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Effect of Rubber particles on Kevlar Fiber Reinforced Polymer composite against High Velocity Impact

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Abstract-Bullet proof vests have been designed for decades to provide protection against different type of threats like small arms ammunition. Although pure fabric is being used in most of bullet proof vests but back face signature is very high in plain fabric. This back face signature or blunt can causes severe damage to body parts resulting in internal bleeding and sometimes even causing death. So it is also an important factor to be considered while designing a bullet proof vest. A lot of different methods are being used in literature to upsurge the impact response of Kevlar Fiber Reinforced Polymer (KFRP) composite like addition of Nano-clay, change of fiber orientation, use of toughened epoxy etc. In this research, effect of different matrix combinations on blunt trauma and energy absorbed by KFRP laminates are studied. KFRP composite samples are prepared with epoxy and different percentages of rubber + epoxy, and are experimentally tested against 9mm Full Metal Jacketed (FMJ) bullet.

The ballistic impact behavior and back face signature measurement of Kevlar/epoxy composite and Kevlar/epoxy with different percentages of rubber are compared with that of pure fabric. Results from the experiments have shown positive effect, of adding rubber in matrix, in terms of energy absorption (i.e. penetration), reduction in back face signature and damage mechanism for ballistic impact event. During experiment it is found that failure of primary yarn, elastic deformation of secondary yarn, delamination and matrix cracking are the main energy absorption mechanisms.

The results have shown that the laminates with a combination of rubber and epoxy give optimum results i.e. better impact resistance with lesser blunt trauma or back signature. Among these samples the sample with 12.5% rubber has best results.

Keywords-Kevlar, High Velocity Impact, KFRP, Polymer Composite.

I. INTRODUCTION

Design of armor system against high velocity impact has evolved reasonably over the last 60 to 70 years. Material started from steel to give protection to the human body and now composite materials took over. According to Personal Armor System for Ground Troops (PASGT) or Advanced Combat [i], use of composite materials started at the end of 20^{th} century. Personal armor system and ballistic vests were used by US military in 1980s. In 2000, most of helmets and bullet proof vests were made by light weight composite structures. Moreover, researchers are using advanced materials to enhance the impact resistance and also reduce the weight of PASGT helmet and vest[ii]. They studied use of prepreg in ballistic application. They analyzed the performance of prepreg in ballistic application as compared to the performance of structural prepreg. Structural prepreg are resin rich with about 40-50% resin content, while ballistic prepreg have only 10-20% resin content. That is why ballistic prepreg performed better.

Fibers which are used in bullet proof vests and other defense equipment are either woven or non-woven. Fibers can be woven into a number of configurations. Different weave pattern have different effects on ballistic impact resistance of fiber. Plain weave pattern has significant effect on impact resistance of Kevlar fiber as less fiber gets influenced by crimp effect. Satin weave gives much better results than plain weave[iv].

Low density and high strength fibers such as aramid have been used for high velocity impact resistance applications in vehicles, body armors and structural and mechanical elements. Angle ply unidirectional and woven fabrics are most commonly used reinforcements for these composite materials. Nevertheless, glass fiber reinforced composites are used mainly due to their low cost. Indeed one of the main weakness of glass-epoxy composites is its poor resistance to impact loading due to the lack of plastic deformation mechanism for absorbing impact energy. To overcome this weakness we use hybrid composites, composites of Kevlar and glass fiber, a compromise between high structural performance and low cost of composite structure for impact loading.

On ballistic impact, polymer composites retard the projectile by absorbing its kinetic energy. At low velocities there is penetration resistance due to high strain energy. Strain energy is associated with conical deformation, matrix cracking and delamination. At high velocities different mechanisms such as tensile failure of fibers, elastic deformation of secondary fibers, delamination, matrix cracking, friction between projectile and composites, kinetic energy of moving cone formed on back face of plate, shear plugging etc. absorb kinetic energy of projectile [v].

