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Development of a Green Combat Armour from Rame-Kevlar-Polyester Composite

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ABSTRACT

This study was conducted for the development of the green protection garments. For this purpose, laminate composite material was developed from Kevlar 29-ramie-unsaturated polyester resin. The aim of this study was to develop a solid body armour that meets the specific requirements of ballistic resistance. This composite is subjected to high impact loading. The target was shot using gas gun machine that is supported by camera hardware to capture the projectile speed. In order to achieve the goal of the research, several experiments were conducted with the aim to estimate the ballistic limit, maximum energy absorption, composite failure mode, life time rupture, target geometry, and environmental effect. The results of these experiments indicated that the maximum ballistic limit validated at impact speed is in the range of 250 m/s to 656.8 m/s for the second protection level. The targets are improved in term of the impact response with the increase in the relative humidity, i.e. the range of 50% ± 20%, whereas, reduction of resistance results in the increase of temperature. The range of temperatures was between 20ºC and 70ºC. A limited delamination was generated under multiple shots. Targets geometry plays a major role in increasing the impact response. Hence, the results present a high resistant impact for pairs from the panels with total thickness arrived to 15 mm ± 3 mm. This body armour is one of the most economical armour products, in which common materials are used in its production, particularly to reduce the amount of Kevlar, and this could further lead to a decrease in its production cost. On the other hand, this armour meets the ballistic threats under 623 m/s of 15 mm ± 3 mm target thickness and 837.5 m/s of 25 mm ± 2 mm. Thus, the armour is equivalent to the third level of protective ballistic limits in the National Institute of Justice (NIJ) standards.

Keywords: Green protection, composites, natural fibre, Kevlar, ramie fibre, polyester resin

INTRODUCTION

Human's protection has been an important issue since the beginning of creation. Throughout the recorded history, there have been various types of material that are utilized as protection garments from injury, such as in battles and other dangerous situations. Thus, different materials were used as body shield; these include animals' skin, as well as wooden shield and metal shield. Since the introduction of the composite materials, a number of the armour systems involving composites have been designed to protect human lives from vital instruments (Sanjay, 2001). Recently, the interest is being directed to natural fibre as a ballistic protective fibre due to economic and environmental benefits that are seriously considered in various applications related to automotive, building,

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furniture, and packaging industries. Friendly materials commonly contribute to reduction in production cost, in addition to its highest possible filling levels. In particular, ballistic embedding represents the necessary issues in this perspective to create reinforce natural fibre.

Ramie is one of the commercial fibres that has been widely used for its significant properties (Mohanty *et al.*, 2000). Another commercial fibre that was utilized in the current investigation was the Kevlar which represents one of distinct protective textiles and commercialized under different types from productions and styles to meet the necessary protection requirements (Yang, 1993).

The composite protective property has attracted the researchers' attention, particularly due to its highest protection level and other significant properties. Morye's (2000) investigation was directed to analyze the impact event of three types of the polymer composite targets. Meanwhile, Shokrieh and Javadpour studied the penetration analysis of a projectile in the ceramic composite armour and their finding reveal a good agreement between the analytical method and numerical solution. In general, the metal hard armour performance is determined by the material's properties, as in the front and rear the armour. Hence, the front face erodes the projectile while the laminate of the target rear face absorbs the residual kinetic energy of the projectiles to prevent penetration. Rimantas (2007) carried out a numerical study to study the hard armour ceramic response. The amount of energy absorption function to the amount the transferring composite mass with projectile kinetic energy, the fibre deflects. Hence, the tensile forces will pull the material towards the impact point. The shape of the projectile has a major role in pulling the fabric. More details can be found in the report by Tan (2003).

