2D/3D Woven Fabrics for Ballistic Protection

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ABSTRACT

Woven construction of high performance fibres play important roles in ballistic protection. This paper reports on the recent research on the engineering design and evaluation of 2D and 3D fabrics emphasising on the influence of construction of ballistic fabrics on ballistic performance. Based on preliminary research, a new concept of fabrics with material continuity and enhanced yarn gripping was put forward. Accordingly, fabrics with enhanced yarn gripping were engineered, manufactured, and evaluated, and results showed improved ballistic performance in terms of both projectile penetration and trauma impact. Based on the new concept, 2D and 3D fabric constructions were discussed for ballistic protection. Formation of 3D panels was investigated and it was found that angle-layering for creating panels improves the isotropy and hence better impact performance. Hybrid design of ballistic panels from the commonly used woven and UD fabrics indicated that it is possible to improve the ballistic performance by using layer materials according to the impact mechanism. FE simulation was also carried out for the investigation of strain distribution in the ballistic fabrics and panels, which provides information for optimisation of fabric construction.

Keywords: woven fabrics, ballistic, 2D and 3D, yarn gripping, angle-layering, hybrid panels

1. Introduction and the Problem

Ballistic protection remains to be an important issue in the modern time, due to the threats coming from regional conflicts, terrorism, and some anti-social activities. The main users of ballistic personal protection equipment are the soldiers, police officers, security staff, and celebrities including politicians. Personal protection equipment had been used throughout the history in all region of the world [1], and the means used for protection is closely related to the threat of weapon used at the stage of history. Leather and metals are among the most important materials used for personal protection before the more firearms were employed in wars. Invention of modern firearms has certain challenged the engineering design of protection equipment. The basic requirements for ballistic protection equipment are the prevention of projectile from perforating, reduction of blunt trauma to the human body caused by ballistic impact, lightweight and flexibility to guarantee wearer's mobility, and thermal and moisture comfort associated to the use of protection equipment. Protection equipment is made in many form, the mostly used is the ballistic vest to protect the torso of the wearer.

Engineering of body armour can be said to include three aspects. The first should be the selection of materials for making the body armour. The current approach for making body armour against ballistic impact is using high performance fibres to produce fabrics as layering materials for the body armour panel. New methods are being searched but so far there seem to be no replacement found to replace the fibre technology. The second aspect for body armour engineering is the fabric construction from the selected high performance fibre. The important issue here is to design the most effective fabric structure which is most energy absorbent against the ballistic impact. There have been some fundamental researches attempting to reveal the fabric failure mechanism. Such work has influenced the engineering design of fabrics. The third aspect for body armour engineering is the design of the ballistic panel for the body armour. The use of layering materials in the right place is an important issue.

2. State of the Art

Ballistic impact encountered in personal protection is normally a low-mass high-velocity impact onto an assembly of soft and non-homogeneous materials, which is usually woven fabrics made from high performance fibres, such as aramid and high performance polyethylene, by a more rigid projectile travelling at a high velocity. Understandably, a ballistic impact event represents a complex mechanical process. The effectiveness of the protective material is measured on two counts, i.e., the ability to stop projectile from penetrating, and the ability to absorb and migrate the impact energy. The principles used in minimizing the effects of energy transfer from a projectile are explained by Hepper *et al* [2]. The effect of energy transfer can be minimised in two general ways. The first is to promote energy absorption through breaking, stretching, and compressing the protective materials, or by extension of time over which the impact energy is applied to the body. The second is to redistribute or dissipate the impact energy to wider areas of the protective material so as to reduce the impact energy density over the protective material.

High performance fibres are constructed mostly into plain-woven fabrics as the layering materials for the body armour. Plain-woven structure became a natural candidate for ballistic fabrics because this fabric structure provides the best structural stability and strongest holding of the constituent yarns. This had been supported by the numerous investigations on the effect of inter-yarn friction on the ballistic performance. Briscoe and Motamedi [3] experimented on a plain-woven ballistic fabric with three different treatments. The results showed that the fabric with the highest friction between the fibres was most energy absorbent and created least vertical deformation, and vice versa. Rao *et al* [4] reported that through FE modelling, higher initial velocity is required to achieve near zero residual velocity for fabrics with inter-yarn friction than for fabrics without inter-yarn friction. In another numerical study, Duan *et al* [5] simulated the ballistic performance of plain-woven fabrics under different boundary conditions with inter-yarn frictional coefficient being 0 and 0.5 respectively. The results suggested that the fabric with high friction absorbs more energy than the fabric with no friction in all concerned circumstances. Sun and Chen [6] reported that when plasma treatment is employed to increase the inter-yarn friction for an aramid woven fabric, the resistance to the quasi-static yarn pull-out from the fabric quadrupled when compared to the same fabric without plasma treatment. This research also showed through an FE study that the fabrics with rougher yarn surfaces are able to absorb more energy from the impacting projectile.

