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HIGH-STRENGTH HYBRID TEXTILE COMPOSITES WITH CARBON, KEVLAR, AND E-GLASS FIBERS FOR IMPACT-RESISTANT STRUCTURES.

A REVIEW.

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Keywords: *hybrid textile composites, fiber architecture, finite-element analysis, impact behavior, delamination damage phenomenon*

The paper reviews the characterization of high-performance hybrid textile composites and their hybridization effects of composite's behavior. Considered are research works based on the finite-element modeling, simulation, and experimental characterization of various mechanical properties of such composites.

1. Introduction

Composite materials are formed by combination of two or more individual materials in a definite ratio to have a desirable set of mechanical and physical properties of their components, such as a high strength, low weight, high stiffness, high corrosion resistance, long fatigue life, high impact resistance, good thermal conductivity, etc [1-3]. In most of composite materials, one material is continuous and is called matrix, but the second one, which is usually discontinuous, but can also be continuous, is referred to as a reinforcement and is stronger than the matrix. In some cases, a filler is used. The matrix phase holds the imbedded/reinforcement phase in place, shares the load with the reinforcement phase, and also protects the reinforcement from surface damage [4]. Usually, the properties of composite materials are anisotropic, which can be either their advantage or disadvantage [5-7]. With advancement of technology, composites are increasingly used in structures subjected to a wide spectrum of static loads, including low/high-velocity impacts, during their lifetime [8], to replace not only metals,

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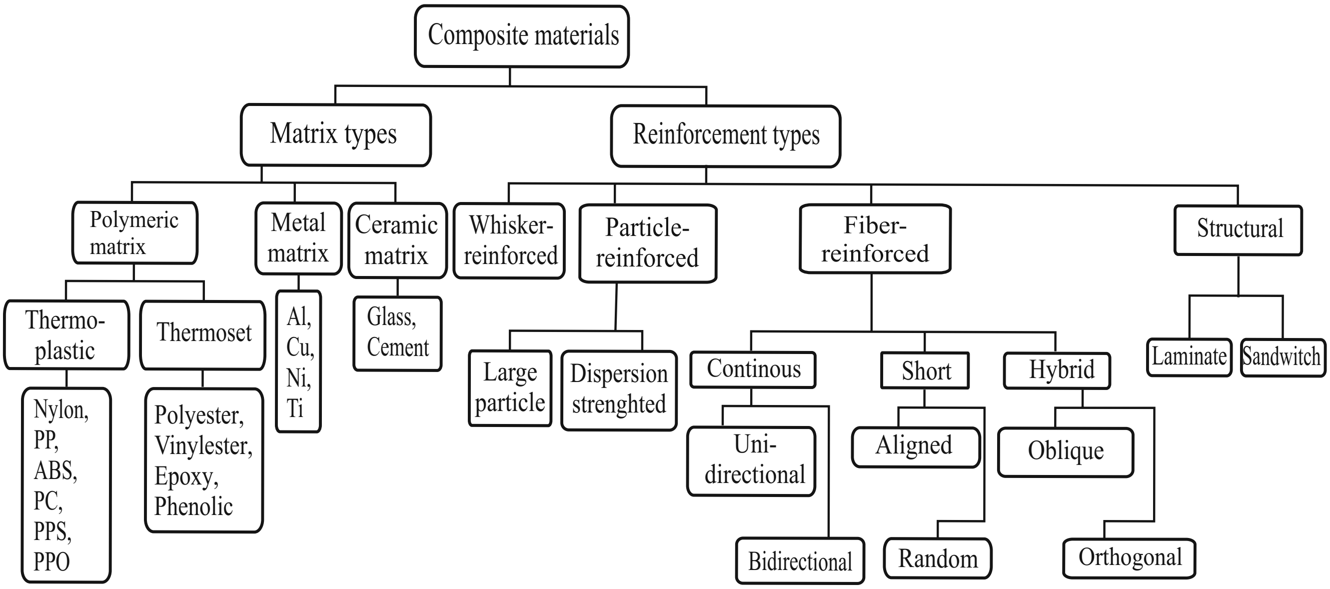

Fig. 1. Classification of composite materials based on reinforcement and matrix types.

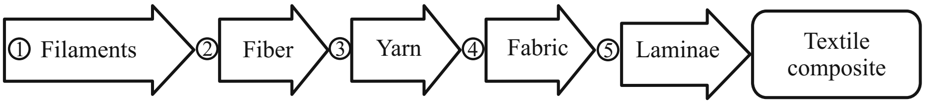

Fig. 2. Manufacturing process of textile composites.

but also their light-weight alloys. Depending upon the basic ingredients used in production of composite materials, they can be classified as shown in Fig. 1 [9-13].

Textile composites are fabricated by introducing reinforcing fibers, in a woven or nonwoven form, into thermosetting or thermoplastic matrix materials to endow them with structural rigidity and stability [14]. The manufacturing process of textile composites includes five steps, as shown in Fig. 2.

The fiber material, reinforcement architecture, weaving pattern, fiber orientation (straightness/deviation from a straight path), stacking sequence, and number of fabric layers are important factors to be considered in designing textile composites [15]. Textile composites can be monolithic (only one type of fiber material is used) or hybrid (more than one fiber material). Morye et al. [16] experimentally investigated the effect of various matrix and reinforcement materials, under the same ballistic impacts, on the mechanical properties of various textile composites with Nylon 66 and aramid fibers and phenol formaldehyde and polyvinyl butyral matrices.

Wong et al. [17] estimated the ballistic limit V_{50}, delamination area, and compression strength for five textile composites with E-glass fiber plies and different matrix materials.

Isa et al. [2] investigated the mechanical properties of monolithic Kevlar-, glass-, and Nylon-FRPs, and hybrid Kevlar/glass-, Nylon/glass- and Kevlar/glass/Nylon-FRPs textile composites with an unsaturated polyester resin matrix. Textile composite reinforced with fibers are classified [18] as shown in Fig. 3.

Textile composites are by unidirectional impregnation within the matrix material posses much better in-plane mechanical properties, but are prone to delamination. To cope with this drawback, woven/braided/knitted fabric composites [19] are used to achieve better mechanical properties in both in-plane and transverse directions [20]. For laminated composites, the first-order shear deformation theory and semiempirical formulae have been used in multiple studies [21-23] to analyze their impact behavior by predicting such process parameters as the peak force, contact duration, peak strain on the back surface, etc.

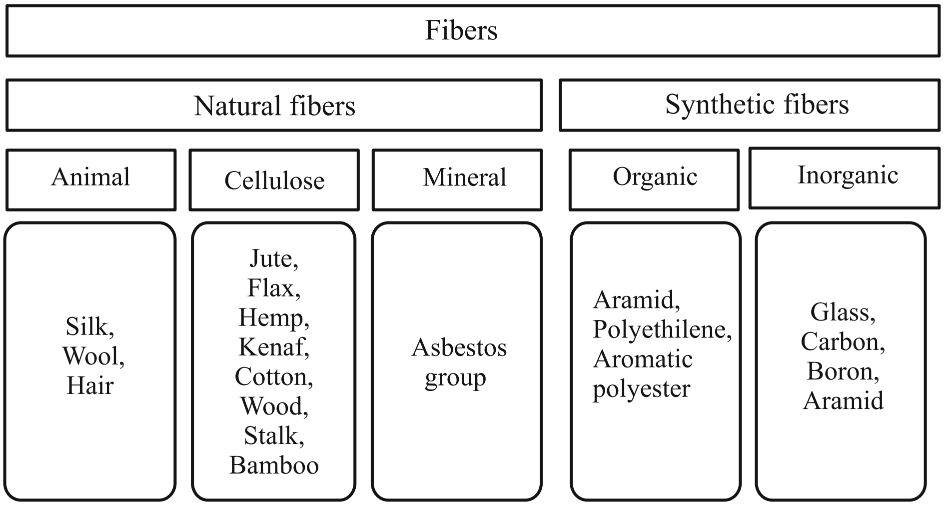

Fig. 3. Classification of fibers.

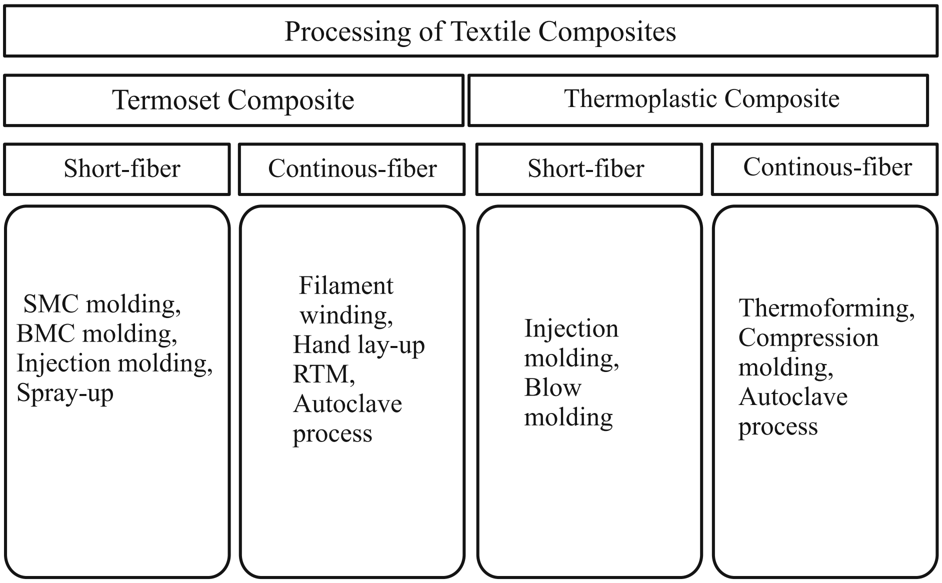

Fig. 4. Processing techniques of textile composites.

