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High velocity impact behavior of Kevlar/rubber and Kevlar/epoxy composites: A comparative study

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Abstract

This paper presents a comparison of behavior and energy absorption of neat Kevlar fabric and polymer matrix composites under high velocity impact loading. Two types of matrices including rubber and thermoset (epoxy) matrices were used in order to study the effect of a hard and brittle matrix compared with the soft and flexible matrix on energy absorption of the composite. Moreover, two types of rubber matrix with high hardness (HH) and low hardness (LH) were used in this study to investigate the effect of rubber matrix formulation on impact resistance of composites. Ballistic impact tests were performed by firing a 10 mm hemispherical projectile onto neat fabric and composites in a velocity range of 30 m/s to 150 m/s for two- and four-layer samples. Results show that the matrix affects the ballistic performance of composites significantly. Rubber matrix enhances the energy absorption of the fabric by keeping composite flexibility. Increase the number of layers for Kevlar/rubber composite results in better ballistic performance. On the contrary, the thermoset matrix leads to an inflexible composite that restricts the fabric deformation and has a negative effect on the fabric's ballistic performance. Finally, damage mechanisms were discussed in detail for each sample.

Keywords: High velocity impact, Kevlar fabric, TS matrix composite, Rubber matrix composite, Energy absorption.

1. Introduction

Flexible or soft armor is used for body protection against ballistic injuries without significantly restricting the mobility of the wearer [1-3]. The main soft armor materials are woven fabrics composed of high-strength fibers. Fabrics based on high-performance polymeric fibers such as Kevlar, Twaron, and Dynama fibers are among the advanced materials used in modern body armor designs. Energy absorption and ballistic resistance of such materials have been extensively investigated via experiments and analytical methods [4, 5]. From the point view of energy transfer, it can be stated that when a projectile impacts a fabric, the projectile kinetic energy is dissipated through a combination of mechanisms such as tension in primary yarns, deformation of fabric, energy dissipated through frictional slips (yarn/yarn and projectile/yarn), yarn breakage, and yarn pull-out from the fabric [6-8]. The mechanisms that dominate a particular ballistic event depend on a number of factors, including yarn's material properties [9, 10], friction between yarns [11, 12], the projectile shape [13, 14], and fabric boundary condition [15-17].

Polymer matrix composites are produced by combining high-strength high-modulus fabrics with a polymer matrix. Adding different matrices to the woven fabric changes the ballistic performance of composites. Moreover, mechanical behavior and failure mode are affected by matrix type. Although there are some studies that show the effect of the matrix, it is little known how the matrix influences the impact behavior of polymer matrix composites. Vieille et al. [18, 19] compared the impact response of TS-based (epoxy) and TP-based (PPS or PEEK) laminates. They found that Carbon/epoxy composite presents the highest ratio of dissipated energy, whereas the energy dissipated during impact was virtually the same in Carbon/PPS and Carbon/PEEK composites. Their results showed that

Carbon/epoxy laminates experience larger delamination than TP-based laminates. Lee et al. [20] found the spectra/vinyl ester laminates with stiff matrix had higher energy absorption than spectra/polyurethane laminates with flexible matrix. Also, they concluded that the composites failed at a much higher load than neat fabrics because they would require more force to break many yarns simultaneously than to break them one or two at a time. On the contrary of the work of Lee et al., Gopinath et al. [21] found that the ballistic performance of laminates with a flexible matrix, is better than the counterparts with a stiff matrix. Similar to pervious work, Wang et al. [22] studied the response of composite laminates made of a Dyneema woven fabric and four different resin matrices under impact loading. The results showed that the laminates with flexible matrices performed much better in energy absorption, but had a greater extent of deformation than the laminates with stiff matrices. It was found that the matrix played a crucial role in restricting the transverse deformation propagation, and therefore affect the local strain and impact resistance of composites.

Polymer matrix composites are still dominated by thermoset (TS) matrices because they are appropriate for impregnation into fabrics. In the literature, there are many experimental, numerical, and analytical studies on the impact response of composites made of TS matrices [23-26]. Fabric material, fabric structure, thickness, lay-up sequences and shape of projectile are parameters which affect the ballistic performance of thermoset composites [27-30]. Despite the interesting mechanical properties of TS resin, it leads to hard and inflexible composite that has a negative effect on the fabric’s ballistic performance. Therefore, using other polymer matrices was considered. High-performance natural rubber offers an alternative instead of TS matrix while maintaining the flexibility of the composite. Rubber materials have been widely used in shock absorbers, Impact resistance panels and other engineering applications [31-33]. Besides, high flexibility [34] and high damping properties [35] make rubber matrix composites a good option for blast and ballistic applications. Recently, some studies have been done to model the behavior of fabric reinforced rubber composites [36, 37]. Yang Heng [38] developed an anisotropic hyper-viscoelastic constitutive model for the reticulated fabric reinforced rubber composites. He considered the effects of fiber fabric, the interaction between the rubber and the fiber fabric, the viscoelastic properties of rubber and temperature. Ahmad et al. [39-41] have published several articles on the coating of high-performance fabrics with natural rubber latex and studied its resistance under impact loading. They used high strength unidirectional (UD) polyethylene fabrics coated by natural rubber latex. The ballistic performance of neat and coated fabrics was investigated and a 45-59% increase was observed in the energy absorption for different combinations of the neat and coated fabrics compared to the all-neat system. Majumdar and Roy [42] investigated the impact performance of natural rubber (NR) coated Kevlar fabric. Fabrics were coated with different concentrations of NR solutions and were produced with different add-on percentages. They found that the energy absorption of single layer NR-coated fabrics is lower than neat fabric, but there is an improvement in the energy absorption of the two-layered rubber coated Kevlar fabrics compared to untreated two layered ones.

In this study, the high-velocity impact resistance of neat Kevlar fabric and composites made by TS and rubber matrix is investigated, followed by comparing the energy absorption of composites. For this purpose, high velocity impact tests were carried out using the gas gun machine and the projectile residual velocity was considered to determine the impact resistance of the samples. The paper deals with the relation between matrix type, number of layers, impact energy and damage mechanisms. The ballistic limit and energy absorption of composites are studied and an investigation was carried out to obtain the failure mode and damage mechanism of each composite.

2. Materials and experimental procedures

2.1. TS matrix composite

The fabric used in the high velocity impact tests was a type of plain-woven aramid high performance Kevlar fabric with the areal density of 180 g/m^2 and thickness of 0.23 mm. To manufacture TS matrix composite plates, an epoxy matrix based on ML-506 resin and HA-11 hardener (curing agent) was used. The weight ratio of resin/hardener systems can be varied to produce laminates with different properties, specially flexibility or hardness. In this study the hardness/resin weight ratio of 1/12 was chosen. The TS matrix composite was manufactured by hand lay-up method. For curing process, laminates were retained at a constant pressure (15 MPa) during 24 h. The chemical reactions and curing process were carried out at ambient temperature.

2.2. Rubber matrix composite

Vulcanization is a chemical process for converting raw natural rubber into a material with desired properties by the addition of fillers, activators, sulfur or other equivalent curatives and accelerators. These additives modify the rubber by forming cross-links between polymer chains. To understand the effect of rubber components on the impact resistance of rubber matrix composites, two types of rubbers with different formulation were used. The NR compounds formulation for two types of compounds is presented in Table 1. Natural rubber (SMR 20) with Mooney viscosity of 65 was supplied by the Rubber Research

Institute of Malaysia. Zinc oxide (ZnO), stearic acid, and sulfur were obtained from LG, Korea. Fillers including carbon black (N330) and calcium carbonate were purchased from Doodeh Sanati Pars Company and Yazd Tire Company, Iran.

