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Ballistic protective clothing: An overview

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Various materials have been employed in the past for the protection against the ballistics with only limited satisfaction without realizing the underlying mechanism of ballistic impact. With the advent of high performance materials and computing techniques in the recent years, the mechanism of ballistic penetration has clearly been established, paving a path for the selection of newer materials for better protection and satisfying the requirements of both the wearer and the technologist. This review attempts to coalesce the ideas of exuberant research that has gone into the field of ballistic protection right from material selection to modelling with emphasis on evaluation methods and mechanism.

Keywords: Armour, Ballistics, Ceramics, Kevlar, Penetration mechanism, Projectile velocity, Soft composites, Spider silk, Ultra-high modulus polyethylene fibre

1 Introduction

Ballistic protection is a class of protective clothing which aims at protecting the individuals from the bullets and steel fragments from hand-held weapons and exploding munitions. The use of armour to protect the personnel has a long history and dates back to time immemorial. As the man developed newer weapons with time, he also looked for better clothing for protection. The list of armour materials has included every conceivable material[1-5] including the traditional materials like aluminium, steel and less traditional ones like leather and silk. The best known method of protecting the human body in old days from all kinds of missiles, was to use a hard rigid material which resisted the penetration and dissipated the load of impact[6-11]. With the advent of synthetic textiles, better ballistic protective systems have been developed. Although the basic idea of spreading the load over a large area is still applied, it is better to dissipate the energy of impact by deformation and breaking the protective material. Nylon, which has high work of rupture (toughness), was thought to be ideal for ballistic protection. However, it became very clear that simple toughness is not the only criterion for ballistic protection. Then came the use of aramids due to the fact that ballistic protection process is a complex phenomenon involving the transverse velocity propagation, tensile properties and the fine structure. In the recent years, ultra-high modulus polyethylene (UHMPE) fibres produced by gel spinning witnessed increased application in the ballistic protection systems[12-15] due to a host of properties which make these fibres highly suitable for ballistic protection.

With the current trend towards eco-friendly and natural products for various applications, spider silk is gaining importance in ballistic protection. The spider silk is obtained from a spider, 'Black Vido', found exclusively in South America with some exceptional properties like elongation at break up to 270% and strength higher than Kevlar fibre.

In this review, a brief account of various fibres used for the designing of ballistic protective clothing has been given. The penetration mechanism and the modelling of ballistic protection has also been discussed.

2 Ballistic Requirements

The basic objective of the body armour research is to manage the conflicting goals of producing low-cost, light-weight yet comfortable ballistic protection systems with superior performance.

No armour design is suitable for all the situations[8] and the armour system produced for a specific application should be able to fit in both user's and technologist's points of view. For users, the comfort, degree of mobility and maximum protection against injury/trauma are important, while for technologists, the level of protection required, time span for which the protection is required, and energy absorption characteristics of the material are important.

In normal warfare, one tries to ensure minimum weight of the protective garment with maximum personal mobility and maximum protection. Therefore, in designing the protective garment normally the legs and arms are left exposed, as injury on these parts is least likely to cause death and the vital organs like heart, liver, etc. are covered. This provides additional advantage of mobility. Since these garments are worn for greater duration, comfort along with protection are given greater importance. On the contrary, for more hazardous jobs like bomb disposal, heavy weight garment is employed covering the whole body. Here, the overall protection, not the comfort and mobility, is important.

Energy absorption characteristics of the body armour[16-18] are very important. According to Capilli and Rothulzen[11], five types of energy absorption occur to fulfil the basic function of personnel body armour. These include:

- Kinetic energy of the out-of-the plane fabric movement (the pyramid).
- Strain energy accumulated in the yarns of the pyramid.
- Kinetic energy of the fabric moving towards the point of initial impact, in the original fabric plane between the pyramid and the longitudinal wave form.
- Strain energy accumulated in the original fabric plane between the pyramid and the longitudinal wave form.
- Energy dissipated as heat by friction (fibre/fibre & fibre/projectile).

More details regarding energy absorption characteristics will be dealt later.

3 Material Selection

No armour design is suitable for all the situations and the performance of the protective system depends on the interaction of its various components. Hence, it is important to understand the mechanism of the ballistic protection by which generalizations can be made regarding the ballistic efficiency of the system[6,7].

3.1 Fibre Selection

The bullet-resistant clothing has to stop the bullet from penetrating and absorb its kinetic energy converting it into work of deformation. Therefore, the primary factors which influence the performance of bulletproof or protective material are strength, modulus and elongation at break, deformability of the projectile and the velocity of transverse shock wave in the fibre. Some of the important properties of various fibres considered for armour applications are given in Table 1.

3.1.1 Nylon 66

Nylon fibres were the material of choice for most of the ballistic applications in the early days. During the second world war, American Army produced 'flak jackets' using steel plates with nylon 66 backing[8]. Nylon usually absorbs twice the amount of energy as *p*-aramids (Fig. 1).

In *p*-aramids, the transverse wave velocity is almost 3-4 times higher to that in nylon. Hence, stress propagation is more efficient with aramids which is clear from Fig. 2. Here, the elongation of the yarn around the point of impact[10] was measured approximately 10 μs after the shot was fired at a speed of 400 m/s. It is evident that the strain in *p*-aramid fibre fabric is spread over a much larger area and the elongation is much lower. Moreover, nylon creeps under such high strain rates at which the

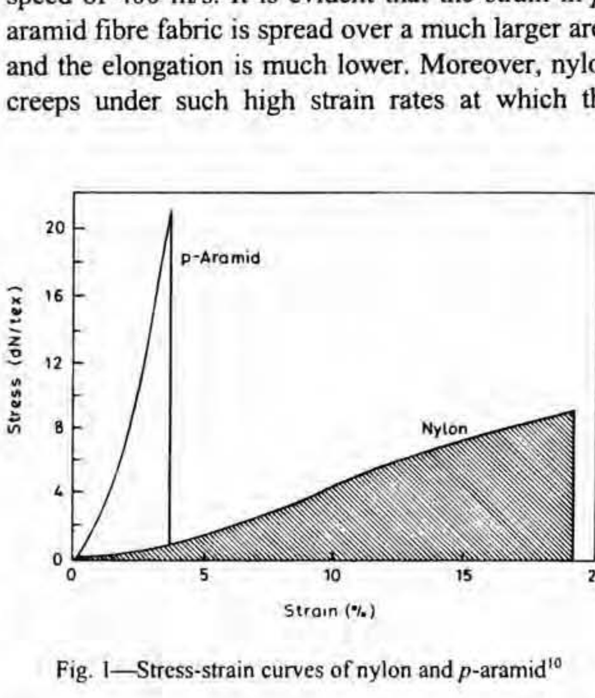

Fig. 1—Stress-strain curves of nylon and *p*-aramid[10]

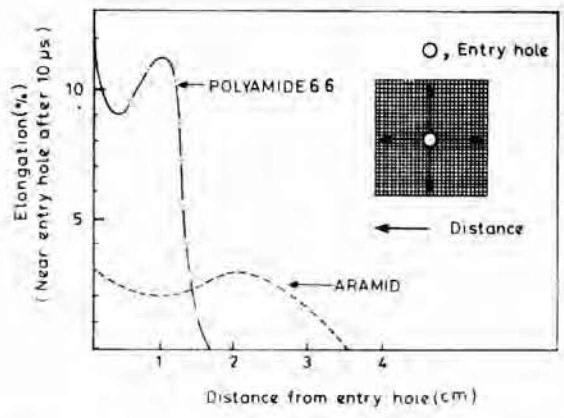

Fig. 2—Ballistic comparison between nylon 66 and aramid fibre fabrics[22]

ballistics operate and sometimes melting and fusion at the interlacement points has also been noted[18].

3.1.2 Aramids

Since its inception in 1972, Kevlar readily replaced the nylon in the ballistic protective garments due to its good dynamic energy absorption characteristics, high specific strength and modulus, and excellent thermal properties.