Potti & Sun (1996) investigated a dynamic penetration process and related it with the length, mass and the shape of the projectiles, the delaminated area based the velocity level and the target area. Meanwhile, BΦrvik shifted to understand the mechanisms damage, which represented the main key of a successful design, at the micromechanical level. The delaminating and penetration mechanisms of laminated Kevlar were studied by Goldsmith (1992). The environment has effects on the area of this field. Andreia (2005) presented the environment effects at ultrahigh molecular weight polyethylene (UHMWPE) fibres and affirmed the external factors as sunlight, raining and radiation, which possessed the main role of changing the mechanical and physical properties of the composite. Based on above fact, the potential response of natural composite for arrest the impact threat is evident. Therefore, the objective of this study was to develop a combat armour material from the Ramie fibre of natural fibre composites.

Sample Preparation

The current paper delineates the accredited methods for fabricating composite laminates using three materials with accurate descriptions of the specific tasks. The advancement in designing a new composite constructor is embodied in the composite compounds arrangement and the tactical ways that are depended on the assembled layers. Meanwhile, the target geometry is a sensitive point in this investigation, and the adjacent panels have the responsibility to reduce the projectile kinetic energy.

The target preparation processes include composite preparation and geometry of the target. Hence, the composite was constructed from the Kevlar and ramie layers, since the target area was 15 × 10 cm. In particular, the ramie and Kevlar layers were arranged and impregnated using polyester resin to have the interfacial linkage between the layers, as illustrated in *Fig. 1*.

The Experimental Procedures

In this study, the ballistic experiments were conducted using a high-pressure gas gun to propel the projectile in the targets. In addition, a high speed camera hardware was used to capture the projectile speed. *Fig. 2* illustrates the gas gun equipment and impact set-up.

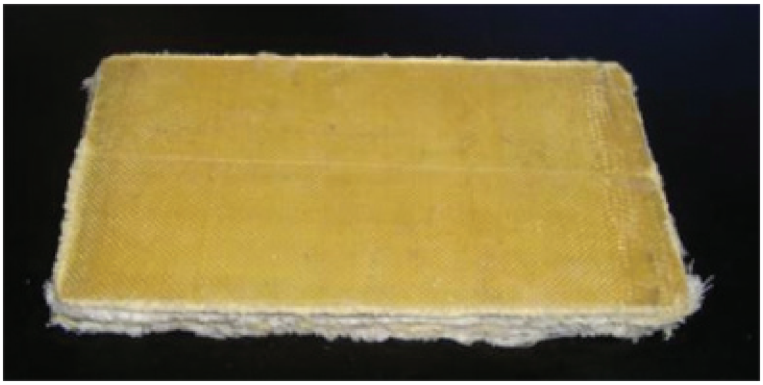
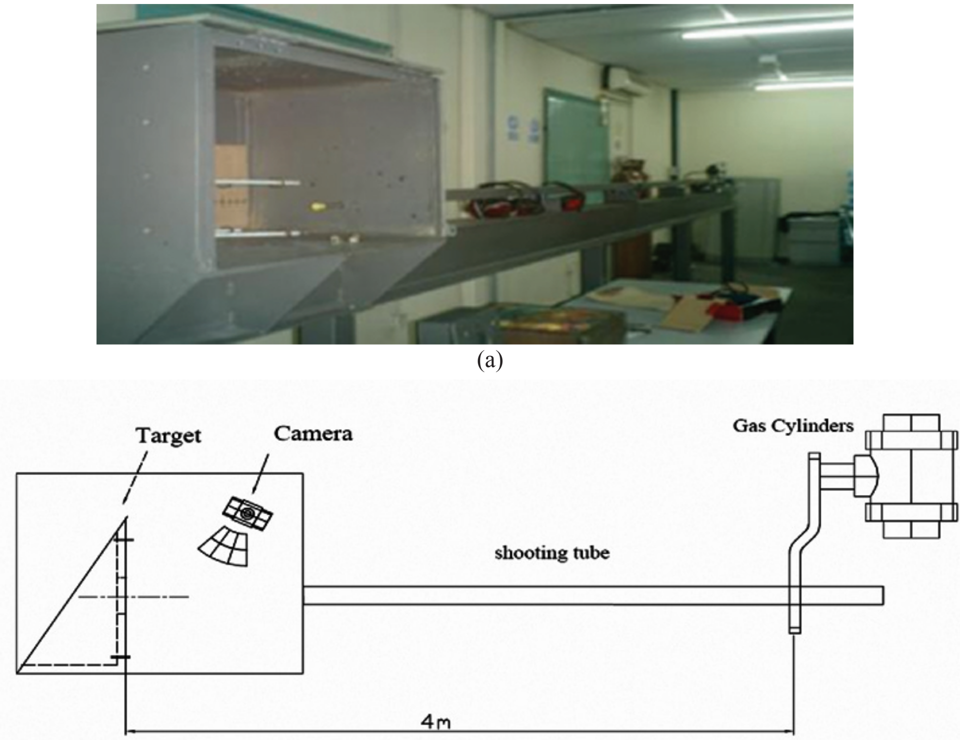