Rubber compounding is carried out on an open two-roll mixing mill (Polymix 200 L, Germany) at 40 rpm and mixing time of 15 min. The vulcanization characteristics of the NR compounds were determined by an Oscillating Disc Rheometer (ODR) model 4308 (Zwick Co., Germany) at 160℃. Disc is embedded in the test piece and is oscillated through a small specified rotary amplitude to characterize the cure characteristics of rubber compound. The result are shown in Table 2. In this table, the compound minimal torque, $_{\text{min}}$, is the lowest torque required to oscillate the disc inside the rubber. Also vulcanizate maximum torque, $_{\text{max}}$, is the highest torque on the vulcanization process, which characterizes the cured rubber stiffness. Also t_{iM} indicates the time required that i% of torque increases, i.e., t_{10M} is a time required which the torque reach to 10% of the maximum achievable torque.

The impregnation of the Kevlar fabric for the preparation of the rubber matrix composite target was facilitated by diluting rubber compound in Toluene at a 2:3 volume ratio. Individual fabric layers were soaked in the diluted rubber compound for 24 h. After impregnation with the toluene/rubber mixture, fabric layers were placed in ambient temperature for 24 h and then placed in an oven at 40℃ for 2 h to remove the toluene. Next, 2 and 4 coated fabric layers were assembled and subsequently cured under hydraulic pressure at 160℃ by a 25 tons hydraulic press (Davenport, England) based on rheometer results. The schematic procedure of manufacturing rubber matrix composite is shown in Fig. 1.

Figure 2 shows the neat Kevlar fabric and composites including TS, LH and HH rubber matrix composites. The nominal thickness of the TS and rubber composite samples were approximately 1 and 2 mm, made up of 2 and 4 layers, respectively. Characteristics of the TS and rubber matrix composites are presented in Table 3. The apparent difference of the TS and rubber matrix composites was their flexibilities. As it is expected, the LH rubber matrix composite was more flexible than HH composite. The hardness test (Shore D) was performed to evaluate the hardness of composites. The average hardness was calculated by using of 10 different measuring point on the surface of specimens. Results revealed that the hardness of TS matrix composite was 85.2 (Shore D) which indicates an extra hard and inflexible material. On the other hand the hardness of LH and HH rubber matrix composite was 22.5 and 33.6 (Shore D), respectively which shows profound difference between TS and Rubber composite flexibility.

2.3. High velocity impact tests

High-velocity impact tests were carried out using a gas gun on neat Kevlar fabric and TS and rubber matrix composites in a velocity range of 30 to 160 m/s. The gas gun was made of a pressure vessel of 120 bar capacity, a high speed firing valve, a hollow steel barrel with 6 m long and a target chamber for fixing samples. The inside diameter of barrel was 10 mm. The exact impact velocity of each projectile was measured with a chronograph immediately before and after impacting the target. The tests at each velocity were carried out three times and their mean were reported. The specimens were comprised of two and four plies with a dimension of 130×130 mm. All four sides of the specimens were constrained completely in the fixture and were fixed in Target chamber (Fig. 3). The projectile is a hemispherical steel 4330 with a diameter of 10 mm and mass of 9.32 g.

The straight way to evaluate the ballistic performance of a composite is to calculate its energy absorption. For the perforated specimens, it was assumed that the loss of projectile's kinetic energy is equal to the energy absorption by composite target in the perforation event. Therefore the energy absorption of composite can be theoretically calculated by subtracting the residual energy of the projectile from its initial energy. Consequentlly the amount of energy absorption can be calculated as:

$$E_i = \frac{1}{2} m V_i^{2} \tag{1}$$

$$E_r = \frac{1}{2} m V_r^{2} \tag{2}$$

$$E = \frac{1}{2} m (V_i^{2} - V_r^{2}) \tag{3}$$

Where E_i (J) and E_r (J) are the projectile energy before and after the impact, E (J) is dissipated energy during the impact process, m (kg) is mass of the projectile, V_i (m/s) is projectile initial velocity, and V_r (m/s) is residual velocity.

3. Results and discussion

3.1. Residual velocity

Projectile residual velocity versus impact initial velocity of two and four-layer of neat Kevlar fabric and composites made by Thermoset and rubber matrices are depicted in Fig. 4. Moderate enhancement in ballistic performance in terms of lower residual velocity for 2 and 4-layer rubber matrix composite specimens was observed compared to corresponding neat fabric, i.e., composites made by rubber matrix show a better penetration resistance compared to the neat fabrics. Due to viscous damping characteristics of rubber, it has a high-energy absorption capacity and leads to a reduction in velocity of the projectile. In addition, better performance can be attributed to the remaining primary yarns in contact with the projectile surface area during penetration and perforation compared to neat fabric. Fig. 4 also shows better ballistic performance for the HH rubber matrix composite compared to corresponding LH matrix rubber. By increasing the fillers loading, the mechanical properties of rubber improve. Van Der Waals force is a major source of reinforcement between the fillers and the rubber. Also, carbon black surface grafted the rubber chains by covalent bonds. The interaction at the rubber-filler interface leads to reinforcement of rubber. Therefore, rubber matrix with higher mechanical properties has a higher capacity to perform more effective under impact loading. Besides, the thermoset matrix has a severe negative effect on the ballistic performance of fabric by limiting the yarns movement and preventing primary yarns to transfer projectile energy to secondary yarns. So, the energy cannot be shared with whole fabric.

3.2. Ballistic limit

The ballistic limit is considered to be the most important achievement of the ballistic test. $V_{50\mathrm{M}}$ is ballistic limit velocity and it is defined as the average of equal number of highest partial penetration velocities and lowest complete penetration velocities of a projectile and a target combination, which occur within a specified velocity range. In other words, $V_{50\mathrm{M}}$ defines incident impact velocity at which there is 50% probability of partial penetration and 50% probability of perforation. A minimum of three partial and three complete penetration velocities are used to compute $V_{50\mathrm{M}}$ [43].

Fig. 5 presents the ballistic limit of two and four-layer samples. As can be seen, the ballistic limits of HH rubber matrix composites are 68 m/s and 114 m/s for two and four-layer, respectively which show 19 and 41% improvements compared to two and four-layer neat fabric. The ballistic limits of LH rubber matrix are 62 m/s and 98 m/s for two and four-layer, respectively, which enhance the ballistic limit of neat fabric about 9 and 21%. On the contrary, using TS matrix leads to an inflexible composite that has a negative effect on the fabric's ballistic performance. The ballistic limit of two and four-layer of TS matrix composite is 30 and 40 m/s, which shows 47 and 51% declines compared to the neat fabric.

3.3. Energy absorption

When a projectile impacts a fabric, primary yarns engage the projectile and absorb the majority of the kinetic energy during impact. Transverse deflection of the principal yarns pulls secondary yarns that are not in a direct contact with the projectile. These yarns assist to dissipate projectile's energy [44]. It is of note that due to relative motion between the orthogonal yarns as the fabric deflects outward, an amount of energy spent to overcome frictional forces at the crossover points.

The rubber helps primary yarns to transfer the impact load well into the secondary yarns and whole fabric resist to absorb projectile's energy. Presence of rubber matrix leads to better fabric arrangement, more consistent, uniform, and integrated fabric coating, elimination of sliding, extracting, windowing under impact loading, and a better stress distribution and consequently a higher energy absorption. In addition, rubber with high damping properties has a major contribution to the absorption of projectile energy. HH rubber matrix composite has shown a higher absorption capacity compared to LH rubber matrix composite. This higher energy absorption capacity of high-hardness than low-hardness panel is due to the presence of stronger molecular chains.