High T_g and thermal stability ensure integrity of the ballistic structure at relatively high temperature in the event of ballistic impact. Its highly crystalline and oriented structure gives rise to high dynamic modulus which enhances the rate of wave propagation to 7700 ms^{-1}, which is 3-4 times higher than that for nylon[19], and rapid response to longitudinal deformation. This high wave speed along with specific modulus is instrumental for its ability to involve large volume of material which is a critical factor in ballistic protection. Moreover, high tenacity and moderate elongation of Kevlar aramid fibres provide high toughness and results in fairly effective absorption of longitudinal strain energy and transverse kinetic energy of the ballistic impact.

Kevlar has a tenacity of 18-26 gpd (Table 1 & Fig. 3), twice that of nylon or glass fibres[20], with an elongation of only 1.5-4.4% and initial modulus of 430-1100 gpd. Its specific modulus lie in between those of fibreglass, boron and carbon fibres.

Kevlar fibres support large fraction of their breaking load for longer time than nylon or polyethylene (PE). Using a safety factor of 2-3, Kevlar provides a service life of >100 years, nylon

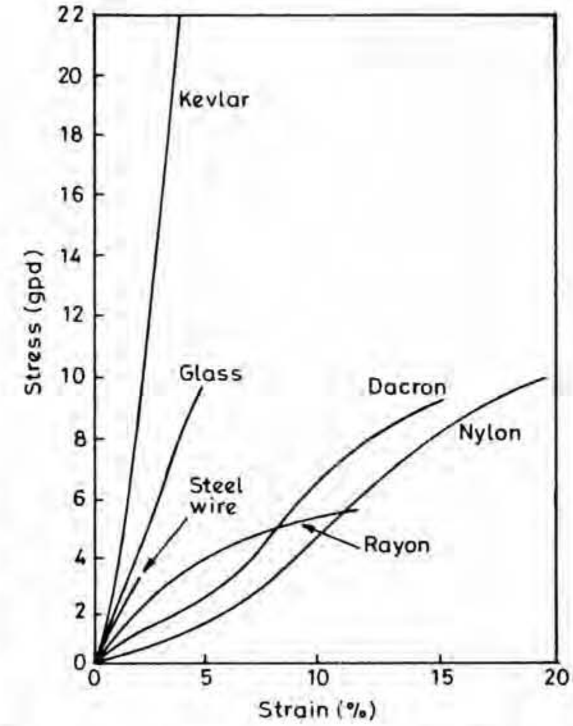

Fig. 3—Stress-strain behaviour of various high performance fibres and steel wire[20]

3-4 years, while PE insignificant at 0.5 fraction of normal breaking load (Fig. 4). Hence, Kevlar outperforms most of the materials.

Kevlar creeps little at low loads due to high crystallinity and orientation, but creeps under relatively high stresses. Creep rate is almost uniform and the amount of creep strain increases linearly with log (time) to break.

Kevlar has relatively low compressional properties. When subjected to axial compression or severe bending, it will undergo plastic deformation in the form of bands at 55-60° to the fibre axis called as "KINK BANDS" which is due to its structural anisotropy. The axial compressive strength of Kevlar fibre is about 1/5 of the tensile strength, while compressive strain at the fibre yield point is 0.5% compared to 2.5% at the tensile break. Properties of the various commercially available aramid fibres are given in Table 1.

3.1.3 Ultra-High Modulus Polyethylene (UHMPE)

The commercial success of these fibres is due to their outstanding mechanical properties, their unmatched damage tolerance, fatigue resistance and their ability to fail in shear or compression without

Table 1—Properties of high performance fibres[20]

Fibre type	Density gcm^{-3}	Strength gpd (GPa)	Elongation %	Modulus[a] gpd (GPa)	Maximum use temp. °C	Wave velocity[b] ms^{-1}
Aramids						
Kevlar 29	1.43	23 (2.9)	3.6	550 (70)	250	6996
Kevlar 49	1.45	23 (2.9)	2.8	950 (135)	250	9649
Kevlar 119	1.44	24 (3.1)	4.4	430 (55)	250	6180
Kevlar 129	1.45	26.5 (3.4)	3.3	780 (99)	250	8263
Kevlar 149	1.47	18 (2.3)	1.5	1100 (143)	250	9863
Nomex	1.38	5 (0.6)	22	140 (17)	250	3509
Technora	1.39	27 (3.3)	4.3	570 (70)	250	7096
Ekonol	1.4	31 (3.8)	2.6	1100 (136)	150	9856
Vectran	1.47	25 (3.2)		700 (91)	150	7868
UHMPE						
Spectra 900	0.97	30 (2.6)	3.5	1400 (120)	100	11123
Spectra 1000	0.97	35 (3.0)	2.7	2000 (171)	100	13277
Carbon fibres						
Thornel P55 (Med M)	1.8	10.8 (1.7)		1940 (308)	500	13081
Thornel P100 (HM)	1.96	10.8 (1.86)	0.38	3300 (517)	600	16241
Celion 3000 (HS)	1.8	25 (4.0)	1.8	1440 (230)	500	11304
Ceramics						
Boron	2.5	11.6 (2.55)	1.0	1800 (400)	2000	12649
SiC	2.8	16 (4.0)	0.6	1700 (420)	1300	12247
Alumina	3.25	6.3 (1.8)	1.2	730 (210)	1200	8038
Nextel	2.5	7.8 (1.72)	2	690 (152)	1200	7797
E-glass	2.55	11.6 (2.6)	3	320 (72)	350	5313
S-glass	2.48	21.9 (4.8)	5.3	390 (85)	300	5854

[a]Modulus (GPa)=(gpd×density)/11.33; and [b]Wave velocity = $\sqrt{\frac{\text{modulus}}{\text{density}}}$

Fig. 4—Tensile behaviour of various fibres under fixed load with time[20]

losing great amount of tensile strength. On the weight basis, they are the strongest and almost the stiffest commercially available materials offering the highest percentage of absorbed energy versus total impact energy[13].

One of the most interesting features of UHMPE is the large modulus increase with increasing rate of deformation, particularly at elevated temperature[21]. About 40% increase in tensile strength involving ballistic impact with deformation rates exceeding 10^3 min^{-1} (from 4 GPa at room temperature to 5.6 GPa) is because of the unique morphological structure of UHMPE. In addition, due to its low density (0.97 for Dyneema and Spectra compared to 1.45 for Kevlar) the velocity of longitudinal stress wave is very high, reaching a value almost equal to that of diamond[12]. All the above factors make the

UHMPE the most sought material for ballistic protection.

Fig. 5 shows interesting relationship between the energy absorption and diameter of the projectile. It can be readily seen that at smaller diameter of projectile, aramid structures are advantageous due to high coefficient of friction. In all the other conditions, Spectra (UHMPE) outperforms Kevlar.

Despite all the advantages of UHMPE like specific strength, light and chemical resistance, low specific weight and good dynamic properties, negligible moisture sensitivity[14], it is the creep, low temperature resistance, adhesion and compression properties that limits its application. Various UHMPE fibres are commercially available under the trade names like Dyneema SK 60 from DSM and Spectra from Allied Signals.

3.1.4 Carbon Fibres

Carbon fibres have very high modulus and tensile strength. Fig. 6 shows that energy absorption rate increases steadily with the modulus, but flattens out as the fibre modulus exceed 500 gpd, signifying that while high modulus is needed to achieve high rate of wave propagation, but is accomplished only at the cost of elongation at break. Thus, increasing the fibre modulus would generally increase the fibre brittleness and ultimately would reduce its ability for strain energy absorption.

Carbon fibres being high-modulus and high-tenacity fibres and having very low strain-to-failure would shear readily under compression (Fig. 7) as reported by Tanner[22]. These factors make carbon fibres unsuitable for ballistic applications.

