Ballistic Impact Resistance of Plain Woven Kenaf/Aramid Reinforced Polyvinyl Butyral Laminated Hybrid Composite

Suhad D. Salman,[a,c,]* Zulkiflle Leman,[a] Mohamed T. H. Sultan,[b] Mohamad R. Ishak,[b,d] and Francisco Cardona [b]

Traditionally, the helmet shell has been used to provide protection against head injuries and fatalities caused by ballistic threats. In this study, because of the high cost of aramid fibres and the necessity for environmentally friendly alternatives, a portion of aramid was replaced with plain woven kenaf fibre, with different arrangements and thicknesses, without jeopardising the requirements demanded by U.S. Army helmet specifications. Furthermore, novel helmets were produced and tested to reduce the dependency on the ballistic resistance components. Their use could lead to helmets that are less costly and more easily available than conventional helmet armour. The hybrid materials subjected to ballistic tests were composed of 19 layers and were fabricated by the hot press technique using different numbers and configurations of plain woven kenaf and aramid layers. In the case of ballistic performance tests, a positive effect was found for the hybridisation of kenaf and aramid laminated composites.

Keywords: Kenaf fibres; PVB film; Kevlar fibres; Ballistic properties; Helmet

Contact information: a: Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia; b: Aerospace Manufacturing Research Centre (AMRC), Level 7, Tower Block, Faculty of Engineering, 43400 UPM Serdang, Selangor, Malaysia; c: Materials Engineering Department, Faculty of Engineering, The University of Mustansiriyah, Baghdad, Iraq; d: Laboratory of Bio-Composites Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia;
** Corresponding author: suhaddawood2007@yahoo.com*

INTRODUCTION

The global market for personal protection systems alone is worth between 300 and 400 million euros per year (Rahner 2012), with an annual growth rate of more than 5%. The ballistic helmet shell type known as the Personnel Armour System-Ground Troops (PASGT) is a standard infantry combat wear used by the U.S. military that has changed relatively little since the 1970s. The shell is a one-piece structure composed of multiple (at least 19) layers of Kevlar® (an example of an aramid) ballistic fibre. The primary goal of the PASGT helmet shell is to protect the soldier from a variety of prevailing threats by limiting the perforation of fragments or bullets through the helmet (Walsh *et al.* 2005). Kevlar® fibres are among the high-performance fibres used as the reinforcement in many high-velocity impact applications against projectiles and fragments (Salman *et al.* 2015a).

Recently, (Bandaru *et al.* 2016) have investigated the ballistic impact response of Kevlar® fabric and polypropylene (PP) composite armors having different fabric architecture against ballistic test standard NIJ-STD 0106.01. It was observed that good interfacial compatibility was acheived between PP and Kevlar® laminates with reduced density as compared to that of the thermoset-based laminates. The effect of hybridization on the hybrid composite armors under ballistic impact has been studied using hydrocode simulations by Bandaru *et al.* 2015. The hybrid composite armor is constructed using different combinations and stacking sequences of woven kevlar, glass, and carbon fibres reinforced composites, for a fixed thickness of the target. The results indicated that at a fixed thickness of the hybrid composite, stacking sequence of hybridized layer shows a significant effect on the ballistic performance. The energy absorption and ballistic limit velocity were sensitive to projectile geometry. These armors, however, give rise to practical issues such as their high cost and their potential for harmful effects including eye, skin, and upper respiratory irritation (Tham *et al.* 2008).

Ballistic helmet protection is generally used by those in the armed and civilian police forces and entrepreneurs, so there is an urgent need to develop a head protection helmet that can become more readily available and affordable. Environmental regulations, availability, cost, and lightweight factors encourage researchers to develop new hybrid composites with natural fibres to reduce the dependency on the ballistic resistance component. Kenaf (*Hibiscus cannabinus* L.) bast fibre is the most suitable natural fibre for hybridisation with Kevlar®, as determined using the analytical hierarchy process (AHP) (Yahaya *et al.* 2014). It has the highest priority among 13 natural fibre alternatives (Salman *et al.* 2015c). Hybridisation of kenaf and synthetic fibres has several advantages, including that it reduces dependency on petroleum, which is the source of the synthetic fibres used in PASGT helmets (Salman *et al.* 2015d).

A few attempts have been made to study the response of either Kevlar®/cellulosic or kenaf/synthetic composites under ballistic impact conditions (Wambua *et al.* 2007). The first serious discussions and analyses were carried out by Sohaimi (2003), who evaluated the potential of using coconut shell powder/Twaron®-reinforced epoxy (COEX) for ballistic applications. The higher ballistic limit has been obtained from using Twaron® layers on the exterior and coconut layers in the interior. In 2009, Radif *et al.* (2011) conducted a ballistic impact test on different types of laminated hybrid composites of Kevlar®/ramie-reinforced polyester resin for application in body armour. It was concluded that the panel geometry has the greatest effect in increasing the impact ballistic limit, the greatest energy absorption, and the life time rupture.

Further research on optimising the layered configurations and environmental effects on the Kevlar® 29/ramie-reinforced polyester resin was carried out by Ali *et al.* (2011). The results indicated that the developed personnel armour composite was improved in terms of the impact response with increasing relative humidity in the range of 50 ± 20%. Abdul *et al.* (2011) carried out experiments to determine the ballistic limit of coir yarn and Kevlar®/epoxy hybrid composites for ballistic applications. They examined the effect of stacking sequences of Kevlar® fibre on residual velocity and failure mechanism of the composites. They concluded that delamination and fibre fracture were the major failure modes in high-velocity impact tests, whereas matrix fracture and fibre sliding failures were the main mechanisms in quasi-static tests for thick-walled panels.

Not much experimental work has been reported on the high-impact response of kenaf/synthetic hybrid laminated composites. Davoodi *et al.* (2012) performed experiments on the potential of using hybrid kenaf/glass-based epoxy hybrid material in a passenger car bumper beam. The impact properties can be improved by optimising the thickness of the beam and improving the material, such as through epoxy toughening, to modify the ductility behaviour to improve energy absorption.

