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A mini review on the ballistic protection performance of 2D and 3D woven fabric structures woven from woven with technical yarns for body armor materials in military applications

Abstract

This mini-compilation study included a review study conducted on the ballistic protection performances of 2D and 3D structured woven fabric structures for body armor materials in military applications. In conclusion, orthogonal type 3D woven fabric structures have higher ballistic protection performance compared to conventional 2D woven fabric structures by locking the high-performance yarns used and preventing slippage between layers. It is recommended to use ceramic-structured front plates such as B4C to break armor-piercing bullets, reduce penetration, and absorb a significant portion of their high kinetic energy. UHMWPE, PPD-T, and PBO technical yarns, which have fine yarn counts (between 466 dtex and 933 dtex) can be produced by 1x1 plain woven fabric construction as woven fabric structures (in lamina form). They must have also high warp and weft density values (between 30 warp/cm and weft/cm and 40 warp/cm and weft/cm), orthogonal 3D woven fabric structure, high warp, and weft yarn tension (between 20 cN and 50 cN per warp yarn). Moreover, they must have 160 rpm for their production speed, and multi-layered (between 13 layers and 16 layers in lamina form) in honeycomb (sandwich) geometry. Moreover, the impregnation process can be applied to them with CaCO3, SiO2, PVB, or CNT particles (in the range of 100 nm to 400 nm for particle sizes) with chemicals such as PEG (in the range of 60% to 75% for concentrations), in the range of 80 °C to 160 °C temperatures and between 1 hour and 3 hours. Coating (STF) applications are extremely important and successful for ballistic protection performance at IIIA, III, and IV levels for NIJ standards. Future studies should include orthogonal 3D structured woven fabric applications from UHMWPE, PPD-T, and PBO technical yarns by applying STF technology in this field. They should be also examined comparatively from an experimental perspective.

Keywords: 2D and 3D woven fabric structures, armor materials, military applications, ballistic protection performances

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Introduction

The purpose of this mini-review study was to the body armor materials used in military applications. It was a mini compilation explanation based on the optimization results of the design criteria, raw materials used, production methods, production processes, and their effects on the ballistic performance of textile-based 2D and 3D technology woven fabric structures, supported by experimental studies.

Design criteria for armor materials used in military applications

The most basic needs of modern armies' defense materials should be extreme humidity, heat and cold (-60 °C), thermally comfortable (between 36 °C and 38 °C as temperature), resistant to hypothermia and hypoxia, and durable in environments such as mountains, deserts, air and sea, and flame retardant. These needs can be met with textile-based and multi-layered raw woven or knitted fabrics or by adding functionality by applying a finishing process such as coating (STF) on them.[1,2] The vital protection levels of military personnels are known as ballistic protection levels depending on certain design criteria thanks to NATO STANAG (4569), NIJ (between I and IV) -(NIJ0101.06), and MIL-STD-662F standards in military applications.[2,3–6] The design criteria in military armor materials are the light-weight, low-cost, easy to produce, has high dimensional stability, has high toughness, can completely absorb the kinetic energy coming from the bullet, can distribute the resulting stress homogeneously and over a wide area, has a low thermal expansion coefficient, high stabbing, high cutting, and high puncture. They must provide also qualities such as impact, shrapnel, tensile, biological, chemical, and pressure trauma resistance by certain military standards, too. Their mechanical and ballistic protection performances depend on the type of yarn used, the chemical structure of the yarn, the number of the yarn (dtex), the specific modulus of elasticity of the yarn (GPa), the specific tensile strength of the yarn (GPa), the specific density of the yarn (g/cm³), the cross-sectional shape of the yarn, the fluctuation speed of the yarn (m/s), the friction force of the yarn (N), the specific energy absorption of the yarn (J), the construction of the woven fabric, the density values (warp/cm) and (weft/cm) of the woven fabric, the crimp and ripple behavior of the woven fabric, the type of matrix chemical, the concentration of the matrix chemical (%), viscosity of the matrix chemical, number of layers (between 10 and 30), arrangement angle of the layers (°), fiber-to-volume ratio (%), type of bullet, mass of the bullet (g), speed of the bullet (m/s), geometry of the bullet, and the interfacial bond strength between fiber and matrix materials.[2,3,5–20,21-28]