Layers of single ply fabrics are used to form the ballistic panel for body armour. Considerable effort has bee made to investigate the 3D woven fabric panel constructions and their effect on ballistic performance of the panel. The stress and strain distribution through the thickness direction indicates what properties the layering fabric should have and how the panel should be constructed. 3D fabric structures have also bee investigated on their effectiveness in protection against ballistic impact.

This paper presents some achievements made on 2D and 3D fabrics for ballistic protection based on the research at the University of Manchester.

3. Stress and Strain Distributions

A soft armour system defeats the projectile by absorbing the kinetic energy and spreading it over a larger area to minimise the effect of the ballistic impact. During a ballistic impact event, cone formation takes place on the exit side of the target just behind the point of impact because of the transverse wave propagation [7, 8, 9]. The surface radius of the cone increases with time, and the cone moves along with the projectile and thus the depth of the cone increases. The projectile displacement at any instant of time and the cone depth formed would be the same. Naik *et al* [7] reported the variation of cone surface radius against time. Initially, the transverse wave velocity increases significantly and then remains nearly constant during the remaining period of ballistic impact event. The rate of increase of cone depth decreases with time, and this depends upon the velocity variation of the projectile during the ballistic impact event. Variation of cone surface radius is nearly linear with respect to time, whereas the change in cone depth against time is non-linear.

Porwal and Phoenix [10] studied the relationships between cone wave positions in different layers and found that cone wave velocity C_i in the i^{th} layer can be written as:

$$C_i = const_i \times a_{0i}^{1/3} \left(\frac{V}{\sqrt{2}} \right)^{2/3} \quad (1)$$

where a_{0i} is the longitudinal strain wave velocity in the i^{th} layer, which is constant for each layer, $const_i$ is constant, and V is projectile velocity.

Radius of cone wave front, Ψ_i, normalized by projectile radius in layers i is presented by:

$$\psi_i = 1 + \left(\frac{a_{0i}}{a_{0j}} \right)^{1/3} (\psi_1 - 1) \quad (2)$$

where a_{0i} and a_{0j} are the longitudinal strain wave velocities in the i^{th} layer and j^{th} layers respectively.

The longitudinal wave velocity a_0 for isotropic solids is expressed as follows according to Lyons [11] as:

$$a_0 = \sqrt{\frac{E}{\rho}} \quad (3)$$

where E is young’s modulus and ρ is material density.

In an impact situation**,** faster moving longitudinal waves and slower moving transverse waves help to dissipate the impact energy through the yarns involved at the impact site [12]. The length of the yarns involved in the waves increases with time and is subjected to various stress levels and strain rates. Propagation speed of the shock waves formed in the protective material during the ballistic impact is related to the fabric’s capability in energy absorption and is important from ballistic point of view. Energy absorption and propagation ability of fabric layers are dependent on tensile modulus of fibres and yarns forming the fabrics. The tensile modulus along with tensile strength of yarns is the main parameter affecting ballistic performance.

Whilst the mechanical properties of constituent yarns are important, fabric parameters such as fabric density, yarn count as well as weave structure can also have a significant effect on ballistic performance. 2D woven fabrics are the most commonly used structures for ballistic fabrics. The plain weave fabric exhibits the highest level of intersection density followed by twill and then satin. Therefore, the dimensional stability and the control over yarns in a plain weave fabric is the highest among these three basic structures. Stempień [13] studied the influence of a woven fabric structure on the propagation velocity of a tension wave and found that the propagation velocity of a tension wave in a woven fabric depends not only on the propagation velocity in yarn, but also on the parameters of the woven fabric structure, such as the weave, and weft and warp densities. Maximum propagation velocity of the tension wave occurs in woven fabrics with plain weave. 3D fabrics are constructed by interlacing the yarns in the network-forming fashion while introducing the third dimension other than the planar dimension. The main advantage of a 3D structure is reinforcement in through-the-thickness direction; hence the dimensional stability of 3D fabrics is much greater than that of 2D fabrics [14]. A combined structure has also been created to improve the protection against bullets. Steeghs *et al* [15] invented a kind of ballistic vest containing a stack of flexible fabrics and a stack of flexible unidirectional layers, in which the fabrics contain strong fibres of a first kind, the unidirectional layers contain strong fibres of a second kind, and in which the fibres in a unidirectional layer run essentially parallel and are disposed at an angle to fibres in an adjacent layer. Roylance [16] studied ballistic impact of textile structure and found that the vast majority of ballistic energy was seen to be deposited in the orthogonal fibres passing through the impact point, while the other fibres are essentially ineffective, which suggests possible improvements in the design of textile structures intended for dynamic impact applications. Cork and Foster [17] studied the relationship between fabric width and ballistic impact performance. In his study two narrow fabrics with and without selvages were compared with a full-width sample of the same structure. The result was shown that the narrow fabric strip without selvages had improved ballistic performance over larger clamped fabric sheets, or wider strips. The inclusion of a selvedge to the narrow fabric strip further increases ballistic performance. For a given type of fibre used, Sun and Chen [18] found that the construction of the woven fabric is the main influencing factor affecting how the waves propagate, which is directly related to the protective performance of the fabrics.