3.1.5 Ceramics

Though ceramics have very high density values as metals (Table 2) they are still suitable for ballistic applications, primarily due to high compressive strength and hardness. Since the dynamic stress limits of ceramics are higher[1], sharp point of the projectile is quickly eroded, leaving less effective blunt cylinder having lower mass. This would greatly reduce the energy of impact, further enhancing the effectiveness of ceramics. However,

Table 2—Density and HEL of common ceramics[2]

Material	Density g/cm³	HEL GPa
Al_2O_3	3.98	11.2
Al_2O_3	3.92	9.2
B_4C	2.50	15.0
Glass	2.48	7.3
BeO	2.84	8.5
MgO	3.57	8.9

HEL: Hugoniot Elastic Limits

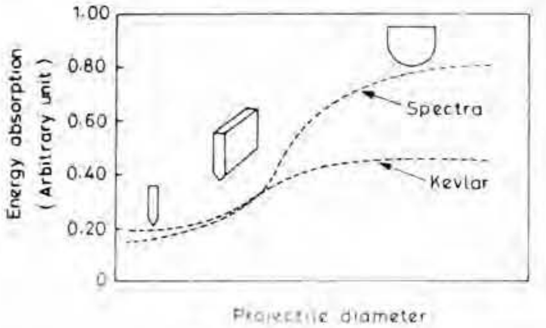

Fig. 5—Energy absorption characteristics of Kevlar and Spectra[12]

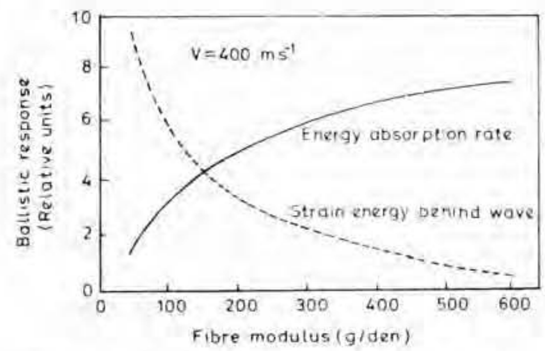

Fig. 6—Effect of carbon fibre modulus on ballistic response [Units (Y axis), 10 = 0.03 gpd for strain energy and 900 gpd for energy absorption rate[21]]

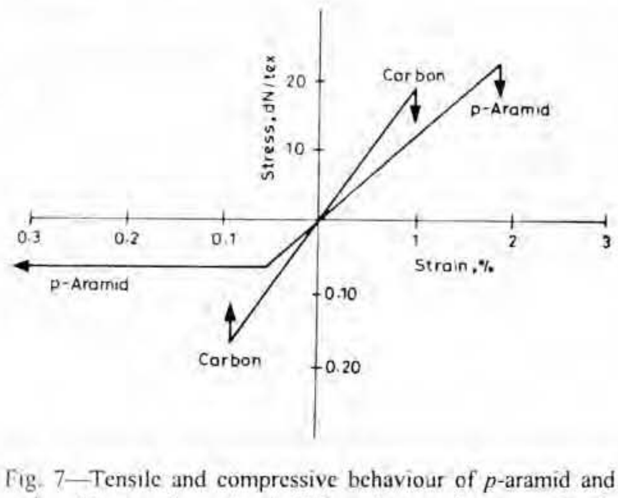

Fig. 7—Tensile and compressive behaviour of *p*-aramid and carbon fibres with tension in NE quadrant and compression in SW quadrant[22]

inherent brittleness and lack of flexural strength of ceramics renders them incapable of being used alone as single material for the fabrication of the armour.

3.2 Influence of Yarn Structure on Ballistic Protection

Friction plays an important role in the ballistic protection, which, in turn, depends on the method of yarn production. Many of the fibres commonly used for ballistic protection are highly drawn, hence the fibre surface is smooth which means that in the event of an impact by any object there is a tendency for the yarns to slip apart simply because of their low coefficient of friction, e.g. UHMPE is highly drawn up to draw ratios of 20-30 with very low coefficient of friction. Therefore, efforts have been put to roughen the fibre surface by chemical or mechanical means to overcome this problem. Coating the surface of fibre is another slow and painstaking method. However, current practice is to use corona treatment[23]/plasma etching for surface treatment.

Such high friction fibres comprise a minimum in the total structure and should only be 10-20% by weight. Hogenboom[24] proposed that filaments with high coefficient of friction should be combined with fibres having high tensile strength and modulus and low coefficient of friction. The two types of fibres may even be twisted or core spun together as a yarn. It is also suggested that very thick high performance components may be combined with very thin high friction elements, leading to improvement in the performance.

For polyethylene ballistic-resistant fabric, Harpell *et al.*[15] suggested that the yarn with a denier of not more than 500 and a tensile modulus of atleast 200 gpd can be used.

It was also observed that the fabrics made from fine aramid yarns[9] of 220-440 dtex perform better than those made from the coarser yarns. But due to high costs of the finer yarns, usually 1,100 dtex is used.

Weinberg and Schwartz[25] reported that a twist level above 1 turn/cm for Kevlar yarns lowers the modulus and strength. A twist factor of 1.1 is found to be suitable for Kevlar yarns[20].

3.3 Fabric Design for Ballistic Protection

Cunniff[16] found that, to a large extent, the ballistic response of fabrics appears to be closely related to the ballistic response of the single yarns.

In woven fabrics, since there is an extensive interaction among the yarns due to interlacements, it was found that transverse deflection causes loading of the crossover yarns and up to 50% of the total energy absorption may occur in the secondary yarns. Therefore, fabric construction particulars have a major role in the final ballistic protection[16,26]. For instance, if the weave is too tight or the fabric is too stiff, deflection will be restricted, causing shear failure due to the concentration of stress at the impact point. Whereas too loose a weave or a soft fabric having low yarn-to-yarn friction would allow the projectile to penetrate easily by pushing the yarns aside or giving too much deflection which can cause serious injuries or trauma to the wearer.

Therefore, it is the balanced force distribution with maximum interlacements in a given unit area which makes plain weave construction most suitable for the ballistic protection. Various other weaves like basket, satin, crowfeet, etc., though inferior to plain weave, are employed depending on specific application.

Table 3 shows various weaves and construction particulars with Kevlar fibres employed for ballistic protection. A plain weave of 1,100 dtex aramid filament yarn with 31 x 31 threads/inch and 280 g/m^2 fabric weight is regarded as the standard material. Generally, warp with lower modulus and higher extension than weft with fabric having same stiffness in both warp and weft directions is preferred[24].

Xu and Weitsman[27] studied the compressive response of unidirectionally reinforced hexagonal arrays of graphite/PEEK composites by finite element analysis. Unlike the other models which assume layered geometries, the results of this study show the three-dimensional features of stress and displacement fields and exhibit the presence of significant stress concentrations in these hexagonal fibrous array.

Knitting though offers considerable advantage in terms of cost and in the production of final design of contoured armour[8], it has never proved to be successful in the armour field due to the degree of interlocking of the yarns that occur in the knitting process.

Table 3—Ballistic fabrics of Kevlar 29 and Kevlar 129 aramid[20]

Kevlar	Yarn size		Weave	Ends/cm×Picks/cm	Wt of fabric
	Denier	Decitex			g/m^2
29	1000	1110	Plain	12.2×12.2	282
29	1500	1670	Plain	9.4×9.4	326
29	1500	1670	Plain	6.7×6.7	231
49	1420	1580	Plain	6.7×6.7	231
29	1500	1670	2×2 basket	13.8×13.4	475
29	1500	1670	8×8 basket	18.9×18.9	669
29	3000	3330	Plain	6.7×6.7	475
29	3000	3330	4×4 basket	7.9×7.9	550
29	3000	3330	4×4 basket	9.4×9.4	672
129	840	935	Plain	12.2×12.2	231
129	840	935	Plain	12.2×12.2	231

Needle-punched nonwovens are useful in the ballistic applications. For ideal ballistic protection, the nonwoven felt has to have a high level of entanglements of long staple fibres with only a minimum degree of needling, as excessive needling can produce too much of fibre alignment which would aid projectile penetration. Considerable care, therefore, should be taken to optimize the felt structure.

Felts of lower weights are probably the most effective materials known for ballistic protection. The effectiveness decreases as the weight increases and the nonwovens are overtaken by woven textiles and ultimately by ceramics and metals at higher projectile velocities.