Knowing the failure modes involved in the particular impact, analytical approach can be developed to determine the energy required for penetration that can be used to predict the ballistic limit V50 and residual velocity of projectile after impact. For a given target projectile combination the ballistic limit is defined as the lowest initial velocity of the projectile that will result in complete penetration. At this impact velocity, V_{50} residual velocity of the projectile is zero. Certain amount of variability is always present in the definition of ballistic limit; the ballistic limit is often defined as the velocity that will result in penetration of 50% of the samples when large numbers of tests are performed [vi].

Kevlar is a fiber which is most commonly used in ballistic impact application. It belongs to aramid family. Kenaf fiber is a natural fiber and is used to increase the impact resistance of Kevlar. *R. Yahaya et al* studied the effect of kenaf fiber orientation on the mechanical and flexural properties of kenaf/Kevlar hybrid composite. It is reported that woven Kenaf/Kevlar hybrid composite showed superior mechanical properties compared with unidirectional and non-woven kenaf/Kevlar hybrid composites. [vii] This author also studied the behavior of ballistic impact resistance and energy absorption of woven kenaf/Kevlar hybrid composite against Fragment simulating projectiles (FSPs). It is found that lower volume fraction of kenaf fiber in hybrid structure enhance the impact response and the failure in hybrid composite is due to fiber fracture, delamination and fiber shear [viii].

Ramie fiber has not only increased impact resistance but has also improved the blunt trauma. They [ix] proposed 10-20% reduction in ballistic blunt trauma when 7.62mm projectile hit the multilayer hybrid composite structure (Kevlar-Ramie/epoxy). Addition of Ramie fiber by 30% volume fraction in Kevlar increases the energy absorption of projectile and also minimizes the ballistic blunt trauma injury. This structure has improved in shattering of projectile and debris of projectile captured by both Kevlar and Ramie [ix]. To reduce trauma depth researchers used felt and anti-trauma liner mix with different fibers like Kevlar, Twaron, and dyneema. They found that if hybrid package consists of 20 layers of dyneema, 3 layers of Twaron felt and 3 layers of Twaron LFT-AT flex then 21% trauma decreases as compared to homogenous structure (32 layers of dyneema). If hybrid package consists of two components i.e. 28 dyneema and 3 Twaron felt and 20 layers dyneema and 5 layers of Twaron LFT-AT flex, then 14 % and 21% decrease in trauma is observed. Twaron Felt material has positive effect on decrement of trauma but it has high thickness as compared to others fibers [x].

It has been analyzed [xi] the hybrid structure made from natural fiber coir and Kevlar which has great effect in reducing the blunt trauma as well as increases the ballistic impact resistance against NIJ level III. They have studied the influence of stitching parameters on ballistic performance in term of blunt trauma capability of Kevlar fabric [xii]. Different types of stitching techniques like cross, perimeter and cross-perimeter is used to investigate the depth of blunt trauma. It is found that cross-perimeter type stitching has low blunt trauma and high ability to absorb energy comparative to other types of stitching. Because cross-perimeter stitching technique decreases the flexibility of panel and increases the impact resistance and reduces the depth of blunt trauma. [xiii]

Modern combat helmet and bullet proof vest are designed to provide good penetration resistance and safety to human life from serious injuries caused by explosives and sharpened threats [xiv-xvi]. Now a day's vest are lighter than older ones. But reduction in weight has also caused increase in back face signature or blunt trauma. Many researchers are working on this side and few are also successful in optimizing the depth of blunt trauma and ballistic impact resistance of target. Blunt trauma can have severe effects on the body. Traumatic Brain Injury (TBI) is most vulnerable injury caused by explosive and ballistic impact of shell fragments or bullet. Behind Armor Blunt Trauma (BABT) may cause severe injuries due to impact of small arms ammunition [xvii]. Most of armors are designed to stop the bullet, while they do not focus on the effect of trauma caused by projectile and there is hardly any data available in this regard.

II. EXPERIMENTATION

A. Material

High performance composite materials are widely used in many applications like turbine blade, torpedo propeller, automotive industry and ballistic applications [vi, xviii]. Their high strength to weight ratio makes them suitable for use in ballistic application.

