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Process of Preparing a Nonwoven/Filament/Woven-Fabric Sandwich Structure with Cushioning Effect of Ballistic Resistance

Abstract
Non-penetrated damage is a main index that expresses the safety of bulletproof cloth in use. The kinetic energy of the bullet needs to be dissipated and dispersed by the bulletproof cloth after shooting to prevent excessive impact indentation. The nonwoven cushion structure is useful for improving the non-penetrating damage of the bulletproof cloth after a bullet is shot into it. In this work, the novel cushion material of the sandwich structure, made of the filament-laying layer and nonwoven fabric, is used to improve the properties of ballistic resistance. The design of the nonwoven cushion structure is expected to be suitable for reducing the impact indentation of the bulletproof cloth after a bullet is shot; it must be able to replace the original cushion material. The impact indentation of the bullet-shooting test can express the ability of the ballistic resistance or the resistance of the non-penetrating damage. The analytical results show that the design of the nonwoven cushion structure is effective in improving the non-penetrating damage of the bulletproof cloth after the bullet has been shot.

Key words: *non-penetrated damage, bulletproof cloth, nonwoven cushion structure, impact indentation.*

Introduction

Bulletproof cloth is important equipment for police officers to protect themselves. It is made from a hard or soft bulletproof material. The hard materials of the bulletproof cloth are stainless steel, titanium alloy, aluminium alloy, and alumina-ceramic. The soft bulletproof material is made of polyaramid. The bulletproof cloth made of soft materials is suitable for the police because of its light weight, comfortable wearing and better bulletproof effect.

To achieve advancements in body armour performance levels at a reduced weight will not only require further advancements in materials, but the use of models and simulations to develop innovative system designs. Many investigations have focused on the construction and analysis of the ballistic resistance models. High-velocity impact response is dominated by stress wave propagation through the material, in which the structure does not have time to respond, leading to very localised damage [1-3]. Meanwhile, fibre failure occurs at the point of impact due to locally high stresses, and also due to the impact indentation effects related to high fabric deformation. For resistance to low-velocity impact, the ability to store energy elastically in the fibres is the fundamental parameter. Our study used the design of the sandwich structure to obtain the cushioning effect in ballistic resistance.

Micro-mechanisms such as frictional fibre sliding are important energy-absorbing mechanisms. The energy absorbed due to frictional forces is a continuous function of displacement, and is strongly affected by the displacement rate. The frictional sliding mechanism would absorb a significantly greater fraction of the energy than fibre fracture. This work used compound nonwoven fabric through the bonding of needle punching and a thermal calender in order to increase frictional sliding and so to absorb the impact energy.

Frictional sliding can be a significant contributor to energy absorption if this mechanism can be triggered under impact conditions. An inter-phase that has lower strength may better contribute to energy absorption, while an inter-phase with higher strength is needed for structural integrity. Roylance and Wang have shown that materials possessing a high modulus and low density disperse the strain wave rapidly away from the impact point, which distributes the energy over a wider area and prevents large strains from developing at the impact point [3-5]. The sandwich structure was used to disperse the impact stress and dissipate the impact energy, due to its layer structure and the vertical bundle structure made from needle punching.

Materials with high-wave velocity were advantageous, since the stresses and strains could propagate more quickly to neighbouring fibres and layers, thus involving more material in the ballistic event. Although the tensile strength, modulus and strain-to-failure of a yarn play large roles in ballistic performance, each property individually does not control it overall. Prosser et al. [6] stated that if ballistic performance would be based only on yarn toughness, nylon would be a better performer than Kevlar (which is not right). Prosser has also discussed in his work the enlargement of yarn spacing. They defined the hole formed by the yarn spacing enlargement as a 'trap door'. The 'trap door' formation is a function of not only the fabric structure, but also the mobility of the yarns, and the projectile geometry. In the study, it was expected that the nonwoven structure made by nylon staple fiber was used to increase the energy absorption by the frictional behaviour of fibres in the 'trap door'. In addition, the conditions of the compound nonwoven fabric were easily controlled, and the structural design was useful for increasing the toughness of the material.

The material's properties and the fabric geometry combine to produce a structural response. Loosely woven fabrics and fabrics with unbalanced weaves result in inferior ballistic performance. Loosely woven fabrics are more susceptible to a projectile wedging through the yarn mesh. With low-impact velocities, the yarns do not fail during the initial stress rise; therefore, the transverse deflection of the fabric has time to propagate to the edge of the panel, which allows the fabric to absorb more energy. With a high-velocity impact, the damage is localised, and the yarns fail before a significant transverse deflection can develop. The sandwich structure of the compound nonwoven fabric was bulk and laminated, so the impact energy was transmitted and dissipated by the deformation of the compound nonwoven fabric.

