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Preliminary Investigation on the Ballistic Limit of Ultra High Molecular Weight Polyethylene Unidirectional Coated Fabric System

Abstract
This paper reports an investigation on the ballistic impact performance of high strength unidirectional (UD) fabrics UHMWPE coated with natural rubber latex (NRL). The effects of adding calcium carbonate in the NRL on the ballistic impact were also studied. Several NRL coated UD fabrics were assembled together with neat UD fabrics in a 12-ply fabric system. The ballistic limit and energy absorption of the fabric systems were determined. Results of the ballistic limit test showed that the NRL coated UD fabrics gave some positive effects in enhancing the ballistic impact performance of the fabric systems in comparison with all-neat fabric systems. Several mechanisms of energy absorption were observed on the fabric systems which include burn marks, fibre stretching, fibre pull-out, shearing, delamination of fabric plies for completely penetrated fabric systems and a punched-out effect on the back ply of partially penetrated fabric systems.

Key words: *unidirectional fabric, natural rubber latex, ballistic limit, energy absorption.*

Introduction

Ultra high molecular weight polyethylene fibres (UHMWPE) in the form of a UD configuration are used in protective clothing applications due to their excellent energy absorption characteristics and have advantages in terms of flexibility and lower weight in comparison with woven ballistic fabrics. UHMWPE fibre is produced by the gel-spinning process, which includes the extrusion of UHMWPE solution, spinning the solution, gelation and crystallisation of UHMWPE before undergoing the superdrawing stage [1]. In general, these fibres have high strength and modulus properties due to the higher molecular weight, excellent orientation and crystallinity [2]. These fibres are able to absorb extremely high energy and have a very low density of 970 kg/m^3, which make it very suitable to be used in ballistic material application. The fibres are arranged in an unidirectional (UD) structure, where straight fibres are laid in a 0°/90° arrangement and adhesive resin used as glue or binder to offer more efficient and fastest energy distribution along the fibres due to the absence of cross-over points which normally exist in woven fabrics [3]. According to Jacobs and Van Dingenen [4], the UD configuration of the fibres allows the energy transferred from the impact of the projectile to be distributed along the fibres much faster and more efficiently than in conventional woven fabrics. The fibres in a UD fabric system are laid in parallel without the crossover points as in woven fabrics, thus allowing the energy to quickly spread along the fibres. In contrast with woven fabric systems, the absorption power of the yarn is normally lost at the crossover points, as they reflect rather than absorb the shockwaves of the impact. Stempien [5] pointed out that the propagation velocity of the tension wave in fabrics depends on their structure. For the UD fabric structure, the propagation velocity of the tension wave is the highest. In consequence, it leads to a better ballistic performance of the UD fabric structure than that of woven fabric. Ballistic tests show that the backface deformation of UD systems after being hit by a projectile is significantly smaller than those assembled of woven fabric.

Recently much attention has been given to the coating of high strength fabrics for application in ballistic clothing. Studies by Liu et al. [6] on UD fabrics showed that the ballistic resistance performance improves by 20% when shell particles are laminated. In addition, Chu et al. [7] found that improvement in the ballistic resistance properties of UD fabrics was due to the fabric lamination effect, which improves the stability of the fabric construction. Several works [8 - 10] revealed the use of silica particles coated on ballistic fabrics, which improves the ballistic performance at a low velocity impact, especially against fragments. Lee et al. [8] reported that Kevlar-KM 2 fabrics impregnated with silica particles dispersed in ethylene glycol increase the amount of projectile energy absorbed by the fabric. In another study [9], STF-coated Kevlar fabrics were reported to give superior results when tested for stab resistance. Tan et al. [10] used the same silica particle concept, but instead of ethylene glycol the particles were suspended in water before impregnating the Twaron fabrics. The study found that in general, the ballistic limit of the samples increased with the particle concentration in the suspension, but at the expense of the areal density of the samples.

Recently NRL coated ultra high molecular weight polyethylene unidirectional fabrics under penetration resistance have been investigated by Hassim et al. [11] and it was found that the presence of NRL on unidirectional fabric enhances the penetration resistance due to the higher frictional effects. Thus NRL has the potential to be used as a coating material on high strength fabric with the purpose of improving ballistic protective fabrics. In another study, Ahmad et al. [12, 13] claimed that the combination of NRL coated and neat woven high strength fabrics gave some 60% increase in the energy absorption in comparison with uncoated fabric systems. Ahmad et al. [13] also showed that the integration of two plies of neat and two plies of NRL coated fabric in a four-ply fabric system gave higher ballistic performance and energy absorption in comparison with uncoated fabric systems.

