A Review on Material & Ballistic Energy Absorption of Body Armour

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Abstract: **Body armour is a material used by the force to protect body from various kinds of injuries, high speed projectile bullet and in other hazard situations. Body armour is always a compromise: mobility and comfort (with its speed and stamina). Currently used bullet proof vest & helmets used by force are very heavy causing a lot of discomfort & leaving the personnel at a disadvantage during an encounter with heavily armed terrorist. Due to the various invention in firearms there are various materials used in body armour i.e. ballistic fabrics, ceramics and laminated composites so that it can be light in weight, damage resistant, great energy absorbing capacity, comfort in use, flexible in design and manufacturing and most important less in cost. Based on comprehensive and critical review of the researches carried out, a comparative study of the commercial and current development of material used, their various material properties and ballistic energy absorption capacity is studied in this paper.**

Keywords: **Projectile bullet, Firearms, Ballistic fabrics, Damage resistant**

I. INTRODUCTION

Body armour is a type of protective clothing which is designed to absorb or deflect slashing, bludgeoning and penetrating attacks by various weapons. In ancient time, it was used to protect military personnel, whereas today, it is also used to protect police (riot police in particular), private citizens, private security guards etc.

Modern body armours are mainly two types:

- Soft body armour
- Hard body armour

Table-1 various feature of soft & hard body Armour [14]

Features	**Soft body armour**	**Hard body armour**
Protection level	Low	High
Weight	Light weight (below 4.5kg)	Heavy weight
Flexibility in body movement	High	Less
Absorb energy level &Impacting velocity	low to medium energy Up to 500 m/s	Resist projectile velocity of NIJ level IIIA or more than 500m/s
Level of threat	Low level	High level
Usage	General use for proving adequate protection	Law enforcement officers and military personnel
Material	Multiple layers of fabrics (up to 50 layers)	Ceramics, reinforced plastics, metal plates and composites.
Mechanism	During impact, the load from the projectile applies some tension to the yarns. This tension is applied in the fabric plane as well as in the vertical direction to the fabric plane due to the crimp. The load in the vertical direction to the fabric plane is directed towards the back of the panel, which causes the yarn to displace towards the back of the fabric panel more, resulting in deeper trauma. The inter-yarn friction also affects the ballistic protection .Higher inter yarn friction makes movement of the yarns in the fabric plane more difficult and this tends to slow down or stop a projectile.	Hard body armour absorbs the energy of the projectile by a plastic deformation mechanism by dissipating the kinetic energy of the projectile through the fracture of the hard material in the armour.

1.1 Hard Body Armour Material:

For hard armour panels includes metal plates (603 armoured steel), ceramic tiles (transparent ceramic, glass ceramic, alumina ceramic), and silicon carbide or boron carbide plates. The ceramic used in body armour is called alumina (Al_2O_3) . Moreover, silicon carbide (SiC) can also be bonded together by sintering to form very hard ceramics to be used in ballistic applications.

Transparent armour consist in a set of several layers composed by laminates of borosilicate glass or soda-lime, thermoplastic hot melt adhesives and polymeric anti-spall layers.

Table-2 Main hard body armour material [15]

Main hard body armour material		
Type	**Weight**	**Construction**
Ceramic	5.7 lbs /2.6 kgs	Ceramic (alumina oxide) with aramid backing
Steel	7.7 lbs /3.5 kgs	Tempered Steel/Specialised metals

UHMWPE	3.1 lbs /1.4 kgs	Pressed polyethylene Dyneema or Spectra shield
Glass Ceramic	4.2 lbs /1.9 kgs	Glass ceramic with aramid or UHMWPE backing

1.2 Soft Body Armour Material:

For increased ballistic performance, soft body armour is used, which include several types of fibre as Kevlar, Nomex, Twaron and Dyneema [1]

