Soft Body Armor: An Overview of Materials, Manufacturing, Testing, and Ballistic Impact Dynamics

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Soft Body Armor: An Overview of Materials, Manufacturing, Testing, and Ballistic Impact Dynamics

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Naval Undersea Warfare Center Division Newport, Rhode Island

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PREFACE

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14. ABSTRACT

This report documents the development of today's soft body armors including their designs, materials, manufacturing methods, National Institute of Justice ballistic and North Atlantic Treaty Organization fragment threat categories, and qualification testing requirements. Material characteristics are discussed for each of the multiple material dimensional scales, which include the molecular, fiber, yarn, and fabric scales. Ballistic impact effects on single fibers and both single and multilayered woven fabrics are presented as well as numerical models used to depict stress and transverse wave propagations, projectile blunting, and fabric penetration.

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LIST OF ABBREVIATIONS AND ACRONYMS

ARL-WMRD	Army Research Laboratory’s Weapons and Materials Research Directorate
BABT	Behind armor blunt trauma
BFS	Back-face signature
BL	Ballistic limit
DAP	Deltoid axillary protector
ESAPI	Enhanced small arms protective insert
FSP	Fragment simulating projectile
gpd	Gram force per denier
IBA	Interceptor body armor
NATO	North Atlantic Treaty Organization
NIJ	National Institute of Justice
OTV	Outer tactical vest
PBI	Polybenzimidazole
PBO	Polybenzobisoxazole
PET	Polyethylene terephthalate
RCC	Right circular cylinder
SAPI	Small arms protective insert
STANAG	Standardization Agreement
UD	Unidirectional
UHMWPE	Ultrahigh molecular weight polyethylene
USSOCOM	US Special Operations Command

SOFT BODY ARMOR: AN OVERVIEW OF MATERIALS, MANUFACTURING, AND BALLISTIC IMPACT DYNAMICS

INTRODUCTION

Man's history is marked by his constant struggle to survive; that is, to overcome or defeat that which threatens his existence: for example, natural environmental events, hostile animals, and fellow man. Depending on the threat, protection is sought in various ways—shelter to avoid proximal threats, mobility to flee confrontation, and protective clothing and devices to directly engage the enemy. This investigation explores only one facet of man's effort to survive—protective clothing. Specifically, this report focuses on the design, materials, and testing of fabric-based, protective clothing, namely soft body armors, used for ballistic protection.

BODY ARMOR

BACKGROUND

Coping and survival instincts led to early developments in body armors often taking the forms of protective clothing and primitive shielding devices. Body armors—defined as any defensive coverings worn to protect the body from physical attacks—have evolved from readily available materials such as animal skins or natural fibers made from thatch, cotton, and silk often woven in textile forms to metals such as copper, steel, and iron used in plate and chainmail forms to the technologically complex armors used by today's armed services and law enforcement. In short, sophisticated weaponry increases threat effectiveness levels, which, in turn, drives the search for enhanced body armors.

Recent innovations in materials and manufacturing technology during the 20th century led to the discovery of advanced manmade textile materials (such as nylon, fiberglass, Kevlar, and many other synthetic fibers) that have provided body armor with extraordinarily improved ballistic protection levels at a significantly reduced weight—a potent combination for enhancing the effectiveness and mobility of military troops, law enforcement officers, and security personnel. While those same demands (increased protection at decreased weight) continue today, it is recognized that future improvements will be increasingly difficult to achieve because the financial costs associated with developing new fibers are becoming cost-prohibitive and the time-to-market for their commercialization remains long term.

DESIGN CRITERIA

Body armors must be worn to be effective. Weight, mobility, and comfort therefore are vital to ensuring their use; the armors must conform to the user's body, properly distribute their weight over the body to minimize user fatigue, provide sufficient breathability for extended use—especially during high temperatures, and must not interfere with or restrict the user's mobility. The significant challenge is to balance the level of protection required for specific threat type(s) against weight, comfort and flexibility, cost, environmental exposure (heat, ultraviolet light, moisture, etc.), and service life.

The principal factor that dictates the design of body armors is the type(s) of threat(s) for which protection is required (that is, ballistic, fragment, blast, stab, slash, chemical, fire, etc.). Armors optimized for protection against one threat type may not, however, be suitable for other threat types. For example, textiles designed for ballistic protection require sufficient yarn mobility within the weave to avoid premature failures and will not perform well for stab protection. Textiles designed for stab resistance require dense weaves to prevent yarns from being pushed aside from the tip of sharp-pointed objects such as knives, needles, awls, and ice picks. Dense weaves that prevent punctures can lead to premature or punch-through failures in ballistic impacts. Design parameters for optimizing both ballistic defense and stab defense often work against each other, as shown by figure 1. Multithreat armors are commonly designed by integrating separate armoring solutions—a process that achieves only minimal synergistic efficiencies at best. Armors that combine multiple defeat elements are often categorized as "in-conjunction" armors in which each component provides an enhanced level of protection for a given threat or multiple threat types.

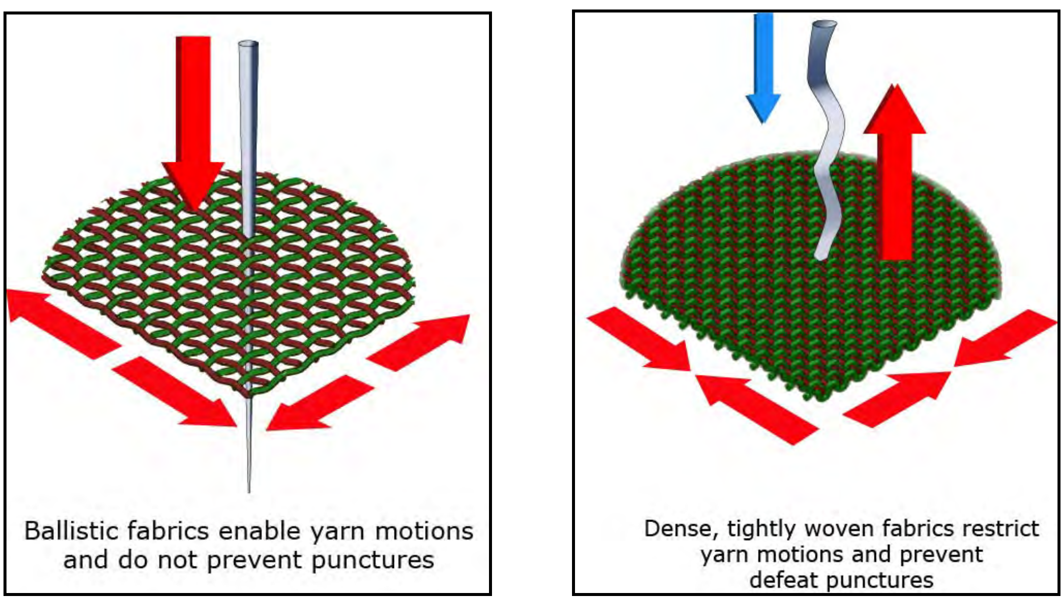
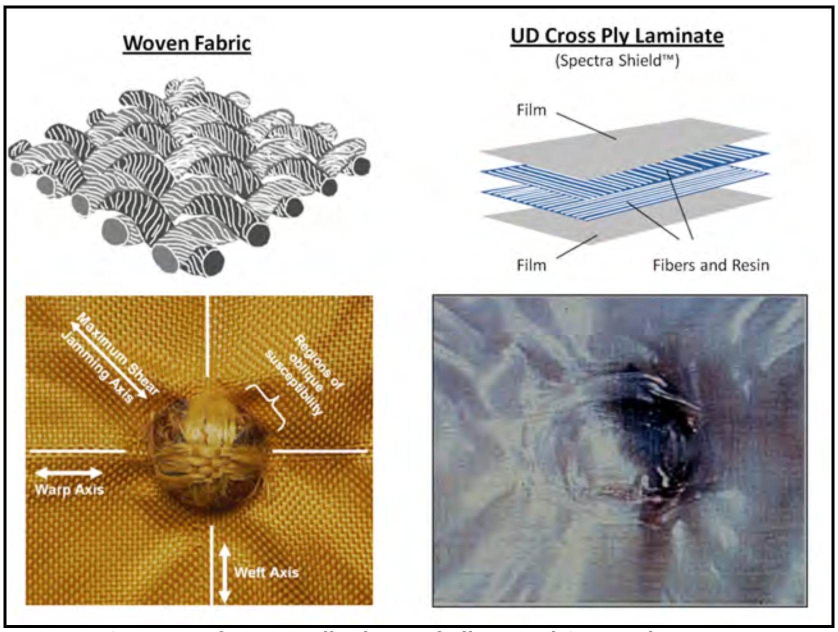


