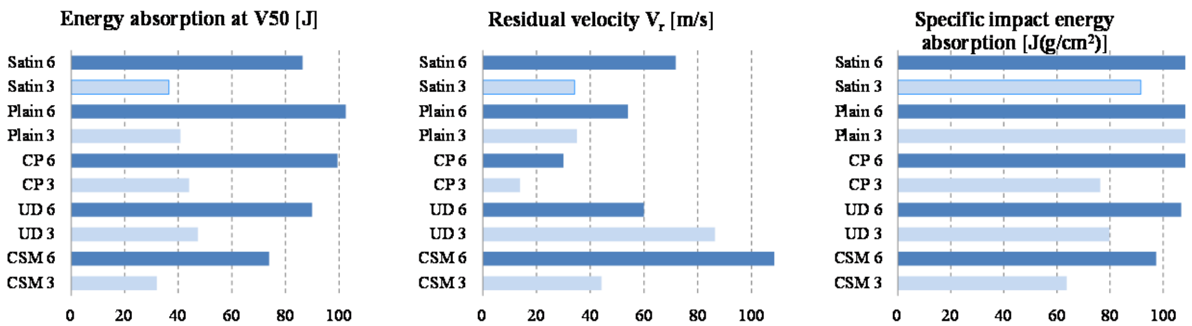
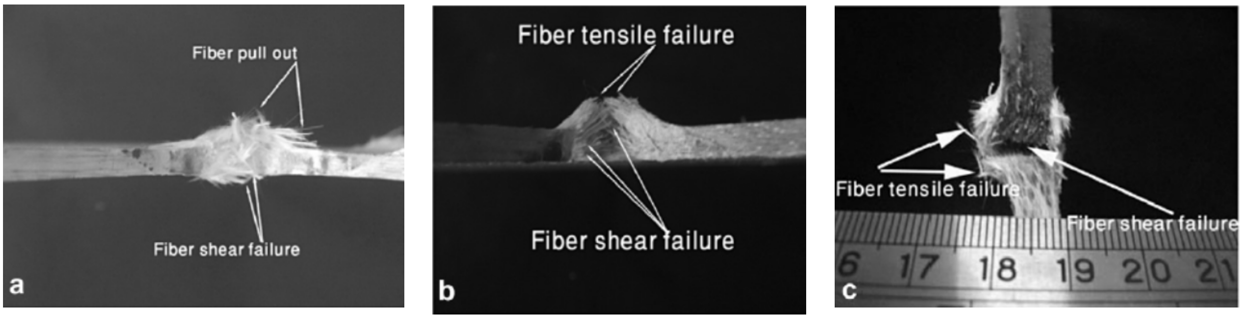


Figure 9. Characteristics of several panels obtained with different types of glass fiber and the same matrix: CSM - randomly oriented glass chopped strand of 400 g/m^2, UD - unidirectional fabric of 300 g/m^2, CP - cross ply laminate, [0°, 90°] with unidirectional fibers, Plain - a plain-woven roving cloth of 400 g/m^2, Satin - a satin cloth of 300 g/m^2, 3 - 3 mm thickness, 6 - 6 mm thickness [38]



a) chopped strand mat (CSM) b) satin c) plain weave

Figure 10. Quarter section of 3 mm thin-walled reinforced samples (95 m/s) [38]

The differences between simulation and experimental data could be qualitatively explained by the energy dissipation by friction between layers as it is pointing out in [41].

Shukla et al. [16] tested vehicle armor panels with 2D and 3D woven composite backings. The armor panels with 3D woven backing had a higher ballistic efficiency than the 2D baseline panels, with controlled delamination and fewer complete penetrations. However, due to higher complete penetrations, it is believed that the projectile was able to penetrate the backing through direct tearing of the in-plane crimped fibers, without energy absorption through delamination. The majority of the delamination within the 3D composite panels transversed the full length of the panel. Because of the uncrimped nature of the warp and weft fibers, the individual lamina effectively act as a woven net to stop penetration, and allow kinetic energy to be absorbed mainly through intralaminary delamination. The delamination severity (opening) in the 3D composite panels decreased with increasing areal density, with the most controlled delamination seen in the vehicle armor panels with 2.77 kg/3D and 5.38 kg/3D composite backings.

Conclusions

Even if the glass fiber composites are challenged by polymeric, other ceramic or metal fiber, they still have been of interest for ballistic application, either as part of or as the entire of a protection system or as they exhibit good impact resistance at lower costs. Researches are conducted to increase the ratio of fibers, but also in finding more suitable matrix for a specific application.

This review could be useful for the start of a research on ballistic panels based on or including glass fiber fabrics, for making the researchers familiar to their particular failure mechanisms.

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