Kevlar is an aramid fiber belongs to aromatic polyamide. It is high performance manmade fiber which is used in ballistic applications [xii]. Kevlar is an aramid fiber, with high modulus, which is used as reinforcement in many ballistic applications. It has high strength to weight ratio. In this study, plain woven

Kevlar 29 style 731 is used and has areal density 170 g/m^2.

Rubber is an elastomer which is used as damper in many application. When NBR is used as matrix in ballistic application [xix], it increases the impact resistance of fabric up to 60%. Therefore, in this study, NBR is used which has hardness 45 shore A and tensile strength is 17 MPa. LY 564 is used as Epoxy and hardener Aradur 22962 is used. Ethyl acetate is used to make the solution of NBR.

B. Sample Preparation

Six different samples of Kevlar/epoxy and Kevlar/(epoxy + rubber) are prepared for ballistic impact testing. Cutting of Kevlar in accordance with required dimension is done by special scissor. Dimension of sample is set to 200mm x 200mm. Scheme of sample preparation is as per Table I. For preparation of samples, a close Mold which is made of Mild Steel is used which can be seen in Fig 1.

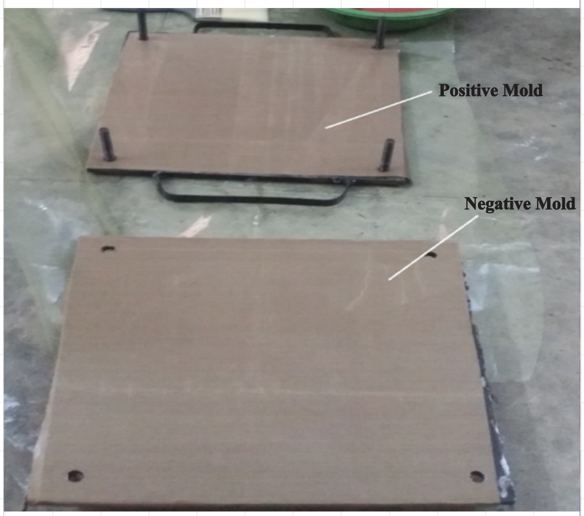


Fig. 1. Mold for Sample Preparation

LY 564 is used as epoxy and Aradur 22962 is used as hardener. In preparation of Kevlar/epoxy sample, hand lay up process is used. After applying resin onto the fabric, tight the mold with the help of nuts and bolts. Extra resin will flow outside the mold. Curing of sample is done at room temperature and sample is set to cure for 2 days.

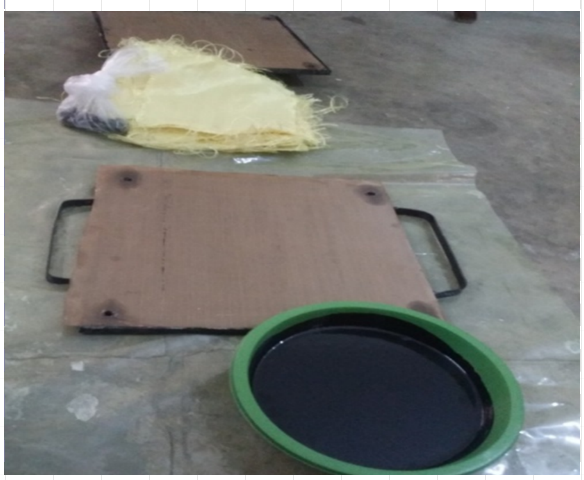
For preparation of Rubberized Kevlar/epoxy sample, method is little bit different from Kevlar/epoxy. Weigh the rubber as per required percentage and dissolve it into ethyl acetate in ratio 1:4. Place the beaker on Magnetic Hot plate, stir and dissolve the rubber into ethyl acetate as shown in Fig. 2.

