Experimental Analysis of High Velocity Impact Properties of Composite Materials for Ballistic Applications

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Abstract This chapter presents a review of the use of composites as personnel protective armours. It lays out the various standards and specifications that are used in evaluating the effectiveness of an armour for personnel protection. The NIJ standard which is popularly used to evaluate the armours is thoroughly discussed along with common terminologies associated with the same. The study also explores the various testing equipment and ammunition used for testing from shapes to materials and their impact on the armour panels. It is essential to follow the standards meticulously to ensure safety and success of any testing. Composites are gaining increased prominence in modern day warfare and has evolved from use of metals since the days of the first and second world wars.

Keywords Personnel protective armour · Ballistic impact · Composite materials · Standard testing

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1 Introduction to Ballistics

Ballistic is a division of applied physics which deals with the motion of projectiles propelled by different energy sources like solid, liquid, gas, electrical, electromagnetic and laser sources. This field can be further divided into four categories. They are interior ballistics, intermediate ballistics, exterior ballistics and terminal ballistics. Interior ballistics is concerned with combustion of material and the propagation of gas in the gun/rocket whereas intermediate ballistics deals with behaviour of a projectile while leaving the barrel/launcher. Exterior ballistics is study of motion of a missile/projectile/rocket after the launch from a platform of a muzzle of a weapon. The fourth category, terminal ballistics is study of effects of projectiles after they have reached the target (Bilisik 2017). Velocities greater than 50 m/s but less than 1000 m/s are considered as high velocity. Any velocity below 50 m/s is termed as low velocity while above 1000 m/s is referred to hyper velocity (Ismail et al. 2019). Projectiles travelling at such a velocity has potential to cause excessive damage in spite of the fact they are light in weight. Some of the examples of ballistic impact include bird hitting airplanes in their flight, hailstorm, debris hit causing damage to automobile structure, military applications like firing bullets, flying sharpnels from a bomb blast, etc. (Salman et al. 2015). Thus it is imperative to develop materials which can provide protection against damage caused due to ballistic impact. The material should be efficient enough to provide complete protection but at the same time should be cost effective, light in weight, easy to fabricate. Continual research and development has resulted into shift from materials like manganese to polymer composite materials. The focus of this chapter will be on development of composite materials, mechanism of composite materials in absorbing impact energy, standards used, different testing methods, terminologies in ballistic testing and failure modes.

2 Composite Materials as Anti-Ballistic Materials

During the Second World War, armours were mainly made with heavy manganese and steel which restricted personnel movement and used to overheat. These disadvantages eventually led to the use of manganese steel sheets within multi-layered nylon. Further development led to all-nylon armour without any metal. Fibre reinforced plastic armours could be used over a range of temperature but they failed in protection from rifle projectiles. In 1965 aramid fibre was developed with light weight and, high stiffness and strength. Several high-performance fibres developed were, Twaron® and Kevlar®, Dyneema® and Spectra® from Ultra High Molecular Weight Polyethylene, and Polybenzoxazole (PBO) fibre (Rosenberg and Dekel 2016; Zaera 2011).

Later, Multi-layered Ballistic Armour System (MBAS) also known as dual-hardness armours with ductile backing material made up of high performance fibre and brittle hard front face for absorbing kinetic energy were developed. For the front face, materials like steel, titanium, aluminium, aluminium nitride, titanium diboride, silicon carbide, zirconium oxide and boron carbide were used (Rosenberg and Dekel 2016). Presently, along with synthetic fibres, natural fibre reinforcements are also being explored as they are inexpensive and hybridized polymer composites have reported superior ballistic performance (Salman et al. 2015; Zakikhani et al. 2016). Any composite material consists of two distinct phases, matrix which is a continuous phase and reinforcement which is discontinuous phase. Based on matrix, composite materials can be broadly classified into three categories viz. polymer matrix composites, metal matrix composites and ceramic matrix composites. Other than fibres, reinforcements come in forms, like particulates, flakes, and whiskers (Schwartz 1984).

