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Ballistic Impact Resistance Mechanism of Woven Fabrics and their Composites

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Abstract—**The development of the new generation of tough, high-strength, high-modulus fibers has led to the use of fabrics and their composites for a number of ballistic protection applications, in particular, for body armor. Numerous studies have been conducted to identify material properties and ballistic impact resistance mechanism that are important to the performance of ballistic fibers and their composites. The paper reviews the factors that influence ballistic performance including mechanisms of ballistic impact resistance, specifically, material properties of the yarn, fabric architecture, projectile geometry and impact velocity, boundary conditions, multiple plies and friction effect. It is important to note that almost all of the parameters that affect ballistic penetration resistance of a fabric are interrelated and the attempts to single out an individual effect cannot lead to a conclusive result. This makes the studies very complicated.**

Keywords— ballistic impact, fabric, strain wave, armor, composites

I. INTRODUCTION

Humans throughout recorded history have used various types of materials to protect themselves from injury in combat and other dangerous situations. At first, protective clothing and shields were made from animal skins. As civilizations became more advanced, wooden shields and then metal shields came into use. Eventually, metal also was used as “clothing,” what we now refer to as the suit of armor associated with the knights of the Middle Ages. However, with the advent of firearms (c.1500), most of the traditional protective devices were no longer effective. In fact, the only real protection available against firearms were manmade barriers and manmade fortifications such as trenches and ditches; or natural barriers, such as rocks and trees. One of the first recorded instances of soft armor use was by the medieval Japanese, who used armor manufactured from silk [1, 2]. Much later, at the late 19th century, the US army explored the possibility of using soft armor manufactured from silk. But while the garments were shown to be effective against the low-velocity bullets (travelling at 120 m/s or less)), they did not offer protection against the new generation of handgun ammunition being introduced at that time that traveled at velocities of more than 180 m/s. This, along with the high cost, made the concept unacceptable. The next generation of ballistic vests was introduced during World War II. The “flak jacket,” constructed of ballistic nylon, provided protection primarily from munitions fragments and was ineffective against most pistol and rifle threats. These vests also were very cumbersome and bulky and were restricted primarily to military use. It would not be until the late 1960s that new fibers would be discovered that would make today’s generation of body armor possible.

The first high-strength and high-modulus fibers were developed in the 1960s and ushered in a new era of fabric based body armor that protects against lower-end firearms. Considerable research has been conducted since then, resulting in development of new generation of very strong and light high-performance ballistic fibers such as aramids (Kevlar®, Twaron®), ultra-high molecular weight polyethylene (Dyneema®, Spectra®), PBO (Zylon®). Application of these fibers makes fabrics stronger, with increased ballistic penetration resistance while still maintaining their flexibility.

Depending on class to which they belong to, different fibers have different structural properties, leading to different responses to ballistic impact when woven into fabrics. Individual yarns do not possess the strength to safeguard against ballistic impact. However, when woven into a fabric they possess a strength that is much higher than the sum total of the individual strands and also possess a strength-to-weight ratio which is 10-15 that of good quality steel [3]. This is attributed to the fabric weave, architecture, yarn crimp, projectile properties and the various mechanisms of energy absorption of the fabric.

II. IMPACT INTO BALLISTIC FABRICS

Over the past few decades many different techniques have been used to derive constitutive relations and model overall fabric behavior for use in ballistic impact applications. Different models include various effect and phenomena associated with ballistic impact of fabrics; however there is no single comprehensive model that reproduces and represents all phenomena at the same time. However, many simplistic models have been found to yield results that are realistic [4-6].

The impact and perforation of fabric are functions of a number of parameters including the material properties of the yarns, the fabric structure, the projectile geometry and velocity, the interaction of multiple plies, the far-field boundary conditions and the friction between the yarns themselves and between yarns and the projectile. Before going into the discussion of the influence of each of these factors a general description of the physical phenomena of fibers impact deformation will be described next.