Figure 1. Puncture Behavior of Ballistic Versus Stab-Resistant Woven Fabrics

Traditionally, soft body armors for ballistic protection were manufactured using layers of woven fabrics stitched together; now they include laminates stacked with nonwoven, unidirectional (UD) layers and combinations of woven/nonwoven laminates. Considering the UD laminates, fibers within each UD layer are aligned in a parallel arrangement and are reinforced with a compliant polymer resin or matrix such as Kraton that binds the fibers together. The UD layers are produced in very thin sheet forms and are stacked, for example, in an alternating 0°/90° cross-ply fashion as shown in figure 2. Polyethylene films are added to protect the layers, and the final laminated shape is attained by applying heat and pressure. Commercial UD laminates used for ballistic protection include Honeywell's Spectra Shield (ultrahigh molecular weight polyethylene (UHMWPE) fibers) and Gold Shield (Kevlar fibers)[1] and DSM's Dyneema (UHMWPE fibers). In contrast, hard-textile or composite armors, such as helmets, are not flexible and are defined as those using a rigid resin material to bind the fibers together. Today's textile-based armors, such as bullet-resistant vests and helmets, integrate many sophisticated polymer materials and textile processing technologies that are optimized across multiple dimensional scales.



Courtesy of Honeywell Advanced Fibers and Composites, Inc.

Figure 2. Examples of Woven and UD Fabric Laminate Constructions with Ballistic Impact Deformations Shown

BODY ARMOR STANDARDS FOR MILITARY AND LAW ENFORCEMENT PERSONNEL

Current soft body armors used for ballistic protection are worn to protect the torso and extremity regions; they are developed in conjunction with rigorous standards and specifications to ensure proper performance and reliability levels against ballistic and fragment threats. For example, the National Institute of Justice (NIJ) prepared the "Ballistic Resistance of Body Armor NIJ Standard-0101.06"[2] to categorize ballistic threats including projectile types, sizes, and velocities; establish deformation limits; develop sample conditioning protocols; and specify acceptance testing procedures for nonmilitary body armors as shown in figure 3. Table 1 lists the NIJ Standard-0101.06-specified projectile types (deformable, steel-jacketed, high-hardness core, armor-piercing, etc.), velocities, and maximum allowable back-face signature (BFS) depths.

(a) (b)

Figure 3. (a) Soft Body Armor Concealable Vest Constructed with UD Laminates Used by Law Enforcement Officers for Ballistic Protection[3] and (b) Ballistic Test Showing Arrested Projectile[4]

Table 1. NIJ Body Armor Standards

Armor Type	Test Round	Test Bullet	Bullet Mass	Armor Test Velocity	Hits Per Panel at 0° Angle	Maximum Back Face Signature	Hits Per Panel at 30° or 45°
IIA	1	9mm, FMJ RN	8.0 g (124 gr)	373 m/s (1224 ft/s)	4	44 mm (1.73 in)	2
	2	.40, S&W FMJ	11.7 g (180 gr)	352 m/s (1155 ft/s)	4	44 mm (1.73 in)	2
II	1	9mm, FMJ RN	8.0 g (124 gr)	398 m/s (1306 ft/s)	4	44 mm (1.73 in)	2
	2	.357 Magnum, JSP	10.2 g (158 gr)	436 m/s (1430 ft/s)	4	44 mm (1.73 in)	2
IIIA	1	.357, SIG FMJ FN	8.1 g (125 gr)	448 m/s (1470 ft/s)	4	44 mm (1.73 in)	2
	2	.44, Magnum SJHP	15.6 g (240 gr)	436 m/s (1430 ft/s)	4	44 mm (1.73 in)	2
III	1	7.62 mm NATO FMJ	9.6g (148 gr)	847 m/s (2,780 ft/s)	6	44 mm (1.73 in)	0
IV	1	.30 Caliber M2 AP	10.8 g (166 gr)	878 m/s (2,880 ft/s)	1 to 6	44 mm (1.73 in)	0

AP–Armor piercing, FMJ–Full metal jacket, FN–Flat nose, JSP-Jacketed soft point, RN–Round nose, SIG-Sig Sauer, SJHP–Semi jacketed hollow point, S&W-Smith & Wesson

1.0 gram (g) = 15.4324 grains (gr)

Acceptance testing of soft armors determines their ballistic limit velocities for prescribed projectiles, projectile velocities, and angles of incidence. A variety of ballistic limit velocities are defined with each having a statistical significance. These include the V_0, V_{50}, and V_{100} ballistic limit velocities and are designated as the maximum velocity at which no complete penetration will occur, the velocity at which a 50% probability of complete penetration will occur, and the minimum velocity at which 100% probability of complete penetration will occur, respectively. Ballistic tests are performed on both dry and wet body armors by firing a number of projectiles at prescribed locations apart from each other, at angles of incidence of 0° (normal) and 30° (oblique), at seams, and at specific distances from the edges. Testing has shown that ballistic limit velocities are proportional to the areal weight density of the woven fabrics.

Ballistic testing of military armors for personnel, vehicles, and other systems subject to small arms munitions is governed by Military Standard MIL-STD-662F.[5] Fragment testing of military personnel armors resulting from fragmenting munitions, such as grenades and mortar rounds, is performed in accordance with the North Atlantic Treaty Organization (NATO) Standardization Agreement (STANAG) 2920.[6] Fragment simulating projectiles (FSPs) are often used as test projectiles with a range of sizes including 2-, 4-, 16-, and 64-grain sizes. The FSPs are shaped as right circular cylinders (RCC) as shown in figure 4 with a fixed length-to-diameter ratio equal to 1.0 and are made of hardened steel to resist deformations upon impact. A study by the U.S. Army's Ballistic Research Laboratory[7] concluded that 95% of all bomb fragments under four grains (0.26 gram) have a limit velocity of 3000 ft/sec or less. The study also determined that a textile system with a minimum areal weight density of 1.1 lb/ft^2 was required to defeat fragment threats of the complete grain series at the limit velocities. The NIJ Standard-0101.06,[2] Army MIL-STD-662F,[5] and STANAG 2920[6] standards use the V_{50}-designated ballistic limit velocity.

Courtesy of Warwick Mills, Inc.

Figure 4. FSPs from Left to Right: 2-, 4-, 16-, and 64-Grain Size

Results of ballistic impact tests are often reported by plotting the energy absorbed by the fabric versus the initial projectile velocity V_i as shown in figure 5. The ballistic limit graphically corresponds to the highest initial projectile velocity that does not produce through-penetration failures in the fabric.

