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Ballistic impact mechanisms - A review on textiles and fibre-reinforced composites impact responses

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Abstract: Ballistic impact mechanism is a very complex mechanical process mainly depends on the thickness, strength, ductility, toughness and density of the target material and projectile parameters. Nowadays, the developments of tough, high-strength, high-modules fibres have led to the use of fabrics and their composite laminates for various impact-related applications. In this review paper, the various ballistic textiles and composites involved in the ballistic application including body armour will be outlined. Besides, various technical approaches used for better understanding of the very complex process of the ballistic impact mechanisms and their responses of the materials will be discussed. The different influential mechanisms which prominently affect the ballistic impact performances of the target will be discussed. While discussing the different factors, beside experimental research work different analytical, numerical modelling and empirical techniques based research approaches have been also considered.

Keyword: Ballistic impact mechanism; Ballistic textiles; Fibre-reinforced composites; Impact responses; Ballistic affecting mechanisms; Ballistic performance approaches

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1. Introduction

Protection of the human body from different kinds of threats such as sharp object and combat projectile dates back to the history of mankind. Peoples were wearing cloths made of different kinds of primitive and old age materials such as animal skin (leather), wood, stones, copper, steel etc. to protect themselves from various kinds of threats. Various textiles and laminates made of traditional fibres such as linen, cotton, silk and nylon have been also used not only for clothing but also as protecting materials against different threats including ballistic applications [1][2][3]. For example, personnel protection garments made of leather on the Grecian shields, various layers of silk in ancient Japan and, armour suits with chain mail during Middle Ages was used in different ways for protection. However, the current modern military operations, technology-driven war tactics, on-street weapons and ammunition imposes the development of advanced damage-resistant, flexible, lightweight, and of great energy absorbing ballistic protection armour systems [4]. The revolution of modern generation of ballistic vests arose in the late 1960s following the development of novel synthetic fibrous materials with antiballistic performance. The fast development of such high-strength and high-modulus fibres has also brought a new era of fabric-based protection systems with the above-mentioned qualities for different kinds of ballistic treats. Even after, an immense researches were conducted continuously to enhance not only the ballistic impact performances of the existing material but also inventing new ballistic materials along with various mechanical properties for enormous kinds of technical application including body armour systems. Due to these, various high performance fibre types with different structural properties and responsible for particular ballistic impact responses and performances at the stage of yarn, fabric and its compliant composite laminates etc. has been developed. Para-aramids and ultra-high molecular weight polyethylene (UHMWPE) are the two well-known high-performance fibres to produce protective textile material due to their high resistance-to-impact damage [5][6][7]. Twaron® (a registered trademark of Teijin), Kevlar® (a registered trademark of DuPont), Dyneema® (a registered trademark of DSM) and Spectra® (a registered trademark of Honeywell) are among the well-known high-performance fibres which have been extensively used for flexible personnel ballistic protection armour due to their desired engineering properties such as high strength, high tenacity, and good chemical resistance and lightweight characteristics [8][9][10]. Zylon (Toyobo); Spectra® (Allied Signal), M5 Vectran (Hoechst Calaneses), Technora (Teijin), and Nextel (3M Ceramic Fibre Products) are also other commonly used high performance fibres. Those developed high performance fibres possessed a unique performance as compared to the traditional fibres and even each other. The property and application of the above mentioned and other high performance fibres will be discussed in detail in **section 2.1.**

In general, in order to deliver much better strength and to safeguard against different kinds of ballistic impact, the mention high performance fibres should be changed in to different phases of applications, i.e., in the form of yarns, fabrics or related textile reinforcement composites [11][12][13][14][15]. However, other than the unique properties of the material (fibre), there are also various mechanisms that should be considered to enhance the ballistic performance of the final ballistic target. For example, the usual method to improve the ballistic protection against the ballistic impact next to selecting appropriate materials properties are adding more number of layers in different arrangement during ballistic panel production [16][17][18][19][20]. Even though increasing the number of layers of the ballistic target improves the ballistic performances, but it will also affect the total weight and flexibility of the final target [21][22][23]. Besides, there are also various alternative and different critical parameters that could increase the ballistic material performances. The different internal factors include fibre properties, yarn properties, fabric properties, finishing of materials and external factors including target situation, projectile situation, panel arrangement etc. The mechanisms involved in fabric ballistic materials subjected to a ballistic impact mostly depend on a combination of those factors in a synchronous manner. Different researchers (it will be reviewed in details in section 4) have discussed the mentioned ballistic performance of influencing parameters. Besides, various researchers have also used different kinds of approaches for better and clear understanding of the various internal and external influencing parameters on the ballistic material performance [24][25][26][27][28][29]. Those approaches include experimental, empirical, numerical, analytical or combination methods. Those approaches have been usually used to analyse and understand the relation and simulate the overall ballistic materials behaviour in response of ballistic impact depending on the environment conditions. More examples regarding the different types of approaches and its application supported by different research works will be discussed in detail in **section 3**. Moreover, few researchers have also comprehensive work on analysing and discussing different research works on modelling and simulations, experimental testing, ballistic penetration resistance, projectile characteristics, failure modes of ballistic materials and composites for different applications [30][31][32]. Nowadays, high-strength woven fabrics made of polymeric yarns are also widely used due to their low density and high toughness, as well as good resistance to high-speed loading, particularly ballistic impact. Due to such properties, these ballistic materials were introduced in many applications in the areas related to protective clothing for military and law enforcement personnel, protective layering in turbine fragment containment, armour plating of vehicles, external structures of aircrafts and other similar applications involving protection resistance against a high velocity projectile protection against ballistic impact, such as personnel body armour. However, their response to impact is complex, due to mainly the woven architecture and rate-dependent behaviour of their constituent yarns. The armour-based ballistic materials possess exceptionally high strength and impact resistance.

The main purpose of this paper is to review and discuss mainly on different types of ballistic textile fabrics and textile composites materials, ballistic impact response, impact performance mechanisms and various important influential mechanisms, which affect the ballistic impact resistance performances of the final targets. Among the several factors, some of them including material properties, projectile situations, impact target conditions, target ply design and arrangement etc., will be carefully identified and reviewed. The paper also tried to outline the different approaches, which are used to analyse and discuss the ballistic impact mechanisms and performances of the materials. Besides, the paper also reviewed and outlined not only experimental works but also it encompasses different study approaches including analytical, numerical, and empirical techniques for investigating the ballistic impact performance of the material.

2. Ballistic impact protection materials

In the late 1960s, high-strength, high- modulus fibres has been invented to escort the new era of protection through producing body armour system against different ammunition including small missiles. USA army has early introduced body armour with Interceptor, by which it consists of outer tactical vest (OTV) by inserting hard ceramic insert to stop the high-speed rifles and hand guns. Nowadays, military personnel and law enforcement officers use different kinds of body armour with rigid ceramics plates throughout the world. Depending upon the threat level, these two types of material can be combined to protect various parts of the human body. Even though armours with heavier inserts are essential to protect against armour piercing, it also results excessive weights in the armour system, which will affect the mobility of a soldier in the field. Today, soft body armour vests are also utilized by military personnel and law enforcement officers made of high-strength/modulus fibres based woven fabrics [33]. The following section will be briefly discussed on some of the currently applied protection fibre materials in the body armour and other ballistic protection solutions.

2.1 Fibre materials

The ballistic-resistance armour system basically helps to stop the projectile from penetrating, and absorbed its kinetic energy by converting it into different forms of ballistic absorbing mechanisms such as deformation, surface damages, tension in primary yarns, deformation of secondary yarns, delamination and matrix cracking etc. (it will be discussed in detail later in **section 3.2.2**). Therefore, the primary factors, which affect the performances of the protective materials, are strength, modulus and elongations at break, deformability of the projectile and velocity of transverse shock waves of the fibre. The following sections tried to highlight the different fibres used in the ballistic protection world.

2.1.1 Traditional fibres

Nowadays, High performance fibres are typically used in the form of woven, non-woven fabrics or woven or non-woven reinforcements within PMCs for different ballistic protective applications including ballistic vests. However, in the ancient time, materials such as animal skin, leather and even silk were also used in combination with metal plates in body armour systems to deliver the required protection until the Korean War [34]. During World War II, new ballistic vests were also designed and developed from E-glass fibre/ethyl cellulose composite to provide both bomb and grenade fragments protection. Besides, Nylon fibres were also used as a backing material for most of the ballistic application in the early age particularly in the Second World War especially for the development of ‘flak jacket’ along with steel plates by the American army. Even though Nylon absorbed twice the amount of energy as compared to p-aramids, however, nylon was not efficient to give a sufficient protection and accounted for many soldiers’ deaths and injuries. Still today both E-glass and nylon fibres are continued to be used due to their low cost. Considering such problems in the ballistic world, a huge amount of research work has been carried out for the last many decades to produce lightweight and flexible ballistic materials for developing next generation ballistic systems including body armour with enhanced mobility and good protection against specified threats. The development of such ballistic materials from high performance fabrics will be greatly depends on high tenacity yarns made from fibres with high modulus, high strength, and excellent anti-degradation traits [4]. High performance along high-strength/modulus fibres have been used for developing an impact-resistant fabrics not only in protective clothing for military and law enforcement personnel but also for various applications such as armour plating of vehicles, protective layering in aircraft and helicopter components (i.e. turbine fragment containment), electrical and electronic parts, honeycomb sandwich constructions etc. [35]. Even such high performance fibres are now becoming the standard for most fabric based vests and other fibre reinforced armour applications.

The following sub-section will discuss some of the most common types of high-strength and modulus polymer fibres including para-aramid and high performance polyethylene fibres, which are used to develop different 3D, 2D woven, and knitted fabrics for various protection applications. **Table 1** shows the specifications of some basic high-strength/modulus fibres.

2.1.2 Para-aramid fibre

Para-aramid fibre is one of commonly used high-strength and high modulus fibres, which have good resistance to melt at high temperature. Even though such fabrics are sensitive to ultraviolet light (UV) but also have low affinity for water. Extremely strong and heat resistant aramids fibres are a class of synthetic fibres which introduced first by DuPont™ in the early 1960s. They are among the different polymeric fibers which is most recognized in the applications of protective systems. It is also constituted polyamides created from aromatic acids and amines [36]. Due to their strong adhesion between amide groups and aromatic groups, they could provide much better thermal resistance and traction compared with nylon fibers [37]. Even though it is relatively expensive, fabrics made from such kind of fibres can provide high strength, high modulus and good tenacity, which are desirable properties for the ballistic applications [38]. Due to these specific properties, they have increasingly replaced the Nylon fibers in military armor. Besides, the aramid materials also introduced the inherent flexibility and lightweight properties which could develop a comfortable ballistic vest along with excellent protective performances. Nowadays, these fibers are of the para-aramid type and marketed under the names Kevlar® and Twaron® [39]. Even though aramid made fabric provides a light weight and better protection, the protecting solution design will be forced to reduce the number of fabric layers required without compromising the effectiveness of the final protecting armor to reduce the cost. In general, aramid fibers are 43 percent lighter than fibre glass (at density of 1.44 g/cc compared to 2.55 g/cc for fibre glass) , twice as strong as E-Glass, ten times as strong as aluminium, same strength as of high strength carbon on a specific tensile strength basis. It is also display excellent dimensional stability with a slightly negative coefficient of thermal expansion (-2.4 X 10-6/°C) and could resist chemicals with the exception of a few strong acids and alkalis. Moreover, the aramids fibre exhibited an excellent stability over a wide range of temperatures for prolonged periods with , no strength loss at temperatures as low as -320ºF (-196ºC) and do not melt but will start to carbonize at approximately 800ºF (427ºC). Kevlar® and Twaron® ((Teijin), are the two commonly used para-aramid materials in the development of bullet proof vests. The both are even five times stronger than steel but yet flexible. They are also heat resistant, cut resistant, chemical resistant, and can handle high ballistic impacts [40]. Technora (Teijin) is also another p-aramid fibre available with low creep, high melting point, and good abrasion and flexural resistance. Due to its early development, Kevlar® production has been refined significantly. The initial Kevlar® 29 was an innovative which makes the protective panels development not only more flexible and concealable but also provides a lightweight product that people were comfortably on an everyday basis. Later, in 1988 DuPont™ developed Kevlar® 129 for body armour use which significantly lighter than its predecessor with improved ballistic resistance capacities and can resist high-velocity rounds from guns such as the 9mm FMJ. Moreover, the most recently released version of Kevlar® called Kevlar® Correctional (Introduced in 1995) could protects against knife and other weapon threats, and has led to the production of multi-threat vests that can halt both bullet and stab attacks. In general, based on their ballistic impact behaviour, the properties of para-aramids can be summarize as follows [41]:

- ✓ Same compressive strength as E glass fibers
- ✓ Good resistance to abrasion
- ✓ Good chemical resistance
- ✓ Good resistance to thermal degradation (-42 ° C to + 180 ° C)
- ✓ Excellent dimensional stability with a slightly negative coefficient of thermal expansion
- ✓ Constant high temperature stability
- ✓ Ballistic resistance restored to wet fibers after drying

2.1.3 Ultra-High-Molecular-Weight Polyethylene (UHMWPE) fibres

UHMWPE known as ultra-high-molecular-weight polyethylene is another high-strength and high-modulus fibres common used in the ballistic panel material that is present in a variety of body armour products. UHMWPE are mainly obtained from thermoplastic polyethylene's of great mass molecular and were first introduced around mid-1980s by the Allied-Signal, now Honeywell Advanced Fibres and Composites (Colonial Heights, Va., U.S.A.), and DSM High Performance Fibres (Heerlen, The Netherlands) [36]. With characteristics similar to para-aramids, this fibre is a polyolefin composed of extremely long polyethylene chains. Among the various manufacturing techniques of UHMWPE, compression moulding and ram extrusion are the most commonly used one. However, for the purposes of body armour production, Ultra-high modulus polyethylene fibres (UHMWPE) is produced through gel-spinning process, which involves creating a gel material by drawing dissolved ethylene through a number of tiny holes. Thanks to this technology, it is possible to achieve high fibre molecular orientation which provides a good toughness, good chemical resistance and abrasion properties. Moreover, with twin pieces of gel sealed under polyethylene film, a composite could be also generated for the manufacturing of soft armour ballistic panels, or rigid plates of hard armour. Such manufacturing techniques also produced a high-strength and high-modulus fibres with very high flexibility and flexural fatigue resistance which allows them to absorb large amount of energy. Such kinds of high-strength and modulus fibres can be also used in high strain rate loading but possess low melting temperature, no hygroscopic and do not absorb water. The UHMWPE fibers possess 144ºC-152ºC melting point but its tenacity and modulus could decrease at higher temperatures and increase at sub-zero temperatures. According to the manufacturer's research demonstration, the strength-to-weight ratios of UHMWPE are as much as 40 percent higher than para-aramid fibres with similar weight basis [42]. This property gives the UHMWPE a strength-to-weight advantage over aramids in terms of lighter ballistic armour with larger energy absorption capacity[43]. However, UHMWPE have shown also some disadvantages in weak softening, low melting temperature and easy creep high loading [44]. Unlike para-aramid fibre, Dyneema^{TM} (DSM) and Spectra^{TM} (Honeywell) are the two common commercially available and widely used Ultra-high modulus polyethylene (UHMP) fibres. Spectra fibres are ten times stronger than steel and 40 % stronger than aramid fibre which also capable of withstanding high-load strain-rate velocities [45]. The brief description of the properties related to the f the ballistic performances of the HMPE fibers are mention below [41].

- ✓ Good resistance to abrasion and chemical
- ✓ Good thermal degradation (+ 50 ° C to + 100 ° C)
- ✓ Low permeability
- ✓ Good resistance

2.1.4 Poly (p- phenylene-2, 6-benzobisoxazole), or PBO fibres

It is a new fibre manufactured by Toyobo Co. Ltd. (Osaka, Japan) under the trade name Zylon around 1998 with the help of immense research activities and technology. It is a high strength and modulus fibre with remarkable thermal stability. The PBO fibres has been used first to manufacture the Second Chance Body Armour Inc. (Central Lake, Mich., U.S.A.) and others ballistic vests [46]. Zylon woven fabrics has also an ability to absorb nearly twice the energy per unit areal density than both Kevlar and Spectra when gripped on all four edges, and almost 12 times that of aluminium fuselage skin but costs several times as much as aramid or polyethylene. The ballistic impact performance of PBO systems is substantially superior to Kevlar 29 systems and marginally better than Kevlar KM2 systems [47]. Moreover, PBOs provide a vest with equivalent protection to aramid vests at half the thickness. However, PBO has been faced problem from vest manufacturing market due to performance decline at aging regardless of climate in a relatively mild environmental conditions of moisture [48] and sunlight heat [49] according to Toyobo test figures posted on the BSST Web site (by which it showed a 15 percent decline in performance). Another study on the PBO degradation mechanisms not only with moisture but also acid and radiation from the UV–vis spectrum has been investigated. Loosening of fibre morphology to increase number and size of defects were observed while exposed to moisture. Besides, presence of aqueous acid brings both loosening of fibre structure and hydrolysis of the oxazole ring structure, whereas UV radiation was primarily affected the hydrolysis of material near the fibre surface with attendant formation of amide linkages [50]. Considering both the poor shear modulus and strength properties of high modules and high strength fibres due to their weak transverse bonds, a new types of fibre, M5 (poly {2,6-diimidazo(4,5-b 4050-e) pyridinylene-1,4-(2,5-dihydroxy) phenylene}) was also invented with stronger intermolecular bonds to increase their corresponding transverse bond [51].

2.1.5 Glass fibres

These filaments are among the most versatile industrial material produced by fusing silica with minerals , then rapidly cooling the molten mass to prevent crystallization and formed into glass fibres by a process also known as fibrillation [52]. E-glass, S-Glass, C-Glass, M-Glass, A-Glass and D-glass fibres are the different available glass fibre with their specific properties which are readily available in the market as shown in **Table 2** [52][53]. Glass fibres and fabrics are employed in ever-increasing varieties for a wide range of applications including composite reinforcement, filtration, insulation, or other applications. Among the different glass fibres types, E-Glass and S-Glass (both S-Glass and S-2 Glass) are currently widely used high-performance glass fibre in many applications. E-Glass is made of CaO, Al_2O_3, and SiO_2, conditionally with B_2O_3 from 0 to 10 wt. %, with suitable mechanical, electrical and chemical stability for most glass fibre-reinforced plastic (GFRP) composite and numerous general industrial applications [54][55]. S-glass is another commonly used glass fibre, which is mainly composed of silica (SiO_2), alumina (Al_2O_3), and magnesia (MgO) and was first developed in the 1960s primarily for high-temperature and high-strength applications and later in 1970s for military ballistic protection applications. Normally S-2 Glass fibre possesses around 35 to 40% strength higher than that of E-glass [56] and offer an outstanding structural performance and ballistic protection for hard composite armour applications due to the high inherent tensile and compressive strengths of the fibre and its composite applications. The high ultimate elongation properties of the fibre put it to play an important role in the dynamic ballistic impact-absorbing mechanism. Besides, the fibres are also highly considered in defence market due to its structural performance, protection against fire, smoke and toxic gas, reduced costs and weights for a given ballistic performance. Generally, the advantages of glass fibres are low cost, high tensile and impact resistance, and high chemical resistances, whereas its disadvantages includes low modulus, high-fibre abrasiveness, low fatigue resistance, and poor adhesion to matrix resins [57].

2.1.6 Carbon fibres

It is another most important polymer fibre in the ballistic world, which is made from acrylic fibre with high tensile strength, high stiffness for weight, and very low thermal expansion properties. Carbon fibre sometimes is five-times stronger and twice as stiff but lighter as compared to steels. This behaviour makes it ideal mainly for reinforcements in a variety of weaves, styles, and widths from tapes and fabrics to heavier knits and unidirectional form for manufacturing not only ballistic materials but also different part in various applications. Graphite fibres sometimes knowns as carbon fibres which show a special structure in which adjacent aromatic sheets overlap with one carbon atom at the centre of each hexagon [58][59].

2.1.7 Ceramic fibres

The ceramic fibre is a high resistance fibre at high temperatures and commonly used in high thermo-mechanical performance required areas including aerospace and rocket industries. Moreover, for the last many decades, due to its low density, high compressive strength, and high hardness, it is considered among the most important materials for lightweight ballistic personal armour applications and vehicle protection system [60]. However, while using for armour, such fibres have also show some drawbacks including high cost, processing hindrances, and lack of proper ballistic performance prediction due to the material property [61]. Mostly, the common ceramic fibres are produced by chemical vapour deposition, generally to produce silicon carbide fibres, and spinning methods to obtain alumina ceramic fibres. Various researches have investigated on the commercial available monolithic ceramic materials such as Carbide (SiC), Boron Carbide (B_4C), Silicon Alumina (Al_2O_3), and Titanium Diboride (TiB_2) while used in the development of personnel and vehicular ballistic protection armour systems [62][63][64][65]. The density and Hugoniot Elastic limits (HEL) of the commonly used ceramic fibres are shown in **Table 3.** Al_2O_3 is the most economical ceramic fibre among advanced ceramics with high modulus of elasticity and refractoriness and high hardness. However, Al_2O_3 brought not only heavier final protection system due to its highest density but also lowest ballistic efficiency compared to the other ceramic types. Unlike it is hardest ceramic; B_4C become weak at high impact pressures due to an amorphization process weakens the ceramic. Even though SiC does not have the amorphization issue, but it is heavier than B_4C. Besides the porosity and grain size of the ceramic plays a great role on the final performances of the material. For example, ceramics with low porosity and small grain size generally performs better ballistic performance than ceramics with high porosity and larger grain sizes respectively [66]. In general, owing to their low specific gravity, and high stiffness, hardness, strength and thermal stability, the ceramic-based systems have shown potential for improving upon current standards for ballistic performance, which includes multi-hit capability.

Another special fibres such as metallic and boron fibres were also used for various application including ballistic protections [67]. Besides, different cellulose-based natural fibres including Jute [68][69], hemp, flax, sisal and coir are recently claimed to be used in the form of composite and rigid plate applications due to not only to their low cost but also their environmental friendly and recycling properties [4][70][38].

2.2 Ballistic fabrics

Textile fabrics are one of the widely used materials in either soft or rigid forms for personal and equipment protection against different kinds of ballistic and related impact threats. Light weight, high protecting performance and low cost as well as comfort are the parameter to select the required textile fabrics [35]. Thanks to the dedicated researchers and companies, now it is possible to fulfil these requirements through using high performance fibres/matrices and layered different type of textile structures such as two-dimensional (2D) and three-dimensional (3D) preforms. Nowadays, ballistic fabrics made of various types of materials are used in various technical applications including ballistic protections. Moreover, the developments of high tenacity yarns made from fibres with high modulus, high strength, and excellent anti-degradation traits plays a significant role on the manufacturing of high performance ballistic fabrics for next generation ballistic protective body armour and armouring vehicles. The structural responses of such fabrics are also widely used in engineering applications due to their lightweight, impact resistance and high-energy absorption ability properties. However, in addition to fibre properties, combinations of various parameters including the fabric structure and geometry play an important role in determining ballistic performance of fabrics and its composite [71]. Currently, various types and structures of ballistic fabrics are available in the market for such applications. In general, textile structures used in ballistic protection are woven fabrics, unidirectional (UD) structures, and nonwoven fabrics [72]. In particular biaxial 2D woven fabrics (including plain, basket etc.), tri-axial fabrics and unidirectional laminates are the most common and widely used in the different technical applications including bulletproof vest and composite industry [73]. However, such fabric has faced low impact performances due to their crimp formation; low delamination and low in-plane shear properties. Even though it shows low in-plane properties, 3D woven fabrics have been widely used in various technical applications since it confiscate the problems of delamination due to the presence of Z-fibres in the structure. However, multi-axis 3D woven fabrics with multiple layers could solve both delamination problems due to the presence of Z-fibres and enhanced in-plane properties due to the bias yarn layers [74]. The following section will tried to discuss on some of the textile fabrics widely used in the ballistic fabrics or/and its corresponding composite applications.

2.2.1 2D fabrics

2D Plain weave fabric is the simplest and commonly used 2D woven structure fabrics in the ballistic applications. It is produced by interlacing the two types of yarns, namely yarns run along the length of the fabric (warp) and yarns that run from selvedge to selvedge (weft) based on the predefined checkerboard pattern. Multiple 2D woven fabrics can be layered to design structures with a range of thicknesses. Alternatively, these layered structures can be stitched in one or more directions to enhance the ballistic and stabbing resistance, especially by decreasing the back face deformation [75][76]. 2D woven fabrics can be coated with elastomers to improve the fracture toughness of the structure. On the other hand, it was claimed that para-aramid fabric becomes more flexible and resistant to ballistic penetration/stabbing when impregnated with shear thickening fluid made of Nano silica particles dispersed in ethylene glycol [77]. In the woven fabrics, especially in plain weave, the percentage of gross area, which is covered by the fabrics, also known as covers factors, played an important role on the ballistic protection performances. Researcher has suggested that, ballistic fabrics with cover factors of more than 0.95 and less than 0.6 will not give better ballistic protection due to degrading of yarns by the weaving process and too looseness of the fabric respectively. On the contrary, fabrics with the cover factors between 0.6 to 0.95 values will be ideal and more effective while utilizing in ballistic applications [78]. **Fig. 1** shows creations of ‘wedge through’ effect on the woven fabrics while impacting by the ballistic projectile. The loose the fabrics becomes, the higher ‘wedge through’ would be exist than the tight fabrics. Such phenomenon occurred not only through fabrics structure but also the sizes of the ballistic projectile could affect it and were studied widely by various researchers [43][79][80][81][82]. 2D knitted and nonwoven structures are other 2D fabrics, which are also used for various technical applications. For example, knitted fabrics could be used for cutting and stabbing-resistant materials due to their structural flexibility and their ability to bring more yarns by shearing during cutting or slashing, whereas non-woven structures are also engaged mostly in the low-speed projectile applications due to its stick-slip mechanism of the short fibre-to-fibre crossing.