III. TRANSVERSE IMPACT BEHAVIOR OF A SINGLE FIBER

Numerous experimental and theoretical works have been conducted to understand the transverse impact behavior of single yarn and single fabric layer, during the past several decades. Roylance [7], Smith et al. [8], and Morrison [9] studied the response of yarns to high speed impact, while Briscoe and Motamedi [10], Smith et al. [11] and Wilde et al. [12] studied the response of single fabrics layer. An investigation on the transverse impact behavior of a single fiber makes a good starting point into description of the impact behavior of fabrics. When a single yarn is struck transversely by a projectile, two waves, longitudinal and transverse, propagate from the point of impact. The longitudinal tensile wave travels along the fiber axis at the sound speed of the material. As the tensile wave propagates away from the impact point the material behind the wave front flows toward the impact point, which has deflected in the direction of motion of the impacting projectile, Fig.1. This transverse movement of the fiber is the transverse wave, which is propagated at a velocity lower than that of the sound velocity of the material.

Fig. 1 shows a projectile transversely impacting a single straight fiber. The longitudinal wave velocity, w (m/s), is given by Smith et al. [13]:

$$w = \sqrt{\frac{E}{\rho}} \qquad (1)$$

Where:
E= tensile module of the fiber in Pa,
ρ = density of the fiber in kg/m^3.
The strain of the fiber is zero ahead of the longitudinal wave front, and a constant tensile strain is developed behind of the wave front.

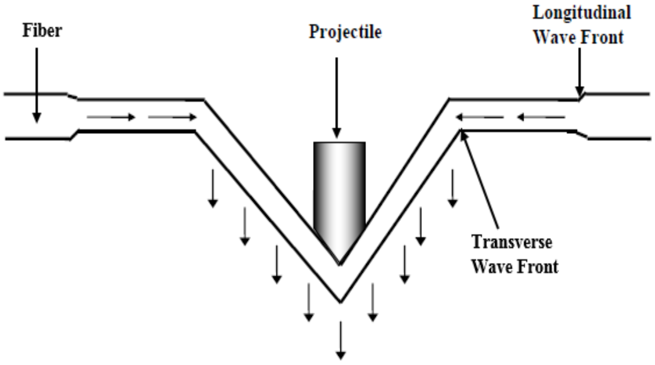

Fig. 1. Transverse impact on a single fiber [16]

The tensile strain (ε), is determined by the fiber tensile elastic modulus (E), density (ρ), and the impact velocity (v). It is presented by:

$$2\varepsilon\sqrt{\varepsilon(1+\varepsilon)} - \varepsilon^2 = \frac{\rho v^2}{E} \qquad (2)$$

The transverse wave propagates away from the impact point at a relatively lower speed and its wave velocity (u) in (m/s) is given by:

$$u = w\sqrt{\frac{\varepsilon}{1+\varepsilon}} \qquad (3)$$

The strain of the fiber does not change ahead of the transverse wave front but the motion of the fiber shows a rapid change. Ahead of the transverse wave front but behind the longitudinal wave front, fiber moves longitudinally toward the impact point. Behind the transverse wave front, fiber material moves transversely in the impact direction.

IV. TRANSVERSE IMPACT OF A SINGLE LAYER OF FABRIC

The response of a single layer of fabric shows similarities with a single fiber response. Cuniff [14] notes that when a projectile impacts the fabric, it produces analogues transverse deflection of the yarns that are directly hit by the projectile (defined as primary yarns) and generates longitudinal strain waves that propagate at the sound speed of the material along the axis of the yarns. Additionally, orthogonal yarns (defined as secondary yarns; those are the yarns that intersect the primary yarns) are then pulled out of the initial fabric plane by the primary yarns. These orthogonal yarns undergo a deformation and develop a strain wave like those observed in the primary yarns. Similarly, these orthogonal yarns then drive yarns with which they intersect. These yarn-to-yarn interactions, which are function of the friction between them, produce bowing and subsequent misalignment of the orthogonal yarns toward the impact point. The transverse deflection proceeds until the strain at the impact point reaches a breaking strain.