Fig. 1. Final Kevlar29 - ramie composite (the front panel from the TSP)



(a)

(b)

Fig. 2. Gas gun equipment, (b) Experimental set-up impact

The tests were conducted using two types of simulation projectiles over a range of up to 623 m/s. The mentioned projectiles are ogival and semi-conical projectile heads with 5 and 7g, respectively. Two stiff panel contents from eight layers of Kevlar and eight layers of ramie were impacted for the tested the ballistic limits. The target area was 15 cm ×10 cm which was clamped in the iron frame (see *Fig.* 3).

(a) (b)

Fig. 3: (a) Projectiles types, (b) Target frame

TESTING AND DISCUSSION

Target Geometry

A geometry target has the major role of increasing the life time rupture in the target, beside significantly increasing energy absorption. For the purpose of the current study, several tests were conducted on three types from the targets geometry, the panel content from Kevlar layers in the front target face and the ramie layers of the back face. This system is defined by one solid panel (OSP). The second target geometry is defined by two solid panels (TSP). Finally, the flexible–tough panels (FTP), which is defined by the front face soft Kevlar layers, in addition to a series of back face solid panels of the back face of target board as illustrated in *Fig. 4*. The ballistic impact tests were conducted on these targets and the results recorded a high impact resistance of the TSP targets. Meanwhile, all the projectiles have been fully arrested at the TSP, with probability of penetration at OSP and FTP. *Fig. 5* shows that the TSP has a higher ballistic limit compared to the others.

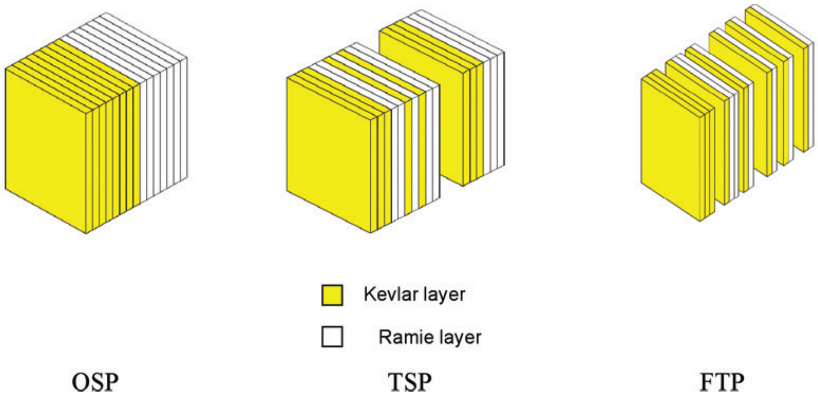


Fig. 4: Target geometry

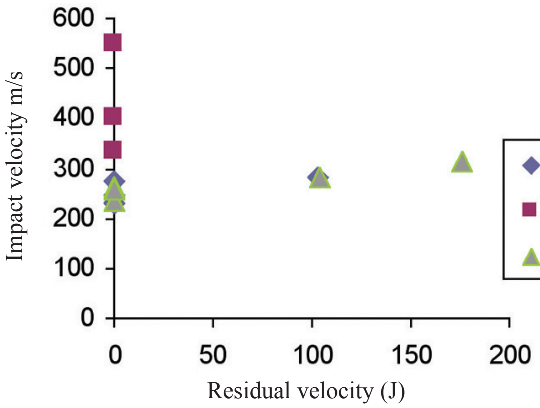


Fig. 5: Initiation projectile velocity vs. residual-based target geometry

Projectile Parameter and Target Response

It is crucial to note that the simulation projectile head and impact force represent the most important parameters to limit the failure level mode. In this study, two types of projectile, namely ogival and semi-conical ends, were impacted to estimate their effectiveness. The recording cylinder gas pressure date represents the applied pressure at the projectile end. Thus, the propellant force can be estimated using the following equation:

$$P_{APPLIED} = \frac{\text{Propellant Force}}{\text{Projectile Cross Section Area}} \tag{1}$$

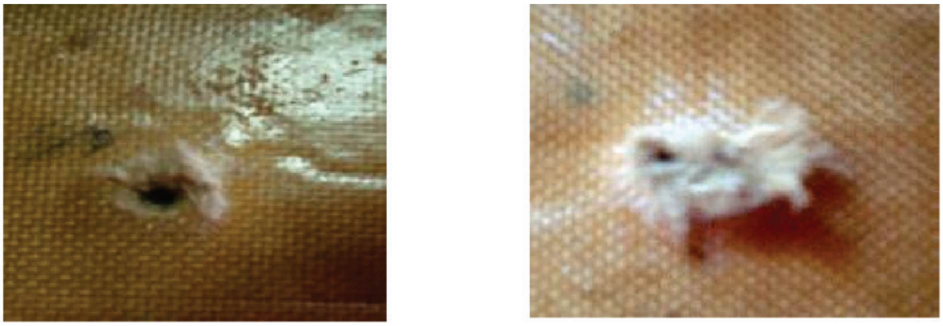
Where the dynamic energy that is required to propel the projectile through long panel of ballistic gun machine reaches 4.30 m in length, as clarified in equation (2) below:

$$\text{Propellant Energy} = \text{Propellant Force x Panel Gun Length} \tag{2}$$

The initiation velocity (V_i) can be estimated from the propellant energy and the mass of propelling bullet, as follows:

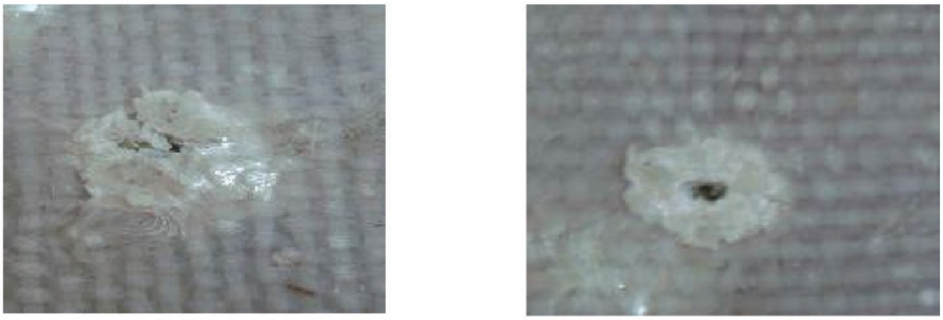
$$\text{Propelling Energy} = \frac{1}{2}mv_i^2 \tag{3}$$

Essentially, the mass has a direct relationship with the size of damage, which can be generated after the impact event. Meanwhile, the flat end surfaces can be increased from the projectile resistant against the target hardness. Thus, there is a reduction in the projectile deformation. Sharp angle edges play the role of digging at the impact point and shearing the fabric, whereby the Kevlar filaments will travel with the ogival head due to the missing sharp edge that is responsible for the dynamic shear stress. After projectile propelling, all the cutting Kevlar filaments will be reflected on outside of the front face. *Fig. 6* illustrates the projectile effect of the front and rear faces of the TSP panels at 700 psi using semi-conical and ogival projectile head.