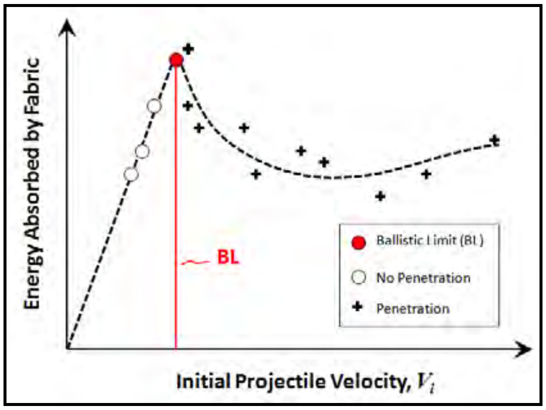


Figure 5. Example of a Ballistic Limit Plot

Although soft body armors are used to prevent penetration by specified small arms projectiles, deformations in the form of indentations can occur to the extent that further life-threatening injuries remain possible. Impact deformation limits are often specified to help minimize indentation depths, which are also known as BFSs. The NIJ standard[2] specifies a maximum BFS of 44.0 mm (1.73 inches). BFSs, as shown in figure 6, may lead to blunt trauma injury, which is also known as behind-armor-blunt-trauma (BABT). Serious injury to tissues, skeletal structures, and organs can occur and may be fatal. Blunt trauma may not be immediately detected—it may manifest itself at a later time and can be damaging to organs remote from the impact site depending on the propagation of stress waves into the body.[8,9]

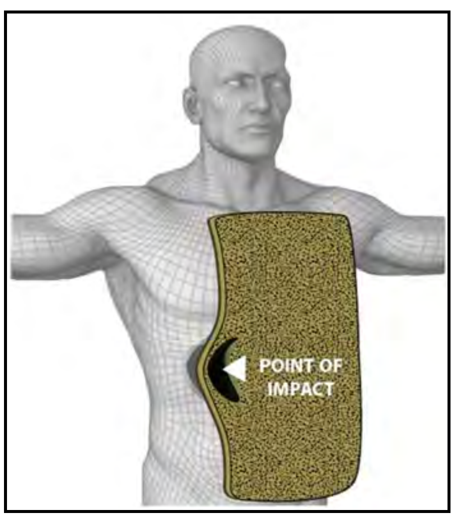


Figure 6. Blunt Trauma Resulting from Excessive Impact Deformation

BFS measurements are made during ballistic testing of vests backed with oil-based modeling clay known as Roma Plastilina No. 1. This clay has mass properties similar to those of a human body and does not spring back after ballistic impact—a key feature for locking-in the indentation depth for measurement purposes, as shown in figure 7.

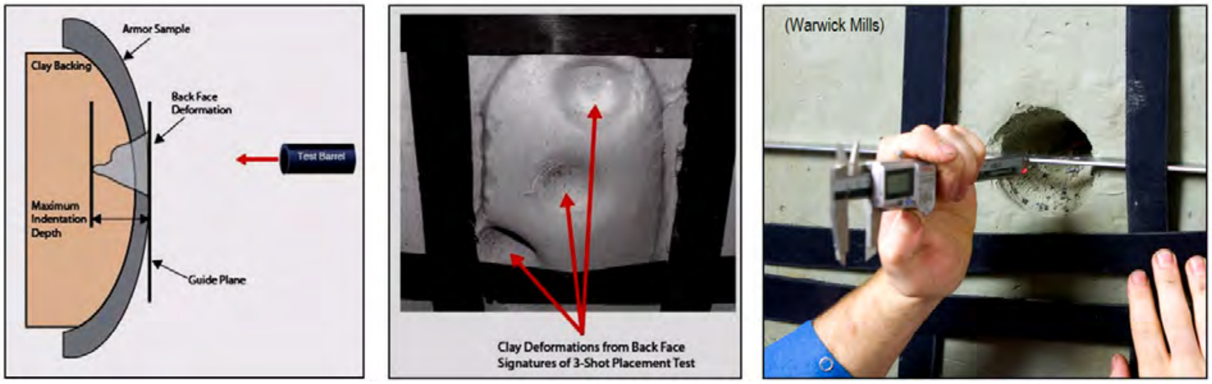


Figure 7. Clay-Backed Ballistic Testing and BFSs

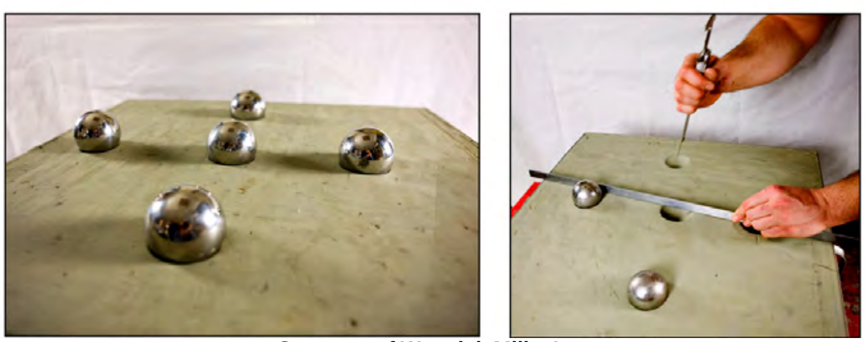
A calibration process is used to qualify the clay for ballistics testing:

1. The clay must be maintained at a controlled temperature.

2. Five steel spheres, 63.5 mm ± 0.05 mm in diameter and 1043 g ± 5 g, are dropped from 2.0 m above the clay at defined spacing from the clay edges and each other as shown in figure 8.

3. The depth of clay deformation from each sphere is then measured.

The clay is qualified if the average depth measures at 19 mm ±2 mm with no depths measured less than 16 mm or greater than 22 mm.



Courtesy of Warwick Mills, Inc.

Figure 8. Calibration Testing and Depth Measurements for Roma Plastilina No. 1 Clay

DESCRIPTION OF BULLET RESISTANT SOFT BODY ARMOR VESTS

Today's body armor vests are often constructed with lightweight, breathable nylon or cotton outer shells that include ballistic packs or panels contained within carriers (pockets). The ballistic packs are assembled from woven, nonwoven, or combined woven/nonwoven fabrics and can prevent penetrations by NIJ threat categories IIA, II, and IIIA with a sufficient number of layers. For example, 20 to 30 layers of fabric may be used to arrest deformable projectiles fired from handguns (see figure 9).

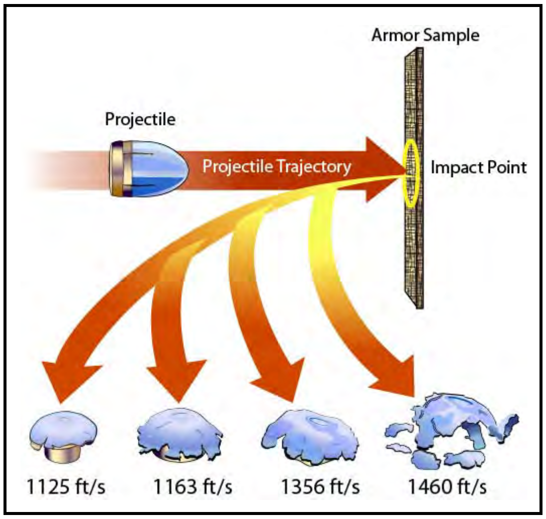


Figure 9. Formation of Blunting Deformations and Petal Fractures in Bullet*

Further protection from blunt trauma is achieved through the addition of rigid trauma plates or inserts mounted in carriers of vests, etc. to further distribute the impact force in the plane of the armor. Threat levels III and IV, however, are designated for much higher velocity and hardness rounds fired from rifles that can easily penetrate fabric armors. Military body armors such as the interceptor body armor (IBA) vest for Army personnel and the releasable body armor vest for the US Special Operations Command (USSOCOM) Special Operations Forces protect against these higher velocity threats by integrating rigid plates known as small arms protective inserts (SAPI) or enhanced SAPI (ESAPI) plates (inserts made of boron-carbide ceramics, etc.), as shown in figures 10 and 11. These plates are positioned within carriers in front of the various strike faces of the armor vests to force the projectile to erode (fracture) upon impact prior to any penetration in the fabric serving to spread the load throughout the armor plane as shown in figure 12.