Damage mechanisms are dependent on the projectile's geometry and velocity, as well as the properties of the fibres. Thomas found that using a nonwoven facing on a woven fabric provided enhanced protection against handgun threats, rather than just Spectrashield alone. In addition to the local yarn failure, yarns away from the impact site were observed to break. Through frictional interaction with other yarns, remotely failed yarns still exerted a significant load on the penetrator. Increasing the friction between the projectile and the fabric and the yarns themselves will hinder the mobility of the yarn, and require the projectile to engage and break more yarns, which would result in greater energy absorption. The researchers conclude that even modest changes in yarn-yarn friction and inter-filament friction can produce changes in the fabric's ballistic performance. In this work, the structural design was used to improve the cushioning effect of the bulletproof cloth and replace the original cushion material (polyamide plain wove fabric).

Factors affecting the ballistic resistance of a bulletproof vest

The impact and perforation of fabric and compliant laminates 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 the yarns and the projectile. The sandwich structure was also laminated; it was made of nonwoven fabrics and the laying filament. The processing conditions influenced the cushioning effect in the complex multi-layer Kevlar fabric.

Material properties, fabric structure, projectile geometry, impact velocity, multiple ply interaction and friction all play a role in affecting the ballistic resistance. At a sufficiently low velocity, below what is termed the critical velocity, this initial stress increase is insufficient to rupture the fibres; thus allowing the transverse deflection and resultant yarn extension time to propagate, resulting in the absorption of energy by the fabric [6-7]. Fibres possessing high-tensile strengths and large failure strains can absorb a considerable amount of energy. Fibre straining is the primary mechanism of energy absorption in the penetration failure of ballistic textiles.

The influence of structural design

A better function of energy absorbing is performed when a cushion layer is added to the bulletproof vest in structure designing, as the non-penetrated damage is improved. The bulletproof mechanism, which mainly includes the tensile and shearing fractures of fibres, results from the impact of the bullet, while the soft materials such as polyaramid fibre and high-performance polyethylene fibre are used for the bulletproof cloth. Meanwhile, the impact energy is transmitted along the region beyond the impact spot, and absorbed by the deformations and fractures of the fibres and fabrics. The blunt bullet is wrapped in the layers of the bulletproof fabrics.

The bulletproof properties are determined by the characteristics of fibre such as strength, elongation, modulus, rupture and so on. Additionally, the characteristics of fabric such as its structure, thickness, and the number of layers also affect the bulletproof properties. The breaking energy of the fibre and the transmitting velocity of the stress wave determine the property of the material that is used for impact resistance. The stress wave needs to be dispersed rapidly, and the breaking energy needs to be increased in order to raise the impact resistance. The breaking energy of the material is its ability to resist the breaking of an external force, and is a function relative to the tensile strength and the elongation. The ability to absorb energy is better, while the tensile strength and the deformation capacity are greater in theory [8]. The material that is applied to the bulletproof cloth is not allowed excessive deformation in practice, so it needs to have the ability to resist excessive deformation.

The vibrating wave of radial direction is produced by the impact of the bullet at the region of the impact spot in general, and is transmitted along the yarns or filaments. When the stress wave reaches the interlacing spot, a portion of it is transmitted beyond the interlacing spot; the other portion is reflected along the original yarn to form reflecting wave. There are more interlacing spots in woven fabric. Through the interaction on the yarn of the interlacing spot, the kinetic energy of the bullet is transmitted after shooting. Meanwhile, the yarn is broken under the increasing tensile force, due to the overlapping of the stress wave and the reflecting wave. The increasing density of the fabric increases the penetrating resistance and the strength of the fabric, but results in raising the negative effect of the overlapping stress wave, owing to the reflecting wave.

The needle punching nonwoven felt was made of a large number of staple fibres. There is no reflecting wave, because the needle punching nonwoven felt does not exist in the interlacing spots. Many researches show that the modulus of the fibre and the density of the felt are the factors which influence the bulletproof effect. The needle punching nonwoven felt is used for the military bulletproof cloth to resisting the fragments.

The protective mechanism includes three processes; the first is the resistance of the bullet. The kinetic energy was transferred to the deforming energy of the bulletproof cloth, the bullet and the heat energy. The second process is absorption; a portion of the kinetic energy was decayed by the break of the fibres and fabric, as well as the non-penetrating deformation of the bulletproof cloth. The third process is dispersion; the impact force was dispersed to the plane component force or sustained over a larger region. The three processes nearly concur, but are of various degrees in different materials.