In the present study, an attempt was made to design plain woven kenaf/aramid-reinforced polyvinyl butyral (PVB) hybrid composites; their responses to ballistic impact tests, as well as their damage characteristics, were experimentally evaluated. Poly-vinylbutyral (PVB) film is now employed in a wide array of industrial and commercial applications because of its impressive mechanical performance and outstanding versatility. PVB offers advantages like longer shelf life and a stable ballistic performance over a broad temperature range, as well as it can be shaped into all manner of protective equipment. Identifying the proper configuration of woven kenaf fibre, resin, and reinforcement architecture for specific requirements of the PASGT shell material to provide equivalent protection at a reduced cost was the goal of this study.

EXPERIMENTAL

Two types of woven fabrics were used: plain woven kenaf and Heracron® aramid fibres double-side coated with 12% PVB-phenolic. Table 1 shows the physical characteristics of plain woven kenaf (Salman *et al.* 2015e), supplied by ZKK Sdn Bhd, Malaysia. The PVB-phenolic is a vinyl polymer with an additional 5% phenolic. It is commonly used to manufacture traditional PASGT helmets because of its low cost, easy fabrication, long durability, and good mechanical and chemical properties (Torki *et al.* 2012). Films of PVB are one of the most popular interlayer materials used for laminated safety glass. They are commonly used in the automotive and architectural fields bonded between two panels of glass. The polymer interlayer of PVB is tough and ductile, mostly used for applications that require strong binding, adhesion to many surfaces, toughness, and flexibility.

Table 1. Physical and Mechanical Properties of Materials (Manufacturer Data Sheet)

Material	Thickness (mm)	Areal density (g/m^2)	Density (g/cm^3)	Average breaking strength (MPa)	Average maximum strain (%)
Woven kenaf	2 ± 0.20	890	1.200	101	17.3
Heracron® aramid coated with PVB-phenolic	0.60	704	1.173	2390	3.3
PVB film	0.38	410	1.078	≥ 20	≥ 200

Fabrication of Composite Samples

The hot hydraulic press technique was used to fabricate hybrid laminates of different kenaf fibre weight content with PVB film and aramid fabric coated with PVB-phenolic film, as shown in Fig. 1.

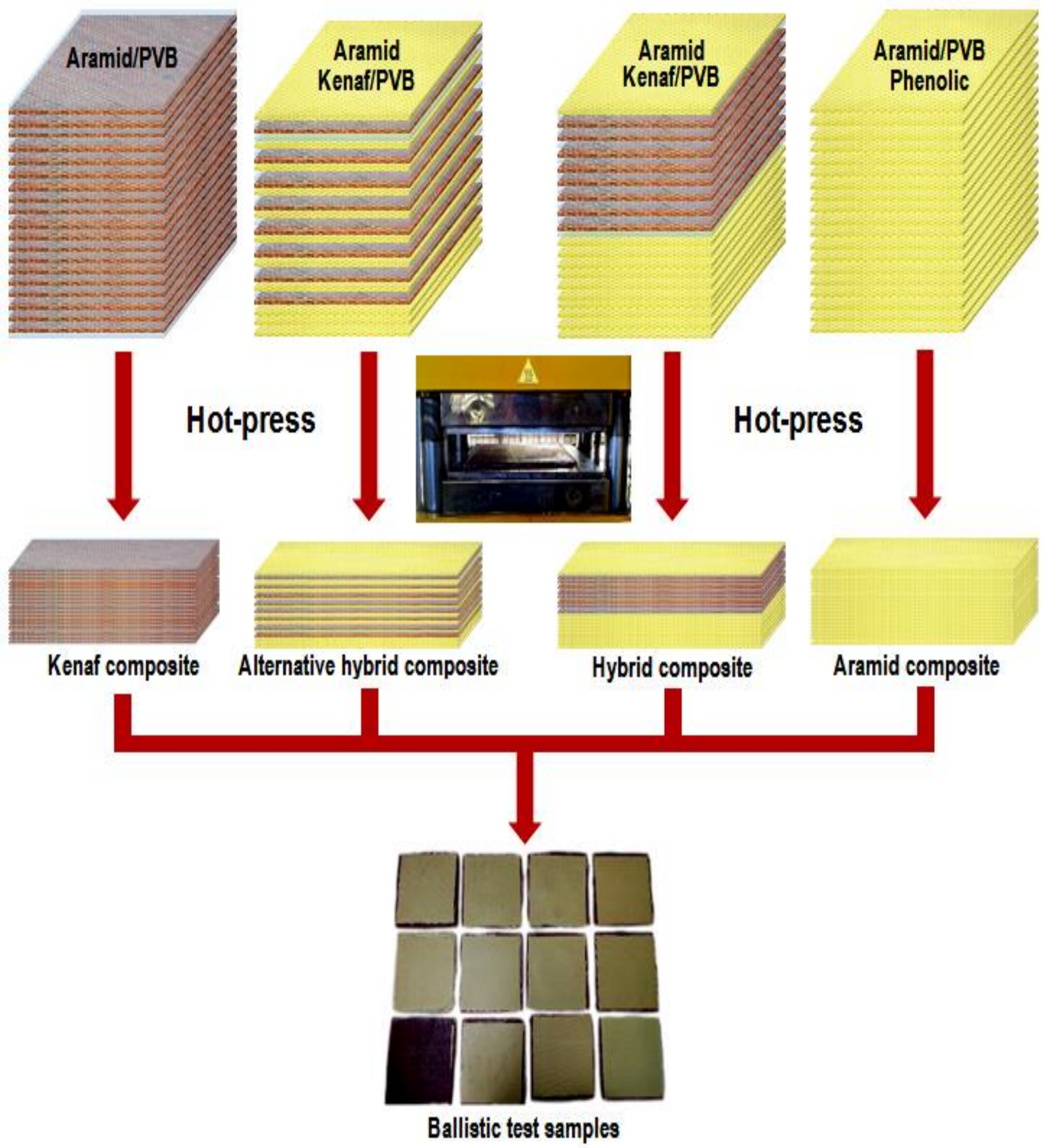
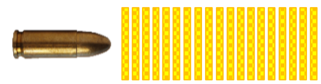
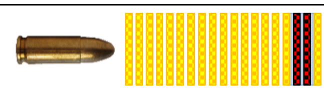
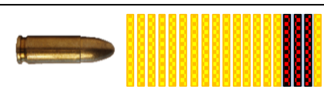
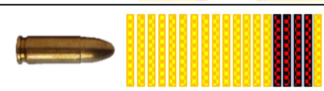
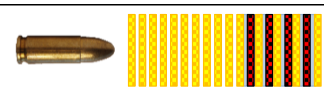
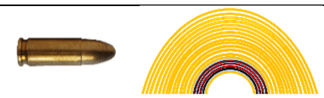
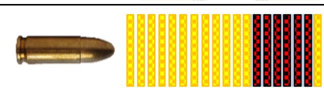
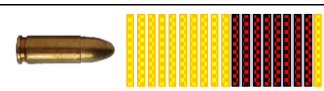
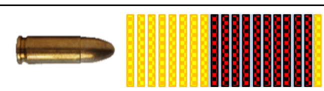
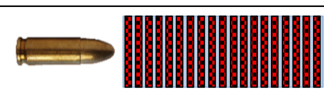


