Fibers and Polymers 2013, Vol.14, No.7, 1184-1189 DOI 10.1007/s12221-013-1184-2

Investigating Ballistic Impact on Fabric Targets with Gripping Yarns

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(Received August 30, 2012; Revised December 1, 2012; Accepted December 25, 2012)

Abstract: The purpose of the research is to investigate the fabric structure (with gripping yarns) in influencing ballistic performance aiming to improve the ballistic performance of the currently used body armour materials. Thirteen different fabrics having gripping yarn were designed along fabric warp and/or weft directions. Their ballistic performance in terms of energy absorption has been studied and comparisons made among the single layered fabrics and between the two double layered fabrics, as well as to the conventional used a plain woven fabric for both cases. It was found that fabrics with gripping yarns have improved fabric ballistic performance. The inter-jointed two-layer fabric performed better than the un-jointed two-layer fabric, and it showed a 16.6 % increase in the energy absorption. The implication of the research is that body armour can be made lighter without reducing ballistic impact performance by using gripping yarns.

Keywords: Ballistic impact, Weave structure, Gripping yarn, Impact performance, Body armour application

Introduction

A flexible armour system defeats the projectile by absorbing the kinetic energy and spreading it over an area to minimise the effect of the ballistic impact. Yarns are comprised of hundreds of filaments and display a progressive type of failure with individual filaments redistributing loads amongst themselves until the complete yarn failure by filament fracture or pullout. Aramid fibres, such as Kevlar and Twaron, are currently used in many different ballistic applications including body armour systems and armed vehicles. Aramid fibres/yarns exhibit a fairly linear elastic behaviour up to failure under tension [1,2]. Aramid fibres have high tensile modulus (up to 120 GPa), are chemically stable under a wide variety of exposure conditions (except for UV exposure) and have a high melting point (550 °C). Whilst the mechanical properties of constituent yarns are important for ballistic protection, the construction of fabrics can also have a significant effect on ballistic performance as has been pointed out by many. Two-dimensional woven fabrics constructed through interlacing of yarns at 90 °C angle are the most common structures for ballistic applications. Basic two-dimensional woven structures are plain, twill and satin weaves. Among them, the plain weave fabric exhibits the highest level of yarn-interlacing-density or weave-crimp-density, followed by twill and then satin weave. Therefore, the dimensional stability of plain weave is the highest among these three basic structures [3].

A combined structure has also been created to improve the protection against bullets. Steeghs *et al.* [4] invented a type of ballistic vest containing a stack of flexible fabrics and a stack of flexible unidirectional layers, where 2 types of ballistic fibres are used for the two stacks of fabrics. Cheeseman and Bogetti [5] reviewed of the factors that influence ballistic performance; specifically, the material properties of the yarn, fabric structure, projectile geometry and velocity, far field boundary conditions, multiple plies and friction. Each physical mechanism is described in details, and original references are cited to allow further investigation.

Fabric mechanical properties can be characterized in terms of yarn physical properties and fabric structures. Many researchers have developed fabric structural models to understand their mechanical properties and ballistic impact behaviour [6-11]. The shell element-based computational approach presented in the paper reported by Shahkarami and Vaziri [10] provides an efficient technique for modelling the impact response of multi-layer fabrics while accounting for the detailed geometrical and material properties of fabric panels described by such parameters as crimp, yarn geometry at a crossover, and transverse compression of yarns. Duan *et al.* [9] pointed out that the frictional forces help to protect fabric structure during ballistic impact. Tan *et al.* [7,8] investigated the effect of crimp on ballistic properties of fabrics by developing a method of computer modelling.

Cork and Foster [12] studied the ballistic performance of a range of narrow fabrics and compared to that of wider fabric panels. In contrast to conventional ballistic fabrics, it was found that the performance of narrow fabrics was highly sensitive to changes in fabric specification. Furthermore, it was shown that square weave fabrics may not necessarily be superior to unbalanced fabrics in narrow fabric form. It was also confirmed that narrow fabrics absorb more energy than wider fabric panels when undergoing direct ballistic impact, particularly when gripped in a two-sided configuration. Ways were sought of utilising these improvements in performance when the narrow fabrics are brought together to make full-width armour panels. Potentially, the observed improvements in performance could have been offset by the lines of weakness between adjacent fabric strips or by the weight of the structure required to grip on two sides. However, after

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investigating a number of potential solutions, significant improvements in the performance-to-weight ratios over simple fabric armour were achieved using an assembly of narrow fabrics attached to a lightweight composite frame. This is in line with results reported elsewhere [13,14]. Furthermore, they revealed that square fabrics which possess the same thread density and yarn linear density, provided better ballistic impact performance than others under the same fabric areal density.