Front face - semi-conical

Front face - ogival



Rare face - semi-conical

Rear face - semi-ogival

Fig. 6: The effects of projectile shape

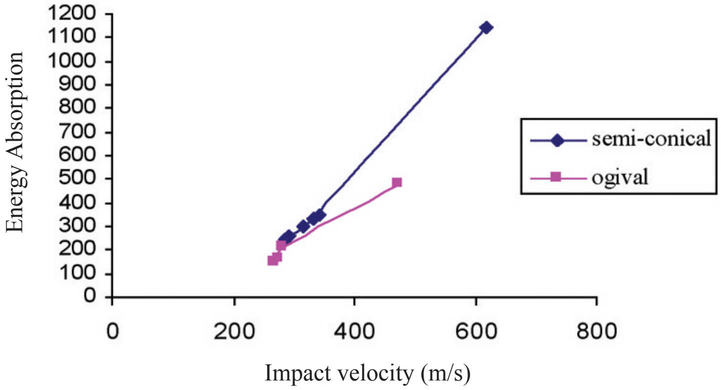


Fig. 7: Energy absorption based on the projectile shape

In addition, target thickness also plays an essential role of increasing the target response, apart from increasing the friction between the projectile and the target. *Fig. 7* depicts the higher amount of energy absorption of the target that has been shot by a semi-conical bullet, whereby, the flat end requires a high propelling energy to disrupt the composite fabric with no deformations in the projectile head due to the superiority of the projectile hardness. In contrast, in the state of the actual projectile, the target reaction against the projectile direction leads to the exhaustion of the projectile which is interpreted as a consumption of energy that generates a deformation of the projectile shape and exceptional attenuating of the projectile hazard.

Environmental Effect on the Test Result

In this study, the targets were exposed to a range of temperatures and wet conditions, as well as shot under these conditions. The data recorded the impact velocities under specific temperature and wet condition. The relative humidity was 50% ± 20%, which was controlled by steeping the target in water pool for different periods of time. The method used to determine the moisture content was similarly to one proposed by Gloria (2001). The weight of the composites was recorded both in the dry and wet conditions. Meanwhile, the drying temperature in the oven was set to 103ºC for 15 min, and this was followed by the use of the following equation:

$$\text{Moisture content} = \frac{W_w - W_d}{W_d} \text{ x } 100\% \tag{4}$$

The temperature has an essential role in determining effectiveness, particularly in changing the properties of the composite. Thus, the impact experiments were carried out under a range of temperatures, i.e. between 20ºC and 70ºC and the shots were done using semi-conical projectiles. The temperature effect versus energy absorption is illustrated in *Fig. 8*. There are direct proportional between the increase in humidity and energy absorption. In this perspective, the increase in the energy absorption was direct proportional with the increase in the weight, which will be reducing of the amore user mobility. Both the specimen humidity and energy absorption are shown in *Fig. 9* below:

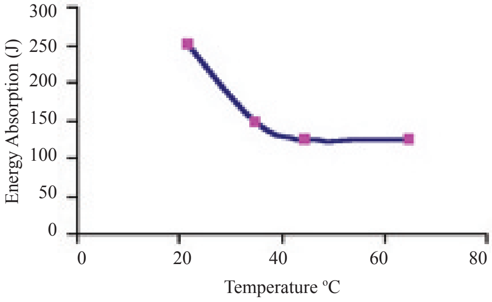


Fig. 8: Temperature in relation to energy absorption

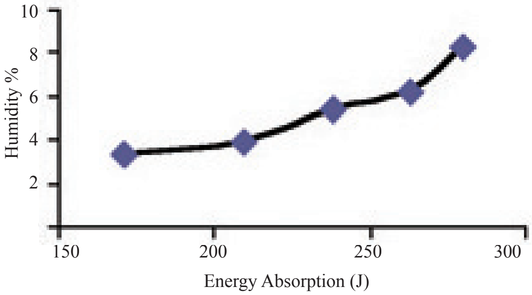


Fig. 9: Humidity content in relation to energy absorption

Multi-Shots Impact Results

The multi-shots test was conducted for the TSP target to estimate the lifetime rupture and failure percentages of the target. The specimen volume was 15 × 10 ×15 cm under multi-shots. Table 1 presents the data that were derived from the multi-shots test, and these are also plotted in *Fig.10.* The minimum distance between the adjacent hits with no penetration was found to reach 1 cm within the limit area of the target centre which is 3.8 × 2 cm, as shown in *Fig. 11*. It was found that a limited deformation (narrow rupture) was generated under the multi shots that was concentrated of tiny area of the target derived from the target stiffness effect.

