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Ballistic Performance of Coconut Shell Powder/Twaron Fabric against Non-armour Piercing Projectiles

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ABSTRACT

Body armour technologists over the years are seeking to develop protective systems which are both effective and lightweight. However these hard armour materials are very expensive and have certain weight constraints. From this point of view, natural fibres and fillers have attracted the attention of researchers due to their low density with high specific strengths, abundance, availability, renewability and being environmental-friendly. This paper reports the potential use of coconut shell powder-epoxy composite (COEX) panel bonded with Twaron CT716 fabric as a hard armour material and the characteristics of its fracture imprints from a specific threat level when subjected to ballistic tests[1] (NIJ Standard 0108.01). It was observed that the imprint patterns on the particulate composite (COEX) could be identified according to effectiveness in impact energy dissipation. COEX/Twaron test panel was found to withstand impact equivalent to NIJ Level IIIA using 9 mm FMJ ammunition but perforated at NIJ Level III of 7.62 mm FMJ bullet impacts. Test results showed that COEX panel do possess shock absorbance characteristics and can be utilised as an armour component in the hard-body armour system. Dependency on Twaron fabric layers as ballistic reinforcements has been reduced up to 3-time with 170 per cent improvement on energy-absorption capabilities when using COEX composite as the frontal component of the armour.

Keywords: Coconut shell powder, ballistic impact, armour panel, natural composite material, composite armour, twaron fabric

1. INTRODUCTION

Design of ballistic armour systems must take into account several factors such as the type of ballistic threat, the ability to manufacture the armour system and the properties of the armour components. These factors can also be further supplemented with multi-hits performance, environmental conditions, space limitations, manufacturing challenges, cost and weight limitations, physical properties of facing and backing material, and overall ballistic performance of the system.Oxide ceramics, in particular alumina ceramics, have a high level of physical properties that are suitable for hard armour application. Ceramics can be manufactured using a variety of methods for instance, slip casting, pressing and injection molding, without the expensive equipment. Despite elevated density (up to 3.95 g/cm^3), ceramics is known to be used for ballistic protection. Evaluation of ballistic performance of ceramics has been a difficult task due to the number of reasons such

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as the type of threat, projectile velocity, projectile geometry, nature of ceramics, target configuration in terms of front and backing material and their thicknesses, angle of impact and support conditions can have a profound influence on the ballistic results.

However, in recent years, researchers have started to venture the possibility of integrating natural-based product into the ballistic related studies. Wambua[1], *et al.*, have evaluated flax, hemp and jute-reinforced polypropylene composites, with or without mild steel backing or facing, under ballistic impact test conditions. They concluded that the ballistic limit or V_{50} of the natural fibre composites was found to be increasing non-linearly while increasing areal density and composite thickness. Jute composites demonstrated the least V_{50} and kinetic energy absorption of the plain composites probably due to the low strength and brittleness of the fibers. In terms of energy absorption, hybrid structures have a clear advantage over mild steel and the plain natural[2] based composites. Rozi[2], *et al.* have reported to investigate the ballistic impact performance of high-strength, high-modulus fabrics coated with natural rubber (NR). The effect of different coating techniques and NR modulus were studied. In general, it was found that all coated specimens increased in weight and thickness regardless of the type of NR used. In the 2-layer fabric system, the highest ballistic impact resistance was obtained from fabrics coated using the single-dip coating technique. The combination of two neat and two NR-coated Twaron fabrics in the 4-layer fabric systems absorbed more ballistic impact energy than all-neat fabric systems. It is believed that the enhancement to ballistic impact was related to higher frictional effects among the yarns.

Most of the research on green composites to date has used plant-based fibres because of their ready availability. However, opportunities exist for using high-strength protein fibers, such as dragline silk obtained from the golden orb spider as reported by Netravali and Chabba[3]. On a per weight basis, these fibres are five-ten-time stronger than steel and could form the basis of advanced green composites. Unfortunately, silking the golden orb spider is a difficult and time-consuming process. These small creatures are only capable of producing about 1 mg of dragline silk per day. As a result, many research groups were studying the structure and the chemistry of spider silk in an effort to synthesize polypeptide molecules with similar chemistry and produce artificial fibres in the lab (Gould[4], Grubb and Jelinski[5]). Several researchers have introduced spider genes into various bacteria and other animals to produce similar proteins. The most notable efforts have been those of Nexia Biotechnologies, Inc. as reported by Gould[4] which has successfully developed high-strength BioSteel® fibres based on spider silk protein by transferring spider silk genes into goats. The technique allows spider silk proteins to be expressed in the goat's milk. The goats are milked by conventional means, the proteins extracted from the milk, and spun into filaments. Since continuous filaments are produced, there is the possibility of using these fibres for many applications, such as body armour application and aerospace materials.

This study aims to initially investigate the ballistic impact performance of in-house formulated natural-based composite tiles, which are made from coconut shell powder at different shape configurations. Although termed as a particulate composite material due to its constituents consisting of a reinforcement material (coconut shell) and matrix (epoxy), the COEX composite exhibits brittle like characteristic and comparable to a ceramic material. A series of ballistic tests, according to NIJ Standard 0108.01[6] (Ballistic Resistant Protective Materials) at threat levels II, IIIA, and III were respectively carried out. Impact damage characterisations and the fracture behaviour of the present composite armour panel was observed for this work.

2. MANUFACTURING PROCEDURE

Tile shape configuration is one of the common attributes of ceramics-based armour that is used to improve the multi-hit capability of the armour. This multi-hit capability can be defined as the ability of the armour to withstand more than one projectile impact at a specific area on the armour. For this purpose, COEX armour panel is made of separate small tiles that are connected together by bonding each tile onto a backing element and also between the tile edges. A projectile hitting the armour may destroy one or more tiles at a time, and the remaining tiles serve to prevent penetration over the remaining surface of the armor. The curvature shape configuration is also another typical shape used in modern body armour design. This design trend is becoming more ergonomic in extent that the relative rigidity of an armour plate must be contoured to the curvature of the wearer body to impart good ballistic protection and comfort to the wearer.

Therefore to evaluate the ballistic potential of COEX composite material, these shape configurations were considered for the COEX composite ballistic performance evaluation process. To produce the COEX tile configuration panel, 12 pieces of the 60 x 60 mm COEX tiles were produced using a square shape compression mold and were bonded together between the edges using epoxy to form flat armour panel. For the curvature configuration, a larger compression mold was used to fabricate a 300 x 240 cm monolithic and curvature shape COEX armour panel. The curvature dimension was based on an actual ceramic armour panel contributed by Teijin Twaron, Australia.