2.2.2 Unidirectional laminates

It is another widely used fabrics structure for the ballistic applications, which comprises a non-woven structures composed of unidirectional-layered sheets that are mutually rotated and bonded together. Sheets also known as prepregs are produced by a process of pre-impregnation of straight and parallel fibres with the use of resin or rubber. Fibres in unidirectional laminates have different orientations in different layers and the same orientation in a single layer [83].

2.2.3 3D fabrics

For protection against ballistic projectile or combined threat type, soft vests made of 3D orthogonal woven, 3D angle interlock woven and 3D fully/partly interlaced woven as well as multi-axis 3D woven or knitted preforms have been employed [74][84]. Hybrid 2D/3D fabric-based vest structures can also be made by using single-layer and multi-layered nonwoven and braided structures [74]. 3D woven fabrics (mostly 3D warp interlock) has been also widely used as a fibrous reinforcement for composite material in some applications not only to replace laminated structures where it is no longer suitable but also due to its technical and economic advantages compared to other reinforcements [85][86][87][88]. It also shows a high performance in ballistic protection with high flexibility and light weight [89] over 2D woven structures [90]. However, due to its complex structure it creates some confusion among various researchers, scientists and weaving technologists. Considering such problems, unlike other woven structures some researchers have studied dedicatedly on detail descriptions, components and general design specification of 3D warp interlock fabrics for better clarification and understanding [91]. However, 3D warp interlock fabrics have been also facing some drawbacks which are inherent in its manufacture and specific structure [92][93]. The different types of 2D and 3D woven fabric structures are shown in **Fig. 2**.

2.3 Fibres-reinforced composites

Nowadays, along high-strength polymer fabrics, the fibre-reinforced laminated composites (FRPC's) have been also widely used as primary structural materials in fields of defence, aerospace, transportation and other industrial applications due to their superior engineering properties (e.g., high stiffness and strength, low specific gravity and excellent flexibility). Moreover, apart from traditional fibres like nylon fibres, high performance fibre such as glass, carbon, aramid, UHMWPE etc., have been also exploited and applied in fibre-reinforced laminated composites applications including soft, flexible fibre mats for body armour or as reinforcements in rigid polymer matrix composites (PMCs) for lightweight vehicle armour. The laminated composites are mostly composed of layered sheets of different materials that are bonded together. Such lamination is expected to give the best aspects of the constituent layers due to combining of the directional dependence of strength and stiffness of a material. Different from random chopped fibre-reinforced composites, the unidirectional fibres in laminated composites have different fibre orientations in different layers but have aligned distribution in the same layer. The fibres in laminated composites are generally considered continuous because of the large aspect ratio of fibres. Generally, in ballistic applications two main types of matrices namely, thermoset and thermoplastic can be used. The most common used thermoset matrices are polyester, vinyl ester, epoxy and phenolic, whereas some of the thermoplastic matrices include polyethylene, polypropylene, acrylic polymer, polyamides and polyurethanes. Thermoset matrices are used mainly to convert the fabric into a rigid plate to obtain good thermal and mechanical properties, whereas thermoplastic matrices contribute to the ballistic fracture toughness of the resulting material. Polyester resin is particularly easy to process, fast cure time, low cost and possess good moisture resistance, however, it is flammable and has moderate mechanical properties. Vinyl ester resin is also low cost, have good moisture resistance and better mechanical properties with easy manufacturing process, but it is flammable and releases smoke upon combustion. Besides, epoxy has outstanding mechanical, thermal and fracture toughness properties and moisture-resistant, but expensive and requires high processing temperatures during curing. In general, even though thermoplastic matrix aramid systems show excellent, mass-efficient ballistic properties, but it is also less rigid as compared to thermoset.

Such behaviour brings a significant effect on the overall static structural stability and resilience of the thermoplastic aramid shell, as well as the dynamic deflections while ballistic impact for the development of hard body armour [94]. **Fig. 3 (a)** shows different deformations stages of thermoplastic–aramid panels used light weight ballistic armour development [94]. The rigid impact protecting items including composite helmets, hard body armour and other ballistic items are mainly, produced from thermoplastic or thermoset resin matrix in a certain ratio in different form of prepregs. Prepregs are composite materials in which a reinforcement fibre is pre-impregnated and having unique properties as they are cured under high temperatures and pressures. **Fig. 3 (b)** shows a single-piece textile reinforced riot helmet shell developed using vacuum bagging [95]. Unlike hard body armour, weak fibre-matrix adhesion of fibre-reinforced laminated composites such as thermoplastics matrices is recommended than thermosetting matrices for the developments of soft body armour or lightweight ballistic protection, due to the capacity of fibres to undergo maximum deformation for better energy absorption [30][96]. Moreover, additions of small thermoplastic resin in the fabric layers could improve the ballistic impact performances [51] due to its ability to maintain the orientation and position of the fibres during an impact event and distributes the load caused by the impact among the fibres. Apart from deformation, the matrix in the laminated composite could also help to absorb the impact energy through delamination and debonding [97] and protects the fibres from environmental factors such as high humidity [98] and ultra-violet radiation [99][100].

3. Ballistic impact mechanisms

High performance structure material made of high specific stiffness and high specific strength needs resistance to high velocity impact since it is an important requirement during ballistic impact [101]. Ballistic impact is normally a low mass with high velocity impact caused by a propelling source. For the effective use of such materials in structural applications, the material ballistic behaviour under high velocity impact should be clearly understood. However, while impacting the ballistic material, it passes in to a very complex ballistic penetration mechanisms, which really need a complete and quantitative analysis for better understanding. This complete understanding of ballistic process would help not only for current ballistic material application but also for further reliable design and development of an improved and appropriate ballistic material for different fields including armour. Researchers and scientists have done extensive researches in order to better understand the ballistic impact mechanisms of different materials with various parameters. Apart from the properties of ballistic material (fibre properties), various parameters would have also a great chance to influence the final ballistic resistance performances of the target material. Those factors includes external and internal parameters such as ballistic material system characteristics in terms of yarn properties, weave pattern, areal density and number of plies, as well as impact parameters such as impact velocity, impact angle, projectile geometry, boundary conditions, etc. These different internal and external factors, which affect the ballistic impact performances of given materials, will be discussed in details in the next section 4. Moreover, developing an innovative system on the final target design such as body armour using different approaches such as modelling and simulations could also give better performance at a reduced weight [102]. This section will try to review and discuss on different types of approach to analyse and understand ballistic mechanisms and the material responses while ballistic impact.

3.1 Different research approaches to the ballistic impact mechanisms

For many decades, various researchers have also adopted various methods and approaches to derive and understand the constitute relation and simulate the overall ballistic materials behaviour in response of ballistic impact in order to use in various ballistic impact application. This section will discuss in brief the different approaches used to investigate, analysed and understand the ballistic impact behaviours of the different materials.

3.1.1 Experimental approach

Experimental approaches are one of the commonly used methods to investigate the ballistic impact performances of different materials, and to characterize and obtain relevant data to optimise applications of the ballistic material [103][104][22][105][106][106][107][108][109]. During experimental methods, the effect of different target configuration and target mechanical properties on ballistic performance of the material can be observed when struck by various standard bullet or FSP (Fragment simulating projectile) at the different velocities [109]. The experimental approach while ballistic impact test could also help to determine the energy absorbed by the target and transmitted beyond the target based on different parameters while using in body armours [22]. The different phenomenon including backface signature (BFS), damaged targets, residual velocity and caught bullets will be thoroughly examined using various techniques and equipment including optical microscope, SEM and high speed camera etc. for further analysis and interpretations. After the test, the impacted projectile could be either perforated the material or trapped inside the target. In the non-perforation situation, the projectile might be either stopped inside the material or bounce back by leaving the trauma indentation at the backing material. This ability of the target which prevents the happening of internal injuries is known as trauma resistance. The trauma depth and diameter value created on the back of the ballistic material mainly helps to determine not only the energy absorbed by the target and transmitted to the back of the target but also the overall ballistic performance capabilities of the armours solutions [110][111]. Moreover, apart from using as a performance measurement, the trauma depth values should be measured less than 44 mm [112] according to National institute of Justice (NIJ)-standard. If the depth is higher than this value, the projectile will create a fatal injury in the vital organ of the wearer. Various researchers have used different approaches including high speed camera to capture and measured the values of the backface signatures on the standard backing clay (Roma Plastilina No.1- to preserves its shape after unloading) which is placed at the back of the target to support the packages [113][114]. Another experimental study investigated the ballistic perforation and trauma resistance of different hybrid armour packages including laminate of plain-woven and multiaxial fabrics to felt. Even though the hybrid panels with stiff anti-trauma liners shows 10% reduction of back face deformation than compared to homogenous packages, however too much stiff layers shows a tendency of worsens the perforation resistance by shortening the distance in which a projectile is arrested. Moreover, hybrid panel with felt shows an improvement on trauma and perforation resistance [115].

Apart from backface signatures, the target perforation resistance[115] and surface damages [106][108] are also another variable which will be considered after the test to determine the ballistic impact performances of the final target. Some researchers are also tried to find out experimentally the damage modes, ballistic limit velocities, absorbed energies due to penetration, specific perforation energy capacity and some structural responses of the different target after impact test [107]. The back face, front face and inter-laminar failure views are also some of the surface damages which can be analysed and interpreted by the failure region shape and broken yarns of the targets. Besides, during the impact test, shock energy wave propagations on the target also creates various local and global damages including target compression below the projectile and around the impacted zone, cone formation on back panel, primary yarn failure due to stretching and tensile, secondary yarn failure due to tensile deformation, bowing of yarn, friction between the projectile and the target, matrix cracking and delamination, which all depends on various parameters [116] . Different researchers tried to analyse such failure mechanisms at the micro, meso and macro-level by the help of optical microscope, digital camera, SEM etc. for investigation and interpretation. For example, an experimental investigation on multi-functional panels, which consist of two layers, one made of fibre-reinforced plastics (FRP), and the other of a self-healing ionomer, assembled in four different configurations with different surface density were carried out against under high velocity impact conditions. With a total of 16 impact experiments, different types of panel responses were observed. The panels with ionomer plate and carbon FRP laminate shows hole sealing and as the ionomer panels were placed at rear side the damages has also been reduced [108]. Moreover, while experimental ballistic investigation, the ballistic test are mainly carried out according to the different standard [117][118][119]. The two most common standards are the National Institute of Justice NIJ-standard 0101.06 [120] [112] and Home Office Scientific Development Branch (HOSDB) ballistic body armour standards for UK Police [121]. These different standards could give general guidelines for procedure, equipment, physical conditions and terminology in order to evaluate the ballistic impact performances of different targets including textile and fibre-reinforced composite armour against small projectiles. The experimental ballistic test procedure described in this standard could determine the V50 ballistic limit of the target armour. The ballistic limit velocity is considered as the average of maximum velocity at which full penetration does not occur and the minimum velocity at which full penetration occurs [107]. Even though this experimental method gives the real scenario, but due to its most costly task, destructive and very time consuming nature, different methods were also available and have been used for better analysis and to minimize comprehensive experimental ballistic and impact tests.

3.1.2 Analytical approaches

Analytical methods are one of the approaches used to investigate, analyse and understand the ballistic impact mechanisms of the different materials. Generally, such method is mostly considered as important, convenient and alternatives methods when a very close mathematical equations can be derived to designate both the mechanical and physical phenomena during the impact process. It is also noticed that, any ideas generated using an analytical methods is usually considered as a good guide, and essential for the development of empirical and numerical investigations. Several researchers [122][123][124][125][101][126][126][127][102][128][129][130] have applied generally two approaches (analytical models of momentum equations based geometrical laminate deformation during the impact and energy-conservation laws based analytical model to investigate the ballistic impact process based on various parameters including theory, material, systems etc. which can have a direct contribution in the ballistic impact processes. Unlike the experimental investigation, the numerical simulation and analytical study of composite materials faces difficulty for the applications of personal and vehicle armors. However, considering different primary components of the composite, it is possible to study its behaviour using an analytical model. Such model could determine not only residual velocities and, fabric strain but also the absorbed energies [124]. Considering the fiber as linear elastic fracture and projectile as rigid, the impact behaviour of soft body armours including ballistic curve, the impact force, each target layer tension, distance and speed of the layers and bullet, stress and strains of yarn and surface damaged could be also developed using an analytical model [125].