3 Mechanism of Shock Absorption During Ballistic Impact

Any projectile travelling will possess kinetic energy. As the projectile impacts the armour this energy acts over a very small area and allows the projectile to perforate through the materials. In general armour absorbs this kinetic energy and spreads it over a large area thereby making it difficult for the projectile to punch through. Modern day armours make use of woven fabric in armour systems. The yarns in theses woven fabrics are known to have high specific strength and modulus (Mostafa et al. 2016). High modulus of yarns results in dissipation of the energy along its length. As the dissipated energy meets a junction in the woven fabric, it gets divided by a number of possible mechanisms. It may continue along the yarn, it may get reflected back or it may travel along the crossing yarn. This dissipation and division of energy takes place at several such junctions and in several layers in the armour until the projectile has lost sufficient amount of energy that it cannot further penetrate into the material. As the projectile impacts into the first layer, shearing of the layer takes place and also absorbs some amount of energy. Figure 1 shows the distribution of energy along a yarn of the fibre.

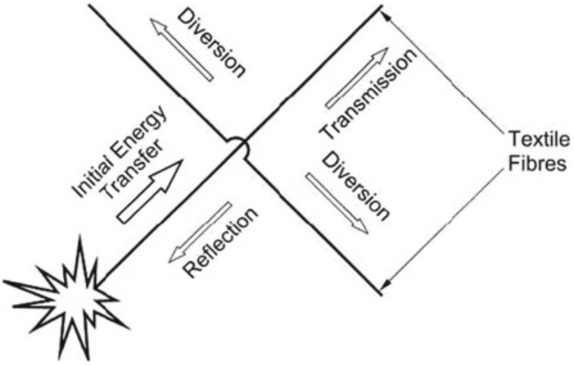

Fig. 1 Mechanism of defeating the projectile by distribution of kinetic energy (Cooper and Gotts 2005)

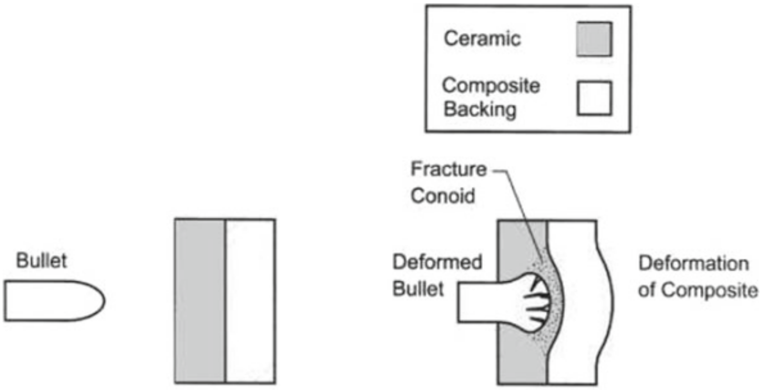

Fig. 2 Mechanism of defeating the projectile armours with hard front face (Cooper and Gotts 2005)

Absorption of energy due to shearing of the fabric layer is another mechanism by which the projectile is defeated in its travel. Mostly all the types of armours nowadays uses a hard front face which is responsible for distorting the projectile before the backing composites spreads the energy over a larger area. Figure 2 depicts the mechanism by which the projectile is defeated with the combination of hard front face and a backing composite layer (Cooper and Gotts 2005).

4 Ballistic Testing

4.1 Standards of Ballistic Testing

Standards are imperative to all forms of studies conducted. They provide basis for comparison, deduction and improvising existing or new methods/materials for varied applications. They serve as a set of universal rules for testing and maintaining uniformity in recording results.

The various standards used for ballistic testing are US National Institute of Justice, European Committee for Standardization, Joint Technical Committee MS/43 (Australia and New Zealand), State Standardization Committee of Russian Federation, North Atlantic Treaty Organization and US Department of Defence. These standards vary from each other in terms of scope of application. Various standards cater specifically and efficiently to a class of materials such as ballistic helmets, armoured vehicles whereas others cover all ballistic materials. Another major point of difference between the standards is the level of threat. This is accounted in terms of gun calibre and ammunition employed (Zaera 2011). The US National Institute of Justice is the most widely used and recognized standards among the many.

Table 1 Levels of protection and its details (Samuels 2000)

Level of protection	Size of bullet	Mass of bullet	Velocity
IIA	9 mm FMG RN	8 g	373 m/s ± 9.1 m/s
	0.40 S&W	11.7 g	352 m/s ± 9.1 m/s
II	9 mm FMG RN	8 g	398 m/s ± 9.1 m/s
	0.357 Magnum	10.2 g	436 m/s ± 9.1 m/s
IIIA	0.357 SIG	8.1 g	448 m/s ± 9.1 m/s
	0.44 Magnum	15.6	436 m/s ± 9.1 m/s
III	7.62 mm FMJ	9.6	847 m/s ± 9.1 m/s
IV	0.30 caliber AP	10.8 g	878 m/s ± 9.1 m/s

For body armours to be tested for ballistic resistance, the NIJ standard—0101.06 is the most imperative. The scope of this standard is to ascertain the limits of performance of personnel protective gear and test methods for ballistic applications against gunfire. Table 1 has all the details of the various levels of protection as put down by NIJ standards.