3.4 Finishes for Ballistic Protection

It is interesting to note that the performance of garments for ballistic protection is influenced significantly with the moisture content, weaving oils, sizes and other lubricants present in addition to the fabric weave and other weaving parameters. This is due to the fact that the interfacial behaviour of the yarns is altered, so is the yarn mobility in the fabric, due to the presence of moisture or weaving oils.

Ballistic protective garments are therefore made hydrophobic[9]. About 40% reduction in the ballistic protection has been observed when the bulletproof garment is made wet without any change in the properties of the component yarns[8,9]. This suggests that water acts as a lubricant between the projectile and the fabric.

Scouring of the fabrics is therefore necessary to remove the size, oils, etc. in addition to the anti-slip finishes to the ballistic protective garment which would increase the cohesion between the warp and the weft yarns.

Lamination of the fabric has been found to increase the anchoring strength of the yarn by a factor of about 10-15. As a consequence, the yarns hit by bullet do not pull from the fabric. Another positive aspect of the coating is that the yarns movement is impeded in their sideward displacement by piercing projectiles. Kevlar coated with neoprene chlorosulphonated polymer elastomer is resistant to acids, fire, toxic gases and steam and is able to form an impermeable seal[28].

Temmerman[29] used electroless metallized materials to coat a layer on the fabrics which improved lightning strike protection.

Ward[30] found that for UHMPE, oxygen plasma treatment reduced the delamination during impact with a corresponding reduction in energy absorption.

Aramid fabrics coated with heat-resistant fluoro polymers showed improved sputtering resistance for steel mill workers. The film is formed at an angle of 0-200°. The composite fabric of *m*-aramid, *p*-aramid and fire-resistant rayon was impregnated with a fluoroolefin-vinyl ether copolymer, squeezed and treated at 110-160 °C for 8 min to give good sputtering resistance[31].

Nonwoven felts manufactured from linear polyethylene[32] modified by corona/plasma treatment or with a filler by folding the web of the carded fibres in zigzag direction, calendering, stretching in transverse direction, stitching or hydroentangling, gave high impact resistance than conventional textiles.

Apart from polyethylene, fabrics comprising *p*-phenylenediamine-terephthalic acid copolymer having elongation at break > 4 %, modulus <600 gpd and breaking strength >24 gpd showed good ballistic properties[33].

In addition to all these, armour made from Kevlar should have an extra finish which would reduce the UV light absorption, as Kevlar loses strength upon exposure to UV light. While for the armours made from PE, a finish is required to reduce the creep.

4 Designing of Ballistic Protective Clothing

Principally, two classes of materials, viz. fibrous materials and ceramics, have emerged having great potential in the designing of the ballistic protective garments / composites.

Depending on the mode of their application, ballistic protective clothing can be broadly divided into soft armour made from textile material, and composite laminate armour or hard armour.

4.1 Soft Armour

Soft armour is constructed from multiple layers of woven fabric without a resin binder, sewn together with meander or crosswise seam. Depending on the calibre to be stopped and the yarn count, the number of fabric layers in making a bullet proof vest varies from 10 to 50 weighing around 3 kg. Various fabric layers are stacked with parallel yarn alignment which harbours the risk that two bullets impacting in succession at not too great a distance from each other will damage the same warp or weft yarn in all the layers. The layers are sewn together with high tenacity aramid sewing threads which seem to perform better if they are close together due to the fact that these sewing threads themselves participate in the energy absorption. It has been observed[9] that very high stitch frequencies of the order of 10 stitches /cm^2 can reduce the fabric yarn tenacity by up to 40%.

Kunzendorf[34] reported that Kevlar fibres woven in plain weave with fabric weight up to 200 g m^{-2} with careful wash treatment made into 3 quilted layers offer protection against the pistol bullets. The wearer suffers mearly a haematoma from the impact of the bullet.

Allied Signals[35] revealed the construction particulars for ballistic protective garments: multilayer construction with 20-30 layers, stitched together using threads of high modulus (~200 gpd), with areal densities in the range of 3.5 ~ 6.2 kg/m^2 made out of Kevlar or UHMPE.

Montgomery[36], in an interesting experiment, revealed the construction particulars of 10 layers of Kevlar 49 plies sufficient to prevent complete penetration of the bullets within a impact velocity range of 200-400 ms^{-1}.

Yarn linear density, 1490 den; Weave, plain; Ends/cm × picks/cm, 9.45 × 9.45; and Fabric weight, 330 g/m^2.

Projectile – For 0.22 calibre, 2.6 g, RNSP: V_{50} 334 ms^{-1}
For 0.38 calibre, 10.2 g, RNSP: V_{50} 309 ms^{-1}

Study also revealed that the more pointed projectiles are not decelerated as fast as the blunt ones.

Sacks[37], in a US patent, disclosed a light weight bulletproof garment consisting of several layers sandwiched between an outer cover. The layers comprise closely woven fabrics made from aramid fibres of high tensile strength and high stretch resistance.

Zufle[38] also described the construction of a bulletproof garment which includes an outerlayer and inner layer stitched together. Total structure comprises several layers of different ballistic materials including an outer layer of Kevlar, which serves as fireproof material as well as an impact absorbing surface, and a reinforcing ply. Inside this outerlayer are eight plies of spectra shield, ten plies of Kevlar and beneath are the eight plies of spectra shield and a single ply of Kevlar. A reinforcing panel of 1.5 mm made from Lexan polycarbonate is positioned against this last Kevlar ply. There is a reduction in the back-face deformation of the armour from normally expected distance of 3.2-3.6 cm to only 1.5-1.9 cm. This construction claims substantial increase in the resistance to penetration of projectile, thereby reducing the possibility of injury to the wearer.

4.2 Hard Armour

Composite laminate armour or hard armour consists of multilayered fabrics combined together with a resin binder. Another class of hard armour uses armour plates made out of ceramics and fibre-reinforced plastics (FRP) of about 10 mm thickness. The main function of such a vest is to reduce the shock effect on the body by absorbing the energy of impact partially or completely. The bullet also deforms upon impact with reduction in kinetic energy and hence can be easily stopped by subsequent layers[9].

Armours made from the resin binder show less dependence on weave construction as the matrix is responsible for the distribution of the energy to subsequent layers. Therefore, the choice of construction is often dictated by the particular type of projectile. For example, protection against fine projectiles requires a close weave and finer denier while large fragments can be effectively stopped with a loose weave and coarser denier.

Selection of the resin binder greatly influences the ballistic protection[1]. Ductile resins such as vinyl esters tend to perform better than more brittle or thermosetting ones such as epoxy. Resin showing increasing ductility absorbs more energy in both crack initiation and propagation. It has also been proved[9] that for best ballistic protection, resin content should be 20-25 wt%. Laminates with lesser resin content show increased ballistic protection, but the deformations are severe and unacceptable for most of the applications. For maximum ballistic efficiency, fibrous armours must be allowed to deflect and delaminate, hence should never be combined with rigid components in a way that restricts deflection.

A number of products and patents[39-48] have appeared in the recent past. Owens Corning fibreglass Corp[39] reported a rigid ballistic material which is fire resistant, smoke resistant, non-toxic, non-conductive, self supporting and stiff. The material is made by coating high strength magnesia alumino silicate glass fibres with a solution of partially-condensed low-molecular weight phenol formaldehyde resole reaction product, from which the solvent is evaporated. Coated fabrics are then heated to increase the resole molecular weight and to prepare easy handle prepeg. Plies of the prepeg are then moulded by heating under pressure when volatile by-products are escaped and then heating at elevated temperatures to get crosslinked resin.

Abott[8] reported the construction of the flak jackets to reduce the problem of trauma caused to the wearer due to the ballistic impact. Here, the protective panels intended for covering the body are equilateral metal triangles or hexagons fixed to the protective layers beneath. These are so arranged that the projectile cannot penetrate between the joints or overlay areas. This type of construction had a total weight of 3.5 kg compared to 3.9 kg of matching standard of Kevlar fabric vest. This design also offers more comfort and flexibility to the wearer.