Fig. 2. Preparation of rubber solution in ethyl acetate

TABLE I
SCHEMATIC OF SAMPLE AND % OF EPOXY AND % RUBBER

Sr. No.	Sample Name	% of Epoxy	% of Rubber
1	Kevlar/epoxy	100	0
2	Kevlar/epoxy with 6.23% Rubber	93.77	6.23
3	Kevlar/epoxy with 12.5% Rubber	87.5	12.5
4	Kevlar/epoxy with 25% Rubber	75	25
5	Kevlar/epoxy with 50% Rubber	50	50

After making the rubber solution, add epoxy LY-564 and hardener Aradur 22962 with ratio 1:4. Mix them well and use hand lay up process. The whole process can be seen in Fig. 3.



(a) Hand Layup Process

(b) After curing of Kevlar/epoxy with rubber sample
Fig. 3.

All samples are cured at room temperature and after curing calculate the weight of samples. Fiber to matrix ratio is calculated and enlisted in Table II. Cured samples have irregular edges, which is why grinder is used to trim all edges of samples.

TABLE II
FIBER TO MATRIX RATIO OF SAMPLES

Sr. No.	Sample Name	Weight of Sample	weight of matrix	Ratio of fiber to matrix
1	Kevlar/epoxy	421.3	159.3	62.18 : 37.8
2	Kevlar/epoxy with 6.23% Rubber	477.2	237.2	50.3 : 49.7
3	Kevlar/epoxy with 12.5% Rubber	395.3	132	67.5 : 33.5
4	Kevlar/epoxy with 25% Rubber	426.2	161.1	62.2 : 37.8
5	Kevlar/epoxy with 50% Rubber	438.6	180.9	58.8 : 41.2

C. *Microscopic Analysis of Samples*

Fig. 4 shows the optical microscopic analysis of Kevlar/epoxy and Kevlar/epoxy with rubber samples. Different section of Kevlar/epoxy shows that there are less percentage of voids and bubbles found in this structure and fibers are tightly bonded with epoxy as shown in Fig. 4.

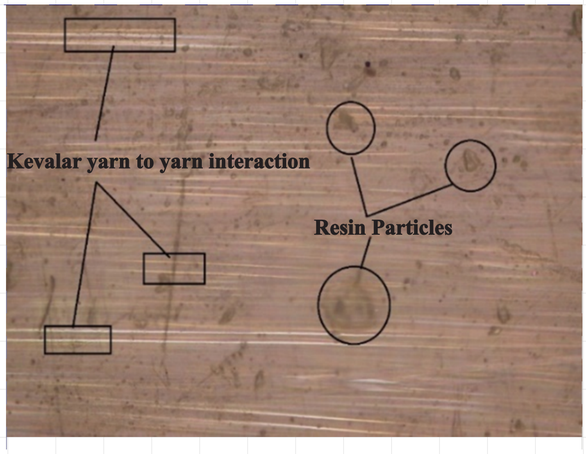
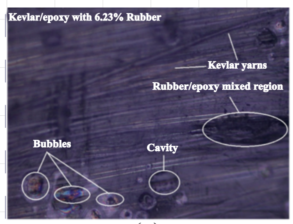
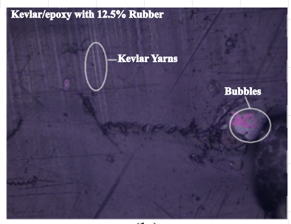


Fig. 4. Microstructure of Kevlar/epoxy sample

While in case of 6.23 %, 12.5%, 25% and 50% rubber of Kevlar/epoxy samples, results are different from Kevlar/epoxy. Voids and bubbles are present in its structure as seen in Fig. 5. These voids play role in instability of mechanical structure and also produce weak bond of fiber to matrix. These voids, cracks and bubbles are responsible for propagation of stress wave through the fiber to matrix. As a results, interlaminar shear strength of each ply decreases and delamination may happen more as compared to Kevlar/epoxy [viii], matrix cracking also happens severely in this case. Overall structure's mechanical properties are not so much effected by these voids. Theses voids, bubbles and cracks can be overcome by minimizing human error (such as the pressure applied during fastening mold or the ratio of epoxy applied to each layer of Kevlar) , as we can see there are much lesser defects in samples with 12.5% and 25% rubber. As the rubber quantity increases, it becomes difficult to avoid these defects, so maximum defects are seen on the surface of sample with 50% rubber.