4.2 Important Terminologies

There are a number of terminologies used to denote various aspects of ballistic testing with some of them being more repetitive and prominent than others. It is discussed in detail over Table 2.

4.3 Interpretation of the Test Results

Analysis and interpretation of results conclude any process and establish the success rate of the tests conducted. Various methods and standards have been developed to evaluate various categories of testing and analysis. The armour specimens are evaluated based on the back face signature and ballistic limit values ascertained from the testing.

Impact velocity meters and residual velocity meters are used to record the values of ballistic limit for the projectiles. Ballistic limit varies with shape of the projectiles. A projectile is expected not to penetrate the composite panel below the ballistic limit. Hence suitability of composite panels for ballistic applications is decided based on

Table 2 Important terminologies (Samuels 2000)

Terminology	Definition
Angle of incidence	The angle between the line of bullet strike and the perpendicular to the surface of backing material (Fig. 3) at the point of incidence is termed as angle of incidence
Armour carrier	A non-ballistic resistant material that is employed to secure the armour material to the body of the user
Armour conditioning	Values of mechanical an environmental parameters of the armour before testing. It includes humidity, temperature and mechanical damage
Back face signature	The highest depth of indentation caused by a bullet that does not pass through the armour being tested is termed as back face signature
Baseline ballistic limit	It is the ballistic limit value derived experimentally for a new ballistic armour panel
Backing material	A layer of oil based clay stationed in close contact with the armour being tested is called backing material
Backing material Fixture	It is a rigid structure shaped like a box with a detachable back which houses backing material. This detachable back is employed during perforation-backface testing and not during V50 testing
Ballistic limit	For a particular type of bullet the velocity at which the bullet is expected to perforate the armour panel at a probability of 50% is termed as Ballistic Limit. The Ballistic Limit is also referred to as V50
Compliance test group	A batch of armour panels turned in for testing as per a particular standard
Dew point	The temperature of an air parcel which is required to be cooled to, keeping constant barometric pressure in order to condense the water vapour to water (dew)
Fair hit	Refers to the impact created by the bullet on the composite armour panel subjected to standard velocity requirement and shot spacing
Full metal jacketed bullet (FMJ)	Refers to a lead bullet coated with copper alloy on all surfaces except the base. The alloy consists of 90% copper and 10% Zinc

comparing the general expected velocity of real ammunition to the V_{50} (Ballistic Limit).

Ballistic limit is found to be independent of the thickness of the projectile but is dependent on the sharpness of the projectile. It varies inversely with the sharpness of the projectile (discussed in Sect. 4.5) used with highest numerical value recorded for blunt projectiles (Ansari and Chakrabarti 2017). Ballistic limit increases with increase in thickness of the composite panels (VanderKlok et al. 2018). Shear strength of composites play a major role in deciding the ballistic limit since the major means of failure involve shear snapping. The modes of failure are discussed in the next

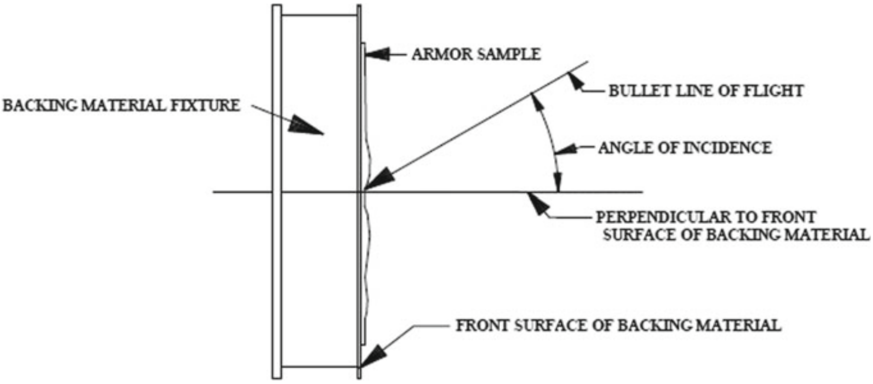

Fig. 3 Angle of incidence (Samuels 2000)

section (Sect. 5), The decrease in shear strength causes an almost doubling increase in the values of ballistic limits for composite panels (Wang et al. 2017).