Armellino and Armellino[40], in an US patent, revealed a ballistic protection wear comprising at least 3 plies of ballistic woven aramid fibre fabric each individually impregnated with resorcinol/formaldehyde latex, at least nine plies of non-impregnated ballistic woven aramid fibre fabric, and further a layer of impregnated fabric from the outer protective side to the inner side.

In another patent, Lee[41] disclosed the design of a bulletproof protective shield. It comprises layers of woven aramid fabric extensively bonded together to form a stiff region. An antiballistic ceramic tile is bonded to the laminate. An adhesively mounted metal plate or an additional stiff support of adhesively bound aramid or glass fibre layers may be disposed between the stiff regions and the tile. The shield may also include a trauma pack.

Lee[41] reported the use of light weight armour made out of Dyneema SK 60 or Spectra with aramids. Construction involves outer multilayers of aramid positioned in front of matrix comprising a first layer, a second layer and a mass of fibres arranged perpendicular to the layers.

Higham Ferrers[42] developed a range of ballistic materials, most of which are based on the use of glass fibres, incorporating Dyneema (UHMPE) or an aramid. These new types of materials not only have an impact absorbing surface, but also tend to retain the projectile rather than cause it to skid away. A combination of UHMPE and fine filament glass roving is capable of withstanding impact from most of the small projectiles and would also resist penetration of knives, daggers and even arrows.

In another patent, ICI[43] disclosed the construction of composite armour of a polymeric matrix reinforced with continuous filaments that will resist penetration by sharp objects. The matrix is normally a polymerizable liquid such as acrylic or methacrylic acids or methyl esters or styrene or some such mixtures. A second component will contain at least two acrylate or methacrylate groups such as triethylene glycol acrylate. The polymer matrix has a tensile modulus of at least 0.5 GPa.

There should be a strong fibre-matrix interface which should have a trans-flexural strength of at least 24 MPa, preferably > 50 MPa. The continuous filament reinforcement should be in the form of collimated filaments extending the length and width of the material. These continuous collimated filaments may be arranged in superimposed layers; filaments in adjacent layers being arranged transversely to one another.

In a typical construction, the filament content should be 30-70% by weight made out of UHMPE, aramids, carbon or glass. The armour developed will have an areal density of at least 6-8 kg/m^2. Another preferred alternative is based on the use of woven fabrics with balanced weaves such as plain or twill which may then be built up as layers to create quasi-isotropic orientation of the filaments in the resultant structure.

Allied Signals[44] reported a light weight, flexible nonwoven composite which is more effective than the conventional armour fabric. The spectra shield composite is based on UHMPE Spectra fibre which is coated with a very thin layer of polymer resin, cross-plied and then encapsulated in another thin protective film. This spectra shield is some 2.5 lb ft^{-2} (12.2 kgm^{-2}), lighter than either glass or aramid composites, and can withstand almost all the ballistics.

In a completely new approach to making a spectra shield[45], hundreds of fibre bundles are laid side by side in a unidimensional aligned beam, which is then drawn through bath of thermoplastic polymer to produce flexible composite layer, cut and cross-plied (in a 90° orientation) and pressed to produce a single ply. These plies are then stacked and pressed together for required ballistic application.

Sumitomo Bakelite Co. revealed[46] high strength polyethylene fibre-reinforced plastic composites with excellent impact resistance. The composite contains nonwoven fabric sandwiched between woven fabrics. This composite is made from isoprene rubber nonwoven fabric prepeg, sandwiched between bisphenol A epoxy resin. Woven fabric prepeg showed surface density of 6.1 kg/m^2 and thickness of 6.5 mm with no impact penetration.

High strength polyurethane composite especially useful for sails and ballistic-resistant articles has been reported by Allied Signals[23]. The composite consists of network of high strength fibres and thermoplastic polyurethane matrix material derived from an aliphatic diisocyanate and polyol.

DSM[47] reported the use of Dyneema SK56, a special ballistic yarn, for the applications where high energy absorption and low weight are the criteria. The armour is made by pressing resin-impregnated fabrics into the desired shapes. Lin *et al.*[48] have reported high strength composite for ballistic protective clothing made from a network of high strength fibres and a matrix compound made out of a vinyl ester and diallyl phthalate.

Bulletproof vests are generally so tailored that they protect the body all round, the front of the vest may be stronger than the back assuming that a shot will generally come from the front.

In a US patent, Coppage and Coppage[49] disclosed a bulletproof dress shirt that is adjustable to accommodate wearers of different sizes. It is made from standard dress shirt fabric and has inner layers on the front and back panels that are made from bicomponent materials to draw perspiration away from the wearer. In the garment there are panels that can be closed and which will hold removable bulletproof pads such as layers of Kevlar fabrics or a construction of woven Kevlar with layers of nonwoven spectra shield. The front of the shirt may have an additional layer of fabric enclosing as a vital area pad to meet the specific need. All pads are removable so that the front and back of the shirt can be laundered normally. Typical construction of garments consists of an outer layer of the shirt which is visible on the wearer which includes buttons, pockets and areas of stitching, and areas of shirt which does not open and merely gives the appearance of buttoning of the dress shirt.

Finally, it should be borne in mind that no single ballistic protective garment can provide complete protection against all types of projectiles. It is a compromise between various factors like the extent of protection required, cost, weight and comfort.

5 Performance Evaluation

For quantitative assessment of the performance of the ballistic protective clothing, two fundamental quantities, viz. ballistic protection and weight efficiency, are always considered[50].

5.1 Ballistic Protection

This gives details about the degree of protection provided by the armour against a specified projectile or a series of projectiles.

Most popular method[8] for testing is V_{50} which is defined as the approximation of the velocity at which 50% of the impact would result in complete penetration and 50% in partial penetration (i.e. stopped by the armour) or the projectile velocity at which the probability of penetration is 50%. It is determined by taking the arithmetic mean of an equal number of the highest partial and lowest complete penetrations impact velocities within an acceptable velocity range as described by Abott[8] and Stein[9].

Taking V_{50} as the measure of the efficiency, Blumberg[10] showed that at low weight per square metre, soft ballistics are more efficient than hard ballistics, while at weights greater than 10 kg m^{-2}, hard ballistics are more efficient which may be due to the difference in the rigidity between the hard and soft ballistics (Fig. 8).

A less common but useful protection criterion is the limit velocity. It is defined as the velocity below which 100% of the projectiles would fail to penetrate through the target or the maximum velocity at which the projectile can still be stopped. This is primarily a theoretical concept because it is difficult to define from ballistic tests alone[1].

It can be found by fitting the data to form.

$$V_r = \begin{cases} 0, & V_s < V_l \\ P\,(V_S^t - V_l^t)^{1/t} & V_S > V_l \end{cases}$$

where V_s is the striking/impact velocity; V_r, the residual velocity; V_l, the limit velocity; and P & t, the constants for projectiles and target.

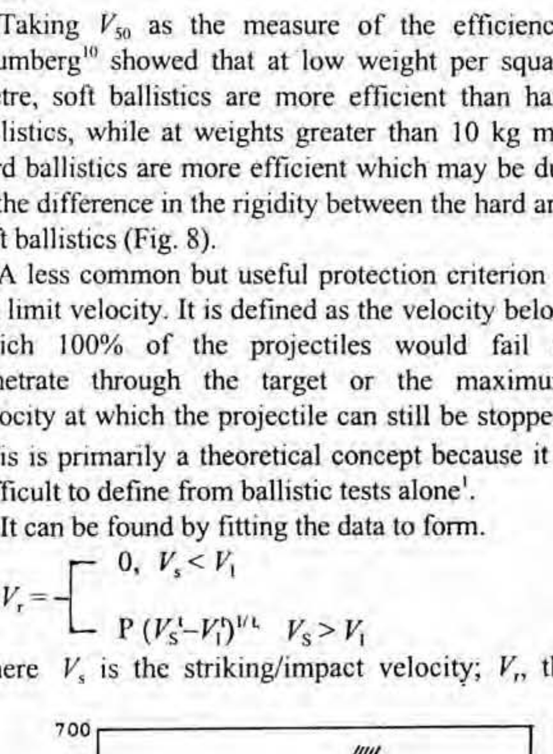

Fig. 8—Ballistic behaviour of soft *vs* hard composites[10]

In this process, a thin aluminium plate is placed behind the armour and when the projectile debris from the armour penetrates the plate, the armour is considered to be defeated.