4. Ballistic Fabric Engineering

4.1 Formats of fabric penetration

In general, high velocity projectiles may penetrate ballistic fabrics in three modes, depending on the interaction between the impacting projectile and the fabric layer. Firstly, the projectile can break the fibre and get through the fabric. This happens to the first few fabric layers in the body armour panel when the projectile still carries high level of impact energy. From this point of view, use of fibres with stronger impact strength would certainly contribute to better protective body armour. The second mode in which a projectile penetrates a fabric is that it passes between the adjacent yarns. The use of tight fabric constructions such as the plain weave in ballistic fabrics certainly helps the resistance to the pushing force to the yarns in the impact vicinity. Some researchers reported on the use of unidirectional fabrics for better performance but they had to constrain the fabric by other means. The third form that a projectile penetrates a fabric is by pulling the yarns out of the plane of the fabric. This happens especially when the projectile is about to be stopped in the fabric assembly. The second and the third forms of penetration both indicate the influence of the fabric construction and between-yarn friction on ballistic performance of the fabric.

The energy loss is calculated from v_0 and v_1 which are the projectile velocities before and after penetrating the fabric target as follows.

$$\Delta E = \frac{1}{2} m(v_0^2 - v_1^2) \tag{4}$$

The energy loss for the projectile or the energy absorption for the fabric panel is used as a performance indicator by many for single-layer or multi-layer ballistic panels based on penetration tests.

4.2 Fabric balance indicator

Cork and Foster [17] defined balance indicator for woven fabric as follows:

$$S = \min\left\{\frac{n_1 T_1}{n_2 T_2}, \frac{n_2 T_2}{n_1 T_1}\right\} \tag{5}$$

where n_1 and n_2 are the warp and weft densities and T_1 and T_2 are the linear densities of the warp and weft yarns, respectively. Obviously, S=1 indicates that the cover of a fabric in both and weft directions are the same, and a small value of S tells that the fabric cover in warp and weft direction are very different. They were able to show that fabrics with high a balance indicator cause bigger energy loss of the projectile.

4.3 Fineness of fabric

It was also demonstrated that for the given fabric areal density, fabric panels made of finer fabrics cause more energy loss than that of coarser fabrics. This suggests that fine ballistic fabrics are able to provide better ballistic protection than the coarse ones. However, when taken the cost into consideration the use of fine fabrics for ballistic protection is more expensive than the use of coarse fabrics.

4.4 Yarn gripping

Researches show that inter-yarn friction in a woven fabric help improve the ballistic performance [3]. In practice, different measures can be taken to enhance the yarn gripping. Researchers at University of Manchester devised different methods to increase yarn gripping in woven fabrics through weaving. Among which are fabrics GRPG-1 and GRPG-2.

GRPG-1 is a novel 2D woven structure that can be readily manufactured using the existing weaving technology with virtually no added cost. This fabric ensures that the fabric is woven using the optimised weave but with extra gripping on the constituent yarns. Yarn pulling-out tests were carried out in order to examine the effectiveness of the structure used in GRPG-1.

