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Effect of fabric stitching on ballistic impact resistance of natural rubber coated fabric systems

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Abstract

The effects of different stitching patterns on the ballistic impact resistance of multiple layer fabric systems were investigated. Several neat and natural rubber (NR) coated layers were combined and alternately arranged to form each fabric system. The fabric systems were stitched with 1-in. field diamond, 2-in. field diamond, diagonal, and perimeter stitching patterns. The ballistic limit performances of the fabric systems were compared with unstitched fabric system. The results showed that certain fabric stitching enhanced the ballistic resistance of the fabric systems. The 2-in. field diamond stitched system gave the highest ballistic limit in comparisons with other stitched patterns and unstitched fabric systems. Further ballistic tests revealed that at impact velocities between 407 and 420 m/s, the 2-in. field diamond stitched panel showed some improvement in reducing the backface deformation from fabric systems.

Keywords: Textiles; Fabrics; Impact and ballistic

1. Introduction

Textile materials selected for soft body armours have superior properties in terms of dynamic absorption characteristics, strength-to-weight ratio and modulus. During ballistic impact, kinetic energy from the projectile is absorbed by several layers of fabric and prevents the projectile from completely penetrating the system. There are several ballistic and material parameters that influence the ballistic impact resistance of fabric systems in soft body armours. Cunnif [1] identified that fibre property, fabric structure, number of fabric layers, areal density, projectile parameters and impact parameters as major factors in energy absorption of fabric systems. Cheeseman and Bogetti [2] added that besides the above, fabric layers interactions, the effect of boundary conditions, yarn–yarn friction, and projectile–yarn frictions are also important factors in impact energy absorption.

One of the possible methods to increase the energy absorption characteristics by the fabric layers is through fabric coating. Generally, any type of fabric coating changes the inter-fibre and yarn–yarn friction. Extensive work by Briscoe and Motamedi [3] concluded that even a slight change in friction significantly affected the ballistic performance of the fabric systems. Higher friction among the fibres and yarns resulted in more energy absorption by the fabric due to higher frictional contact with the projectile and less mobility of yarns upon impact [2]. Lower friction, on the other hand, results in the projectile being able to easily slide through the fabric by pushing the yarns aside. Bazhenov [4] showed that water acted like a lubricant and decreased the ballistic impact resistance of fabric systems.

In a previous investigation, multiple layer fabric systems consisting of neat and natural rubber (NR) coated high strength fabrics have been reported to give as high as 60% increased in energy absorption in comparisons to all-neat fabric systems [5]. It was believed that due to the increased in yarn–yarn friction, the NR coated fabric layers

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helped to increase the energy absorbed by the fabric system. The friction effect was found to be in agreement with the work on fabric coatings by other studies [6,7]. Lee et al. [6] and Tan et al. [7] used shear thickening fluid (silica particles suspended in certain liquid), to coat ballistic fabrics. Both studies reported some increase in the amount of energy absorbed by fabric systems with several layers of silica coated fabrics. It was pointed out that the enhancements in ballistic performance of the fabric systems were due to the increased in the yarn–yarn friction in the silica coated fabrics [7]. The improvement in the ballistic resistance for these studies was with the expense of increase in the areal density of the fabric systems.

The above studies [5–7] were done on unstitched fabric systems. Very often, commercial fabric systems intended for soft body armour are stitched in some form or the other to reduce the non-penetrating injuries of the internal organs otherwise known as blunt trauma. Blunt trauma is measured by the depth of depression of the backing material (backface deformation) after projectile impact which should not be more than 44 mm as specified by National Institute of Justice (NIJ) Standard-0101.04 [8]. However, there are inadequate reports detailing the effects of stitched fabric systems (soft composites) on ballistic impact performance (ballistic resistance and blunt trauma) and research results are proprietary. Bajaj et al. [9] have reviewed several fabric systems which were stitched to improve energy absorption but did not described how the stitches were able to contribute in blunt trauma reduction. There are also limited studies in the case of stitched rigid composites on ballistic impact resistance. Investigations by Hosur et al. [10] showed that stitching of woven carbon/epoxy composites generally improved the damage resistance after ballistic impact but somehow gave lower ballistic limit than unstitched composites. In contrast, studies by Kang and Lee [11] and Mouritz [12] reported a slight increased in the resistance of ballistic impact loading of stitched composites in comparisons to unstitched composites.