5.2 Weight Efficiency

This is measured in terms of weight-merit- rating (WMR), which is a useful method to rank the armours and to ascertain the weight advantage offered by a new armour when compared to the standard. It is defined as the ratio of areal density of the reference materials to that of the new armour. The reference material for vehicular type armours is MIL-A-12560 steel[20] while for personnel armour it is cotton duck fabric.

5.3 Ballistic Protection Standards

The ballistic requirements to be met are normally specified by national standards based on calibre type, weight of the projectile and velocity. Various protection classes have been established reflecting different levels of exposure. Most widely used are The National Institute of Justice (NIJ), National Bureau of Standards (NBS), Personnel Protection Armour Association (PPAA)[20] and Ballistic Protection Standards for Germany. Most commonly employed ones are the NIJ standards as listed in Table 4.

Uniform specifications for Europe are being currently worked out in the form of European standards in which the specification for vest include:

- Safe retention of projectile in accordance with special protection class.
- Maximum deformation of plasticine.
- Maximum garment weight or weight per unit area of the ballistic vest.

Various experiments were conducted for evaluating the performance of the ballistic protection systems by different set ups. While Prosser[18] conducted these experiments with Fragment Simulating Projectile (FSP) to know the energy lost by the FSP in penetrating through the layers of nylon fabric, Zee *et al.*[51] used micro velocity sensors to obtain time delays due to slowing down of the projectiles shot from a light gas gun for knowing the penetration mechanism and fracture behaviour. These experiments are

Table 4—NIJ classification of armour systems[20]

Type	Wt of projectile g	Type of projectile	Velocity ms^{-1}
I	2.6	0.22 calibre lead	320 ± 12
II A	10.2	0.357 magnum jacketed lead soft point (JSP)	381 ± 15
	18	9 mm full - metal jacket (FMJ)	332 ± 15
II	8	0.357 magnum JSP	425 ± 15
		9 mm FMJ	358 ± 15
IIIA	15.55	0.44 magnum	838
	8	9 mm FMJ	425
III	—	223 Remington (556 mm FMJ)	—
	—	0.3 carbine FMJ	—
	—	12 gauge rifle slug	—
IV	10.8	0.3 calibre armour-piercing bullets (US military APM2)	868

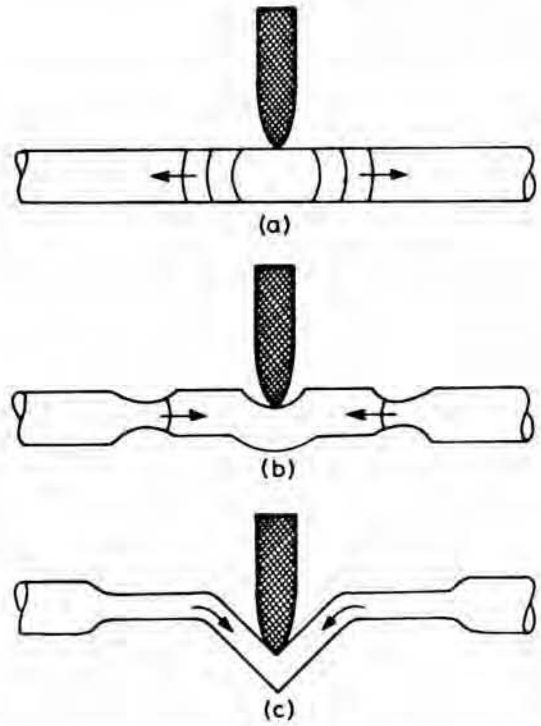

Fig. 9—Failure mechanism of single fibre under ballistic impact[2]: (a) Propagation of longitudinal compressive waves, (b) Reflection as tensile wave, and (c) Elongation of the fibre

instrumental in understanding the mechanism of ballistic protection as discussed later.

6 Failure Mechanism in Fibrous Materials

The basic idea of ballistic protection with fibrous materials is essentially based on the conversion of the kinetic energy into work of deformation. Hence, the principle influencing factors would be the tensile properties of the protective material, the deformability of the projectile and the armour[9].

Fig. 9 shows the mechanism of deformation when a single fibre/yarn is subjected to impact by a projectile, with the longitudinal axis of the fibre perpendicular to the path of the projectile. The impact leads to longitudinal wave propagation and deflection[1,2,21]. The longitudinal wave propagation velocity 'C' is nothing but speed of the sound in the material which can be expressed in terms of density and modulus as under :

$$C=(E/\rho)^{1/2}$$

where C = Speed of the sound or longitudinal wave velocity, E = Initial modulus, and ρ = Density.

The wave reaches the end of the fibre and is reflected back as a tensile wave. This reflection of the tensile wave is necessary so as to satisfy the boundary condition of zero stress at the fibre ends. This movement of tensile wave back towards the point of impact causes the flow of material in the same direction. Ultimately, a tensile strain is experienced by the fibre in contact with the projectile, the magnitude of which is dictated by the impact velocity of the projectile. Continued wave reflections intensify the tensile strain with energy absorbed by the fibre being proportional to this strain. At the same time, a second and slower wave propagates along the transverse axis, i.e. across the diameter of the fibre, moving parallel to the projectile and at the same velocity. Because of this transverse wave, the fibre starts moving in the same direction as the projectile path. The fibre continues to absorb energy and deflects until the projectile is decelerated and stopped or the fibre strains past the dynamic yield point and breaks. If the impact velocity is sufficiently high, the fibre cannot respond fast enough to exhibit strain and the lowest velocity for which the fibre breaks without exhibiting strain is called "Critical Velocity". It is a function of wave speed, which is indirectly related to the fibre modulus and density as mentioned earlier.

$$U = C\left(\frac{\varepsilon}{1+\varepsilon}\right)^{0.5}$$

and $V = C\left[\varepsilon(1+\varepsilon) - \{\varepsilon(1+\varepsilon)^{0.5} - \varepsilon\}\right]^{1/2}$

where

U = Transverse wave speed,
C = Longitudinal wave propagation speed,
ε = Fibre strain, and
V = Projectile speed.

Thus, if strain represents the strain-at-break, then V is the critical velocity of the projectile above which the material would never be able to stop the projectile because the interaction between the yarn and projectile is minimum, e.g. Kevlar 29 at 4% elongation and a modulus of 48.5 N/tex showed the critical velocity[12] of 900 m s^{-1}.

Therefore, the longitudinal wave velocity is the one which determines the amount of material involved in the interaction with the projectile.

One can generalise three main regimes that exist in the materials subjected to ballistic impact[2] as under:

- Regime-I: At low projectile velocities, the fracture in brittle materials is well described by linear elastic fracture mechanics.
- Regime-II: The projectile velocity approaches sonic velocity (~500 ms^{-1}) and loading history gets dominated by the shock wave propagation. This transition occurs at the strain rates of about 10^3 sec^{-1}.
- Regime-III: Transition to this occurs when the damage is dominated by inertial effects and the adiabatic response of the target leads to melting. In this region, increasing the projectile velocity would eventually result in the melting and fusion of the material at the point of contact.

The mode by which the fibre separates is also important in determining its resistance to penetration. Three principle modes have been identified, viz melting, brittle fracture,and plastic deformation with longitudinal splitting.

Nylon 6 exhibits large deformations before breaking, therefore high energy is absorbed by the fibre. Brittle fracture with low elongation-to-break is typical of glass fibres. Kevlar shows some degree of plastic deformation before rupture while UHMPE splits along its longitudinal axis, which would not only absorb energy but acts as an efficient crack arrestor.