In general, narrower fabrics would give better ballistic performance than their wider counterparts because of more effective weft yarn gripping by the two fabric selvages in narrow fabrics. However it is obvious that narrow fabrics have inconvenience in the manufacturing of body armour. It will need to find an appropriate method to make the narrow fabrics jointing together for a broad fabric used for body armour. Therefore it is time and money costing. Also from the ballistic performance point of view, the selvages between two narrow fabrics will create weak points and have negative effect on overall ballistic performance, also place uncomfortable during wearing.

This paper reports the design of plain weave wide fabric with yarn griping separations to achieve similar effect to that of the selvages of narrow fabrics, and to overcome the disadvantages of narrow fabrics. In this research, yarn pulling out test is used to examine the yarn gripping effect of the design and the ballistic performance of such fabrics made by using gripping separations.

Experimental

Fabric Design

Thirteen broad woven fabrics made of Kevlar49 yarn (made by DuPont) with griping effect, along with the plain woven fabric, have been designed and manufactured. The detailed specifications of these fabrics are listed in Table 1. Figures 1 and 2 show a repeat unit of the weave structure and cross sectional shape of broad regular two-layer (B2LRe) and

Table 1. Fabric specifications

Fabrics		Fibre type	Yarn densities		Yarn counts		Weave structures	Fabric weight (g/m^2)
			Warp (ends/cm)	Weft (picks/cm)	Warp (tex)	Weft (tex)		
Plain		Kevlar 49	7.5	7.5	158	158	Plain evenly woven structure	237
2LPlain							2 separate layer fabric with plain evenly woven structure	
Warp gripping	WG02						Warp gripping yarns are designed in every 2cm (16ends) intervals along fabric width	
	WG04						Warp gripping yarns are designed in every 4cm (32ends) intervals along fabric width	
	WG06						Warp gripping yarns are designed in every 6cm (48ends) intervals along fabric width	
	WG08						Warp gripping yarns are designed in every 8cm (64ends) intervals along fabric width	
	WG10						Warp gripping yarns are designed in every 10cm (80ends) intervals along fabric width	
Warp and weft gripping	WWG02						Both warp and weft gripping yarns are designed in every 2cm (16ends/picks) intervals	
	WWG04						Both warp and weft gripping yarns are designed in every 4cm (32ends/picks) intervals	
	WWG06						Both warp and weft gripping yarns are designed in every 6cm (48ends/picks) intervals	
	WWG08						Both warp and weft gripping yarns are designed in every 8cm (64ends/picks) intervals	
	WWG10						Both warp and weft gripping yarns are designed in every 10cm (80ends/picks) intervals	
B2LRe			7.2	7.2			Two fabric layers joint in one with 8 weft yarns in every 48 weft yarns intervals along fabric length – B2LRe (Broad 2 layer regular)	456
B2LIn			6.4	6.4			Two layers joint in one with 8 weft yarns in every 48 weft yarns intervals along fabric length, the two layers exchange in each joint – B2Lin (Broad 2 layer inter change).	405

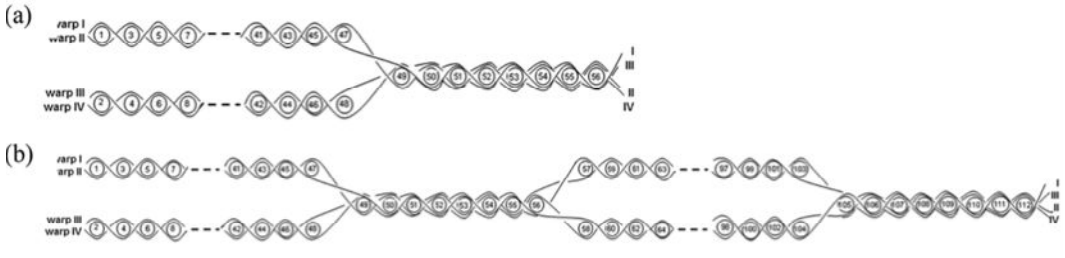


Figure 1. Weave structure of (a) B2LRe and (b) B2LIn.