Fig. 6 and Fig. 7 present energy absorption of different samples. Energy absorption of each specimen calculated according to equations 1-3 by measuring the initial and residual velocity of projectile impacting the specimen. As can be seen, the energy absorption of HH and LH rubber matrix composites is greater than the energy absorbed by the neat fabric. According to these figures, with an increase in impact velocity, an increase in energy absorption of rubber matrix composite is achieved. This behavior may be attributed to the fact that in high strain rates, the response of the rubber may differ significantly from the behavior in the rubbery state. When the local segmental dynamics of the rubber become slower than the mechanical strain rate under impact loading, a transition to the glassy state and consequently brittle failure occurs. This failure is accompanied by significant energy dissipation. Therefore, the higher the velocity of the projectile, the greater the absorption of energy by the rubber matrix composite would be. On the other hand this phenomenon is directly related to rubber reinforcements. So we can see that energy absorption of HH rubber composite is more affected in high velocities compared to LH rubber composite.

TS matrix composite has the lowest energy absorption compared to neat and rubber matrix composite. When a projectile strikes the TS composite, primary yarns resist the impact energy but deformation cannot transfer to the secondary yarns. TS matrix restricts the fabric deformation and does not let the whole fabric resist against the projectile and, consequently, local damage occurs.

3.4. Reinforcement factor

The reinforcement factor (RF) is proposed to provide a better measure of the improvement in the ballistic performance of composites that comes with the additional layer. RF is the ratio of the ballistic energy absorption by a four-layer composite to that of ballistic energy absorption by a two-layer. Ballistic energy absorption refers to energy absorption at ballistic limit velocity. Fig. 8 shows the reinforcement factor for neat fabric and TS and rubber matrix composites. As shown for neat fabric, the reinforcement factor value is slightly more than 2, suggesting a positive effect of increasing the number of layers. The positive interaction of the layers on each other and more effective resistance to projectile penetration improve the fabric's ballistic performance with more number of layers. There is no benefit from adding layers for TS composite. Addition of fabric layer to TS composite results in a thicker specimen, which is much stiffer than the two-layer one. Stiffer target without effective deformation cause a decrease in the ballistic performance.

Results demonstrate that the additional layer in a rubber matrix leads to higher reinforcement factor. Not only rubber absorbs energy itself due to high damping properties but also it acts as a support to fabric and helps the fabric to maintain its structure. A better performance is achieved in the case of HH rubber where RF factor is higher than LH rubber. By doubling the number of layers, the ballistic energy absorption is 2.82 times of two-layer HH rubber matrix composite.

3.5. Specific energy absorption

In the section 3.3, the energy absorption of TS and rubber matrix composites was investigated. To understand the energy absorption effectiveness of each composite, the specific energy absorption (SEA) was calculated based on Equation (4).

$$\text{Specific energy absorption} = \frac{\frac{1}{2} m V^2}{\text{Areal density}} \quad (4)$$

Fig. 9 shows the specific energy absorption for TS and rubber matrix composites. As can be seen, HH rubber matrix composite has the highest SEA. The SEA of two and four-layer HH rubber matrix composites are 15.25 and 22.3 Jm^2/kg, respectively, which are 3.14 and 5.13 times greater than the SEA of two and four-layer TS matrix composite. Although HH rubber composite has higher weight comparing to TS and LH rubber composites, but the amount of energy absorbed is much higher, and therefore the SEA is the highest. The SEA of two and four-layer LH rubber matrix composites are 13.66 and 17.41 Jm^2/kg, respectively. These values are 2.71 and 3.78 times greater than SEA values of TS matrix composite.

3.6. Deformation and Mechanisms of damage

3.6.1. Neat Kevlar fabric

In woven fabric, yarns are interlaced together and have relative movement in the fabric. Therefore, primary and secondary yarns deformed until the projectile perforate the fabric. Fig. 10 shows perforated Kevlar fabric under high-velocity impact loading with different velocities of the projectile. It is shown that by increasing the impact velocity the damage of fabric increases. The whole fabric resists against projectile energy and stretched yarns are visible. In this figure, the “wedge through” phenomenon can be seen. Hemispherical projectile slips through the opening of fabric and pushes yarns ahead instead of breaking them. The number of broken yarns is less than the number of yarns that intersect the projectile.

The microscopic images of Kevlar fabric damages under impact loading are shown in Fig. 11. The most important mechanism of failure is yarn breakage. When a projectile strikes the fabric, yarns are stretched until reaching tensile strength of yarns and breakage occurs. Also, yarn pullout is an important mode of failure that occurs in the penetration of hemispherical projectile. Yarn pullout occurs when yarns do not break, but one end of the yarn is pulled out of the fabric mesh. When the projectile wedges through the fabric, bowing phenomenon occurs. Bowing is observed when the warp yarns are not orthogonal to the weft yarns. Bowing phenomenon occurs especially in the high-velocity impact, as shown in Fig. 11b.

3.6.2. TS matrix composite

Fig. 12 shows some pictures of the front and back face of the damaged TS matrix composite under projectile's impact with different velocities. As can be seen, a severe damage occurs that is characterized by big deformation in the impact zone. Failure of matrix and fibers is observed in this area. When projectile's velocity increases, the damaged zone increases.

The typical macroscopic damages of the TS matrix are shown in Fig. 13. Different mechanisms governing penetration of hemispherical projectile into TS matrix composite are shown in this figure. Three major modes of failure due to high-velocity impact are matrix failure, yarn breakage, and delamination. Due to the brittle nature of thermoset, matrix damage is the first type of failure induced by a transverse high-velocity impact and occurs around the projectile impact. Although matrix cracks do not necessarily result in perforation, it affects the global behavior of the TS composite. Besides, it decreases the stiffness of the composite and leads to the formation of other failure modes. Delamination is another critical damage mode under high-velocity impact loading. Delamination is produced by interlaminar stresses, which form the resin-rich area between plies. It can deeply influence the strength of the composite, yet there may be little or no indication of damage on the surface. The main failure mode is fiber breakage that generally occurs at last in the fracture process. Fiber failure occurs under the projectile due to locally high stresses and the indentation effects of shear forces.

3.6.3. Rubber matrix composite

Composites made of Kevlar fabric and rubber matrix have a remarkable ballistic performance due to the high damping characteristics of the rubber. Fig. 14 presents the response of LH and HH rubber matrix under high-velocity impact and a picture of the front and back face of each rubber composites. Due to the presence of rubber, the layers are attached together and effectively resist against projectile. The presence of elastomer does not restrict the fabric deformation such that the fabric experiences its maximum stretch. Furthermore, yarn pullout is not observed for both types of rubber used in this study.

According to our results, failure modes of LH and HH rubber matrix composites look like each other and cannot distinguish specific difference after perforation. Fig. 15 presents the damage mechanism of the rubber matrix composite under impact loading. Fiber breakage is the most important failure mechanism that occurs when maximum stress of fabric is reached. This breakage is shown under the impact point of the projectile. The rubber tearing is shown in fig. 15 which occur after yarn breakage. In some cases, a detachment of rubber matrix was observed.

4. Conclusion

This study was conducted to investigate the response of neat Kevlar fabric and composites made of Kevlar fabric and TS and rubber matrices under high-velocity impact loading. For this purpose, two types of rubbers with different hardness (i.e., LH and HH) were used. The results show that the rubber matrix enhances the energy absorption of fabric. The best performance was achieved when using HH rubber matrix, which increases ballistic limit about 19% and 41% for two- and four-layer fabric compared to the neat fabric. These values are 9% and 21% for two and four-layer LH rubber matrix composite. On the contrary, TS matrix decreases the ballistic performance of Kevlar fabric by restriction of fabric deformation. Yarn pullout and yarn breakage are the most important damage mechanisms of neat fabric. Damage mechanisms of TS and rubber matrix are local. Delamination, matrix cracking, and fiber breakage are observed for TS matrix composite, while fabric breakage and rubber tearing occur in the rubber matrix under the impact point of the projectile. The main behavior difference of TS and rubber matrix are the deformation of fabric. Rubber matrix doesn't restrict the yarns through which the whole fabric resists against projectile energy. This behavior is contrary to the TS matrix, in which only a few yarns in impact zone resist. This difference significantly changes the ballistic performance of TS and rubber matrix composite.