Various ballistic behaviour and energy absorbing mechanisms through micro, meso and micro levels of material based analytical modeling formulations were predicted by various researchers. For example, a single-yarn analytical model was used to understand the ballistic impact mechanisms of multi-layer woven fabrics involving different internal and external parameters. Such analytical model were generally used both strain phenomenon and shear failure mechanisms to understand and describe not only the primary yarn strain distribution history within each layers of the panel but also clearly show how the shear failure occurs before tensile failure for the front layers during ballistic impact of multi-layer woven fabrics [131]. The Fabric microstructure based analytical model approach was also constructed in order to investigate the ballistic penetration damage, deformation and energy absorptions of three-dimensional angle-interlock woven fabric (3DAWF). Based on the ballistic test, the strike velocities versus the residual velocities curve were obtained and impact damage of the 3DAWF was observed. Based on the analytical modelling emphasizing strain rate effect, both the weave density and yarn crimp coefficient found to be key factors influencing fabric ballistic behaviour [132]. Another yarn pull out and yarn migration analytical solution was also applied to understand the various plain-woven fabric architectures, crimp imbalance and energy absorption capacities interactions while impacting through when rigid projectile. Moreover, based on the determined projectile residual velocities and contact angles α relations, the analytical simulation shows that highly crimp-imbalanced woven fabrics perform much better than equally-crimped woven fabrics [133]. The ballistic performances and energy absorbing mechanism of textile and fibre reinforced material can be also predicted using wave propagation (weave theory) and energy balance based analytical simulations. The research studies were applied such modelling formulations to investigate the ballistic performances of ballistic hybrid panels made of woven fabric as front part and UD material as real part. According to the prediction, the prediction result revealed that more tensile resistances by woven fibres and tensile resistance by UD yarns were achieved in front and rear layers respectively for better ballistic performance [72]. A similar wave based theory analytical methods were also applied to predict the ballistic impact behaviours including back face cone formation, primary yarns tension, secondary yarns deformation, delamination, matrix cracking, shear plugging and friction during penetration of two-dimensional woven fabric composites. By analysing the energy absorbing mechanism for the above parameters using analytical formulation, it was possible to predict and agree with experimental results both in ballistic limit, ballistic limit contact duration, cone surface radius and damaged zone radius for the specified composite structures [101]. Recently, the ballistic impact behaviour of the two-dimensional woven fabric composites through different damage mechanisms (including cone formation, primary yarns tension, secondary yarns deformation, delamination, matrix cracking, shear plugging and friction etc.) and energy absorbing mechanisms were investigated through an analytical formulation. In this formulation, it was possible to determine the projectile speed reduction and absorbed energy

within each time interval. Moreover, the analytical prediction solutions, later compared and validated with laboratory result, were basically based on the properties of material and projectile parameters [101].
Another analytical modelling approach based on theoretical finding can be also used to investigate the energy and projectile momentum changes while perforation of monolithic and composite materials. One of the study, used such analytical modelling approach, later validated through laboratory test, suggested that both energy and momentum transfer values were reduces when impact velocity exceeds the ballistic limit velocity but higher at the "just-stopped" condition[126]. While impacting, both the material properties and deflection geometry can be also formulated using an algorithm based analytical model followed by some experimental measurements [127]. For validation and comparison purpose, an experimental study along with theory was carried out on Kevlar 29 fabric against 0.22 and 0.357 caliber bullets.

3.1.3 Numerical modelling approach

Enormous researchers have also preferred and used a numerical modelling approach which relies on techniques, such as finite element and finite difference methods by the help of commercial packages, such as ABAQUS, DYNA3D, LSDYNA, ANSYS etc. to establish projectile-fabric simulation model and conduct the ballistic impact performances of the materials [134][135][136][137][138][139] [140][141][142]. This method is generally an effective approach in terms of time and cost as compared to the experimental approach due to it reduces the work of experimental test. However, it still required high computing power and resources for simulating the process. Generally, three main numerical methods are commonly used, namely pin-jointed model [143][144][145][146], full 3D continuum model [147][148][149][150] and mesoscale unit-cell based model [151][152][153][154][155] to model the fabric structure. Regarding fabric modelling, both 3D continuum and pin-joint model considers the woven fabrics construction methods using warp and weft yarns, whereas, unit-cell based model bases woven fabric as an assembly of crossovers [156]. Moreover, the unit-cell model has shown better efficiency to predict the ballistic impact responses of multi-ply fabric panels compared to both pin-jointed and 3D continuum model [157]. But, this model also faced problems of analysing the primary and secondary yarns behaviours in the fabric due to the yarns are not explicitly modelled and their corresponding stress distributions are different [71]. For example, numerical modelling based research on the ballistic impact performance of Kevlar®-29 against different double-nosed stepped cylindrical projectiles was developed to analyse and predict the ballistic limit, failure mode and deformation of the targets. It was also given a possibility to compare the impact behaviours of the material on double-nosed, single-nosed flat and conical projectiles. Significant influence of the nose shape on ballistic performances of the intended fabric was demonstrated and, lowest ballistic limit has been observed in conical nose shape projectiles. The modelling shows projectile nose geometry has lower and higher effect on the ballistic limit velocity for thin and thick targets respectively [158].The delamination growth of non-crimp fabric (NCF) composite materials were investigated using stiffness averaging method (SAM), modified virtual crack closure technique (MVCCT) and penalty method (PM) based on numerical simulations. The modelling result gives good correlation with the experimental work in terms of the deformed shapes and load–displacement curve [159]. Another finite element (FE) numerical modelling were also applied to study the effect of different angle of ply arrangement (3-ply align-laid [0/0/0] and angle-laid [0/30/60]) on ballistic impact performances of multi-ply UHMWPE fabric panels. Based on the simulations a 3-ply fabric panels reveal a critical velocity whereas, improved energy absorption was achieved by angle-laid panel due to its enhanced inter-ply isotropy [160].

3.1.4 Empirical methods

An empirical and semi-empirical methods is another methods which mainly focus on data from experimental work to investigate the ballistic material impact responses and different failure mechanism [161][162][163]. It is also one of the most straightforward and important method to investigate the ballistic performances of material. For example, a parametric model based on six-dimensional nonlinear regression analysis of extensive test data for Kevlar 29 with user-defined areal density has been developed to predict the performance of body armour systems under ballistic impact by a chunky steel projectile of arbitrary mass, shape, impact velocity, and impact obliquity. Based on identifying the predominant mechanism of energy, the model tried to implicate and suggestions for designing, optimizing, and evaluating the functional utility of body armour systems [161]. However, the method also has drawbacks due to its costly nature, time-consuming, and most importantly lack of necessary data mining systems to generate and involve sufficient data for better analysis and getting genuine results.

3.1.5 Combinations of two or more approaches

Sometimes it was also found very difficult to fully understand and describe the ballistic impact phenomenon using solely experimental, empirical, numerical or analytical methods. Various researchers have used to applied the combinations of experimental, numerical, experimental and analytical approaches for better understanding, discussion and analyse of useful information during ballistic impact mechanisms [164][165][137][166][167][168] [145][169][170][171][131] [172][173][174][175][176]. The blunt trauma resistance of different fabrics (plain woven, unidirectional laminates and multiaxial fabrics) made of high strength fibres using experimental and numerical approaches were investigated. The absolute values of depth of the depression and the amount of energy transferred of each fabric were compared and normalised based on their thickness and areal density. Both approaches proved that most fabrics provide similar level of protection, but the best blunt trauma resistance is given by multiaxial fabrics and the least by plain woven fabrics based on the normalised values [177]. A microstructure numerical modelling followed by experimental investigation was carried out on the ballistic impact damages of 3D orthogonal woven fabric (3DOWF) penetrated under a conically cylindrical rigid projectile. The result shows that the numerical simulation can analyse the impact damage better than experimental while comparing damage morphologies and residual velocities of the projectile after perforation. However, for better optimization of the 3DOWF structure, a combined experimental and numerical investigation is further required both on material and architectural aspects [178]. Besides, another study involving a combined theoretical and semi-empirical penetration model involving both short-time shock compression and long-time dynamic penetration on a thick section composites against ballistic penetration was developed and the result shows a good correlation with finite element analyses of similar situations [179]. The ballistic performances of different materials including ballistic textile (Kevlar) against the improvised explosive devices (IEDs) were experimentally tested separately before making the combinations of different materials to develop the final target with optimized protection. Besides, numerical simulation using DYNAFAB® and LS-DYNA® has also applied to develop an appropriate and optimised design parameters of the target, and a good correlations were obtained between the models and the experiment [180]. Different 2D woven fabric composite laminates were involved in the stress wave propagation and energy balance based analytical formulation to predict its ballistic impact behaviour against rigid cylindrical projectile. Among several damage and energy absorbing mechanisms, the designed analytical formulation analyses both shear plugging and tensile failure during conical deformation and solutions were presented. Beyond the formulations, experimental investigations on some laminates were also carried out to validate the analysed results [181]. Another experimental data on ballistic performance tests of 3D warp interlock woven fabric against FSP (Fragment Simulating Projectile were validated by numerical modelling using both the dynamic and static states. According to the study, the dynamic state numerical result performs a good prediction on the 3D woven fabric impact behaviour than the static state values [182]. Besides, various researchers have also applied different material impact analysing methods. The micromechanical approach [140][183][184][185][186] is used where fabric geometry is mostly exemplified by (RVC) representative volume cell to deliver the entire fabric structure through repeated translation. Basically, the different parameters such as displacements, strains, and stresses will be computed by the cells, which are analysed by equilibrium of forces or variation potential energy methods. Besides, the other approaches considering an assumption on various fabric behaviours at different scales due to the inherent multiscale nature of fabrics are called Multiscale Constitutive methods [155][187]. Variational is another numerical based methods to manage equations using varies principles such as Reissner variational principle, Galerkin method, Rayleigh–Ritz method and principal of minimum potential energy [188][189][189].

3.2 Ballistic impact responses of textile materials

3.2.1 Ballistic impact responses and wave propagations of yarns and fabrics

Over the past many decades, woven fabric has been used for constructing soft body armour [30][190]. Enhancing soft body armour performance constructed from woven fabrics requires full understanding of the ballistic impact response and wave propagation during the ballistic impact process. So far, various techniques have been involved to derive constitutive relations and model overall fabric ballistic behaviour including deformation and failure process against ballistic impacts to better understand, improvement and use in different applications. While the projectile impacts fabrics, generally two types of yarn are involved against the projectile as shown in **Fig. 4**. The yarn which are in direct contact with the projectile is known as primary (principal) yarns, and those that are not in direct contact called secondary yarns [103]. During impact, projectile creates a transverse deflection in the primary yarns, whereas longitudinal stress waves also propagate away from the impact point along the axes of principal yarns at the sound's speed. However, the number of warp/weft yarns hit by the projectile makes the fabric energy absorption process very complicated. This is due to the fact that, projectile may hit on yarns, interlacements, or on gap between yarns. When the projectile hits only few yarns on the impacted area, the results will be very complicated. However, in a very ideal situation where the whole end area of the projectile touches the fabric, the numbers of warp and weft yarns hit by the projectile can be calculated as follows:

$$N_e = {d_{pro}}/{d_e} \qquad (1)$$

$$N_p = ({d_{pro}}/{d_{pl}}) \times n_1 \qquad (2)$$

Where, d_{pro} is the diameter of the projectile

d_e is the distance between the neighbouring warp yarns;
d_{pl} is the distance between the neighbouring weft yarns
n_l is the number of weft layers.

For example, the impact area of the fabric hit by the projectile is equal to the end area of the projectile and, the diameter of the projectile, d_{pro} will also determine both the length and width of the fabrics [191].
Therefore, numbers of warp and weft yarns in a single layer fabric directly hit by the projectile is given by:

$$N_e = {}^{d_{pro}}\!/_{d_e} \tag{3}$$

$$N_p = {}^{d_{pro}}\!/_{d_{pl}} \tag{4}$$

$$d_e = {}^{1}\!/_{n_e} \quad \text{and} \quad d_{pl} = {}^{1}\!/_{n_p} \tag{5}$$

Where, n_e and n_p are the warp/weft density respectively.
So, the number of warp ends and weft picks in a single layer impacted by the projectile will be calculated as:

$$N_e = d_{pro} \times n_e \tag{6}$$

$$N_p = d_{pro} \times d_{pl} \tag{7}$$

Where, Ne and Np are the number of warp and weft yarns in a single layer impacted by the projectile respectively.
For a better understanding of a very complex projectile impact process along with the complexity of fabric structure, it is better to start studying from a single yarn wave propagation subjected to ballistic impact.