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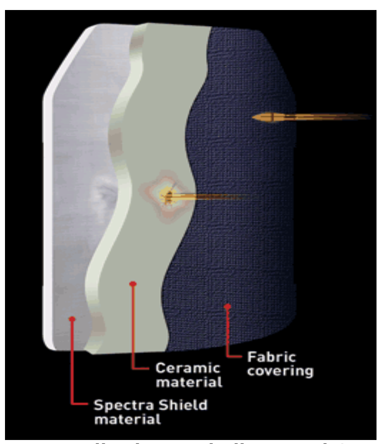
* Figure 9 is based on the notional blunting deformations and bullet petal fractures originally depicted by Warwick Mills, Inc., Ipswich, NH. The Naval Undersea Warfare Center Division, Newport, RI, modified the Warwick Mills' illustration for this report.

Figure 10. IBA for Army Personnel

Figure 11. Releasable Body Armor Vest for USSOCOM Special Operations Forces



Courtesy of Honeywell Advanced Fibers and Composites, Inc.

Figure 12. Example of High-Velocity Rifle Round Protection Using a Ceramic Strike Face Backed with Spectra Shield

MAXIMIZING ENERGY ABSORPTION LEVELS IN SOFT BODY ARMOR

The design of woven fabrics for armor applications is complex because it requires an understanding of the related dynamics and the capability to optimize a system of systems. Numerous hierarchies are present; the smallest considered in this report is the molecular level from which a single fiber is produced. Multiple fibers (or filaments) are bundled to form a yarn, yarns are woven to form a fabric layer, and fabric layers are stacked and joined to form body armors. Mechanical properties, however, do not efficiently translate across these hierarchies; that is, fiber properties do not directly translate to yarn properties, yarn properties do not directly translate to fabric properties and, likewise, single-ply behavior does not directly translate to multi-ply behavior for stacked layers. Quality control testing, therefore, is typically conducted at each level.

To maximize energy absorption levels, therefore, one must understand the materials and mechanics of the (1) fiber bundles within the yarns, (2) type of woven architecture that forms the layers, and (3) stacking arrangement and stitching patterns of the layers that form the ballistic packs. Engineers and scientists must consider the woven armor as a system of subsystems that span multiple dimensional scales to maximize protection levels, as shown in figure 13.

(a) **(b)** **(c)** **(d)**

Figure 13. Multiple Dimensional Scales for Polymer Material Forms Used in Soft Body Armor: (a) Molecular Chains,[10] (b) Fibers, (c) Yarns,[11] and (d) Fabrics[11]

POLYMER MOLECULES

For convenience, the smallest scale considered in this report is the molecular level having dimensional units described in nanometers (10^{-9} meters). The molecular structures of polymer materials detail their building blocks, which are responsible for the desired fiber performance attributes such as strength, stiffness, toughness, environmental and chemical resistances, and melting temperature. These attributes directly depend on the spatial arrangement and integrity of the chemical bonds formed during the polymerization process by which monomer molecules are joined to form polymer molecular chains. The types of organic polymers used in today's soft body armors include the aramids, polyesters, and polyethylenes.

FIBERS

Next is the fiber (also referred to as "filament") scale in which fiber diameters are often measured in units of micrometers (10^{-6} meters) (also referred to as microns). For comparison, fiber diameters used in soft body armors are several times smaller than that of human hair. Fiber weights are classified by denier, which is the linear density defined as "the weight in grams of a 9000-meter-long fiber (or yarn)." Fiber tensile strength is defined as "tenacity having units of grams-force per denier (gpd)." Tenacity generally increases with decreasing fiber diameter. The stiffness of a fiber is designated by its elastic modulus *E*. The elastic modulus is obtained from tensile tests of a fiber (or yarn) and has units of grams-force per denier; it is computed as the initial slope of the tensile stress-strain curve. Many polymer fibers exhibit visco-elastic behavior (combined elastic and viscous traits) to the extent that tenacity and elastic modulus are sensitive to rates of loading; that is, these properties can increase with increasing strain rates. Elongation at break is the amount of stretch that a fiber (or yarn) experiences during a tensile test at failure. Elongation is computed as a percent of the initial tested length. Additional properties helpful for weight-sensitive applications are specific strength and specific modulus—the strength and modulus values divided by the fiber density, respectively; both have units of length alone. Specific strength is also referred to as the "breaking length," which is equivalent to the length of fiber required to break under its own weight when it is hanging vertically. Specific gravity is the ratio of the material density to the density of water. Fibers are buoyant if their specific gravities are less than one. The properties of various high-performance fibers are listed in table 2 in conjunction with those reported by Yang[12] with steel fibers shown for comparative purposes.

Table 2. Properties of Several High-Performance Fibers

Fiber	Manufacturer	Grade	Polymer Type	Spinning Method	Density (g/cc)	Strength (gpd)	Modulus (gpd)	Elongation at Break (%)	Specific Strength (10^6 in)	Specific Modulus (10^8 in)	Fiber Diameter ($x10^{-6}$ m)	Maximum Temperature (°C)
Dyneema	DSM	SK75, SK78	Polyethylene	Gel	0.97	38-45	1267-1552	3-4			12-21	
		SK60, SK62, SK65	Polyethylene	Gel	0.97	28-38	759-1158	3-4				
		SK25	Polyethylene	Gel	0.97	25	608	3-4	25.8			
Spectra	Allied Signal	1000	Polyethylene	Gel	0.97	35	2000	2.7	13.4	7.6	28	100
		900	Polyethylene	Gel	0.97	30	1400	3.5	11.5	5.3	38	100
Kevlar	DuPont	149	Aramid	Gel	1.47	18	1100	1.5	6.9	4.2	12	250
		129	Aramid	Gel	1.45	26.5	750	3.3	10.1	3	12	250
		119	Aramid	Gel	1.44	24	470	4.4	9.2	1.6	12	250
		49	Aramid	Gel	1.45	23	950	2.8	8.8	3.6	12	250
		29	Aramid	Gel	1.43	23	580	3.6	8.8	2.1	12	250
Nomex	DuPont		Aramid	Wet	1.38	5	140	22	1.9	0.5	121	250
Nylon		6,6	Polyamide	Melt	1.14	9	50	19	3.4	0.2	25	150
Technora	Tejin Aramid		Aramid	Dry	1.39	27	570	4.3	10.3	2.2	12	250
Twaron	Tejin Aramid		Aramid									
Vectran	Kuraray America	HT	Polyester	Melt	1.43	25.9	600	3.8	9.89	2.3		N/A (Chars >400)
		UM	Polyester	Melt								276
PBI	PBI Performance Products		Polybenzimidazole	Dry	1.43	3.1	45	30	1.2	0.2		250
PBO	Toyobo	HM	Polybenzobisoxazole		1.56	42	2034					
PBT			Polybenzobisthiazole		1.57	25	2690	1.3	9.6	10.3		350
PET					1.39	9.5	100					
E-Glass	Owens Corning		Glass	Melt	2.55	11.6	320	3	4.4	1.2	5-25	350
S-Glass	Owens Corning		Glass	Melt	2.48	21.9	390	5.3	8.4	1.5	5-15	300
Steel					**7.8**	**11**	**220**	**4.8**	**4.2**	**0.8**		**500**

CONVERSIONS:
GPa = gpd x density (g/cc) /11.33
Specific strength (in)= tenacity (gpd) x $3.82x10^5$
Specific modulus (in)= modulus (gpd) x $3.82x10^5$

FIBER PRODUCTION

Polymer fibers are produced using a variety of spinning methods including dry, wet, gel, and melt spinning as depicted in figure 14. Spinning refers to the process of extruding fibers through a series of small holes in devices known as spinnerets. Spinnerets used to produce manmade or synthetic fibers are dies that closely resemble showerheads. The polymers (and solvents, if present) are forced through holes in the spinnerets. As the polymer exits the spinneret, the polymer solidifies, forming fibers having controlled and consistent diameters and cross-sectional shapes with nearly unlimited lengths. The fibers are then stretched and drawn onto takeup rollers. Stretching further enhances the fiber tensile strength and toughness properties by aligning the molecular chains along the fiber axis.