(a)



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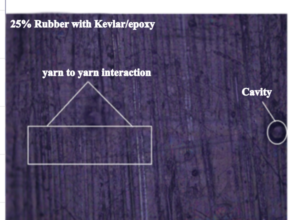

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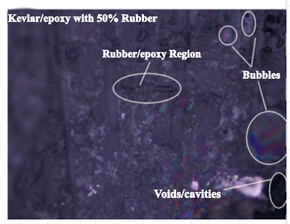

(d)

Fig. 5. Optical micro structure analysis of rubberized Kevlar/epoxy sample

D. Ballistic Impact Testing

When composite structure suffers an impact by a projectile having low mass, then different damage mechanism take place. According to reference[xx] they studied the impact, stages of penetration and perforation of projectile in 2D composites. When projectile hits the composite target, the region which comes directly in contact with the projectile is considered as `1 and yarns under this region are primary yarns [xxi]. While in region 2, transverse waves travel along the in-plane direction and all yarns under this region are secondary yarns. A schematic diagram of the setup used for ballistic testing is shown in Fig. 6 [xxi].

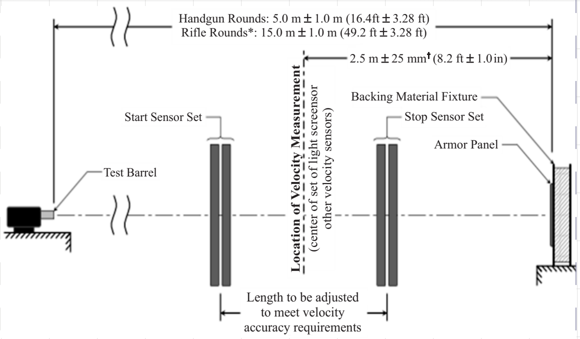

Fig. 6 Ballistic impact event in composite Target against High Velocity Impact [xxi]

An outdoor ballistic impact testing facility is used and setup is shown in Fig 7. Ballistic impact testing of all samples are performed as per NIJ Standard and NATO Stang 2920. Samples are placed in fixture and on the other end weapon is placed. Distance between sample and weapon is set as per NIJ Standard. To measure the velocity of bullet, velocity meter is used.

9mm full metal jacketed (FMJ) bullet is used in this testing. Bullet has weight 12.2 g and velocity 380 m/s. It has inner core made of lead and outer core made of copper jacket.

Fig. 7. ballistic Impact testing facility

E. Blunt Trauma measurement

Blunt trauma measurement for ballistic impact test are done by using NIJ Standard. According to NIJ standard, blunt trauma is also known as Back Face signature. These tests are done against NIJ Level –IIIA armor type (426 ± 9 m/s impact velocity). 9mm handgun with full metal jacketed round nose (FMJ RN) having velocity range 407-420m/s is used for testing. This velocity is enough to compare the indentation produced by bullet to sample.

Sample is fixed in square box system and behind the sample standard molding clay is used to measure the back face signature of samples as seen in Figure 8. When bullet is fired then its indentation on the sample is transferred to molding clay which can be measured by Vernier caliper.

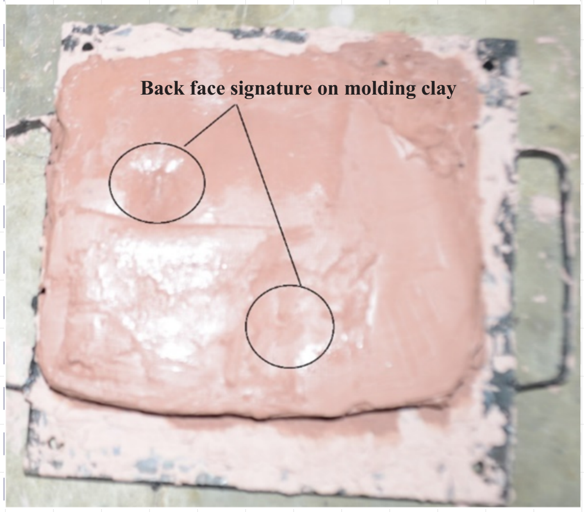

Fig. 8. Impression of blunt trauma on Molding Clay

III. Results & Discussion

During ballistic test, five laminate samples with different combinations of Kevlar with epoxy and % of rubber are prepared and tested against high velocity impact. Scheme of tested samples, their masses and back face signature is listed in Table III. Efficiency and performance of structure is explained by the depth of back face signature, and no of layers perforated. Histogram of five different samples is shown in Fig. 8**.** Moreover, each bar is divided into different sections as per percentage of rubber and epoxy in hybrid structure.