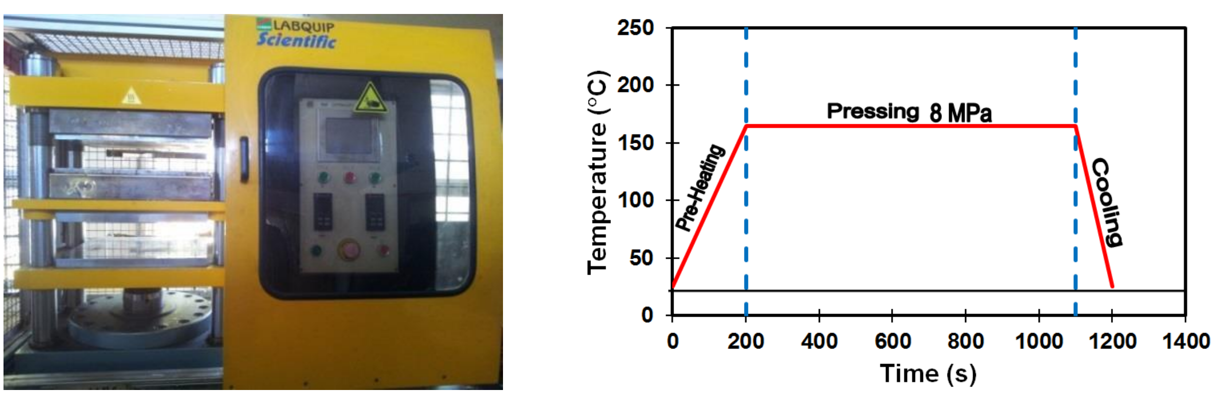
Fig. 1. The hybrid composite specimens prepared using the hot press technique

Table 2 illustrates the various configuration layers and stacking sequences of the hybrid laminates and helmets. To reduce the number of aramid layers and to identify the effect of layering sequence, plain woven kenaf layers were placed in eight different locations. Studies were also carried out on 19 layers of aramid/PVB-phenolic composite and plain woven kenaf/PVB composite for the purpose of comparison.

To fabricate a square flat laminated panel, the PVB film stacking between woven kenaf layers and coated aramid/PVB-phenolic were cut into 335 × 335 mm sheets. A mould release agent was sprayed on the mould surfaces before any moulding process to prevent adhesion as well as to obtain a smooth sample surface. The stacks of 19 layers of different laminates were centred between two stainless-steel moulds and hot plates of a compression moulding press.

Table 2. Specifications of the Laminated Hybrid Composites

Specimens descriptions	Sample code	Stacking sequence	Specimens thickness (mm)	Fibre volume fraction (%)	
				Aramid	Kenaf
19 Aramid 29	KV		8.8	61.94	0
17 Aramid / 2 Kenaf	H1		10.1	48.42	11.62
16 Aramid / 3 Kenaf	H2		10.6	43.56	16.69
16 Aramid / 3 Kenaf	HH2		10.6	43.56	16.69
15 Aramid / 4 Kenaf	H3		11.1	39.14	21.28
15 Aramid / 4 Kenaf Alt.	H3A		11.1	39.14	21.28
15 Aramid / 4 Kenaf	HH3		11.1	39.14	21.28
13 Aramid /6 Kenaf	H4		12.3	31.29	29.46
11 Aramid / 8 Kenaf	H5		13.1	24.55	36.44
9 Aramid /10 Kenaf	H6		14.3	18.75	42.48
19 Kenaf	KF		17	0	61.96



(a) Hot press (b) Processing cycle

Fig. 2. Compression moulding hot press and temperature profile

Subsequently, the platens were closed, the hot press plates were heated to 165 °C for 20 min, and the compression pressure was set to 8 MPa, as shown in Fig. 2. Once the temperature of the platens reached 165 °C, the compression pressure was increased to 8 MPa and held constant for 15 min. After this compression cycle, the platen temperature was reduced to room temperature (25 °C), while the pressure was maintained at 8 MPa until the temperature reached 25 °C. Once the platen temperature reached 25 °C, the hybrid composite laminates were taken out of the compression moulding frame. The same procedure was followed for fabricating the hybrid to produce the helmet shell (arc shape), but with another moulding hot hydraulic press, as shown in Fig. 3. The dimensions and mass of the hybrid laminates were measured to calculate the density and the areal density of the hybrid materials.