The aim of work

The aim of our work presented was to designe a new bullet-proof material with cushioning effect of ballistic resistance, prepared a multilayer sandwich structure of a polyamide/polyester (PA6/PET) nonwoven, polyester (PET) filament layer, and a polyaramide (Kevlar) woven fabric, as well as initially to confirm its effectivity. The new material was intendend to replace a material hitherto used in bullet-proof vests.

Characteristics of the sandwich structure made of compound nonwoven fabric

The sandwich structure made of compound nonwoven fabric forms a laminated structure resulting from the laying filament and nonwoven fabrics. The laminated structure is useful for transmitting the impact stress. In this study, the spread polyester filament was laid on the pre-punching polyamide web with low melted-temperature polyester staple fibres to form a sandwich structure by being covered with another web. After the bonding of needle punching and the thermal calender, the compound nonwoven fabrics were obtained. Figure 1 shows the photograph of the vertical bundle and the sandwich structures. The vertical bundle structure of the fibres formed by needle punching is helpful in energy transmission. Moreover, the increased fracture work of the compound substrate resulted from the breaking of the needle-punching plot when the filament straightened under tensile force (shown in Figure 2).

Table 1. The comparison of the kinetic energy loss of the bullet between the two types of cushion material.

Type of cushion material	Initial velocity of bullet, m/s	Kinetic energy loss of bullet, J	Coefficient of variation, %
Original cushion material	363.4	118.9	9.56
Compound nonwoven fabric (replacing original cushion material)	364.3	157.3	5.45

The test of energy absorption after the bullet's penetration

The process of the penetration and perforation of ballistic-resistant materials is extremely complex, involving not only the inhomogeneity and anisotropy of the material, but also complicated dynamic and thermal effects, finite displacement and rotation with inelastic strain, fracture & tearing, and so on [9]. The energy absorption was important for a better cushioning material for ballistic resistance. The specimen was made of ten layers of Kevlar plain woven fabric and one layer of the original cushion material (Nylon plain woven fabric) or a compound nonwoven fabric that was put on the back of the eighth layer of Kevlar plain woven fabric. For the bullet shooting test, the energy absorbed by the specimens corresponding to the kinetic energy loss of the bullet (W) is given by:

$$W = \frac{1}{2} m \left(V_i^2 - V_r^2 \right) \qquad (1)$$

where m is the mass of the bullet, and V_i and V_r are the initial impact and residual velocities of the bullet respectively. The result shows that the compound nonwoven fabric has better energy absorption after the bullet penetrates, shown in Table 1.

The test of the penetrating resistance or impact indentation

The penetrating ability of a bullet is determined by characteristics such as the material, and the weight, shape, incident velocity and incident angle of the bullet. The weight and the initial velocity of the bullet determine its kinetic energy. The

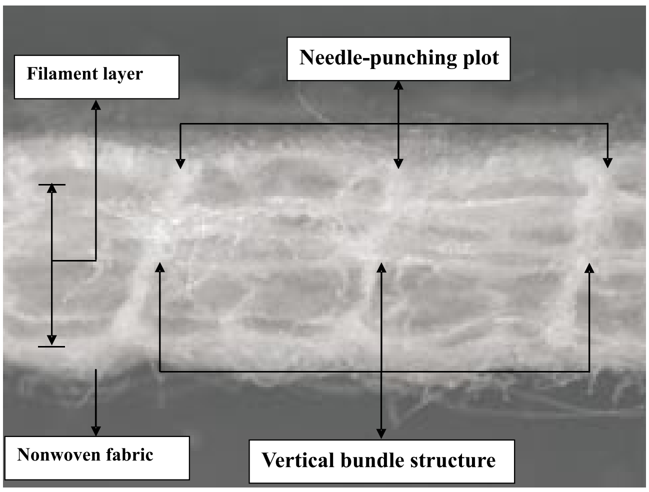

Figure 1. Photograph of the vertical bundle and the sandwich structures.