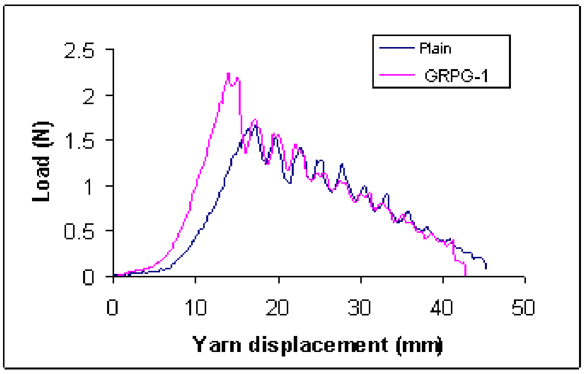


Figure 1 Resistance to yarn pull-out from GRPG-1 fabric

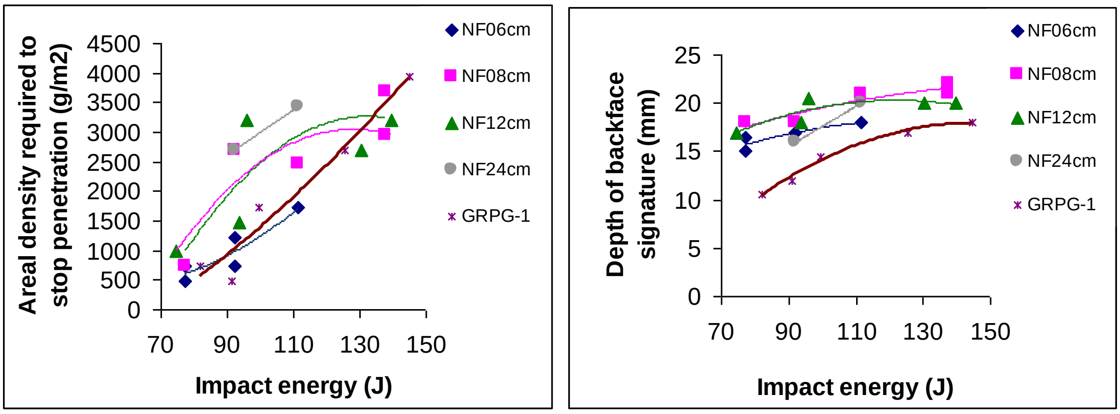
Figure 1 shows the load-displacement relationship between the plain and GRPG-1 ballistic fabrics. The GRPG-1 fabric demonstrates higher resistance to the yarn pull-out during the process. It is noted that the GRPG-1 fabric offers 40% more resistance than its plain counterpart. According to the Lyons [11], fabrics with this feature would contribute to a faster longitudinal propagation and therefore would dissipate impact energy more effectively. After the yarn has been pulled out from the fabric, the plain fabric and the GRPG-1 fabric demonstrated similar yarn movement with similar resistance. This is advantageous for the GRPG-1 fabrics as it shows despite the tighter gripping on yarns, the new fabric also permits necessary yarn displacement during fabric deformation to absorb impact energy.

GRPG-2 is another 2D woven fabric that offers enhanced gripping to its constituent yarns. The first samples of this type of fabric were developed based on hand-loom weaving and the fabric is able to be manufactured on power looms with minor and necessary modification to the loom.

5. Experimental Evaluation on 2D Fabrics

5.1 Effectiveness of yarn gripping

For comparison purposes, the 2D broad fabric with enhanced yarn gripping, GRPG-1, was tested and compared with 4 narrow fabrics with natural selvedge, which were shown to be advantageous over the fabric stripes without weft yarn gripping [17]. All fabrics were evaluated on the amount of materials needed to stop the projectile and on the depth of the backface signature. Figure 2 shows the comparison between the two groups of ballistic fabrics.



(a) Materials needed to stop penetration (b) Depth of backface signature

Figure 2 GRPG-1 vs narrow fabrics

From the study on narrow fabrics, it was concluded that narrow fabrics with natural selvedge demonstrated better ballistic properties over their narrow stripe counterparts [Cork and Forster][Sun and Chen]. However, the problem of the narrow fabrics for ballistic protection is that they cannot offer the material continuity necessary for impact energy dissipation. GRPG-1, as an engineered fabric, offers both material continuity and extra yarn gripping. Figure 1(a) compares the two types of fabrics on the areal density needed for blocking the projectile under different levels of impact energy. It shows that the GRPG-1 fabric can stop the impacting projectile with almost the lowest areal density regardless of the impact energy applied. Figure 5(b) shows clearly that when the GRPG-1 fabric is the best in absorb and dissipate the residual impact energy as it relates to the smallest depth of the backface signature. To summarise, the engineered GRPG-1 fabric based on the new engineering concept out-performs the narrow fabrics with natural selvedge and poses to be a strong candidate material for ballistic protection.

5.2 Energy loss

Equation (4) describes the calculation of energy loss of the impacting projectile due to the fabric it goes through. This is the indicator for the fabric effectiveness in absorbing and dissipating the impact energy carried by the projectile.

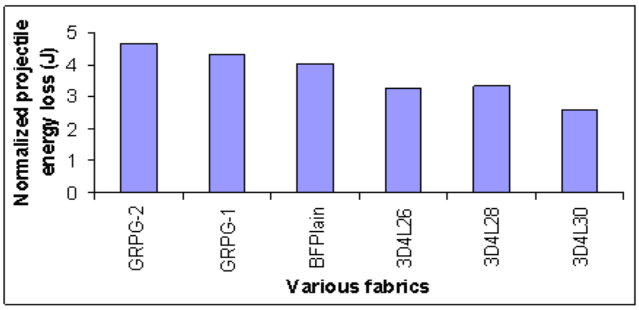


Figure 3 Fabric types and their normalised projectile energy loss

Ballistic fabrics with different structural features were tested for projectile energy loss. Besides GRPG-1, the fabric GRPG-2, with more rigorous gripping, was also tested along with the broad plain-woven fabric. The comparison also involved a type of 3D fabrics which has potential application for female body armour, denoted as 3D4LXX where XX is the weft density of the fabric. As illustrated in Figure 3, PRGP-2 caused the most energy loss from the projectile, which is followed by GRPG-1. This is attributed the enhanced yarn gripping in both fabrics. The 3D fabrics for female body armour compared less favourably among these fabrics. This is because the 3D4LXX fabrics contain free yarns which are under the lowest level of yarn gripping. The broad plain-woven fabric BFPlain ranked the third in this exercise. Figure 4 shows the effectiveness of yarn gripping for wider range of methods. The similar tendency is displayed for the wider choices of yarn gripping methods in plain woven fabrics.