With regards to NRL, some studies have been made to improve the performance of NRL film by adding fillers to the compounding. Cai et al. [14] claimed that ultrafine calcium carbonate could enhance the tear strength, tensile strength and

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modulus of NRL film. As the amount of calcium carbonate increases, the modulus increases with even calcium carbonate particle distribution within the NRL film. According to Ain et al. [15], the amount and types of filler may affect the properties of Carboxylated Acrylonitrile –Butadiene rubber (XNBR) latex films. Carbon black fillers gradually increase the mechanical properties with the increment of the filler content with even distribution within the film. The calcium carbonate filler did not increase the mechanical properties. However, the tensile strength of XNBR-latex films increases accordingly with the increment of their loading.

In a separate study, Bhatnagar et al. [16] concluded that rubberised ballistic resistance nonwoven fabrics offer a significant physical improvement over rubberised fabrics. The vulcanised rubber layer, comprising of at least one surface of fabric through the moulding method under sufficient heat and pressure, offer superior ballistic penetration resistance which exhibits excellent properties against deformable projectiles.

Currently, studies on the coating of NRL on UHMWPE UD fabrics for ballistic impact performance have not been reported in open literature. Based on previous studies [12, 13], NRL have shown to give good energy absorption characteristics with improvement in the ballistic impact performance and blunt trauma of the fabric system. However, the studies were conducted on high strength woven fabrics. In this paper, a study on the ballistic limit of NRL coated UHMWPE UD fabrics is reported. The effects of calcium carbonate as a filler in NRL film coated UD fabric are also reported. Some of the modes of fabric failure observed from the experiments are discussed.

Experimental procedure

Materials

The study used UD UHMWPE with an areal density of 150 ± 5 g/m^2 which was bought from Compass Industrial System PTE LTD, China. Pre-vulcanised NRL was supplied by Revertex Malaysia Sdn. Bhd. and was used to coat the fabrics. The NRL has a 60% total solid content (TSC) and viscosity of about 30.2 s (Ford Cup 3) at 25°C. Precipitated calcium carbonate dispersion ($CaCo_3$) in paste form was used as a filler added to the NRL. The WG-3 type Calcium Carbonate has a pH of 12.0 ±1.0.

Coating process and fabric configuration

Fabric samples of 30 cm × 30 cm in size were cut and prepared for coating. The fabric samples were coated with 100% NRL and also NRL mixed with Calcium Carbonate dispersion. The Calcium Carbonate dispersion was added to the NRL with three different NRL:$CaCo_3$ ratios which were 1:1, 7:3 and 9:1.

Two samples were assembled together for the coating process, which was done so that each sample was coated on only one surface. The fabrics were coated using the dipping method, where each sample was completely dipped into the NRL before taking it out slowly, hung and dried at room temperature for 24 hours.

Ballistic tests

Ballistic limit tests were performed in accordance with Mil-Std-662F (V50 Ballistic Test for Armour) using Fragment Simulation Projectiles (FSP) [17]. The ballistic test was conducted in an indoor ballistic shooting range using a PROTOTYPA Universal test gun. ***Figure 1*** shows the ballistic test set-up. Each fabric system was clamped at all four edges and positioned 5 meters away from the gun barrel. The impact and residual velocities of the fragment were captured using chronographs. North Atlantic Treaty Organisation (NATO) standard FSPs were placed in a sabot and 7.62 mm bullet casing and fired at a 0° obliquity shooting angle. The velocity of the projectile was determined by the amount of propellant powder placed in the bullet casing.