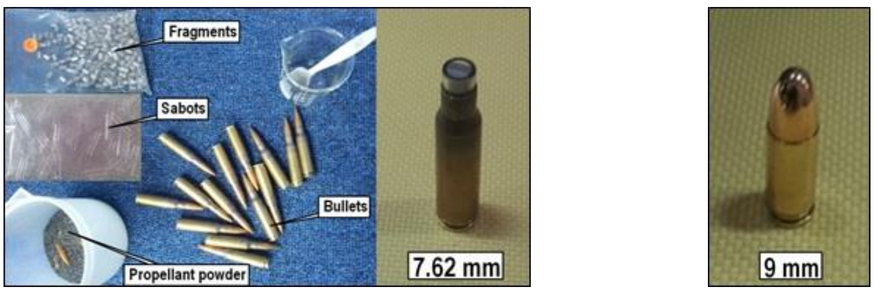
Fig. 3. Ballistic hybrid helmet fabrication processes

High-Velocity Impact Test

The high-velocity impact tests were performed using a 9-mm full metal jacket bullet with a powder gun on fabricated square panels with various impact velocities. The ballistic limit velocity V_{50}, hybrid failure mode, and NIJ levels were evaluated. NIJ standards are used for law enforcement armors by using a standard set of test methods under ARMY MIL-STD-662F. This approach defines each armor program and can select a unique series of projectiles and velocities as required in the armor standards. The ballistic experiments were conducted in an indoor firing range at the Science and Technology Research Institute for Defence, Ministry of Defence, Kajang, Selangor, Malaysia (STRIDE). The high-impact tests were performed according to four standards of helmets: NIJ-STD-0106.01 (Standard-0106.01 1981), the V_{50} requirement of the U.S. military specification for the PASGT helmet (0108.01 1985), military standard MIL-STD-662F (MIL-STD-662F 1997), and MIL-H-44099A (ML-H-44099A 1986). Using a powder gun, two types of bullets were fired: 9-mm, 8.0 g full metal jacket (FMJ) bullets to investigate the NIJ levels, and .22 calibre (diameter of 7.62 mm) fragment simulating projectiles (FSPs) to determine the V_{50} ballistic limit (shown in Figs. 4a and 4b). These tests were performed on both flat panels and on helmets with partial lateral support positioned 5 m in front of the test barrel's muzzle to produce impacts of 90° obliquity (illustrated in Fig. 5).

The general method for characterising a material's ballistic limit is to perform a V_{50} ballistic test, the velocity at which there is an equal probability of a partial (target was not defeated) or a complete perforation (target was defeated) for the given armour and threat. In this study, the NIJ methods were used to determine minimum performance requirements for ballistic resistant protective materials levels.

To carry out a V_{50} (ballistic limit) test, the propellant charge was put inside the projectile, then closed by two pairs of sabots around a small steel fragment to produce fragment simulating projectiles (FSPs). The amount of propellant for different impact velocities was determined through an empirical method by adjusting the mass of the propellant. The propellant fill for the shots and next shot were adjusted until three partial and three complete penetrations had been achieved within a velocity spread of not more than 38 m/s, as recommended by the standard ML-H-44099A 1986. Both chronographs and Doppler radar antenna, combined with a computer, were used to measure the projectile velocity. One chronograph was positioned 2 m in front of the target and another behind it, as shown in Fig. 5. Projectiles, which passed through the panel, were considered to be a complete penetration (CP), while the others were defined as partial penetrations (PP), following the NIJ definitions. The impact striking velocities (v_s) and residual velocity (v_r) of the projectiles were recorded, while the ballistic limit (V_{50}) was calculated.



(a) (b)

Fig. 4. (a) Fragment simulating projectiles for V_{50} tests, (b) 9-mm projectile for NIJ tests

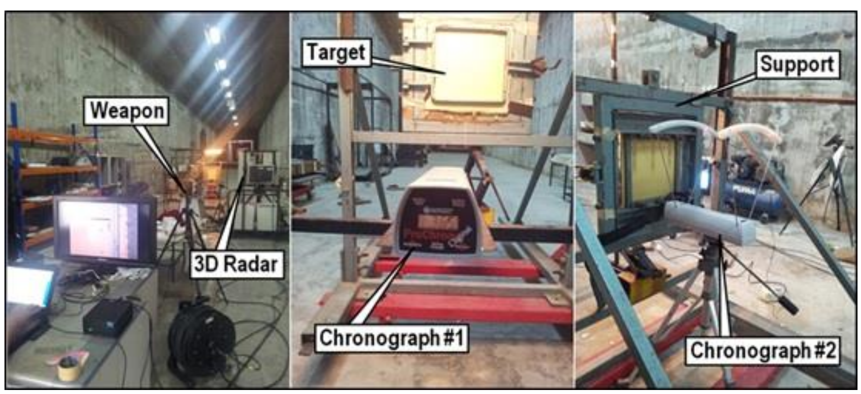


Fig. 5. Actual set-up for ballistic impact tests

RESULTS AND DISCUSSION

The effects of hybridisation on ballistic limit and NIJ levels was studied for high-velocity impacts. Initial impact velocities and residual velocities were measured experimentally to evaluate the ballistic limit (V_{50}) and NIJ levels of laminates. The NIJ results showed that the H1, H2, HH2, H3, H3A, and HH3 passed the fourth level (III-A), while H4, H5, and H6 passed the third level (II) (shown in Table 3). The positive effect in terms of NIJ levels compared with the aramid composite showed that hybridisation contributed to the same performance in high-impact penetration tests. In accordance with hybrid H3A (alternating woven kenaf layers with aramid 29 fabric layers) and hybrid H3 (placing woven kenaf layers together and aramid 29 layers separately), the results indicated that NIJ levels were not affected at the same hybrid volume and thickness. Based on Table 3, additional layers of kenaf fibres increased the thickness of the hybrids, while using different layering sequences had an insignificant effect on the NIJ Level of the hybrid composites. It is clear that the ballistic limit (V_{50}) of the hybrid composites was lower than that of the helmet shell composite. Signifying that this arc-shaped geometry provides a better penetration resistance compared to the flat panels. In the case of a flat panel that has the same configuration and sequence of shells shape, shells exhibited smaller deflections than a flat panel. The reason for this is due to decrease the strain distribution at the bottom surface of the arc-shaped geometry, as reported by (Choi 2016).

