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Numerical and experimental investigations into ballistic performance of hybrid fabric panels

Xiaogang Chen [a,*], Yi Zhou [a], Garry Wells [b]

[a] School of Materials, University of Manchester, Manchester M13 9PL, UK
[b] Dstl, Porton Down, Salisbury SP4 0JQ, UK

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ABSTRACT

Strong, low density fibres have been favoured materials for ballistic protection, but the choice of fibres is limited for making body armour that is both protective and lightweight. In addition to developments of improved fibres, alternative approaches are required for creating more protective and lighter body armour. This paper reports on a study on hybrid fabric panels for ballistic protection. The Finite Element (FE) method was used to predict the response of different layers of fabric in a twelve-layer fabric model upon impact. It was found that the front layers of fabric are more likely to be broken in shear, and the rear layers of fabric tend to fail in tension. This suggested that using shear resistant materials for the front layer and tensile resistant materials for the rear layer may improve the ballistic performance of fabric panels. Two types of structure, ultra-high-molecular-weight polyethylene (UHMWPE) woven and unidirectional (UD) materials, were analyzed for their failure mode and response upon ballistic impact by using both FE and experimental methods. It was found that woven structures exhibit better shear resistance and UD structures gives better tensile resistance and wider transverse deflection upon ballistic impact. Two types of hybrid ballistic panels were designed from the fabrics. The experimental results showed that placing woven fabrics close to the impact face and UD material as the rear layers led to better ballistic performance than the panel constructed in the reverse sequence. It has also been found that the optimum ratio of woven to UD materials in the hybrid ballistic panel was 1:3. The improvement in ballistic protection of the hybrid fabric panels allows less material to be used, leading to lighter weight body armour.

1. Introduction

The use of high-performance fibres for ballistic protection has made it possible to produce lightweight soft body armour. This provides more mobility and comfort to body armour users such as soldiers and police officers. Efforts to design more protective body armour at a reduced weight have continued. Various approaches, such as silica colloidal suspension impregnation [1,2] and structure modification [3], have been used to improve the ballistic protection of flexible body armour. Other approaches include combining more than one type of fabric or other materials in a ballistic panel [4–6].

The performance of hybrid panel is influenced by many factors. Cunniff [7] suggested that the subsequent plies of fabric may constrain the transverse deflection the front plies, which is considered to affect the performance of a panel. As a result, he believed that placing low modulus materials on the impact face and high modulus on the subsequent plies may avoid this phenomenon and improve the performance of ballistic panel. In addition, Nader and Dagher [8] used nonaggressive barbed needles to place fibre through the thickness in a panel, preventing the projectile from spreading the individual yarns and the adjacent layers from delamination. Chitrangad [9] found that the weft yarns are stretched to break before the warp yarns in a ballistic event. By using a fabric with the weft yarns having a higher elongation to break than the weft yarns may enable the warp and weft yarns to break at the same time, which improves the performance of a fabric or panel.

When a composite panel is impacted, the projectile tends to exhibit through-the-thickness shear failure in the front layers, forming a plug while for back layers, the fibre damage mode resembles tensile failure [10,11]. Similar phenomena were also found with dry fabric panels by Chen et al. [12]. The fact that different layers of fabric exhibit various responses to ballistic impact suggests an advantage in combining more than one type of material in a panel. The aim would be that mixing different materials in an appropriate

* Corresponding author.
E-mail address: xiaogang.chen@manchester.ac.uk (X. Chen).

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sequence would make the best use of their corresponding properties and consequently enable the ballistic panel to be more energy absorbent.

One notable step to achieve design of hybrid panels is the combination of unidirectional (UD) fibre-reinforced laminates (also termed as UD fabrics) with woven fabrics. UD fabric is composed of angle-plied fibre net laminated by films [13]. In such fabrics, the flexibility of the laminates are retained due to the low resin content (no more than 20% [14]). In woven fabrics, due to the existence of crossovers, high performance filaments are not stretched along their axis until the yarns are fully de-crimped. This greatly reduces the velocity of the longitudinal wave and influences how the fibre performance is exhibited [3]. Because of the non-crimped fibre profile, the longitudinal wave travels faster in UD fabrics than in woven fabrics. This enables more fabric material to participate in energy dissipation. The superior performance of UD fabrics over woven fabrics has been mentioned in much of the literature [11,15–17]. Hybrid panels formed by UD fabrics and woven fabrics show better performance than single material panels. Non-penetration ballistic impact tests carried out by Thomas [4] showed that single material aramid filament panels gave deeper back face signature than hybrid panels. Karahan et al. [5] showed that around 13.9% less energy was transmitted to the backing materials through a hybrid panel than through a single material UD fabric panel. Price et al. [6] found that hybrid multi-plied fabric assemblies tended to exhibit a higher V_{50} than single material woven or UD assemblies.