Various tools [20], such as the rule of mixtures, theory of random functions, boundary variation methods, composite cylinder models [24], and finite-element analysis [25-26], have been employed for estimating the mechanical and impact response of textile composites.

Along with fabric properties, matrix properties and composite processing techniques also govern the mechanical ballistic properties, their energy absorption ability and failure mechanisms of woven textile composites [27-31]. Figure 4 shows the processing techniques [32] utilized in producing textile composites, and Fig 5 — their classification [9, 20].

In woven composites, the warp and weft yarns are interlaced in a definite sequence, specific fiber-matrix volume ratios and lamination configurations are used to produce materials with a higher transverse tensile strength, fracture toughness, and dimensional stability than UD composites [33]. Naik et al. [34] analyzed the failure mechanism in different plain weave laminated composites made from glass/epoxy and T300/5208 carbon/epoxy and subjected to low-velocity transverse impact loads causing delamination due to the interlaminar or inplane stresses. Woven fabrics made of such high-performance fibers as, e.g., aramid (Kevlar/Twaron), UHMWPE (Spectra, Dyneema), PBO (Zylon), and AuTx ones, are effective materials for protec-

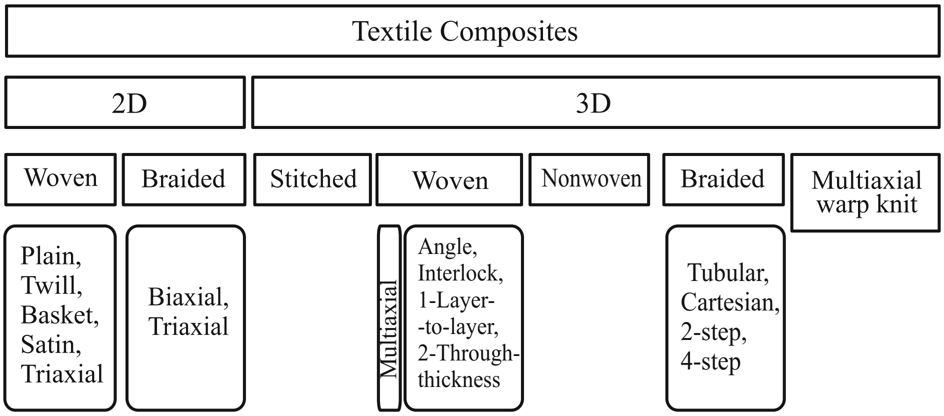

Fig. 5. Classification of textile composites depending upon their formation.

tion against ballistic impacts, but woven fabrics made of such high-stiffness fibers as carbon and glass ones are excellent for structures subjected to high compressive loads [35, 36]. Textile composites found their traces of application initially by the US military in the 1970's, and now are increasingly employed in fighter and commercial aircraft, train and racing cars, etc. [8, 37].

1.1. Properties and classification of hybrid textile composites

The advantages of structural textile composites are their low weight, high corrosion resistance, and high stiffness [38], but they have a poor impact resistance. This factor calls for further research to enhance the impact resistance of structural textile composite by their hybridization with some impact-resistant material without affecting its other superior mechanical properties [39, 40].

In hybrid composites, one type of reinforcing material is introduced into a mixture of different matrix materials [41], or two or more reinforcing materials are introduced into a single matrix [42] or both [43], to provide a good combination of such properties as a high tensile modulus, compressive strength, and impact strength, which are important characteristics of input materials [44] and improve the resistance to delamination, fiber breakage, fiber pull-out, and matrix cracking of textile composites [45].

In fabrication of hybrid textile composites, the governing factors are the material of reinforced fibers and matrix, the weaving pattern of fibers, the stacking sequence, the number of monolithic fiber layers, the type of fabric-matrix bonding, and processing techniques [46]. The reinforcement of hybrid composites can be performed using the following hybridization techniques.

i. Thoroughly mixing two (or more) types of long/short fibers and then blending them into a polymeric matrix, or blending them into such a matrix separately, one by one [47, 50].

ii. Sandwiching fabrics or laminates made from reinforcing fibers and a polymer in orthogonal or oblique directions, as shown in Fig. 6 [40, 48].

Sandwich composites posses a low impact resistance because of their weak transverse mechanical properties. The complex interaction between the face sheets and the core material makes the characterization of damage and failure mechanisms of textile sandwich composites difficult.

iii. Incorporating nonwoven (stacking of laminates), woven intrayarn (yarn by yarn), or interyarn (fiber by fiber) fabrics of reinforcing fibers in a matrix as, shown in Fig. 7 [51, 52].

The impact response of unidirectional (UD) laminated composites (with a high in-plane specific strength and low transverse tensile strength) has been investigated by many researchers [34]. Uyaner and Kara [53] estimated the impact behavior of UD reinforced E-glass/epoxy laminates under low-velocity impacts and found that the laminates were more susceptible to impact damage, resulting in delamination.

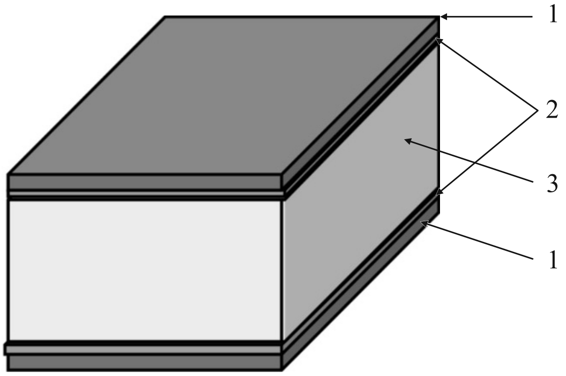

Fig. 6. Sandwich laminate: 1 — face sheets, 2 — adhesive layer, and 3 — core.

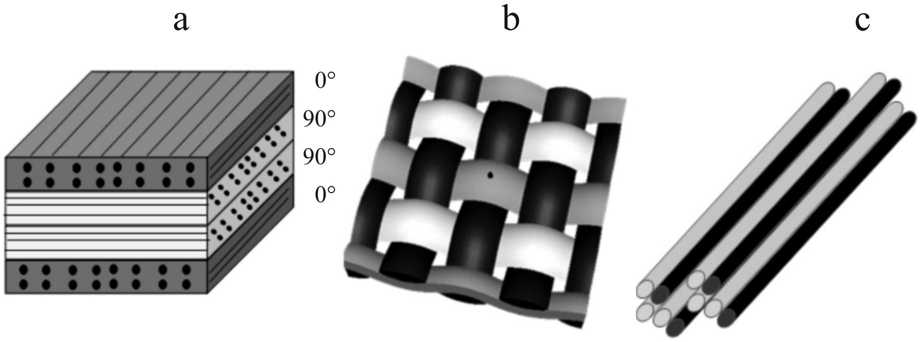

Fig. 7. Nonwoven [0/90/90/0] fiber laminate (a) and woven intrayarn (b) and interyarn (c) fabrics of Kevlar (grey) and carbon (black) yarns.

2. Research Status of Monolithic Textile Composites

Monolithic textile composites with a reinforcement fabric made of single material fibers posses excelent mechanical structure, or ballistic properties attributed by reinforced fibers in the supporting mattrix material. Structural textile composites posses excellent tensile compression strength, and stiftness while ballistic composites posses excellent fracture toughness fatigue, and impact resistance. Research status for structural and ballistic composites is presented below.

2.1. Structural monolithic textile composites: CFRPs and GFRPs

In the modern era, “The Composite Era”, researchers are enhancing the application of composites in various fields — structural, chemical, ballistic, underwater, civil, and military. Structural composites (CFRPs and GFRPs) are sometimes also subjected to high/low-velocity impacts during their operation. CFRPs have been extensively used as structural materials in bicycle frames, aerospace structures, bridges, etc [54, 55].

Carbon-fiber composite materials posses an excellent specific strength and modulus, good thermal and electrical conductivity, and a very low coefficient of thermal expansion, but a low fracture energy, which results in a poor impact strength, poor fracture toughness, and poor delamination (interlaminar cracking, separation) resistance. These drawbacks are explained by the absence of plastic deformations in the matrix material [56, 58] and the low strain at failure ($< 1\%$) of carbon fibers.

Investigations show that the fracture toughness of CFRPs is improved 4-8 times if the matrix toughness is increased 25 times by addition of some rubber-based compounds. It was also found that interleaving an adhesive material with a high tough-

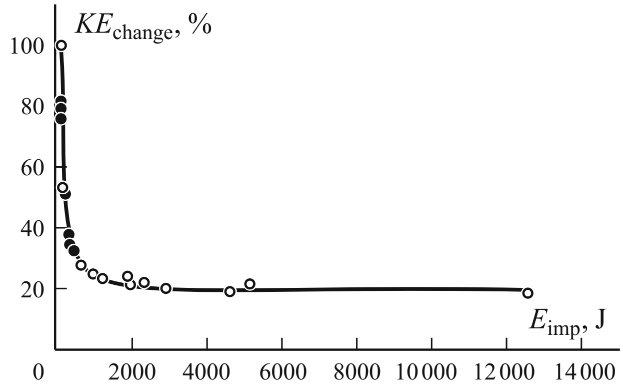

Fig. 8. Change in the kinetic energy, KE_{change}, absorbed by a laminate vs. impact energy E_{imp} [66].

ness between CFRP layers can improve the interlaminar cracking resistance. This motivates researchers to enhance the fracture toughness and flexural stiffness of structural textile composites by adding materials able to absorb the fracture energy [59].