TABLE III
BALLISTIC IMPACT TEST OF DIFFERENT SAMPLES

Sample Description	% of epoxy	% Rubber	Thickness (mm)	Striking Energy (J)	Absorbed Energy (J)	trauma depth (mm)
Kevlar Epoxy	100	0	6.79	893.20818	893.20818	5.7
Kevlar/epoxy with 6.23 % Rubber	93.77	6.23	7.17	893.20818	893.20818	7.49
Kevlar/epoxy with 12.5% Rubber	87.5	12.5	5.88	922.17522	922.17522	7.53
Kevlar/epoxy with 25% Rubber	75	25	6.36	912.46818	912.46818	8.98
Kevlar/epoxy with 50% Rubber	50	50	7.295	931.93362	931.93362	10

In this research, effect of addition of rubber into epoxy on ballistic impact resistance of hybrid structure have been studied against high velocity impact. To predict the energy absorption capacity of composite laminate, measure the impact velocity, bullet mass, impact energy and residual velocity experimentally. Impact energies calculated on the basis of bullet mass and impact velocity of projectiles. While energy absorption is determined at the end of experiment. If bullet perforates the composite structure then calculate the residual velocity and measure energy absorption of structure. From the experiment, it is clear that energy absorption capacity of Kevlar/epoxy is less than the Kevlar/epoxy + rubber structure.

The result have shown that Kevlar/epoxy with 50% Rubber has absorbed more energy than other samples. It also proves that this structure has better penetration resistance and ballistic limit as shown in Table III and Fig. 9.

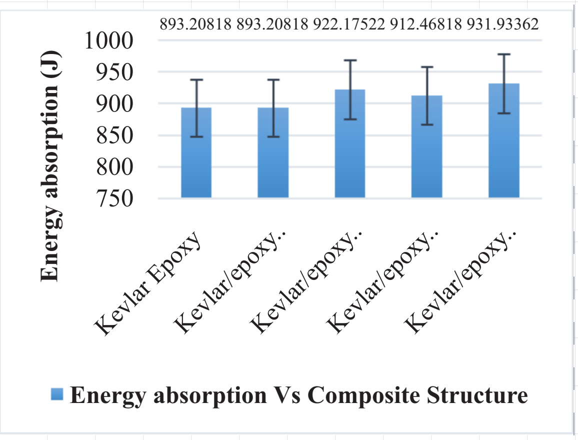

Fig. 9. Energy absorption by composite structure

A. *Perforated Layers of Composite Structure*

In Kevlar/epoxy sample, maximum no. of layers are perforated. Damage can be seen in last layer**.** Frictional effect in case of Kevlar/epoxy target is very low. Moreover, interlaminar shear strength of layers is also very low. However matrix play significant role in energy absorption of projectile.

While in case of Kevlar/epoxy with rubber structure, bullet has perforated very few layers of composite. The main reason is that layer to layers friction is very high in this case. Due to frictional effects, bullet is unable to penetrate and perforate more layers and thus got stopped by target easily. No. of layers perforated in different composite structures is shown in Fig. 10. The composite with 50% rubber has lowest no. of perforated layers which is 16.