1.2.1 Kevlar:

Kevlar is an aramid fibre, which is in essence a molecular combination of coal, air, and water, with a combination of properties allowing for high strength , low weight, flame resistant, along with chemical and cut resistance and the fibre is unaffected by immersion in water. In 1965, DuPont developed a technology for creating a spun synthetic fibre, which became the product Kevlar in the 1970s. Kevlar has a strength more than 5 times that of steel, with higher tensile strength and elasticity than similar spun synthetics.[15]

Table 3: Various variant of Kevlar fibre [15]

Fibre	**Year of development**	**Usage**
Kevlar brand fiber	1965	First material identified for use in the modern generation of a concealable bulletproof vests
Kevlar 29	1970	Helped to make the production of a flexible, concealable bulletproof vest practical for the first time
Kevlar 129	1988	A bulletproof vest with this fabric offered increased ballistic protection capabilities against high energy rounds such as the 9mm FMJ.
Kevlar Correctional	1995	Provides puncture resistant technology to both law enforcement and correctional officers against stabbing weapons.
Kevlar Protera	1996	High-performance fabric that allows lighter weight, more flexibility, and greater ballistic protection in body armor materials due to the molecular structure of the fiber.
Kevlar XP		Used in soft body armor technology, helps manufacturers provide a more comfortable vest design with a 10% reduction in overall weight.
Kevlar XP™S104		Maintains its strong ballistic performance and comfort even in wet conditions; ideal when working in tropical climates or when performance is required in wet conditions.

1.2.2 Dyneema:

In the 1990's, DSM patented a method of "gel-spinning" polyethylene fibers that were exceptionally light and durable ,named Dyneema ®.It is a polyethylene fiber with an extremely high strength-to-weight ratio (a 1-mm-diameter rope of Dyneema can bear up to a 240-kg load). The fiber is light enough that it can float on water, and has high energy absorption characteristics and has been adapted for use in a wide range of products, from fishing line and nets, to medical implants.

In the field of ballistic protection, Dyneema can be used in soft armour or hard armour. The fibres are laid in sheets of parallel strands, with the sheets being laid on top of each other at 90^0 angles. Dyneema Force Multiplier Technology is the latest innovation from DSM Dyneema resulting in vests that are up to 25% lighter.[2]

1.2.3 Spectra:

Honeywell's Spectra line of products has been in production since the 1980s in various forms. Honeywell expanded their Spectra ballistic products to include a product called Spectra Fibre and currently offers the materials Spectra Shield, Gold Shield and Gold Flex.

Table 4: Various variant of Spectra fibre [14]

Fibre Type	**Trade**	**Usage**
Spectra Shield II hard armour product	SR-3124	Providing the highest levels of protection for breastplate, helmet, and vehicle applications.
Spectra Shield II soft armour products	SA-3118 and SA-3113	SA-3118 maximizes ballistic performance, SA-3113 was designed for added flexibility and comfort, while maintaining high levels of performance.
Spectra Shield hard armour product	SR-1214	Used in plate, helmet and vehicle application.
Spectra Shield soft armour product	SA-1211	Designed to meet the comfort and flexibility demands of the user, while maintaining strong ballistic performance and reducing the effects of blunt trauma.
Aramid fibresGold Flex & Gold Shield	Gold Shield LCR GoldFlex Gold Shield PCR	Concealable bulletproof vests & used in the manufacture of hard armour, such as ballistic panels and helmets

1.2.4 Zylon:

Zylon was made by a Japanese corporation(Toyobo) as synthetic polyurethane fibre in 1998,which was the brand name of poly(p-phenylene-2,6-benzobisoxazole). It was the lightest of any of the ballistic garments in market at that time. It was significantly stronger than the polyethylene's and aramids , and had versatility in manufacturing purposes.

1.2.5 Twaron:

In 1972, AKZO came out with its first aramid version called Arenka (later renamed Twaron) for bullet proof vests. According to Akzo Nobel, this fibre uses a 1,000 or more finely spun single filaments which act like an energy sponge, absorbing a bullet's impact energy and quickly dissipating that energy through adjacent fibres. If more filaments are used, the rate of dispersed the impact increase more quickly.

