Ballistic Performance of Natural Fiber Based Soft and Hard Body Armour- A Mini Review

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Increase in awareness towards utilization of eco-friendly materials, encouraged the researchers to find a sustainable alternative to synthetic fibers for different engineering applications. High performance Kevlar fabrics are widely used in ballistic applications such as bullet proof helmets, vest, and other armour systems. Ballistic impact produces shock waves which may cause severe trauma injuries to the soldiers. Kevlar fabric based armour system provides acceptable range of protection to the soldiers. However, disposal of Kevlar affects the eco system and pollutes the environment. Replacing Kevlar fabric in the protective structures with an eco-friendly light weight material, together with an improved kinetic energy absorption and dissipation has become an interesting approach to enhance the ballistic performance of the composite panels. This mini review addresses the effect of adding different natural fibers on the ballistic performance of soft and multilayered hard body armour systems. Many researchers explored the possibility of utilizing eco-friendly natural fibers (Kenaf, Cocos nucifera sheath, Malva, rami, curaua, bagasse, jute, bamboo) as an alternate material to Kevlar fabric in the armour system and reported that natural fibers can act as a potential reinforcement in the ballistic structures.

Keywords: synthetic fiber, natural fiber, polymer composites, ballistic performance, soft body armour, hard body armour

INTRODUCTION

Ancient body armours were made by using plant fiber or animal hide. After the arrival of metallic materials, body armors have been made as a plate by using iron, copper, and steel. Nonetheless, innovations in material science in the 20th century have led to the discovery of high performance synthetic fibers and its composites (Hani et al., 2012). Synthetic fiber reinforced polymeric composites offer many advantages such as higher specific strength, stiffness, corrosion resistance and enhanced fatigue properties compared to conventional metallic materials.

Aramid fiber based polymeric composites are widely used in ballistic applications such as bullet proof helmets, body armour vest, and other armor systems due to its ability to resist high kinetic energy projectiles. Even though these aramid fibre composites having higher specific strength, impact strength and corrosion resistance most of the fibres are manufactured from petroleum based resources (Naveen et al., 2019). Depletion of petroleum based resources urges the researchers to find

FIGURE 1 | Classification of body armour system. Roy et al. (2019)
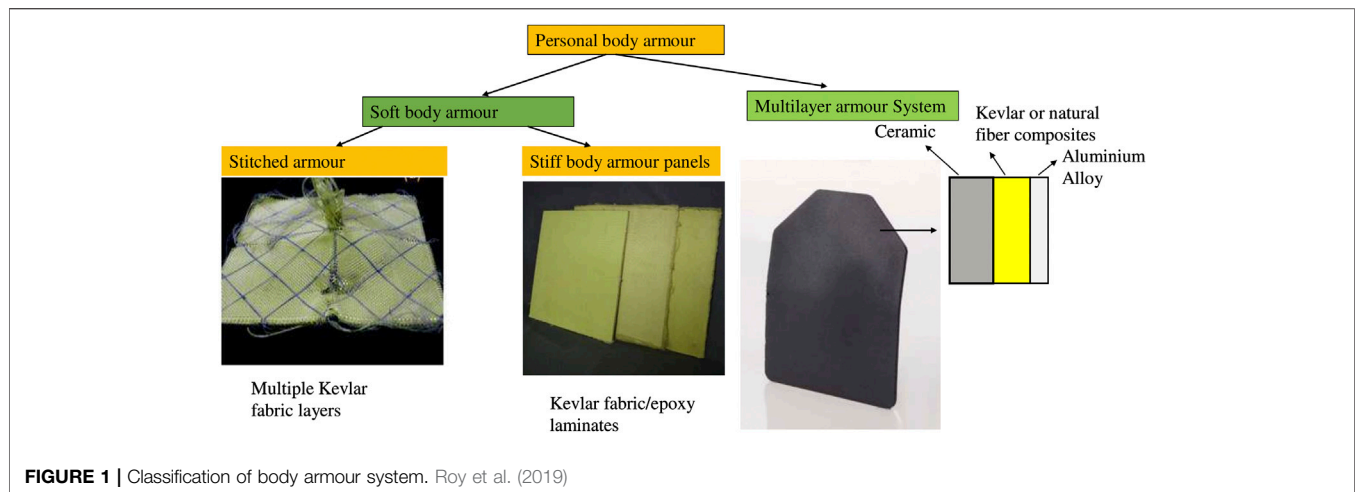
a sustainable replacement. Moreover, disposal of Aramid fiber pollutes the environment (Jesuarockiam et al., 2019). Hence, it is imperative to find an alternate material to man-made synthetic fiber for armour applications.