General technical structure of armor materials used in military applications

Armor materials are generally divided into two as soft and hard. They are hard armor materials that provide ballistic protection against bullets with high penetration, perforation, and speed.[5,6,20,28] Multilayer structures are generally used in armor materials. There is a ceramic plate made of structures such as TiO_2, Al_2O_3 or B_4C on the front (in order to break the bullet) and on the back there is a reinforcement or raw materials in textile-based woven or knitted fabrics (in lamina form). They can be produced by some technical or convensional yarns are such as ultra-high molecular weight polyethylene (UHMWPE - Dyneema and Spectra), poly-m-phenyleneisophthalamide (Nomex), poly-p-phenyleneterephthalamide (PPD-T - Twaron and Kevlar), poly-p-phenylene-2,6-benzobisoxazole (PBO), polyarylate (PAR - Vectran), polypyridobisimidazole (M5), carbon (C - Toray), carbon nanotube (CNT), glass (E and S2), basalt, cotton, silk, spider silk, kenaf, curaua, sisal, ramie or PA 6. Moreover, they can be produced helping of some chemicals such as BN, BNNT, CMC, NR, PA 6, PA 6.6, PP, PEI, PEG, PAA, PVA, PVB, PMC, PVP, PEO, PPS, PEEK, PMMA, POSS, GO, TPU, SiO_2, $CaCO_3$, phenolic, silane, unsaturated PET or epoxy resins as matrix materials in liquid or particle forms. Their production methods generally are pressurized hot press, pressurized cold press, stirring, hand lay-up, spraying, chemical vapor deposition (CVD), vacuum bagging, vacuum-assisted resin infusion (VARTM). They can also be used as composite material structures produced by being functionalized (to absorb the remaining kinetic energy of the bullet and spread it over a wide surface) by methods such as transfer molding (RTM), ultrasonication, sol-gel, bottom coating, spin coating and electrospinning, too.[2,3–20,21,24,26–28] The fibers such as ramie, jute, sisal, linen and kenaf are used as reinforcement materials in the form of woven fabric structures (laminate form) in body armor materials thanks to their low density (lightness), easy availability, cheapness and environmental friendliness.[27] Ultra-high molecular weight polyethylene (UHMWPE - Dyneema and Spectra), poly-p phenyleneterephthalamide (PPD-T - Twaron and Kevlar), poly(p-phenylene-2,6-benzobisoxazole (PBO), polypyridobisimidazole (M5), carbon (Toray), carbon nanotube (CNT), and glass (E and S2) are extremely effective and widely used thanks to their high specific tensile strength as reinforcement materials in the form of woven fabric structures.[3,4,6,8,9,11,13–15,17,19,20,28] Specific tensile strength and specific modulus of elasticity of the strongest fibers known nowadays were presented in Figure 1.[8]

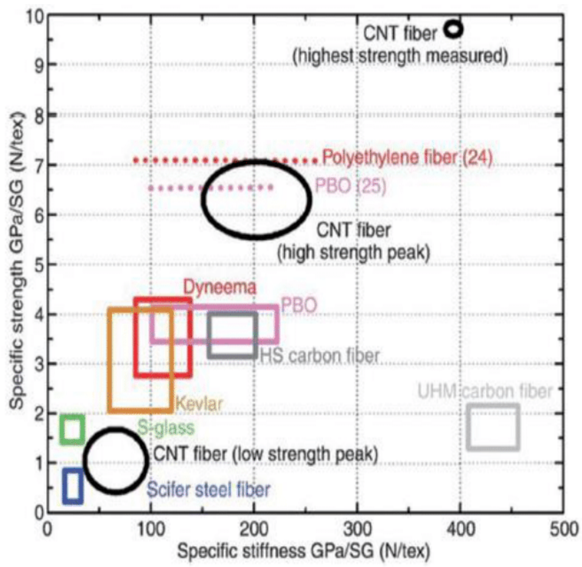

Figure 1 Specific tensile strength and specific modulus of elasticity of the strongest fibers known nowadays.[8]