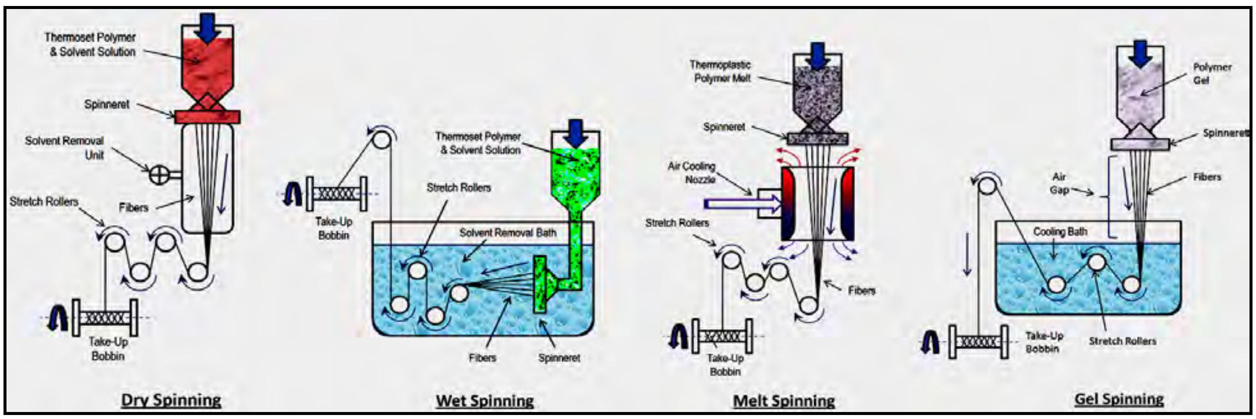


Figure 14. Spinning Methods for Producing Polymer Fibers

Fiber-spinning methods are selected based on polymer compatibility; for example, thermoplastic polymers require melt spinning, and thermoset polymers require dissolution in a solvent. Aramid (Kevlar) and UHMWPE (Dyneema and Spectra) fibers are produced by gel spinning; nylon (polyamide), Vectran (liquid crystal polyester), and PET (polyethylene terephthalate) fibers are formed by melt spinning; and PBI (polybenzimidazole) fibers are made by dry spinning. Additional postprocessing methods are also applied to fibers including sizings. Sizings are surface treatment agents applied to the fibers or yarns to (1) improve performance in the final product, (2) reduce abrasion for improved handling and weaving processes, (3) control moisture absorption, (4) protect the fibers from environmental effects, and (5) increase compatibility for bonding with matrix materials in fiber-reinforced composites.

Today's fiber research areas include (1) the development of next-generation ultrahigh performance fibers through advanced polymer chemistry, (2) carbon nano-tube reinforcement technologies to produce unprecedented fiber strengths, and (3) polymer spinning processes capable of reducing fiber diameters from the micron to the nano scale.

YARNS

Production of today's woven body armors requires the bundling of tens to hundreds of continuous fibers to create a single yarn resulting in cross-sectional dimensions measured at the millimeter scale (10^{-3} meters). The number of fibers within a yarn is referred to as "filament count." Yarns constructed of continuous filaments often align the fibers in a straight configuration or in a slightly twisted helix and are processed onto pirns or bobbins. The helical fiber arrangement results from the addition of twist. Twist is a mechanism that can significantly increase the tensile strength of staple (discontinuous) yarns; twist, however, is used only minimally for continuous fiber yarns to improve handling during weaving operations by restricting lateral motions of individual fibers. Twist is measured by the number of turns per unit length of yarn. Yarns are often categorized by denier rather than filament count with many woven body armors constructed of deniers from 500 down to as low as 70.

Examples of ongoing research of continuous filament yarns include (1) hybridization of yarns spun from comingling or co-extruding multiple polymers, (2) nanotechnology reinforcements, and (3) strain-rate effects on tenacity and modulus properties.

WOVEN FABRICS

A single layer of woven fabric has characteristic length and width dimensions on the order of 10^0 meters and, for a plain weave, is formed by interlacing yarns of two principal families, designated "warp" and "weft," at right angles to each other as depicted in figure 15.

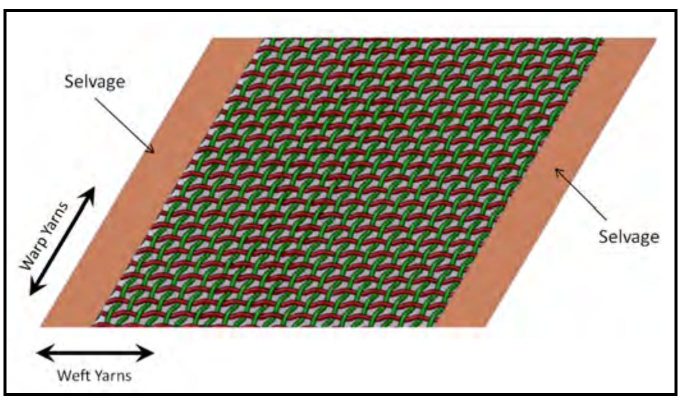


Figure 15. Warp and Weft Yarn Directions for a Plain-Woven Fabric

The yarns of each family pass over and under yarns of the crossing family in a periodic fashion. Woven fabrics are referred to as "crimped fabrics" because yarns of one direction are bent around their crossing neighbor yarns. Warp yarns run parallel to the selvage (fabric edges) and are virtually unlimited in their length. The weft (or fill) yarns run across the fabric width. The undulations, which are referred to as "crimp," are shown in Pierce's geometric fabric model[13] (figure 16) for a plain weave. Pierce's geometric model relates the fabric parameters as they are coupled among yarn families. The crimp height *h* is related to the crimp angle α and yarn length *L* as measured between yarns and the sum of yarn diameters at the crossover regions by the equations described by Hearle, Grosberg, and Backer[14] in figure 16. Crimp, denoted as *C*, is the amount of waviness produced in a yarn when woven in fabric form as shown in figure 17; it is a geometric property of the weave because of the woven architecture used. Crimp is obtained by measuring the length of a yarn in the woven state, L_{fabric}, and the length of that same yarn after being extracted from the fabric and straightened, L_{yarn}, and then computed according to equation (1) as a percentage.

$$C = \frac{L_{yarn} - L_{fabric}}{L_{fabric}}. \qquad (1)$$

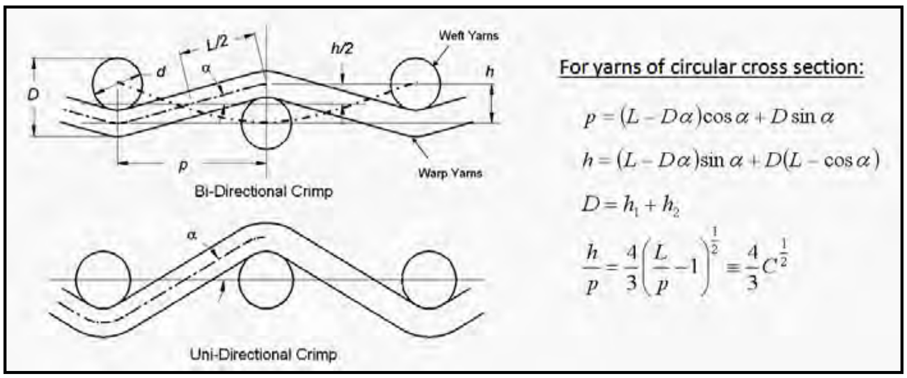


Figure 16. Examples of Pierce's Geometric Model for Plain-Woven Fabrics with Bidirectional and Unidirectional Crimp

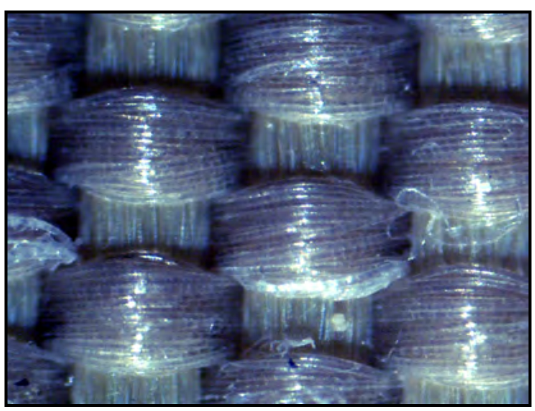


Figure 17. Enlarged View of a Unidirectionally Crimped, Plain-Woven Fabric with Continuous Multifilament Yarns

Often, crimp contents are greater for warp yarns than for weft yarns because of the differences in yarn weaving tensions. Figure 18 shows an extracted warp yarn removed from the woven fabric of figure 17 to demonstrate the permanent crimping deformation. The category of woven fabrics includes a variety of weaving architectures such as plain, basket, twill, satin, braid, leno, and triaxial weaves.