The present study investigates the effects of different stitching patterns on the ballistic impact resistance (ballistic limit) of fabric systems consisting of neat and NR coated fabrics. A follow-up investigation was also done to assess the blunt trauma performance of the composites.

2. Experimental

2.1. Material preparation

Kevlar 29 Style 731 with an areal density of 280 g/m^2 was used in the study. The square plain structure fabric consists of 1000 Denier yarns with warp and weft density of 31 yarns per inch. Pre-vulcanised NR latex (Revertex Malaysia Sdn. Bhd.) of high modulus type was used to coat the fabrics. The NR latex has 60.5% total solid content (TSC) and viscosity of about 35 s (Ford Cup 3) at 25 °C. Fabric samples of 0.32 m × 0.32 m were cut and prepared for coating. Coating was done by straight dipping process, where the fabric was dipped into the prevulcanised NR latex. After a few seconds, the fabric was withdrawn slowly from the prevulcanised NR latex, leaving a thin film coating the fabric. The NR coated fabrics were dried overnight at room temperature. The resultant weight of each NR coated fabric after drying and conditioning was 485 ± 10 g/m^2.

For the ballistic limit tests, five fabric systems consisting of 8 neat and 8 NR coated fabric layers were assembled. In each fabric system, the neat and coated layers were arranged alternately. Fig. 1 shows the schematic arrangement of the neat and NR coated layers in the fabric system. Four types of stitching patterns (through-the-thickness) were investigated (Fig. 2). Stitching was done using a 4-ply Kevlar thread on a standard stitching machine with a stitch density of 5 stitches per inch. One sample was left unstitched for comparison. In the blunt trauma assessment, several fabric systems of 24–32 layers were assembled and this is summarized in Table 1.

2.2. Ballistic limit determination

Ballistic limit is the test to determine the velocity at which 50% of the time the projectile is stopped by the target [13]. In the study, the average of three complete penetrations (CP) and three partial penetrations (PP) were calculated for ballistic limit on each fabric system. The difference between the average lowest CP and highest PP shots was less than 27 m/s. Table 2 gives the ballistic limit test details and Fig. 3 shows the schematic of the ballistic limit test set-up.

2.3. Blunt trauma measurement

Ballistic impact tests for blunt trauma measurement were conducted according to NIJ Standard-0101.04, which is known as backface signature (P-BFS) [8]. The tests were initially done to satisfy Level IIIA armour type (impact velocities at 426 ± 9 m/s), however, the test gun system (9 mm SMG Sub Sterling Gun) was only able to fire shots in the range of 407 m/s–420 m/s using standard 9 mm Full Metal Jacketed Round Nose (FMJ RN) bullets. Nevertheless, these shot velocities were sufficient for comparing the indentation depth among the samples and will not indicate to satisfy the Level IIIA armour type.

The gun-to-target distance was the same as the ballistic limit determination. The fabric system was tied using elastic straps on a square box filled with standard modeling clay backing material which gave the indentation depth (by forming a crater) from each shot. The indentation depths were measured using a vernier caliper (in millimeters) from the plane defined by the front edge of the clay box fixture. This was done after three shots were fired for each sample. All the ballistic impact tests were performed in an indoor ballistic shooting range.

3. Results and discussion

3.1. Ballistic limit results

Fig. 4 shows the ballistic limit test results of the fabric systems. The results indicate that stitched fabric systems have some effects on the ballistic impact resistance of the composites. Except for the 1-in. field diamond stitching, other stitching patterns gave higher ballistic limit than the unstitched fabric system. The highest ballistic limit result was from the 2-in. field diamond stitched fabric

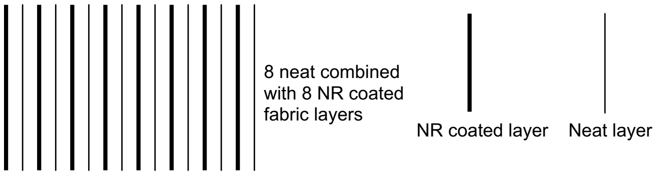

Fig. 1. Arrangement of neat and coated layers in the fabric system.