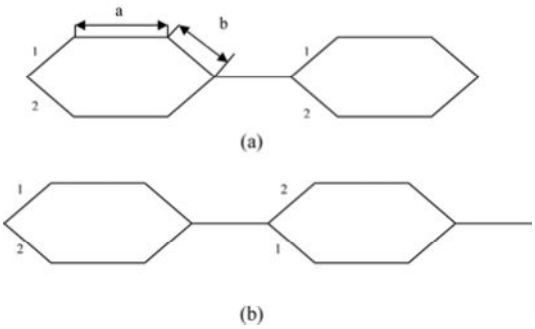


Figure 2. Two layers honeycomb fabric structure: (a) regular 2-layer and (b) interchanging 2-layer.

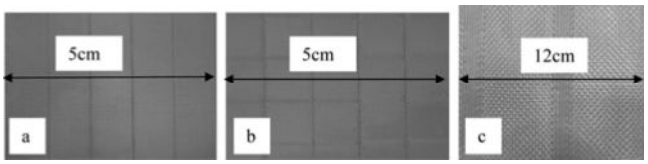


Figure 3. From left to right: (a) fabric with warp gripping yarn, (b) fabric with both warp and weft gripping yarn, and (c) two layered fabric with jointed yarn.

broad interchanging two-layer (B2Lin) respectively. In the above two layered honeycomb fabric structures, the variables "a" and "b" indicated in Figure 2 are used for varying the wall length for both bonded and free walls respectively. Figure 3 are photographs of the manufactured three types of innovative fabrics.

Yarn Pulling-out Test

In order to understand the influence of gripping yarns on the control of warp/weft yarns, yarn pulling-out test was carried out to examine the resistance of pulling-out warp/weft gripping yarns from the fabrics with comparison to pulling out a yarn from the plain woven fabric.

An instron tensile tester (Model No 4411) was used for this experiment. The fabric was held by the lower clamp in this set up and corrugated jaws were used to prevent fabric slippage from the clamp jaws.

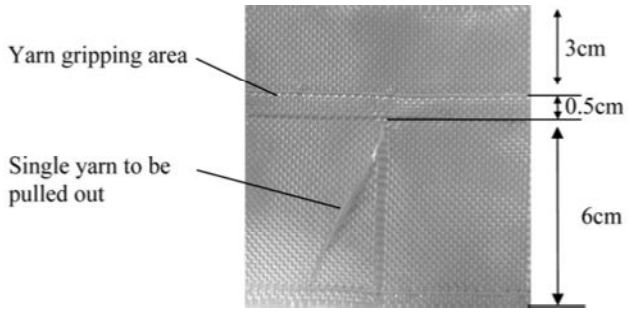


Figure 4. Specimen for yarn pulling out test.

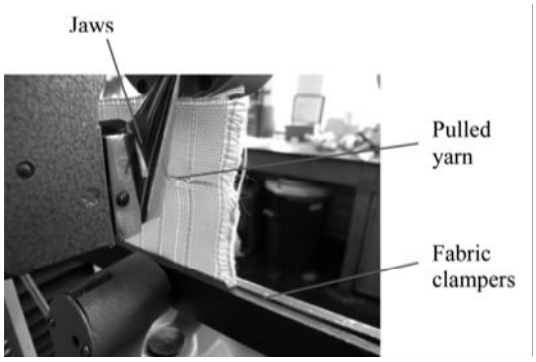


Figure 5. Yarn pulling out testing.

Samples were cut into 9.5×9.5 cm in dimension, as shown in Figure 4. The specimens were clamped in such a way that the yarns to be pulled out were in the vertical direction. Warp/weft yarns of 6 cm were taken out from the lower end of the specimens before being clamped, and the effective yarn length was therefore 3.5 cm. Only one warp/weft gripping was pulled out from each fabric specimen, and it was 3 cm from the top of the specimen. 5 samples were tested for each types of fabrics.

For the yarn pull-out test, the distance between the clamp and yarn jaw was set to 20 mm before testing. The fabric specimen was clamped on the lower edge while the yarn was clamped by the upper jaw, as is shown in Figure 5. The rate of movement of the upper jaw was set to 100 mm/min. The test stopped when there was no load applied on the pulled yarn.

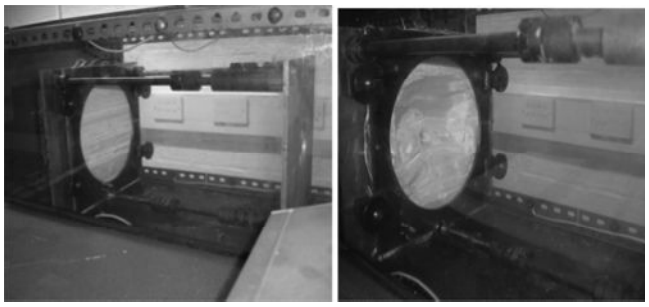


Figure 6. Projectile energy loss test before shooting – left and after shooting - right.