The utilization of natural fibers have been encouraged by "end of life" regulation in Europe and Asia (Holbery and Houston, 2006). The main advantages of using natural fibers are low density, non-abrasive, non-corrosive, inherent biodegradability, low cost, higher specific strength and stiffness, easily available and recyclable. Moreover, while comparing the cost of commercial armour material (Dyneema), natural fibers can reduce the cost upto 70%. The possibility of utilizing natural fibers for ballistic applications were explored (Benzait and Trabzon, 2018; Monteiro et al., 2019). It has been found that plant fibers or natural fibers can act as an alternative and sustainable replacement to synthetic fibers in both soft armour panels and multilayer armour system (MAS).

Ballistic impact produces shock waves which may cause severe trauma injuries to the soldiers (Naveen et al., 2019). MAS are the efficient personal protective system against high kinetic energy ballistic threats (7.62 mm caliber). Generally, MAS consist of ceramics (SiC), composites (Kevlar/epoxy) and metal (Al). On the other hand, the monolithic armour vests which are made up of aramid fabrics or steel required a large thickness. It predominantly affects the mobility and comfort of the wearer. Hence, the combination of ceramics, composites and metal could be the effective solution.

The notion of this review is to analyze the ballistic performance in terms of energy absorption, limit velocity and depth of indentation of natural fiber based soft and multilayer armour system. Also, this review addresses the different types of body armours, different standards of armour testing according NIJ standards.

CLASSIFICATION OF BODY ARMOUR

Generally, different fabrication methodologies were employed to produce efficient body armour depending upon the threat type and velocity. **Figure 1** shows the different types and fabrication

techniques of body armour panels. Personal body armour could be classified into soft armour and hard armour. Soft body armours are further classified into stitched and stiff armour. Stitched armour contains multiple layers of fabrics up to 50 layers and weighs below 4.5 kg, while the stiff armour panels were made with Kevlar fabrics reinforced in the epoxy matrix (Naveen et al., 2018). Generally, the stiff body armour panels were fabricated by using a simple hand lay-up method followed by hot pressing at 105°C temperature with 275 bar pressure for 1 h. Soft body armour has to bear the impact velocity up to 500 m/s. MAS are made with different combinations such as ceramics/ composites, ceramics/metal, composites/metal and ceramics/ composites/metal. The ceramics/composites/metal has been widely used in defence sectors. Ceramics are well-known for its ballistic performance and it has been used as a striking face to improve the effectiveness of the multilayer armour. The second composites layer absorbs and dissipate the kinetic energy of ballistic threats or projectiles. The aramid fabrics (Kevlar™ and Twaron™) and ultrahigh molecular weight polyethylene (Spectra™ and Dyneema™) are the most commonly used second layer in the multilayer armour. The third metallic layer further stops the impact energy carried by the projectile. These three layers were joined together with polyurethane adhesives (Monteiro et al., 2016).

STANDARDS AND TESTING

The armour panels has to stop the projectile and it should absorb the kinetic energy of the projectile according to NIJ standards (0101.06) IIA, II, IIIA, III and IV. The velocities for different levels are as follows, Level IIA (373 m/s), level II (436 m/s), level III (448 m/s), level IIIA (847 m/s) and level IV (878 m/s). Ballistic testing investigates the energy absorption, ballistic limit and depth of indentation or blunt trauma. Different varieties of ballistic limit velocities are V_0 (maximum velocity with no penetration), V_{50} (50% probability of complete penetration), and V_{100} (100% penetration) (Naveen et al., 2018). Ballistic limit and energy absorption can be calculated using **Eqs 1**, **2**

$$V_{50} = \sqrt{V_s^2 - V_r^2}, \quad (1)$$

$$E_{abs} = \frac{mv_s^2 - mv_r^2}{2}, \quad (2)$$

where V_s is the striking velocity; V_r is the residual velocity.

During ballistic testing according to NIJ standards the Multilayer armour system has to be fixed over a ROMA Plastilina block or clay witness. This clay witness simulates the human body being secured by the multilayer armour and should carry the shock waves up to a standard back face signature limit of 44 mm. Beyond this depth of indentation in the ROMA Plastilina block will lead to severe blunt trauma (Monteiro et al., 2016).

Composites structures are subjected to different loading condition during its service life. However, the composite panels for armour applications and protective structure's should resist the high kinetic energy projectiles and ballistic threats (Naveen et al., 2018). Depending on the velocity, impact can be categorized into four different types such as; 1) low velocity impact (<30 m/s), 2) high velocity impact (30–200 m/s), 3) ballistic impact (>200 m/s) and 4) hyper velocity impact (15000 m/s) (Loganathan et al., 2019) During low velocity impact the contact period of the projectile or impactor is longer compared to the duration of lowest vibrational mode. The impact waves move towards the edges of composite panels causing its full vibrational response. On the contrary, in ballistic or high velocity impact the contact duration of the impactor is much lower than the contact period of the lowest vibration mode. On the other hand, at hyper velocity impact the target behaves like fluids.

