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Ballistic Response of Natural Rubber Latex Coated and Uncoated Fabric Systems

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The intrinsic properties of natural rubber latex (NRL) such as excellent strength, adhesion and flexibility make it very suitable for coating on textile fabrics. In this study, high strength fabrics were coated with NRL and assembled with uncoated fabrics into several fabric systems. The fabric systems were shot with 9 mm bullets at 367 ± 9 m/s to assess the blunt trauma performances. The results showed that both the 18-layer and 21-layer uncoated fabric systems failed the blunt trauma test. However, fabric systems with NRL coated fabric layers gave lower blunt trauma of between 25 mm – 32 mm indentation depths. The modes of failure after the ballistic impact were believed to be closely related with friction among the yarns in the NRL coated fabrics. The relative measure of friction was evaluated through the yarn pull-out strength and puncture resistance tests on the uncoated and NRL coated fabrics. Higher frictional effects were evident from the NRL coated fabrics in comparison with the uncoated fabrics.

Key words: natural rubber latex; coated fabrics; ballistic impact resistance; blunt trauma; yarn pull-out; puncture resistance

Soft body armours for personal protection are usually worn by law enforcement officers to ensure their safety when dealing with situations that may involve shooting from common handguns, long guns and shotguns. Fabric materials such as poly(p-phenylene terephthalamide) (Kevlar®, Twaron), high modulus polyethylenes (Spectra®, Dyneema®) and poly(p-phenylene-benzobisoxazole) [PBO] (Zylon®) have been widely used as fabric systems in soft body armours because of their low density, high strength and high modulus properties. Zylon®, for example, is one fifth of the weight of steel but is ten times stronger than steel[1]. Fabric parameters such as fabric structure and number of fabric layers have significant influence in determining the ballistic impact characteristics of the fabric systems. However, multiple layers of these fabrics are needed, up to 50 layers, for protection against certain bullet types, sizes and velocities. Many investigations and research efforts have been directed towards enhancing the ballistic impact performances of the fabrics and have been reviewed by Cheeseman and Bogetti[2]. One of the efforts which is of interest in this study is fabric coating.

In an earlier study[3], the improvements in ballistic impact resistance of fabric systems

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consisting several uncoated and NRL coated fabrics were reported. The tests were done using standard Fragment Simulation Projectiles (FSP) to measure the ballistic limit *i.e*. the velocity at which the fabric system stops the projectile for at least half the time. It was believed that the enhancement in ballistic impact resistance was contributed by higher frictional effects among the yarns in the NRL coated fabrics. The friction effects were in agreement with other studies[4–7]. The yarns may have been held tightly by the NRL coating, restricting their mobility and thus resisting the projectiles much better than uncoated fabrics.

NRL is specifically chosen as the coating matrix because it meets both technical and cost effective requirements. Apart from that, NRL also gives excellent adhesion and flexibility. Vulcanised NRL film has a high tensile strength (28 MPa), high elongation at break (900%), and a high tearing energy (100 kJm^{-2}), which are attributed to its ability to crystallise on straining due to its regular microstructure[8,9]. In general, NRL is well known in applications such as industrial and medical gloves, catheters, children toys, condoms, balloons, baby bottle nipples, and various healthcare applications[10]. In comparison with the majority of synthetic latices, dipped NRL goods and NRL sheets have higher flexibility, excellent puncture and tear resistance, high mechanical strength and ease of processing[11]. These properties make NRL very suitable for modifying properties of high performance textile fabrics such as Kevlar®, Twaron and Nylon. Furthermore, the cost of NRL is 6 times lower than most synthetic polymer latices. Other textile applications of NRL are in carpet backings, elastic band, and threads for clothing materials[10,12].

The study is now extended to evaluate the ballistic impact resistance in terms of blunt trauma performance against 9 mm bullets. Blunt trauma (also called Backface Signature) is the non-penetrating injuries to the internal organs and is measured by the depth of indentation created on the fabric system after each impact shot. According to the National Institute of Justice (NIJ) Standard-0101.04[13], a body armour will fail, if the indentation depth in any of the shots is greater than 44 mm.

In addition, to further understand the friction effects mentioned earlier, it is essential to investigate the relative measure of the friction among the yarns in the coated fabrics. This can be achieved by doing measurements on the yarn pull-out strength and puncture resistance. Yarn pull-out has been identified as one of the mechanisms of energy absorption associated with friction among the yarns[3,4,7,14]. Yarn pull-out is where the yarns do not break upon impact but are rather pulled out from the fabric[2]. Similarly, puncture resistance (quasi-static) test is used to measure friction effects on ballistic fabrics. Briscoe and Motamedi[6] reported that fabrics with high friction dissipated more energy than fabric with lower friction. Other investigators[15–17] have shown that the results from puncture resistance tests provide a useful indication of the penetration resistance upon ballistic impact. The test could also provide some form of ranking on the penetration resistance of fabrics[17].