2.1.1. Experiments, modeling, simulation, and failure mechanisms of CFRPs. Dixit et al. [60] investigated the thermomechanical performance of a 2 × 2 twill weave textile composite in tension, compression, and bending. Specimens were tested in air at room temperature, in water (24.9 to 96.7°C), and in liquid nitrogen (–96.9 to 99.4°C), and their storage modulus and tan δ at various temperatures were estimated.

Hazell and Applieby-Thomas [54] reviewed the recent advances in the application of rigid structural CFRP and GFRP composites under ballistic conditions at impact speeds of 300-2000 m/s. Cantwell et al. [61] and Cantwell [62] experimentally examined the high-velocity impact response of structural fibrous composite materials and found that high-velocity particle impacts caused significant matrix cracking, fiber breakage, and delamination [53]. Cantwell and Morton [63] revealed that, at low-velocity impacts, the elastic flexural response of target, shear deformation, and delamination were the three major energy-absorbing mechanisms; at high-velocity impacts, as the failure was more localized, the elastic flexural response played a minor role.

Reid and Wen [64] experimentally studied the critical energy required for perforation of laminates and surmised that this energy is affected by the static and dynamic contact pressure between the projectile and target surface. The static pressure depends on the static linear elastic compression limit of the base composite in the thickness direction, but the dynamic pressure depends on the strain rate in the composite material. Caprino et al. [65] found that the Cantwell–Morton theory of impact perforation, developed further by Reid and Wen, was a better model for calculating the perforation energy and residual velocity of projectile. Hazell et al. [66] established a relation between the impact energy of projectile and the kinetic energy absorbed by a 6-mm-thick laminate, made of a 5HS (harness) woven CFRP, at impact velocities from 1062 to 1875 m/s and found that the delamination level was slightly affected by an increase in the velocity. As shown in Fig. 8, at elevated impact velocities, the kinetic energy absorbed by the base plate remains constant.

Lopez et al. [67] performed experiments to estimate the effect of penetration angle on the damage caused by a 7.5-mm spherical steel projectile. They concluded that, at the ballistic limit, normal incidence produced more severe damage than an oblique one, but at impact velocities below the ballistic limit, greater damage was caused by oblique impacts.

Belingardi and Vadori [68] experimentally estimated the effect of low-velocity impacts on carbon/epoxy laminates with three different thicknesses.

Goldsmith et al. [69] conducted ballistic and low-velocity tests on thick carbon/epoxy laminates by using a cylindrical impactor and found that the major damage mechanisms were crack propagation, fiber failure, delamination, hole enlargement, and friction during penetration. Nguyen et al. [35] experimentally estimated the impact behavior of monolithic and bondline specimens of a 4-mm-thick CFRP under low-, medium-, and high-velocity impacts by using drop weight and gas gun setups at 10-, 40-, and 120-J impact energies. They established that the bondline specimens were better than monolithic materials under impact loadings.

Sanchez-Saez et al. [70] investigated the compression after impact (CAI) of different CFRP laminates at low temperatures (–60 and −150°C) and conducted low-velocity impact tests on thin plates at room temperature. They found that, for tape laminates, the CAI strength decreased at lower temperatures, but temperature did not affect the variation in the compression strength retention factor. At low temperatures, the woven laminate showed a higher strength than the tape ones.

Dixit et al. [71] investigated the mechanical behavior of plain weave textile CFRPs under a compressive loading. The finite-element method was employed to analyze the effect of compression loading [72] and variation in the transverse-longitudinal shear (TLS) modulus on different energy parameters and behavior of fabric [73]. An analysis indicated that not all surface portions of yarns were under the same compressive stress simultaneously and concluded that, for fabrics under compression, their mechanical behavior, strain energy, and energy dissipation mainly depends on the TLS modulus.

Wan et al. [74] performed the surface treatment (air oxidization) of carbon fibers to improve the performance of carbon-fiber composites. The resulting composites showed good flexural properties. However, the advantages of these materials were significantly offset by their susceptibility to impact damage. Therefore, Kevlar fibers were selected to make Kevlar/epoxy composites with a high impact resistance.

Wan et al. [74,] prepared various samples of a 3D braided carbon-Kevlar 49 hybrid fabric, based on an epoxy resin (bisphenol-A), with a fiber volume fraction of 45 ± 2%, 16° braiding angle, and 3:2 C:K ratio and unidirectional CFRP, KFRP, and hybrid carbon-Kevlar-epoxy resin composites with a fiber volume fraction of 30%, by using the vacuum-assisted resin transfer molding (VATRM). Further, the surface treatment of braided hybrid, unidirectional hybrid, and unidirectional carbon (with anodic oxidation), and Kevlar fabric (treated with acetic anhydride for 1 min) was performed. The flexural strength and modulus of resulting composites were determined. It was concluded that the two-step surface treatment (anodic oxidation in $(NH_4)_2$ HPO_4 and chemical treatment in H_3PO_4) of unidirectional hybrid and braided hybrid composites increased their flexural strength.

2.1.2. Experiments, modeling, simulation, and failure mechanisms of GFRPs. The increasing use of structural FRP in the aviation, automotive defence, and other sectors is owning to their highest specific mechanical strength and stiftness compared with conventional materials. Talking about one of the major disadvantages of GFRPs is their low impact resistance because of the absence of plastic deformations to absorb the impact energy. The brittleness of glass fibers make them very sensitive to impact loadings. Many investigations have been conducted to estimate the mechanical and impact properties of GFRPs.

Shaktivesh et al. [76] estimate the ballistic impact on a 2D plain weave E-glass woven fabric by high-velocity projectiles. They considered the shear plugging and tensile deformation of yarns in both primary and secondary regions of the impacted zone, compression of the fabric in both regions, the conical deformation at the back of fabric target, and friction factors in the composite. The analytical formulation was based on the theory of stress wave propagation and the energy dissipated. The experimental and calculated values of the ballistic impact limit velocity were in agreement.

Naik and Srirao [77] analytically computed the velocity reduction, contact duration of projectile, ballistic limit, and damaged zone for plain weave E-glass/epoxy and twill weave carbon/epoxy composites, considering the properties of base materials and projectile parameters as input data, and found that the ballistic limit for E-glass/epoxy was higher than that of the T300 carbon/epoxy one. During the analysis, different damage mechanisms, such as the tensile failure of yarns in the primary and secondary zones, delamination, matrix cracking, and shear plugging, were considered.

Tanabe et al. [78] compared the energy absorbed by the cross-ply arrangement and woven pattern of carbon-fiber laminates and found no major difference between them. The authors suggested to maximize the energy absorption by the laminate by using fibers with a high tensile strength near their rear surface.

2.2. Ballistic-resistant monolithic Kevlar-fiber-reinforced plastic (KFRP) textile composites

Jia et al. [79] conducted experiments to estimate the ballistic impact behavior of a 3DOWF composite with a Twaron fabric (roughly the same as Kevlar by Dupont, USA) experimentally and verified the results for the residual velocity vs. strike velocity, deflection vs. time, and stress wave propagation at different nodal points obtained by the finite-element method using

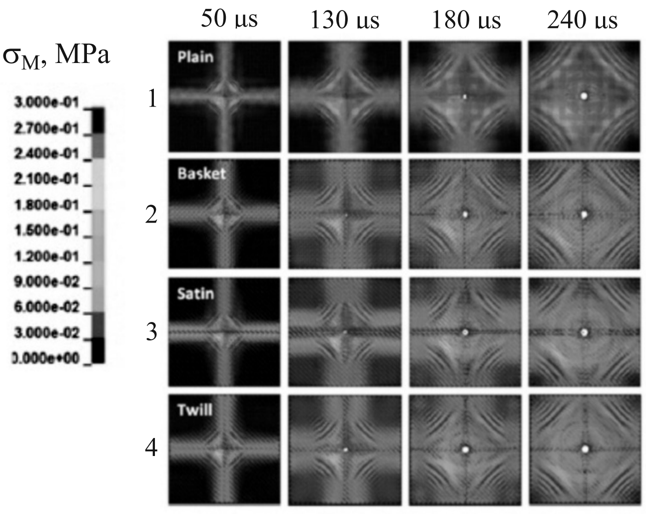

Fig. 9. Evolution of the von Mises stress distribution (MPa) at multiple impact events [28].

a C3D8R element. They concluded that the FEA model accurately simulated the behavior of 3DOWF under ballistic impacts, with an only difference for the residual velocity vs. strike velocity at lower strike velocities, because the Twaron yarn was modeled as continuos rod in the FEM, while, in fact, it is composed of filaments.

2.2.1. Experiments, modeling, simulation, and failure mechanisms of KFRPs. Sorrentino et al. [80] conducted ballistic tests on plain-weave Kevlar-29 fiber layers, impregnated with a thermosetting resin, using a gas gun and projectiles 9 mm in diameter. Experimental data were compared with the analytical results of Walker's analytical model.

Manes et al. [81] numerically investigated the ballistic resistance of a Kevlar 29-epoxy fabric plate under impact loadings by using LS-Dyna finite-element codes. The research was mainly focused on the residual velocity of projectiles of various shapes.

Lee et al. [82] conducted experiments to determine the ballistic penetration performance of Kevlar-KM2 fabrics impregnated with a colloidal shear-thickening fluid.