The ballistic limit is the value of velocity at which there are equal chances that the fabric system is completely penetrated or stopped by the projectiles. It is determined from the average of several complete penetration and partial penetration velocities. When the projectile partially penetrates the fabric system and rests within it (partial penetration), there is no residual velocity and therefore the energy

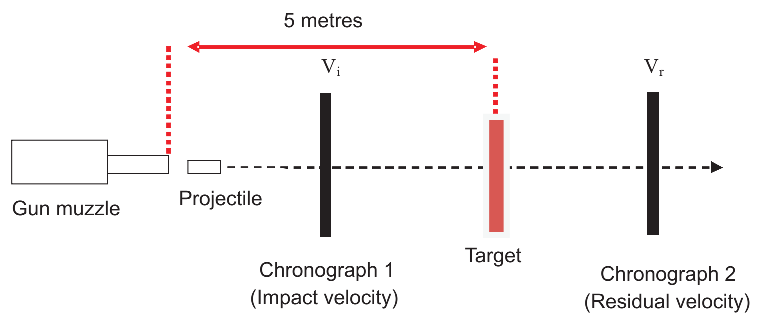
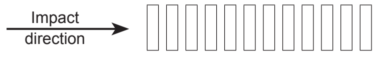
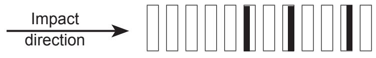
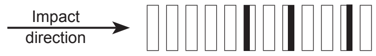
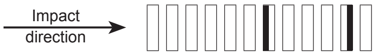
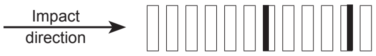
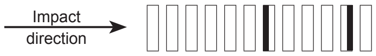
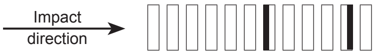


Figure 1. *Ballistic test set-up for ballistic limit determination*

Table 1. *Target characteristics.*

Configurations	Target descriptions	Target characteristic
All neat		12- neat
A1		9-neat with 3-NRL
A2		9-neat with 3- NRL + $CaCo_3$ (1:1)
B1		10-neat with 2-NRL
B2		10-neat with 2- NRL + $CaCo_3$ (1:1)
B3		10-neat with 2- NRL + $CaCo_3$ (7:3)
B4		10-neat with 2- NRL + $CaCo_3$ (9:1)
▯ = Uncoated ▮ or ▮ = Coated on one surface		

absorbed (E) by the fabric upon impact can be calculated by:

$$E_{target} = 1/2\ m_p\ (V_i)^2 \qquad (1)$$

where m_p is the mass of the projectile and V_i is the impact velocity at the ballistic limit.

However, when the projectile penetrates the fabric system (complete penetration), the residual velocity of the projectile can be recorded and the velocity is always less than the impact velocity since some of the energy has been absorbed by the fabric system. Therefore the energy absorbed by the system is given by:

$$E_{target} = 1/2\ m_p\ (V_i^2 - V_r^2) \qquad (2)$$

where V_r is the residual velocity.

Target configuration

Table 1 shows a description of each target for the 12-layer fabric systems. The NRL coated UD fabrics were positioned at the rear in each fabric system. The coated fabrics were assembled alternately at the backface in the two fabric configurations, which are A and B, where only 2 and 3 coated plies were incorporated to limit the weight, and the effect of the NRL and filler loadings were observed. For each target type, 6 samples were prepared.

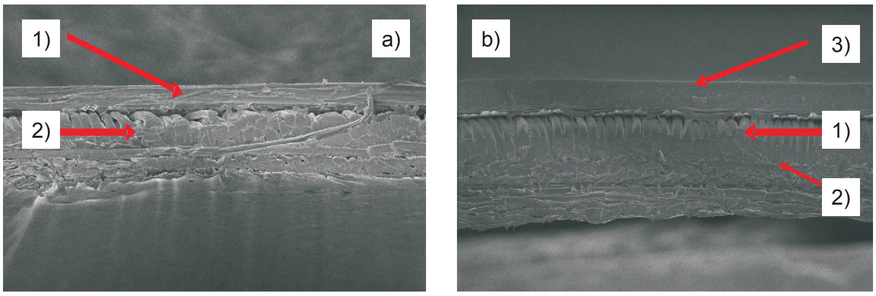


Figure 2. *FESEM images: a) cross section of neat UD fabric, b) cross section of NRL coated UD fabric; 1) fibre at 0°, 2) fibre at 90°, and 3) NRL layer.*