EXPERIMENTAL

Sample Preparation

Plain Twaron fabric (Barrday Inc., Canada) consisting of 1000 Denier yarns were used. The fabric had 22 yarns per inch in weft and warp direction with an areal density of 190 g/m^2. The fabric was cut into square layers measuring 32 cm × 32 cm each. High modulus prevulcanised NRL (Revertex Malaysia Sdn. Bhd.) was used to coat the fabrics. The colloidal and physical properties of the latex are given in *Table 1*. Coating was done by means of a straight dipping process, where the fabric was dipped into the prevulcanised NRL. After a few seconds, the fabric was withdrawn slowly from the prevulcanised NRL, leaving a thin NRL film coating the fabric. The NRL coated fabrics were dried overnight at room temperature. The resultant weight of each NRL coated fabric after drying and conditioning was 400 ± 10 g/m^2. The thickness of the NRL film coating was measured using a thickness gauge.

Several 18-layer and 21-layer fabric systems were assembled and stacked together, consisting of all-uncoated layers (A and B), and combined uncoated with 4 coated layers (C - H). The four coated fabric layers were placed at the rear of the fabric systems in different configurations as shown by the schematic diagrams in *Figure 1*.

Ballistic Impact Tests

The ballistic impact tests were conducted to evaluate blunt trauma performance in accordance to NIJ Standard-0101.04[13]. Each fabric system was secured on a target holder against a box of modeling clay and positioned five meters away from the muzzle of the test gun. The test gun was an SMG Sub Sterling Gun using 9 mm Full Metal Jacketed Round Nose (FMJ RN) test bullets. For each fabric system, three shots were fired at 0º angle of incidence with impact velocities of 367 ± 9 m/s, which is equivalent to NIJ Level II. The impact velocities were measured using the Doppler Radar System (Weibel) and Projectile Velocity Measuring System (PVMS). The indentation depths in millimeters were measured from the front plane surface of the clay box using a vernier caliper.

Yarn Pull-Out Strength Test

Twaron *CT709* fabrics were used in both the yarn pull-out and puncture resistance tests. The fabric parameters are given in *Table 2*. Samples of size 80 mm × 100 mm were prepared with several yarns at one end of the sample protruding, as shown in *Figure 2*. The yarn pull-out test setup is shown in *Figure 3*. Ten yarns at the center of one end of the sample were gripped in the upper clamp. The other end of the sample was gripped using a fabricated bottom clamp which has a 2 cm rectangle groove at the center. This groove allowed yarns at the center of the fabric sample to be pulled out when the clamps moved apart. A Testometric Tensile Tester with a 2-kN load cell was used to perform the test with a crosshead speed of 100 mm/min.

TABLE 1. PROPERTIES OF HIGH MODULUS PREVULCANISED NRL[18]

Properties	Values
Colloidal properties:	
Total solid content (%)	60.5
Ammonia content (%)	0.68
Viscosity (s), (Ford Cup 3 at 25ºC)	35.0
Mechanical stability (s)	975
Physical properties (unaged values):	
Modulus at 700% elongation (MPa)	15.5
Tensile strength (MPa)	25.0

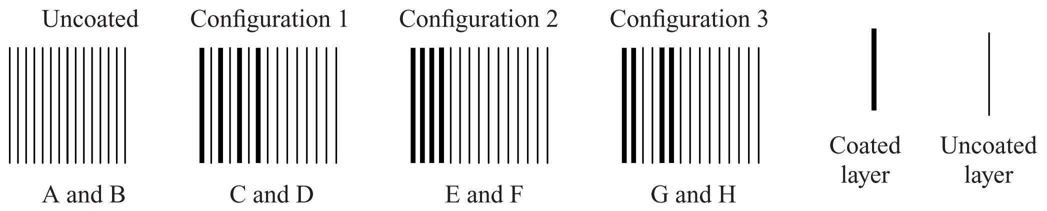


Figure 1. Arrangement of fabric layers.