TABLE 1
Multi-shots data

Test number	Layers number	Initiation velocity m/s	Residual velocity m/s	Energy absorption J	Probability of enetration
1	8k-8R	247	0	183.02	No
2		232	0	161.47	No
3		276	0	228.52	No
4		275	0	226.87	No
5		282	103	206.74	Yes
6		288	0	248.83	No
7		333	0	332.66	No
8	8k-8R	618.6	0	1147.99	No
9		623	0	1362	No
10		342	0	350.89	No
11		285	0	243.67	No
12		315	0	297.67	No
13		294	0	259.30	No
14		337	0	340.707	No
15		312	176	199.104	Yes

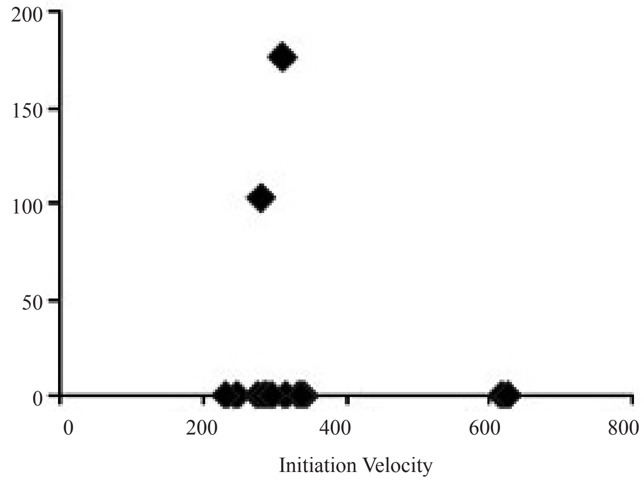


Fig. 10: Multi-shots data at 15×10 cm of the target area

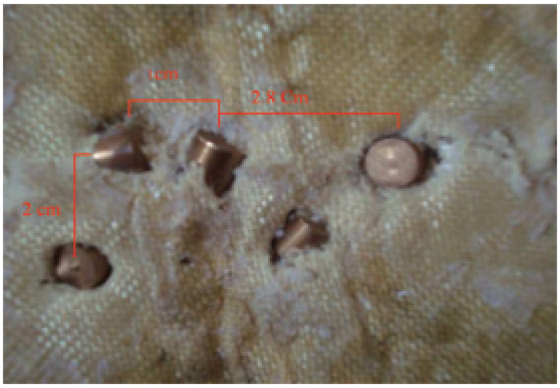


Fig. 11. Kevlar-Ramie specimen upon the multi-shots test

CONCLUSIONS

This paper presents gas gun experiments for the developed laminates composite model. As compared to modern hard armour, there are improvements observed in term of the target weight and thickness, beside the economical cost and ability to maintain. Thus, the increase of the current composite thickness is supported by its high protection level. A failure mode is embodied in the front and back faces deformation, in addition to the delaminating which is generated from the high strain rates. Under multi-shots, local delaminating was found to be generated in the target rear face, whereas the delaminating area could be increased according to the number of shots that are concentrated in the limited area.

The environment effects, which are temperature and relative humidity, were investigated and the results indicated an inversely proportional between the rise of temperature and the target response, while there is a relative effect at the temperature ranging between 20ºC and 70ºC. The temperature has been found as a factor causing composite degradation at a temperature higher than 70ºC. Meanwhile, increasing humidity has direct proportional with increasing of weight. As compared to common hard armours, the Kevlar-ramie armour has been shown to meet the third level of the NIJ threats by increasing the number of panels.

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