Yang et al. [28] conducted a study to clear up the effect of various weaving patterns on the impact resistance and energy absorption of single- and multilayer Twaron fabrics with plain, twill, 4H satin, and basket weaving patterns by using a mesoscale finite-element model and validated it experimentally using a gas gun assembly. Figure 9 shows that the ballistic resistance offered by the single-layer fabrics depended upon the interlacing points and stresses encounter the maximum resistance in the plain weave, followed by the twill and basket weaves, with the minimum resistance in the satin weave. It was concluded that, for the multilayer fabrics, the weaving architecture less affects the ballistic resistance property.

Chu and Chen [83] experimentally compared the ballistic limit V_{50} of plain and twill weave Kevlar 29, with an identical denier and yarn count, impacted by 8-g (full metal jacket) FMJ bullets, 5.1-g steel core bullets, and 7.62-mm fragment-simulating projectiles (FSP)s. The twill weave fabric was found to absorbed less energy than the plain weave one for both the bullets and FSPs.

Bandaru et al. [84] experimentally investigated the ballistic impact response of a thermoplastic-based Kevlar 29 fiber composite (2D plain-woven, 3D orthogonal, and 3D angle interlock-woven) with a polypropylene matrix of grade MI3530 and a MAg-PP coupling agent. Ballistic tests were performed with a 9-mm full metal jacket (FMJ) projectile at speeds of 350-440 m/s.

Walsh et al. [85] proposed a helmet made of a hybrid composite consisting of a graphite layer applied to a thermoplastic matrix-based Kevlar ply as a "core" for an improved ballistic protection. V_{50} tests were conducted, which revealed a 25% reduction in the overall areal density, compared with that of a monolithic Kevlar 29-phenolic (thermoset matrix) composite, without significantly affecting the ballistic properties of the helmet.

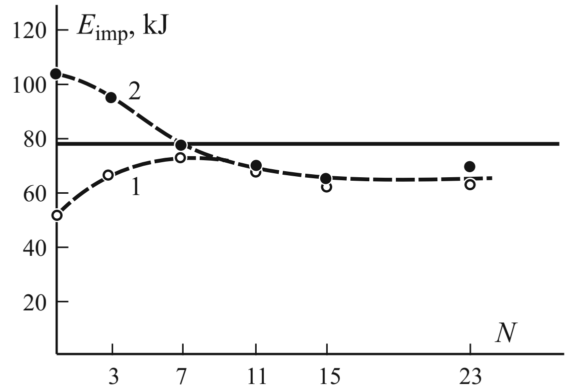

Fig. 10. Impact energy E_{imp} as a function of the number N of exchanged layers, with carbon (1) and Kevlar (2) fibers in the outer layers [46].

TABLE 1. Ballistic Performance of Hybrid Composites with a Carbon Layer in Kevlar Laminates

T, mm	Projectile shape	Ballistic limit, m/s				Absorbed energy, J			
		1st	2nd	3rd	4th	1st	2nd	3rd	4th
3.6	B	225	195	195	165	188.6	141.6	141.6	101.4
	H	135	105	105	92	67.9	41.1	41.1	31.5
7.2	B	335	315	315	307	418.0	369.6	369.6	351.1
	H	285	255	255	245	302.6	242.2	242.2	223.6
14.4	B	555	525	525	505	1147.4	1026.7	1026.7	950.0
	H	525	505	505	495	1026.7	950.0	950.0	912.7

3. Research Status of Hybrid Textile Composite

Structural members made of CFRPs and GFRPs, such as aircraft components (canopy, radar antennas, turbine blades, windshields, wings, etc.), bridges, ships, etc., can be exposed to undesirable impact loadings during their production or during their service life by low-flying obejects, debris, shock waves, bird strikes, etc., causing severe damage or immediate failure to the structures [86, 87]. Hybridization of these composites with tough fibers, such as Kevlar or Spectra ones, having a high impact strength, can strengthen them against low-velocity (1-10 m/s), high-velocity (Ballistic, below 1000 m/s), and hyper high-velocity (above 1000 m/s) impacts [88-90].

Drop-weight, Izod and Charpy impact test are the different techniques used to determine the low-velocity impact properties of composites [91]. Investigations show that low-velocity impacts usually produce delaminations in the inner layers of composites, without damaging the outer surface [92].

3.1. Experimental and analytical investigation of the failure mechanisms and the mechanical and impact behavior of hybrid composites

Hybridization is one of the effective ways to enhance the desirable mechanical properties, penetration resistance, and energy absorption ability of composites by using high-strength fibers, such as carbon and Kevlar ones, and also to decrease their cost by using more economic fibers, such as glass ones [93]. During hybridization of fibers, the fiber weaving pattern for interply hybridization, layer stacking sequence for Intraply hybridization and bonding of fabric are of great importance in

TABLE 2. Research Summary of Textile Hybrids of Carbon (C), Kevlar (K), and Glass (G) Fibers

Reference/ methodology	Hybridi zation level	Fabric weaving pattern	Material	
			Reinforcement	Matrix
1. S. N. Yadav et al. [59]/ experimental	Interply	Satin weave	Carbon, Kevlar 49 chopped fibers	Epoxy resin (ciba geigy ay 250)
2. R. J. Muhi et al. [89]/ experimental, numerical	Interply	Both plain-woven fabrics	E-glass, Kevlar-29 fibers	Thermoset polyester resin
3. J. Gustin et al [95]/ experimental	Intraply and interply both	Plain weave carbon, 4 H satin for K49, Twill weave for hybrid C-K	Kevlar 49, carbon	Eastpointe fiberglass epoxy (f-82 resin and tp-41 hardener)
4. S. L. Valenca et al. [104]/ experimental	Intraply	Twill-woven	Kevlar 49, S-glass	Thermorigid epoxy resin
5. Y. Z. Wan et al. [105]/ experimental	Intraply	3D braided	Kevlar 49, carbon	Bisphenol-A type epoxy resin
6. D. Campbell et al. [106]/fabrication process	Interply	Biaxial weave	Kevlar-49, CF/PUS structural shell	Thermo-plastic matrix polyurethane
7. T. D. Jagannatha [107]/ experimental	Intraply	Bi-directional weave	Carbon and E-glass fibers	Epoxy resin
8. P. J. Hazell [108]/ experimental	Interply	Plain weave Kevlar 29	Carbon, Dural (Al 6061-T6) and Kevlar 29	Adralite 2015 adhesive, Resin-Hexcel RTM 6
9. K. S. Pandya et al. [109]/ experimental	Interply	8H satin weave carbon, plain weave, E-glass	Carbon, E-glass	Epoxy resin (LY556)
10. R. Park [110]/ Experimental	Interply	Both fabrics are plain-woven	Surface-treated Kevlar 29 fibers, S2-glass fibers	Vinylester resin (modified with CTBN* for better impact properties).

TABLE 2. Research Summary of Textile Hybrids of Carbon (C), Kevlar (K), and Glass (G) Fibers

Tests	Aim of investigation	Conclusions/remarks
Equipment/ Tools used		
1. Mode II fracture toughness G_{II} and flexural modulus/UTM, SEM	To compare the sandwiching effect of Kevlar- reinforced interleave and unreinforced interleave on the fracture toughness and flexural modulus.	KF-interleaved hybrid has a high fracture toughness due to the high energy absorbance and the highest flexural modulus due to higher stiffness of the interleaf resin, increased with addition of Kevlar.
2. High-velocity (176 m/s) impact/Ballistic impact tester, velocity measurement unit	To verify the effects of stacking sequence of kevlar layer on the impact behavior of GFRP	Found an improvement in the impact behavior of hybrid with increment of absorbed energy by moving Kevlar layer from the 1st to 4th (distal one) due to increased toughness, stiffness.
3. Tensile stiffness and compression after low-velocity impacts (5-45J)/Drop tower, MTS fatigue test system.	To analyze variation in the absorbed impact energy and partial/total penetration of top and bottom facesheets of in sandwich textile composite by varying the impact energy.	Kevlar and hybrid layers increased the maximum energy absorbed approximately by 10%, the tensile stiffness (e1, e2), and the nonimpacted compressive strength.
4. Tensile, low-velocity impact (5.5J), and bending/UTM	To analyze the mechanical and low-velocity impact properties of Kevlar and glass fiber hybridized at the yarn level	Hybrid composite with Kevlar and S-glass in weft yarns (fabric type C_{90}) showed the best mechanical properties and $C_{0\ \text{the}}$ the best impact properties compared with other samples.
5. Flexural strength, shear, damage tolerance/XCJ-500 Impact Tester, optical microscope	To analyze the effect of variation in carbon to Kevlar ratio in hybrid composites.	Decrement in the energy absorbed, shear and flexural strength with decrement of C:K ratio and hybridization improved the impact damage tolerance.
6. Wrinkling/ thickness variation with shear angle θ/ Thermoforming setup	To fabricate thermoplastic antiballistic infantry helmets via thermoforming.	Potential design developed for a hybrid helmet by coforming the structural and ballistic layers
7. μ hardness, ultimate tensile strength and modulus/Vickers μ hardness test/UTM	To investigate the effect of carbon fiber addition on the mechanical properties of GFRP.	Carbon fiber hybridization enhanced the UTS, microhardness, peak load, and ductility of GFRP.
8. High-velocity impact (92-459 J)/High-speed camera, SS spherical projectile (11.97 mm dia	To compare the effect of hybridizing CFRP with Dural, Kevlar 29 in woven and nonwoven composites on the ballistic performance.	Hybridization of Kevlar layers at the rear face of CFRP also enhanced the dissipation of kinetic energy at lower impact energies. The nonwoven samples outperformed the woven ones
9. Ultimate tensile strain, compressive and tensile strengths/UTM	To study the tensile and compressive in-plane quasi-static load behavior along the warp direction by varying the stacking arrangement.	Hybrid H1 posses a higher ultimate tensile strain than H2, as glass with a higher ultimate strain constrains damage evolution in carbon laminates.
10. Total impact energy, fracture damage (impact with 4m/sec, 160 J)/Dart impact tester, penetrant injection, SEM	To compare the effect of improved adhesion of surface-treated and untreated aramid fiber on the impact behavior of hybrid composites.	Position of aramid fabrics affected the total impact energy more in untreated and less in treated fiber composites due to the restriction of deformation of aramid fibers.