NATURAL FIBER BASED SOFT ARMOUR SYSTEM

Hybrid composites provide superior properties. Different hybrid combinations are as follows 1) two or more reinforcing phases embedded in a single continuous phase (matrix), 2) Single reinforcing phase embedded with two or more matrices 3) Two or more reinforcement incorporated in multiple matrices. The main advantage of hybrid composites relies on the fact that the benefit of one type of constituent could surpass the limitations of the other constituent Hybrid ballistic panels were made up of two or more high performance synthetic fibers.

Hybrid synthetic/cellulosic fiber-based laminated composites combine the advantages of individual layers. Replacing Kevlar fabric in the body armors with an eco-friendly light weight material, together with an improved kinetic energy absorption and dissipation has become an interesting approach to enhance the body armors ballistic performance (Naveen et al., 2019). Fibers which possess higher ballistic resistance and lower density are the most promising alternative to Kevlar fabric.

Garicia et al. studied the effect of different volume fraction of Piassava fibers (10, 20, 30, 40, and 50 Vf) on the energy absorption and limit velocity of Pissava fiber/epoxy composites using a 7.62 mm M1, full metal jacketed bullet with 9.7 g. It was observed that the composites samples with 10 Vf of Pissava fiber

exhibited excellent ballistic performance compared to Kevlar™ (Garcia Filho et al., 2020).

Naveen et al. (2018) investigated the ballistic performance of Kevlar, hybrid Kevlar/coconut sheath and coconut sheath based epoxy composites. The velocity range was in between 300 and 330 m/s. Two stage gas gun has been together with a high speed camera has been utilized to find the impact velocity and residual velocity of the projectile. It has been observed that coconut sheath can act as an efficient alternative to Kevlar fabric in the epoxy composites for ballistic applications. Also it was found that the moderate interfacial properties are essential to achieve better ballistic performance. However, addition of graphene nanoplatelets in the Kevlar/coconut sheath composites did not show much improvement on the ballistic performance due to improved interfacial interaction which is not suitable for ballistic application (Naveen et al., 2019).

FRP composites for high velocity impact or ballistic applications require high specific strength and stiffness, impact resistance, crack resistance and low density. Interestingly, the requirements of ballistic composites differ from other structural laminated composites. The properties of ballistic composites include moderate fiber/matrix adhesion, higher fiber loading, moderate fiber impregnation and voids. Also, the shape and size of the projectile plays an important role in the energy absorption, ballistic limit, and life of the body armor (Naveen et al., 2018) On the other hand, ballistic performance of body armor also depends upon the fiber loading, weaving nature or architecture, panel thickness, and the layering sequence. It has been found that the fibers exhibited different failure modes depending upon their layering pattern and location in the thickness direction, when it is subjected to ballistic impact. During ballistic impact, top layer of the ballistic panel exhibited shear failure while the bottom layer has failed through tensile mode of failure. Hence, while hybridizing different materials, optimized layering sequence of different laminas takes the advantage of individual constituents and consequently improved the ballistic performance of the composite panel (Naveen et al., 2018). **Table 1** shows the reported literatures on the ballistic performance of hybrid synthetic/natural composites.

NATURAL FIBER BASED MULTILAYER ARMOUR SYSTEM

Now a days, combination of ceramic, composites and metallic armour has been preferred due to its combined advantages such as ballistic efficiency, light weight and cost (Monteiro et al., 2015). Generally, synthetic fiber based composites were utilized as a middle layer. Nonetheless, in order to reduce the utilization of synthetic fibers, natural fiber based materials are incorporated in the polymeric matrix. Also, nano filler modified polymeric composites and nano filler coated fiber reinforced polymeric composites has been used as a middle layer. The third metallic layer further stops the impact energy carried by the projectile.

Several studies were conducted by incorporating natural fiber composites as a mid layer in the Multilayer armour system.

TABLE 1 | Ballistic performance of Natural fiber based soft and hard armours.

Sl.No	Natural fiber based stiff/soft armours				References
	Fiber	Matrix	Energy absorption (J)	Ballistic limit (m/s)	
1	Kenaf/Kevlar (30/70)	Epoxy	148	—	Jambari et al. (2017)
2	Kenaf/Kevlar (Vf6/Vf 47)	Epoxy	175	590	Yahaya et al. (2016)
34	Coconut sheath/Kevlar (wt% 5/25)	Epoxy	240	—	Naveen et al. (2018a)
3	Curaua fiber (30 Vf)/epoxy composites	Epoxy	197	—	de Oliveira Braga et al. (2017b)
4	Kevlar/Basalt (50/50)	Polypropylene	112	—	Bandaru et al. (2016)
5	Piassava fiber (10 vf)	Epoxy	272 ± 19 J	236 ± 8	Garcia Filho et al. (2020)
6	Fique fiber	Polyester	155 ± 7	—	Pereira et al. (2019a)
7	Fique fabric	Polyester	154 ± 5		