3.2.1.1 Wave propagation in a yarn under ballistic impact

It is good to start the investigation on the transverse impact behaviour of a single fibre to understand various impact behaviours of the fabrics. As it is also mentioned above, when a single yarn is subjected to projectile impact, a conical-shaped transverse deflection with time has been formed in the yarn as shown in **Fig. 5 (a).** This is due to the fact that, the yarn is enforced to move forward along with the projectile, whereas concurrently a longitudinal wave gradually builds up in the yarn and rapidly propagates away from the impact centre at the velocity of sound in the material, travelling in the direction of the axis of the yarn. In the longitudinal wave front, the yarn material is set in motion inwardly toward the impact centre due to the stretching. The inwardly flowing material continues to feed the advancing transverse deflection until the strain in the yarn reaches its breaking strain. Various researcher were intensively work on transversely impacted single yarn based on theory and yarn mechanics [192][193][103][30][194]. Besides, the longitudinal wave propagations different characters in the single yarn were also studied [195][196].
The ballistic behaviour of a single yarn subjected to projectile impact will be calculated as follows [192].

$$(\varepsilon) = \sqrt{({}^{\rho}\!/_{\sigma\varepsilon})} \;\; for\; non - elastic\; yarn \tag{8}$$

$$C = \sqrt{({}^{E}\!/_{\rho})} \quad for\; elastic\; yarn \tag{9}$$

Where C is the longitudinal wave velocity;
E is fibre young's modulus and
ρ is volume density of yarn;

$$u_{lag} = \sqrt{({}^{\varepsilon}\!/_{(1+\varepsilon)})} \tag{10}$$

$$u_{lab} = \sqrt{({}^{\varepsilon}\!/_{(1+\varepsilon)})} - \varepsilon \tag{11}$$

$$V = \sqrt{2\varepsilon \times ({}^{\varepsilon}\!/_{(1+\varepsilon)}) - \varepsilon^2)} \tag{12}$$

Where, C is the transverse wave velocity;
u_{lab} is the transverse wave velocity in yarn [197] laboratory coordinates;
ε is the instant strain level between strain wave front and point of impact;
σ is the stress and
V is the impact velocity of the projectile.

Besides, the amount of energy absorbed by fibres is largely dependent upon their strain to failure as depicted in **Fig. 5 (b)**. The transverse deflection of principal yarns generates of longitudinal stress wave in the secondary yarns. As soon as the principal yarns fail at their breaking strain, the fabric transverse deflection reaches its limit

[79]. Researchers have studied the role of principal yarns and secondary yarn very well numerically as well as experimentally [71]. It is observed that, most of the projectile energy is absorbed by principal yarns mainly in the forms of kinetic and strain energy. However, the secondary yarns are often not fully stressed before ply failure. The limited involvement of secondary yarns in energy absorption is brought by the inherent orthogonal nature of plain weave structure.

3.2.1.2 Wave propagation in a fabric under ballistic impact

It is clearly noted that the ballistic response and wave propagations of the fabrics shows basic similarities with the single yarn [103][30]. The heterogonous and anisotropic material such as fibre-based materials (woven fabrics) undergo basically two different kinds of strain waves namely, longitudinal and the transverse waves in the fabric plane and out-of-plane directions respectively. When a bullet hits those fabrics with single-layer, both transverse deflection in the primary yarns and longitudinal wave propagation away from the impact centre along the axes of the primary yarns are produced as shown in (**Fig. 6 (b) and (c)**). During impact, initially the fabric faces a small amount of strain around the impact position, and later with time the wave starts to propagate to the neighbouring and adjacent points along the yarn axis while the strain at the point of initial stress increases [198]. Besides, the longitudinal stain waves were considered to have uniform distribution toward the length, however this will not work out at higher projectile velocities. This indicated that the strain wave varies from minimum (negligible) to higher (breaking) values elsewhere which contributes for the stress–strain curve. In the contrary, the considering out-of-plane fabric direction transverse wave, the yarn mass generally flooded to the thickness direction away from impacted areas of the fabric depending upon the amount of impact energy [194].
The correlation between the projectile velocity and fabric strain [194] will be given as:

$$\varepsilon = {}^{V}\!/_{c} \tag{13}$$

$$c = \left[{}^{1}\!/_{\rho} * E\right]^{1/2} \tag{14}$$

Where, ε is the material strain upon impact;
V is the projectile velocity (m/s);
c is the impacted velocity (m/s);
ρ is the material density (g/cm^3) and
E is the tensile modulus of material (GPa).

The speed of stress wave propagation formed on the fabric mainly depends on the energy absorption and propagation ability of both fabric layers and fibre types. For example, the stress wave propagates faster through the yarns and transmits quickly to the adjacent yarns in the fabric at higher Young's modulus of elasticity of the fibre and lower density of the fibre as indicated in **Eq. (9) (14)**. Thus, in order to increase the energy dissipation, higher number of yarns should be involved in the energy absorption process [199][200]. As it is clearly observed from the above two equations, when the tensile modulus and material density increase, the propagation of stress waves through the yarns and the fabric's will be faster. This further revealed that, the energy will be absorbed by a large number of yarns and also leads to increase the energy dissipation as the stresses and strains are quickly transmitted to the adjacent yarns [145]. The energy absorbed by the fibre-based woven fabrics will be calculated as follows:

$$E_m = {}^{1}\!/_{2}\, m\,(v_i^{2} - v_e^{2}), \qquad if\ v_i > v_p \tag{15}$$

$$E_m = {}^{1}\!/_{2}\, m\, v_i^{2}, \qquad if\ v_i < v_p \tag{16}$$

Where m is the projectile mass (kg);
v_i is the impact velocity of the projectile (m/s);
v_e is the exit velocity of the projectile (m/s),
v_p is the penetration velocity of the projectile (m/s), and
E_m is the projectile energy loss (joule).

Practically this equation is used easily to measure the ballistic limits of soft body armour. However, if the impact bullet perforated the soft vest completely, the residual velocity should be measured using high-speed camera to exactly understand the energy absorption capabilities of the panel. Moreover, the different mechanisms involved in a woven fabric subjected to a ballistic impact also depend on a combination of different factors (will be discuss in detail in **Sec. 4**). In general, the energy lost by the projectile and absorbed by the fabric panel depends on various damage and energy-absorbing mechanisms, namely, yarn pull-out, fibre plastic deformation, fibre fracture [4][133][201], and fibre type, yarn linear density, fabric settings, fabric weave, fabric surface finishing, sample fabric dimensions, number of fabric plies and their arrangement [80][202][31][203].

3.2.2 Ballistic impact process in composite laminates

Over the past few decades, due to a significant application of polymer matrix composites in different traditional and advanced technical fields, the demand toward high-specific strength and stiffness materials have been increased. However, composite structure applied in defence, marine, automotive, civil structures and aerospace could be also subjected to a localized projectile impact, which might face indentation, partial penetration or perforation depending on composite material, composite thickness, projectile mass, projectile velocity, projectile shape etc. For example, hailstones, bird strikes, impact of runaway debris, small and medium calibre bullets, and blast fragments might occur on aerospace and defence structures. Though, it is very important to clearly and complete understanding of different structure loading conditions including protection against penetration by external high-velocity projectiles to ensure the safety of composite structures before using it in specific applications. Extensive research based on different approaches has been carried out to investigate, discuss and understand the ballistic impact process and behaviour of polymer matrix composites. For example, the impact behaviours of different composites were intensively investigated not only analytically [171][204][205][206][207][208][209], but also experimentally [210][211][212][213][214][215] for better understanding and validations of theoretical, analytical and numerical analysis of various composite material impact behaviours. Unlike heterogonous and anisotropic materials such as fibre-based materials (woven fabrics), both homogenous and isotropic material possess waves of stress and the deformation propagate around the impacted region with some velocity under load impacting. In the impacting process, the material become deformed with both transverse distortion (shearing) and longitudinal distortion [216]. This can be expressed with the following equations [216].

$$c_1 = \left[{}^{E}/_{\rho}\right]^{1/2} \tag{17}$$

$$c_2 = \left[{}^{E}/_{\rho}\right]^{1/2} \left[\frac{(1-2v)}{2(1-v)}\right]^{1/2} = c_1 \left[\frac{(1-2v)}{2(1-v)}\right]^{1/2} \tag{18}$$

Where c_1 is the velocities of propagation of the plane wave of longitudinal dilatation;

c_2 is the velocities of propagation of the plane wave of transverse distortion;
E is the tensile modulus of the material and
v is the Poisson's ratio of the materials

As it is observed in **Fig. 7**, a sequence of possible events might and different impact mechanisms occur in the lightweight material system in order to halt an armour-piercing bullet. One of the study investigates such sequences of events using a 10g bullets steel core (grey) with a lead nose (black) and a gliding metal surface (copper colour) as shown in **Fig. 7(a)**. In present armour systems, bullet blunting is provided by a 5 – 10 mm hard ceramic surface (e.g., B_4C) and the bullet deformation sequence reflects observations from X-ray experiments [122][217].

During ballistic impacts of composite materials, depending on the target material properties, target conditions and projectile parameters; the following three conditions may happen:

(a) Complete perforation of target with certain residual velocity. Here the initial projectile energy is higher than the energy that can be absorbed by target.
(b) Complete perforation of target with zero residual velocity. The initial projectile velocity with the given mass are considered as ballistic limit, by which all the impact energy is completely absorbed by the target.
(c) Partial perforations of the target. The initial energy by the projectile is lower than the energy absorbed by the target in which the projectile is stuck inside the target or bounce back depending on the material property.

While impacting the composite target, the incident kinetic energy of the projectile would be absorbed by the target through different kinds of damage and energy absorbing mechanisms. These various kinds of energy absorption mechanisms and damages should be well known and clearly understood. The following topics will raise some of the possible different energy absorbing mechanisms and damages of the target while ballistic impact.

(i) *Compression of the target directly below the projectile*: When compressive wave propagates in the thickness direction, the target compression takes place in the region directly below the projectile as shown in region 1 (**Fig. 7 (b)**)**.** The projectile displacement results in compressive strain in the layers up to the distance travelled by the compressive wave.
(ii) *Compression in the region surrounding the impacted zone*: Another region surrounding the impacted zone up to which the transverse stress wave travels along the in-plane directions as shown in Region 2 (**Fig. 7(b)**)**.** This region also experience compressive strain along thickness direction due to transverse shear wave propagating in the in-plane directions.
(iii) *Conical deformation on the back face of the target:* When the projectile impact the target, because of the sudden drop in contact force, only the upper few layers fails due to shear plugging as the shear wave

propagates along the thickness direction. Then, the undamaged layer absorbs the residual kinetic energy of the projectile through creating a cone shaped deformation when the shear wave reaches at the back face of the target. This back face cone formation was also emphasized by various researchers while investigating the ballistic impact behaviours of different composite targets [170][218].

(iv) *Tension in primary yarns: P*rimary yarns are the prominent yarns to take and resist the direct projectile force into the target and faces the higher strain, which also provide the force to resist the penetration of the projectile into the target. Normally the tension created on the yarn helps to absorb some of the energy. Upon the impact, these yarns tend to fail when the induced tensile strain of these yarns exceeds the ultimate strain.

(v) *Deformation of secondary yarns:* Normally all the yarns other than the primary yarns are called secondary yarns which are responsible also to absorb some energy while impact. Mostly such kinds of yarn absorb energy based on their strain distribution within the yarns and highest values are found near the top face of the deformed cone.

(vi) *Delamination and matrix cracking:* During woven composite impact, both longitudinal and transverse waves propagate along the radial direction. The transverse waves will tend to create cone at the backsides of the target, whereas, the stress wave will decrease as the longitudinal wave propagates along the yarns. Moreover, as the stress state varies from impact point to point where the longitudinal stress wave has reached, accordingly the tensile strain varies from a maximum value at the point of impact to zero at the location up to which the planar tensile stress wave has reached. Around the point of impact, the matrix tends to fail when the tempted strain exceeds the damage threshold strain for the given material. Later, when this matrix cracking occurred which also leads to delamination in Mode II. Normally, both damages will continue until the complete perforation or entire projectile energy absorption takes place. The delamination propagation of woven fabric composites has been also studied in different researches [218][219].