(a) 1-inch field diamond (b) 2-inch field diamond

(c) diagonal (d) perimeter

Fig. 2. Photographs showing the types of stitching pattern on the fabric systems.

Table 1
Description of fabric systems for backface deformation assessment

Fabric system	Descriptions	Number of layers	System areal density (g/m^2)
A	32-neat layers unstitched	32	8992
B	28-neat layers unstitched	28	7868
C	(8 NR coated + 8 neat) 2 in. diamond stitched panel + 10 neat layers	26	8938
D	(8 NR coated + 8 neat) 2 in. diamond stitched panel + 8 neat layers	24	8376

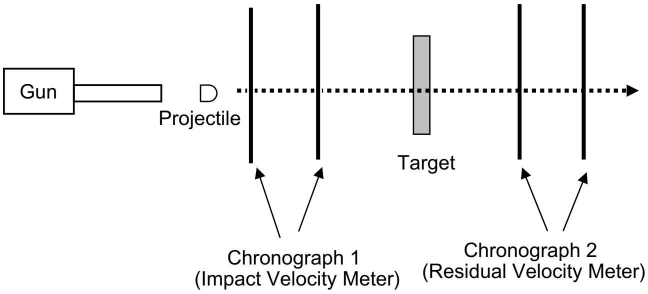

Fig. 3. Schematic diagram of ballistic test set-up.

Table 2
Ballistic limit test summary

Standard	Mil-Std-662F V_{50} ballistic test for armour [13]
Projectile	NATO FSP, chisel-pointed cylinder (1.1 g)
Number of shots per sample	At least six shots
Measurements	Impact velocity, residual velocity, V50
Velocity measurement	CED Millenium chronograph and Doppler Radar System (Weibel)
Gun type	7.62 mm Mauser test gun
Gun to target distance	5 m

system followed by the perimeter and diagonal stitched fabric systems. In comparisons with the unstitched fabric system, the increased in the ballistic limit performance of these fabric systems were 8%, 3% and 2%, respectively. The ballistic resistance between the perimeter and diagonal stitched fabric systems is not statistically significant. The 1-in. field diamond stitching did not give any improvement in the ballistic impact resistance and has lower ballistic limit than the unstitched fabric system.

These results showed that certain stitching patterns may increase the impact energy absorbed by the soft composite fabric system. All the fabric systems showed similar energy absorption relationship as the impact velocity increases. As shown in Fig. 5, at impact velocities below the ballistic limit, there is an increase in the energy absorbed by the fabric systems from the projectile's kinetic energy. All the energy from the projectile is absorbed by the fabric systems. Below the ballistic limit, the projectile is usually stopped by the fabric system and become embedded in between the layers. Beyond the ballistic limit, the projectile completely penetrated the systems leading to the increase in

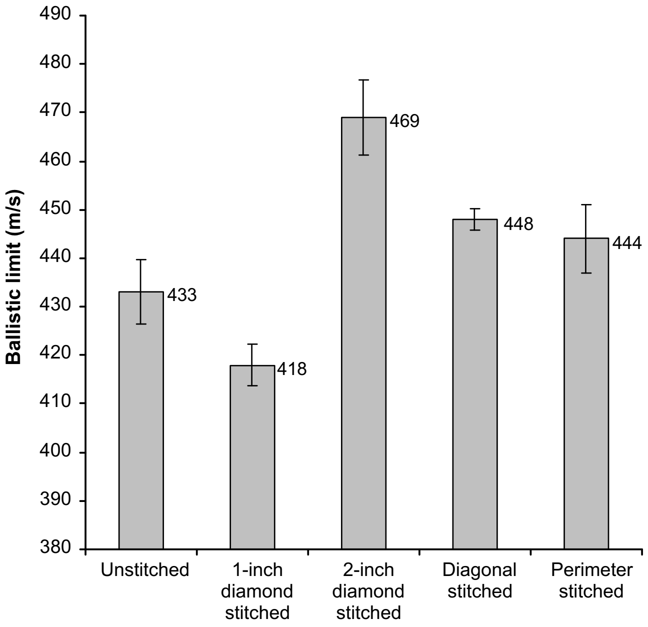

Fig. 4. Ballistic limit of fabric systems.