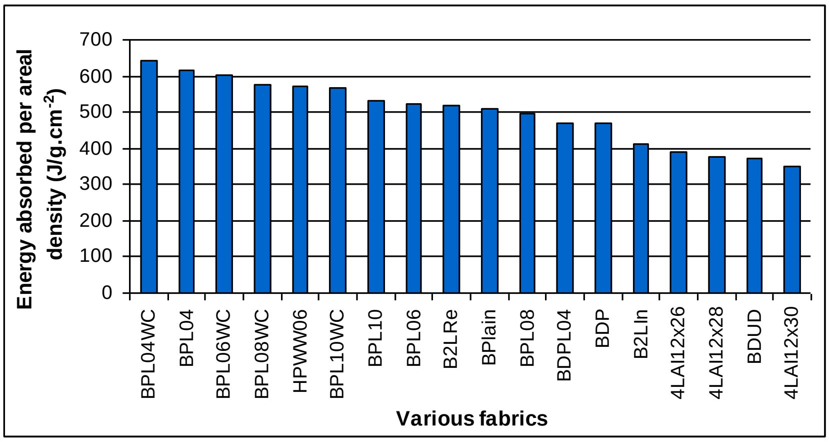


Figure 4 Energy absorption by fabrics with wider choices of different yarn gripping methods

6. Study on Making up 3D Ballistic Panels

6.1 Angle-laid panel

Construction of the ballistic panel is also technologically challenging. Upon impact from a projectile, the stress and strain distribute in each fabric layer and also among the layers. Woven fabrics are formed by interlacing warp and weft yarns and therefore they are highly orthotropic. When a woven fabric is impacted, the strain mainly happens to the directly hit warp and weft yarn, which are termed primary or principal yarns. In most ballistic panels made for body armour, fabrics are layered up in the same orientation. This makes the panel to be orthotropic too. In an ideal situation, an isotropic ballistic panel would maximise the energy absorption. This is illustrated in Figure 5. In one of the research at the University of Manchester, experimental and FE analyses were carried out to create the panel with angled layering of the constituent fabrics, because layering offers the opportunity to change the panel structure.

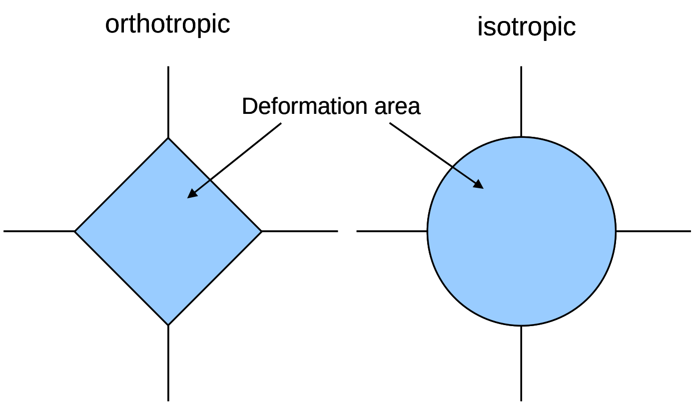


Figure 5 Comparison of deformation area for orthotropic and isotropic panels

In the present study, four groups of fabric panels, i.e., 2, 3, 4 and 8 plies are selected to study the influence of the angle laying on the energy absorption during high strain rate impact. The plans for all 4 panels are shown in Figure 6.