11. N. Shaaria et al. [111]/ Experimental	Interply	Twil-woven Kevlar 49, plain-woven C-glass	C-glass fibers, Kevlar 49	Epoxy resin (Mocrete BJC 39)
12. G. Belingardi et al. [112]/ Experimental	Interply and Intraply both	Biaxial ±45° weave	E-glass, carbon	Epoxy resin
13. D. Zhang et al. [113]/ Experimental	Interply	3D orthogonal interlock weaving	Carbon, S-2 glass, and Kevlar (Z direction).	SC-15 Epoxy resin
14. B. Yang et al. [114]/ Experiment and FEM	Interply	All plain-woven	Carbon and glass fibers	Polymerized poly butylene terephthalate (PCBT)
15. M. Bulut et al. [115]/ Experimental	Interply	2X2 Twill Kevlar, plain-woven carbon and S-glass	Kevlar, carbon, and S-glass fibers	Epoxy resin (MOMENTIVE-MGS L285)
16. K. Naresh et al. [116]/ Experimental	Interply	Both plain-woven	Carbon and glass fibers	Epoxy (Araldite (LY556)) and hardener (HY951
17. M. Sayer et al. [117]/ Experimental	Interply	Unidirectional carbon and E-glass fabrics	Carbon and E-glass fibers	Epoxy resin (CY225 epoxy prepolymerand HY225 hardener)
18. N. K. Naik et al. [118]/ Experimental	Interply	Plain weave E-glass, Twill weave carbon	Carbon and E-glass fibers	Epoxy resin (LY 556 and hardener HY 951)

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[*] CTBN- Carboxyl-terminated butadiene acrylonitrile (rubber)

11. Drop weight impact test (45.9 J), damage pattern/Instron. Dynatup 8250, CMM	To analyze the effect of a sandwiching KFRP laminate on the impact resistance properties of woven GFRP composites.	Addition of KF to GF decreased deflection at the peak load, with a slight reduction in stiffness and increased load carrying capability, and resistance to deformation.
12. Static tensile, flexural, 4-point fatigue bending/UTM, bending fatigue machine	To study the bending fatigue behavior of CFRP hybridized interplay and intraply with EFRP.	Reduction in stiffness and elastic modulus depends on the magnitude of applied fatigue loading.
13. Bending modulus, flexural yield stress/ SEM, UTM	To study the effect of increasing specimen thickness on the strain to failure ratio in the flexure mode.	Flexure loading tends to increase the strain: failure ratio with thickness increment more for glass than for carbon due to better energy absorption.
14. 3 pointt ENFT, drop-weight impact (3,5,7 m/s)/Servoelectric testing m/c, ABAQUS/ Explicit	To analyze the hybridization effect on the energy absorption and damage behavior/failure mode of the composite under low-velocity impacts.	Hybridization enhanced the impact resistance of CFRP with enhanced perforation thresholds. The main failure modes were fiber breaking and matrix cracking followed by delamination.
15. Quasi-static penetration test/Shimadzu AGX , Circular-cylindrical punch	To analyze the quasi-static punch penetration force to displacement ratio of C-K-G hybrids with different stacking sequences.	Hybrid KCG and KGC showed less damage. Hybrids with Kevlar outer layers showed less fiber breakage and delamination.
16. Tensile test (0.0016-542 s^{-1})/ Drop-weight impact machine, UTM, SEM	To investigate the influence of strain rate on the tensile properties of molithic and hybrid (G-C/epoxy)compos..	The strain rate increases the modulus and strength, as stiffening mechanism takes place and decreases the failure strain.
17. Low-energy impacts (10 to 35 J) at low and high temp/ Drop-weight impact tester	To investigate the impact response and failure mechanisms of hybrid composite at temp. of –20, 20,and 60°C,.	Energy absorbed by the composite (Ea) was highest at room temp (20°C) as penetration threshold was smallest.
18. Low-energy impacts (19.76J, velocity = 2.9m/s)/ Drop-weight impact test apparatus, UTM	To investigate the impact behavior, notch sensitivity and postimpact compression strength of hybrid.	H1-[C4G4]s had the lowest notch sensitivity and highest damage tolerance, as carbon withstand higher stresses than other hybrids.

governing the mechanical and impact resistant properties of composites. Cheeseman et al. [94] experimentally examined the weak adhesion/bond between fibers and matrix, which leads to the delamination of fabrics and fiber breakage/failure, thereby facilitating the dissipation of an extra amount of the energy from the projectile.

Marom et al. [46] experimentally explored changes in the impact behavior caused by changing the stacking sequence and degree of hybridization in ten carbon/Kevlar-epoxy hybrids. Three-point-bending tests performed with 1.02 m/s at a 12.2-J energy gave the ultimate tensile and shear stresses from impact traces. Figure 10 shows the effect of the number of layers exchanged in carbon- and Kevlar-based composites on the impact energy. It was found that, at a lower degree of hybridization, positive hybrid effect, according to the rule of mixtures, existed for both the carbon- and Kevlar-based composites.

Gustin et al. [95] experimentally estimated the effect of replacing the top four layers of the impact-side facesheet from carbon laminates to Kevlar fiber (1K-4K) or carbon/Kevlar fiber hybrid (1H-4H) ones. It was found that the addition of Kevlar layers increased the amount of absorbed energy by approximately 10% and the decrement by approximately 10%. The addition of hybrid layers increased the maximum absorbed energy by 5% compared with that in the case of Kevlar ones.

Randjbaran et al. [96] investigated the effect of varying stacking sequence of plain-woven laminates with Kevlar KM2, carbon and glass fibers in an epoxy resin on the ballistic response of the textile composites, under high-velocity (182 m/s) impact loadings, for five hybrids with different stacking sequences and concluded that the specimens with the first layer made of glass fibers (Hybrid 2 and 4) performed better, with absorbed energies of 95.17 and 95.15 J, than the those with Kevlar ones.

Ozen [97] performed low-velocity impact tests (7.5, 15, and 22.5 J) on six samples of sandwich composites with carbon, E-glass, and S-glass fibers in epoxy resin matrix facesheets and with a PVC foam core. The stacking sequence of the top and three bottom fabric layers (hybrid 1- ESC- E-glass/S-glass/carbon/polythene foam/carbon/S-glass/E-glass) was varied to clear up the impact (the peak load and deflection) and postimpact (the flexural strength after impact) behavior of the composites. The composites with carbon fibers in the outermost layers had the highest bending stiffness.

S. Behnia et al. [98] experimentally investigated the effect of different notch angles and stacking sequences of carbon, basalt, glass and Kevlar fabrics in eight five-layer specimens on the energy absorbed at low-velocity impact loadings. The energy absorbed by the specimens with Kevlar in the outer layers of carbon or basalt composites significantly increased with growing notch angle. For the samples with Kevlar in the outer layers, the main failure mode was fiber pull-out, for those with glass — fiber pull-out and matrix cracking, and for those with carbon — only fiber breakage, without delamination.

Along with experimental investigations of the mechanical and ballistic behavior of hybrid textile composites, researchers have also employed numerical methods and finite-element simulations. Shokrieh and Fakhar [99] compared analytical solutions for the deformation and stored energy of sandwich composites with calculations by an LS-DYNA model and using experimental data obtained at low-velocity impact loading of a composite with E-glass/epoxy facesheets and a Divinycell HT-110 foam core. For low velocities, the numerical model showed good agreement with experimental data.

Bandaru et al. [100] developed a finite-element model to evaluate the effect of varying stacking sequence of Kevlar 29, carbon, and glass laminates in hybrid lay-ups on the impact resistance of 12 composites with different thicknesses impacted by blunt (B) and hemispherical (H) projectiles with velocities of 176-800 m/s. The hybrid with a carbon layer showed the highest ballistic limit velocity and absorbed energy (Table 1), without complete penetration of the blunt projectile with carbon as the first layer because of bulk fiber degradation of carbon fibers followed by further delamination of Kevlar layers.

Behavior of hybrid textile composites strongly depends on the hybridization level of reinforcing fibers. Woo and Kim [101] investigated the hybridization effect on damage mechanisms of woven composites with carbon warp and Kevlar weft fibers subjected to high strain rates and compared them with that of KFRPs. The matrix failure, break of the brittle carbon fibers, fiber pull-out, and compressive plastic deformations causing crushing and fibrillation of Kevlar fibers, turned out to be the major failure mechanisms dissipating the impact energy.

The performance of hybrid composites under impact loadings also depends on the loading velocity. White et al. [102] investigated the effect of hyperhigh-velocity impacts on a layered carbon/Kevlar-epoxy hybrid structure and compared its behavior with that a monolithic CFRP. Numerical simulations using AUTODYN-2D were conducted to validate the numerical model used and to find out the optimum configuration of the structure. According to experimental data, addition of a Kevlar-epoxy layer to the front, and rear faces of the CFRP structure reduced the delamination damage of the structure and increased the impact energy required to perforate its rear surface.