Numerical studies of Roylance [15] have shown that the majority of the kinetic energy of the projectile is transferred to the primary yarns as strain and kinetic energy, whereas, the contribution of the orthogonal yarns to energy absorption is small. Roylance has observed that the wave velocity in a fabric, w', is a fixed fraction of the wave velocity in a single fiber, w:

$$w' = \frac{w}{\alpha} \qquad (4)$$

According to Roylance, α is a numerical factor which, generally, has a value greater of unity. It can be attributed to the effective increase of lineal density caused by crossovers. In a square woven fabric, the lineal density of a fiber along which a wave is propagating is effectively doubled. This retards the wave velocity according to the expression for the wave speed, *w*, by a factor of:

$$\alpha = \sqrt{2} \tag{5}$$

V. MECHANISM AFFECTING BALLISTIC PROPERTIES OF FABRIC

Ballistic performance of fabrics is affected by a number of mechanism as noted by Cheeseman and Bogetti [16], Tabiei and Nilkantan [17] who reviewed the mechanisms influencing the ballistic performance of woven fabrics. Ballistic penetration resistance and mechanism involved are a combination of many simultaneous factors. It is therefore not possible to single out any one factor as the controlling parameter in ballistic impact or to investigate the role of an individual parameter without first explicitly stating the influence of other parameters in the investigation. Roylance et al. [18] summed this up in his observation that the response of fabric cannot be determined from the properties of the fibers alone since the material properties and fabric architecture combine to produce unique structural response. Cunniff [19] derived a dimensionless fiber property U^*, defined as the product of the specific fiber toughness and strain wave velocity, which could be used to quantitatively assess the performance of fibers,

$$U^* = \frac{\sigma\varepsilon}{2\rho}\sqrt{\frac{E}{\rho}} \tag{6}$$

where σ is the fiber ultimate strength, ε is the fiber ultimate tensile strain, E is Young's modulus, and ρ is the fiber density. Cunniff demonstrate that U^* may be a major factor that relates ballistic impact performance to fiber mechanical properties, independent of other parameters, such as impacting projectile mass, presented area or areal density. Although the exact relationship between the mechanical properties of a yarn and the ballistic resistance of a plied fabric from such yarn has never been established, the conclusion that the mechanical properties of the yarn would affect a fabric ballistic characteristics seems obvious.

5.1. Material properties

The development of high-strength, high-modulus fibers has allowed the development of current bullet-resistant fabrics. When impacted, the yarn undergoes a sharp increase in stress, the magnitude of which is related to the impact velocity. At a low velocity, bellow what is called the "critical velocity", this initial stress increase is insufficient to break the fibers; thus allowing transverse deflection and resultant yarn extension time to propagate and disperse the stress wave rapidly away from the impact point resulting in absorption of energy by the fabric. Field and Sun [20] showed that materials having higher wave velocity were advantageous since the stress and strain can propagate more quickly to the neighboring fibers and layers, thus involving more material in ballistic impact resistance. At impact velocities greater than V50 (the velocity at which the probability of full penetration of projectile is 50%) fabrics are perforated during the initial stress rise. As a result, no time is allowed for transverse deflection to propagate, which reduces fiber straining; therefore the energy absorbed above V50 is small.

5.2. Fabric structure

Apart from the high-modulus and high-strength properties of constituent yarns, the construction is what gives a fabric its unique ballistic resistance mechanism.

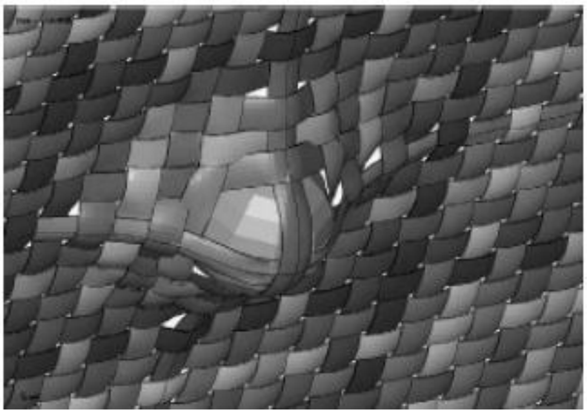

Fig. 2. Wedge-through phenomenon [16]