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REFERENCES

[1] Roylance D, Wang S-S. Penetration mechanics of textile structures. MASSACHUSETTS INST OF TECH CAMBRIDGE; 1979.

[2] Shim V, Guo Y, Tan V. Response of woven and laminated high-strength fabric to oblique impact. International Journal of Impact Engineering. 2012;48:87-97.

[3] Khodadadi A, Liaghat G, Vahid S, Sabet AR, Hadavinia H, Ballistic performance of Kevlar fabric impregnated with nanosilica/PEG shear thickening fluid, Composites Part B (2019), doi: https://doi.org/10.1016/j.compositesb.2018.12.121.

[4] Mamivand M, Liaghat G. A model for ballistic impact on multi-layer fabric targets. International Journal of Impact Engineering. 2010;37:806-12.

[5] Yang Y, Chen X. Study of energy absorption and failure modes of constituent layers in body armour panels. Composites Part B: Engineering. 2016;98:250-9.

[6] Briscoe B, Motamedi F. The ballistic impact characteristics of aramid fabrics: the influence of interface friction. Wear. 1992;158:229-47.

[7] Carr D. Failure mechanisms of yarns subjected to ballistic impact. Journal of materials science letters. 1999;18:585-8.

[8] Jacobs M, Van Dingenen J. Ballistic protection mechanisms in personal armour. Journal of Materials Science. 2001;36:3137-42.

[9] Wang Y, Chen X, Young R, Kinloch I. A numerical and experimental analysis of the influence of crimp on ballistic impact response of woven fabrics. Composite Structures. 2016;140:44-52.

[10] Chu T-L, Ha-Minh C, Imad A. A numerical investigation of the influence of yarn mechanical and physical properties on the ballistic impact behavior of a Kevlar KM2® woven fabric. Composites Part B: Engineering. 2016;95:144-54.

[11] Duan Y, Keefe M, Bogetti T, Cheeseman B, Powers B. A numerical investigation of the influence of friction on energy absorption by a high-strength fabric subjected to ballistic impact. International Journal of Impact Engineering. 2006;32:1299-312.

[12] Khodadadi A, Liaghat G, Sabet A, Hadavinia H, Aboutorabi A, Razmkhah O, et al. Experimental and numerical analysis of penetration into Kevlar fabric impregnated with shear thickening fluid. Journal of Thermoplastic Composite Materials. 2018;31:392-407.

[13] Nilakantan G, Wetzel ED, Bogetti TA, Gillespie Jr JW. A deterministic finite element analysis of the effects of projectile characteristics on the impact response of fully clamped flexible woven fabrics. Composite Structures. 2013;95:191-201.

[14] Hudspeth M, Chu J-m, Jewell E, Lim B, Ytuarte E, Tsutsui W, et al. Effect of projectile nose geometry on the critical velocity and failure of yarn subjected to transverse impact. Textile Research Journal. 2017;87:953-72.

[15] Nilakantan G, Gillespie Jr JW. Ballistic impact modeling of woven fabrics considering yarn strength, friction, projectile impact location, and fabric boundary condition effects. Composite Structures. 2012;94:3624-34.

[16] Zeng X, Shim V, Tan V. Influence of boundary conditions on the ballistic performance of high-strength fabric targets. International Journal of Impact Engineering. 2005;32:631-42.

[17] Chu Y, Min S, Chen X. Numerical study of inter-yarn friction on the failure of fabrics upon ballistic impacts. Materials & Design. 2017;115:299-316.

[18] Vieille B, Casado VM, Bouvet C. About the impact behavior of woven-ply carbon fiber-reinforced thermoplastic-and thermosetting-composites: a comparative study. Composite Structures. 2013;101:9-21.

[19] Vieille B, Casado VM, Bouvet C. Influence of matrix toughness and ductility on the compression-after-impact behavior of woven-ply thermoplastic-and thermosetting-composites: a comparative study. Composite Structures. 2014;110:207-18.

[20] Lee B, Walsh T, Won S, Patts H, Song J, Mayer A. Penetration failure mechanisms of armor-grade fiber composites under impact. Journal of Composite Materials. 2001;35:1605-33.

[21] Gopinath G, Zheng J, Batra R. Effect of matrix on ballistic performance of soft body armor. Composite Structures. 2012;94:2690-6.

[22] Wang H, Hazell PJ, Shankar K, Morozov EV, Escobedo JP. Impact behaviour of Dyneema® fabric-reinforced composites with different resin matrices. Polymer Testing. 2017;61:17-26.

[23] Evci C, Gülgeç M. An experimental investigation on the impact response of composite materials. International Journal of Impact Engineering. 2012;43:40-51.

[24] Aktaş M, Atas C, İçten BM, Karakuzu R. An experimental investigation of the impact response of composite laminates. Composite Structures. 2009;87:307-13.

[25] Naik N, Shrirao P, Reddy B. Ballistic impact behaviour of woven fabric composites: Formulation. International Journal of Impact Engineering. 2006;32:1521-52.

[26] Ahmadi H, Liaghat G, Sabouri H, Bidkhouri E. Investigation on the high velocity impact properties of glass-reinforced fiber metal laminates. Journal of Composite Materials. 2013;47:1605-15.

[27] Caminero M, García-Moreno I, Rodríguez G. Experimental study of the influence of thickness and ply-stacking sequence on the compression after impact strength of carbon fibre reinforced epoxy laminates. Polymer Testing. 2018;66:360-70.

[28] Sikarwar RS, Velmurugan R, Madhu V. Experimental and analytical study of high velocity impact on Kevlar/Epoxy composite plates. Central European Journal of Engineering. 2012;2:638-49.

[29] Taghizadeh SA, Liaghat G, Niknejad A, Pedram E. Experimental study on quasi-static penetration process of cylindrical indenters with different nose shapes into the hybrid composite panels. Journal of Composite Materials. 2018:0021998318780490.

[30] Katz S, Grossman E, Gouzman I, Murat M, Wiesel E, Wagner H. Response of composite materials to hypervelocity impact. International Journal of Impact Engineering. 2008;35:1606-11.

[31] Yang H, Yao X-F, Wang S, Ke Y-C, Huang S-H, Liu Y-H. Analysis and Inversion of Contact Stress for the Finite Thickness Neo-Hookean Layer. Journal of Applied Mechanics. 2018;85:101008.

[32] Tubaldi E, Mitoulis S, Ahmadi H. Comparison of different models for high damping rubber bearings in seismically isolated bridges. Soil Dynamics and Earthquake Engineering. 2018;104:329-45.

[33] Khodadadi A, Liaghat G, Ahmadi H, Bahramian AR, Anani Y, Razmkhah O, et al. Numerical and experimental study of impact on hyperelastic rubber panels. Iranian Polymer Journal. 2018:1-10.

[34] Yang H, Yao X, Zheng Z, Gong L, Yuan L, Yuan Y, et al. Highly sensitive and stretchable graphene-silicone rubber composites for strain sensing. Composites Science and Technology. 2018;167:371-8.

[35] Pouriayevali H, Guo Y, Shim V. A visco-hyperelastic constitutive description of elastomer behaviour at high strain rates. Procedia Engineering. 2011;10:2274-9.

[36] Dong Y, Ke Y, Zheng Z, Yang H, Yao X. Effect of stress relaxation on sealing performance of the fabric rubber seal. Composites Science and Technology. 2017;151:291-301.

[37] Yang H, Yao X-F, Ke Y-C, Ma Y-j, Liu Y-H. Constitutive behaviors and mechanical characterizations of fabric reinforced rubber composites. Composite Structures. 2016;152:117-23.