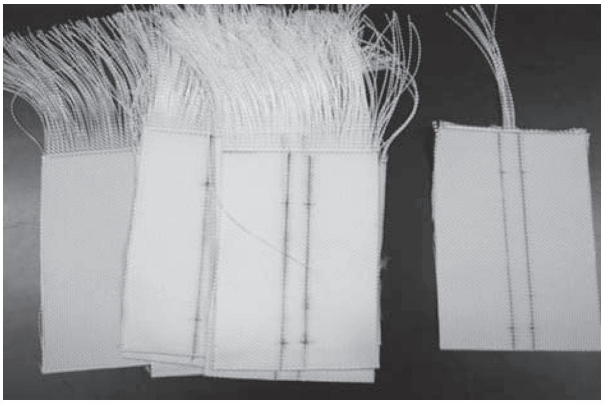


Figure 2. Yarn pull-out sample.

Puncture Resistance Test

Principally, a probe of known diameter and shape was allowed to slowly push itself through the fabric. The purpose was to measure the force needed to puncture the fabric and the amount of deflection that the fabric gained upon penetration. In this test, a single fabric sample was held horizontally by a circular clamp of 10 cm diameter. The test set-up is as shown in *Figure 4*. The circular clamp had several fasteners (bolts) to grip the sample and prevent slippage during the test. A probe made of stainless steel having dimensions of 25.4 mm diameter and cone angle of 120º was used. It was attached to the base of the Instron Tensile Machine (Model 5582). Before the test, the probe was positioned with its tip just touching the fabric's surface. During the test, the probe moved vertically downwards at a constant speed of 100 mm/min. The maximum force (N) to penetrate the sample indicates the puncture resistance of the material.

RESULTS AND DISCUSSIONS

Ballistic Impact Results

Table 3 shows the results of the blunt trauma assessment for the fabric systems. It was observed that for the all-uncoated fabric systems, at least one of the shots gave an indentation depth of more than 44 mm.

TABLE 2. UNCOATED AND NRL COATED FABRIC PARAMETERS FOR YARN PULLOUT AND PUNCTURE RESISTANCE TESTS

Properties	Twaron *CT709* Uncoated	Twaron *CT709* NRL coated (single dipping)
Construction	Plain (1 × 1)	–
Yarn size (Denier)	840	–
Warp/in × Weft/in	27 × 27	–
Areal density (g/m^2)	202	338
Thickness (mm)	0.29	0.37

TABLE 3. BLUNT TRAUMA RESULTS

Fabric systems	Descriptions	No. of layers	Impact velocity (m/s)			Indentation depth (mm)		
			Shot 1	Shot 2	Shot 3	Shot 1	Shot 2	Shot 3
A	18-layer all uncoated	18	359	361	361	43	39	46
B	21-layer all uncoated	21	360	357	362	39	46	42
C	Configuration 1	118	367	360	361	28	28	29
D	Configuration 1	21	379	362	360	30	29	30
E	Configuration 2	18	359	358	353	25	31	26
F	Configuration 2	21	365	358	362	32	32	30
G	Configuration 3	18	364	362	362	27	30	25
H	Configuration 3	21	363	354	358	26	28	28

Thus the results show that the 18-layer and 21-layer all-uncoated fabric systems failed the blunt trauma test in accordance with the NIJ standard. However, the blunt trauma could probably be reduced to below 44 mm by adding a few more layers of fabric.

In contrast, fabric systems with NRL coated fabric layers gave lower blunt trauma regardless of the configurations and number of layers. The indentation depths of these fabric systems were between 25 mm – 32 mm. Comparison of the fabric systems with different configurations of NRL coated and uncoated layers showed that the differences in their blunt trauma performance were marginal.

Modes of Deformation

In all fabric systems, the bullets were mostly stopped between the 3rd and 5th layer and deformed into a 'mushroom' shape (*Figure 5*). Closer examinations on the fabric systems revealed that most of the bullets deformed as soon as contact was made with the fabric systems. The deformed bullets could be visibly seen on the front (strike face) of the fabric systems. Jacobs and van Dingenen[19] reported that a substantial amount of energy (up to 25% of the total kinetic energy of the bullet) was absorbed by the bullets during the course of this deformation.