6.1 Mechanism of Ballistic Penetration in Woven Fabrics

Situation obviously gets complicated when 2-D woven fabrics with crossover points are considered. Its importance is with wave propagation in the fabric; say with 10^6 crossover points in a square meter of the fabric, one can expect redistribution of the signals at these points[1]. A fraction of the wave will continue along the yarn, part of it will be reflected back (if node is fixed, all the signals will be reflected back) and a part will be redistributed along the yarn which is perpendicular to the former. Transverse deflection of the fabric is responsible for 50% of the total energy absorbed by the secondary yarns/fibres. It is assumed that the transverse wave transfers the energy to the adjacent yarns by frictional contact[8]; hence, the type of weave employed in addition to the fibre selected plays a major role.

6.2 Ballistic Penetration Mechanism in Fibrou Composites

The failure of the composite laminates is far more complex process characterized by interactions occurring in the individual planes and across those planes in adjacent fabric layers. Because of the numerous crossover points found in these woven fabrics, energy is quickly dissipated as the wave encounters more and more fibre crossovers. This dissipation usually limits the impact damage to a small area adjacent to the impact point[52]. Energy transfer to adjacent layers (between layers) is facilitated by the use of resin binder[1,2,8]. Strain waves are transmitted from the fabric layer to resin matrix and thus to adjacent layers; at the same time, elastic waves are reflected into the fabric matrix at each interface. Since the transverse wave energy is transferred to the adjacent yarns by frictional contact, more the yarns being utilized, the better would be the transfer of energy. Thus, in the textile structure, resin bonding restricts the yarn movement, which reduces the ballistic performance[9].

The amplitudes of these waves are determined by a quantity called Mechanical Impedence *(I)*, defined as:

$I = \rho C,$

where ρ is the density of fabric, and C, the wave speed.

Elastic waves may be reflected or transmitted according to the following :

$$P_t = \left(\frac{2\ I_t}{I_t + I_o}\right) \times P_o$$

$$P_r = \left[\frac{I_t\ -\ I_o}{I_t\ +\ I_o}\right] \times P_o$$

where

P_t = Stress amplitude of transmitted wave,

P_o = Stress amplitude of incident wave,

P_r = Stress amplitude of reflected wave,

I_t = Impedence of transmitted material, and

I_o = Impedence of incident material.

It should be noted carefully that the waves created by the ballistic impact are nearly elastic and transmission of these waves to resin matrix increases the energy absorption capability of the laminate. Cracks are formed in the matrix and propagate parallel to the fabric layers, through delamination process[53]. Impact energy is dissipated in the formation and advancement of these cracks and in the deflection caused by the separation of individual fabric layers.

Zee *et al.*[51] used helium air gun, microvelocity sensor and PE and graphite composites with individual fabrics woven in plain, bound together with epoxy resin of 10 layers each, to demonstrate the failure mechanism. Fig. 10 shows the behaviour of PE composites of 10,20 and 30 layers. Velocity measurements were made at 12 different positions with the help of microvelocity sensor in such a way that initial ballistic contact occurs at the 3rd position with three measurements of incident velocity prior to impact.

The energy loss for all the samples (Fig. 10) started from position 3 only signifies that PE composites do not flex but behave as a rigid system, leading to fracture of fibres and matrix. It is interesting to note that the slope of the energy profile is proportional to the energy dissipation density and the rate of energy loss in a 10-layer composite is lesser than that in thicker composites because of the reinforcing effect.

However, the graphite composite shows a typical brittle failure with the energy loss observed exactly at the point of impact and energy loss peak in less than 2.5 mm distance (Fig. 11).

In a numerical model developed by Leech and Adeyefa[17] based on Finite Element Analysis, applied for cloth configurations of 11×11 and 21×21 orthogonal woven fabric, the time sequence of fabric deformation beyond projectile arrest is obtained. These time sequences clearly elucidate the dynamics of ballistic impact on woven fabrics as shown in Fig 12. Further, it has been demonstrated that the triaxial fabrics out perform all other types in ballistic protection.

6.3 Ballistic Protection with Ceramics

Although ceramics are typically very brittle, their mechanical behaviour is dependent on (i) confining pressure and (ii) strain rate[1].

These usually fail into rubbles upon uniaxial compression without plasticization. In addition, if confinement pressure is increased the modulus is unaffected, but the compressive failure strength increases significantly. The increase in strength is brought about by the superposition of the compressive failure stresses, which reduce the opening of the microcracks parallel to the loading direction. Strength effects become important thus

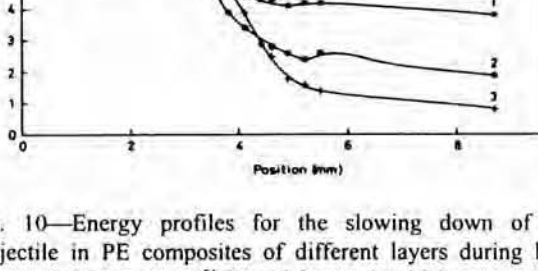

Fig. 10—Energy profiles for the slowing down of the projectile in PE composites of different layers during high velocity ballistic impact[51] [(1) 10 layers, (2) 20 layers, and (3) 30 layers]

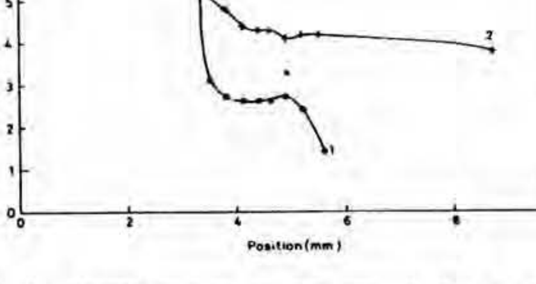

Fig. 11—Energy profiles for the slowing down of the projectile in PE and graphite composites during high velocity ballistic impact[51] [(1) Graphite, 10 layers, and (2) PE, 10 layers]

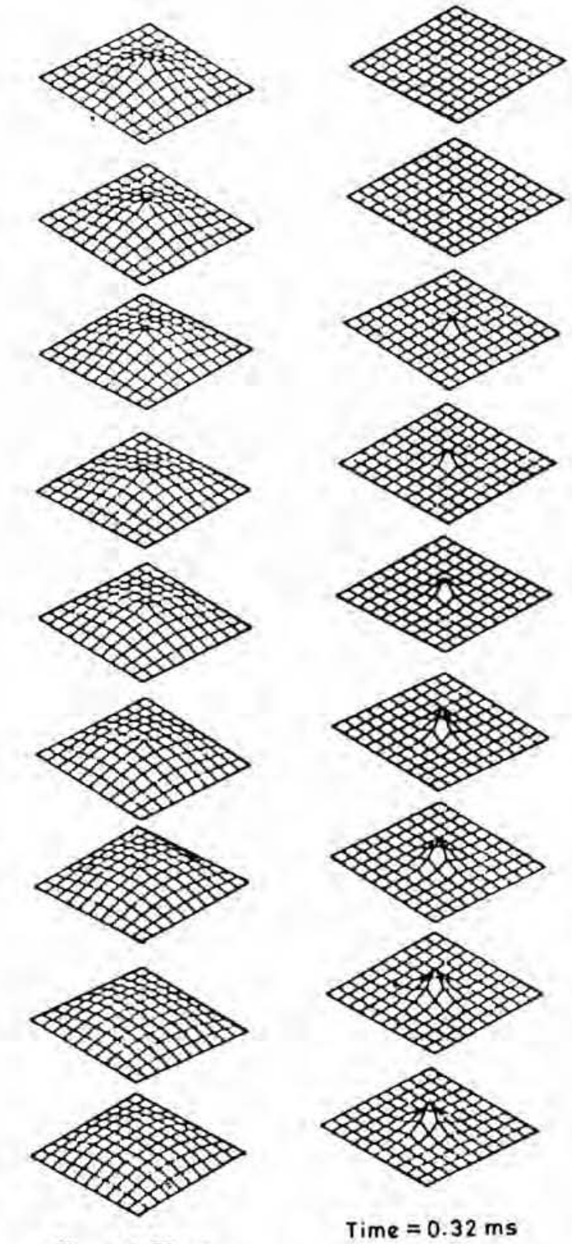

Fig. 12—Time sequence of the fabric deformation under ballistic impact up to and beyond the projectile arrest[17] (Pre strain: 10%. Transverse displacement scaled by 2)