[38] Yang H, Yao X-F, Yan H, Yuan Y-n, Dong Y-F, Liu Y-H. Anisotropic hyper-viscoelastic behaviors of fabric reinforced rubber composites. Composite Structures. 2018;187:116-21.

[39] Ahmad MR, Ahmad WYW, Samsuri A, Salleh J. Ballistic response of natural rubber latex coated and uncoated fabric systems. Journal of Rubber Research. 2007;10:207-21.

[40] Hassim N, Ahmad MR, Ahmad WYW, Samsuri A, Yahya MHM. Puncture resistance of natural rubber latex unidirectional coated fabrics. Journal of Industrial Textiles. 2012;42:118-31.

[41] Ahmad MR, Ahmad WYW, Salleh J, Samsuri A. Effect of fabric stitching on ballistic impact resistance of natural rubber coated fabric systems. Materials & Design. 2008;29:1353-8.

[42] Pandya K, Akella K, Joshi M, Naik N. Ballistic impact behavior of carbon nanotube and nanosilica dispersed resin and composites. Journal of Applied Physics. 2012;112:113522.

[43] Pandya K, Akella K, Joshi M, Naik N. Ballistic impact behavior of carbon nanotube and nanosilica dispersed resin and composites. Journal of Applied Physics. 2012;112:113522.

[44] Cunniff PM. An analysis of the system effects in woven fabrics under ballistic impact. Textile Research Journal. 1992;62:495-509.

Table 1. Formulation of compounds

Ingredients	Loading (Phr)	
	High Hardness	Low Hardness
NR	100	100
Carbon Black (N330)	60	40
Zink oxide	5	5
Calcium carbonate	30	30
Spindle oil	15	30
Sulfur	2	1.5
Volcacit	0.7	0.7

Table 2. Cure characteristics value of compounds

	t5 (min)	t10 (min)	t90 (min)	t95 (min)	t100 (min)	minM (lbf.in)	maxM (lbf.in)
HH rubber	0.28	0.721	2.9	3.4	5.301	7.375	101.8
LH rubber	1.11	1.277	3.6	4.1	5.48	12.423	44.2

Table 3 Characteristics of TS and rubber matrix composites

	Number of layers	Thickness (mm)	Wight (g)	Areal density (kg/m^2)
TS matrix composite	Two	1	19.2	1.14
	Four	2	34.8	2.06
LH rubber matrix composite	Two	1	22.1	1.31
	Four	2	43.4	2.57
HH rubber matrix composite	Two	1	23.8	1.41
	Four	2	46	2.72

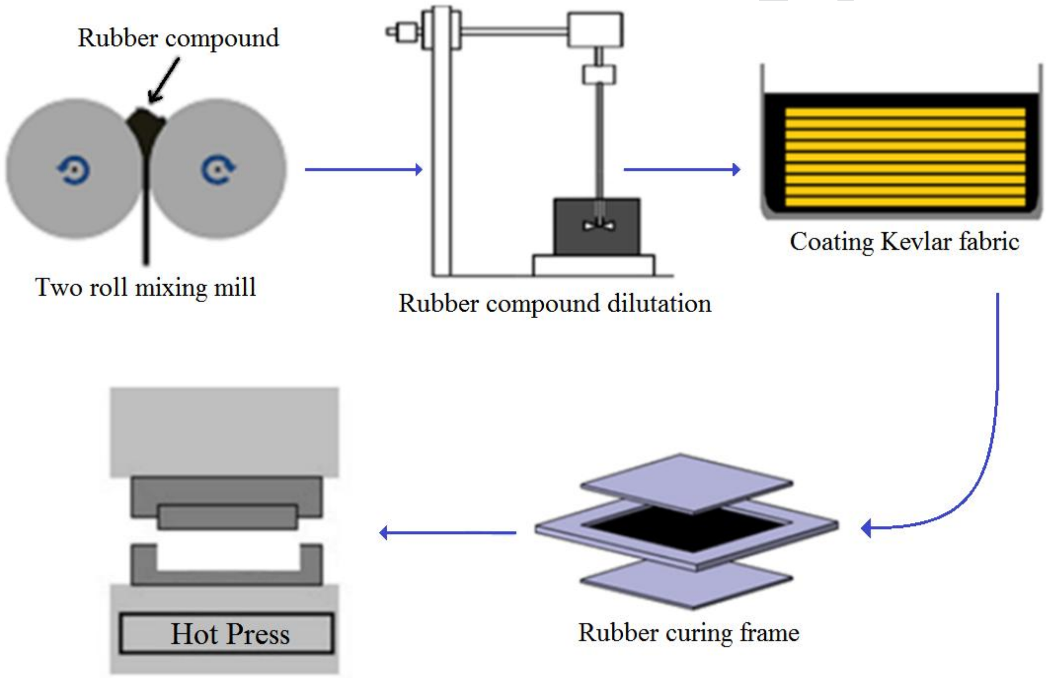


Fig. 1 Procedure of rubber matrix composite manufacturing

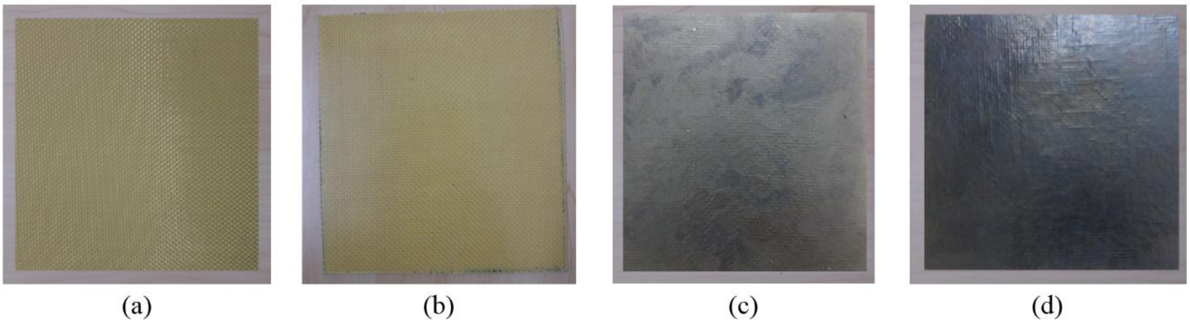


Fig. 2 Specimens (a) Kevlar fabric (b) TS matrix composite (c) LH rubber matrix composite (d) HH rubber matrix composite