Based on the type of testing being done as per the values prescribed by the standards, the ballistic limit is evaluated. The numerical value is ascertained using standard methods. The first one involves the velocity time history where V_{50} is assigned to the maximum impact velocity which stops the projectile. In the second method (specified by US MIL-STD-662E), an average of the lower range of velocities displaying full perforation is taken along with the higher range of velocities having only partial perforations. The range for the higher band is observantly very small (Bandaru et al. 2016).

If a NIJ Standard-0106.01 9 mm FMJ (full metal jacket), type IIIA testing is carried out on a Kevlar composite for probable ballistic applications. While testing an impact velocity of 380 and 400 m/s brings in residual velocities of 68 and 131 m/s. The value of residual velocity begins to approach 0 for an impact velocity of 376 m/s. At this point a number of tests are carried out and an average of impact velocities with 0 residual velocities is arrived at as the ballistic limit of the composite panel (Bandaru et al. 2016).

The composite panel when mounted for testing is generally covered with an additional layer of oily clay to record the impact of the projectile on the laminate. The back face material is then evaluated to obtain the back face signature of a particular projectile. The depth of indentation on the back face material is recorded every time and the material is passed for application if all values fall below 44 mm. The depth is measured with a Vernier calipers as showed in Fig. 4. This is the value above which it is prescribed to be lethal to human beings as per the NIJ standard 0101.04 (Fabio et al. 2017).

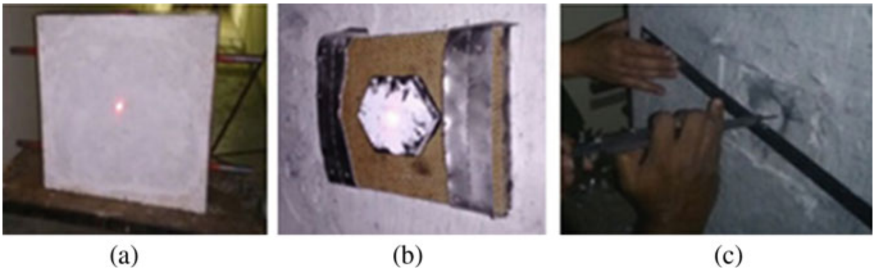

Fig. 4 **a** Clay backing material, **b** testing panel mounted on clay witness, **c** measurement of back face signature (Fabio et al. 2017)

4.4 Testing Methods

Testing is essential in determining the success of fabrication and suitability of the fabricated composite material for ballistic applications. Since human lives are on line during warfare and combat involving ballistics, a range of carefully curated tests have to be carried out and a range of values iterated before the composite can be approved for application. Ballistic armours are tested using a wide variety of methods in Universities, Independent Research facilities and defence/ military organisations in accordance with set standards of testing parameters.

In universities and research institutes, the most popular testing methods include the use of single stage gas guns, two-stage gas guns and powder barrel guns. The gas guns use pressurized gases like helium, nitrogen etc. to propel ammunition towards the armour panel being tested. The velocity of the ammunition fired is controlled by varying the pressure of the gas. The setup consists of a gas supply cylinder, a high pressure cylinder, barrel and muzzle in addition to an exhaust and a valve. Figure 5 is a schematic representation of the test setup for ballistic armours. The

Fig. 5 Typical arrangement of test setup (Luz et al. 2017)

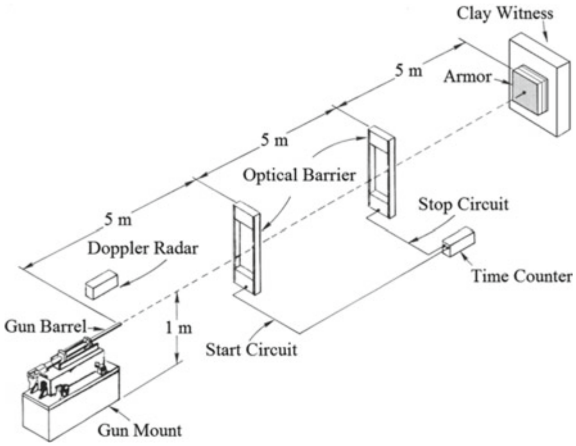

Fig. 6 Field test set-up (Purushothaman et al. 2013)

Gun is mounted to face the armour which is fastened to a clay witness which acts as the backing material. It records the back face signature of the projectile in case of non-perforation.