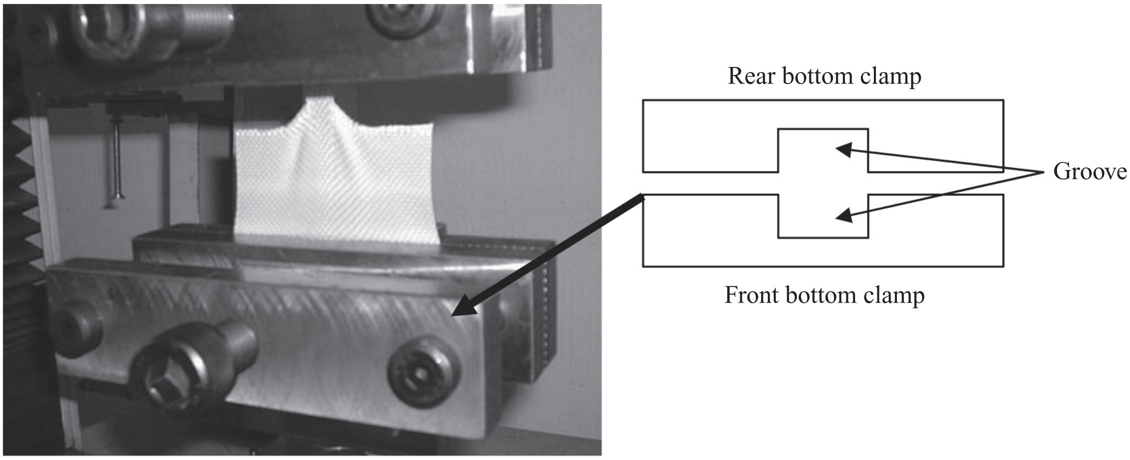


Figure 3. Yarn pull-out test set-up.

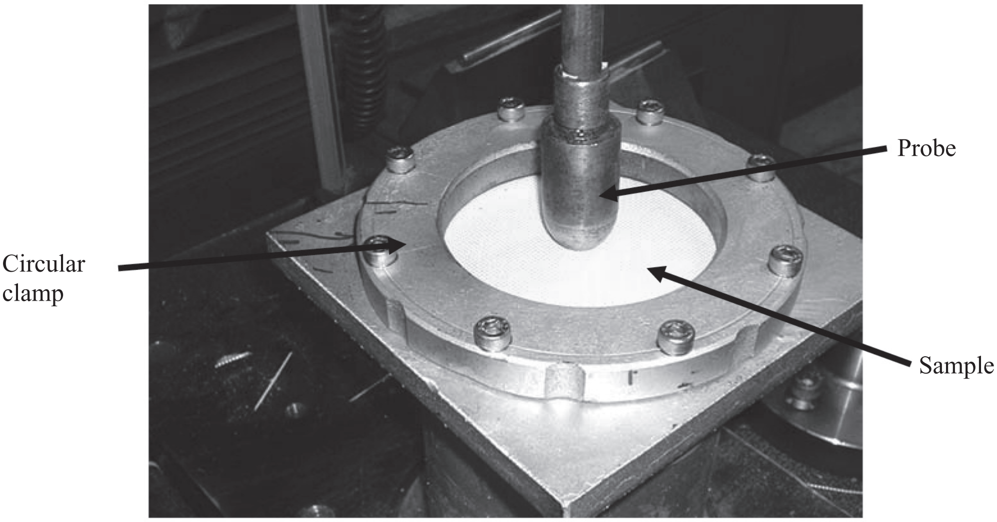


Figure 4. Test set-up for puncture resistance test.

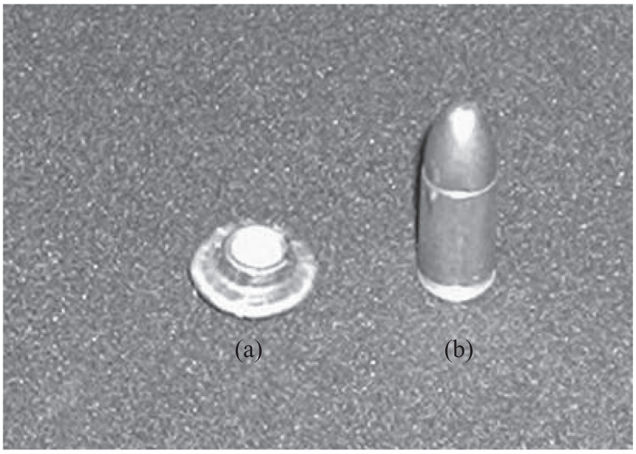


Figure 5. (a) Deformed bullet (mushroom shape); (b) Original bullet shape.

Ballistic impact on the uncoated fabrics in the all-uncoated fabric systems resulted in localised deflection (*Figure 6*). The effect was visible up to the last layer of the all-uncoated fabric systems, the layer that had the largest deflection. The mechanism of energy absorption by the first few layers of the fabric were identified as broken yarns, yarn stretching and yarn pullout. These deformations are shown in *Figures 7(a–c)*. The first two to three layers had the most broken yarns as the bullet completely penetrated through them by breaking the yarns. Yarn pullout effect was obvious at impact locations near the edge of the fabric system. It was interesting to note that crease marks (*Figure 7c*) were also visible on the uncoated fabric but at subsequent layers where the bullets deformed and stopped.