The purpose of use of matrix materials is to increase the mechanical properties by strengthening the high interfacial bond with the fiber.[12]

Specific overall energy absorption is generally includes yarn breaks, yarn slippage and yarn deformations.[27] Specific energy absorption capacity as a function of sound speed for selected high-performance fibers was presented in Figure 2.[4]

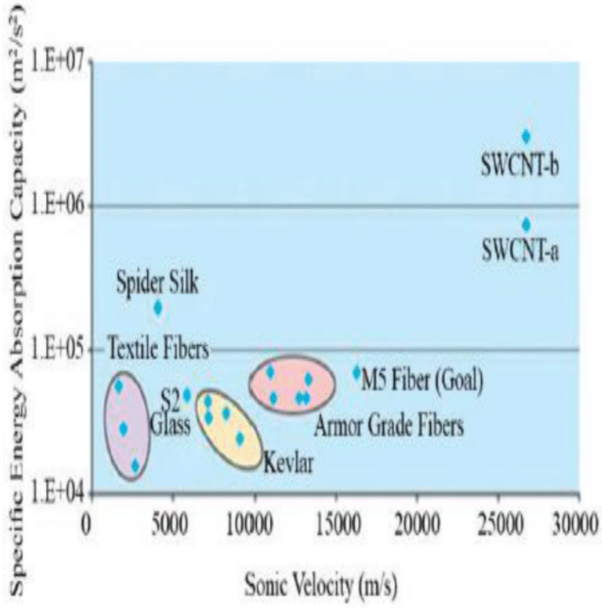

Figure 2 Specific energy absorption capacity as a function of sound speed for selected high-performance fibers.[8]

Technical structure for textile-based woven fabric structures of armor materials used in military applications

The yarns used are their biological, mechanical, chemical and thermal properties are different from each other due to their different chemical structures.[2] Technical yarns such as UHMWPE, PPD-T, and PBO used in armor materials, and low twist 50 (turn/m) is applied due to their brittle properties.[14,15] The yarn counts (dtex) used in armor materials generally are 466, 666, 800, 933, 945, 1090, 1011, 1100, 1210, 1350, 1388, 1400, 1666, 1980, 2500, 3250, 3330, 3360, and 10000.[4,6,10,11,14,15,17,19,20,23,26,27,28] Their filament numbers are 38, 42, 400, 500, and 1000.[15,16,19,27] The fiber-volume ratios (%) used in armor materials are generally between 30 and 64 (although 10 to 30 is rare).[3,5,11,12,14,23,27,28] Woven fabric constructions used in armor materials generally are 1x1 plain, 3/1 twill, 2x2 twill, 4 warp satin, 5 warp satin, 2x2 matt, warp rib, and weft rib.[4,11–20,24,26] The more angles (especially 15°) they are arranged from 0° to 90°, the higher the ballistic protection performance in the layer alignment angles used in armor materials.[4,17,18,23,24] Woven fabric constructions in which 2-yarns are compressed provide higher specific energy absorption compared to woven fabric constructions in which 4-yarns are compressed.[17,18] In terms of woven fabric constructions, for all specific friction energy values, including specific yarn-bullet and specific yarn-yarn friction energies that affect ballistic protection performance in armor materials was 1x1 plain > 4-warp satin > 2x2 twill > 2x2 matt, respectively.[16] In terms of woven fabric constructions, for specific kinetic energy absorption values that affect ballistic protection performance in armor materials was 1x1 plain > 2x2 twill > 2x2 matt > 4-warp satin, respectively.[16] In the woven fabric construction used in armor materials, the higher the yarn-yarn friction force and their surface area and the lower the skip amount, the higher the specific kinetic energy absorption and the higher ballistic protection level it provides,