(vii) *Shear plugging:* Except in glass-reinforced composite due to its high failure strain at high strain rate, it is one of the major damage mode while impact for energy absorptions by the targets. This phenomenon is occurred due to the immediate impact contact force between the projectile and the target results in through-the-thickness shear plugging stress within the target around the periphery of the projectile. If the persuaded shear plugging stress exceeds the allowable shear plugging strength, the target would fail. Researchers have studied and witnessing shear plugging is one of the major damage modes on impact [220]

(viii) *Friction between the projectile and the target:* The frictional coefficient between the projectile and the target has also a tendency to absorb the impact energy. The impact energy which is left after absorbed by all the mechanisms including cone formation, primary yarn tension, secondary yarn deformation, and delamination and cracking, shears plugging or tension etc., the damaged target still provides frictional resistance against the projectile motion. If the projectile does not have enough kinetic energy to overcome the frictional resistance, the projectile would be stuck within the target. Some researchers have modelled the effect of friction force on the energy absorbing mechanisms [220].

4. Mechanisms affecting ballistic material performances against impact

As we discussed earlier, for the last many decades different ballistic materials from felt to metal and composite were used in different applications including armour systems. This has been even further extended on bioinspired materials and its biomimetic conditions [119]. Even though steel was the most preferred materials in battlefield, however for the last few decades new and innovative materials including fibres, composites, laminates and ceramics have been extensively exploited to accomplish the requirement of different modern military and other operational, technology driven applications. Consequently, textile material have been used as ballistic since World War II, as flak jacket for aircraft and now widely used by military and police personnel [221]. Different studies revealed that the effectiveness of the ballistic performance of the materials against impact as a whole depends on various parameters [103][104].This means that the responses of the ballistic materials cannot be evaluated from individual fibre properties or other parameters, indeed, different factors combine to produce a structural response [71]. Various researchers and scientists have investigated on those effects using different material along with various mechanisms. Among the investigations, in general, the different parameters which influence the ballistic impact performance includes material properties, fabric structure, projectile geometry and velocity, far field boundary conditions, multiple plies and friction [30][222]. Fibre type [104], yarn properties [221][96] and its fabric unit area weight has also showed a great effect on ballistic impact performances [78]. Other parameters like ballistic material areal density [114], dimension of target [103][223], target plies numbers [5][104], target ply layering sequence [110][224][104] and textile construction, such as woven/nonwoven and 2D/3D fabrics has also played a vital effect on the final performance [103][225][8][226][227][73]. Besides, friction between projectile–yarn, yarn–yarn and filament–filament [228][229][230][231], bullet speed and geometry [30][97][167][116][30][31][202][232], target frame size and clamping pressure [233] and shooting angle [234] has also contributed an important role in the energy absorbing process during ballistic impact performances of different materials upon ballistic impact. The following section will present different research works, which dealt and discussed on different factors, which affect the final target ballistic performances against ballistic impact.

4.1 Ballistic textile material properties (textile and fibre-reinforced composites)

4.1.1 Effect of fabric structure characteristics

In general, the textile material ballistic impact performances are influenced by various parameters. Among the various mechanisms, textile material properties such as fabric architecture, weave construction, weave and yarn density, fabric thickness, fabric crimp and fabric types are some of the major factors. Studies using various fabrics discussed the effect of those parameters not only in ballistic impact performance [235][236][237][197][238] but also in their flexibility [239][240], mechanical properties, including tension wave speed [241][242], tensile and tear strength [243][244][245][246][247].

The weaving architectures is one of the factors affecting the flexibility, durability, manufacturing processes, ballistic impact resistance and energy absorption of single, multi-layer fabrics and its corresponding composites [73][248][202][249][104][250][251][177][190]. One of the study reported the influences of fabric construction in para-aramid fibrous products with similar material and density on their ballistic behaviour at constant speed and deformation energy test against different projectiles [248]. Different fabric construction namely, 1/1 plain, weave, twill weave, 2×2 basket, and satin constructions (**Fig. 8**) were tested at the at the lower speed projectile and the result, revealed that, a 1/1 Plain weave construction shows better performance against armour-piercing (AP) and Full metal Jacket Rifle Bullets (RB) than the other fabric construction (**Fig. 9**). However, at higher speeds, 2×2 Basket fabric showed better ballistic resistance performance compared to the plain and twill weave construction. Another study with mesoscale numerical models were also investigated on the influence of woven architectures toward the ballistic resistance of single and multilayer Twaron® fabrics and its composites [190]. The experimental test performed only on the plain weave Twaron® fabric to capture the projectile's residual velocity, fabric deformation, as well as failure patterns. Both the numerical and experimental result shows that weaving architectures and fabric firmness are less influential on the overall ballistic protection of multi-ply systems compared to the single-ply cases. Similarly, the effect of fabric structure (plain weave, basket weave and knitted fabrics shown in (**Fig. 10 (a)**) against ballistic resistances of composite textile material have numerically investigated using finite element analysis [250]. Considering all the structure with similar mass per unit area, knitted composite textile possessed the worst performance compared to the others.

The impact-induced damage patterns between plain weave and knitted structure numerical results are also strongly supported by the experimental study. The crack propagation consistence along the ‘course’ direction of the knitted fabric was clearly observed in both experiment and numerical models as shown in **Fig. 10 (c) (iii) and (d) (ii)**. Whereas, 2/2 basket weave exhibited similar ballistic resistance compared to knitted fabrics and provided more shearing and flexibility for fabrics compared to the rigidity of the plain weave. A numerical modelling based study on the ballistic response of different woven fabrics was also supported by the above investigation [251]. Among the different fabrics structure, namely plain, twill and satin, the plain-woven fabric exhibits better energy absorption due to its maximum interlacing points to transmit stress to a larger fabric area by involving more secondary yarns while energy dissipation as shown **Fig. 11 (a).** Besides, as illustrated in **Fig. 11 (b),** in a multi-ply ballistic system, regardless of the type of fabric structure, both fabric density and yarn crimp has relation with the energy absorption capabilities. Another comparative study involving both experimental and numerical approaches on ballistic performances of different fabric architecture made of high strength fibres were investigated [177]. The comparisons based on the depression depth and energy transferred to the backing as described in **Fig. 12,** showed that most of the analysed fabrics provide a similar level of protection, however, multiaxial and plain woven fabrics revealed the best and the least blunt trauma resistance respectively. Besides, the experimental investigation on the ballistic performance of cross-laminated and woven aramid fabrics based on energy dissipation and projectile arrest of the material [73] shows that the cross-ply laminated aramid material gives better ballistic performance than woven fabrics with similar fibre material (**Fig. 13**). The capability to dissipate the impact energy were found 17% and 5%, whereas the minimum number of layer to stop the projectile are one and six for the cross-ply aramid laminates and woven aramid respectively.

The K-Flex UD nonwoven fabric panels has also shown 16% lighter and more flexible than the Twaron woven fabrics while ballistic impact performances test of panels made of 100% woven (Twaron CT 710 type) and 100% unidirectional nonwoven (K-Flex) para-aramid fabric panels (Kevlar 129 yarns) with various fabric ply numbers according to NIJ standards [252]. Beside its light weight panel, K-Flex UD non-woven have also shows lower trauma depth and higher trauma diameter values compared to Twaron woven fabric panels in dry state due to the absence of crimp for better propagation of ballistic impact energy (**Fig.14 (a) and (b)**). In addition, using the measured trauma depth and diameter, unidirectional fabric panels absorbed around 12.5–16.5% more energy, and possess more deformation than woven fabric panels for the unit panel weight ((**Fig. 14 (c) and (d)**)).

Based on series of standard ballistic test, the influence of fabric structure on ballistic performance of UHMWPE composite laminate's reinforced by three different kinds of fabrics (unidirectional (UD) prepreg, 2D plain-woven (2D-P0) and 3D woven single-ply orthogonal (3D-S0)) were also studied [202]. The composite laminates with unidirectional fabrics exhibit higher ballistic impact velocity and absorbed energy capacity compared to others. The 2D plain and single-ply 3D orthogonal woven fabric reinforced laminates have also shown localized damages with little delamination as shown in **Fig. 15**. However, unidirectional composite faces plugging friction for the thin laminate whereas, delamination, fibre tension and bulking in thick laminate were found the most occurring surface damage. Apart from fabric structure, pre-tensioning phenomena while woven fabric production has also an influence on the ballistic performance of the materials. In order to understand its effect both on ballistic limit and in-plane force variation of the woven fabric, ballistic impact test at normal and oblique were examined using a pre-defined experimental setup as shown in **Fig. 16**. In this investigation, the ballistic fabric responses were affected by different factors by which all are affected directly by the pre-tension and impact angle [253]. Moreover, while fabric production, apart from fabric construction, yarn gripping while producing narrow plain woven fabrics has shown a great effect on the ballistic performances of the final material [254][114]. Based on the ballistic impact experimental test on plain woven narrow fabrics with different widths revealed that narrower fabric demonstrates better performance in lower impact energy [254]. This is due to the fact that better weft yarn gripping effect of the selvages and less performance in higher impact energy due to insufficient and discontinuity of the fabric material to dissipate the impact energy as compared to wider fabrics. However, the broad novel fabric incorporating both yarn gripping and material continuity could also possess better ballistic performances in terms of both back face deformation and projectile penetration. Even the panel arrangement (cut and fold form) and (offset and stacked) of the narrow fabrics has also showed an effect on the ballistic impact performances. Folded panels gives better ballistic performance than cut ones due to its good yarn continuity and the offset panel did not perform well due to it lacked the material continuity for the impact to be dissipated sideways and the projectile could also impact on gaps between two pieces. Moreover, even though the ballistic performance of narrow fabrics is highly sensitive to fabric construction, in the fully clamped condition, the energy absorption of strip and narrow fabrics were also found better than the wider fabrics under ballistic impact due to yarn pull out in one direction moderating strains at the impact zone [114]. This makes it possible to develop flexible full-width body armour panel by choosing and combining appropriate narrow fabric with better performance and mounting frame than the standard fabric panels. Besides, it was recommended for further insights for advancements of ballistic performance through optimizations of width and weave of the fabrics. Weave types and weave density are also another influential fabric properties that should be considered while ballistic impact resistance [255][256]. The effect of weave types on the ballistic performance were studied experimentally using different fabrics made from aramid, ultrahigh molecular weight polyethylene (UHMWP), and hybrid (aramid–ultrahigh molecular weight polyethylene) [255]. Considering the combined projectile, yarn count and denier, the ballistic performances of fabrics made of UHMWP and hybrid revealed strong independence on the weave types. Whereas fabrics made of aramid were found insensitive with higher variation in the ballistic performance. A study also deals on the effect of weaving density (loose and tight) plain weave layers made by manual use of unidirectional prepregs on the impact behaviour of laminated woven E-glass epoxy composite under hemispherical impact nose with 12.7mm diameter [256], and the result shows that weaving density and curing pressure plays a great role on the impact response and perforation thresholds of woven composite**.** For example, loose woven composites cured under low pressure showed higher perforation threshold and better impact properties compared to other considered combinations. In the investigation, four woven layers each consists of light and tight weave type having 100 x 100mm dimensions were well aligned, stacked together and cured under low and high pressure.

The thickness of the laminate and dry fabric panel while production and ballistic performance tests of fabric panels and composites also plays a great role independently on the ballistic impact behaviour including energy absorption and failure mechanisms on each dry fabric and its corresponding composites [104][202][257][249][258] A multi-ply panel made with various number of plain woven fabrics layers (made of Spectra 1000 fibres) and fold pattern (unfold, accordion fold and roll fold) were experimentally investigated for its dynamic response by a spherical steel projectile impact at velocity range of 120 to 200 m/s as shown in **Fig. 17** [258]. As it is clearly shown in **Fig. 18 (a),** the perforation resistance and energy absorption capacity were significantly improved by folding a fabric into multiple plies than the unfolded counterparts. The effect of the number of layers on energy absorption efficiency was different among the tested fabrics due to the different inter-layer interactions depending on fold patterns. However, as shown in **Fig. 18 (b)**, fabric folding seemed to have a negligible effect on the back-face deflections of fabric specimens.

On the experimental investigation of different aramid and ultra-high molecular weight polyethylene (UHMWPE) composite laminates, the ballistic behaviour in terms of the ballistic limit velocity and energy absorption shows a linear relationship with the pre-defined specimen thickness regardless of the fabric structure [104]. Due to the existence of exerting high-energy bullets by the weaponry and ammunition, development of new and effective material, which can resist to the ballistic impact, is mandatory. To resist such kind of impact, besides using a high strength material; considerably thick material should be applied. One of the studies tried to investigate the effect of thickness and to determine the minimum value to avoid perforation while ballistic impact of aramid (Kevlar®) fabric laminate subjected to 7.62 MM Ammunition at a speed of 800 m/s with standard procedure [257]. Based on the result, 96 layers (~50 mm) of aramid fabric thickness was required to capture the high-speed bullet, which was much higher than the necessary thickness for multi-layered armour to stop the same 7.62 mm bullet at the specified speeds. Similarly, an extensive experimental study was also conducted to investigate the effects of panel thickness on the ballistic performances of ultra-high molecular weight polyethylene (UHMW-PE) composite [249]. The test were carried out on the composite having a thickness in a range of 9 to 100 mm against 12.7 mm and 20 mm calibre fragment simulating projectiles (FSPs). The study clarifies the result both for the thin and thick composites while ballistic test.