Military establishments make use of various caliber of guns such as an AK-47 in actual application during warfare or combat. They make use of Field Test Set-up as shown in Fig. 6.

Military operations are highly unpredictable and involve close combat and stabbing at times. Hence low velocity impact tests are mostly carried out along with the general high velocity impact tests using guns. Low velocity indenters are used for testing low speed penetration ballistic applications. Personnel protective equipment is tested by using instrumented drop weight testers (Reddy et al. 2017b). The indenters are dropped from a height and strain gauges are used on the armour panels to record the impact energy. Various types and shapes of knives are used as indenters in testing. Double-edged steel knives are a popular choice.

4.5 Types of Projectiles

A variety of Projectiles are used to simulate an actual firing sequence from the fields. Universities and research establishments use a range of projectiles for the same. They give the researchers a real-time experience to further studies on materials with dangerous field applications. Various materials and shapes of projectiles are employed for ballistic testing of armours.

Steel is a popular choice of material for making ammunition. Grades like steel 1020, hardened steel 4340 etc. are employed (Li et al. 2017; Vinson and Walker 1997). Apart from steel, projectiles are also made from brass, silica, aluminium, copper, and lead. (Meng et al. 2017; Li et al. 2017; Shockey et al. 1975).

Hemispherical, Flat, Ogival, Conical as shown in Fig. 7 are some of the most common shapes for projectiles. They are characterised by their diameter, height and specific weight. The velocity of the projectiles is adjusted to the specific weight of

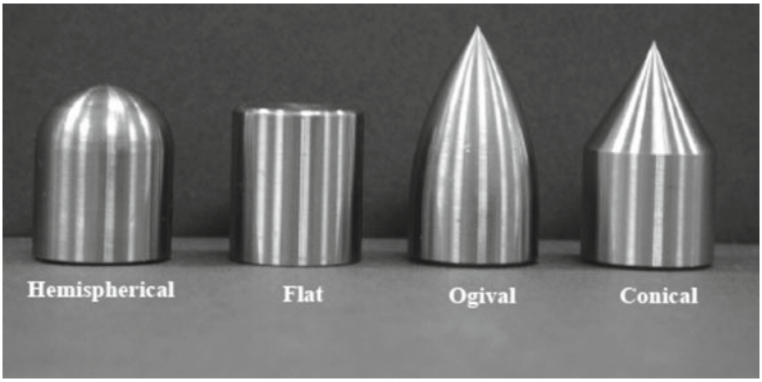

Fig. 7 Types of projectiles used (Tan et al. 2003)

each projectile. Elongated and sharper shapes are known to have lower ballistic limits but there are exceptions to this as well (Tan et al. 2003).

5 Modes of Failure in Composite Armour Panels

Studying the modes of failure is a major step in deciding the efficiency of existing fabrication methods and strength of the fabricated composite panels. Failure is synonymous with extent of bonding between matrix and fibres, rate of energy dissipation and the overall scope for improving current methods and materials. Delamination, matrix cracking, de-bonding, fibre breakage and shear plugging are major means of failure during ballistic testing of composite panels. The failure might be attributed to one of the above phenomenon or a combination of a few of them. This is caused due to high velocity impact and the following interactions between the projectiles and the composite material. It is a function of shape of projectile, mass of projectile, velocity of projectile and distance from which it is fired.

Fibres snap by the sheer force exerted by the sharp edges of the projectile. This is mainly caused by the tension at the back of the composite panel. Fibre breakage as seen in Fig. 8 happens close to the point of impact of bullet and is scarcely detected towards the outer edges of the panel. The panel in Fig. 8 is a glass–epoxy composite. The white arrows in the figure point towards of the area of damage. The image is a lateral cut section of the panel close to the area of damage (Ávila et al. 2011).

Delamination is attributed to fracturing between layers of a panel. It is a macroscopic phenomenon and detectable by visual inspection. Figure 9 shows one such example. Delamination is a major mode of failure and happens due to collective action of micro fractures propagating through the material as an impulse. Impulsive force is directly proportional to the velocity of impact and hence the permanent deformations increase with increase in velocity (Li et al. 2017). Delamination is a function