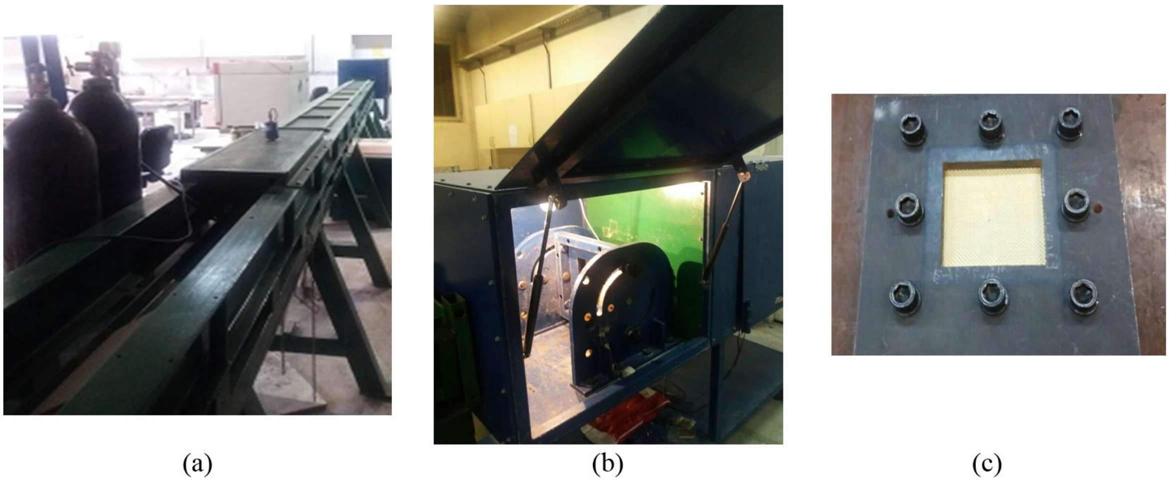


Fig. 3 High velocity impact test (a) Gas gun (b) Target chamber (c) Fixture

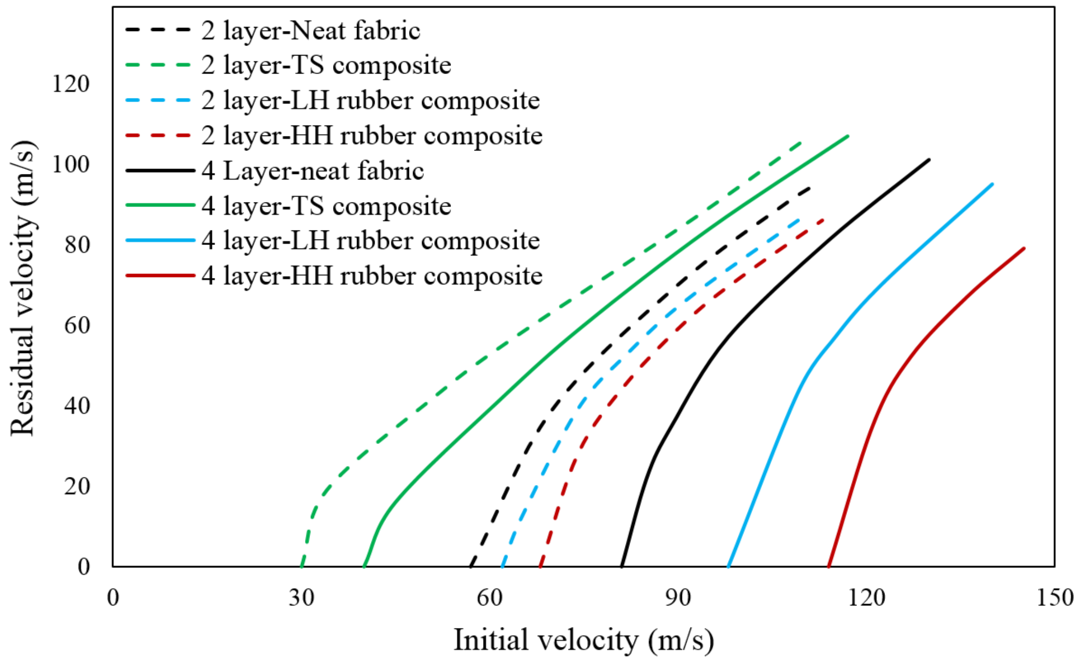


Fig. 4 Residual velocities versus initial velocities of two and four-layer specimens