The COEX fabrication process is based on the adaptation of powder metallurgy concept. The COEX composite were fabricated by pressing coconut shell powder of selected size distribution using a compression mold and pressed using a LHDC-50 press machine. The composites were then cured at 100 °C for one hour. The density of coconut shell is 1.60 g/cm^3 whereas the resin used was epoxy resin Mirapox 240A with the density of 1.15 g/cm^3. The mixing ratio of the resin and hardener was 100:50.

Typical ceramic armour design also incorporated the use of spall liner or backing material, whose primary function was to capture exiting debris or projectile during the impact event, controls the spall generated by the penetration of projectile by dissipating the projectile's force, deforming the projectile, and trapping the fragments in the spall liner's interior[7]. For this study, Twaron CT716 fabrics with specific density of 1.44 g/cm^3 and modulus elasticity of 90 GPa was used. The fabrics were slightly glued between each ply and then bonded to COEX backface panel using epoxy. All test specimens were conditioned at 20 °C to 28 °C (68 °F to 82 °F) for at least 24 h prior to ballistic test.

2.1 Experimental Testing Procedure

The experimental setup was according to guidelines given in the NIJ Standard[6] 0108.01, shown in Fig. 1. The test weapon used was a SMG-sub sterling gun shown in Fig. 2(a) and using 9 mm full metal-jacketed round nose (FMJ) ammunition shown in Fig. 2(b) for NIJ threat levels II and IIIA. A further testing with M-16 type of ammunition, which is the 7.62 mm (FMJ) bullet, was to evaluate the COEX/Twaron panel at NIJ threat level III. The projectile velocity measurement system used in this operation was a Type 858 Optical detector from MS Instruments, UK, which can perform a system scan within an accuracy of 0.1 per cent, record velocities from as low as 10 m/s to in excess of 5000 m/s.

Following are the two test configurations arranged and described:

(a) NIJ Standard ballistic test for Twaron panel comprised of 5 and 15 ply of fabrics.

The purpose of this test was to estimate the spall liner impact energy absorption value and to evaluate the performance of Twaron fabric as a ballistic-resistance material, in the absence of COEX composite material. This was also to re-evaluate the Twaron fabric ballistic resistance level with reference to the Twaron Manual. In the COEX/

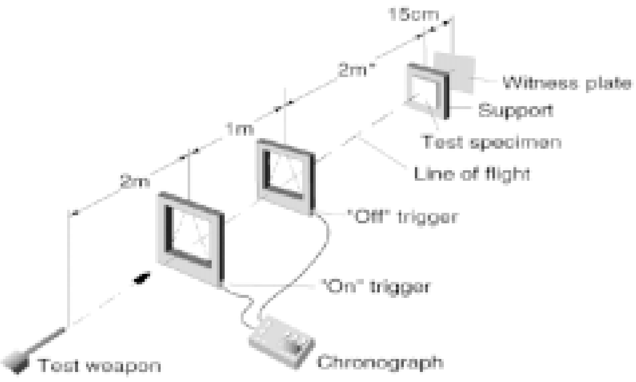


Figure 1. Schematic of ballistic test setup following the NIJ Standard (NIJ-0108.01,1985).


(a) (b)

Figure 2. (a) SMG-Sub Sterling Gun (b) 9mm full metal jacketed round nose bullet.

Twaron armour energy-absorption estimation, the Twaron fabric was termed as the control specimen and was used as the baseline indicator for the COEX material performance at selected NIJ Standard threat levels. Each fabric ply was slightly bonded with epoxy adhesive and no stitching was applied to the panels. For spall liner testing procedure, the test specimens were rigidly clamped between rectangular steel frames. The test panel was perpendicular to the line of flight of the bullet at the point of impact. A thin white paper about 150 mm from the test specimen was used as witness screen to record any bullet perforation, if occurred, during the ballistic testing.

(b) NIJ Standard ballistic test for COEX/Twaron CT716 panels of which comprises the following two design format:

- COEX panel of tile configuration comprised of 5 and 15 ply of Twaron spall liner.
- COEX monolithic panel of curvature configuration comprised of 15 ply of Twaron spall liner

Justification for these approaches is as mentioned in Section 2. For COEX/Twaron panel provisioning, a different target holder was used where the armour panel is placed in front of a flat contoured plasticine block. The plasticine block as described in NIJ Standard[8] 0101.04 is used to evaluate the bluntt trauma signature induced from the impacted COEX/ Twaron panel. The panel is strapped with tapes so that it will not be rigidly fixed to the plasticine block as to simulate an actual impact on body armour material.

Further details of all test specimens configuration for this study are presented in Table 1. It is expected from the limited test specimens that the COEX/ Twaron panel can exhibit a significant evidence of a potential lightweight ballistic-resistance materials.

The damage zone of the COEX composite tiles, including composite fragmentation, and the bullets were observed. Generally, the type and amount of layers of the backing material, including the type of adhesive as well as the bonding techniques used, strongly affected the ballistic performance.

Table 1. Test specimen classification for NIJ Standard testing

Specimen Type	Specimen code	Weight (kg)	Mean thickness (mm)	Length (mm) x Width (mm)	Areal density (kg/m^2)
Twaron panel (5 ply)	TW5	0.19	3.2	300 x 300	2.1
Twaron panel (15 ply)	TW15	0.51	6.1	300 x 300	5.6
COEX tile format /5ply Twaron	CTW5	1.12	23.76	240 x 180	26
COEX tile format/15ply Twaron	CTW15	1.33	24.99	240 x 180	30.7
COEX tile format/15ply Twaron	CTW15A	1.28	26.34	240 x 180	31.2
COEX curvature format/15ply Twaron	CVW15	1.34	16.65	300 x 240*	18.6
COEX curvature format/15ply Twaron	CVW15A	1.40	17.30	300 x 240*	19.4

Therefore, constant bonding process for normal production was applied for all the test specimens.

2.1.1 *Determination of Ballistic Limit*

The definition of ballistic limit or V_{50} according to US MIL-STD-662F[9] is the velocity at which there is a 50 per cent probability of specimen penetration. This represents the velocity at which the projectile barely penetrates the specimen. It is determined by taking the average of an equal number of highest partial penetration velocities and lowest complete penetration velocities which occur within a specific velocity range for a particular specimen configuration. The velocity range requirement is necessary since an unusually high or low data point could offset the average, causing a misrepresentation of the V_{50} ballistic limit..