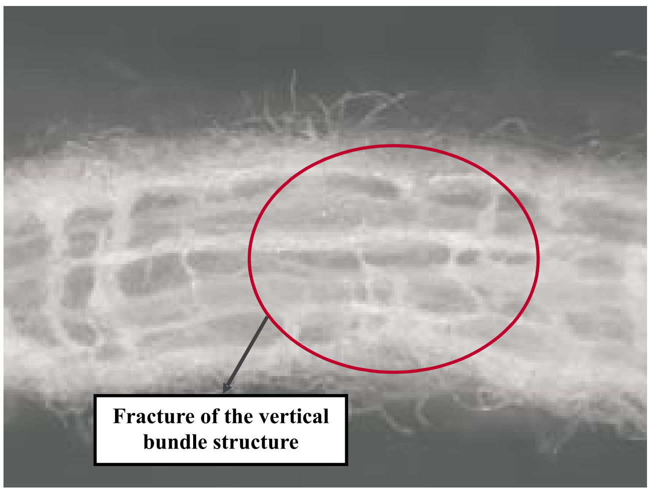

Figure 2. Fracture of the vertical bundle structure after shooting test.

material, the shape and incident angle of the bullet determine its penetrating condition. It is obvious that higher kinetic energy is useful for the the bullet's penetration. Although the bullet did not penetrate the bulletproof vest after its high-velocity impact, the impact kinetic energy hurt the human body through the transmission of the bulletproof vest. Therefore, it is important to transmit and dissipate the impact's kinetic energy to prevent the excessive impact indentation that results in serious damage on the human body. In Europe and America, many countries use oil clay to simulate the muscles of the human body. The bulletproof vest was set on a model that was made of oil clay before the shooting test. The model was deformed by the impact kinetic energy through the transmission of the bulletproof vest and the impact indentation which was caused.

Materials

Nonwoven fabrics

The weight per unit area of the nonwoven fabrics was 150 g/m^2, and the pre-needled density was 100 needles/cm^2. The main material of the nonwoven fabrics was high-tenacity polyamide (Nylon 6) staple fibre with a fineness of 2.5 deniers and a length of 50 mm. Meanwhile, the low-melted staple fibre was polyester (PET) staple fibre, which had a fineness of 4 deniers, a length of 51 mm and melting point of 110°C.

Filament

The filament was high-tenacity polyester (PET) filament with specifications of 2000 deniers/384 f.

Bulletproof fabrics

The bulletproof fabrics were polyaramid (Kevlar 29) plain weave fabrics. The woven densities of the warp and weft were both 28 ends/inch, while their fineness was 1000 deniers.

Parameters

- Content of the low melted polyester staple fibre: 30%
- Needle punching density: 300 needles/cm^2
- Weight of filament per unit area: 500 g/m^2
- Depth of needle punching: 14 mm.
- Needle specification: 15×18×36×3.5R333
- Thermal pressing temperature: 150°C
- Surface velocity of thermal pressing: 1m/min.

Table 2. *Comparison of buffer effect between two types of cushion material.*

Type of cushion material	Iinitial velocity of bullet, m/s	Maximum depth of indentation, cm	Coefficient of variation, %	Weight per unit area, g/m^2
Without cushion material [a)]	342.2	3.89	7.56	-
Original cushion material [b)]	345.7	3.29	19.68	864
Compound nonwoven fabric (replace original cushion material) [c)]	342.7	2.18	9.74	800

[a)] *The test specimen was made of twenty layers of Kevlar plain weaving fabric, with a weight per unit area of the single layer of 295 g/m^2.*
[b)] *The test specimen was made of twenty layers of Kevlar plain weaving fabric and two layers of Nylon plain weaving fabric, with a weight per unit area of the single layer of 432 g/m^2. These two layers of Nylon plain weaving fabric were put on the back of the sixteenth layer of the Kevlar plain weaving fabric.*
[c)] *The test specimen was made of twenty layers of Kevlar plain weaving fabric and one layer of compound nonwoven fabric. The compound nonwoven fabric was put on the back of the sixteenth layer of Kevlar plain weaving fabric.*

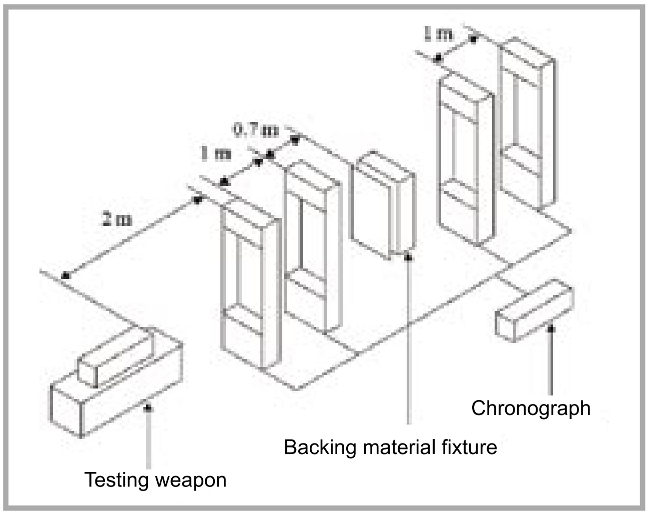

Figure 3. *Shooting test equipment.*

Equipment

- Opening machine
- Feeding machine
- Roller cards
- Vertical lapping equipment
- Needle punching machine
- Thermal calender