For fabric systems with combined uncoated and NRL coated layers, only the uncoated fabrics had some yarn stretching and yarn pull-out effects. The localised deflection was also observed on the uncoated fabric but somehow diminished at the NRL coated layers which was evident from the very small deflection mark (*Figure 8*). No other significant deformation could be observed on the NRL coated fabric layers since they were placed at the rear of the fabric system. It was probable that the NRL coating film may have locked the yarn (reduced yarn mobility) and distributed the remaining energy from the bullet impact over a wider area in comparison to uncoated fabrics at the same position. However, there were peeled off regions of the NRL coated film at the back surface of the last coated layer for each impact location (*Figure 9*). The high impact energy and deformation of the bullet due to the transfer of kinetic energy appeared to impart high shearing action causing the NRL film to peel-off from the fabric and expose the bare fabric at the localised impact region.

Yarn Pull-Out Results

The results of the yarn pull-out force for Twaron uncoated and NRL coated fabrics is shown in *Figure 10*. The peak load was the maximum pull-out force at which the pulled yarns start to slide over the orthogonal yarns. The typical load-displacement curves for the samples are given in *Figure 11*. The yarn pull-

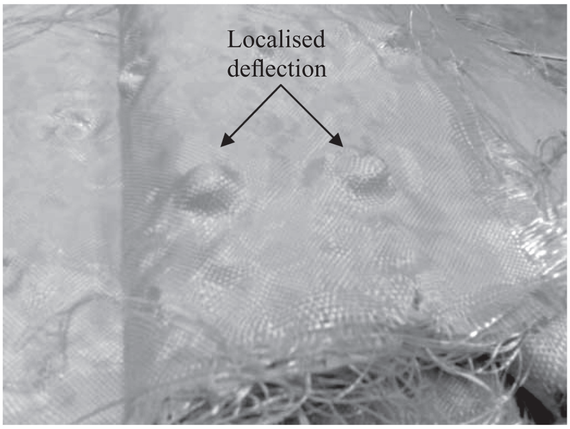


Figure 6. Ballistic punch effect on uncoated fabrics.

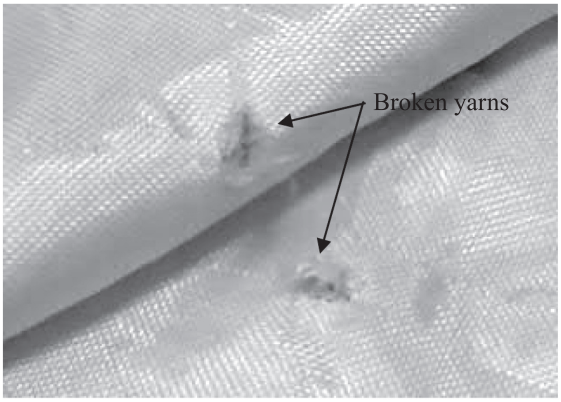
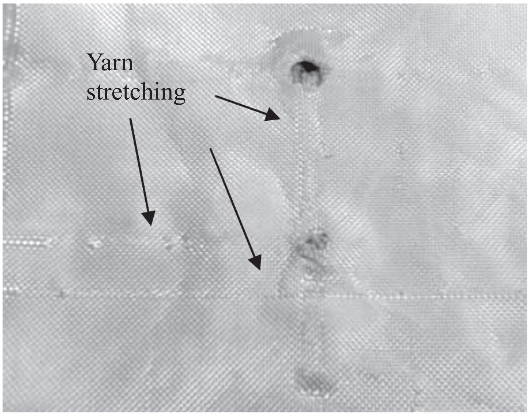


Figure 7a. Broken yarns.



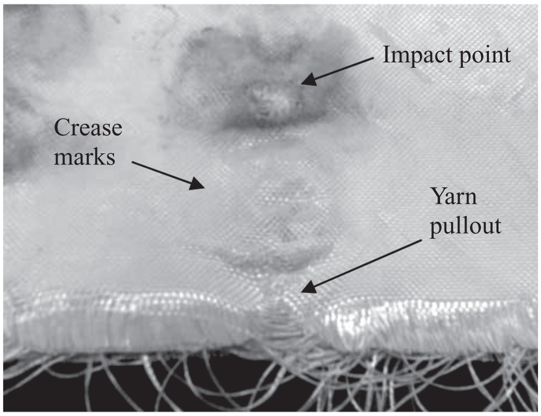


Figure 7b. Yarn stretching.

Figure 7c. Yarn pull-out and crease marks.