Because of the expense of firing tests and the impossibility of controlling striking velocity precisely, plus the existence of a zone of mixed results (in which a projectile may completely penetrate or only partially penetrate under apparently identical conditions), statistical approaches are often necessary, based upon limited firings. This standard is also used to determine blunt face signature (BFS) which predicts the effects of blunt trauma, a terminology of injuries suffered from forces created by the bullet impacting the armour. This type of non-penetrating injury can cause severe contusions (bruises) or internal damage and can even result in fatality. NIJ Standard[6] 0108.01 dictates that all armour material BFS, acquire by measuring the depth of the plasticine backing material after an impact event, such not be more than 44 mm of depth.

However due to bullet constraint that occurred during the test operation, only maximum 4 shots per panel were allowed during the ballistic testing. Also it was predicted that the test specimen may exhibit nonperforation result at certain projectile type and impacting velocity. For example, the 9 mm ammunition has a limitation of an average impacting velocity of 426 m/s and may not be able to penetrate through the test specimen at its maximum speed. The results may not give an accurate V_{50} but an estimation of ballistic limit (BL) from the projectile's highest partial penetration velocity.

2.1.2 *Calculation of Energy Absorption*

It is an established fact that energy absorbed by a specimen in ballistic test is a means to quantify impact-penetration resistance. Therefore the absorbed kinetic energy by armor-projectile interaction can be linked by Eqn (1) where E_{abs}, $E_{initial}$ and $E_{residual}$ are defined as the total kinetic energy absorbed by the armour, the kinetic energy of the projectile prior to impact, and the residual kinetic energy after penetrating through the armour, respectively.

$$E_{abs} = E_{initial} - E_{residual} \tag{1}$$

From this point, Eqn (1) can be further derived into Eqn (2) using the classical physics relationship that describes the kinetic energy of a moving object whereas m_p is the mass of the projectile, v_{initial} and $v_{residual}$ are the projectile initial and residual velocities:

$$E_{abs} = \frac{1}{2} m_p v_{initial}^2 - \frac{1}{2} m_p v_{residual}^2 \tag{2}$$

This can also be further derived with relation to the ballistic test results [Eqn (3)] where the initial velocity can be related as the partial penetration velocity and residual velocity as the complete residual velocity:

$$E_{abs} = \frac{1}{2} m_p v_{partial\ penetration}^2 - \frac{1}{2} m_p v_{complete\ penetration}^2 \tag{3}$$

Wambua[1], *et al*. have conducted similar ballistic tests and used the V_{50} ballistic limit as the impacting velocity differences to estimate the energy absorption of the armour material as shown in Eqn (4).

$$E_{abs} = \frac{1}{2} m_p (v_{50}^2) \tag{4}$$

For each of the test configurations, the energy absorbed by the composite was taken as the metric for impact-penetration resistance. Therefore, to determine the effectiveness of the COEX composite in improving the impact penetration resistance of the whole armour system (COEX/Twaron panel), the variations in energy absorbed wrt the plain Twaron fabric panel will be used. Perc ent changes in energy absorption (% ΔE) were then calculated as

$$\%\Delta E = \frac{E - E_c}{E_c} * 100 \quad (5)$$

where E_c is the energy absorbed by the control specimen (Twaron).

3. RESULTS AND DISCUSSION

Plain TW5 and TW15 panels were first tested to set the baseline for comparison when testing subsequent COEX/TWARON armour panel configurations. The objective of the plain Twaron fabric panel or spall liner testing was to determine the ballistic limit and impact damage characteristics of a typical (non stitched) ballistic resistance fabrics at different ply configurations. It was also to determine the maximum amount of projectile kinetic energy that can be absorbed by the TW5 and TW15 in the absence of COEX composite when subjected to ballistic impacts.

3.1 Twaron Spall Liner

The estimated V_{50} ballistic limit for plain TW5 and TW15 panels were determined using the method described in Section 2.1. For TW5 panel, the four complete penetrations and one partial penetration were used to determine the V_{50} ballistic limit of 226 m/s. For TW15 panel, two partial penetrations and one complete penetration were used to determine the military V_{50} ballistic limit of 374 m/s. The data points for TW5 and TW15 can be summarised in Fig. 3.

The front and back face layout view of the Twaron spall liners is shown in Figs 4(a) and 4(b). The observed mechanisms for absorbing ballistic impact in the TW5 and TW15 panels which as shown in Figs 4 and 5, where fibre shearing, fibre pullout, and delamination type of damage were found between the bonded fabric plies. For the projectile impacted area which caused partial penetration, it was found that the diameter of the shearing damage was similar to the diameter of the projectile on front face (first ply). The damage area increased slightly with depth until to the intermediate plies which exhibit more delamination effect occured between the plies bonded area (Fig. 5). It can be reported that the projectile penetration depth for TW5 and TW15 panels appeared to be dependent on the velocity of the projectile. On the TW5 panel back face, the diameter of shearing damage was found similar to the diameter of the projectile on the back face (Figs 6(a) & 6(b)) and can be suggested that TW5 have little ballistic resistance capability at NIJ Level II threat level.

The damage characteristic results are consistent with observations made by Cantwell and Morton (1990 a) which can be graphically shown in Fig. 7. The localised deformation is observed at the damaged area of TW15 panel due to its high velocity impact