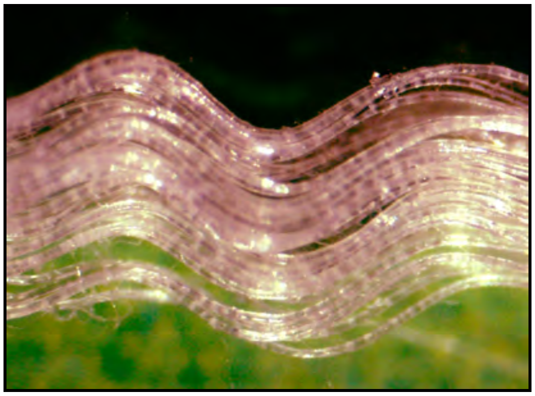


Figure 18. Enlarged View of a Continuous Multifilament, Crimped Yarn Extracted from a Plain-Woven Fabric

The architecture of the woven fabric is further described by the yarn cross-sectional dimensions, number of warp yarns per unit fabric width, number of weft yarns per unit fabric length, and cover factor—all of which affect the energy absorption levels. Additionally, the weight of the fabric is defined by its areal weight density often expressed in ounces per square yard.

Several woven architectures are used in soft body armors including the plain and basket weaves shown in figure 19, which differ only in the number of times or frequency the yarns of one family cross those of the other family prior to the next undulation. The selected woven architecture influences the resulting protection levels.

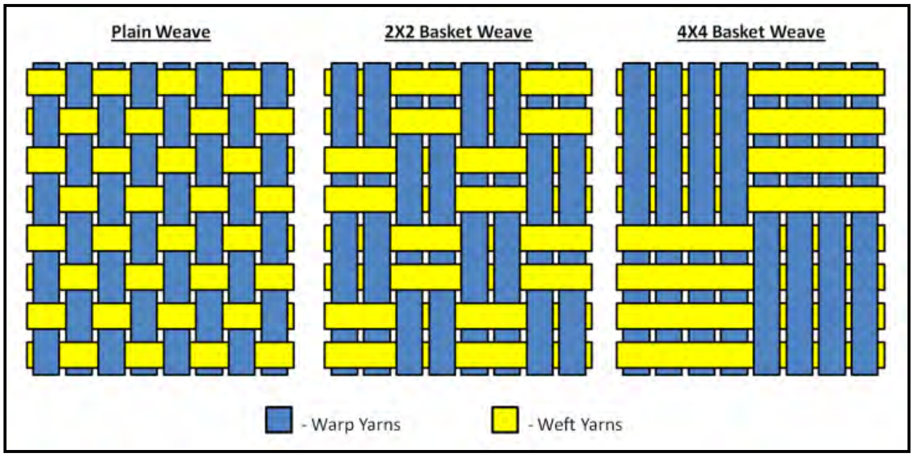


Figure 19. Plain and Basket Weave Architectures

Examples of ongoing research in woven fabrics for soft-body armors include (1) fabrics impregnated with shear thickening fluids, (2) electro-rheological fabrics, (3) bi-modulus fabric weaves; (4) improved experimental techniques using embedded sensors; and (5) advanced numerical modeling methods.

WOVEN FABRIC KINEMATICS

The energy absorbability of woven fabrics subjected to dynamic loading events, such as ballistic impact, stab penetration, and blast pressure, is significantly dependent on the ability of the fabric to enable or restrict yarn motions within the weave. Yarn motions, which are necessary for ballistic energy absorption, occur because of the yarn-to-yarn interactions, such as crimp interchange, shearing (trellising), and friction.

Consider a plain-woven fabric subject to a tension along the warp yarns. The warp yarns attempt to straighten, decrease their crimp heights, and elongate their effective lengths. The weft yarns, however, are forced to increase their crimp heights, resulting in contractions of their effective lengths. This effect is referred to as “crimp interchange” and is analogous to the Poisson phenomenon exhibited in metals. Crimp interchange is a coupling effect exhibited between warp and weft yarns and depends on the ratio of initial crimp contents between yarn families and the ratio of tensions between yarn families; it is a source of nonlinear load-extension behavior for woven fabrics.

Hearle, Grosberg and Backer[14] describe a limiting phenomenon to crimp interchange. Consider the case of biaxial tension. As the biaxial tensions continually increase for a given warp tension-to-weft tension ratio, yarn slip at the crossover regions initially increases and then ceases as the spacing between yarns reach their lowest limit. This configuration is referred to as the “extensional jamming point,” which can prevent a family of yarns from straightening and thereby not achieve its full strength.

Now consider the plain-woven fabric subjected to pure shear as shown in figure 20. The yarn families rotate at the crossover regions with respect to each other and become increasingly skewed with increasing shear load. The change in angle is referred to as the “shear angle.” At larger shear angles, the available space between yarn families decreases and rotational jamming (locking) of the yarn families occur. This phenomenon is known as shear-jamming, and the angle at which the yarn families become jammed is referred to as the “shear-jamming angle.” The shear-jamming angle decreases with increasing yarn counts per unit length and can be estimated from Pierce’s geometric fabric model[13] or obtained experimentally with various trellising or biaxial test fixtures. Continued loading beyond the onset of shear-jamming produces shear wrinkling, a form of localized out-of-plane deformations.

It is important to determine the extension- and shear-jamming points for ensuring proper amounts of yarn mobility that lead to optimized energy absorption levels. In general, jamming is related to the maximum number of weft yarns per unit length that can be woven into a fabric for a given warp yarn size and spacing.

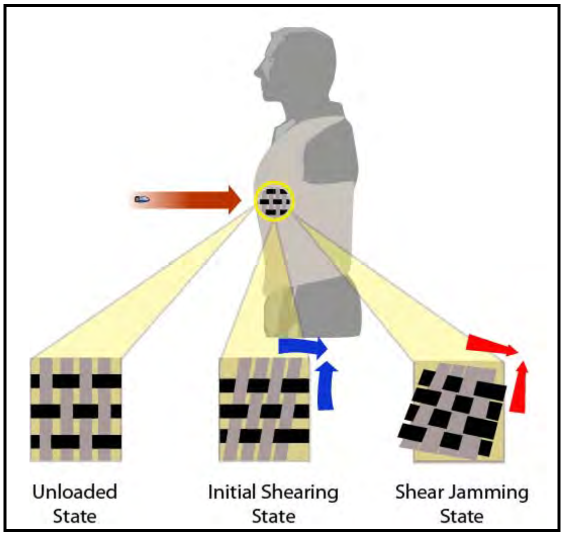


Figure 20. Effect of Shearing Deformations on Plain-Woven Fabrics

Friction between yarns at the crossover regions can be used to minimize yarn migrations away from the impact site and to provide a dissipative energy transfer mechanism.