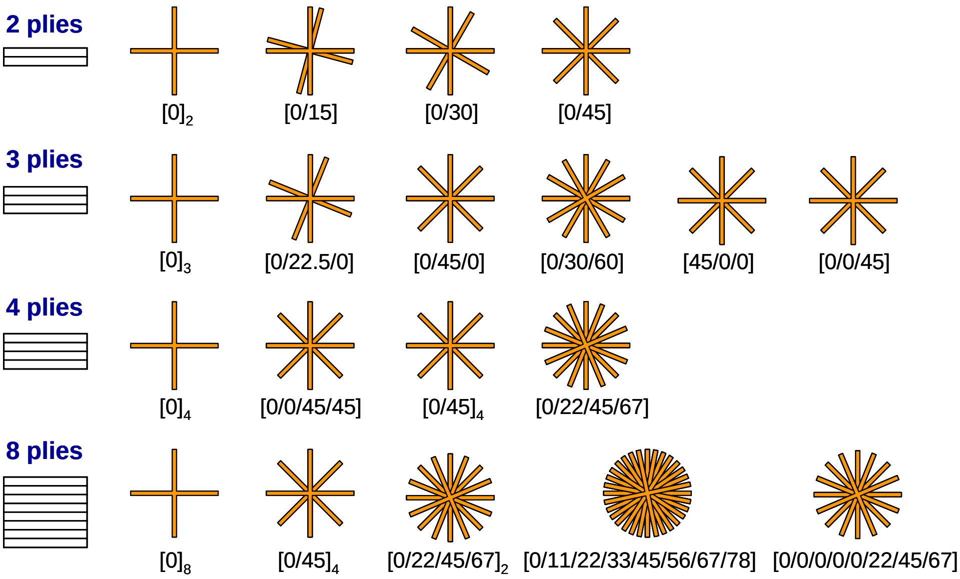


Figure 6 Examples of selected fabric assemblies

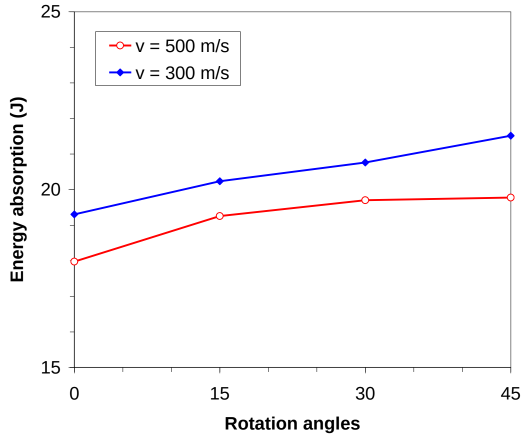
A detailed finite element analysis (FEA) using ABAQUS was carried out to study the transverse impact of a projectile onto various woven fabric panels. The fabric model is modelled at a yarn-level resolution. Typical values for the yarn-crimp wavelength of 2.67 mm, the volumetric density of the yarn of 1440 kg/m^3, and the fabric thickness of 0.345 mm are assumed. The yarn-cross section was meshed using 10 elements and yarn wavelength using twelve elements. The projectile is modelled as a rigid body. Simple Coulomb friction is introduced between yarns and between the projectile and the fabric. A fixed edge boundary condition is applied for all the cases and a projectile velocity of 500 m/s is selected. It is assumed that the inter-yarn frictional coefficient is 0.2.

6.1.1 2-ply panels

Figure 7 shows the FEA simulation results from the case of a 2-ply fabric panel. Two velocities, 500 m/s and 300 m/s are selected to study how the impact velocity affects the ballistic impact performance with various fabric assemblies. The results show that the ply orientations within the fabric assembly significantly affect the energy absorption capacity of ballistic fabrics and energy absorption is increased as the orientation angle θ increases. The energy absorption capacity slightly increases as the impact velocity decreases as depicted in Figure 7(). Compared with the aligned ply panel denoted as [0/0], the energy absorption in the angled panel [0/45] increased by 11.4 % for impact velocity being 300 m/s and 10% for impact velocity being 500 m/s.

6.1.2 3-ply panels

The results from the 3-ply fabric panels are shown in Figure 8. The energy absorption capacity increases when the constituent fabric layers are angle laid in the plies. The energy absorption for all the panels with layer orientation is higher than the aligned panel in the angle-laid panel [0/0/0]. The most energy absorbent panel is [0/30/60], absorbing about 16% more than the aligned panel. It is interesting to note that panels [45/0/0], [0/45/0] and [0/0/45], one 45° ply involved, demonstrated different energy absorption capability, with [0/45/0] being most energy absorbent. The results indicate that the position of the layer has a significant effect on energy absorption. The FE results also show the significant effect of ply orientations on the energy absorption.



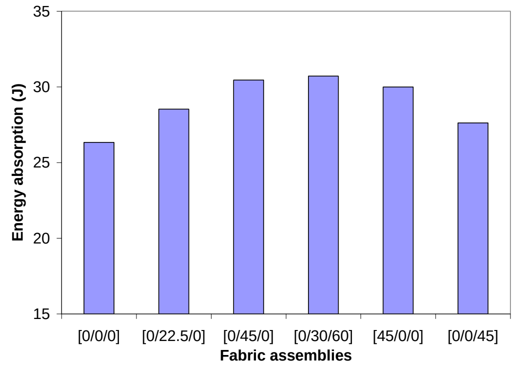
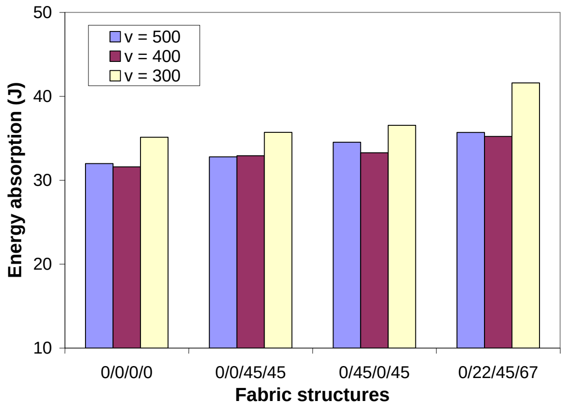