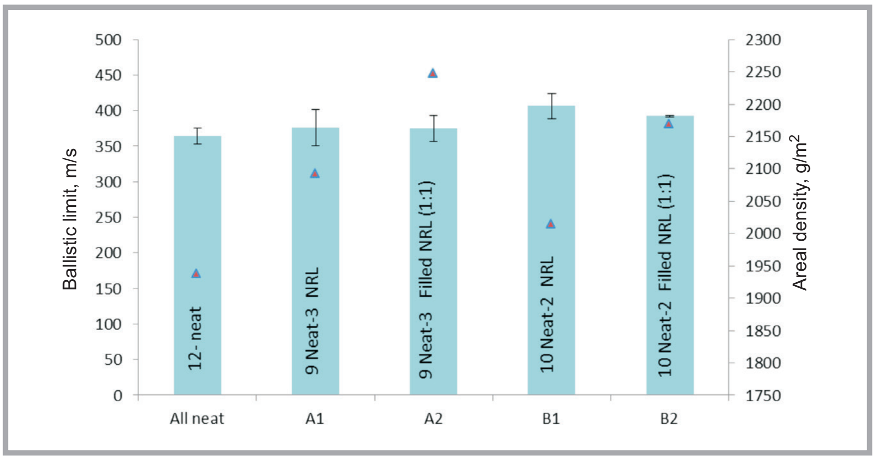


Figure 4. *Comparisons of 12-layer fabric systems with different fabric layer configuration (A and B) and the areal density of fabric systems*

Results and discussion

Surface morphology and cross section of samples

Figure 2 shows cross-sections of the neat and coated samples examined under Field Emission Scanning Electron Microscopy (FESEM).The cross section in ***Figure 2.a*** shows the fibres arranged at 0° and 90° in the neat fabric, while ***Figure 2.b*** indicates that after coating, there was no penetration of the NRL through the UD fabric structure. The NRL merely coats the surface of the fabric, which may be due to the high viscosity nature of the NRL and existence of a laminated resin on the fabric's surface.

Figure 3.a shows the surface morphologies of the thin unfilled NRL film, ***Figure 3.b*** NRL coated UD and (c) NRL filled with $CaCO_3$ fillers at 1000× magnification. From the micrograph, the dispersion of $CaCO_3$ in the NRL was poor, as evidenced by the many particles of $CaCO_3$ aggregates and the large amount of NRL matrix without $CaCO_3$ fillers.

Ballistic limit results

Effect of different configurations

The ballistic limit results of 12-layer fabric systems with different configurations are given in ***Figure 4***. Both configurations A and B are similar when the locations of the NRL coated ply were assembled on the second part of the ballistic packet. However, the insertion of coated ply was different, with A having 3-NRL coated ply and B 2-NRL coated ply. Basically the incorporation of NRL coated ply into a protective fabric system of high strength UHMWPE UD fabric may appear counter intuitive; however the purpose of the NRL coated ply is not to replace the UHMWPE UD fabric as the primary energy absorbent impact material. The NRL coated ply fulfils a number of important complementary functions. The capability of obtaining high stress

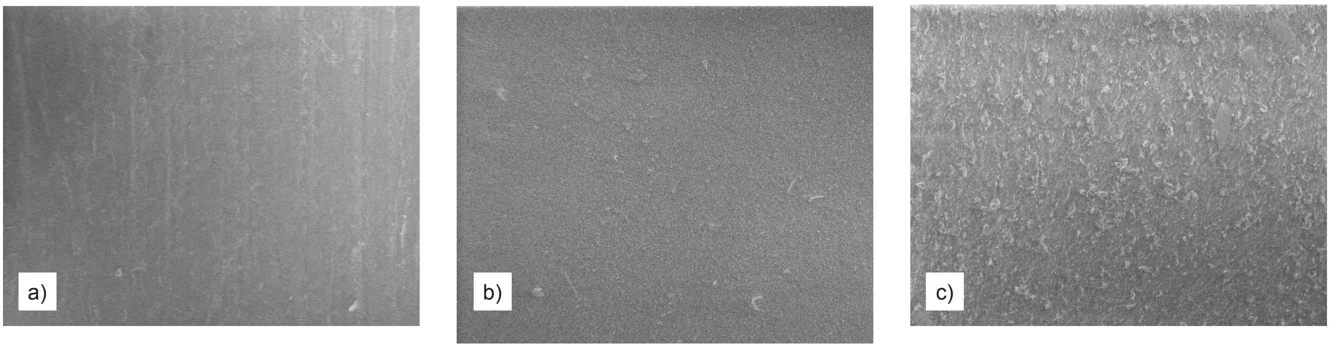


Figure 3. *a) Surface of neat sample (100 × magnification), b) surface of NRL coated UD (100 × magnification), c) surface of $CaCO_3$ filled NRL coated UD (1000 × magnification).*