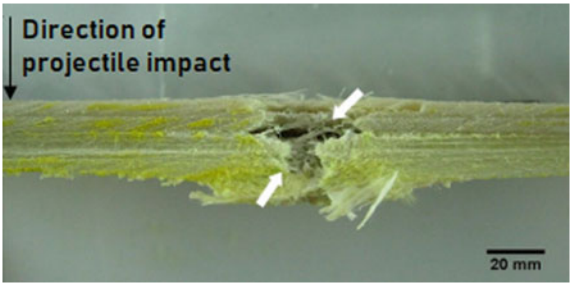

Fig. 8 Fibre breakage (Ávila et al. 2011)

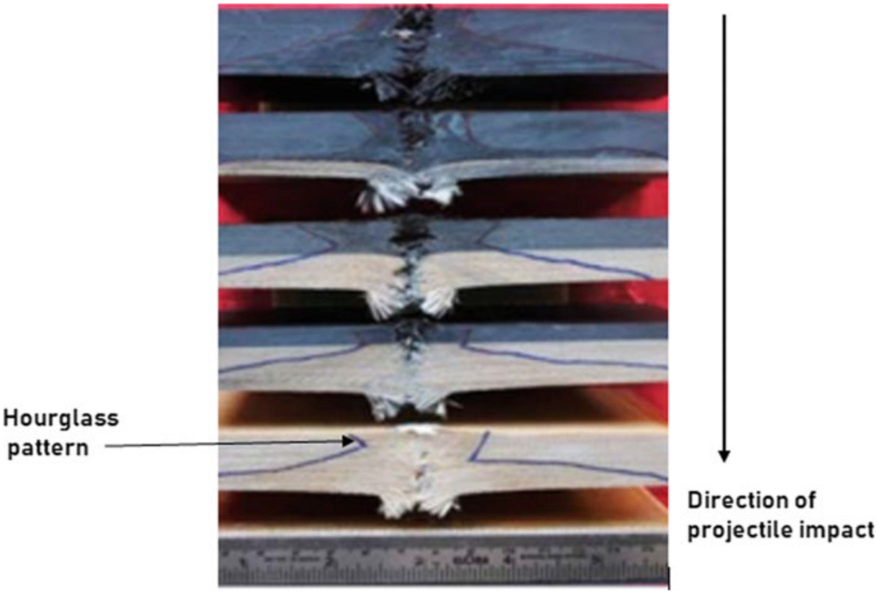

Fig. 9 Overview of delamination in composite panels (Reddy et al. 2017a)

of laminate thickness. An hourglass pattern is observed on the cross-section of panels at the point of impact. The base of the hourglass pattern expands with increase in the thickness pointing to increased extent of delamination in the composite panels (Reddy et al. 2017a).

De-bonding as shown in Fig. 10 is another macroscopic failure characterized by the split of fibres from the matrix. It is prevalent in composites where the resin and fibre have weak interfacial bonds (Benzait and Trabzon 2018). The arrows in Fig. 10 point towards debonding across the panel. Matrix cracking is caused by the impulse force and leads to de-bonding in many of the cases. Miniature fractures propagate through the matrix of the panel from the point of impact.

Shear plugging is caused by compressive load under the projectile. A plug is formed beneath the volume occupied by the projectile in the composite material. It is

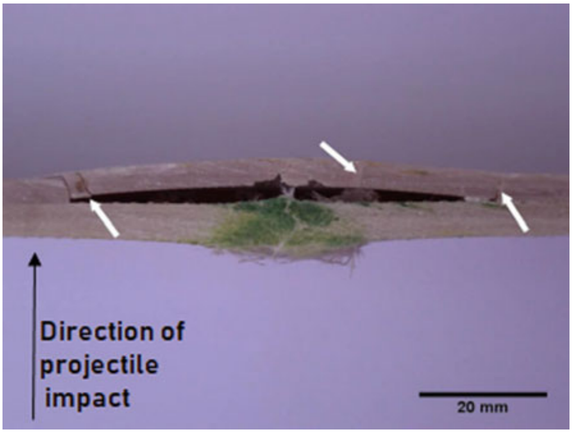

Fig. 10 De-bonding between the fibre and matrix (Ávila et al. 2011)

attributed to displacement of composite volume suspended by the fibres at the edges of the plug. It causes macroscopic failure. Figure 11 depicts a simulation of failure by shear plugging as highlighted by the circular region. The panel is simulation of ceramic fabric reinforced metal matrix composite armour (McWilliams et al. 2016).

There are many mechanisms of interaction between the projectile and composite armours as discussed above. A detailed view of the same can be obtained by studying the interaction of projectiles with stacked up fabrics. Many researchers have lead studies by repeating the tests conducted on composite panels with stacks of woven fibre mats to better understand minute phenomenon that lead to major failures.