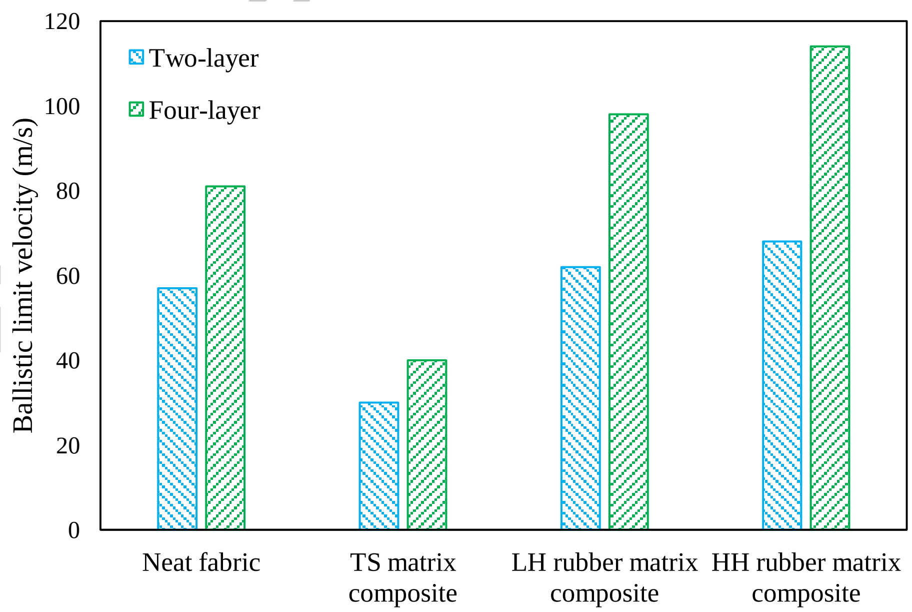


Fig. 5 Ballistic limit of specimens

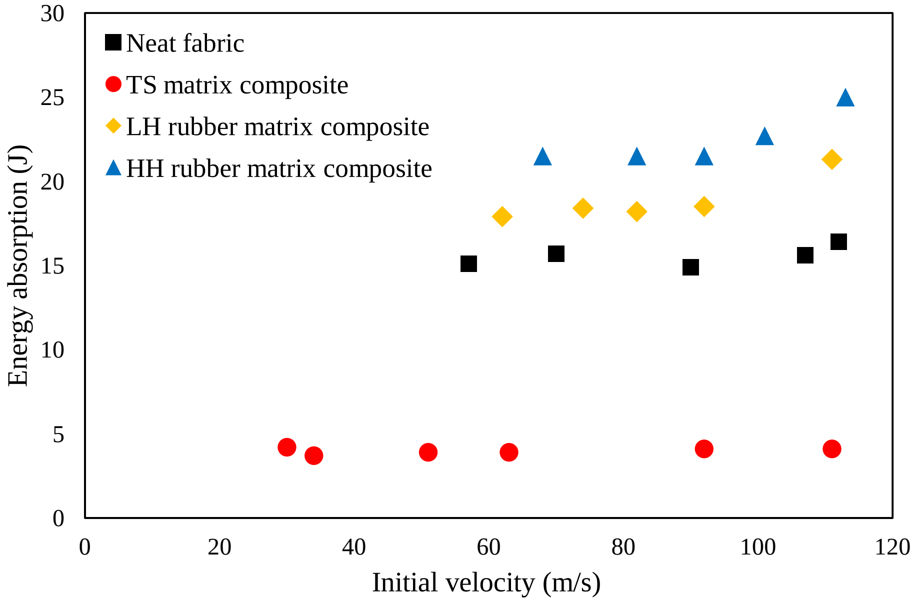


Fig. 6 Energy absorption of two-layer specimens

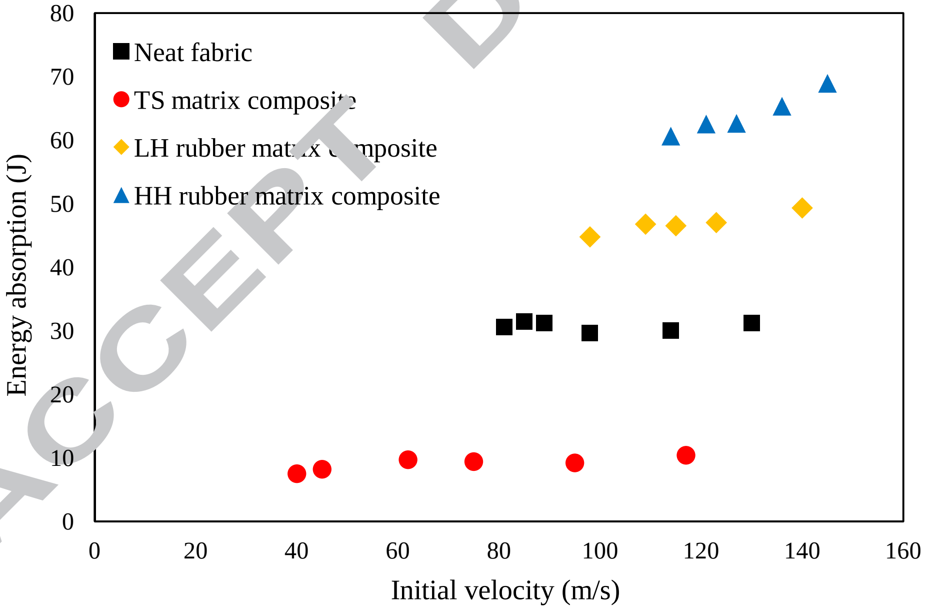


Fig. 7 Energy absorption of four-layer specimens

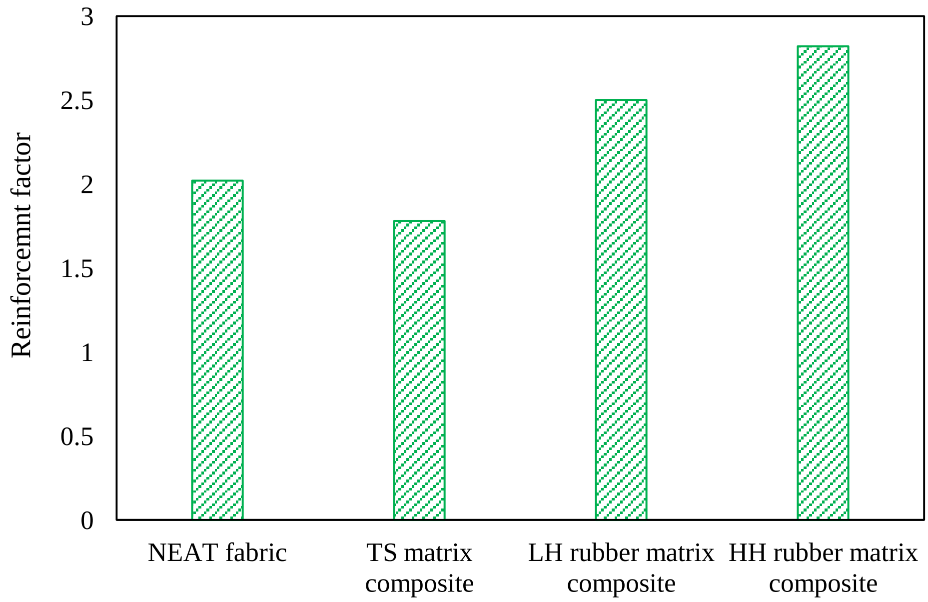


Fig. 8 Reinforcement factor of specimens

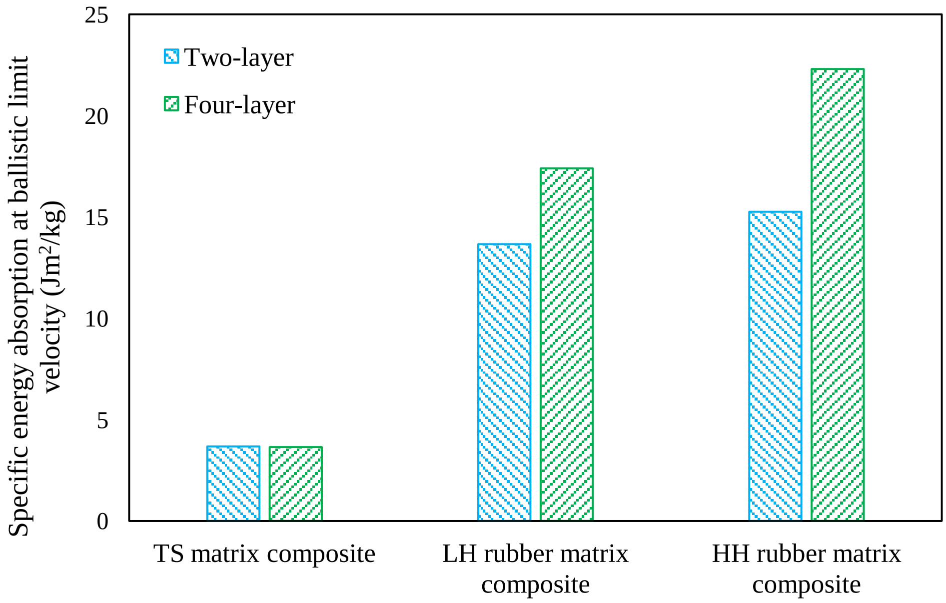


Fig. 9 Specific energy absorption of TS and rubber matrix composites

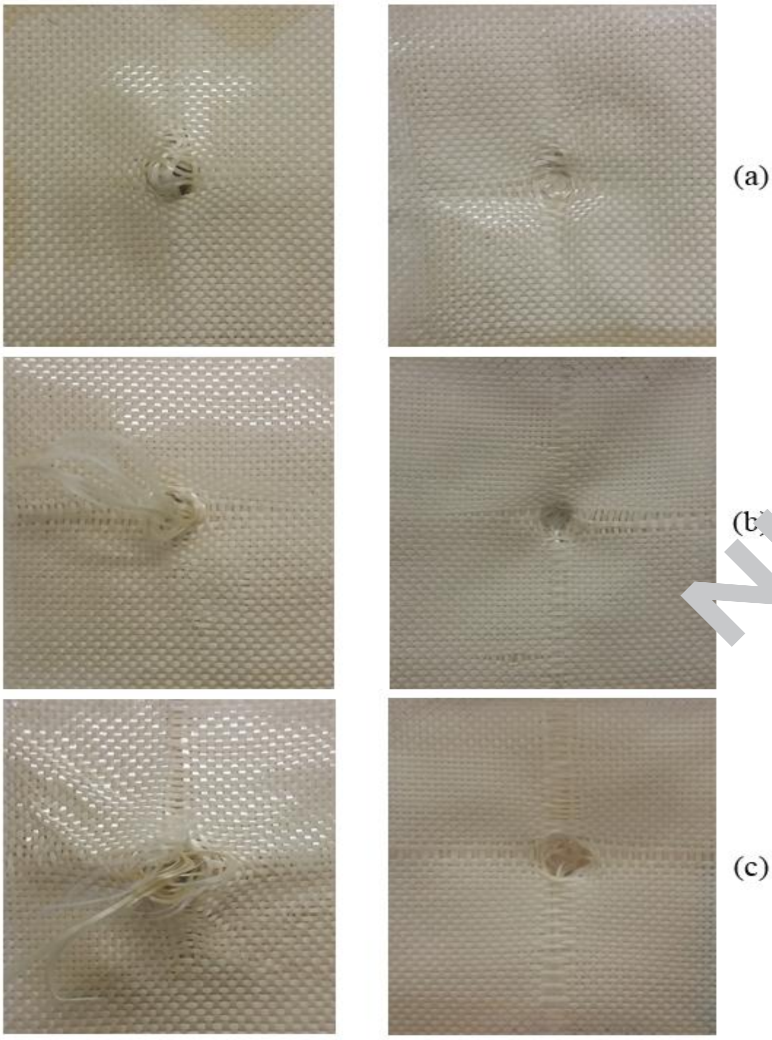


Fig. 10 Front and back face of four-layer neat Kevlar fabric at impact velocity of
(a) 70 m/s (b) 98 m/s (c) 130 m/s