Many of the studies carried out so far have focused more on assessing the superior performance of the hybrid panels over the single material panels than on development of guidelines for hybrid panel design. Based on the understanding developed by the previous researchers, this paper aims to further investigate the response of different layers of fabric in a ballistic panel and to develop a design guideline for performance improvement.

2. Major problems to be solved

This paper is concerned with the investigation of hybrid panel ballistic protection and development of guidelines for ballistic panel design. For this purpose, there are three aspects to be addressed. Firstly, the response of different layers of fabric in a panel upon ballistic impact will be studied. Parallel work regarding the layer response in a textile based ballistic panel includes the experimental work of Lee et al. [11] and the analytical model of Chen et al. [12]. They found that different layers of fabric in a panel tend to exhibit different failure mechanisms, indicating that mixing different materials in a proper sequence would hopefully make the best use of their corresponding properties and consequently enable the ballistic panel to be more energy absorbent. In this study, FE modelling will be applied and the results will be compared with those from other research. This study aims to investigate the failure mode of different layers and develop a set of design guidelines.

Secondly, according to the findings from the first step, research work will be undertaken to indicate the materials which best fulfill the different requirements of each layer. This includes the analysis of the material failure modes and energy absorption capabilities in transverse impact by using both experimental and FE methods.

Thirdly, in order to validate the guidelines developed, hybrid panels will be designed using the selected materials. Non-penetration ballistic tests will be carried out to investigate the performance of hybrid panels.

3. The response of fabric layers in a panel to ballistic impact

3.1. FE model for the woven fabric

Commercial FE software ABAQUS® is used to simulate the ballistic event. In these high velocity impacts, a projectile of a more rigid material collides with a panel of fabric which is flexible. The projectile model is of a cylindrical shape with the diameter and height both being 5.5 mm, and the mass of the projectile being 1 g, identical to the projectile used for practical ballistic tests. The lenticular cross-sectional shape is used as the yarn cross section in the fabric model, as proposed by Shanahan and Hearle [18]. The length and height of the yarn cross section are set to be 1.42 mm and 0.225 mm respectively, according to the measurement of the real fabric. Hearle et al. [19] developed two types of yarn path, i.e. non-constant elliptic curvature and constant elliptic curvature. The latter is used for the yarn path in this fabric model. The length and the height of yarn crimp are set to be 0.13 mm and 1.48 mm respectively.

The woven fabric is simulated at the yarn level and has a yarn density of 6.73 threads per cm in both warp and weft directions. The areal density of a single layer fabric is 240 g/m^2. The woven fabric model is 10 cm by 10 cm. As the model is symmetric about the X and Z axes, only a quarter of the fabric is simulated. In this simulation, the projectile impacts the fabric panel at a velocity of 500 m/s, corresponding to the highest projectile velocity measured in practical experiments. The coefficient of friction between yarns is found to be 0.14. The coefficient between projectile and fabric is obtained from KES FB-4 surface tester, which is 0.175.

Warp and weft yarns are assumed to be a continuum. That is, the inter-fibre movement within a yarn is not taken into consideration. The material is assumed to be transversely isotropy and linear-elastic up to the point of fracture. Since the fibres are oriented along the yarn path, this direction is has the highest of modulus, taken as 130 GPa [20]. For impact simulation, the values of E_{22}, E_{33}, G_{12} and G_{13} must be high enough to make the model stable. As it is not appropriate to use the transverse compression modulus of a yarn in ABAQUS, the values of a fibre are employed to define E_{22}, E_{33} [21]. Transverse shear modulus G_{12} and G_{13} are taken from the literature [22]. As it is not correct to consider the Poisson's ratio ν to be 0 for the all three directions, a value of 0.2 is selected according to Lin et al. [23]. The transverse shear modulus G_{23} is calculated by:

$$G_{23} = \frac{E_{33}}{2(1+\nu_{23})} \tag{1}$$

where ν_{23} is the Poisson's ratio of direction 2 and 3. The values for yarn mechanical properties are shown in Table 1.

A breaking strain of 0.04 is used as element failure criterion of the material. The value is obtained from the DSM data sheet [20]. Once the strain of a single element reaches it failure strain, the element would fail and is deleted from the model.

3.2. FE model for the UD fabric

The model for UHMWPE UD fabric is also simulated by using 3D solid continuous elements. The model is partitioned into four layers to simulate four layers of oriented fibre nets in real fabric.

Table 1
Material parameters (GPa) for UHMWPE yarn.

E_{11}	E_{22}	E_{33}	G_{12}	G_{13}	G_{23}	ν_{12}	ν_{13}	ν_{23}
130	1.21	1.21	3.28	3.28	0.504	0.2	0.2	0.2