Hosur et al. [103] compared the damage caused by high-velocity impacts (275 m/s) to stitched and unstitched laminates of plain and satin weave carbon/epoxy resin stiched with a three-cord Kevlar thread. The complete penetration velocity was found to be higher for the unstitched laminates, with a higher amount of damage in the laminates. The satin weave laminates performed better than the plain weave ones with a 38% higher ballistic limit.

Unidirectional and laminated hybrid textile composites have been investigated extensively, see, e.g., [46, 59, 96, 106, 109, and 110], but hybrid composites still need to be analyzed more thoroughly. Research studies concerning the effect of hybridization of carbon, Kevlar, and glass fibers on the mechanical properties, ballistic impact, and penetration resistance of hybrid composites are indicated in Table 2 categorized by hybridization level, fiber material, weaving pattern, and research methodology.

Apart from Kevlar in ballistic grade fibers, Sapozhnikov et al. [119] experimentally compared the high-velocity (900 m/s) ballistic performance V_{50} of Twaron/LPDE thermoplastic and Twaron/Dyneema hybrid textile composites with different weaving patterns. They found that, for the hybrid composites, the absorbed energy decreased when the projectile energy exceeded 170 J, and the dominant failure mechanisms were fiber fracture, delamination, fabric/matrix debonding, and yarn pull-out. Larsson and Svensson [120] investigated hybridized composites with carbon and Dyneema fibers and found that, with approximately 50% carbon fibers on the impact face of hybrid panels, the ballistic limit was the same as that of the corresponding panels made of 100% Dyneema fibers.

4. Conclusion

This review has been focused on experimental and analytical investigations into the mechanical and impact behavior of hybrid textile composites made from high-modulus/high-strength para-aramid (Kevlar fibers), high-stiffness carbon fibers, and high-failure-strain glass fibers and a thermoplastic or thermosetting matrix material. In designing the impact behavior of composites, either analytically or experimentally, the major parameters include the projectile geometry, impact velocity, reinforcement and matrix materials, hybridization level, weaving pattern and, stacking sequence of plies. The indentation or perforation of a projectile leads to compression of the target directly below the projectile in the thickness direction (zone 1) and to tension in the fabric upon its propagation through the inner surfaces, causing shearing, tensile failure, and delamination of lay-ups and matrix cracking in both the radial (zone 2) and thickness directions.

Analytical designing by finite-element or mathematical modeling shows a good agreement with experimental results regarding the energy absorption, ballistic limits, coefficient of restitution, and level of penetration into the hybrid textile composite target.

The insights gained from this review could be useful in enunciation of the research status of hybrid textile composites and will stimulate their employment in structures exposed to impact loadings because of their good mechanical properties, high impact performance, and low production cost. Investigations into woven hybrid composites still need to be extended to describe their actual impact damage mechanisms with minimum assumptions in order to improve their behavior under the action of impacts and high temperatures.

REFERENCES

1. F. Cardarelli, Materials Handbook-A Concise Desktop Reference, 2nd edition, Springer-Verlag London (2008).
2. M. T. Isa, A. S. Ahmed, B. O. Aderemi, R. M. Taib, and I. A. Mohammed-dabo, “Effect of fiber type and combinations on the mechanical , physical and thermal stability properties of polyester hybrid composites,” Composites: Part B, **52**, 217-223 (2013).
3. A. K. Kaw, Mechanics of Composite Materials, 2nd edition, CRC Press, Boca Raton, FL, USA (2006).

4. G. A. Teters and A. F. Kregers, “Multi-objective optimization of composite structures. A Review,” Mech. Compos. Mater., **32**, No. 3, 252-260 (1996).
5. D. Hull and T. W. Clyne, An Introduction to Composite Materials, 2nd edition, Cambridge University Press, UK (1996).
6. F. L. Matthews and R. D. Rawlings, Composite Materials: Engineering and Science, Woodhead Publishing Ltd, England (1999).
7. O. Bacarreza, P. Wen, and M.H. Aliabadi, in: M. H. Aliabadi (editor), Woven Composites: Computational and Experimental Methods in Structures-Vol. 6, Ch. 1, Imperial College Press, London, UK (2015), pp. 1-74.
8. M. M. Shokrieh and M. N. Fakhar, “Experimental, analytical, and numerical studies of composite sandwich panels under low-velocity impact loadings,” Mech. Compos. Mater., **47**, No. 6, 643-658 (2012).
9. S. N. A. Safri, M.T.H. Sultan, N. Yidris, and F. Mustapha, “Low velocity and high velocity impact test on composite materials-A Review,” Int. J. Eng. and Sci., **3**, Iss. 9, 50-60 (2014).
10. R. Vrashney and A. Madahar, “Innovations in textile composite designing and their applications,” Int. J. Computer Applications (0975-8887), (2015).
11. D. D. L. Chung, Composite Materials: Science and Applications, 2nd edition, Springer-Verlag London (2010).
12. J. S. Colton, Composite Processing: Version 1, Georgia Institute of Technology, USA (2011).
13. F.C. Campbell, Manufacturing Processes for Advanced Composite, Elsevier Advanced Technology, UK (2003).
14. W. Hufenbach, L. Kroll, O. Täger, and B. Zhou, “Material-adapted design of textile- reinforced composite structures with optimized vibro-acoustic and damping properties including shear effects,” Mech. Compos. Mater., **41**, No. 3, 195-204 (2005).
15. C. Thanomslip and P. J. Hogg, “Penetration impact resistance of hybrid composites on commingled yarn fabrics”, Composite Science Technology, **63**, 467-482 (2003).
16. S. S. Morye, P. J. Hine, R. A. Duckett, D. J. Carr, and I. M. Ward, “Modeling the effect of the energy absorption by polymer composites upon ballistic impact,” Compos. Sci. Technol., **60**, 2631-2642 (2000).
17. W. Wong, I. Horsfall, S. M. Champion, and C. H. Watson, “The effect of matrix type on the ballistic and mechanical performance of E-Glass composite armour,” 19th Int. Symp. of Ballistic, Switzerland, May, 7-11 (2001).
18. K. Majeed, M. Jawaid, A. Hassan, A. Abu Bakar, H. P. S. A. Khalil, A. A. Salema, and I. Inuwa, “Potential materials for food packaging from nanoclay/natural fibres filled hybrid composites,” Mater. and Design, **46**, 391-410 (2013).
19. C. M. Pastore, “Opportunities and challenges for textile reinforced composites”, Mech. Compos. Mater., **36**, No. 2, 97-116 (2000).
20. A. Dixit and H. S. Mali, “Modeling techniques for predicting the mechanical properties of woven-fabric textile composites: A Review,” Mech. Compos. Mater., **49**, No. 1, 1-20 (2013).
21. R. L. Ramkumar and P.C. Chen, “Low-velocity impact response of laminated plates,” Am. Institute of Aeronautics and Astronautics J., **21**, 1448-1452 (1983).
22. J. M. Whitney and N. J. Pagano, “Shear deformation in heterogeneous anisotropic plates,” ASME J. Appl. Mech., **37**, 1031-1036 (1970).
23. B. V. Sankar, “Scaling of low-velocity impact for symmetric composite laminates,” J. of Reinforced Plastics and Composites, **11**, 297-305 (1992).
24. J. M. Yang, C. L. Ma, and T. W. Chou, “Fiber inclination model of three-dimensional textile structural composites,” J. Compos. Mater., **20**, 472-483 (1986).
25. G. Zhou, X. Sun, and Y. Wang, “Multi-chain digital element analysis in textile mechanics,” Compos. Sci. Technol., **64**, 239-244 (2004).
26. S. A. Tabatabaei, S.V. Lomov, and I. Verpoest, “Assessment of embedded element technique in meso-FE modelling of fibre reinforced composites,” Compos. Struct., **107**, 436-446 (2014).
27. N. K. Naik and V. K. Ganesh, “Prediction of on-axes elastic properties of plain weave fabric composites,” Compos. Sci. and Technol., **45**, 135-152 (1992).
28. C. C. Yang, T. Ngo, and P. Tran, “Influences of weaving architectures on the impact resistance of multi-layer fabrics,” Materials and Design, **85**, 282-295(2015).