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depending on the bullet geometry.[3,19,20] Thus, 1x1 plain woven fabric constructions provide the highest yarn-yarn friction force and yarn intersection point so they are generally used in armor materials.[20] Weaving limits in the weaving process depend on the type of yarn, number of yarn, diameter of yarn, structure of the yarn, yarn-yarn friction force, yarn-yarn surface area, mechanical properties of the yarn, size amount of the warp yarn, shedding angle, construction of the woven fabric, and weight of the woven fabric.[15,18] A smooth and taut woven fabric can be produced when a force of 5 cN to 13 cN is applied per warp yarn tension in the weaving process.[15] For warp yarn tension in PPD-T structured woven fabrics were 2x2 twill > 1x1 plain > 2x2 matt respectively. As the woven fabric speed increased from 120 rpm to 180 rpm, the warp yarn tension also increased in all woven fabric constructions. 160 rpm was recommended to weave the woven fabric smoothly and with high tension, that was, with the lowest CV % yarn variation. Moreover, warp yarn tension was higher as 2x2 twill > 1x1 plain > 2x2 matt, respectively in thicker yarn such as 1666 denier compared to thinner yarns such as 466 dtex, and 933 dtex. While it was 40 cN to 70 cN in heavy weight woven fabrics with 1666 dtex yarn count, it was 20 cN to 50 cN in low and medium weight woven fabrics with 466 dtex and 933 dtex yarn counts. As warp crimp decreased and skipping increased, warp and weft tension was higher in thicker yarns such as 1666 denier compared to thinner yarns such as 466 dtex and 933 dtex in woven fabric constructions.[15] Shed opening process, and shedding angle (°) affect the quality of the woven fabric.[7,18,25] As the shed angle increased from 28° to 32°, the warp yarn tension increased more in thicker yarn such as 1666 dtex compared to thinner yarns such as 466 dtex and 933 dtex. If the density values were low in woven fabric structures, the decreased in the friction force between the yarns used facilitated the penetration of the bullet by breaking and sliding the yarns more easily.[7,18] Woven fabric density values vary depending on the yarn count (dtex) for warp and weft yarns. Moreover, the values generally are between 4 warp/cm and weft/cm to 44 warp/cm and weft/cm. While high density values are used for fine yarn counts (dtex), lower density values are used for high yarn counts (dtex).[4,6,15,20,23,25,26,27,28] Textile-based composite armor materials can be generally produced by 2D or 3D structured woven fabric structures thanks to technical yarns such as UHMWPE, PPD-T, and PBO. They can be produced as number of layers between 10 and 20 layers for soft armor applications (against projectiles with V_{bullet} = less than 500 m/s) and also between 20 and 40 times for hard armor applications (against projectiles with V_{bullet} = between 500 m/s and 1000 m/s). Moreover, the thickness values of armor materials vary between 0.4 mm and 13 mm.[3,4,6,7,10,20,21-24,26,27,28] The structure of hard armor materials (against bullets between 500 m/s and 1000 m/s) must consist of 3 layers against bullets between 500 m/s and 1000 m/s. They are recommended to use a metallic or ceramic plate with a minimum thickness of 8 mm in the outer-layer, a 3D structured woven fabric structure in lamina form with a thickness of 8 mm in the middle-layer, and a 3D structured woven fabric structure in lamina form with a minimum thickness of 5 mm in the inner-layer.[4]

Technical structure and fractographic damage analyzes for textile-based 2D and 3D woven fabric structures of armor materials used in military applications

2D woven fabric structures consist of only warp and weft yarns. 3D woven fabric structures consist of warp, weft, and z-axis (binder) yarns.[3,4,6,10,20,21-26,27,29,30] Moreover, they have 5 different constructions such as UD, 1x1 plain 2D, orthogonal, angled interlock, and warp interlock.[3,4,6,10,14,20,21-26,27,29,30] The formation mechanism of 3D woven fabric structures on the 2D weaving machine was presented in Figure 3.[10]