The first interaction between the projectile and the fibres is attributed to three probable mechanisms as depicted in Fig. 12. In the first scenario (a), the ammunition forces its way through the material by sheer momentum and velocity. It leaves an

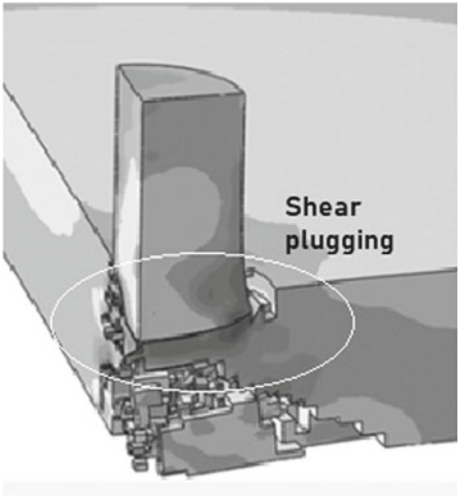

Fig. 11 Failure by shear plugging (McWilliams et al. 2016)

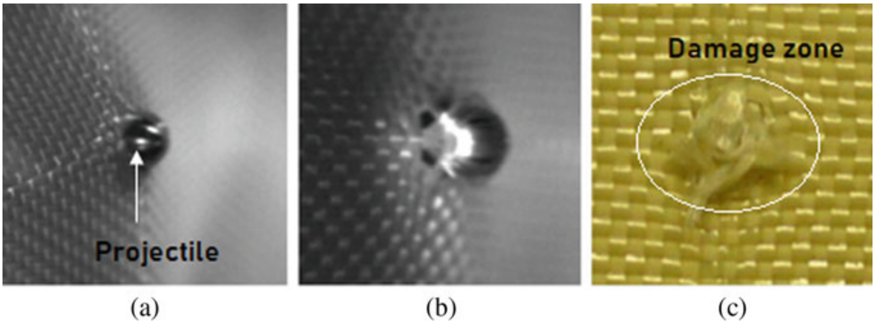

Fig. 12 **a** A hemispherical projectile windowing through the weave, **b** a yarn spreading and sliding out of the way of a hemispherical projectile, and **c** the cutting of some fibres/yarns around the nose of a sharp projectile (Cline et al. 2020)

impression at the point of entry. The second scenario (b) arises when the sharp tip of the projectile slips through the pore of the woven material and enlarges the pore into a rupture as it progresses through the material. The third mechanism (c) involves snapping of yarns and fibres due to the sharp tip of the projectile creating a pathway for the same to enter the ballistic panel (Cline et al. 2020).

The stacked panel fails due to a number of reasons. Yarn rupturing, fibre splitting, fibrillation, friction and bowing are major mechanisms. During the rupture of the fibre stack, the fibres making up the armour snap in a disorderly fashion to cause a depression in the surface of the panel as shown in Fig. 13. Rupturing is majorly attributed to breaking of bonds in the minute scale. These bonds are generally covalent in nature. Disorderly yarn pullout is the indication of failure by rupture. It is generally caused by blunt force trauma to the panels. Figure 13 shows failure of fibre panes caused by (i) Hemispherical; (ii) Flat head; (iii) Ogival head and (iv) Conical head projectiles respectively.

Fibrillation is the process of snapping of fibres into two. This happens due to breakage of secondary bonds, mainly hydrogen bonding between the molecules of the fibre due to the high velocity impact caused by the projectile and the angle of penetration. Friction is another cause of failure. It happens due to the abrasion between the bullet surface and the armour material at high velocity.

A circular or oval disturbance is the signature of failure by bowing. The failure can be seen propagating through the rest of the panel in lines like fault lines from the site of a crack. It is a prevalent mode of failure in ballistic panels with orthogonally woven yarns. It's majorly attributed to the dislocation of yarns in perpendicular direction due to the incident wave of force accompanying the bullet. Figure 14 shows an example of failure seen due to bowing due to (i) Hemispherical; (ii) Flat head; (iii) Ogival head and (iv) Conical head shaped projectiles (Tan et al. 2003).