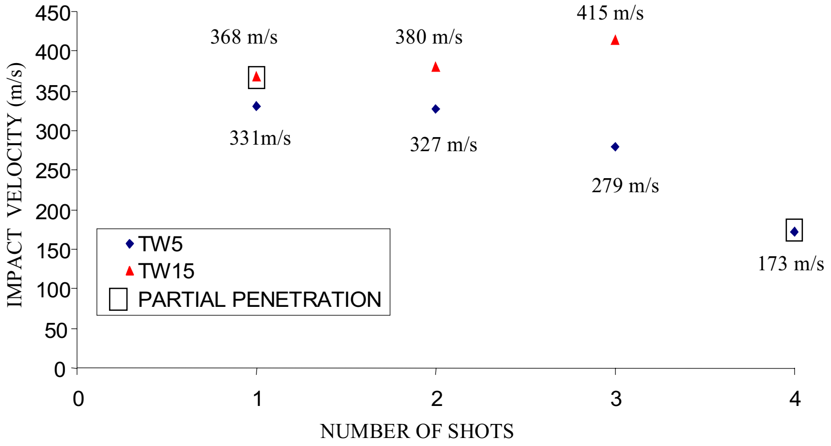
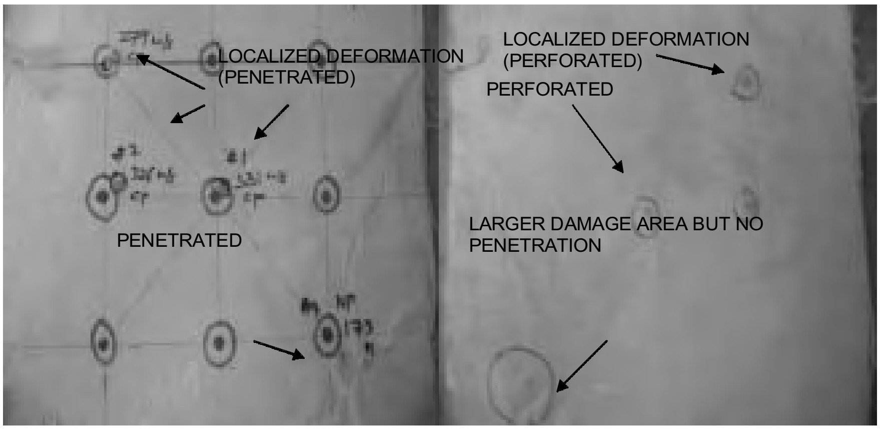
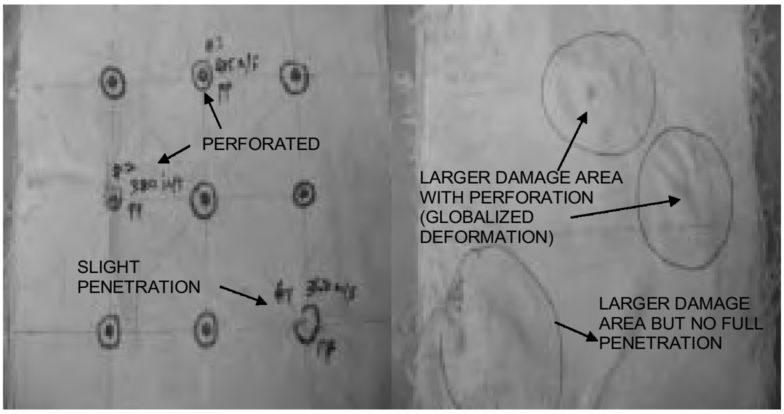


Figure 3. Graphical representation of data points used to determine the ballistic limits for TW5 and TW15 using 9 mm FMJ ammunition.



(a) (b)

Figure 4. (a) Front face and (b) backface of the TW5 subjected to 9 mm FMJ bullet impact at various speeds.



(a) (b)

Figure 5. (a) Front face and (b) back face of the TW15 subjected to 9 mm FMJ bullet impact at various speeds.

where the front and back faces have similar penetration diameter due to shearing effect induced by the ammunition penetrative force as seen in Fig. 5. For TW5 panel, a globalised deformation is observed at the damaged area panel where a large damage initiation occurred (circled) to dissipate the projectile kinetic energy at low velocity, as shown in Fig. 4. The Twaron panels ballistic limit results can be compared with the recommendation by Twaron CT716 fabric's manufacturer Teijin Twaron for body armour fabrication, which is as shown in Table 2.

3.2 COEX/Twaron Panel

A summary of all the V_{50} and ballistic limit test results are shown in Figs 8-11. The ballistic limit of the COEX/Twaron panels from this testing may not give an accurate V_{50} ballistic limit due to the constraints mentioned in Section 2. However the ballistic limit for this work is estimated based on

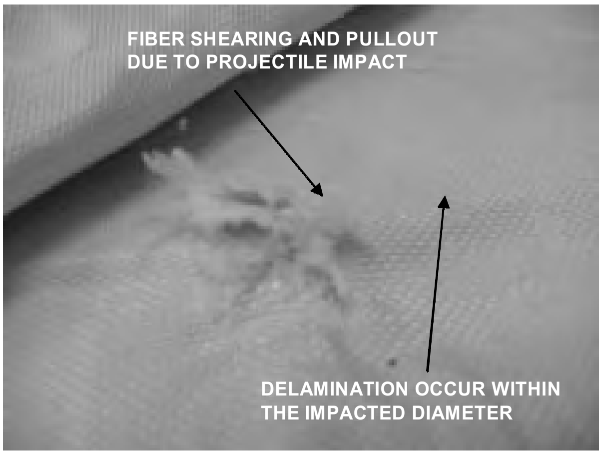


Figure 6 (a). Fibre shearing and delamination within the Twaron fabric ply TW5 upon bullet impact.

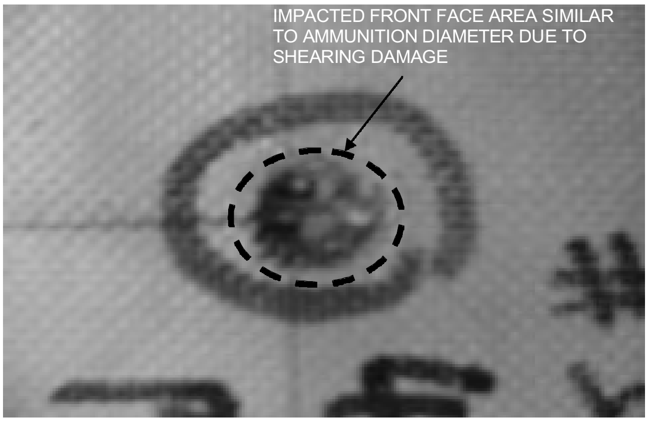


Figure 6(b). Damage area similar to projectile diameter due to shearing effect during penetration process.

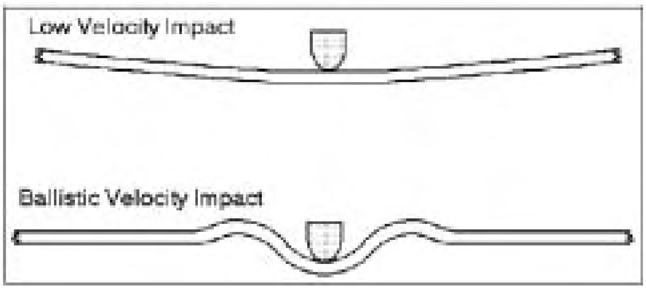


Figure 7. Representation of global deformation in low velocity impact and local deformation in ballistic velocity impact high velocity impact. (Cantwell and Morton, 1995)

the highest partial penetration velocity where this can give an indication that the actual ballistic limit is higher than the estimated velocity.