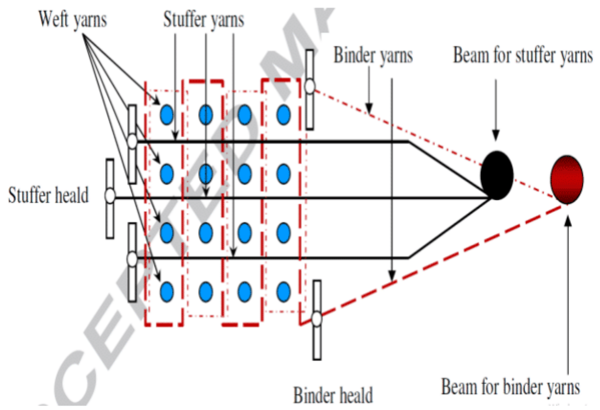

Figure 3 The formation mechanism of 3D woven fabric structures on the 2D weaving machine.[10]

3-D weaving preparation and weaving process flow chart: (a) yarn twisting, (b) yarn warping, (c) drawing-in, (d) arrangement of yarns, yarn tension, (e) fabric production and (f) fabrics produced was presented in Figure 4.[14]

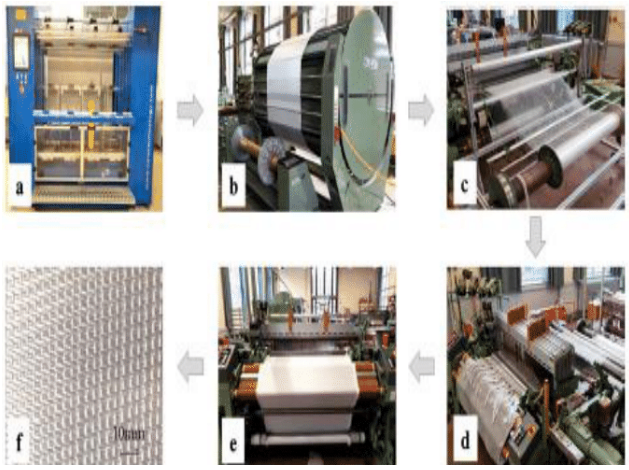

Figure 4 3-D weaving preparation and weaving process flow chart: (a) yarn twisting, (b) yarn warping, (c) drawing-in, (d) arrangement of yarns, yarn tension, (e) fabric production and (f) fabrics produced.[14]

3D structures compared to 2D structures have more easier and cheaper manufacturability, lower labor time, more complex shapes, better dimensional stability, lower damage tolerance, higher fracture toughness, lower crimp behavior, higher bending modulus, higher elasticity modulus, higher impact strength. They have also higher fatigue strength, good stress transfer from layer to layer, and provides thickness reinforcement by eliminating extra stitching, too.[3,4,6,10,14,21-26,27,29,30] Moreover, 3D structures provide higher energy absorption compared to 2D structures by locking the yarns together and preventing the layers from slipping thanks to the yarns in the z-axis in woven fabrics.[3,4,6,7,20,21-26,27,29,30]