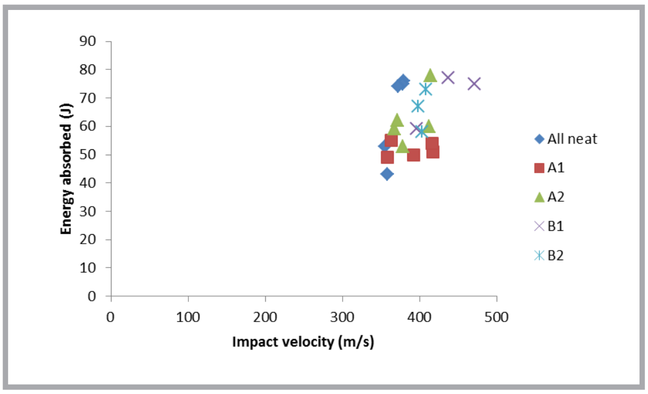


Figure 5. Impact energy absorption for different configurations of the 12-layer fabric system.

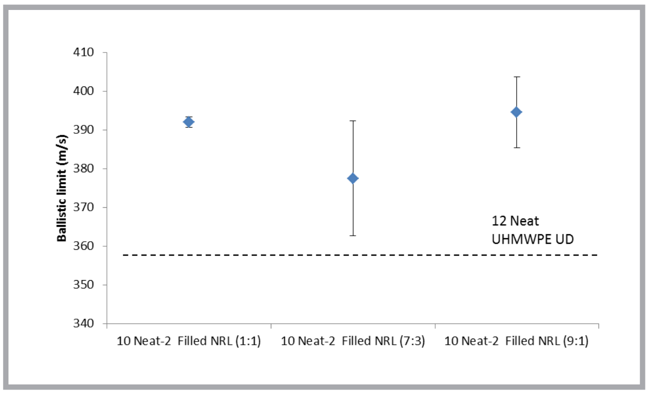


Figure 6. *Comparisons of ballistic limit in different filler loading in the NRL coated and neat fabric systems.*

and shear in UHMWPE fibres plays an important role in allowing energy dissipation and absorption, while the coated ply performs the function of increasing frictional forces with the projectile and slowing its remaining kinetic energy . In consequence, the coated ply supports the fabric system by offering extra energy absorption. Furthermore, the incorporation of coated ply in the second part may prevent the fabric system from being stiff easily, which could allow the projectile to pass through the fabric system. From ***Figure 4***, it can be seen that fabric systems consisting of 10 neat with 2-NRL coated ply (Configuration B1) gave the highest ballistic limit of 12% and 8% in comparison with the all-neat and Configuration A1 fabric systems, respectively. Although configurations A2 and B2 did not give any significant differences to the ballistic limit in the 12-layer fabric system, they performed better than the all-neat fabric system. The triangle shape in ***Figure 4*** indicates the areal density of the fabric system. It is clear that the weight of the combined and neat 12-layer fabric system increased in comparison with the all-neat system. Each of the coated plies may contributed to the increment of the areal density of the fabric; however, they still performed better in ballistic tests. The take up of the 1:1 ratio of CaCo$_3$ filled NRL is higher the bigger the dispersion viscosity.

The impact energy absorption for the neat and combined neat and coated ply in a 12-layer fabric system is shown in ***Figure 5***. The replacement of several neat fabrics with NRL coated ply increased the energy absorption of the fabric system.