WAVE PROPAGATIONS IN FIBERS

Consider a single fiber having restrained ends that is subjected to transverse ballistic impact at its midspan. The impact force produces a stress wave that travels along the longitudinal axis of the fiber away from the impact site. Upon reaching the restrained ends, the wave reflects back toward the impact site because of the restoring forces resulting from the elasticity of the fiber. Stress waves travel at speeds equivalent to the speed of sound in the fiber material *c*, which is computed by equation (2):

$$c = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}, \tag{2}$$

where *E* is the elastic modulus, ν is Poisson's ratio, and ρ is the mass density.

A second type of wave develops and is known as the transverse displacement wave. This wave generates the observable deflections that travel at the same speed and direction as the projectile. The longitudinal stress and transverse displacement waves are depicted in figure 21 (by Roylance, et al.[15]) where *c* is the longitudinal wave speed, ε is the increment of strain, *t* is time, *u* and *v* are the longitudinal and vertical particle velocities, respectively, *V* is the projectile velocity, the product $c(\varepsilon_0)t$ is the instantaneous distance over which the strain is nonzero, the product $c(\varepsilon = 0)t$ is the instantaneous distance to the zero-strain wave front, the product *Ut* is the transverse wave half-width, the product *Vt* is the amplitude of the transverse wave, and *w* is the constant particle velocity.

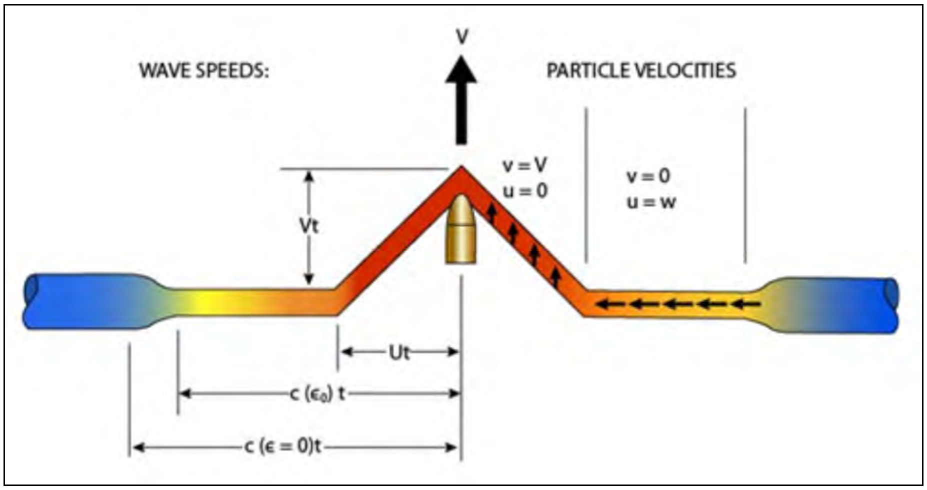


Figure 21. Stress and Transverse Waves in a Single Fiber Subject to Projectile Impact

IMPULSE-MOMENTUM AND ENERGY BALANCE EQUATIONS

The fundamental laws of motion as stated by Sir Isaac Newton relate to the masses, velocities, accelerations, and forces associated with interacting bodies. In addition, the laws of conservation of energy, mass, and momentum provide the governing equations used to fully describe these interactions. First, consider the impulse-momentum equation given by equation (3), which is particularly useful for characterizing the impact force *F* produced by the projectile on the target as a function of the linear momentum change:

$$\int_{t_i}^{t_f} F dt = m(V_i - V_f), \tag{3}$$

where *F* is impact force, *t* represents time, *m* is the mass of the projectile, V_i is the initial velocity of the projectile, V_f is the final velocity of the projectile ($V_f = 0$ for nonpenetrating impacts). Because energy is conserved, the energy balance expressed in equation (4) for a rigid (nondeforming) projectile governs the impact event if heat dissipation, acoustic energy, and any rotational kinetic energies of the projectile are neglected for simplification.

$$\frac{1}{2} m(V_i^2 - V_f^2) = E_{\text{damping}} + E_{\text{elastic}} + E_{\text{plastic}} + E_{\text{friction}} + E_{\text{kinetic}}. \tag{4}$$

The left side of equation (4) represents the kinetic energy of the projectile. Each term on the right side represents a specific energy absorption mechanism provided by the fabric target where E_{damping} is the energy dissipated through viscous damping, E_{elastic} is the elastic strain energy (recoverable), E_{plastic} is the plastic (inelastic) strain energy, E_{friction} is the energy dissipated through friction produced at the yarn crossover regions, yarn-projectile contact interfaces, and layer–to layer interactions, and finally, E_{kinetic} is the kinetic energy. For deformable projectiles, such as lead handgun rounds, similar energy absorption terms are added to equation (4) to include the elastic and plastic strain energies of the projectile.

BALLISTIC IMPACT OF WOVEN FABRICS

Many dynamic effects observed in ballistic impacts on soft, woven body armors parallel that which occurs when a baseball is caught in the webbing of a catcher's mitt. Consider cases in which a deformable projectile and a rigid projectile impact identical multilayered woven fabric armors having clamped edges, as shown in the half-symmetry models of figure 22. Both projectiles initially contact a minimal number of yarns; these are known as the primary yarns. The primary yarns begin to compress in the "through-thickness" direction, and stress waves initiate and propagate along both yarn directions, dissipating energy away from the impact site.

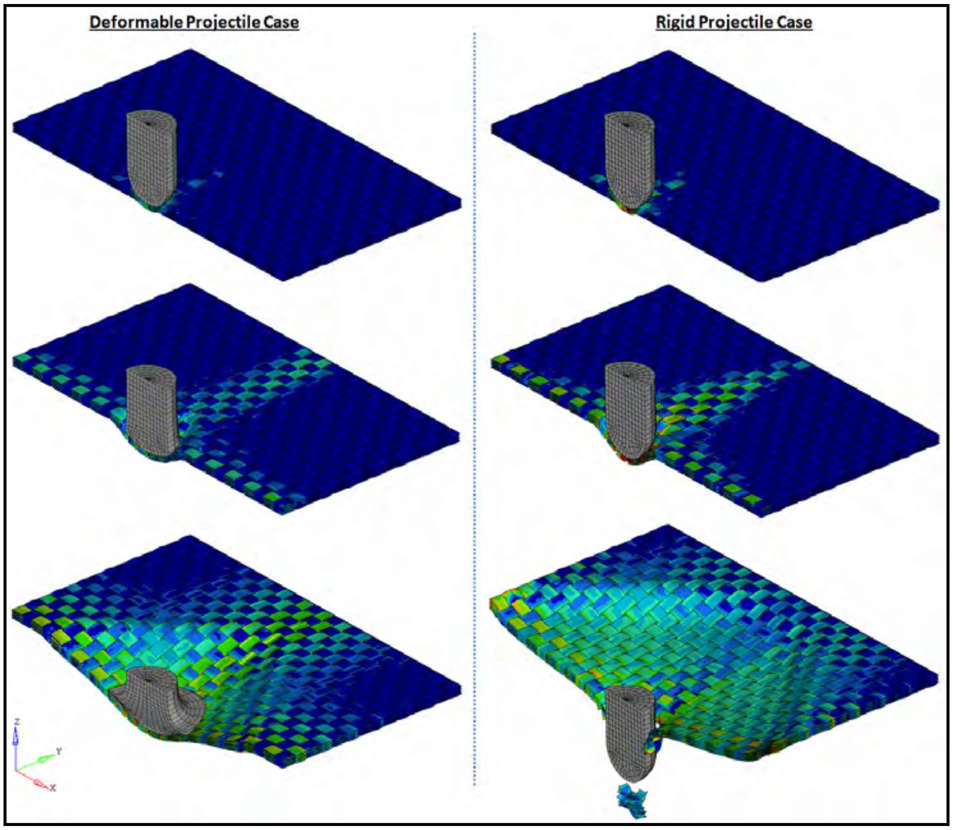


Figure 22. Numerical (Finite Element Analysis) Models of a 4-Ply, Plain-Woven Fabric System Subject to Ballistic Impact Showing Yarn Stress Wave Color Contours, Projectile Blunting (Deformable Projectile Case) and Fabric Penetration Failure (Rigid Projectile Case)

The crossover regions, however, reflect some of the energy back toward the impact site—a negative characteristic of the woven construction in contrast to UD fabrics. The primary yarns begin to deflect out from the fabric plane in the direction of projectile travel. These dynamic deflections are the transverse waves and can lead to yarn pullout, a deformation mode in which the primary yarns grossly displace out from the fabric plane. More primary yarns are gradually recruited (depending upon the projectile shape, diameter, hardness, and yarn sizes) and attempt to straighten (crimp interchange). Friction develops at the crossover regions, and further deflection induces elastic and plastic (inelastic) stretching of the yarns.