Moreover, the two nondimensional ratios (the geometry and density ratios) are other factors which greatly influence and control the impact behaviour of woven laminate plate and multi-layered fibrous materials [259][102][260] [261]. The effects of such parameter on the different ballistic behaviour on composite plates made from woven laminates of E-glass fibres were studied and analyzed using nondimensional formulation of an analytical model at different impact velocities. Based on the formulation, linear proportions were found between both the nondimensional ratios and the ballistic limit. Besides, similar results were also recorded for the contact time between projectile and plate. Regardless of nondimensional ratio, the fibre failure, cone formation and fibre elastic deformation were the principal energy absorbing mechanisms at no plate perforation, impact velocities over the ballistic limit and impact velocities close to the ballistic limit respectively. The formulations were also verified by experimental data for plates up to 7.5 mm in thickness [260]. Similar to the nondimensional ratio, the areal densities were also exhibited an influence on residual velocity, the minimum energy and energy absorption and contact time between the plate and the projectile during the impact event. Study on the high-velocity impact behaviours of monolithic laminates involving various areal densities varies show that the perforation energy, perforation velocity and size of the damaged area varies based on the thickness of the composites [262]. Moreover, the areal density of the composite is linearly proportional to the diameter and areas of the damaged zone for the upper and lower faces of the composite. The ballistic performances of the composites were also depends on the applications of thermoplastic matrix on different types of fabric and composite laminates having similar areal densities. According to the investigations on ballistic performance of plain layered aramid fabric and multi-layer Kevlar aramid fabric composite laminate, the thermoplastic matrix revealed a significant and positive effect on composite laminated ballistic performance than plain layered aramid fabric impact specimens. This is due to the fact that, in the matrix composite laminated facilitates enables different energy absorbing mechanisms as compared plain layered aramid fabric [263]. Similar study on the effects of the areal density of a glass-fibre woven fabric made composite thin-plate based on different ballistic performance mechanisms were also investigated. Based on the findings, the areal density has shown a linear relation along the perforation-threshold energy. The contact time of the plate and the projectile also depends on the energy at the perforation-threshold. However, fibre failures were recorded as the prominent energy absorbing mechanism regardless of the areal density at the perforation areas [264]. Similar to the 2D fabrics and laminated material, 3D woven angle-interlock fabric reinforced composites are used in various ballistic applications and its ballistic performances are also influenced by the areal densities. A non perforation ballistic test on two different 3D woven angle-interlock fabric reinforced composites with same and different area density of panels were carried out. Based on the damaged evaluations, reinforced composites with heavier density exhibits better overall ballistic performance [265]. The ballistic performances of Al2O3 armor tiles has been also increased by adding the thin membranes made of different fibre materials including glass-fiber tape, E-glass/epoxy pre-preg and Carbon-fiber/epoxy pre-preg. Adding of such thin membrane layers of E-glass/epoxy pre-preg could improve the ballistic efficiency up to a 20% with only 2.5% increase in target areal density [266].

4.1.2 Fibre and yarn properties

As it is explained earlier, for a given ballistic materials all the fabric and projectile geometry, material properties, boundary conditions and friction should be coupled for better performance and all play a role in determining ballistic performance. Even though the effectiveness of the ballistic impact performance of the materials depends with various parameters, different studies have also investigated the influences of fibre and yarn properties on the ballistic response. The effect of different configuration patterns of fibres on the trauma penetration depth and ballistic impact resistance for laminated composites such as Personal Armour System for Ground Troops (PASGT) helmet were investigated using a powder gun with 9 mm full metal jacket bullet (level NIJ 0106.00 III-A) and fragment simulating projectiles at various impact velocities [267]**.** The study has investigated and compares the ballistic behaviours of the 19 layers of aramid composite, plain-woven kenaf composite and hybrid-laminated composites. The hybrid-laminated composites absorbed more penetration energy compared to kenaf/PVB composites, and they absorb over three-quarters of the initial impact energy of the bullet through plastic deformation. Moreover, arranging woven kenaf layers alternately with Kevlar 29 fabric layers provides lower energy absorption than placing woven kenaf layers together and Kevlar 29 layers separately for the same hybrid volume and thickness. The effects of high-modulus organic fibres (X-500) against the ballistic protection were investigated for the ballistic protection by involving three different samples made with yarn having different physical properties used in fabric, felt, and laminate form. Sample with most ductile property showed considerable promise with a ballistic resistance significantly greater than normal for a material of such modest tensile strength [268]. While developing woven fabrics for the ballistic material, apart from fibre and fabric properties, the yarn's physical properties play their parts. This was discussed in terms of number of multi-filaments and which is strongly influenced by the ballistic mechanism [269]**.** As the number of multifilament fibres within the fabric increases, it facilitates energy dissipation from a high-speed ballistic projectile, and plays the key role in optimizing the ballistic properties of any given fabric. One of the studies also investigated computationally the effects of the statistical yarn strength distribution characteristics on the probabilistic fabric impact response with the help of five different strength distributions with differing mean strengths and distribution widths [149]**.** The result revealed that yarn strength distributions could be major determinants of fabric probabilistic penetration behaviour. As it is predicted, decreasing yarn mean strength led to reductions in fabric V50 velocity, while increasing the standard deviation in yarn strengths led to an increase in the standard deviation of the probabilistic velocity response. Involving yarn-gripping systems in the fabric production can also increase the inter-yarn friction, which by turn plays a great role in absorbing impact energy in ballistic performances. This has been proved both experimentally and numerically on yarn gripping effects while impact energy absorption of three different variations of the plain woven fabric (leno insertion, double weft and weft cramming) made of Dyneema (UHMWPE) fibre to increase yarn–yarn friction [270]. The fabric energy absorption has been found increased using better yarn–yarn coefficient of friction due to the fact that, certain levels of yarn–yarn friction help to distribute the load not only on primary yarns to be damaged at an early stage, but also to secondary yarns and enable more materials to be involved in energy dissipation. Moreover, numerical simulations on the influence of yarn material properties on the ballistic performance of high-strength plain-weave Kevlar KM2 fabric was carried out [271]. By clamping the two edges to correlate the model with experimental test, the result shows that ballistic performance depends upon friction, elastic modulus and strength of the yarns, where friction improves ballistic performance by maintaining the integrity of the weave pattern since yarns material properties have a significant influence on the effect of friction. Yarn Poisson's ratio, transverse and shear modulus have also shown a different role on the ballistic impact behaviours of the final ballistic materials [272]. Experimental investigation and numerical validation were carried out to study such effects using a crimped yarn and a complete two-dimensional Kevlar plain-weave fabric. Based on both impact cases, the result shows that Poisson's ratio and transversal modulus shows a negligible effect, whereas, yarn shear modulus were found an important parameter that mainly influences the ballistic performance of a two dimensional plain-woven fabric. A finite-element method (FEM) with a series of transient non-linear dynamic analyses were used to investigate two different yarn models ((a) the warp and weft yarns are represented using first-order three-dimensional solid elements and (b) a membrane model in which the same yarns are represented using second-order membrane elements on their ballistic performances of single-ply plain-woven balanced square textile-fabric armour on the yarn-level [273]. The analysis was carried out based on different yarn–yarn and projectile–fabric frictional conditions and under different far-field boundary conditions applied to the edges of the fabric. Based on the result, the roles yarn–yarn and projectile–fabric friction play in the impact process as well as the effect of the far-field boundary conditions applied to the edges of the fabric. Another concept also revealed that the application of coating mechanism on the fibre and yarn surface with some chemical would increase the ballistic performances of its corresponding fabric with superior distribution of ballistic energy compared to fibres that were not coated due to its ability to favour the formation of different forms of frictional behaviour [274][275][276].

4.1.3 Effects of fabric finishing

Fabric finishing has been also considered one of the most influential parameter that has to be considered while investigating the ballistic performances of the materials. Among different dry ballistic fabric finishing methods, impregnation of STF to a fabric is the mostly used methods to increases the frictional force of a single yarn in the fabric, which consequently increases the apparent modulus of the yarn. However, different internal parameter while impregnation should be also well studied to determine precisely its effect on the final performances. The ballistic test were carried out using one panel with all neat Kevlar fabric layers and two hybrid panels of neat and STF impregnated Kevlar fabrics against 9 mm bullets at 436 m/s. Based on the result, the back-face signature were found smaller in the panels where STF impregnated fabrics are laminated behind the neat Kevlar layers as compared with the panel with all neat fabrics as well as hybrid panel with neat Kevlar layers placed on the backside of the panel [277]. This is mainly due to STF impregnated fabrics which is laminated behind the neat Kevlar layers has got the synchronized elongation of the facing yarns both in the frontal and rear layers during the ballistic impact. Beside the laminating sequence, the effect of fabric count and the location of shot impregnated p-aramid fabrics with shear thickening fluid (STF) on ballistic performance were also found as sensitive parameters [26]. An investigation of body armour panels with higher fabric count possess lower ballistic limit (V50) and BFS value due to its favour tensile dissipation over kinetic dissipation against high velocity impact. Besides, due to the larger difference in the warp and weft crimp ratios, hybridization of neat and STF impregnated fabrics for panels of densely woven fabric possesses smaller decrement of back-face signature. The shot-to-edge distance of the impregnated fabrics were also affected both by ballistic limit BFS value of the panel. The shots located closer to the edge and centre of the panel resulted in larger BFS values and higher perforation ratio respectively.

Since improving a surface coefficient of friction is one of the methods to increase the performance of the ballistic performances of the materials, one of the study applied a non-polymerizing reactive plasma gas N2 and chemical vapour $(CH_3)_2Cl_2Si$ to modify plain woven Kevlar fabric surface for ballistic impact application [278]. As shown in **Fig. 19**, based on SEM surface morphological study on treated fabrics, rougher surface is observed in the plasma-treated Kevlar fibre surface than neat fabrics. Moreover, yarn pulling-out test also revealed resistance to pulling out yarns from fabrics plasma-treated treated with N2 and $(CH_3)_2Cl_2Si$ plasma-treated fabric is increased by 18% and 300% respectively, compared with the untreated Kevlar fabric.

Besides, the ballistic composite surface could also be improved by impregnated the fabrics with a colloidal shear thickening fluid (silica particles (450 nm) dispersed in ethylene glycol). One of the research investigation ascertained that the impregnated Kevlar fabric shows significant enhancement in ballistic penetration resistance as compared with simple stacks of neat fabric while tested against Fragment simulation projectile (FSP) ballistic penetration measurements at 244 m/s [77]. Moreover, the STF-impregnated Kevlar fabric provides nearly the same ballistic protection, but much thinner and more flexible as compared with neat Kevlar fabrics of equivalent weight due to an increase in the yarn pull-out force upon transition of the STF to its rigid state. Both particle size of silica while impregnation of plain woven fabrics with Silica Colloidal Suspension and impact boundary conditions has also an impact on the ballistic performance behaviour of the impregnated fabrics. To investigate this, researcher [279] has used different spherical silica particles (with average diameters of 100 nm, 300 nm, and 500nm) to develop and applied Silica Colloidal Suspension (SCS) on the plain woven fabrics. These SCS-impregnated fabrics were subjected against ballistic tests under various boundary conditions and revealed that fabric impregnated with lower SCS silica particles (100 nm average diameter) showed better impact performance than larger particles and untreated fabrics both in terms of impact energy absorption and resistance to blunt trauma due to creating more interfacial friction between filaments and yarns for larger impact energy transfer with interaction of individual yarns in the fabric. Further, the influence of impregnation with SCS on ballistic performance was found to be closely associated with boundary conditions. Thus, the particle size of the SCS and the boundary conditions are the dominant factors that can be manipulated to fully utilize the benefits of SCS impregnated fabrics for flexible body armour. Matrix in the composite laminates has also an effect on the ballistic impact of textile fabric composite laminates. One of the study tried to investigate the effect of matrix on the ballistic impact and damage pattern of aramid fabric composite laminates using different aramid (Twaron) fabric epoxy and aramid fabric-polypropylene (PP)-based composite laminates at different thickness [280]. The result against 7.62 mm armour piercing projectiles with different strike velocity (SV) test showed that the Twaron-PP composites achieved better ballistic limit than Twaron-epoxy composites with equivalent thickness. Besides, Epoxy-based composites faced localized damage mode as compared to a global mode of failure in PP-based composites. Another important research were dealt with effect of clothing fabrics as intermediate targets on ballistic penetration against standard 12-gauge shotgun shell using ordnance gelatine to simulate soft tissue and thin cowhide to simulate skin [281]. Thicker denim and cotton fabrics provided slightly greater protection than polyester. Even though the study was a focused only experimental which need an numerical model to study different shot sizes, different chokes, and different ranges of fire, the result shows that range of fire were found as significant factor for possible pellet penetration not only in terms of more velocity and energy retained at shorter distances, but also more pellets hitting the target due to tight pattern of the fired pellets.