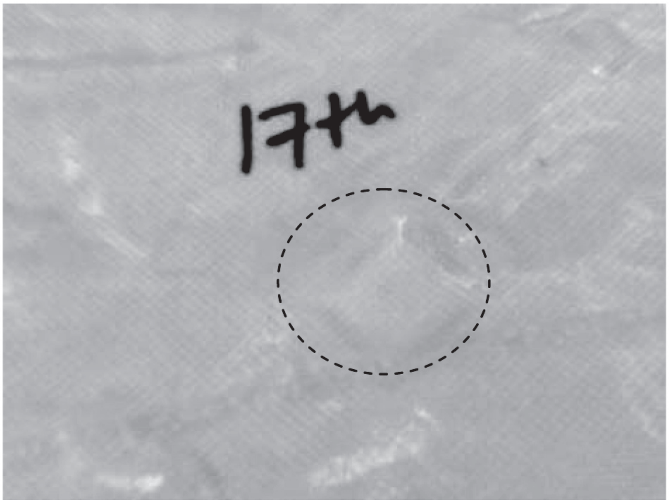


Figure 8. Small deflection at impact point on NR coated fabric layer.

Peeled-off region
exposing bare
fabric

Figure 9. Peeled-off regions of NRL coated film.

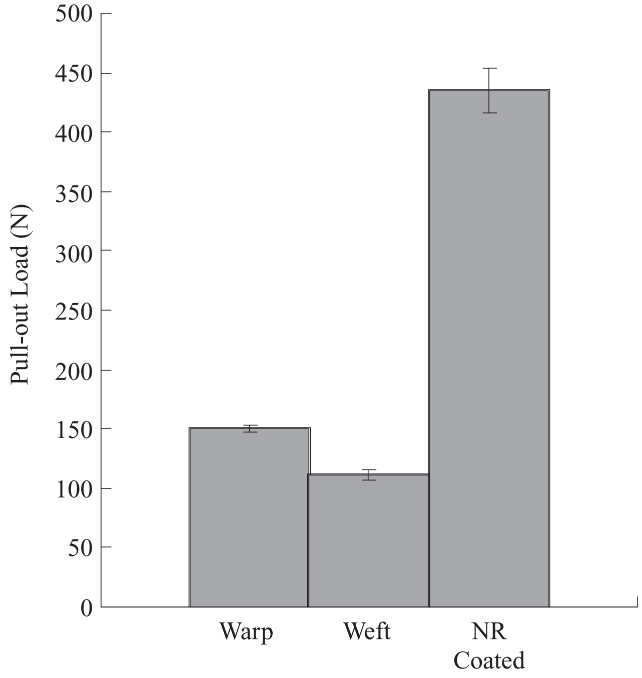


Figure 10. Yarn pull-out force of Twaron uncoated and NRL coated samples.

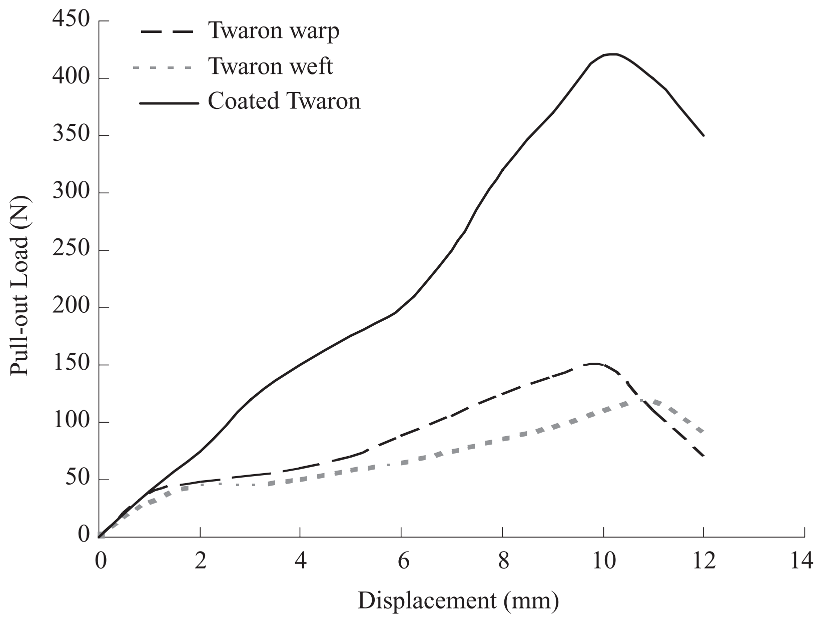


Figure 11. Typical load-displacement curves for the yarn pull-out of Twaron fabrics.

out load in the warp direction is significantly higher than the weft direction (t-test at p=0.05). The results were however not expected as it was earlier predicted that the force to pull-out the warp and weft would be the same as they had similar size, yarn density and crimp. There were probably other factors that had contributed to the differences in the pull-out load of the yarns. The displacements of the warp and weft yarns at load peak were similar, at about 10 mm.