Natural fiber based multilayer armour system					
Striking face (front)	Middle layer	Rear plate	Back face signature or depth of indentation (mm)	Recommended NIJ level (44 mm)	References
Ceramic (SiC)	Kevlar	Al alloy	23	44	Luz et al. (2020)
	Dyneema		42		
	Pineapple leaf fiber/epoxy composites		26		
	Sugarcane bagasse/epoxy composites		39		Monteiro et al. (2016a)
	Mallow fiber (aligned)/epoxy composites		22		Nascimento et al. (2017a)
	Mallow fabric/epoxy composites		22		Nascimento et al. (2017b)
	Bamboo/epoxy composites		19		Cruz et al. (2015)
	Sisal/Epoxy composites		12		Rohen et al. (2015)
	Sisal/Polyester composites		23		Braga et al. (2017)
	Ramie fiber/epoxy composites		18		de Oliveira Braga et al. (2018)
	Ramie fabric/epoxy composites		17		Monteiro et al. (2016b)
	Coir fiber (aligned) epoxy composites		32		da Luz et al. (2018)
	Coir mat/epoxy composites		24		Luz et al. (2017)
	Jute fabric/polyester composites		17		Monteiro et al. (2018)
	Jute fabric/epoxy composites		21		Luz et al. (2015)
	Jute nonwoven mat/polyester composites		24		de Assis et al. (2018)
	Curaua aligned/epoxy composites		22		Monteiro et al. (2015)
	Curaua mat/epoxy composites		28		de Oliveira Braga et al. (2017a)
	Curaua/polyester		22		
	Graphene oxide coated curaua fiber reinforced epoxy composite		27.4		Costa et al. (2019)
	Piassava fiber/epoxy		15.6		Garcia Filho and Monteiro (2019)
	Fique fiber/polyester composites		16		Pereira et al. (2019b)
	Epoxy-15% Fique fabric		20		Oliveira et al. (2019)

Table 1 shows the reported literatures of natural fiber based Multilayer armour system. The recommended depth of indentation or back face signature according to NIJ standard is 44 mm (Luz et al., 2020). compared the pineapple/epoxy composites based multilayer armour with dyneema based hard armour plate. For each test 7.62 mm caliber was utilized with an impact velocity of 849 m/s. The distance between the multilater armour target and the test weapon was around 15 m. They observed that pineapple leaf fiber composites can efficiently replace the dyneema, since it exhibited a back face signature of 26 mm (<44 mm).

Researchers investigated the ballistic performance of ramie fabric/epoxy composites based multilayer amour system. Different vol% of ramie fabric were embedded in epoxy matrix and the composite samples were incorporated as a middle layer in the multilayer armour system. Ballistic testing was conducted with 7.62 mm caliber at 849 m/s. The results revealed that ramie fabric based multilayer armour system exhibited 10–20% smaller back face signature or blunt trauma compared to Kevlar/epoxy composites based multilayer armour system (Monteiro et al., 2016). Similarly, the blunt trauma or back face signature of several natural fiber based multilayer armours were compared with each other (**Table 1**). From the critical comparison, it is clear that the plant fiber based sustainable materials can be an effective alternative for man-made synthetic fibers.

CONCLUSION

Several researchers explored the possibility of utilizing natural fiber based soft and hard body armour panels. The following conclusions were drawn;

- Energy absorption and ballistic limit of natural fiber reinforced polymeric composites are almost matches with high performance aramid fabric composites.

- The striking face of the composite panels has to be designed to withstand the shear plugging whereas the rear side should resist the tensile failure.
- The major difference between soft and hard body armour is that the soft/stiff armor has to bear the impact velocity of 500 m/s, where as Multilayer hard armour system should withstand the impact of the projectile more than 500 m/s when worn in conjunction with soft armor.
- Natural fiber based Multilayer armour systems exhibited lower depth of indentation compared to Kevlar based multilayer armour.

Hence, it is concluded that natural fiber based sustainable armour panels can be efficiently utilized in both soft and Multilayer hard body armours.

FUTURE RECOMMENDATIONS

- As per NIJ level 3 standards the armour panel should not fail for six shots. Nonetheless, most of the natural fiber based hardbody armours were tested for only one shot. Extensive research is required to improve the ballistic performance of natural fiber based multilayer armours in order to commercialize the armour panels.
- On the other hand, the middle composite layer was made with non-biodegradable polymeric composites. Due to eco legislation and awareness towards creating green armours

encouraged the researchers to utilize biodegradable polymeric composites.
- The performance of the natural fiber based armour panels can be improved with shear thickening fluid or with multifunctional nano fillers.

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