29. M. Al-Haik, A. Y. Borujeni, and M. Tehrani, in: X. Chen (editor), Advanced Fibrous Composite Materials for Ballistic Protection, Ch. 5, Woodhead Publishing Series in Composites Science and Engineering: Number 66, UK (2016), pp. 121-143.
30. A. Dixit, R. K. Misra, and H. S. Mali, "Finite element analysis of quasi-static indentation of woven fabric textile composites using different nose shape indenters," Materialwissenschaft und Werkstofftechnik, **46**, No. 10, 1014-1028 (2015).
31. S. P. Yushanov and A. E. Bogdanovich, "Fiber waviness in textile composites and its stochastic modeling," Mech. Compos. Mater., **36**, No. 4, 297-318 (2000).
32. R. Nadlene, S. M. Sapuan, M. Jawaid, M. R. Ishak, and L. Yusriah, "A Review on roselle fiber and its composites," J. Natural Fibers, **13,** 1, 10-41 (2016).
33. A. Dixit, H. S. Mali, and R. K. Misra, "Micromechanical unit cell model of 2×2 twill woven fabric textile composite for multi scale analysis," J. Institution of Engineers, Series E, **95**, No. 1, 1-9 (2014).
34. N. K. Naik, Y. Chandrashekhar, and S. Mduri, "Polymer matrix woven fabric composites subjected to low velocity impact: Part-I. Damage initiation studies," J. Reinforced Plastics and Composites, **19**, No.12, 912-943 (2000).
35. S. Nguyen, T. James, and L. Iannucci, "Low, medium and high velocity impact on composites," 16th Int. Conf. on Composite Structures, ICCS 16.
36. T. J. Singh and S. Samanta, "Characterization of Kevlar fiber and its composites: A Review," Materials Today: Proc. **2**, 1381-1387 (2015).
37. P. Potluriandand and A. Manan, "Mechanics of non-orthogonally interlaced textile composites," Composites:Part A: Appl. Sci. and Manufact., **38**, 1216-1226 (2007).
38. W. Hufenbach, R. Böhm, L. Kroll, and A. Langkamp, "Theoretical and experimental investigation of anisotropic damage in textile-reinforced composite structures," Mech. Compos. Mater., **40**, No. 6, 519-532 (2004).
39. M. Nirbhay, R. K. Misra, and A. Dixit. "Finite-element analysis of jute-and coir-fiber-reinforced hybrid composite multipanel plates," Mech. Compos. Mater., **51**, No.4, 505-520 (2015).
40. URL:http://www.engineeredmaterialsinc.com/products/structural-composites-and-sandwhich-panels/
41. M. M. Thwe and K. Liao, "Durability of bamboo-glass fiber reinforced polymer matrix hybrid composites," Compos. Sci. Technol., **63**, 375-387 (2003).
42. S. Y. Fu, G. Xu, and Y. W. Mai, "On the elastic modulus of hybrid particle/short-fiber/polymer composites," Composites: B Eng., **33**, 291-299 (2002).
43. N. Saba, P. Md. Tahir, and Md. Jawaid, "A Review on potentiality of nano filler/natural fiber filled polymer hybrid composites," Polymers, **6**, 2247-2273 (2014).
44. R. K. Misra, A. Dixit, and H. S. Mali, "Finite element shear modeling of woven fabric textile composite," Proc. Mater. Sci., **6**, 1344-1350 (2014).
45. N. K. Naik, Y. C. Sekher, and S. Meduri, "Damage in woven-fabric composites subjected to low-velocity impact," Compos. Sci. Technol., 731-744 (2000).
46. G. Marom, E. Drukker, A. Weinberg, and J. Banbaji, "Impact behavior of carbon/Kevlar hybrid composites," Composites, **17**, No 2, April, 150-153 (1986).
47. M. S. Sreekala, M. G. Kumaran, M. L. Geethakumariamma, and S. Thomas, "Environmental effects in oil palm fiber reinforced phenol formaldehyde composites: Studies on thermal, biological, moisture and high energy radiation effects," Advanced Compos. Mater., **13**, 171-197 (2004).
48. S. Mishra, A. Mohanty, L. Drzal, M. Misra, S. Parija, S. Nayak, and S. Tripathy, "Studies on mechanical performance of biofiber/glass reinforced polyester hybrid composites," Compos. Sci. Technol., **63**, 1377-1385 (2003).
49. K. G. Satyanarayana, K. Sukumaran, A. G. Kulkarni, S. G. K. Pillai, and P. K. Rohatgi, "Fabrication and properties of natural fiber-reinforced polyester composites," Composites, **17**, 329-333 (1986).
50. A. Pegoretti, E. Fabbri, C. Migliaresi, and F. Pilati, "Intraply and interply hybrid composites based on E-glass and poly(vinyl alcohol) woven fabrics: tensile and impact properties," Polymer International, **53**, 1290-1297 (2004).
51. A. K. Mohanty, M. Misra, and L. T. Drzal, "Sustainable bio-composites from renewable resources: Opportunities and challenges in the green materials world," J. of Polymers and Environment, **10**, 19-26 (2002).
52. Y. Swolfs, L. Gorbatikh, and I. Verpoest, "Fiber hybridisation in polymer composites: a review," Composites: Part A: Appl. Sci. Manufact., **67**, 181-200, (2014).

53. M. Uyaner and M. Kara, "Dynamic response of laminated composites subjected to low-velocity impact," J. Compos. Mater., **41**, No. 24, 2877-2896 (2007)
54. P. J. Hazell and G. J. Appleby-Thomas, "The impact of structural composite materials. Part 1: Ballistic impact," J. Strain Analysis, **47**, No. 7, 396-405 (2012).
55. O. Grāpis, V. Tamužs, N. Ohlson, J. Andersons, and U. Vilks, "Application of CFRP as a rotor shaft material," Mech. Compos. Mater., **31**, No. 2, 163-173 (1995).
56. M. Nirbhay, A. Dixit, R. K. Misra, and H. S. Mali, "Tensile test Simulation of CFRP test specimen using finite elements," Proc. Mater. Sci., **5**, 267-273 (2014).
57. B. Z. Jang, L. C. Chen, C. Z. Wang, H. T. Lin, and R. H. Zee, "Impact resistance and energy absorption mechanisms in hybrid composites," Compos. Sci. and Technol. **34**, Iss. 4, 305-335 (1989).
58. S. F. Chen and B. Z. Jang, "Fracture behavior of interleaved fiber-resin composites," Compos. Sci. Technol., **41**, Iss. 1, 77-97 (1992).
59. S. N. Yadav, V. Kumar, and S. K. Verma, "Fracture toughness behavior of carbon fiber epoxy composite with Kevlar reinforced interleave," Mater. Sci. Eng. B, **132**, 108-112 (2006).
60. A. Dixit, H. S. Mali, and R. K. Misra, "Investigation of the thermomechanical behavior of a 2× 2 twill weave fabric advanced textile composite," Mech. Compos. Mater., **51**, No. 2, 253-264 (2015).
61. W. J. Cantwell and J. Morton, "Detection of impact damage in CFRP laminates," Compos. Struct., **3**, 241-257 (1985).
62. W. J. Cantwell, "The influence of target geometry on the high velocity impact response of CFRP," Compos. Struct., **10**, 247-265 (1988).
63. W. J. Cantwell and J. Morton, "The influence of varying projectile mass on the impact response of CFRP," Compos. Struct., **13**, 101-114 (1989).
64. S. R. Reid and H. M. Wen, in: S. R. Reid and G. Zhou (eds.), Impact behavior of fibre-reinforced composite materials and structures, Ch. 8, Woodhead Publishing Ltd, Cambridge, England, 239-279 (2000).
65. G. Caprino, V. Lopresto, and D. Santoro, "Ballistic impact behavior of stitched graphite/epoxy laminates," Compos. Sci. Technol., **6**7, 325-335 (2007).
66. H. P. Hazell, A. Cowie, G. Kister, C. Stennet, and G. A. Cooper, "Penetration of a woven CFRP laminate by a high velocity steel sphere impacting at velocities of up to 1875 m/s," Int. J. of Impact Engineering, **36**, No. 9, 1136-1142 (2009).
67. J. Lopez-Puente, R. Zaera, and C. Ugena Navarro, "Experimental and numerical analysis of normal and oblique ballistic impacts on thin Carbon/epoxy woven laminates," Composites: Part A, Appl. Sci. Manufact., **39**, No. 2, 374-387 (2008).
68. G. Belingardi and R. Vadori, "Influence of laminate thickness in low velocity impact behavior of composite material plate," Compos. Struct., **61**, 27-38 (2003).
69. W. Goldsmith, C. H. K. Dharan, and H. Chang, "Quasi-static and ballistic perforation of carbon fiber laminates," Int. J. Solids Structure, **32**, 89-103 (1995).
70. S. Sanchez-Saez, E. Barbero, and C. Navarro, "Compressive residual strength at low temperatures of composite laminates subjected to low-velocity impacts," Compos. Struct., **85**, 226-32 (2008).
71. A. Dixit, R. K. Misra, and H. S. Mali, "Compression modeling of plain weave textile fabric using finite elements," Materialwissenschaft und Werkstofftechnik, **45**, No. 7, 566-634 (2014).
72. A. Dixit, R. K. Misra, and H. S. Mali, "Finite element compression modelling of 2x2 twill woven fabric textile composite," Proc. Mater. Sci., **6**, 1143-1149 (2014).
73. A. Dixit, , H. S. Mali, and R. K. Misra. "Unit cell model of woven fabric textile composite for multiscale analysis," Proc. Eng., **68**, 352-358 (2013).
74. Y. Z. Wan, Y. L. Wang, F. G. Zhou, G. X. Cheng, and K. Y. Han, "Three-dimensionally braided carbon fiber-epoxy composites, A new type of materials for osteosynthesis devices. II. Influence of fiber surface treatment," J. Appl. Polym. Sci., **85**, No. 5, 1040-1046 (2002).
75. Y. Z. Wan , J. J. Lian , Y. Huang, Y. L. Wang, and G. C. Chen, "Two-step surface treatment of 3D braided carbon/Kevlar hybrid fabric and influence on mechanical performance of its composites," Mater. Sci. Eng., A **429**, 304-311 (2006).
76. Shaktivesh, N. S. Nair, and N. K. Naik, "Ballistic impact behavior of 2D plain weave fabric targets with multiple layers: Analytical formulation," Int. J. Damage Mech., **24**, No. 1, 116-150 (2015).
77. N. K. Naik and P. Shrirao, "Composite structures under ballistic impact," Compos. Struct., **66**, 579-590 (2004).