Table 3. Ballistic Resistance Results

Specimen description	Sample code	NIJ Standard Level Using 9mm FMJ projectiles	V_{50} (m/s) Using FSPs 7.62 mm bullets	Thickness (mm)
19 Aramid 29	KV	Passed level **III-A** 426 ±15 (m/s) 4th level	691	8.8
17 Aramid /2 kenaf	H1	Passed level **III-A** 426 ±15 (m/s) 4th level	621.2	10.1
16 Aramid /3 kenaf	H2	Passed level **III-A** 426 ±15 (m/s) 4th level	595.3	10.6
16 Aramid /3 kenaf [Helmet]	HH2	Passed level **III-A** 426 ±15 (m/s) 4th level	633.7	10.6
15 Aramid /4 kenaf	H3	Passed level **III-A** 426 ±15 (m/s) 4th level	585.4	11.1
15 Aramid /4 kenaf [Alt.]	H3A	Passed level **III-A** 426 ±15 (m/s) 4th level	570.8	11.1
15 Aramid /4 kenaf [Helmet]	HH3	Passed level **III-A** 426 ±15 (m/s) 4th level	623.3	11.1
13 Aramid /6 kenaf	H4	Passed level **II** 358 ±15 (m/s) 3th level	533.3	12.3
11 Aramid /8 kenaf	H5	Passed level **II** 358 ±15 (m/s) 3th level	496.8	13.1
9 Aramid /10 kenaf	H6	Passed level **II** 358 ±15 (m/s) 3th level	477.5	14.3
19 Kenaf	KF	Does not fulfill the requirement	417.8	17

The ballistic limit velocity (V_{50}) was estimated using experimental data on the basis of whether the projectile penetrated the hybrid composite completely or partially. It is the most common assessment tool to determine the ballistic performance of a material; the accuracy of the estimation, however, increases with increasing number of ballistic tests (Boccaccini *et al.* 2005). Figure 6 shows a plot between the initial velocity and the residual velocity for the hybrid laminated composites. An increase in initial velocity resulted in the increase in the residual velocity (which was zero up to certain initial value) for all the hybrids.

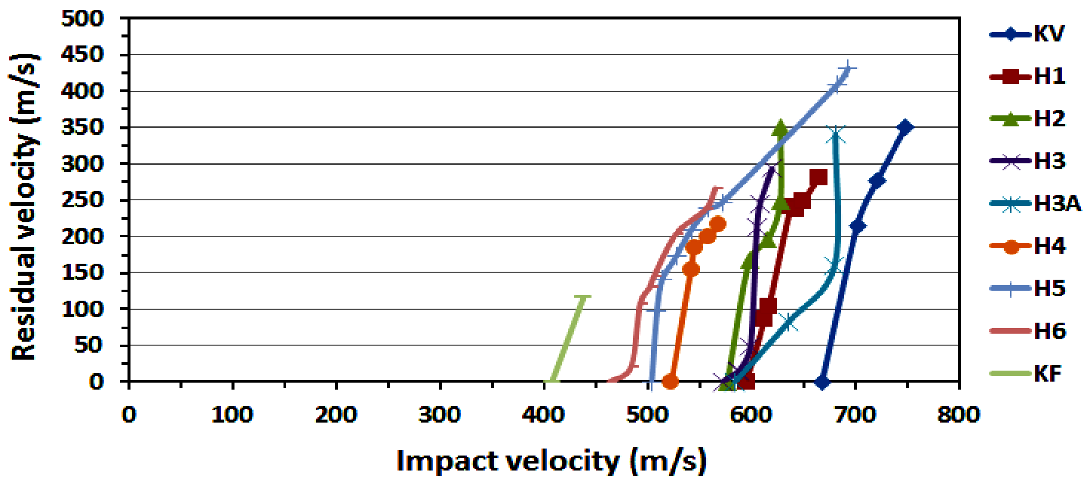


Fig. 6. Residual velocities as a function of impact velocities

Figure 7 shows the ballistic properties of kenaf/aramid hybrid composites in terms of ballistic limit velocity (V_{50}) compared with aramid /PVB-phenolic and kenaf/PVB composites. Hybrid H3A, alternate layers of kenaf and aramid, exhibited less ballistic limit compared to hybrid H3, for the same number of layers and thickness. Both types of hybrids bulged out and higher delamination occurred in the interlaminar surface for fabricated alternative aramid layers with kenaf layers. As reported by (Babu *et al.* 2006), when using different material surfaces (different flexibility and deflection), the magnitude of friction forces will be affected, leading to a decrease in the impact energy absorption mechanisms due to greater delamination. When the number of kenaf layers increased (*i.e.* a thickness increase), the difference in ballistic limit gradually increased in comparison to the aramid composite. Although the KF composite exhibits total perforation to the specimens at the highest impact velocities, the KF composite with a plate thickness of 17 mm was found to have 417.8 m/s ballistic limit.