Effect of filler loading

Figure 6 shows the ballistic limit of 12-layer fabric systems consisting of fabrics coated with NRL + $CaCO_3$. It was found that fabric systems with the lowest $CaCO_3$ content gave a slightly higher ballistic impact in comparison with the other fabric systems. It was observed that the higher amount of $CaCO_3$ in the NRL resulted in the soft and bulky sample, which tends to reduce the shearing properties of the NRL, thus reducing the friction effect during impact. An optimum amount of $CaCO_3$ in the NRL would help to delay the movement of the projectile upon impact and thus increase energy absorption. The sample with a NRL:$CaCO_3$

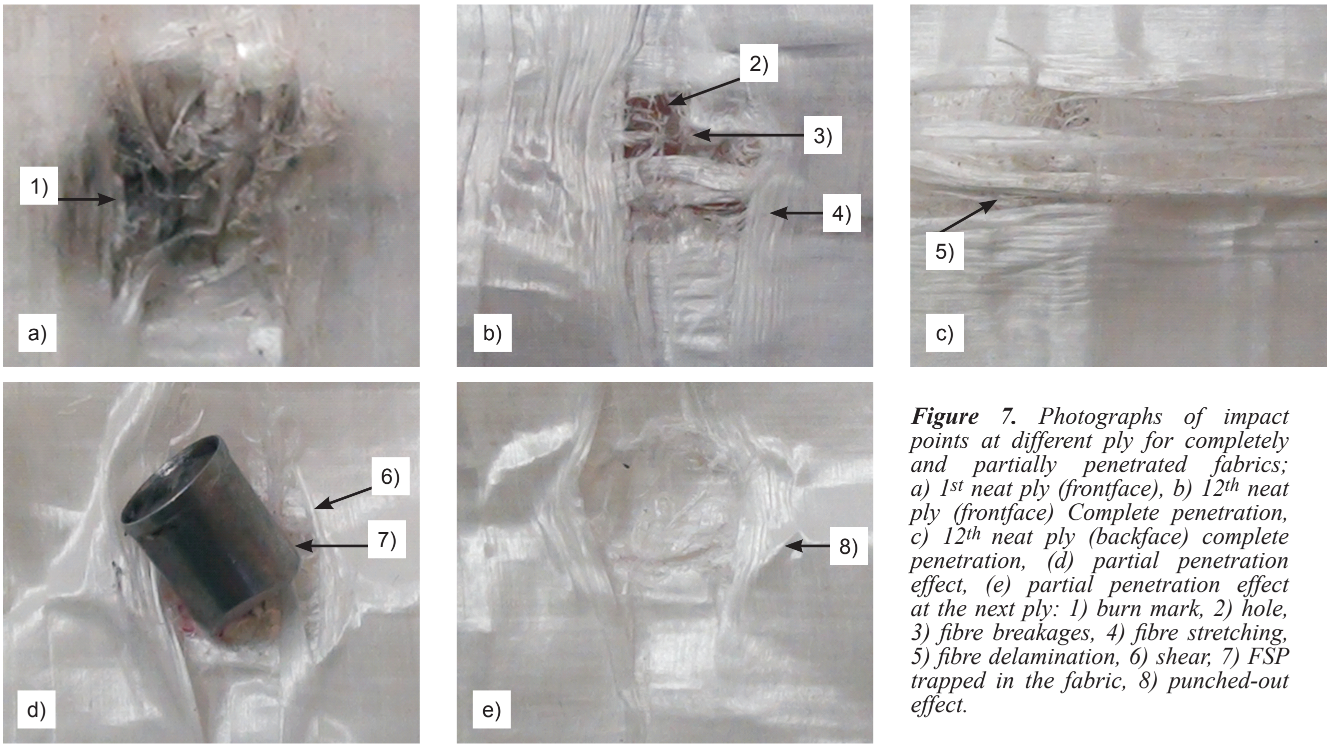


Figure 7. *Photographs of impact points at different ply for completely and partially penetrated fabrics; a) 1st neat ply (frontface), b) 12th neat ply (frontface) Complete penetration, c) 12th neat ply (backface) complete penetration, (d) partial penetration effect, (e) partial penetration effect at the next ply: 1) burn mark, 2) hole, 3) fibre breakages, 4) fibre stretching, 5) fibre delamination, 6) shear, 7) FSP trapped in the fabric, 8) punched-out effect.*

ratio of 1:1 could not perform well due to the high velocity impact, which makes it penetrate the fabric easily because of the bulkiness and lower stickiness of the coated ply. Hence, this may have reduced the frictional forces needed to absorb more kinetic energy.