Figure 7 Energy absorption for 2-ply panels

Figure 8 Energy absorption for 3-ply panels

Figure 9 presents the results for the 4-ply panels. Three impact velocities are used to investigate the energy absorption performance of these panels. Again, the calculated results demonstrated that the angle-laid panels absorb more energy than the aligned one at all impact velocity. It is evident that the low impact velocity causes more energy absorption of all panels. Panel [0/22.5/45/67.5] absorbs most energy at all impact velocity.



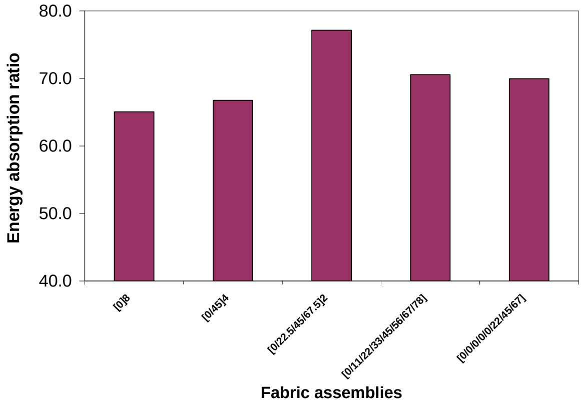


Figure 9 Energy absorption for 2-ply panels

Figure 10 Energy absorption for 3-ply panels

Figure 11 shows the results for the 8-ply fabric panels. The simulation results indicate that energy absorption of fabric panels with ply orientations is greater than that in aligned fabric panel. The maximum energy absorption is seen in the angle-laid fabric panel $[0/22.5/45/67.5]_2$. Compared with the aligned ply panel $[0]_8$, the energy absorption by the angle laid panel $[0/22.5/45/67.5]_2$ is 18.5% higher.

6.2 Hybrid panels

As has been established, the nature of impact between the projectiles and the front layers of fabric in a panel and that between the projectile and the rear fabric layer are quite different. The front layers of the fabric are subjected to high velocity impact whereas the rear layers receive impact with much reduced velocity. In addition, the rear layers of the fabric would have been subjected to pre-strain before the impact. The mode of the impact mechanism changes gradually from the front layers to the rear layers. A study is carried out on the construction of hybrid panels for more effective ballistic protection.

Two types of panel (A and B) were designed from two fabrics made from high performance polyethylene fibres. One fabric is plain woven, and the other is the commercial UD fabric. In order to compare the panel performance, the panels were made to have the same areal densities. In type A panels, woven fabrics were used before the UD fabrics and type B panels were designed in the reverse sequence The proportion of the two types of fabric in a panel was also taken into consideration. Panel details are given in Tables 1 and 2.

Table 1 Type A panels

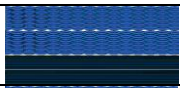
Type A panel	Panel model	Areal density (g/m^2)
40 layers of UD fabric		5,800
6 layers of Woven fabric+30 layers of UD fabric		5,790
12 layers of Woven fabric+20 layers of UD fabric		5,780
18 layers of Woven fabric+10 layers of UD fabric		5,770
24 layers of Woven fabric		5,760

Table 2 Type B panels

Type B panel	Panel model	Areal density (g/m^2)
24 layers of Woven fabric		5,760
10 layers of UD fabric+18 layers of Woven fabric		5,770
20 layers of UD fabric+12 layers of Woven fabric		5,780
30 layers of UD fabric+6 layers of Woven fabric		5,790
40 layers of UD fabric		5,800

Figure 11 depicts the experimental and FE results on depth of backface signature obtained from impacting type A panels. It can be seen in Figure 11 that FE results and experimental results share similar trend. That is, the combination of 6 layers of woven fabric and 30 layers of UD fabric exhibits the lowest value and gives the best performance, followed by the panel of 40 layers of UD fabric.

It is found that the increase of the proportion of high performance polyethylene woven fabrics in the panel leads to an increase in the value. The combination of 24 layers of woven fabric gives the worst performance. It is of interest to note that larger size sample (23×23cm) gives lower values than small size samples (11×11cm). This is because more fabrics get involved in energy dissipation on large size samples, which leads more energy to be absorbed to fabric panels.