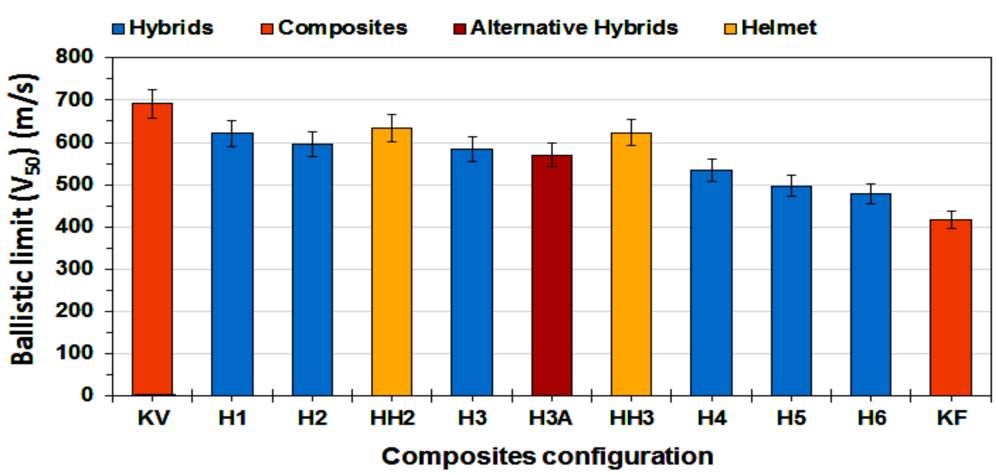


Fig. 7. Ballistic limit (V_{50}) of all composites

According to two ballistics test standards for helmets, NIJ-STD-0106.01 Type II, IIA, III, IIIA, and MIL-H-44099A, the V_{50} requirement of the U.S. military specification for PASGT helmets were calculated. There was a distinct difference between the ballistic limits of aramid /PVB phenolic and kenaf/ aramid hybrid composites. Hybrid HH2 and HH3 composites recorded higher V_{50} than the H2 and H3 composites, which consisted of the same number of kenaf layers, denoting the positive effect of the arc shape of the helmet (Salman *et al.* 2015b). The low values of ballistic limit in H3A hybrid composites compared to the H3 hybrid, which consisted of the same number of kenaf layers, denoted the negative effect of the alternative arrangement. This result can be explained by the fact that an alternating arrangement led to delamination between the inner surfaces, presenting less traveling distance for the projectile within the target (Zhang *et al.* 2014). As a result of less travel distance, there was less surface for energy dissipation (Sabet *et al.* 2009). Figure 8 shows the ballistic limit (V_{50}) *versus* volume fraction curves of kenaf and aramid hybrid composites. The kenaf volume fraction and aramid volume fraction had an important effect on the ballistic limit velocity.

Generally, these curves showed a bilinear behaviour and the line slope changes (increases) as the number of kenaf layers increases. It can be clearly seen that with an increasing volume fraction of kenaf, the ballistic limit decreased. Similarly, the ballistic limit curve increased as the aramid volume fraction was increased. The overall results for the high-velocity impact tests indicate that approximately a 30% volume fraction of both kenaf and aramid fibres was more effective for the ballistic properties. This can be explained by the fact that 30% fibres content presents better interfacial surface properties, which leads to an increase of the surface area for energy dissipation.

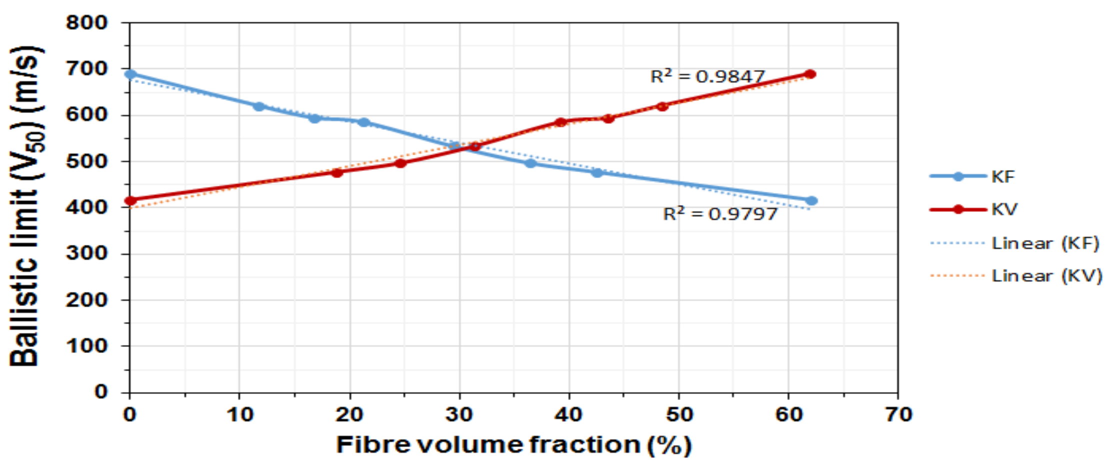


Fig. 8. Ballistic limit (V_{50}) *versus* fibre volume fraction curves of kenaf and aramid hybrid composites

This approach is expected to develop a helmet armour that, when compared to conventional helmet armour, is less costly, more readily available, less associated with the potentially harmful effects of the petroleum products, and will not jeopardise ballistic resistance. This research will open a new avenue for its use in military utilities, aerospace, and marine and civilian structures to reduce the use of aramid fabric in ballistic laminate composites, and meets the prescribed baseline performance specifications.

Damage Mechanisms

Post-test examination of selected specimens was performed to analyse the failure mechanisms during ballistic impact tests. Cross-sections of selected samples at the impact region were cut along the thickness direction to observe the damage failure modes after testing. Interestingly, the region of the specimens affected by the projectiles appeared to become more localised at higher impact velocities, as shown in Fig. 9. Aramid fibre failure is depicted in the damaged surfaces of the aramid 29 composite (Fig. 9a), while the kenaf composite is depicted as bulging and peeling out (Fig. 9d). Figure 9b shows the damaged surfaces of the hybrid that consisted of placing woven kenaf together and aramid 29 layers separately; bulging and fibre failure were observed. The hybrid with alternating layers of kenaf and aramid layers showed a combination of delamination and bulging out of the kenaf layers (Fig. 9c).

Similar behaviour of other types of hybrid materials has been documented in a Pandya research paper (Pandya *et al.* 2011). The main damage mechanisms in these hybrid materials were fibre tensile failure and matrix cracking. It is postulated that delamination only starts at an advanced stage of the loading, resulting in a small rhombic region of delamination just before the specimen is perforated during high-velocity penetration. When the impact velocity is increased, the stress wave propagation occurs, causing randomly broken fibres (Lin and Fatt 2006; Sultan *et al.* 2012; Pandya *et al.* 2013). Generally, the rupture of aramid and kenaf fibres as well as matrix fracture were major failure modes in the high-impact tests.