Akzo claims their patented Microfilament technology allows maximum energy absorption at minimum weights while enhancing comfort and flexibility.

Table 5: Mechanical Properties of Typical Ballistic Fibres.[10]

Material	Tensile Strength (MPa)	Density (g/cm3)	Tensile Modulus (GPa)	Elongation %
Polypropylene	500	0.829	2	6
E-glass	2750	2.57	73	2.5
S-glass	4710	2.48	-	2.8
Carbon fibre	4000	1.75	131	2.8
Spider silk	2000	1.3	30	30
Aramid (Kevlar or Twaron)	3200	1.44	131	4
UHMWPE (Dyneema or Spectra)	3400	0.97	111	4-5
Vectran	3200	1.4	75	-
Zylon (PBO)	5800	1.54	180	-

II. BALLISTIC PERFORMANCE EVALUATION

Many techniques have been used to measure the velocity of a projectile. The most widely used systems are instantaneous, discrete techniques such as sensors or chronographs. The impact or residual velocity of a projectile is calculated from the distance between two sensors divided by the time taken by the projectile flying between the sensors [4]. Sensors currently employed in the ballistic range include light emitting diodes, laser beams, thin wires or infrared beam.

2.1 Energy Absorption Based On Impact And Residual Velocity:

The most direct way to evaluate the ballistic performance of a fabric is to calculate its energy absorption.The following equation has been used;

$$\Delta E = \frac{1}{2} m(v\mathrm{s}^2 - v\mathrm{r}^2)$$

WhereΔE is the kinetic energy loss of projectile in J, *m* is the mass of the projectile in kg, *v*s and *v*r are striking and residual velocities of the projectile in m/s respectively. [6]

2.2 Ballistic Performance Evaluation Based On Back Face Signature (BFS)

The non-penetration test for armour performance evaluation is based on the measurement of the back face signature depression produced on the backing clay i.e Plastilina (clay). US National Institute of Justice (NIJ) is of the widely used as a standard. In this standard, the performance requirement and test method for human body protection against ballistic impact are listed in Table-6.

Table 6: Performance standard of NIJ Standard-0101.04 [12]

Armor Level	Protection
Type I (.22 LR;.380 ACP)	• This armour would protect against: Nominal masses of 2.6 g , .22 Long Rifle Lead Round Nose (LR LRN) bullets at a minimum velocity of 329 m/s or less and 6.2 g against 380 ACP Full Metal Jacketed Round Nose (FMJ RN) bullets impacting at a velocity of 322 m/,this armour is light & providing minimum level of protection .It is no longer part of the standard.
Type IIA (9×19mm;.40 S&W;.45 ACP)	• New armour protects against: Nominal mass of 8 g , 9×19mm Parabellum Full Metal Jacketed Round Nose (FMJ RN) bullets at a impacting velocity of 373 m/s ± 9.1 m/s).Nominal mass of 11.7 g, .40 S&W caliber Full Metal Jacketed (FMJ) bullets at a impacting velocity of 352 m/s ± 9.1 m/s andNominal mass of 14.9 g , .45 ACP Full Metal Jacketed (FMJ) bullets at a impacting velocity of 275 m/s ± 9.1 m/s . • Conditioned armour protects against: Nominal mass of 8 g , 9mm Full Metal Jacketed Round Nose (FMJ RN) bullets at a impacting velocity of 355 m/s ± 9.1 m/s),Nominal mass of 11.7 g, .40 S&W Full Metal Jacketed (FMJ) bullets at a impacting velocity of 325 m/s ± 9.1 m/s ;and Nominal mass of 14.9 g , .45 ACP Full Metal Jacketed (FMJ) bullets at a impacting velocity of 259 m/s ± 9.1 m/s .It also provides protection against the threats mentioned in Types I.This body armour is well suited for full-time use by police departments, particularly those seeking protection for their officers from lower velocity 9mm and 40 S&W ammunition.
Type II (9 mm; .357 Magnum)	• New armour protects against: Nominal masses of 8 g ,9 mm full metal jacketed round nose (FMJ RN) bullets at a impacting velocity of 398 m/s ±9.1 m/s ;andNominal masses of 10.2 g (158 gr) .357 Magnum Jacketed Soft Point bullets at a impacting velocity of 436 m/s ±9.1 m/s. • Conditioned armour protects against: Nominal masses of 8 g ,9 mm full metal jacketed round nose (FMJ RN) bullets at a impacting velocity of 379m/s ±9.1 m/s; andNominal masses of 10.2 g (158 gr) .357 Magnum Jacketed Soft Point bullets at a impacting velocity of 408 m/s ±9.1 m/s.It also provides protection against the threats mentioned in Types I and Type IIA.Type II body armour is heavier and more bulky than either Types I or II-A. It is worn full time by officers seeking protection against higher velocity.
Type IIIA (.357 SIG; .44 Magnum)	• New armour protects against: Nominal masses of 8.1 g,.357 SIG FMJ Flat Nose (FN) bullets at a impacting velocity of 448 m/s ± 9.1 m/s;