Roylance et al. [18] note that response of these fabrics cannot be determined from the properties of the fibers alone, but that "the material properties and the fabric geometry combine to produce structural response". It has been observed that loosely woven fabrics and fabrics with unbalanced weaves result in inferior ballistic performance. Chitrangad [21] noted that fabrics should have cover factor, defined as density of weave, from 0.6 to 0.95 to be effective when utilized in ballistic applications. Yarns are typically damaged by the weaving process when cover factors are greater than 0.95, and they may be too loose for a proper response when cover factors fall below 0.6. Loosely woven fabrics might show a worse performance by having the projectile slide-through action instead of wedge through between the yarn mesh. Weave patterns typically used for ballistic application are plain and basket. When a projectile trikes a layer of fabric, the fabric deflects transversely and the mesh of yarns is distended, resulting in the enlargement of the spaces between yarns as shown in Fig. 2. If the fabric is not too tight and the projectile is relatively small and impacts at an angle, only a few yarns ahead of projectile break, the projectile can slip through the opening or "wedge through" by pushing yarns ahead instead of breaking them. The number of broken yarns is less than the number of yarns that intersect the projectile. Therefore, lateral movement of the yarns results in less energy absorption. This "wedge through" phenomena has been observed by a number of researches [11, 22, 23]. Evidence of this phenomena is that the hole formed in the perforated fabric is smaller in diameter than that of projectile.

Crimp is another fabric structural property that influences the ballistic performance. Crimp is the undulation of the yarns due to their interweaving. The degree of crimp in a plain weave is unbalanced – the warp yarns, which alternatively go over and under the weft yarns, are typically more crimped that the weft. The yarns of a more crimped structure need more time to decrimp during the ballistic impact event (~100μs) and as a result are broken before the sufficient elongation is reached i.e. before they absorb potentially maximum energy. Chitrangad [21] proposed using weft yarns that had a longer elongation to break than the warp yarns, so that both warp and weft yarns would fail at the same moment, reducing the effect of yarn crimp. The resulting hybridized weave was found to have a higher V50 velocity than weaves composed entirely of identical yarns material.

5.3. Projectile geometry

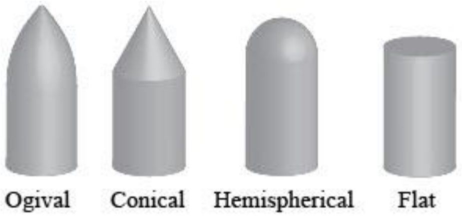

Fig. 3. Projectiles with different geometries

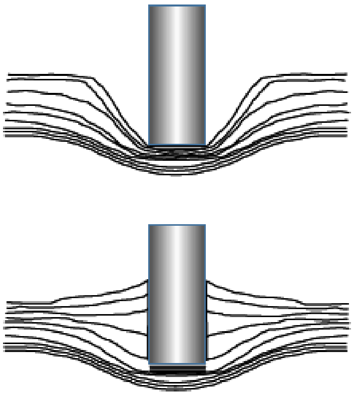

Fig. 4. Cutting actions with flat-tip projectile

The predominant mechanisms that led to perforation of the fabric are highly dependent on the shape of the projectile. Figure 3 shows the common types of different projectile tip shapes. Tan and Khoo [24] have studied the perforation of plain woven aramid fabric laminates by four different tipped projectiles: flat, hemispherical, ogival and conical. All the projectiles were with the same caliber (12.6 mm) and with the same mass (15g). They observed that flat-tipped projectile cut the laminate through a shearing action whereas hemispherical projectiles perforate the laminates by stretching the fibers to failure. Conical and ogival projectiles perforated the laminates by stretching the fibers to failure. Conical and ogival projectiles perforate the fabric with least amount of yarn pull-out, indicating these projectiles were able to slip through the weave. The V50 velocity decreases in the following order of the projectile geometry: hemispherical, flat, ogival, and conical. They also reported that the effect of projectile geometry decreases with the thickness of the laminate. Prosser et al. [25] observed that the cutting action of a projectile possessing sharp edges is a prime mode of penetration, as illustrated in Fig.4.