Several modes of yarn pull-out can be observed from the test. At the start of the test, the pulled yarns have to overcome static friction and this usually involved yarn straightening and uncrimping. After overcoming crimp, the yarns started to stretch and move by sliding over the orthogonal yarns. The maximum force (load) was eventually reached after this. At the same time, orthogonal yarns at the center of the sample (near the pulled yarns) tended to move in the direction of the pull. The yarns at this area were closer to one another and thus giving higher resistance force.

With regards to the effect of NRL coating on the yarn pull-out force, in general, the yarn pullout force increased by 200% after coating with NRL (warp samples). The results indicate that the yarn-yarn friction in the fabric increases after coating. Yarns from the NRL coated fabrics are harder to pull because they have to overcome the high yarn binding imparted by the coating layer. Movement or sliding of the yarns is thus constrained. There were also some instances where the pulled yarns of the NRL coated fabrics broke at the grip during the test. This might be due to higher stress concentration at the grips than at the bulk of the fabric.

In contrast, for the uncoated fabrics, yarn movements are not restricted as there are less friction effects and can thus slide past each other more easily than the coated fabric, once the pulled yarns overcome crimp. There were obvious stretching marks of the pulled yarns at the center of the uncoated fabric (*Figure 12a*) including the displacement of the yarns at the bottom edge of the fabric. For the coated fabrics, the evidence of yarns stretching was not visible but there was a peeled-off region of the NRL coating at the bottom edge of the fabric (*Figure 12b*).

Puncture Resistance Results

Results of the puncture resistance tests are given in *Table 4*. It can be seen that in general, the NRL coated fabrics have higher puncture resistance compared to the uncoated fabric samples as indicated by the puncture load. The force needed to puncture the NRL coated fabrics was 21% higher than the uncoated fabrics. The NRL coated fabric gave a slightly higher deflection than the uncoated fabric probably because the NRL film formed an energy barrier before the probe was able to penetrate the fabric.

Fabric samples of the uncoated and NRL coated fabrics after the puncture resistance tests are shown in *Figure 13(a–b)*. The modes of penetration (failure) were analysed and identified. A previous study[16] had identified three distinct fabric failure modes (for Zylon® fabrics) based on observations during the puncture tests and from the load-deflection curves. However, only two distinct failure modes were identified in this study: yarn breakage at maximum load and minimal yarn stretching. Yarn breakage at maximum load is a breakage that occurs on the yarns that are directly in contact with the probe. The process normally resulted in the formation of a hole in the middle of the sample and accompanied by a sharp burst of sound. Yarn stretching is where a few yarns are pulled by the probe before the yarn breakage mode occurs.

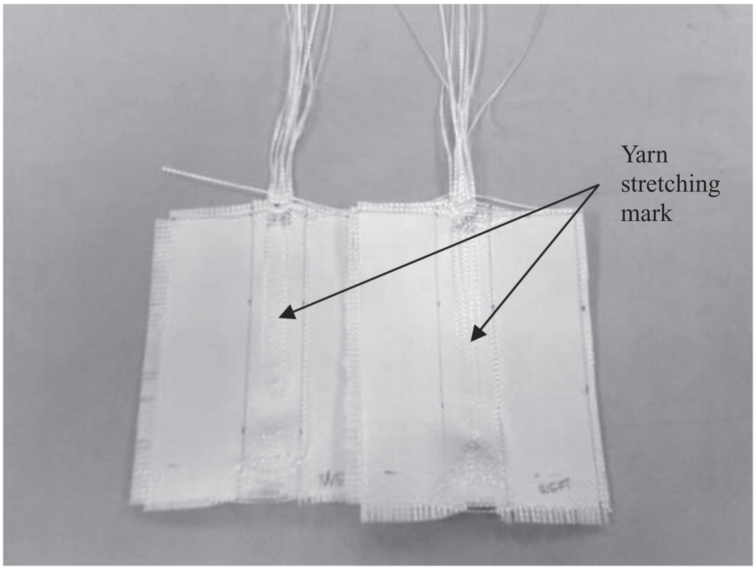


Figure 12a. Yarn stretching mark on uncoated fabric.