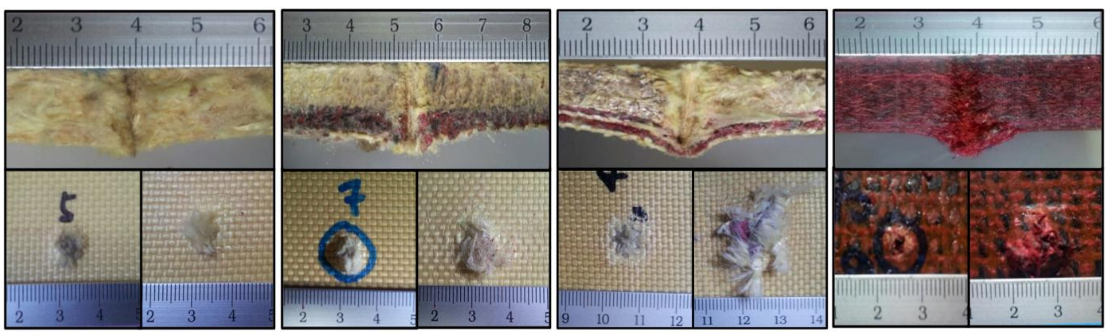

(a) (b) (c) (d)

Fig. 9. Optical pictures of ballistic failure modes of hybrid composite laminates at V_{50}, cross-sectional surface, impacted surface and rear surface for: (a) Kevlar composite, (b) Hybrid consisted of placing woven kenaf together and Kevlar 29 layers separately, (c) Hybrid comprised of alternating layers of kenaf and Kevlar layers and (d) Kenaf composite

CONCLUSIONS

1. The effects of hybridisation and the stacking sequence of hybrid composite materials under high-velocity ballistic impacts were investigated.
2. The arrangement of fibre layers was found to highly affect the ballistic performance of the hybrid composites. Placing woven kenaf alternating with aramid 29 fabric layers provided a lower ballistic limit velocity than placing woven kenaf together and aramid 29 layers separately for the same hybrid volume and thickness.

3. Nineteen aramid /kenaf layers reinforced by PVB were successfully developed to meet the fourth production level of the NIJ standard, with four layers of woven kenaf.
4. The proper configuration of woven kenaf fibre, resin, and reinforcement architecture were identified for specific requirements of the PASGT shell material to provide equivalent protection at a reduced cost.
5. The tested samples were optically observed and demonstrated the following: the delaminated area formed a conical shape for completely penetrated perforation; and there was a punched-out effect on the back ply following partially penetrated perforation, aramid and kenaf fibre breakages, aramid and kenaf fibre stretching, shear, and aramid fibre, kenaf fibre, and matrix rupture and cracking.

ACKNOWLEDGEMENTS

This work was supported by UPM under GP-IPS/2014/9438714 and GP-IPB grants, 9415402. The authors would like to express their gratitude and sincere appreciation to the Mechanical and Manufacturing Engineering Department and Aerospace Manufacturing Research Centre of the Universiti Putra Malaysia. Our appreciation and gratitude also extend to the Ministry of Higher Education & Scientific Research of Iraq and to the Material Engineering Department, College of Engineering, at the University of Mustansiriyah, for scientific assistance and financial support.

REFERENCES CITED

Abdul, R. A. H., Roslan, A., Jaafar, M., Roslan, M. N., and Ariffin, S. (2011). "Mechanical properties evaluation of woven coir and kevlar reinforced epoxy composites," *Advanced Materials Research* 277, 36-42. DOI: 10.4028/www.scientific.net/AMR.277.36

Ali, A., Shaker, Z. R., Khalina, A., and Sapuan, S. M. (2011). "Development of anti-ballistic board from ramie fiber," *Polymer-Plastics Technology and Engineering* 50(6), 622-634. DOI: 10.1080/03602559.2010.551381

Boccaccini, A. R., Atiq, S., Boccaccini, D. N., Dlouhy, I., and Kaya, C. (2005). "Fracture behaviour of mullite fibre reinforced–mullite matrix composites under quasi-static and ballistic impact loading," *Composites Science and Technology* 65(2), 325-333. DOI: 10.1016/j.compscitech.2004.08.002

Babu, M. G., Velmurugan, R., and Gupta, N. (2006). "Energy absorption and ballistic limit of targets struck by heavy projectile," *Latin American Journal of Solids and Structures, an ABCM Journal* 3(1), 21-39. http://www.lajss.org/index.php/LAJSS/article/download/88/82

Bandaru, A. K., Chavan, V. V., Ahmad, S., Alagirusamy, R., and Bhatnagar, N. (2016). "Ballistic impact response of Kevlar® reinforced thermoplastic composite armors," *International Journal of Impact Engineering* 89, 1-13. DOI: 10.1016/j.ijimpeng.2015.10.014

Bandaru, A. K., Vetiyatil, L., and Ahmad, S. (2015). "The effect of hybridization on the ballistic impact behavior of hybrid composite armors," *Composites Part B: Engineering* 76, 300-319. DOI: 10.1016/j.compositesb.2015.03.012

Choi, I. H. (2016). "Geometrically nonlinear transient analysis of composite laminated plate and shells subjected to low-velocity impact," *Composite Structures*, 142, 7-14. DOI: 10.1016/j.compstruct.2016.01.070

Davoodi, M. M., Sapuan, S. M., Ahmad, D., Aidy, A., Khalina, A., and Jonoobi, M. (2012). "Effect of polybutylene terephthalate (PBT) on impact property improvement of hybrid kenaf/glass epoxy composite," *Materials Letters* 67(1), 5-7. DOI: 10.1016/j.matlet.2011.08.101

Lin, C., and Fatt, M. S. H. (2006). "Perforation of composite plates and sandwich panels under quasi-static and projectile loading," *Journal of Composite Materials* 40(20), 1801-1840. DOI: 10.1177/0021998306060173

MIL-STD-662F (December). "V_{50} ballistic test for armor," Department of Defense Test Method Standard, USA.