	andNominal masses of 15.6 g ,.44 Magnum Semi Jacketed Hollow Point (SJHP) bullets at a impacting velocity of 436 m/s ± 9.1 m/s. • Conditioned armour protects against: Nominal masses of 8.1 g,.357 SIG FMJ Flat Nose (FN) bullets at a impacting velocity of 430 m/s ± 9.1 m/s; andNominal masses of 15.6 g ,.44 Magnum Semi Jacketed Hollow Point (SJHP) bullets at a impacting velocity of 408 m/s ± 9.1 m/s. • It also provides protection against most handgun threats, as well as the threats mentioned in [Types I, IIA, and II]. • This body armour provides the highest level of protection currently available from concealable body armour and is generally suitable for routine wear in many situations.
Type III (Rifles)	• Conditioned armour protects against: Nominal masses of 9.6 g ,7.62×51mm NATOM80 ball bullets at a impacting velocity of 847 m/s ± 9.1 m/s .It also provides protection against the threats mentioned in [Types I, IIA, II, and IIIA]. • This body armour is clearly intended only for tactical situations when the threat warrants such protection, such as barricade confrontations involving sporting rifles.
Type IV (Armor Piercing Rifle)	• Conditioned armour protects against: Nominal masses of 10.8 g , .30-06 SpringfieldM2 armour-piercing (AP) bullets at a impacting velocity of 878 m/s ± 9.1 m/s . • It also provides at least single hit protection against the threats mentioned in [Types I, IIA, II, IIIA, and III]. • Type IV body armour provides the highest level of protection currently available. Because this armour is intended to resist "armour piercing" bullets, it often uses ceramic materials.

2.3 Ballistic test setup

In this test (Figure 1), the velocity of a projectile is determined by two chronographs, Total 48 rounds will be fired to complete the test. No penetration is allowed. 16 measurements at normal obliquity will be record and no depth of back face signature is allowed to be greater than 44 mm.