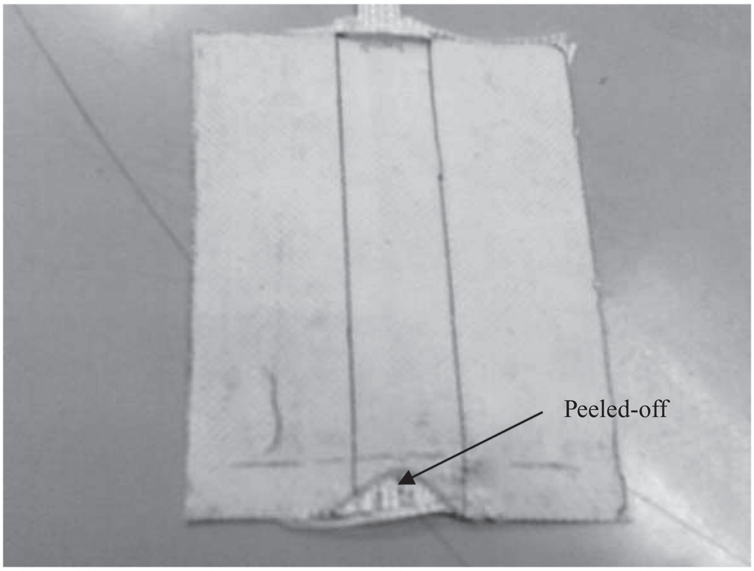


Figure 12b. Peeled-off of NR latex film on coated fabric.

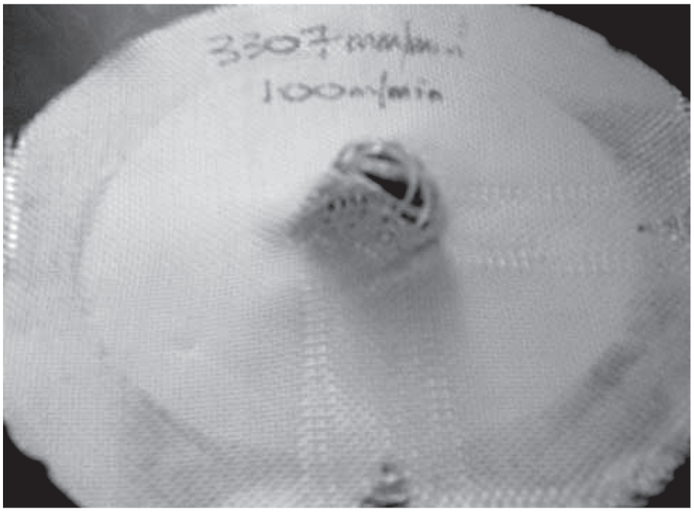


Figure 13a. Failure modes of uncoated Twaron.

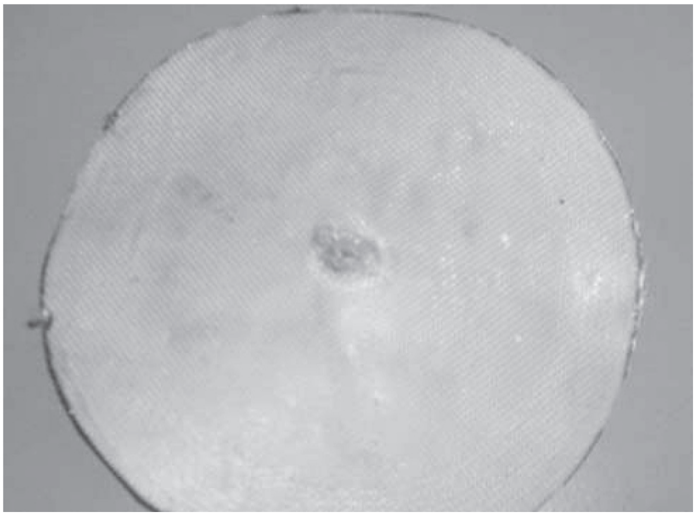


Figure 13b. Failure modes of coated Twaron.

TABLE 4. PUNCTURE RESISTANCE RESULTS

Sample	Load (kN)	Deflection (mm)	Specific puncture load (Nm^2/g)
Uncoated	4.53	25	22.4
NRL coated	5.46	28	16.1

The yarn breakage mode was observed for all samples. However, the uncoated Twaron fabric had minimal yarn breakage at maximum load due to the sliding of the probe in between the yarns resulting in yarn stretching. A small hole was observed from the NRL coated Twaron fabric with only the yarns and one coated layer (on the other side of the sample) penetrated. At maximum puncture load, the probe did not penetrate the NRL layer that was directly in contact with the probe. Some of the yarns were observed to stretch slightly rather than being pulled out since the circular sample was firmly gripped by the clamp.

CONCLUSION

The application of NRL in coating high strength, high modulus fabrics has enhanced the ballistic impact resistance of the fabrics as indicated by the reduction in the depth of indentation due to the better energy absorption associated with friction. The increase in friction was evident from the increase in yarn pull-out strength and increase in puncture resistance of the NRL coated fabrics.

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