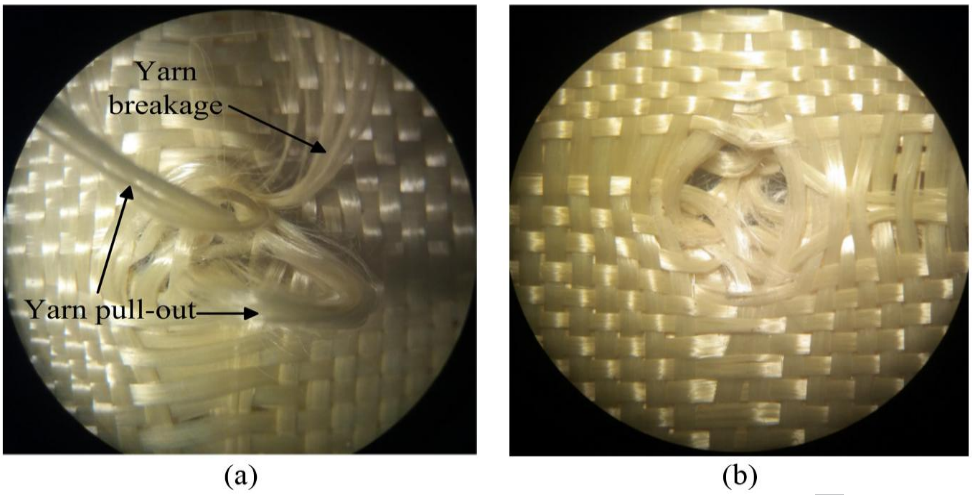


Fig. 11 Failure mechanisms of neat Kevlar fabric under high velocity impact

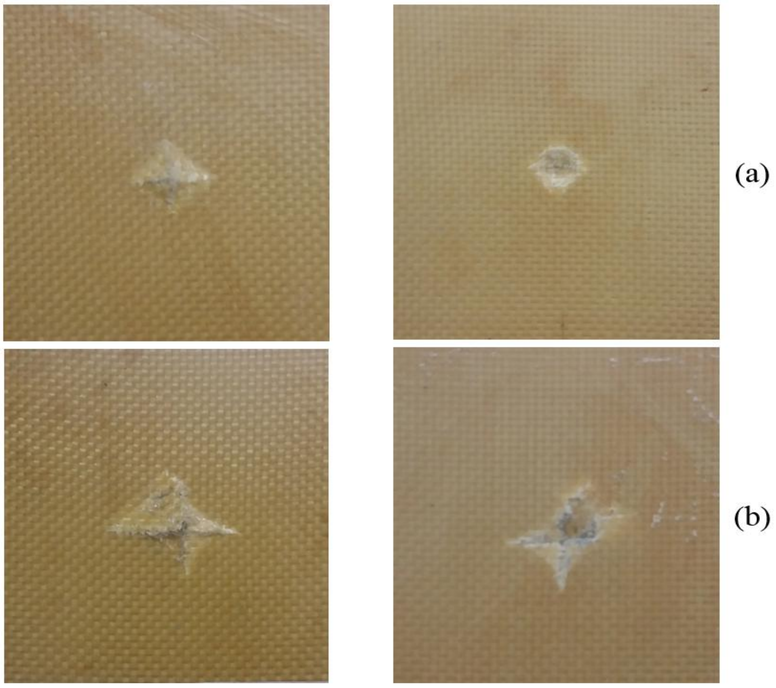
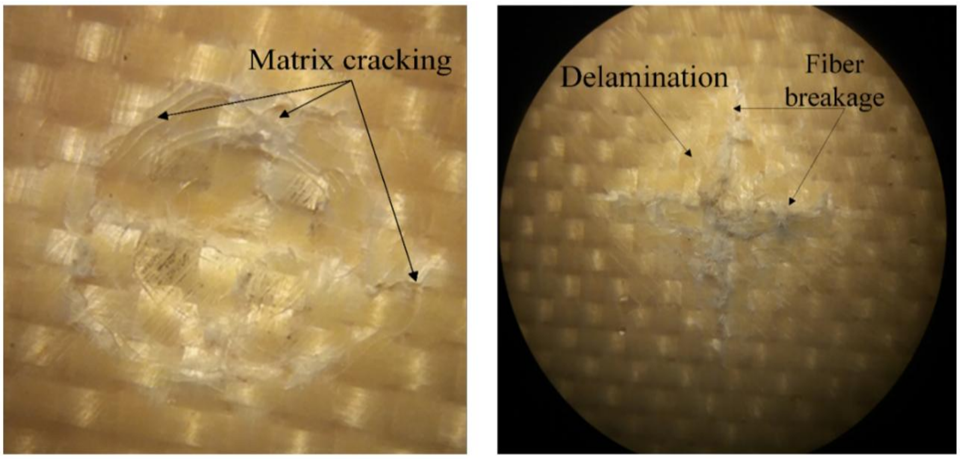


Fig. 12 Front and back face of TS matrix composite after perforation at impact velocity of (a) 75 m/s (b) 117 m/s



(a) (b)

Fig. 13 Failure mechanisms of TS matrix composite under high velocity impact

(a)

(b)

Fig. 14 Front and back face of rubber matrix composite after perforation (a) HH rubber matrix composite (b) LH rubber matrix composite

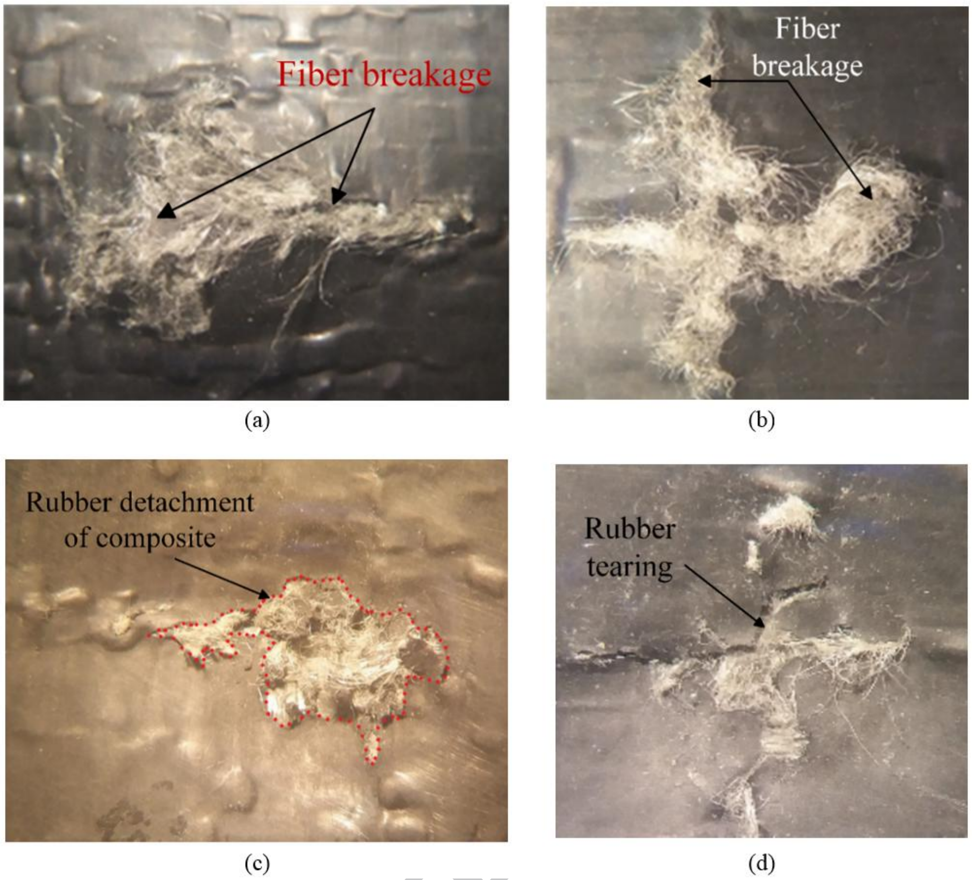


Fig. 15 Failure mechanisms of rubber matrix composite under high velocity impact