Additionally, 3D structures provide a higher level of ballistic protection, higher impact strength, lower deformation area and less cracking of the matrix material compared to 2D structures for the level of ballistic protection against armor-piercing (AP) bullets with high kinetic energy.[4,6,26,27] Various 2D structured woven fabric structures woven in 2x2 twill woven fabric constructions were produced from PPD-T, PBO, PAR and C yarns, which had between 1090 dtex and 1980 dtex as their yarn counts. They were converted into composite body armor materials using epoxy and PP matrix materials. In conclusion, PPD-T+ epoxy (10 J/mm), PPD-T+PP (30 J/mm), PAR+PP 30 (J/mm),C+PP (15 J/mm), C+ epoxy (5 J/mm), PBO+PP 60 (J/mm), respectively was observed for their total energy absorption values.[11] Various 3D structured woven fabrics wovens, which had PPD-T and PBO yarns with their yarn counts between 3250 dtex and 3330 dtex, and E-glass yarn with its yarn count was 6000 dtex, with density values of 2 warp/cm and 2 weft/cm were produced. As conclusion, orthogonal interlock (4.819 J) > angled interlock (4.573 J) > warp interlock (3.940 J) > 1x1 plain 2D (3.169 J) > UD (1.640 J), respectively was observed for their total energy absorption values.[21] Woven fabrics were produced in from 1 layer to 3 layers in 1x1 plain 2D structured and orthogonal 3D structured woven fabric constructions, with density values of 3 warp/cm and weft/cm to 4 warp/cm and weft/cm. As conclusion, 3D orthogonal structured PBO (70 J) > 1x1 plain 2D structured PBO (50 J) > 3D orthogonal structured PPD-T (45 J) > 1x1 plain 2D structured PPD-T (30 J) respectively was observed for their total energy absorption values.[26] Woven fabric structures with 1x1 plain 2D structure at density values of 10.5 warp/cm and 10.5 weft/cm (layer thickness: 0.3 mm) to orthogonal 3D structure at density values of 8.5 warp/cm and 8.75 weft/cm per layer (layer thickness: 0.258 mm) were produced. Both consist of 6 layers. The NIJ IIIA ballistic protection performance of these woven fabric structures against FMJ RN structured 9x19 mm caliber bullets was examined experimentally. It was observed that the number of layers between 30 and 40 for a 1x1 plain 2D structured woven fabric and the number of layers between 13 and 16 for an orthogonal 3D structured woven fabric successfully provide for NIJ IIIA ballistic protection performance.[6] Sewing applications in woven fabrics are not recommended because they cause damage to the fibers and increase stress concentration in the sewing area.[10] During perforation, delamination is observed due to large shear forces between the fibers. In addition, the fibers have a bullet-stopping effect by stretching and providing shear blockage on the surface, in short, by providing energy absorption and distribution.[9]

The importance of honeycomb (sandwich) geometry molds for 2D and 3D woven fabric structures for armor materials used in military applications

3D woven fabric structures with honeycomb (sandwich) geometry have high modulus of elasticity, high tensile strength, high shear modulus, high shear strength, high impact strength, high damage tolerance, high corrosion resistance, high electrical insulation, excellent dimensional stability, excellent energy absorption ability, lower density (lightness), very low. They have also large amounts of voids, high crushing stress and almost constant breaking force, too. Nowadays, honeycomb (sandwich) geometry molds are generally produced from meta-aramid (Nomex), ABS, PE, PC, PP, or aluminum foil materials. ABS material provides optimum and high mechanical performance.[24] Honeycomb (sandwich) geometric mold structure was presented in Figure 5.[24]

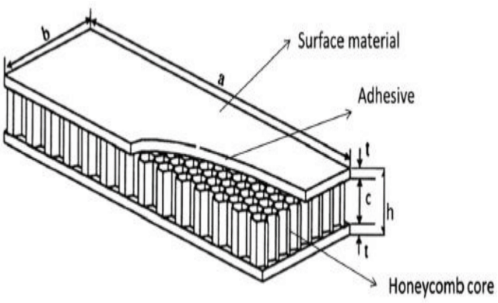

Figure 5 Honeycomb (sandwich) geometric mold structure.[24]

3D dense hollow woven fabric structures with honeycomb (sandwich) geometry were presented in Figure 6.[24]

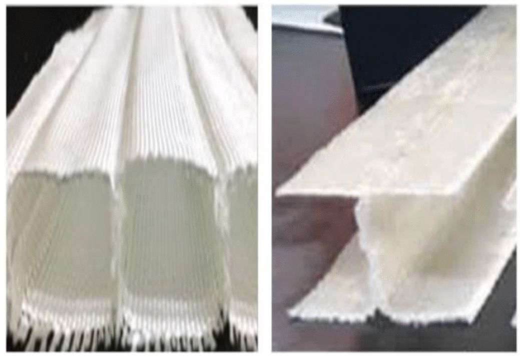

Figure 6 3D dense hollow woven fabric structures with honeycomb (sandwich) geometry.[24]

3D partial cavity woven fabric structures with honeycomb (sandwich) geometry were presented in Figure 7.[24]

