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Technical Report

Effect of different construction designs of aramid fabric on the ballistic performances

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ABSTRACT

Current construction methods for soft armour products involve woven and cross-ply laminates. Both methods claim to offer high-energy absorption capability towards projectile impact. Currently, there are less specific data comparing both construction methods. In the cross-ply manufacturing process, the fibers are aligned in one direction, spread into a web and adhered with a resin. Two fiber resin sheets are layered (one in a 0° direction and another in a 90° direction) and fused. Therefore, this study attempted to investigate the effects of different textile designs of aramid fabrics on the ballistic performance, specifically on the energy dissipation and projectile arrest for soft body armour at a 390 m s^{-1} projectile velocity. It was found that the cross-ply laminated aramid construction exhibited better ballistic performance in terms of higher energy dissipation and minimum layer of projectile arrest upon impact. In five layers of fabric, it was clearly shown that the cross-ply aramid laminates could dissipate the impact energy up to 17% compared to those of the woven aramid (i.e. 5%). At the same level of NIJ standard, the cross-ply aramid laminates have the capability to stop the projectile at the minimum layer of the first ply and the maximum layer of seventh. Meanwhile, for woven aramid, the ability to arrest the bullet was at the minimum layer of sixth ply and the maximum layer of 15th ply. It has been demonstrated that the cross-ply structure can dissipate the energy by threefold compared to the woven structure.

1. Introduction

Textile materials, especially Kevlar, have been used to provide protection against ballistic threats since World War II due to its superior properties in terms of its energy absorption characteristics, strength-to-weight ratio and modulus properties [1]. As the demand for their usage by military and police personnel has dramatically increased, these protection suits have been progressively improved by new constructions made from principally ballistic nylon and impregnated fiberglass. In recent years, the suit has been further improved and developed from aramid fibers (i.e. DuPont's Kevlar 29 or Kevlar 49). The ballistic performance of material can be defined as its capability to absorb impact energy locally as well as to uniformly distribute the energy fast and effectively to the entire surface [2–5]. For this reason, low density and high strength materials are essential in the body amour manufacturing [6,7]. It was found that the absorption of the energy is a result of the deformation of yarns during ballistic phenomena [8]. Lee et al. has pointed out that during the absorption of ballistic energy, fibers were numerously broken and deformed [9]. The kinetic energy from the projectile is absorbed by several layers of fabric and the projectile is prevented from completely penetrating the panel. Cunniff [10] has identified the fiber property, fabric structure, number of fabric layers, areal density, projectile parameters and impact parameters as major factors in determining the energy absorption capability of fabric panels. Cheeseman and Bogetti [11] added that in addition to the above parameters, fabric layer interactions, yarn-to-yarn friction and projectile-yarn friction also play important roles in the impact energy dissipation. The higher friction between the fibers and yarns result in higher absorption by the fabric due to its higher frictional contact with the projectile as well as the decreased mobility of the yarn upon impact.

Furthermore, Karahan [12] has claimed that the fabric ply number used in the ballistic panels is the most important parameter affecting the trauma depth. An increase in the fabric ply number from 20 to 32 has caused a decrease of 35.40% in the trauma depth and 12.7% in the trauma diameter. Likewise, the amount of energy transmitted to the back of the panels has also decreased with the increasing number of fabric ply.

There are two basic types of materials used in soft body armour construction; Aramid (woven) and high performance Polyethylene (cross-ply) fibers. Based on the article by Heinecke [13], Wagner concluded that the construction of the fiber also imparts some of

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the high-strength characteristics. The order of the molecular chains is aligned along the length of the fiber, which enhances the transmission of energy and offers the high-strength quality. Weaving provides interlocks between the fibers, thus the strength orientation is directed both vertically and horizontally. However, at these intersections of the fiber (weaving), energy "roadblocks" are created hence reducing the rate at which energy can be dissipated. For woven fabric construction especially plain weave, weft yarns will break before warp yarns during ballistic impact phenomena [14,7,15]. Chitrangad [16] suggested the use of hybrid panels, which increase the resistance of fabrics and may delay the projectile penetration of the panel.

Today, a new generation fabric configurations for cross-ply constructions with the same type and number of yarns at the same densities in warp and weft directions are preferred for use in ballistic applications. This produces equal deformations along warp and weft directions during ballistic impact and prevents it from the localized damage. In addition, the fabric construction brings the energy absorption capability to a higher level by dispersing the energy to the entire fabric, thus producing globalized damage.