Table 2. Comparison of tested Twaron panel and manufacturer's specification

NIJ level	Teijin Twaron recommendation for Twaron CT716 for body armour fabrication	Tested/lowest complete penetration velocity of Twaron CT716 using 9 mm FMJ bullets
I	7 layers (322 m/s)	5 layers (279 m/s)
IIA	14 layers (341 m/s)	15 layers (360 m/s)
II	20 layers (367 m/s)	15 layers (360 m/s)
IIIA	23 layers (420m/s)	-

From these results, it can be observed that CTW 5 panel have a significant ballistic resistance to 9 mm FMJ ammunition impact which is equivalent to protection level of NIJ Level III A. Figure 8 shows the CTW5 panel ballistic limit is estimated using the highest partial penetration velocity, which is at 420 m/s as the indicator (as discussed in Section 2.1.1). The maximum CTW5 panel BFS value was measured at 30.8 mm and was lower than the 44 mm BFS limit set by the NIJ Standard.

For the tested CTW15 panel (Fig. 12), with reference from CTW5 panel results, confirmed that the COEX composite used as the frontal protective component of the armour possessed a significant ballistic resistance capability at NIJ threat level III A. From Fig. 9, the CTW15 ballistic limit is estimated at 416 m/s (the highest partial penetration velocity value) with a 13.4 per cent depth reduction

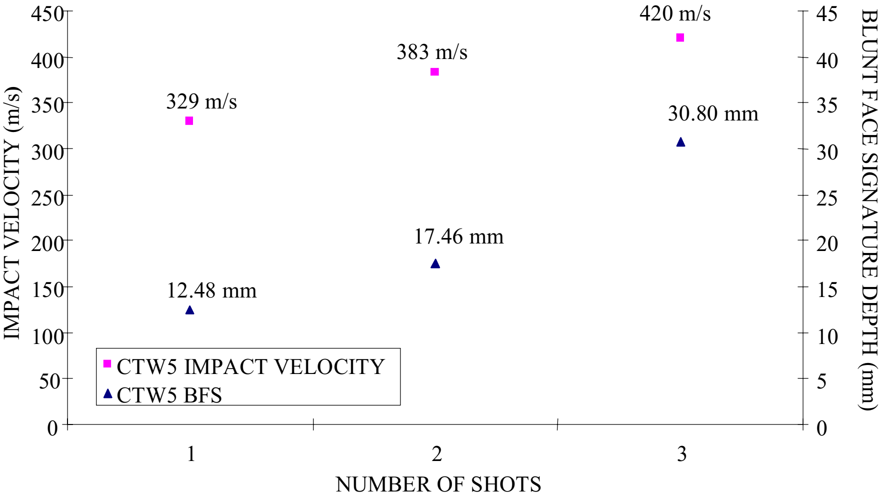


Figure 8. Graphical representation of data points used to determine the ballistic limit for TW5 and TW15 panels using 9mm ammunition.

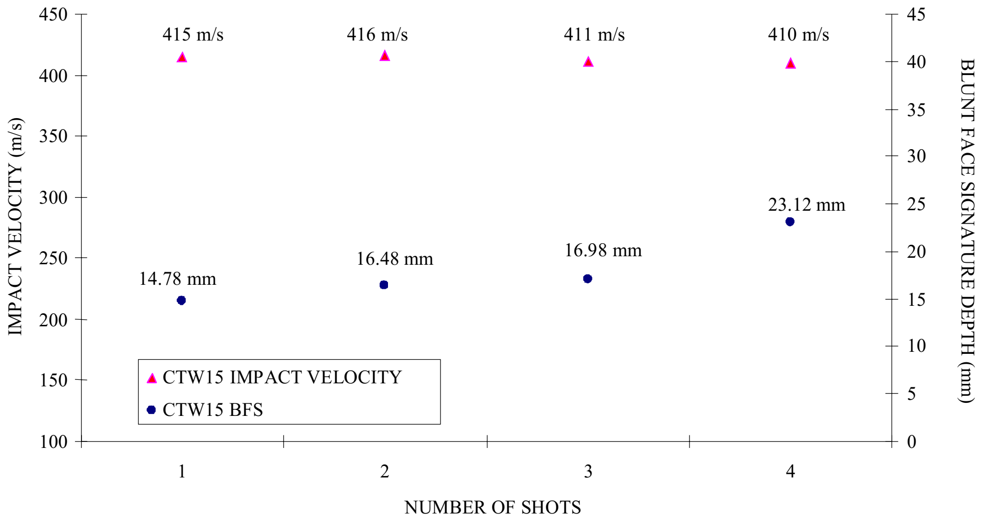


Figure 9. Graphical representation of data points used to determine the ballistic limit for CTW 15 panel using 9 mm ammunition (no perforation occurred).

in the average BFS value when compared to CTW5 panel. The maximum BFS depth for CTW15 measured at 23.12 mm is lower than the 44 mm BFS limit set by the NIJ Standard. The Twaron spall liner bonded on the back face of the COEX composite does provide extra means to absorb ballistic impact energy or with the additional of Twaron 10 ply. This further enhances the ability of the armour panel to absorb shock induced by the project impact, thus reducing the trauma force exerted to the plasticine block.

It is also a known fact that the protective level of typical ceramic armour progressively degrades as impact points approach the edges, corners, and abutting joints between individual tiles. However as shown in Fig. 13(b), CTW15 panel has shown a significant ballistic-resistance capability when subject to projectile impact the tile edges intersection. Also for multi-hits capability where two 9 mm FMJ ammunition were impacted, within one tile cell area and survived with partial penetration, is clearly shown in Fig. 13(c).