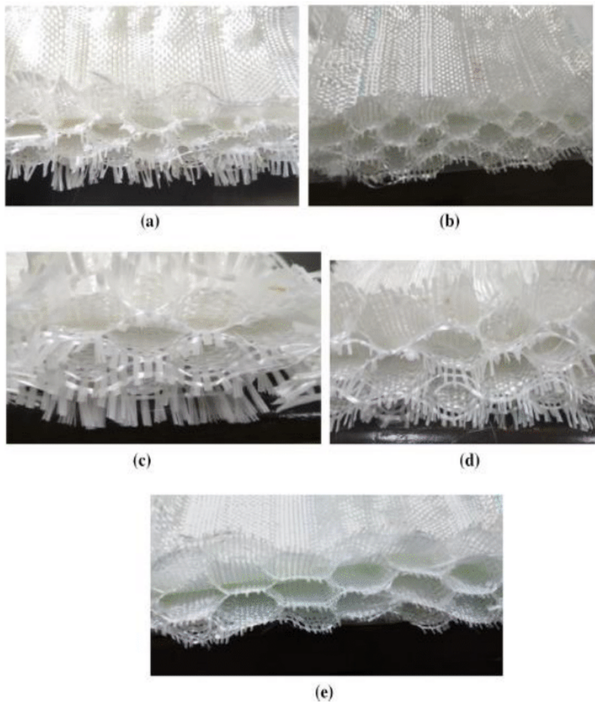

Figure 7 3D partial cavity woven fabric structures with honeycomb (sandwich) geometry.[24]

STF applications for armor materials used in military applications

PPD-T woven fabrics with orthogonal 3D structure, which had 9 layers, between 1.01 mm and 1.17 mm for thickness, the ratio of 4 (SiO_2):1 (PEG) for the hardener/matrix material was 8 hours moisture removal time, and as washing time for 15 minutes with ethanol respectively in STF applications. It was determined that the maximum impact energy absorption was achieved in soft armor materials (V_{bullet} = less than 500 m/s) after impregnation process application under 3 m/min impregnation speed and 2 bar pressure, and ethanol removal for 40 minutes.[10] The purpose of STF applications are lightness, flexibility, and high kinetic energy absorption. They are generally applied at 60% concentration.[10,20,28] The armor materials are generally produced by applying a temperature range of 80 °C to 160 °C and a pressure of 2 bar for a period between 1 and 3 hours in STF applications.[3,4,10,20] The mechanism of applying STF applications to woven fabric structures by the impregnation process was presented in Figure 8.[20]

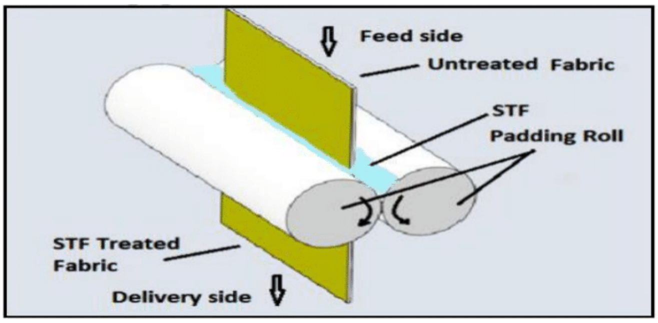

Figure 8 The mechanism of applying STF applications to woven fabric structures by the impregnation process.[20]

When the critical shear rate is exceeded, viscosity increases significantly in STF applications. Thus, a transition from the liquid phase to the solid phase is achieved. The yarn-yarn friction increases significantly and, depending on the woven fabric construction (especially 1x1 plain), the yarns are locked together, preventing the yarns from slipping over each other in the damage analysis. Yarn shrinkage also decreases significantly, too.[4,6,10,20,28] The fractographic damages such as pulling of the fibers and breaking of bonds, delaminations, fiber fibrillation, fiber breakage and matrix material cracking are generally present in the damage analysis of the yarns used.[3,6,11,20,28] Mechanism of energy absorption: (a) before impact and (b) during impact was presented in Figure 9.[10]

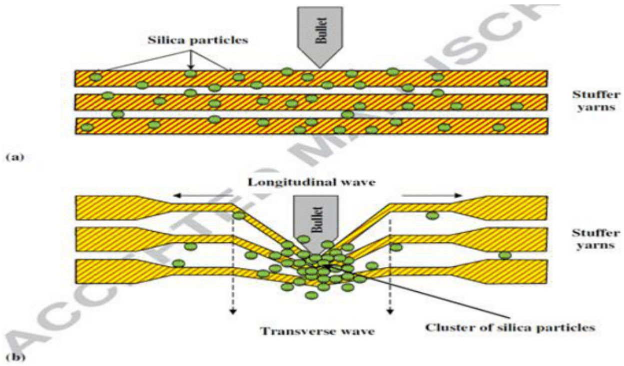

Figure 9 Mechanism of energy absorption: (a) before impact and (b).