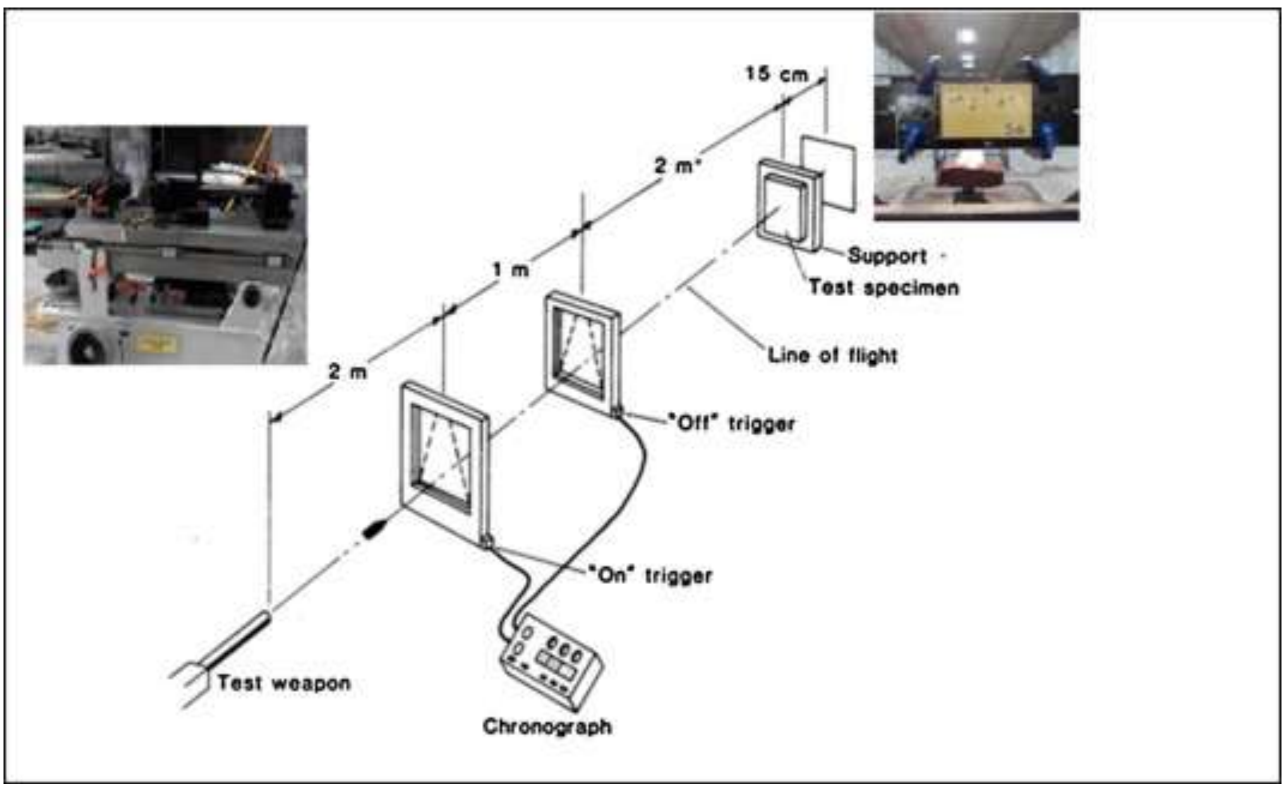

Figure 1: Schematic of ballistic test setup (Ballistic Resistant Protective Materials NIJStandard 0108.01.

2.4 Ballistic Testing V50 and V0:

The primary independent variable in ballistic testing is the penetrating capacity& velocity of a bullet.So for measuring the ballistic performance of armour is totally based on determining the kinetic energya bullet at impact. The key measurement is the velocity at which no bullets will penetrate the armour known as **zero penetration velocity**

(V0).Variability can be reduced the predictive power of a determination of V0. If for example, the V0 of an armour design is measured to be 490 m/s with a 9 mm FMJ bullet based on 30 shots, the test is only an estimate of the real V0 of this armour. If there is a variability, the V0 is tested again with a second group of 30 shots on the same vest design, the result will not be identical.

Another concept in ballistic testing called V50, i.e. the velocity at which 50 percent of the shots go through and 50 percent are stopped by the armour. The aim is to get three shots that penetrate and a second group of three shots those are stopped by the armour within a specific range of velocity.