Energy Loss Test

The ballistic perforation test of fabrics was carried out using the firing range shown in Figure 6. A cylindrical steel projectile with diameter and height both being 5.5 mm passes through the first pair of IR detector before impacting the fabric target and then the second pair of IR detector after perforation. Energy loss of the projectile or energy absorption of the fabric target can be obtained by:

$$\Delta E = \frac{1}{2}m\left(\left(\frac{s_1}{t_1}\right)^2 - \left(\frac{s_2}{t_2}\right)^2\right)$$

where s_1 and s_2 are the distances between the two detectors of the front and back pairs, t_1 and t_2 are the time recorded for the project to pass through the front and back pair of sensors, respectively. The firing distance from the shooting to the target is 1.5 m.

It is worth mentioning that the energy loss of the projectile due to air friction was not taken into account in the equation used above. Five samples were tested for each type of fabric.

Results and Discussions

Resistance of Warp Yarn Pulling-out

Figure 7 presents the maximum load needed to pull out a yarn from the bonded part of B2LRe and B2Lin fabrics and from the gripped part of fabrics with warp and weft griping yarns as a comparison to pulling a yarn from a normal plain weave fabric.

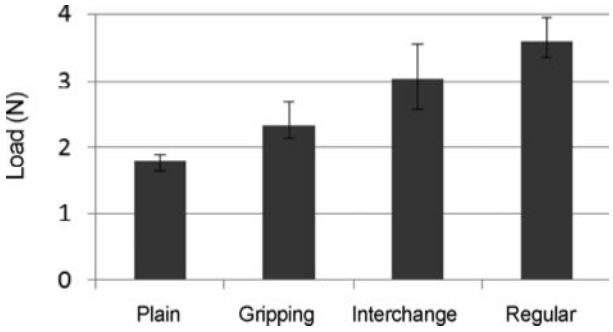


Figure 7. Resistance comparison of pulling yarns out of fabrics.

It shows a 22 % increase of the maximum load needed to pull out a yarn from the plain woven fabric with gripping yarn insertion, compared to the pure plain weave fabric in average. This is believed to be caused by the gripping yarns which restrain the movement of the weft and warp yarns. In the meantime, it was found that there are 40.1 % and 50 % increase of the maximum load needed to pull out a yarn from the B2Lin and B2LRe respectively compared to the plain weave fabric. The increase might be caused by the increased density of the warp yarns in the bonded area and the increased friction between yarns, as a result needing to overcome more friction force to pull out a yarn. In this experiment, the yarn length being pulled out is 3.5 cm, and only one gripping yarn insertion is contained in this length. The result implies that fabrics with gripping yarns seem to be more likely to prevent the yarns from pulling out the fabric under impact loads, therefore have better ability in bringing down the impact trauma.

Ballistic Performance of Fabrics

Figure 8 presents the energy absorption of the plain woven fabric and the ten Kevlar fabrics with weft gripping insertion yarns, and with and without warp gripping yarns. It shows that almost all of the fabrics with gripping yarns have absorbed more energy compared to the plain woven fabric. Fabrics with both warp and weft gripping yarns perform better to their counterparts without weft gripping yarns apart from fabric WWG02.

Considering the fact that projectile speeds vary during the shooting test, it is necessary to normalise the energy absorption by the target impact energy. The nornalized energy absorption is shown in Figure 9, a similar conclusion can be drawn that all the fabrics having gripping yarns outperform the

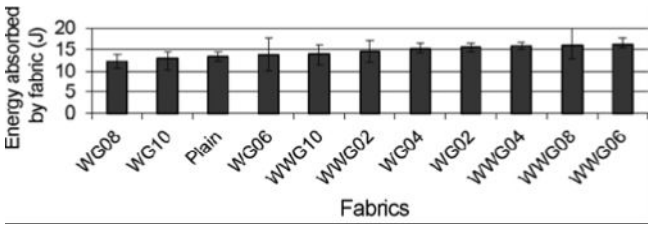


Figure 8. Energy absorbed by various manufactured fabrics.

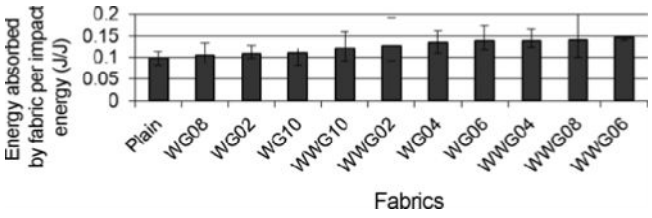


Figure 9. Energy absorption of various fabrics at per unit impact energy basis.