Analysis of damage mechanisms

All-neat fabric system

The fabric failure modes or the damage area on the fabric after impact are associated with the speed of the projectile, shape thereof, as well as with the properties of the fabric materials. Mines et al; [18] mentioned that projectile penetration during high speed velocity are influenced by a few factors such as the type of fibre and volume fraction, matrix, stacking sequence, size and initial kinetic energy of the projectile. In addition, Cheng et al. [19] found that the penetration process can be divided into three stages, which are punching, fibre breaking and delamination.

Figures 7.a - 7.e show the impact point of the 1st layer (frontface and backface) and 12th layer during partial and complete penetration. There is a burn mark effect at the impact point of the 1st layer which clearly indicates heat generation as the projectile strikes the system. In addition, some delamination occurs at the backface of the 1st ply. A few plies of fabrics sheared to absorb the energy until they failed to restrict the projectile from penetration. The first few plies were not severely damaged but there was evidence of fibre breakages and delamination. For partial penetration there were no burn marks at the impact point, which may be due to the lower impact velocity of the projectile.

Combination of neat and coated fabric systems

At a 370 ±3 m/s projectile velocity, burn marks were observed on the 1st ply of the all-neat fabric system and combined neat and NRL coated fabric systems. For the all-neat fabric system, direct contact between the projectile and the fabric leads to fibre stretching and breakages, eventually creating a hole. The fibres were pulled out starting from the 3rd ply and continued until the 7th ply as the size of the hole became greater. Furthermore fibre delamination at the backface of the ply can be seen at the 9th ply as the projectile is trapped and stopped at the 10th . According to Liu et al, [6] the occurrence of delamination shows some energy absorption from the impact. In this case, the energy was absorbed and transferred to the next ply, which led to the 11th ply having a black crease mark due to heat generation and a small punched-out mark.

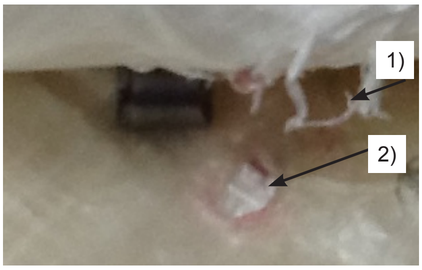


Figure 8. *NRL layer damage on the 7th ply coated fabric; 1) fibre pull out, 2) NRL layer breakage.*

In contrast with configuration B1, at 370 ± 3 m/s impact velocity, the projectile was stopped at the 7th ply, which is the coated ply in the fabric system. The projectile did not leave any crease mark or burn mark at the next ply. It seems that the kinetic energy from the projectile was absorbed by the first few plies and the remaining energy was fully absorbed by the NRL coated ply. Fibre pull-out was observed at the 4th ply up to the 6th ply of the fabric system. Some shearing effects might have taken place upon impact among the fabric plies. Tan et al. [20] pointed out that delamination occurs as a result of large shearing forces between the plies when the fibres are pulled towards the projectile on impact. The interesting part of the coated ply is where the projectile did not damage the fibres at the 7th ply because the NRL had absorbed the energy and restricted the mobility of the projectile. In consequence, the NRL layer was severely damaged, as shown in ***Figure 8***.

Almost the entire sample showed some fibre stretching, fibre pull-out and delamination on the backface of the fabric system. However, the size and length of the fibre pull-out depended on the impact velocity, and it can be said that higher impact velocity (below the ballistic limit) will generate longer fibre delamination.

Conclusions

From the study, it was found that in general, the addition of NRL coated ply increased the weight and areal density of the fabric systems regardless of the number of plies added and presence of $CaCO_3$ as fillers in the NRL. The NRL coated fabrics containing $CaCO_3$ have a rather bulky and thick surface, thus giving a more rigid system. Fabric systems consisting of 10 neat with 2-ply NRL coated fabrics gave the highest ballistic limit and energy absorption in comparison with the all-neat and other fabric systems. This was followed by fabric systems consisting of NRL coated fabrics with the least amount of $CaCO_3$. An optimum amount and good distribution of the $CaCO_3$ particles in NRL are suggested in order to increase the fabric system's ballistic impact performance. The study identified several energy absorption mechanisms such as burn marks on impact with the first layer, fibre stretching, fibre pull-out and shear caused by shearing forces, delamination of fibre on the back ply after complete penetration and a punched-out effect on the back ply for partially penetrated fabrics.

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