The comparison between type A and type B panels based on the experimental investigation is illustrated in Figure 12. It is evident that type A panels which have woven fabric layers on the impact face gives better values in backface signature than type B panel.

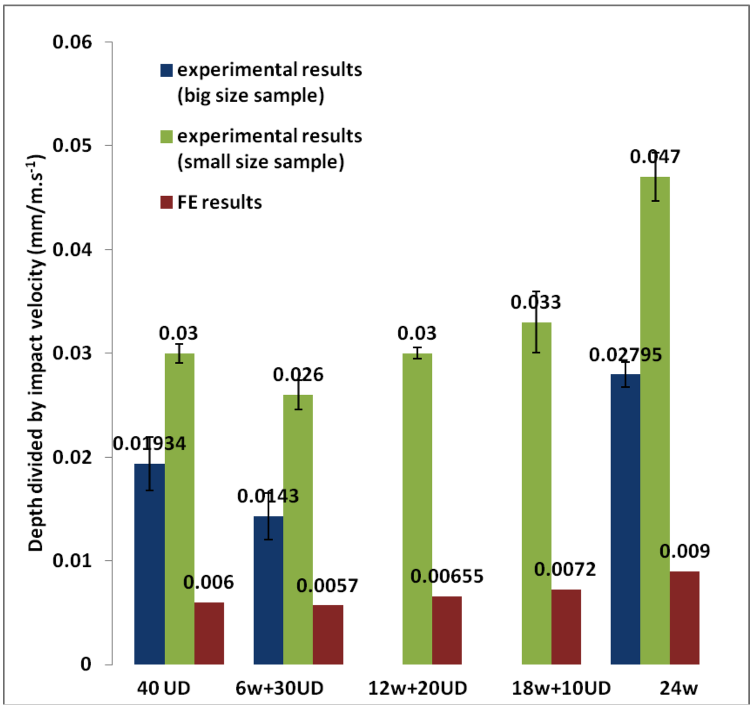


Figure 11 Type A hybrid panels and the depth of backface signature

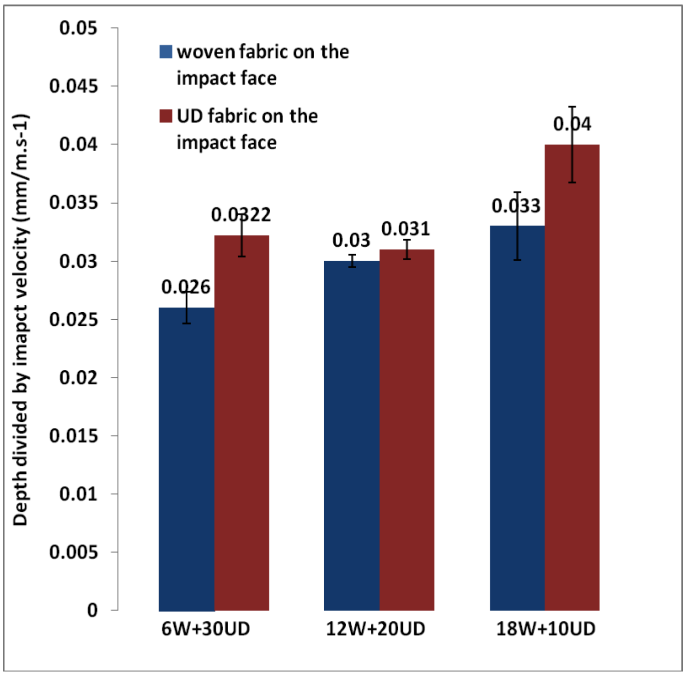


Figure 12 Experimental results for type A and type B panels

7. Conclusions

This paper reported on the engineering of 2D and 3D fabrics for ballistic protection aiming at the improvement of ballistic performance of fabrics and fabric panels. A new concept on ballistic fabric construction has been put forward, which is fabrics with material continuity and more effective yarn gripping in the fabric. This is in line with the previous researches on inter-yarn friction. Different types of fabrics with enhanced yarn gripping and fabric continuity have been engineered, manufactured, and evaluated experimentally and numerically. Better performance of the new fabrics, in term of penetration and trauma, was demonstrated. 2D fabrics with enhanced gripping caused most energy loss to the impacting projectile. Research was also extended to the construction of the 3D fabric panels for ballistic protection. This paper reported on the panel formation by angle-layering the fabric and by using different types of layer materials. In the former case, the research showed that the angle-layering improves the extent of isotropy of the panel and caused higher energy absorption. The study on hybrid design of panels showed possibility of using fabrics with different structures in order to achieve improved performance of the ballistic panel.

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