Secondary yarns (those not directly in contact with the projectiles) begin to participate because of the friction developed at the crossover regions. Once the crossover friction is overcome, slip and shearing between yarn families occur and the interstices (regions of oblique susceptibility shown in the woven fabric of figure 2) expand. The projectiles begin to decelerate. The deformable projectile plastically deforms (referred to as "blunting") with possible fracture sites produced. Blunting often develops a mushroom-shaped appearance that increases the diameter of the projectile's tip, causing an increase in the number of primary yarns and an expanded distribution of the impact force. The rigid projectile does not deform; the distribution of impact force remains localized causing increased probability of stress failures in the primary yarns. A peak deflection is produced, at which point the projectile is either fully arrested or allowed to penetrate if a sufficient number of primary yarns have failed. Yarn failures and penetrations are shown in figures 23 for FSP impacts on single-layer woven fabrics.

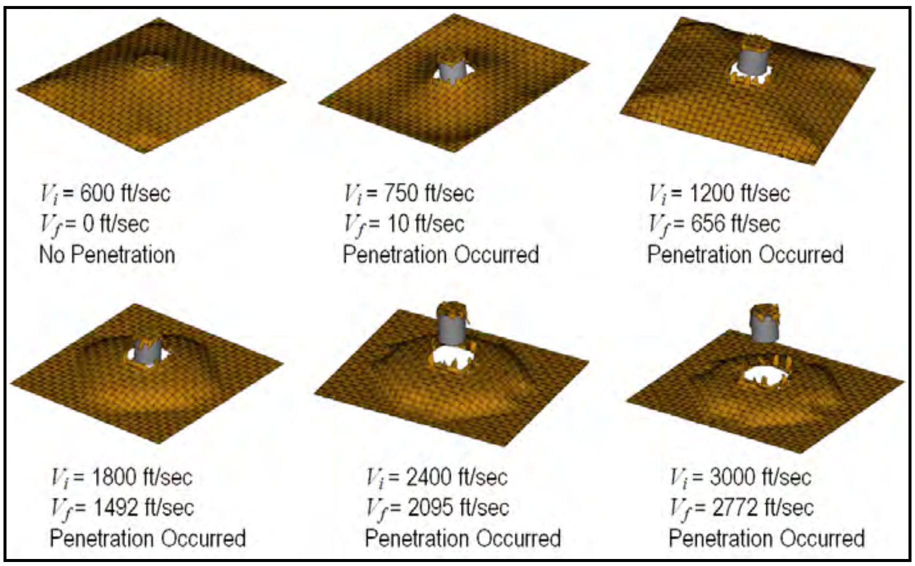


Figure 23. Numerical Models of Plain-Woven Fabrics Subjected to Two-Grain FSP Impacts Showing Transverse Waves and Yarn Failures for Different Projectile Velocities

The proper levels of yarn mobility within the weave (that is, crimp interchange, stretching, shearing rotation, and pullout) enable the fabric to dissipate ballistic impact energy. For the stacked multilayer, soft woven armor, the ballistic energy absorbability does not necessarily scale with the energy absorption capacities of its individual layers. Layer-to-layer interactions may prevent the stacked layers from achieving their individual energy absorption capacities because compressive stresses of the primary yarns in stacked fabrics can exceed those observed in single-layer impacts as reported by Cunniff.[16]

Yarn pullout is an observable deformation mechanism occurring in woven fabrics subject to ballistic impact; therefore, yarn pullout testing is often performed to determine the fabric's frictional characteristics. Studies by Duan, et al.[17] and Cavallaro and Sadegh[18] have shown that the dynamic energy absorption capacities of woven fabrics increase with increasing yarn-to-yarn coefficient of friction μ. These tests are performed by extracting single yarns from a woven fabric and monitoring the force-displacement response using a fixture such as the one developed by Kirkwood, et al.[19] shown in figure 24. The initial extraction force produces a peak resistance. When yarn slippage starts, the resistance force decreases as the extracted yarn is pulled from the weave and the number of actively participating crossover regions sequentially decreases one by one.

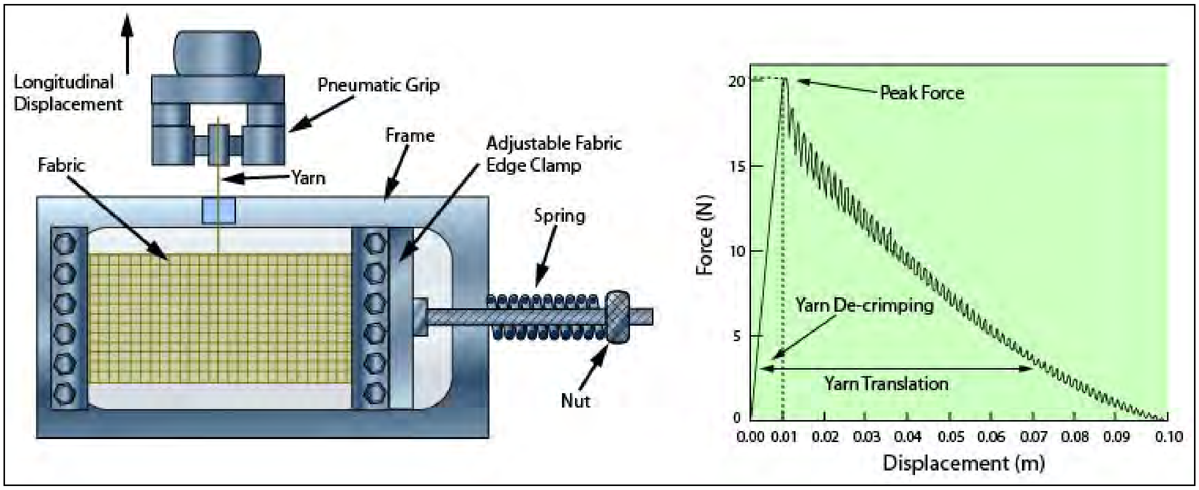


Figure 24. Examples of Yarn Pullout Test Fixture and Force Versus Displacement Plot

CONCLUSIONS

Soft body armors have evolved into highly sophisticated protective devices delivering unprecedented protection levels against some of the harshest physical threats facing mankind. Yet ballistic and fragment threats remain a primary concern for the military and law enforcement communities. Continued effective protection of these communities requires further evolution of body armor; that is, the development of improved fiber materials, manufacturing processes, and relevant mechanics that outpace future increases in weapon effectiveness levels.

As demonstrated here, the research required to advance soft body armor protection levels demands a deeper and more thorough understanding of the material behaviors across many dimensional scales. Further investigation of the complex dynamics at each scale will increasingly incorporate the virtual environment through robust, physics-based, numerical modeling tools using, for example, explicit finite element analysis techniques coupled with experimental validation testing. Advanced numerical models that unite the armor and human body elements will be aggressively pursued for developing new methods and materials for defeating ballistic and fragment threats while mitigating back-face signatures and behind armor blunt trauma injuries.

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