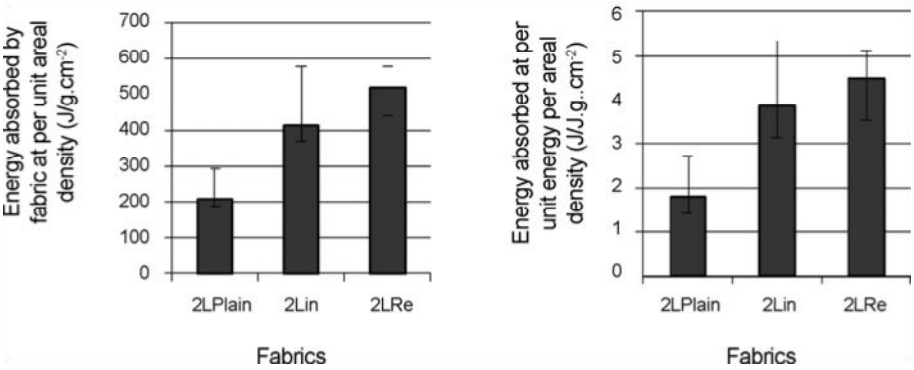


Figure 10. Energy absorption of the two joint layered fabrics as comparison to separated two layer plain weave fabric.

conventional plain woven fabric. In both cases, fabric WWG06 which has gripping yarns in both the warp and weft directions has the best ballistic performance in terms of energy absorption, followed by WWG08 and WWG04. It is also believed from the results that it is not the case that more gripping yarns will produce better ballistic performance there is an optimal spacing between any lines made by the gripping yarns in both warp and weft directions. In this study, this optimal spacing seems to be 6 cm based on the data available. The gripping yarns designed in the fabrics simulate the effect of fabric selvages (in narrow fabrics); this has been explained earlier in the introduction. If the space between the two adjacent yarn gripping lines is too large, the gripped yarns does not seem to be able to make much difference once a projectile impacts on. On the other hand, if this spacing is too small, the yarns with gripping effect will undergo breakage easily because of the greater shear in the gripping yarns.

Energy loss shooting tests were also been carried out on the two specially designed layered Kevlar fabrics, B2LRe and B2LIn. Figure 10 presents the results on energy absorbed by the joint two layered fabrics (2LRe and 2LIn) compared to the separated two layer plain weave fabric. Due to the difference in yarn density of the plain weave fabric and the two layered fabrics, the energy absorbed by the fabrics were normalized by the areal density. The joint two layered fabrics show better ballistic performance than the two layer plain weave fabric in terms of energy absorbed by fabric at per areal density and per unit impact energy basis. In both the above cases, it shows that the regular joint two layered fabric absorbs more energy than the interchanging two layered fabric. This may be due to the higher density in both the warp and weft directions of the regular two layered fabric, which increases the intersections of warp and weft yarns in the fabric. It is understood that the intersections in a fabric helps the strain wave propagation, leading to higher energy absorption.

Figure 11 shows the deformed fabric sample after ballistic impact. The sample size was 24×24 cm.

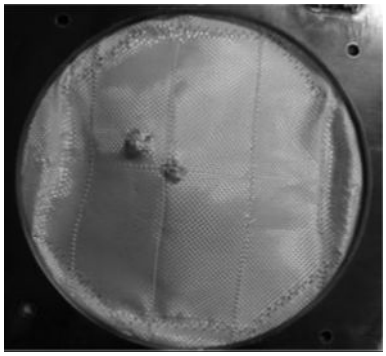


Figure 11. Fabric sample after experiencing ballistic impact.

Conclusion

Based on the designed fabrics and comparisons of their ability to absorb impact energy obtained through the energy loss test, the following conclusions can be drawn:

1. Gripping yarns designed in the fabric restrict the yarn movement when an impact load is applied.
2. Fabrics with gripping yarns improves the fabric ballistic performance. The size of interval between two adjacent yarn gripping lines affects the ballistic performance. 6 cm seems to be the optimal band length in this study.
3. The inter-joint two-layer fabric has better performance compared to the un-joint two-layer fabric.

The inter-joint two or more layered fabrics will be investigated further to study how the spaces of the adjacent joints affect the impact performance. However care must be taken that if the space is two small, the resulted fabrics will become stiff. On the other hand, if the space is too large, then the joint area between the adjacent layers may lose its intended effect.

Acknowledgement

This research is partially founded by UK MOD grant RT/COM/5/030.

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