III. LITERATURE REVIEW

S.N.	Title of Research Paper	Writer of Research Paper	Methodology Adopted	Result
1	Recent Trends in Ballistic Protection[1]	L Wang, S.Kanesangam, R. Nayak R. Padhye	Computational simulation using finite element (FE) analysis is a very useful tool to study the effect of material and architecture on the ballistic performance of the fabrics.	Modern weapons are becoming and lethal whether they are designed to be used against individuals or as weapons for mass destruction. Hence, the designing of protective clothing is really challenging for the developers and researchers. No matterhow sophisticated the weapons become or how remotely they can be used, humans are still likely to be needed in close proximity to targets. Parameters such as extreme environmental and weather conditions (cold, rain, wind, sunlight, snow and dust) should be taken into consideration when selecting material and designing protective clothing.
2	Ballistic Resistant Body Armor: Contemporary and Prospective Materials and Related Protection Mechanisms [2]	N. V. David X.-L. Gao J. Q. Zheng		The development of high performance fabrics for the next generation body armor will depend heavily on high tenacity yarns made from fibers with high modulus, high strength, and excellent anti degradation traits. It has been established that ceramic tiles made from SiC and Al2O3 and polymer composites including nanocomposites will, respectively, be the excellent candidates for the frontal and back face components of the laminated integral and/or the hybrid armour systems. Utilization of natural fiber composites for body armour design is a viable option, and attempts that have been made to investigate the ballistic performance of woven fabrics based on natural fibers provide the testimony for an encouraging future of this class of materials.
3	Bullet – Proof Vests with the Ballistic Inserts Based on the Fibrous Composites[3]	J. Polak, I.Kucinska, G. Grabowska J.BlaszczykE. Ledwon, R. Romek, M. H. Struszczyk	They were tested in the Institute's laboratories (metrological and ballistic one) accredited by Polish Centre.	Modern ballistic body armours and covers for transportation means as well as for buildings made on a basis of textile composites". This shall allow for assessment of not only protection efficiency, but also the ergonomics together with estimation of psycho-physical and psychomotor abilities of the wearers during long-time using of such a product
4	Sugarcane bagasse waste in composites for multilayered armor[4]	Sergio N. Monteiro , Veronica S. Candido , Fabio O. Braga , Lucas T. Bolza, Ricardo P Weber , Jaroslaw W. Drelich	Scanning electron microscopy (SEM) reveals microstructural details of a bagasse fiber. Thermogravimetric analysis (TG/DTG) was conducted in a model 2910 TA Instrument at a heating rate of 10 _C/min under nitrogen.	Fibers extracted from sugarcane bagasse waste were incorporated into an epoxy matrix to fabricate composite plates used as the second layer in a multilayered ballistic armor system (MAS) for personal protection against high impact energy ammunition. The indentation (body trauma) related to MAS with traditional KevlarTM is similar to that with bagasse fiber composite. The application proposed for bagasse waste is also in accordance with the current trend towards incorporating natural fibers into polymer composites, and reducing the environmental impact of plain bagasse waste.
5	The Effects of Stacking Sequence Layers of Hybrid Composite Materials in Energy Absorption under the High Velocity Ballistic Impact Conditions: An Experimental Investigation [5]	Elias Randjbaran*, Rizal Zahari, Dayang Laila Majid, Nawal Aswan Abdul Jalil, Ramin Vaghei and Ramin Ahmadi	The specimens were produced by hand lay-up method. The experimental set-up was according to guidelines given in the NIJ Standard 0108.01.	The results show, first, the Hybrid 2 has the superlative energy absorption of 95.17 J. Second, it can be concluded that stacking the first layer with glass fibre is better than to use the Kevlar fibre, according to hybrid 2 and hybrid 4 impact specimens with ballistic impact energy absorption of 95.17 J and 95.15 J respectively. Moreover, the results indicated that using the combination of carbon and glass is more efficient to use in the central layers. Third, in accordance to Hybrid 1 with ballistic impact energy absorption of 94.36 J, using the carbon fibre is not recommended at the last layer.