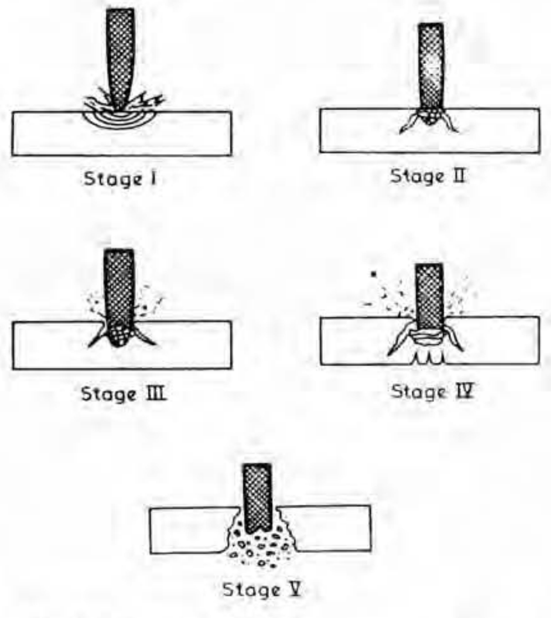

Fig. 13—Failure mechanism of ceramics under ballistic impact[2]

when impact pressure is below twice the "Hugoniot Elastic Limit" (HEL), which is defined as the largest elastic wave that can be transmitted in a material and can be thought of as a measure of dynamic yield stress of a material. Above the HEL, the material undergoes irreversible shear[2]. Theoretically, ceramics are proved to flow hydrodynamically from the fact that at higher pressure, i.e. higher impact velocities, the Hugoniot curve becomes parallel to the pressure curve, which is typical of the liquid state. The final penetration depth of the projectile is given by the formula:

$$P = L.\sqrt{\frac{\rho_p}{\rho_t}}$$

where

L =length of the projectile,

ρ_p =density of the projectile, and

ρ_t =density of the projectile target material.

Since the equation doesn't involve the strength term, the mechanism should be different from that of fibrous materials[1], as shown in Fig. 13 and described below:

- Erosion of projectile tip and formation of spherical shock front,
- Appearance of the fracture conoid and failure of the ceramic in compression,
- Penetration of projectile into ceramic,
- Failure of ceramic in tension, and
- Removal of ceramic debris.

Fracture behaviour of ceramic can be summarized as below :

- At low strain rates ($\varepsilon < 10^2$ sec^{-1}), fracture is controlled by thermal activations of microcracks.
- At higher loading rates, inertial propagation provides significant strain rate hardening.

- At strain rates approaching HEL ($>10^4$ sec^{-1}), failure is by plastic flow with little microfracture. Hence, HEL represents the point of true plastic flow, and microfracture is not initiated until stresses exceed at least twice the value of HEL.

7 Modelling of Ballistic Performance

Numerous models have been developed[16-18,54-64] to predict the performance of ballistic protection but till date, no single model has succeeded in accounting for all the complexities that are involved with the penetration mechanism of the ballistic protection. The major problem is that the whole process typically lasts only for few microseconds and it is very difficult to get the specific information of all the processes that take place and then use them to validate a particular model. Therefore, all the models proposed so far are the poised balance between the performance characteristics and the material properties[2].

- Vinson and Zukas[54] modelled multilayered body armour as single constrained conical shell under quasistatic loading. They used a technique which requires complex experimental work to augment the numerical calculations. The success of this model is impeded mainly due to the simplification of assumptions that are made and excessive dependence on the experimental data which incorrectly showed ultimate strain of 185% for nylon fabric and dynamic modulus of elasticity as only a small fraction of the static one.
- Dent and Donovan[55] modelled with an assumption that only the yarns are directly contacted by the projectile to absorb energy without taking the fabric characteristics into account and hence, concluded incorrectly that the friction was the primary mechanism of energy transfer between the projectile and the fabric. Later, in the refinement of the model, Dent and Donovan[56] proposed crimp interchange as the primary mechanism.
- Roylance and Wang[57] model took care of the essential physics of the impact mechanism along with impact mechanics, still keeping the solution reasonably tractable. The main assumption is that a multilayered fabric can be thought as a single-ply pin-jointed network and the impact is approximated as the point impact. The model successfully indicated that the majority of the energy absorbed by the fabric under ballistic impact was due to the strain and the kinetic energy in the yarns directly in contact with the projectile. This model was further improved by Roylance himself to remove the point impact approximation and is one of the most successful model so far.
- Another model[58], based on finite element analysis, is reported by Allied Signals where the time-step of the method and element spacing were modified so that the predictions of the model matched complementing experimental work. This model is successfully employed to determine the failure criterion of the composite materials.
- Srirengan and Whitcomb[59] developed a finite element based degradation model for composites with transverse matrix cracks. This model was developed by analyzing a three-ply representative volume element for predicting the effective homogenised three-dimensional elastic constants of an interior ply with transverse matrix cracks. Each crack was modelled discretely, and the resulting model was evaluated first by comparing the homogenized extensional modulus for a cracked laminate with experimental results and then with finite element discrete models. Using the degradation model, the prediction of load redistribution for a cantilevered laminated plate with matrix cracks subjected to transverse end load, and in a cracked plain weave composite subjected to uniaxial stress, was compared with a discrete crack model. The degradation model showed good agreement in predicting the homogenized elastic constants and load redistribution.
- Ko *et al.*[60] proposed a modified Florence model for evaluating the effectiveness of ceramic spheres on ballistic impact resistance, using multifunctional armour with Al_2O_3 face and Spectra Shield composite backing plate. Since the Florence model predicts higher ballistic limit with larger size of the damaged area, this modified Florence model is of consequence where a relationship between predicted ballistic limit and areal density is established which could be used to optimize the system by

controlling the thickness ratio of ceramic face and composite backing plates. The ballistic limit evaluation showed that increasing the backing composite thickness significantly affected the kinetic energy absorption of the armour.

- Costa and Thaumaturgo[61] analyzed the effects of shock waves induced by ballistic impact on the impact-energy absorption capacity of woven glass fibre/epoxy composites. They used computer simulation of shock-wave propagation to determine the impact energy in these composites. It was observed that the energy absorbance capacity changes with the acting failure mechanism and is also rate dependent.
- For ceramics, the work done by Wilkins[62] is noteworthy. He used HEMP, a large finite different lagrangian hydrocode, to model the impact of 0.50 calibre projectile into disks of alumina backed by various materials. Through this work, the role of ceramic compressive strength in the initial failure of the projectile tip was established. Also, the mechanism of the tensile failure and fracture and conoid formation were predicted and explained on the basis of mechanics of stress wave propagation.
- Ali *et al.*[63] studied the effect of the impact of a paraboloidal projectile on human skin membrane. Here, the tip of the projectile which is made up of lead was considered to be paraboloidal and the threshold velocity, i.e. the velocity when the skin membrane is about to rupture, has been calculated for human beings of various age groups. It has been found that the threshold velocity for a paraboloidal projectile of certain dimensions is less than that of a spherical projectile under similar conditions for all age groups.
- Kim *et al.*[64], studied the effect of intraply hybridization of the reinforced fibre on the interlaminar properties of Kevlar 29/Spectra 9000 hybrid laminated composites. They found that the interlaminar shear strength of the laminated composite is reduced by intraply hybridization of the reinforced fibre. Intraply hybrid composites show poor intralaminar shear strength with higher anisotropy in thermal expansion coefficient and elastic modulus which would cause higher residual internal thermal stresses after curing of the composite. The hole drilling residual stress measuring technique was adapted for evaluating the thermal residual stress. The hybrid composite showed higher thermal stresses, especially the thermal residual compressive stresses, which exist in the fibre direction. Fibre/matrix interfacial strength reduced as the hybrid composites have higher expansion in Z-direction of the composite, which results in reduced interlaminar strength of the hybrid composite.

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