With the fibers now inter-weaved or laminated into a rolled fabric product, research on the ballistic vest is focusing more on the development of a hybrid design and construction (a combination of woven and cross-ply structures). According to Wagner [13], it was found that by combining or hybridizing the materials allows for a better performance, especially in increasing the energy dissipation capability. In the research process, a hybrid is formulated, in which a precise layering of ballistic materials is constructed to meet the desired threat level. For example, a hybrid may have 21 layers, which consists of seven Gold Flex, seven Spectra Shield and seven Kevlar arranged in a specific sequence. In the research process, researchers may manipulate the order and number of layers to achieve the desired effect. As a result, the stacking sequence and optimum configuration of 21 layers may be broken down into 3 Spectra Shield, 2 Gold Flex, 7 Kevlar, and 4 Spectra Shield and 5 Gold Flex. Subsequently, the specific configurations may improve the ability of the panel to stop the projectile and dissipate the energy in just a few microseconds at impact. However, Wagner has not provided an inclusive database on the energy dissipation for individual cross-ply and woven fabric, respectively. Hence, for each fabric, a distinct and uncombined basic fundamental study for different construction is needed for further analysis in hybrid technique.

This paper discussed further on the effect of different textile designs with respect to the ballistic performance of aramid fabrics. Inclusive experimental work is performed on two types of textile structures; woven fabric and cross-ply laminate, in which the ballistic performance of both designs is characterized by the energy dissipation at various ply numbers (i.e. 1, 5, 10, 15 and 20 layers). The numbers of ply, in which the projectile is completely arrested, are determined as the panel is partially penetrated. In the case where the panel is completely penetrated, the energy dissipation is based on the difference in the residual velocity and the impact velocity. For both fabric configurations, the woven aramid fabric, i.e. Kevlar Argus, is interlaced in plain weave structure while the cross-ply aramid laminate, i.e. Gold Flex, is prepared in a [0/90] fiber arrangement.

2. Experimental procedure

2.1. Theory on energy absorption formulation

Until recently, it has been difficult to construct realistic simulations that are applicable for different ballistic problems. It is much easier to obtain "before and after" impact data and to evaluate the performance of the structures under ballistic events, such as the projectile impact velocity (V_i) and the projectile residual velocity (V_r). The amount of energy dissipated by the composite fabrics is regarded as the energy expended by the projectile in the penetration event. It can be theoretically calculated by subtracting the residual energy of the projectile from its initial impact energy if the panel is completely penetrated (CP). Therefore, the amount of energy dissipation for the situation in which the impact velocity is above the ballistic limits or causing a complete penetration event can be calculated as:

$$E_{\text{dissipated}}\ (\text{Joules}) = 1/2(V_{\text{impact}}^2 - V_{\text{residual}}^2) \tag{1}$$

where $E_{\text{dissipated}}$ (Joules) is the energy absorbed by the fabric, m is the projectile mass (kg) and V_{impact} and V_{residual} (m/s) are the impact and residual velocities respectively.

Based on the assumption from the experiment for the partially penetrated (PP) case, the amount of energy absorbed by the fabric is taken to be equal to the initial impact energy as the impact event occurred under ballistic limits and the projectile kinetic energy is completely absorbed by the fabric:

$$E_{\text{dissipated}}(\text{Joules}) = 1/2\ \text{m}(V_{\text{impact}}^2). \tag{2}$$

Subsequently, the percentage of energy absorption is characterized with reference to the incipient impact energy, given as follows:

$$E_{\text{dissipated}}(\%) = \frac{\text{Dissipated Energy (Joules)}}{\text{Incipient Impact Energy (Joules)}} \times 100\%. \tag{3}$$

2.2. Experimental materials

The Kevlar Argus and Gold Flex (GF 4) fabrics, which are from the same aramid family but with different fiber configurations, were supplied by Teijin, Netherland. Details of these fabrics are highlighted in Table 1.

For the ballistic testing, both materials were cut into $25 \times 25\ \text{cm}^2$ dimensions, and were derived from the same source, i.e. from the same batch/roll of fabric. Each sample of Kevlar Argus and GF 4 were prepared in five sets of panels, consisting of 1, 5, 10, 15 and 20 layers accordingly. In order to prevent the fabric layers from slipping off their position during the testing, double stitching was used for those panels that comprised more than one layer of fabric.

2.3. Experimental methods

The test apparatus was adapted to the NIJ 0101.06 level – IIIA standard [17]; those test parameters are listed in Table 2. There are two different ways to obtain the data result of projectile velocity; one is from a chronograph and the other is based on a radar system. The radar system was installed just below the firing muzzle while facing the sample. All the data sets obtained from the radar system reading were more accurate and precise. Nonetheless, the chronograph reading possessed a higher tolerance, thus, this will be used for data verification in case the radar reading is missing or undesirable. As the study focused on the fundamental

Table 1
Parameters for both type of fabric used in this research.

Properties	Material	
	Kevlar Argus	Gold Flex
Construction	Plain (1 × 1)	Cross-ply (0/90)
Areal density (g/m^2)	312	239
Thickness (mm)	0.33	0.22