NIJ standards for ballistic protection performance were presented in Table 1.[5]

Table 1 NIJ standards for ballistic protection performance[27]

Ballistic protection level	Test round	Bullet type	Projectile mass (grams)	Projectile speed (m/s)	Repeat shooting at 0° angle	Maximum thickness required for ballistic protection (mm)	Repeat shooting at 30° and 45° angles
IIA	1	9 mm FMJ RN	124	373	4	44	2
IIA	2	0.40 S and W FMJ	180	352	4	44	2
II	1	9 mm FMJ RN	124	398	4	44	2
II	2	0.357 Magnum JSP	158	436	4	44	2
IIIA	1	0.357 SIG FMJ FN	125	448	4	44	2
IIIA	2	0.44 Magnum SJHP	240	436	4	44	2
III	1	7.62 mm NATO FMJ	148	847	6	44	0
IV	1	0.30 Calibre M2 AP	166	878	1-6	44	0

Conclusion

General technical implications for body armor materials to be used in military applications are stated below. These are

For the general technical structure of the armor material (plate and lamina form) should have

a) The general technical structure of the armor material (plate and lamina form) should have plates made of metallic (TiO_2, and Al_2O_3) or ceramic (B_4C) materials in the outer layer, with a thickness between 5 mm and 8 mm, with high hardness values can significantly absorb the kinetic energy of the bullet and break the penetrating nose geometry of the bullet. Thus, reducing its penetration into the body armor material and the damage area.

b) Orthogonal 3D structured woven fabric structures (in lamina form) should be used in the middle and inner layers.

c) Fiber-to-volume ratio (%) is recommended to be in the range of 30 to 64 and as high as possible (especially 50 to 55).

d) Matrix materials in liquid form such as PEEK, PVB, phenolic or epoxy, or matrix materials in particle form such as BN, TiO_2 or SiO_2 are dispersed in PEG solution (75% concentration) in 2D or especially 3D woven fabric structures. They can be produced depending on their thermal, biological, chemical, mechanical properties. They should be converted into composite body armor material by applying an impregnation process. Thus, this is the STF application.

e) For 2D or 3D woven fabric technical structures (lamina form) should have UHMWPE, PPD-T or PBO technical yarns with extremely high specific mechanical properties should be used for yarn counts between 466 dtex and 933 dtex.

f) The twist amount of technical yarns to be used in the weaving process should be extremely low. The recommended twist amount value is 50 turns/m.

g) It is recommended that the number of filaments be as high as possible (between 500 and 1000).

h) z-axis yarn should be used in a 4:1 ratio in orthogonal 3D woven fabric applications.

i) The weaving process should be applied by a tension between 20 cN and 50 cN per warp yarn for warp yarn tensions.

j) Weaving production speed should be 160 rpm.

k) The weaving construction should be 1x1 plain. Thus, crimp behavior will be maximum. Moreover, the yarn-yarn friction will be maximum, the yarn-yarn slippage will be minimum, and the stopping and specific energy absorbing ability of the yarns at the yarn-bullet interface will be maximum.

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l) The weaving density values should be determined depending on the yarn count between 10 warp/cm and weft/cm and 40 warp/cm and weft/cm. As the yarn count (dtex) increases, woven density values decrease.

m) Honeycomb (sandwich) structure molds should be used in orthogonal 3D structured woven fabric structures. Moreover, ABS material should be used as mold material and it is recommended to have maximum filling.

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Conflicts of interest

Authors declare that there is no conflict of interest.

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