the residual velocity and therefore giving a reduction in the energy transferred to the fabric system by the projectile. Similar observations were also reported by Tan et al. [14] from fabric systems shot with different shaped projectiles.

The improvement in ballistic impact resistance by some of the stitched fabric systems was also shown by the number of layers penetrated by the projectile. Post-ballistic impact examination on the fabric system (at shots of similar impact velocity and just about their ballistic limit) revealed that there were differences in the number of layers that the projectile passed through. Fig. 6 shows that for impact velocity of 444 m/s, the unstitched and 1-in. field diamond stitched fabric systems were completely penetrated by the projectile. However, for the 2-in. field diamond, diagonal and perimeter stitched fabric system, only 12–13 layers were penetrated by the projectiles. The number of penetrated layers may suggest that the energy is transferred more efficiently among the fabric layers and each layer contributes to stopping the projectile.

The mechanism behind the improvements in the ballistic limit of some of the stitched fabric systems is nevertheless not fully understood. A possible explanation is that, due to the stitching, the fabric layers are closer to one another and that there is no gap between them resulting in better interaction among the fabric layers. Therefore the impact energy is transferred to each fabric layers much faster than unstitched fabric system. Studies which discussed on the issues of spaced fabric system (gap between layers) in comparisons with plied fabric system (no gap between layers) can be closely related to fabric stitching. Lim et al. [15] found that certain projectile shape gave higher ballistic performance with multiple layers of plied systems than the spaced systems. Novotny et al. [16] compared the ballistic performances of spaced fabric systems with 0.5 mm and 1 mm gap among the layers and fabric systems with no gap. The study [16] suggested that fabric systems with the least amount of gap among the layers performed better in terms of specific energy absorption. With respect to fabric stitching, the stitches might have enhanced the interaction among the fabrics layers upon impact by the projectile. This form of energy absorption participation by the fabric layers might have resulted in better trapping of the projectiles. Fabric layer interactions in the 2-in. stitched diamond field fabric system might have been the optimum in comparisons with other fabric systems. As for the 1-in. stitched diamond fabric system, the stitching was too close forming a stiff panel, where the fabric system acted like a rigid panel (a single body system) rather than multiple layer system. There is less interactions among fabric layers and this resulted in lower ballistic impact resistance. As mentioned earlier, contrasting ballistic resistance results were also obtained by investigations on stitched rigid composites [10–12].

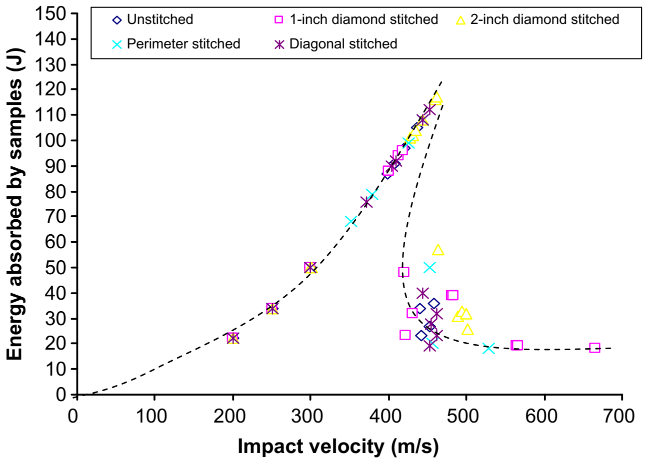

Fig. 5. Impact energy absorbed by the fabric systems.