Bullet shooting test: according to NIJ 0101.04

Devices used for the shooting test (shown as Figure 3)

- Testing weapon: 9 mm handgun (Beretta 92FS)
- 9-mm bullet with full metal jacket: 9 MM×19 cartridges for pistol
- Photo electric light screens: solid state ballistic screen, model 6100
- Chronograph: velocity computing chronograph, model 4010P
- Backing material fixture

Backing material fixture

A minimum of three backing material fixtures (BMF) filled with appropriate backing material are required. The inside dimensions of the BMF are 610 mm × 610 mm × 140 mm ± 2 mm (24.0 in × 24.0 in × 5.5 in ± 0.06 in) deep. The tolerance on all dimensions is 2 mm (0.06 in).

Backing material calibration

The calibration of clay backing material is accomplished before (pre-test), and after (post-test) each six-shot firing sequence. Calibration is accomplished by using the equipment and techniques specified below:

- Drop weight: steel sphere,
- Drop weight size: 63.5 mm ± 0.05 mm (2.5 in ± 0.001 in) in diameter,
- Drop weight mass: 1043 g ± 5 g (2.29 lb ± 0.01 lb),
- Drop height: 2.0 m (6.56 ft),
- Drop spacing: 76 mm ± 3 mm (3.0 in ± 0.125 in) from edges and 203 mm [7].

Comparison of the effect between the original cushion material and the compound nonwoven fabric after the bullet shooting test

In the bullet shooting test, the maximum depth of impact indentation is an important index of the bulletproof vest in the

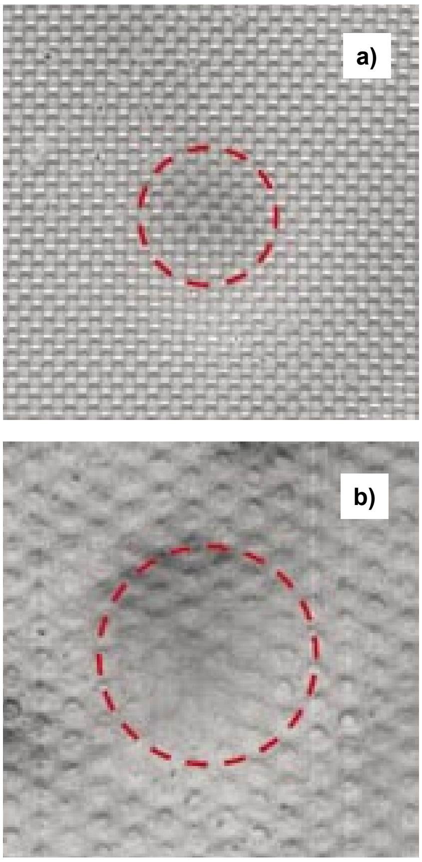

Figure 4. *The comparison of the* indentation *deformation between the original cushion material (nylon plain weaving fabric) and the compound nonwoven fabric after shooting test; a) the original cushion material, b) the compound nonwoven fabric.*

use that is simulated by the oil clay. The result shows that the compound nonwoven fabric is more suitable than the original cushion material, which is made of a polyamide plain-woven fabric, for use as the cushion material of the bulletproof vest, as shown in Table 2. In addition, the compound nonwoven fabric shows a better expanding area of energy transmission after the bullet shooting test (shown in Figure 4). The result shows that the compound nonwoven fabric has a better cushioning effect as compared with original cushion material (Nylon plain woven fabric). Therefore, we can use the compound nonwoven fabric to replace the original cushion material.

Conclusion

The analytical results show that the sandwich structure is useful for the cushion material of the bulletproof cloth. Through structural design, the impact indentation of the bulletproof cloth after bullet shooting is improved to decrease the non-penetrating damage to the human body. Additionally, the performance of the ballistic resistance can be raised. The better cushioning effect is expected at a lower cost.

Acknowledgment

We would like to express our appreciation to the National Science Council of the Republic of China for financial support for this research, under contract no. NSC 93-2212-E-035-024.

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Received 13.07.2004 Reviewed 07.10.2005