5.4. Impact velocity

Clearly, the impact velocity of a projectile highly influences the performance of fabrics/composites. There is a big difference between low impact velocities (bellow the critical V50 velocity) and high impact velocity (above the critical V50 velocity) [26]. Low impact velocities, allow the fabric to absorb more energy because the yarns do not fail during the initial stress rise and the transverse deflection of the fabric has time to propagate thus involving more material in the resistance. High impact velocities cause the damage to localize and yarns failure before significant transverse deflection can develop. Cunniff [27] reported that at impact velocities much higher than the ballistic limit of the textile armor, material near the impact point fails before significant strain energy is absorbed. Similar observation have also been reported by Tan et al. [28].

5.5. Friction

Friction affects the impact performance both directly and indirectly. The friction between the fibers and the projectile is considered as the direct effect while the friction between the fibers themselves as the indirect effect. Generally, increase in friction between the projectile and the fabric and the fibers themselves will hinder the mobility of the fibers and require the projectile to engage and break more fibers, which will result in greater energy absorption. The projectile-fiber friction delays fibers breakage by distributing the maximum stress along the periphery of the projectile-fibers contact zone, and this substantially increases the fiber energy absorption during later stages of the impact [29].

Inter-ply friction is also a source of energy dissipation in multi-ply systems. It was observed [30] that specific energy absorption was significantly higher for multi-ply targets than single-ply targets. This was attributed to the fact that inter-ply frictional forces inhibited sideways motion of the yarns in the first-hit ply, causing an increased ballistic penetration resistance.

5.6. Fabric boundary conditions

When fabrics are impacted by a projectile, the size of the target and gripping conditions can greatly influence the outcome. For instance, a long yarn can absorb more deformational energy than a shorter one before failure; thus a larger area target will show higher energy dissipation. However, this is not true when the velocity of the projectile is very high compared to the velocity of the shock wave in the fibers since then only a small portion of the target can dissipate the kinetic energy of the projectile [31]. The boundary conditions of the target also play an important role. Shockey et al. [30] observed that when the fabric is gripped on two edges it absorbs more energy than a four-edge gripped fabric, and fabrics with free boundaries absorbs the least energy. Chitrangad [21] observed that when pre-tension is applied on aramid fabrics, their ballistic performance is improved. Zeng et al. [32] noted that for four-edge gripped fabrics, energy absorption is improved if the yarns are oriented at 45° relative to the edge.

5.7. Environmental degradation

Environmental factors such as temperature, moisture, and UV radiation may cause high-performance fabrics to degrade, reducing their ballistic performance over time. In particular, aramid and PBO (poly-p-phenylene benzobisthiazole and polybenzoxazole) fibers [31].

VI. CONCLUDING REMARKS

This paper has reviewed the topic of ballistic impact of fabrics and their composites including the mechanisms that affect ballistic performance. Although, it is clear that material properties, projectile geometry, impact velocity and multiple plies have profound influence on performance, other factors, such as fabric structure, boundary conditions, and friction are not as apparent. It appears that considerable amount of work still needs to be done before the exact mechanism of fabric ballistic impact can be understood and replicated, especially inter-fiber, inter-yarn and inter-ply interactions and frictional effects. It is important to note that almost all the parameters that affect the ballistic penetration resistance are interrelated and the attempts to single out an individual effect cannot lead to a conclusive result. A combination of high-rate experimental measurements and computational modelling and simulations is needed to more deeply understand the dynamic deformation and failure mechanisms of ballistic fibers and to provide insight into the most desirable high-level organization of fibers into yarns and yarns into plies and fabrics [31].

It is apparent that studies to fully understand ballistic impact phenomena on textile structures and to optimize their resistance, will go on. One of the possible ways to optimization might be in hybridization of the armor system by layering different materials and even different textiles, such as felts [16].

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