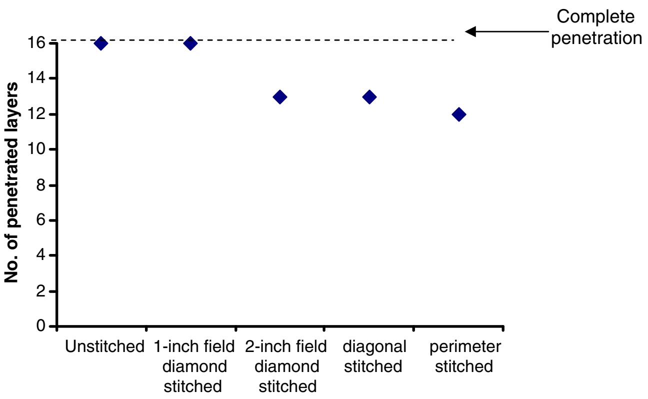

Fig. 6. Number of layers penetrated by the projectile at similar impact velocity (444 m/s).

Table 3
Backface deformation results

Fabric systems	Impact velocity (m/s)			Backface deformation (mm)		
	Shot no. 1	Shot no. 2	Shot no.3	Shot no. 1	Shot no. 2	Shot no. 3
A	410	420	416	22	24	24
B	413	407	410	26	26	25
C	408	410	418	16	18	16
D	413	413	414	18	19	CP

3.2. Blunt trauma results

The combined 8 neat layers and 8 NR coated layers of the 2-in. field diamond stitched fabric system (which gave the highest ballistic limit results) was compared with an all-neat layers unstitched fabric system. However, since the impact velocities were high, a 16-layer fabric system was not sufficient to provide resistance to penetration from the 9 mm bullets. Therefore, additional neat fabric layers were added to the fabric systems.

The results of the blunt trauma measurements are given in Table 3. At similar impact velocities, the 32-neat (A) and 28-neat (B) layers fabric systems gave marginal backface deformation of between 22 and 25 mm. The difference of four neat layers between the two fabric systems did not give any significant effect in the blunt trauma on the backing material. Fabric system C has 26 layers of fabrics including the 2-in. field diamond stitched panel and gave good performance in terms of reducing the backface deformation in comparisons with fabric systems A and B. However, it has similar areal density as fabric system A. The contributions of fabric coating to ballistic performance were also showed by Lee et al. [6], where silica particles coated Kevlar fabric system gave lower blunt trauma in comparisons with all-neat Kevlar fabric system. In this study, the improvement may suggest two effects; the influence of the NR coated layers, and the influence of stitching. It can be said that with these two effects, less number of layers are needed in the fabric system for comparable or better blunt trauma performance in comparisons with all-neat layer fabric system. Fabric system D (which has 2 neat layers less than fabric system C) was not able to stop the bullet in one of the three shots, despite giving lower blunt trauma in the first two shots. There are insufficient fabric layers in fabric system D to contribute and participate in energy absorption upon ballistic impact at velocities between 407 and 420 m/s. The fabric system is considered a failure but might be suitable for lower impact velocities.

4. Conclusions

The effect of stitching on the ballistic limit performance of combined 8 neat and 8 NR coated layers has been studied. The evidence suggests that fabric stitching might influence the ballistic impact resistance of the fabric system. In comparisons with unstitched fabric system, the 2-in. field diamond, diagonal, and perimeter stitched fabric systems gave much higher ballistic limit performance. However, the 1-in. field diamond stitched fabric system gave lower ballistic limit than the unstitched fabric system. Higher ballistic limit results indicate higher energy absorption by the fabric systems. For optimum number of layers for a certain impact velocity, stitching of fabric systems helped to reduce the indentation depth in comparisons to unstitched fabric systems. One thing to note is that stitching of fabric layers into a panel made the system stiffer in comparison with unstitched fabric system. Unstitched fabric systems offer better flexibility but have problems with movement (shifting) of fabric layers during ballistic impact tests. The results from this study are not conclusive and it is recommended that further studies on the issues of fabric stitching with ballistic impact performance are needed.

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