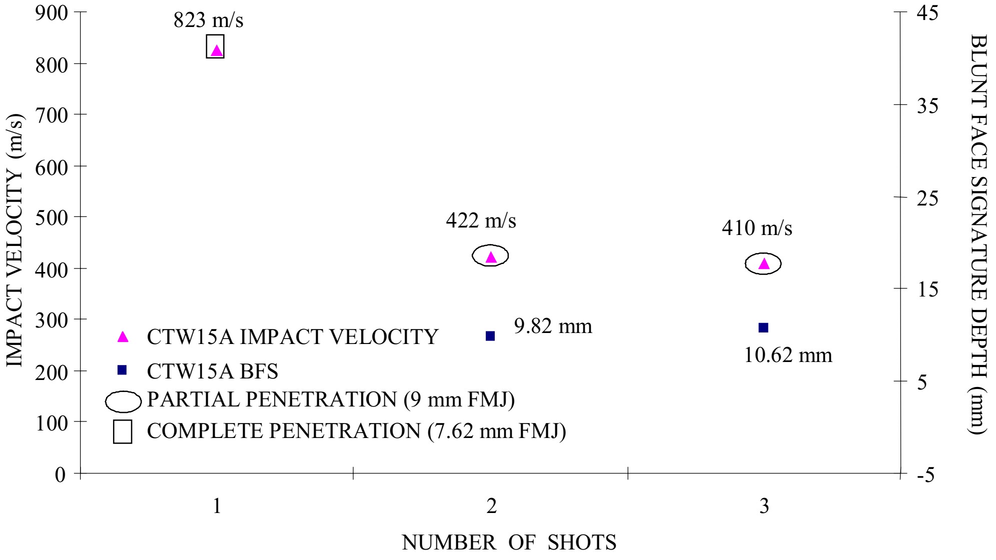


Figure 10. Graphical representation of data points used to determine the ballistic limit for CTW 15A panel using 7.62 mm and 9 mm ammunitions.

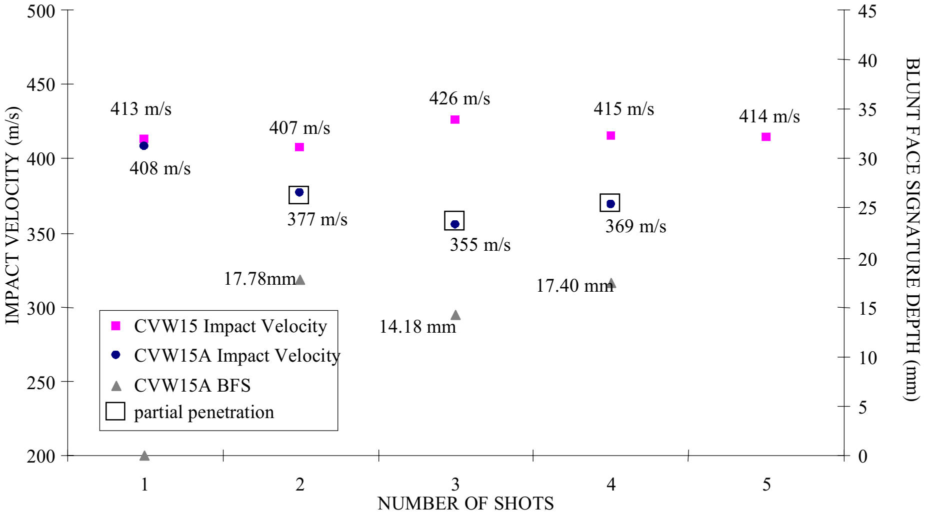
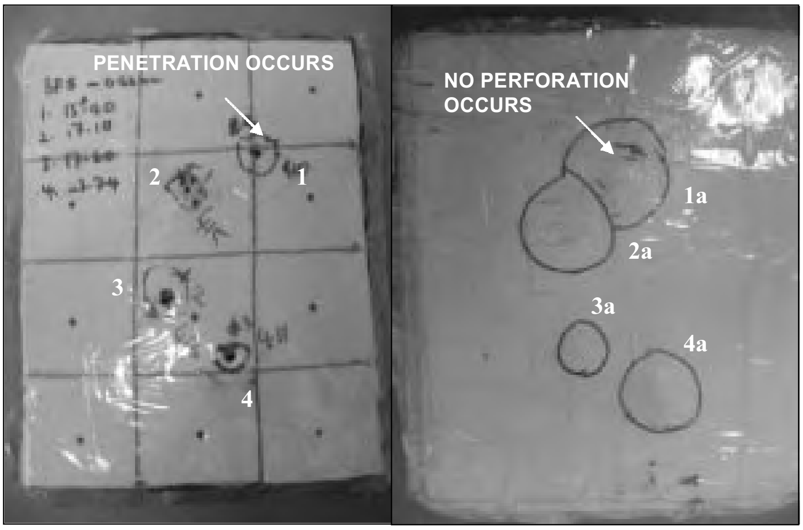


Figure 11. Graphical representation of data points used to determine the ballistic (partial penetration) limit for COEX panel B (15 ply) 9 mm ammunition.

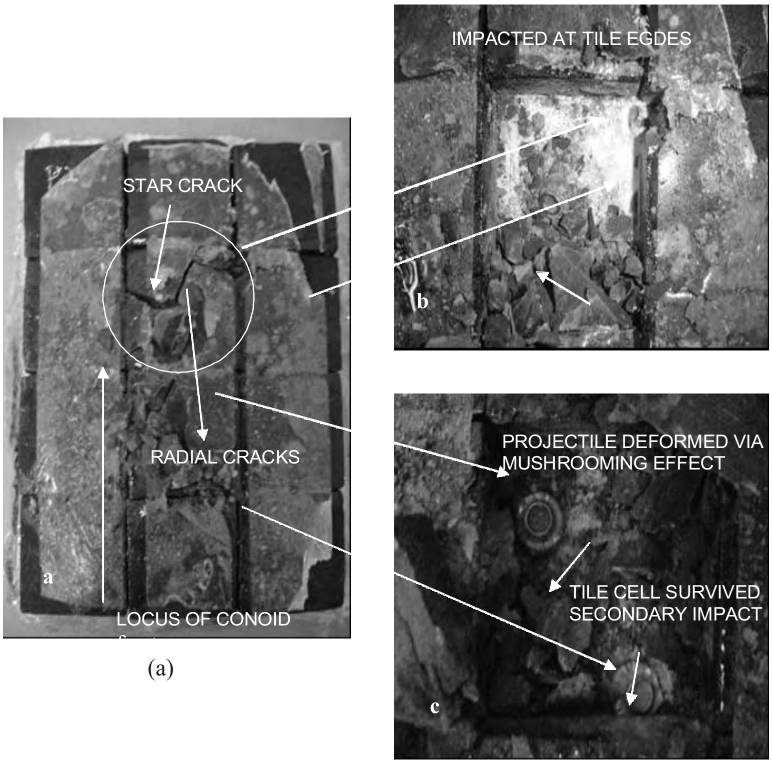
From Fig. 10 test data, CTW15A panel was tested at NIJ threat level III using a 7.62 mm ammunition and the result have shown that the panel exhibit, no ballistic resistance (perforation occured) at impacting velocity of 800 m/s. This is because at higher impacting energy, neither the COEX composite nor 15 ply of Twaron fabrics are not able to fully absorb and dissipate the impact energy as efficiently as typical ceramic armour. Another probability is the inferior mechanical characteristic of COEX composite in terms of hardness and compressive strength when compared to ceramic armour. However as shown by the CTW15 panel, at lower threat level (NIJ Level III A) using 9 mm ammunition, the CTW15A panel survived at impacting velocity of 422 m/s (estimated as CTW15A's ballistic limit). From this deduction, the overall ballistic resistance capability of CTW5 and CTW15 panels conforms to NIJ Level III A at 9 mm FMJ ammunition impacting velocity of 427 m/s.