78. Y. Tanabe, M. Aoki, K. Fujii, H. Kasano, and E. Yasuda, “Fracture behavior of CFRPs impacted by relatively high-velocity steel sphere,” Int. J. of Impact Eng., **28**, 627-642 (2003).
79. X. Jia, B. Sun, and B. Gu, “A numerical simulation on ballistic penetration damage of 3D orthogonal woven fabric at microstructure level,” Int. J. of Damage Mech., **21**, March, 237-266 (2012).
80. L. Sorrentino, C. Bellini, A. Corrado, W. Polini, and R. Aricò, “Ballistic performance evaluation of composite laminates in Kevlar 29,” Proc. Eng., **88**, 255-262 (2015).
81. A. Manes, L. M. Bresciani, and M. Giglio, “Ballistic performance of multi-layered fabric composite plates impacted by different 7.62-mm calibre projectiles,” Proc. Eng., **88**, 208-215 (2014).
82. Y. S. Lee, E. D. Wetzel, and N. J. Wagner, “The ballistic impact characteristics of Kevlar R woven fabrics impregnated with a colloidal shear thickening fluid,” J. Mater. Sci., **38**, 2825-2833 (2003).
83. C. K. Chu and Y. L. Chen, “Ballistic-proof effects of various woven constructions,” Fibres & Textiles in Eastern Europe, **18**, No. 6 (83), 63-67 (2010).
84. A. K. Bandaru, V. V. Chavan , S. Ahmad , R. Alagirusamy, and N. Bhatnagar, “Ballistic impact response of Kevlar reinforced thermoplastic composite armors,” Int. J. of Impact Eng., **89**, 1-13, (2016).
85. S. M. Walsh, B. R. Scott, and D. M. Spagnuolo, “The development of a hybrid thermoplastic ballistic material with application to helmets,” Army Research Laboratory, Aberdeen Proving Ground, MD 21005-5069, ARL-TR-3700 (2005)
86. J. Pernas-Sanchez, D. A. Pedroche, D. Varas, J. Lopez-Puente, and R. Zaera, “Numerical modeling of ice behavior under high velocity impacts,” Int. J. of Solids and Structures, **49**, 1919-1927 (2012).
87. N. R. Mathivanan and J. Jerald, “Experimental investigation of low-velocity impact characteristics of woven glass fiber epoxy matrix composite laminates of EP3 grade,” Materials and Design, **31**, Iss.9, October, 4553-4560 (2010).
88. K. N. Shivakumar, W. Elber, and W. Illg, “Prediction of low velocity impact damage in thin circular laminates,” Am. Institute of Aeronautics and Astronautics J., **23**, No. 3, 442-449 (1985).
89. R. J. Muhi, F. Najim, and M. F. S. F. de Moura, “The effect of hybridization on the GFRP behavior under high velocity impact,” Composites: Part B, **40**, 798-803, (2009).
90. M. Ansar, W. Xinwei, and Z. Chouwei, “Modeling strategies of 3D woven composites: A review,” Compos. Struct., **93**, 1947-1963 (2011).
91. J. M. Duell, in: M. R Kessler (ed.), Advanced Topics in Characterization of Composites, Ch. 6, Trafford Publishing, Canada, 97-112 (2004).
92. C. Meola, and G. M. Carlomagno, “Impact damage in GFRP: New insights with infrared thermography,” Composites: Part A, 1839-1847 (2010).
93. M. Bulut, A. Erkli, and E. Yeter, “Hybridization effects on quasi-static penetration resistance in fiber reinforced hybrid composite laminates,” Composites: Part B, **98**, 9-22 (2016).
94. B. A. Cheeseman and T. A. Bogetti, “Ballistic impact into fabric and compliant composite laminates,” Compos. Struct., **61**, 161-173 (2003).
95. J. Gustin, A. Joneson, M. Mahinfalah, and J. Stone, “Low velocity impact of combination Kevlar/carbon fiber sandwich composites,” Compos. Struct., **69**, 396-406 (2005).
96. E. Randjbaran, R. Zahari, N. A. A. Jalil, and D. L. A. A. Majid, “Hybrid Composite Laminates Reinforced with Kevlar/Carbon/Glass Woven Fabrics for Ballistic Impact Testing,” Hindawi Publishing Corporation, The Scientific World Journal, **2014**, Article ID 413753, 7 Pages (2014).
97. M. Özen, “Influence of stacking sequence on the impact and postimpact bending behavior of hybrid sandwich composites,” Mech. Compos. Mater., **52**, No. 6, 759-766 (2017).
98. S. Behnia, V. Daghigh, K. Nikbin, A. Fereidoon, and J. Ghorbani, “Influence of stacking sequence and notch angle on the Charpy impact behavior of hybrid composites,” Mech. Compos. Mater., **52**, No. 4, 489-496 (2016).
99. M. M. Shokrieh and M. N. Fakhar, “Experimental, analytical, and numerical studies of composite sandwich panels under low-velocity impact loadings,” Mech. Compos. Mater., **47**, No. 6, 643-658 (2012)
100. A. K. Bandaru, L. Vetiyatil, and S. Ahmad, “The effect of hybridization on the ballistic impact behavior of hybrid composite armors,” Composites: Part B, **76**, 300-319 (2015).
101. S. C. Woo and T. W. Kim, “High strain-rate failure in carbon/Kevlar hybrid woven composites via a novel SHPB-AE coupled test,” Composites: Part B, **97**, 317-328 (2016).

102. D. M. White, E. A. Taylor, and R. A. Clegg, “Numerical simulation and experimental characterization of direct hypervelocity impact on a spacecraft hybrid carbon fibre/Kevlar composite structure,” Int. J. Impact Eng., **29**, 779-790 (2003).

103. M. V. Hosur, U. K. Vaidya, C. Ulven, and S. Jeelani, “Performance of stitched/unstitched woven carbon/epoxy composites under high velocity impact loading,” Compos. Struct., **64**, 455-466 (2004).

104. S. L. Valenca, S. Griza, V. G. Oliveira, E. M. Sussuchi, and F. G. C. Cunha, “Evaluation of the mechanical behavior of epoxy composite reinforced with Kevlar plain fabric and glass/Kevlar hybrid fabric,” Composites: Part B, **70**, 1-8 (2015).

105. Y. Z. Wan, J. J. Lian, Y. Huang, F. He, Y. L. Wang, H. J. Jiang, and J. Y. Xin , “Preparation and characterization of three-dimensional braided carbon/Kevlar/epoxy hybrid composites,” J. Mater. Sci., **42**, 1343-1350 (2007).

106. D. T. Campbell and D. R. Cramer, Hybrid Thermoplastic Composite Ballistic Helmet Fabrication Study, Society for the Advancement of Material and Process Engineering, Fiberforge Corporation, Colorado (2008).

107. T. D. Jagannatha and G Harish, “Mechanical properties of carbon/glass fiber reinforced epoxy hybrid polymer composites,” Int. J. Mech. Eng. & Robotics Research, **4**, No. 2, April, 131-137 (2015).

108. P. J. Hazell and G. J. Appleby-Thomas, “A study on the energy dissipation of several different CFRP-based targets completely penetrated by a high velocity projectile,” Compos. Struct., **91**, 103-109 (2009).

109. K. S. Pandya, Ch. Veerraju, and N.K. Naik, “Hybrid composites made of carbon and glass woven fabrics under quasi-static loading,” Materials and Design, **32**, 4094-4099 (2011).

110. R. Park and J. Jang, “Impact behavior of aramid fiber/glass fiber hybrid composite: Evaluation of four-layer hybrid composites,” J. Mater. Sci., **36**, 2359-2367 (2001).

111. N. Shaaria, A. Jumahata, and M. K. M. Razifa, “Impact resistance properties of Kevlar/glass fiber hybrid composite laminates,” J. Technologi (Sci. & Eng.), **76**, No. 3, 93-99 (2015).

112. G. Belingardi, M.P. Cavatorta, and C. Frasca, “Bending fatigue behavior of glass–carbon/epoxy hybrid composites,” Compos. Sci. Technol., **66**, 222-232 (2006).

113. D. Zhang, A. M. Waas, and C. F. Yen, “Progressive damage and failure response of hybrid 3D textile composites subjected to flexural loading. Part I: Experimental studies,” Int. J. of Solids and Structures, **75-76**, 309-320 (2015).

114. B. Yang, Z. Wang, L. Zhou, J. Zhang, and Wenyan Liang, “Experimental and numerical investigation of interply hybrid composites based on woven fabrics and PCBT resin subjected to low-velocity impact,” Compos. Struct., **132**, 464-476 (2015).

115. M. Bulut, A. Erkli, and Eyüp Yeter, “Hybridization effects on quasi-static penetration resistance in fiber reinforced hybrid composite laminates,” Composites: Part B, **98**, 9-22, (2016).

116. K. Naresh, K. Shankar, B.S. Rao, and R. Velmurugan, “Effect of high strain rate on glass/carbon/hybrid fiber reinforced epoxy laminated composites,” Composites: Part B, **100**, 125-135 (2016).

117. M. Sayer, N. B. Bektas, E. Demir, and Hasan Calliog˘lu, “The effect of temperatures on hybrid composite laminates under impact loading,” Composites: Part B, **43**, 2152-2160 (2012).

118. N. K. Naik, R. Ramasimha, H. Arya, S. V. Prabhu, and N. Shamarao, “Impact response and damage tolerance characteristics of glass-carbon/epoxy hybrid composite plates,” Composites: Part B, **32**, 565-574 (2001).

119. S. B. Sapozhnikov, O. A. Kudryavtsev, and M. V. Zhikharev, “Fragment ballistic performance of homogenous and hybrid thermoplastic composites,” Int. J. Impact Eng., **81**, 8-16 (2015).

120. F. Larsson, and L. Svensson, “Carbon, polyethylene and PBO hybrid fibre composites for structural lightweight armour,” Composites: Part A, **33**, Iss. 2, February, 221-231 (2002).