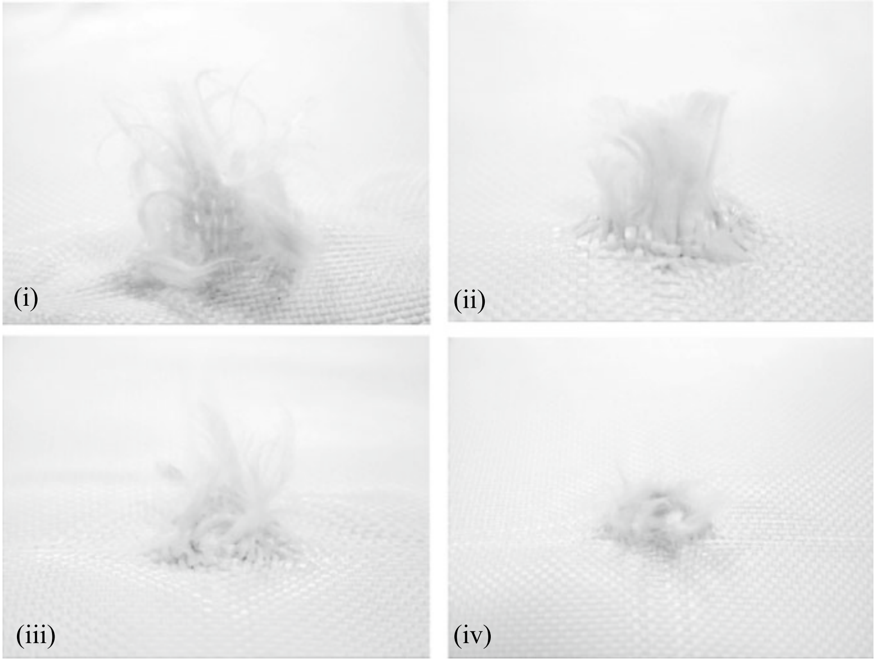

Fig. 13 Representation of failure due to rupture of yarns with impact of **i** Hemispherical; **ii** Flat head; **iii** Ogival head, **iv** Conical head (Tan et al. 2003)

6 Conclusion

This section comprehensively introduces the aspect of standardization in ballistic testing for personnel protective armor and safety vests employed in warfare. It explores the various shapes and materials used to make the projectiles and gives an insight to the steps of testing involved. Gas gun are most often employed for testing. The tested samples are mostly evaluated with respect to the ballistic limits and back face signatures and classified into classes of a standard. The most common modes of failure include debonding, matrix cracking and delamination. This process of standardized testing has meticulously advanced research and brought a sense of uniformity to the data and work going on around the world in the field of protective materials.

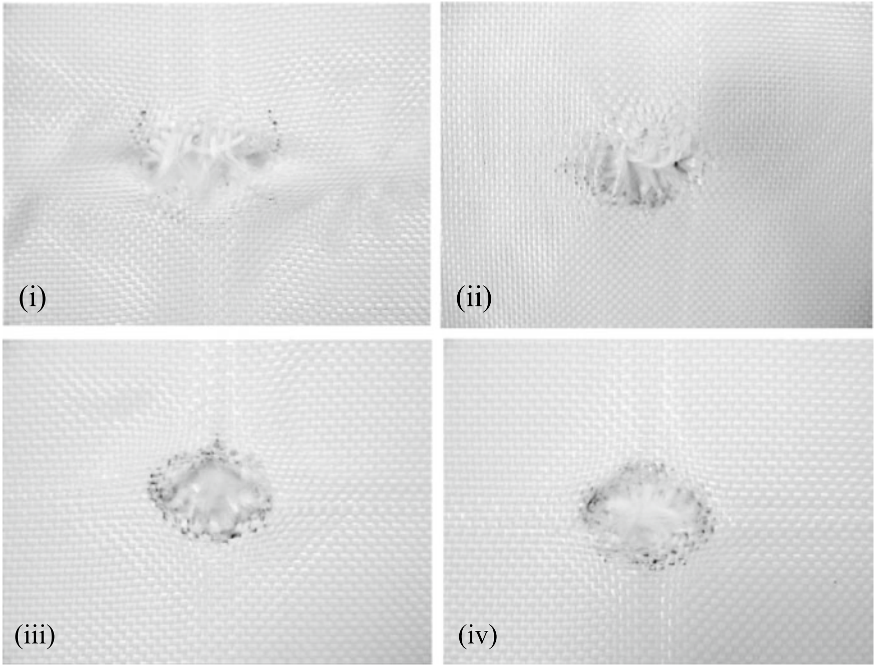

Fig. 14 Representation of failure due to bowing of yarns with impact of **i** hemispherical; **ii** flat head; **iii** ogival head, **iv** conical head (Tan et al. 2003)

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