For CVW15 panel tested at NIJ threat level IIIA, it shows no ballistic resistance at impacting



(a) (b)

Figure 12. (a) CTW15 panel front face (b) CTW15 panel backface after 9mm FMJ bullet impact at various speeds.



(a) (b) (c)

Figure 13. Damage observation of CTW15: (a) front face (b) close-up view of section impacted at the tile edges, and (c) close-up view of section impacted with two projectile within one tile cell.

velocity > 400 m/s(as indicated in Fig. 11). This may be due to the CVW15 monolith COEX composite thickness level < 78 per cent from the nominal flat COEX tile panel (CTW15) and shape curvature configuration was unable to distribute efficiently the projectile kinetic energy evenly throughout the composite surface area as compared to plain flat tile configuration (CTW15 panel). However for CVW15A panel, as indicated in Fig. 11, shows a ballistic limit of 377 m/s (estimated from the highest tested partial penetration velocity) with the maximum BFS depth was measured at 17.78 mm. From physical observation shown in Figs 14(a) and 14(b) and 15(a), 15(b), and 15(c), it can be noted that COEX monolithic panel exhibits a greater degree of crack propagation, particularly after multiple hits, rather than smaller COEX tiles which are separated within the seams of the abutting joints by epoxy. As a result of this increased crack propagation, a greater percentage of the overall CVW15 and CVW15A panels is prone to intense damage than would be the case with smaller tiles.

The mechanisms of ballistic protection for a composite armour and metal armour are significantly different. Metals typically absorb the projectile kinetic energy through plastic deformations. As for composite materials, in this case particulate composite (coconut powder/epoxy composite), which is typically brittle and behaves similar to ceramic material, absorbs the projectile kinetic energy by fracture and cracking mechanisms. For all ballistic impacts on typical ceramic tiles, a locus of conoid coaxial cracks starts at the impact point[6]. However, various types of cracks are formed during the ballistic impact (Fig. 16). This damage characterisation, which shows a typical bullet imprints observed in ceramic armour under high energy dissipation, is also found on all impacted COEX/Twaron panels. Generally, the imprints may be classified into four patterns.

Clean penetration occurred in COEX composite against high-velocity impact where it was observed that radial tensile cracks were initiated at the back

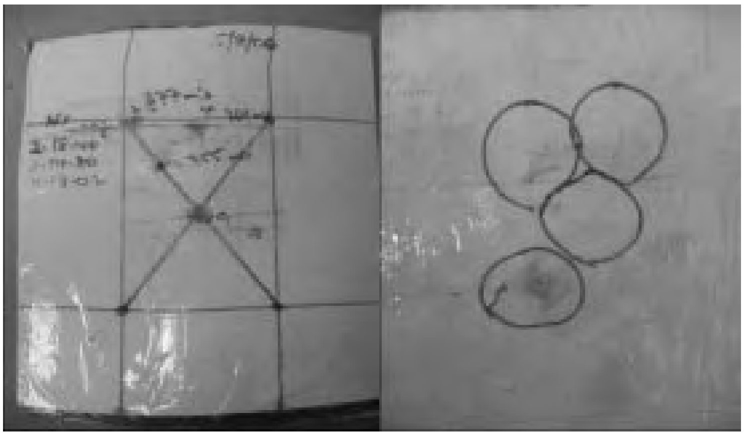


Figure 14. (a) CVW15A panel frontface (b) CVW15A panel after to 9 mm FMJ bullet impact at various speeds.

surface close to the axis of impact [Fig. 13(a)]. Impact load generated local bending deformation, causing the large reflected tensile stresses at the bottom of the COEX tile. These stresses produced the radial cracks propagating towards the upper surface of the COEX composite. A network of radial cracks lying from conoid to free boundary of the COEX can also be observed in Figs 13(a) and 15(a).

Star shaped cracks were formed on the side of conoids, as shown in COEX tile penetrated by 9 mm ammunition. In this case, tangential spall cracks occured due to shear stress waves reflected from the edges of the tile and formation of cone cracks. Lateral spall cracks may also be formed because of longitudinal stress waves reflected from the backing support. Cone formation is also predicted by shear dominating mechanism caused by high compressive stresses and the cone propagated as plug through the direction of the projectile. The cone was crushed and fragmented into small pieces and even pulverised along with propagation of the projectile. The projectile pushed the conoid composite away from its path for deeper penetration.

As for typical ceramic tiles that effectively absorb the ballistic energy, fragments of damaged COEX specimen were observed to have various sizes, ranging from big chunks to a fine powder, are after fracturing due to projectile impact. The chunks with bigger sizes were formed for explosive shattering at impact, as shown in Figs 13(b) and 15(c).

Finally, the overall COEX panel may fail if impact occurs on (or near) an interface between COEX tile cell, as shown Fig. 13(a). Hence, part of armour design strategy is to make the tile size large enough to withstand the target threat level, but small enough so that in normal service, no cell is it more than once. The smaller COEX tiles allows the preservation of adjacent areas of an armour panel to support multiple direct-fire impacts. For example, if one tile is impacted, the damage should be contained to that tile only, leaving the surrounding tiles intact to defeat additional shots in neighbouring areas.

3.3 Energy Absoprtion

The energy-absorption efficiency is estimated on the ballistic limit velocity acquired from ballistic testing results whereas Eqn. (3) was applied for test specimen without the V_{50} values and Eqn. (4) was applied for test specimen with V_{50} values. It is acknowledged that these values may not represent the actual condition, which is predicted to be higher due to various discrepancies in the ballsitic test results but this estimated value can at least provide basic indication that the COEX/Twaron armour panel energy-absorption capabilities in ballistic application.