ML-H-44099A (1986). "Military specification helmet, ground troops and parachutists," Department of Defense Test Method Standard, USA.

NIJ 0106.01, (1981). "Ballistic helmets," U.S. Department of Justice, Washington, DC, USA. https://www.ncjrs.gov/pdffiles1/nij/077182.pdf

NIJ 0108.01 (1985). "Ballistic resistant protective materials," U.S. Department of Justice, Washington, DC, USA. https://www.ncjrs.gov/pdffiles1/nij/099859.pdf

Pandya, K. S., Veerraju, C., and Naik, N. K. (2011). "Hybrid composites made of carbon and glass woven fabrics under quasi-static loading," *Materials & Design* 32(7), 4094-4099. DOI: 10.1016/j.matdes.2011.03.003

Pandya, K. S., Pothnis, J. R., Ravikumar, G., and Naik, N. K. (2013). "Ballistic impact behavior of hybrid composites," *Materials & Design* 44, 128-135. DOI: 10.1016/j.matdes.2012.07.044

Radif, Z. S., Ali, A., and Abdan, K. (2011). "Development of a green combat armour from rame-Kevlar-polyester composite," *Pertanika Journal of Science and Technology* 19(2), 339-348.

Rahner, C. P. (2012). *Analytical Evaluation of Impact Test Equipments to Simulate High Caliber Ballistic Threats*, Master's Thesis, Federal University of Santa Catarina, Florianópolis, Brazil.

Sabet, A. R., Beheshty, M. H., and Rahimi, H. (2009). "Experimental study of sharp-tipped projectile perforation of GFRP plates containing sand filler under high velocity impact and quasi-static loadings," *Polymer Composites* 30(10), 1497-1509. DOI: 10.1002/pc.20720

Salman, S. D., Hassim, W. S. W., and Leman, Z. (2015a). "Experimental comparison between two types of hybrid composite materials in compression test," *Manufacturing Science and Technology* 3(4), 119-123. DOI: 10.13189/mst.2015.030407

Salman, S. D., Leman, Z., Sultan, M. T., Ishak, M. R., and Cardona, F. (2015b). "Mechanical and morphological properties of 45°/-45° woven kenaf reinforced PVB-phenolic resin produced using a hot press technique," in: *Malaysia Polymer International Conference 2015 (MPIC 2015)*, Putrajaya, Kuala Lumpur, Malaysia.

Salman, S. D., Leman, Z., Sultan, M. T. H., Ishak, M. R., and Cardona, F. (2015c). "The effects of orientation on the mechanical and morphological properties of woven

kenaf-reinforced poly vinyl butyral film," *BioResources* 11(1), 1176-1188. DOI: 10.15376/biores.11.1.1176-1188
Salman, S. D., Leman, Z., Sultan, M. T. H., Ishak, M. R., and Cardona, F. (2015d). "Kenaf/synthetic and Kevlar®/cellulosic fiber-reinforced hybrid composites: A review," *BioResources* 10(4), 8580-8603. DOI: 10.15376/biores.10.4.8580-8603
Salman, S. D., Sharba, M. J., Leman, Z., Sultan, M. T. H., Ishak, M. R., and Cardona, F. (2015e). "Physical, mechanical, and morphological properties of woven kenaf/polymer composites produced using a vacuum infusion technique," *International Journal of Polymer Science* 2015, 894565. DOI: 10.1155/2015/894565
Sohaimi, R. M. (2003). *Experimental Damage Investigation of Composite Plates Subjected to Impact Loading Conditions*, Master's Thesis, Universiti Putra Malaysia, Selangor, Malaysia.
Sultan, M. T. H., Worden, K., Staszewski, W. J., and Hodzic, A. (2012). "Impact damage characterisation of composite laminates using a statistical approach," *Composites Science and Technology* 72(10), 1108-1120. DOI: 10.1016/j.compscitech.2012.01.019
Tham, C. Y., Tan, V. B. C., and Lee, H. P. (2008). "Ballistic impact of a KEVLAR® helmet: Experiment and simulations," *International Journal of Impact Engineering* 35(5), 304-318. DOI: 10.1016/j.ijimpeng.2007.03.008
Torki, A. M., Stojanović, D. B., Živković, I. D., Marinković, A., Škapin, S. D., Uskoković, P. S., and Aleksić, R. R. (2012). "The viscoelastic properties of modified thermoplastic impregnated multiaxial aramid fabrics," *Polymer Composites* 33(1), 158-168. DOI: 10.1002/pc.21260
Walsh, S. M., Scott, B. R., and Spagnuolo, D. M. (2005). *The Development of a Hybrid Thermoplastic Ballistic Material with Application to Helmets* (ARL-TR-3700), Army Research Laboratory, Aberdeen Proving Ground, Maryland, USA. http://www.dtic.mil/dtic/tr/fulltext/u2/a441165.pdf
Wambua, P., Vangrimde, B., Lomov, S., and Verpoest, I. (2007). "The response of natural fibre composites to ballistic impact by fragment simulating projectiles," *Composite Structures* 77(2), 232-240. DOI: 10.1016/j.compstruct.2005.07.006
Yahaya, R., Sapuan, S. M., Leman, Z., and Zainudin, E. S. (2014). "Selection of natural fibre for hybrid laminated composites vehicle spall liners using analytical hierarchy process (AHP)," *Applied Mechanics and Materials* 564, 400-405. DOI: 10.4028/www.scientific.net/AMM.564.400
Zhang, D., Sun, Y., Chen, L., Zhang, S., and Pan, N. (2014). "Influence of fabric structure and thickness on the ballistic impact behavior of ultrahigh molecular weight polyethylene composite laminate," *Materials & Design* 54, 315-322. DOI: 10.1016/j.matdes.2013.08.074

Article submitted: April 26, 2016; Peer review completed: June 12, 2016; Revised version received and accepted: June 28, 2016; Published: July 14, 2016.
DOI: 10.15376/biores.11.3.7282-7295