6	Bulletproof Vest and Its Improvement – A Review [6]	Naveen Kumar	Fiber manufacture tests the fiber and yarn tensile strength, and the fabric weavers test the tensile strength of the resultant cloth	1. This paper tells us different properties of materials like Kevlar, spectra shield etc. 2. We learn how we can increase performance of bulletproof vest. By using grapheme, UHMWPE, Dyneema etc. 3. The final conclusion of this paper that Dyneema SB61 is best material for making bulletproof vest as it is waterproof and light weight. 4. We can use the fabric (developed in California University) in bulletproof vest to make sweat away from body. So a soldier can wear it 24 hours.
7	Enhancement in ballistic performance of composite hard armor through carbon nanotubes [7]	Jason Gibson, James McKee, Gregory Freihofer, Seetha Raghavan & Jihua Gou	The processing techniques to make various armor composite panels consisting of Kevlar29 woven fabric and the subsequent V50 test results for both 44 caliber soft-point rounds and 30 caliber FSP (fragment simulated projectile) threats are presented. SEM imaging &Raman Spectroscopy was also utilized.	In this study, MWCNTs were utilized in both interleaving and dispersion into composite laminates and evaluated for their ballistic performance. Raman Spectroscopy was successfully utilized to get a representation of the amount of kinetic energy absorbed during stress wave propagation in a ballistic event through the measurement of residual strain in Kevlar®29 fibers.
8	Ballistic performance of hybrid thermoplastic composite armors reinforced with Kevlar and basalt fabrics [8]	Aswani Kumar Bandaru, Suhail Ahmad, Naresh Bhatnagar	Ballistic performance of hybrid thermoplastic composite armors reinforced with Kevlar and basalt fabrics of 2D plain woven (2D-P) and 3D angle interlock (3D-A) architectures was investigated through experiments and simulations	Based on the ballistic impact tests and predictions made from hydrocode simulations, the following conclusions were drawn: -The implemented material model was able to predict the different failure modes such as matrix cracking, fiber failure, shear plugging and delamination efficiently for thermoplastic hybrid armors. -There was no significant influence of stacking sequence on the front face damage patterns, however, it was changed for back face damage patterns. -The H-1 armor was failed to withstand 9mm FMJ while the H-2 armor was confronted successfully in a velocity range of 366.52–415.22 m/s. -The H-2 armor exhibited full perforations beyond the velocity of 415.22 m/s. Out of six rounds, three partial and three full perforations were observed.
9	Design and analysis of weightless bullet proof jacket [9]	S.Eswaran , P.Sasithara, A.Soundha, R.Kavibharathi,R. T.PrabhuKumaran	Finite element analysis	Finite element analysis is carried out on the Full Cure 720 and Mild steel to determine the deformations and stresses when it is striked with high bullet of velocity 879m/sec. While comparing of other materials using of polymers and M.S.is give better output. They are having the desired mechanical properties i.e good strength, resistance to chemical reactions, less moisture sensitivity.

IV. CONCLUSIONS

Body armor design has evolved into the present form over thousands of years of improvement and with the help of advances in materials science. As Modern weapons are becoming more sophisticated so the designing of protective clothing is really challenging for the developers and researchers. The major aim of modern body armour should keep the combatants alive and comfortable in addition to providing the desired level of protection with less fatigue . The main factors that directly influence the ballistic limits of body armor systems aredensity, elastic modulus, strength, toughness, thickness, type and velocity of projectile, and material configuration andmost important properties that affect the projectile defeat mechanisms and influence the impact energy absorption of body armor. In addition, other parameters such as environmental and weather conditions (rain, wind, dust, sunlight, coldand snow) should be taken into consideration when selecting material and designing protective clothing.

V. FUTURE SCOPE

For the manufacturing of body armour a design concepts motivated by nature as the use of natural fiber composites for body armor design is a viable option .Various attempts should be investigate for encouraging future of this class of materials to improve the ballistic performance of woven fabrics based on natural fibers . These natural fiber based woven fabrics have unique advantages in the context of biodegradability environmental safety, and manufacturing cost.

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