The increase in energy absorption calculation of the various COEX/Twaron panel configurations wrt the plain Twaron fabric panel was based on the ballistic limit values. The energy absorption

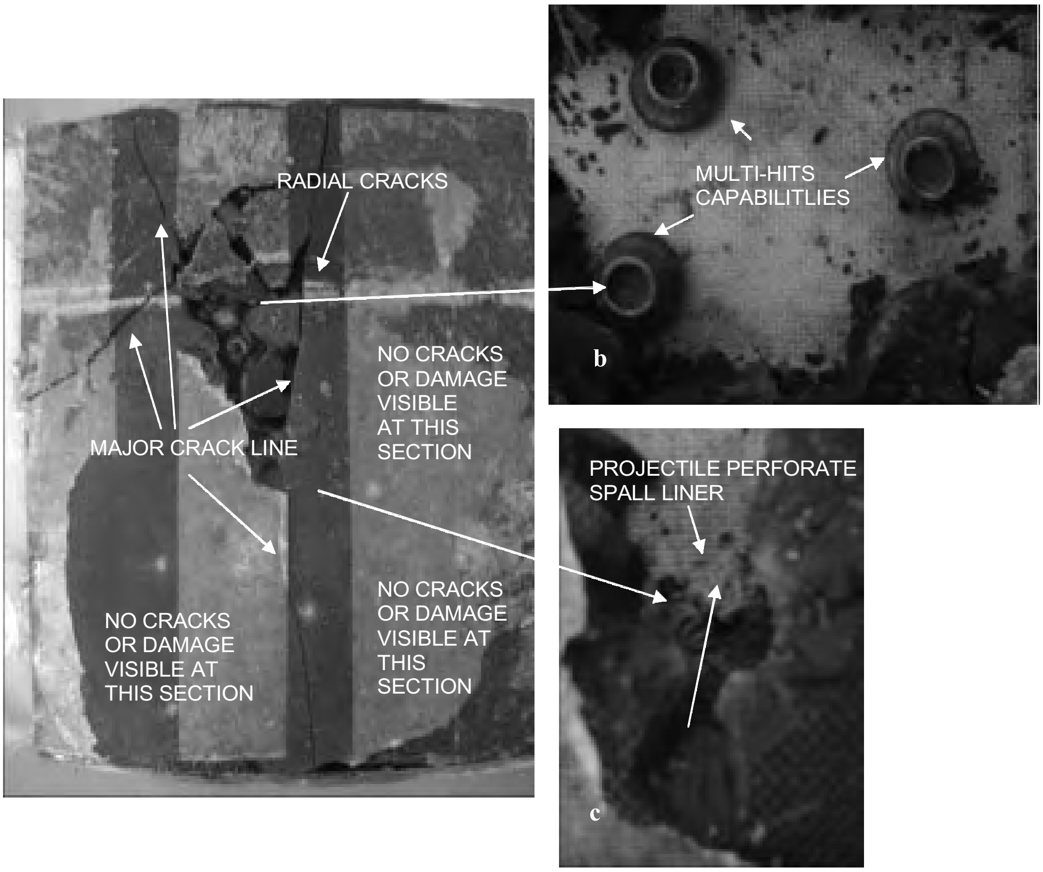


Figure 15. Damage observation of CVW15A (a) front face (b) close-up view of deformed projectile in multi-hits event, (c) close-up spall liner with fibre tearing damage.

variation for CTW5 panel configuration displayed more than an additional 170 per cent increase than using stand-alone TW5 panel.

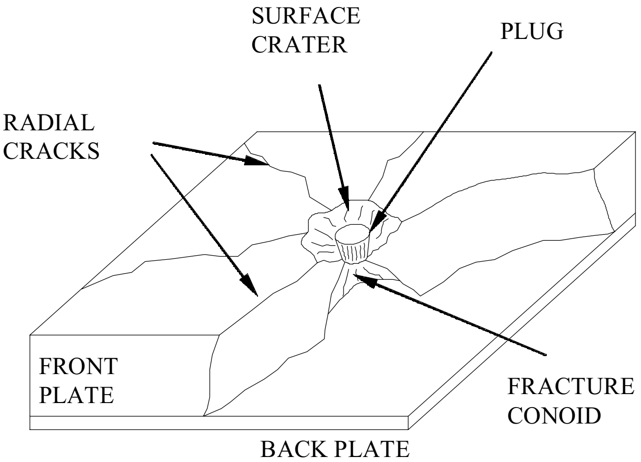


Figure 16. Typical ballistic impact damage imprints on ceramic armour[13].

For the CTW15 displayed an additional 24 per cent increase than using a stand-alone TW15 panel. For CVW15 and CVW15A panels, the energy absorption variation displayed an additional 10 per cent increase than using a stand-alone TW15 panel. However this is due to the reduction of 78 per cent in thickness when compared with COEX tile and curvature configurations.

As the projectile hits the armour, COEX composite deforms in tensile and flexural behaviour and erodes the projectile, thus reducing the kinetic energy of the projectile. The rest of the kinetic energy in the system is then consumed in the deformation of the backing spall liner. During the entire process, COEX composite fails and breaks; but it was commonly assumed that fracture of ceramic does not consume much of the energy.

The ability of a material to provide a useful contribution to an impact event depends on the hardness of the material, which is critical for blunting a projectile, and the strain to failure, which determines the ability of that material to absorb energy via a global deformation process involving brittle cracking in the case of COEX composite, or plastic deformation in the spall liner.

4. CONCLUSIONS

It can be concluded that by adding COEX composite material at 5 ply of Twaron fabric, it is able to withstand 9 mm ammunition ballistic impact up to threat level IIIA, and conforms to the NIJ Standard blunt trauma depth requirements. During ballistic impact, various types of cracks are formed on the COEX composite panel. Three patterns of ballistic imprints on COEX armour panels subjected to high velocity impacts were identified, namely clean penetration, star crack, and big chunks, which are prominent imprints for ceramic armour when subjected to ballistic impacts.

The nature and thickness of backing materials have a significant influence on crack propagation depending on their ability to dissipate the impact stress. The ballistic test results also show that COEX panels using curvature shape configuration also have significant ballistic resistance, up to threat level II at a reduced thickness.

The study also shows that by the addition of COEX composite tile configuration to the armour panel, the energy-absorption efficiecy of COEX/Twaron armour panel (5 ply) increased 175 per cent compared to Twaron armour panel (15 ply). For COEX composite curvature configuration, the energy absorption efficiency was found to be lower than its corresponding tile configuration due to its monolithic shape that contributed most of the failure damage.

The study shows that COEX composite has a significant ballistic resistance potential as a hard armour component which is light weight and has lower cost than the existing materials, such as ceramic, can offer. However, further evaluation can be carried out to enhance the ballistic resistance capabilities at higher threat levels.

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