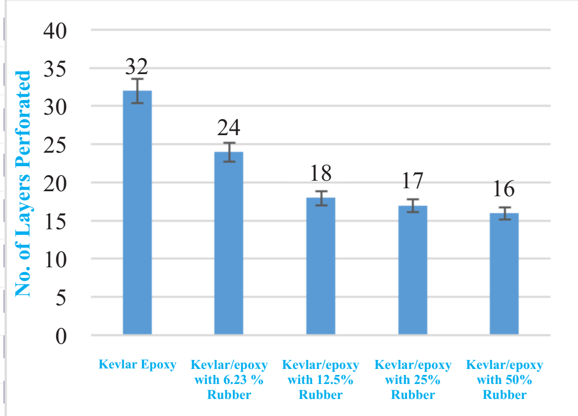

Fig. 10. No. of layers perforated in composite structure

B. *Comparison of Experimental Results with Published Data*

Blunt Trauma or Back Face Signature (BFS) of Kevlar/epoxy with 50% rubber sample which has highest ballistic limit value is compared with Kevlar/epoxy and Kevlar/epoxy with 6.23%, 12.5% and 25% rubber. Measurement showed that structure having 12.5% rubber has low back face signature/blunt trauma comparative to others composites and results are compared with Published Data[xxii].

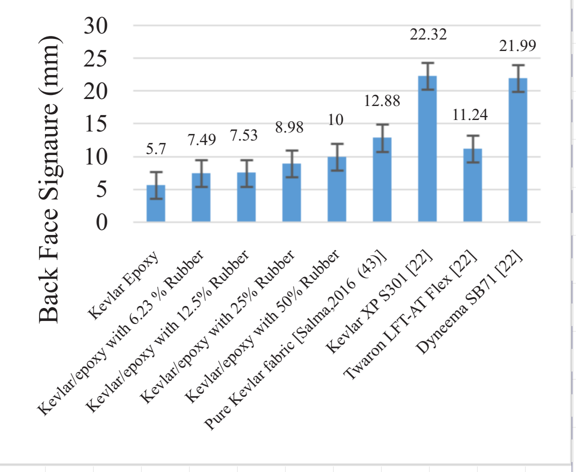

Fig. 11. Comparison of Back Face signature of different composite structure with Published data

They have studied experimentally the effect of kenaf fiber on Kevlar to improve impact resistance and reduce the blunt trauma. It is evident from the results that pure Kevlar fabric has high blunt trauma which was 12.88 mm [xxii]. While in this research, max blunt trauma 10 mm is observed in case of 50% Rubber/epoxy target which shows that KFRP laminates have better back face signature and high impact resistance.

It has been studied that addition of anti-trauma lines in Kevlar fabric not only reduce back face signature but also improve impact resistance [x]. They concluded that Twaron LFT-AT Flex has best back face signature which is 11.24mm. When our experimental results of Back face signature of composite laminate compare with the [x], it is estimated that Kevlar/epoxy with 12.5% rubber laminate has minimum back face signature about 7.53mm. From these results, it can be concluded that composite laminate with some percentage of rubber has best blunt trauma value as compared to pure fabric.

IV. Conclusion

When projectile hits the composite target, there are following types of failure in composite target[v].

1. Tensile and compression failure of secondary yarn
2. Delamination of composite layers
3. Matrix cracking
4. Elastic Failure of primary yarn

In this research, effect of addition of rubber into matrix is studied against the NIJ Level-IIIA. Following points are concluded:

1. Addition of rubber enhances the impact resistance of Kevlar fiber reinforced polymer composite. Rubber addition into matrix enhances the ductile behavior while reduces the brittle nature of matrix.
2. In case of rubberized matrix composite laminates, blunt trauma value is very less as compared to pure Kevlar. In case of brittle matrix based Kevlar/epoxy composite, trauma is low but impact resistance is very low. So addition of rubber enhances the impact resistance and also lower the value of blunt trauma.
3. Increase in addition of rubber into matrix creates weak bonding between layers of Kevlar. Moreover it increase the delamination of laminates.
4. The optimized results are achieved at 12.5% rubber to epoxy ratio. Therefore, addition of rubber particles more than this value is not recommended.
5. The experiments were performed in open air and it was observed that the fiber to matrix ratio gets effected due to high temperature or humid environment which may lead to increase in voids and early cracks.
6. Curing is recommended under controlled conditions for uniform distribution of rubber particles throughout the laminate.

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