4.1.4 Effect of friction on the ballistic panel system

Among several parameters, coefficient of friction in different parts or within parts of the material is one of the parameter, which has a significant effect in determining the ballistic impact performance of ballistic materials. Even though the structural complexity of ballistic material creates difficulties, many efforts have been made experimentally on how different friction affects ballistic impact response of ballistic materials in the past decades. For example, slip between the yarns becomes more difficult as the friction force increases between them. When the bullet penetrates the fabric structure, it breaks the high-tenacity yarns and tries to pass through the fabric; however, the bullet loses most of its energy and its effect decreases significantly. But in the case of lower frictional force between the yarns, the bullet pushes yarns to the left and right and opens a way for itself, which finally causes less bullet energy loss, and therefore the bullet passes through more fabric layer. The frictional effects are also most prominent at low velocities but diminish at higher velocities. At high velocities, material at the impact point is broken on contact and more yarns are severed, hence, friction from projectiles squeezing through the perforation is less significant but this phenomenon is also less distinct with the sharper projectiles [282]. However, even though various experimental works have shown that an interfacial friction affects the energy absorption of fabrics subjected to ballistic impact, still how it plays a role is rarely understood. However, it is also very important to clearly understand how friction affects the distribution of stress and the magnitude of stress in yarns, fabrics or composites in order to determine both the failure of the material in the ballistic materials and the energy absorption in a ballistic event. For better understanding, various researchers have worked dedicatedly using modelling and simulation methods on effect of friction toward ballistic impact behaviour. The influence of friction through modelling of two clamped and two free edges boundary conditions high-strength plain weave Kevlar fabric during ballistic impact clearly indicated that considering different yarn material properties, initial projectile velocities and the set of boundary conditions, the ballistic performance directly depends upon friction by maintaining the integrity of the weave pattern and material properties of the yarns. In doing so, fabrics comprised of yarns characterized by higher stiffness and strength relative to the baseline Kevlar exhibited a stronger influence on ballistic performance [271]. Mostly, textile structures used in ballistic protection are woven fabrics, unidirectional (UD) fabric structures, and nonwoven fabrics. Nowadays, 3D woven fabrics are also highly involved in the application due to various advantages. Due to its current popularity as promising materials to replace the 2D structures in the field of ballistic protection, one of the research also tried to study the frictional effect on 3D fabrics against ballistic impact performance [231]. In general, the ballistic performance of the interlock woven fabrics can be improved by using fibres with great friction coefficients. A new geometrical tool was used to investigate the effects of friction onto the ballistic impact behaviour of 3D warp interlock Kevlar KM2® fabric with different frictional configuration. Unlike fabric/projectile frictions, the result showed that friction among yarns (yarn/yarn) affects considerably on the impact behaviour of this fabric due to its ability to keep the fabric structural stability during the impact event as shown in **Fig. 20**.

Another numerical investigation on inter-yarn friction influence against ballistic impact behaviour of plain-woven fabrics shows that, increasing inter-yarn friction contribute for better energy absorption by decreasing the longitudinal wave velocity which ultimately causes the projectile longer time to penetrate and to reach fracture strength of the yarn, and vice versa [283]. Besides, as inter-yarn friction increase, the transverse wave velocities has been increased which affects the depth and width of impact indentation in the fabric. However, the back face signature shows no influence by the inter-yarn friction while the width is significantly increased for higher levels of inter-yarn friction to absorb more energy. Moreover, the effect of frictions on the ballistic impact of a square patch of single-ply plain-woven fabric with three different types of boundary conditions namely, four edges clamped, two edges clamped, and four edges free [113] was studied numerically using commercially available FEA code, LS-DYNA. The more energy was absorbed in fabrics with more friction as compared to fabrics with less friction. Similarly, another researcher studied the effects of friction between yarns and friction between projectile and fabrics using FEA code (LS-DYNA) on ballistic impact of a rigid sphere into a square patch of plain-weave fabric considering four edges clamped and two opposite edges clamped boundary conditions [284]. The model result clearly shows that the friction in the fabric helps to reduce the failures of the fabrics impact load improvement by reducing the bullet residual velocity and later increase and facilitate the absorption of energy by the fabrics. Moreover, the frictional effect on the fabrics was influenced by the boundary conditions of the fabrics. Another experimental and modelling research on the effects of inter-layer friction of woven body armour considering both yarn crimp and its viscoelastic properties shows that the responses of the woven fabric during ballistic performances were sensitive toward low coefficient yarn friction and then become nonsensible after some level [285].

Moreover, the energy absorption capabilities of the fabrics become very low as the inter-yarn friction become higher by increasing the rupturing of the yarn. Another numerical study also deals both projectile-fabric and yarn–yarn friction effect on the energy absorption capabilities of a square plain-woven fabric panel, which firmly clamped along its four edges during ballistic impacts. Unlike the above result, the mentioned friction affects mainly depends on the impacted regions of the intended fabric structure than the other regions due to its ability to hinder the principal yarns which helps to propagate and absorb more energy by delaying yarn breakage for distributing the maximum stress. During impact, fabrics with projectile-fabric friction helps to hinder the breakage of yarn by distributing the maximum stress at projectile-fabric contact zone. Whereas, fabrics with yarn–yarn friction helps to reduce the motion within yarns which later helps to decrease the de-crimping of woven fabrics. Even though both type of friction has its effect, the final result will not be also summing up of the two effects [28].The influence of inter-yarn friction on two types of fabrics made of Twaron® and Dyneema® yarn during ballistic impact were researched and the result considering the primary and secondary yarn in the fabrics shows that higher inter-yarn friction gives not only involving secondary yarns during the impact energy but also gives less slippage of primary yarns at impact centre.

Besides, the inter-yarn friction has its limited coefficient values to enhance the energy absorption capabilities since higher values would create the earlier fabric failure due to creating stress concentration on the primary yarns [286]. This was also supported by another researcher while investigating the effect of inter-yarn friction coefficient on failure mechanism and energy distribution characteristic of plain woven fabric structure using semi-analytical model first by developing inter-yarn static and kinetic coefficients of friction and then by determining friction coefficients of the fabrics as shown in **Fig. 21**.

Even though the higher the inter-yarn friction brings better ballistic performance, increasing the inter-yarn friction beyond the optimal values may not always give better ballistic performance and even adversely affect the energy dissipation and failure mechanism. Moreover, it is also observed that the effect of projectile nose on the failure mechanism becomes insignificant for higher friction coefficients [287]. The influences of interface friction on the various fabrics during ballistic impact characteristics of different aramid fabrics were also studied. Based on the investigation, both filament-filament and yarn-yarn interface friction becomes a critical factor which affects the ballistic performance of the corresponding fabrics [288]. Applying shear thickening fluids (STF) on the materials through impregnation would give better ballistic resistance without hindering flexibility as shown in **Fig. 22**. Even though it is insufficient to fully expressing during high impact velocity, the numerical simulation and experimental validation on the effects of friction during high velocity rifles impacts on STF impregnated Kevlar fabric and net fabrics shows that friction between the impact projectile, fabric, and yarns within the fabric during impact is the main factors on energy absorption mechanism (**Fig. 23**) [289].

4.2 Ballistic material structure

4.2.1 Hybridization of layers in the panel system

In general, strong and low-density fibre materials have been used for ballistic protection. However, due to their various limitations to be used in different ballistic protection application, developments of improved fibres or using alternative approaches are required for creating more protective and lighter ballistic materials. In the last section not only fibre properties, but also we have tried to see the effects of fabric properties including structure, type, density etc., friction and fabric finishing role in determining ballistic performance of ballistic textile and its composites. Nowadays, hybrid panels with high-strength yarns such as aramid, ultrahigh-molecular-weight polyethylene etc. are also widely used for the ballistic protection because of their lightweight and high performance against impact [290]. However, the performance of hybrid panel has been also influenced by various factors [103][81][131]. Several researcher and scientists have studied and assessed the superior performance of the hybrid panels over the single material panels, development of hybrid panel design and the effect of ballistic material hybridization on different projectile velocity impact behaviour [291][292][293][294][295][296]. The effect of material combination and stacking sequences on the ballistic performances on different hybrid armour made of high-strength/high-stiffness carbon fibre-reinforced epoxy (CFRE) and a high-ductility/high-toughness Kevlar fibre-reinforced epoxy (KFRE) composite laminates of different thicknesses were investigated using a non-linear dynamics transient computational analysis by developing [297]. Based on the result, impacted by fragment simulating projectile (FSP), at a fixed thickness of the armour both the stacking sequence and the number of CFRE/KFRE laminates substantially affect the ballistic performance of the armour, which is also rationalized using an analysis of the elastic wave reflection and transmission behaviour at the inter-laminate and laminate/air interfaces. Another study were also investigated the ballistic protection of the hybrid fabric panels which consists of two types of structure namely, woven fabrics as the front layers and UD material as the rear layers based on analytical model of wave propagation and energy balance between the projectile and the target [72]. Based on the result, hybrid armour with more shear resistance material (woven fibres) in the front layer and material with more tensile resistance (UD yarns) in the rear layer provides better ballistic performance. The model were also involved the crimp phenomena and transverse reflection wave at the intersection point of fabric, and tried to indicated the optimum ratio between shear resistance (woven fibre) and tensile resistance (UD yarn) based on material properties for developing final hybrid ballistic panel with better performances. The effects of hybridization on composite laminates which consists of polyethylene nonwoven and woven fabrics and their comparisons with nonwoven fabrics were numerically studied against steel spheres of 5.5mm in diameter impact [298]. Polyethylene woven fabrics shows low energy absorption compared to polyethylene nonwoven fabric due to low resistance toward projectile penetration between the yarns due to yarn slippage. However, designing hybrid panel laminates comprising nonwoven layer at the front and woven layers at the back gives higher values both in ballistic limit and energy dissipated as compared to the sum of the energies dissipated by the woven and nonwoven fabrics. Moreover, polyethylene hybrid also showed better impact performance specially to hold fragments within a wide range of calibres including a very small one, which can easily penetrate between woven yarns as compared to aramid woven fabrics laminates with similar areal weight as shown in **Fig. 24**. Thus, these hybrid polyethylene shields are a very good option to arrest fragments within a wide range of calibres, especially those that are small enough to penetrate easily through the woven yarns. The deformation and failure mechanisms obtained in the numerical simulations were in agreement with the experimental results and they provide more details about the origin of the efficient behaviour of the hybrid shield.

The effect of hybrid fabric panels for failure mode and responses of different layers of Unidirectional (UD) and ultra-high-molecular-weight polyethylene (UHMWPE) woven fabric using two types of hybrid ballistic panels (**Fig. 25)** were studied. Based on the ballistic responses, the front layers faced breakage in shear whereas back layers fail due to tension. The woven and UD structures gave better shear resistance and better tensile resistance with wider transverse deflection upon ballistic impact respectively [299]. In this regard, the hybrid materials has been designed with shear resistant materials (woven structures) and tensile resistant materials (UD materials) in as front layer and rear layers respectively for better ballistic performance than in the reverse sequence.

Moreover, the optimization ratio of woven to UD materials in the hybrid panel was found 1:3 that will helps to design to use less ballistic material but better performance along with lighter weight body armour.

The effect of hybridization on the hybrid composite armours constructed in different combination and sequences of fibre-reinforced composites (high specific-modulus/high specific-strength Kevlar fibre (KF), tough, high strain-to-failure fibre Glass fibre (GF) and high strength/high stiffness Carbon fibre (CF)) were numerically simulated against ballistic impact. The hybrid composite were KF layer in GF laminate, GF layer in KF laminate, KF layer in CF laminate and CF layer in KF laminate at various positions of hybridized layers for a fixed thickness of the target [300]. The numerical model result was validated for KF layer in GF laminate with experimental in terms of energy absorption and residual velocity and good agreement was observed. The effect of stacking sequence, projectile geometry and target thickness were also examined for different combinations of hybrid composite armours in terms of ballistic limit, residual velocity and energy absorbed by the target as shown in **Fig. 26**. Based on the result, arranging the KF layer at the rear side, GF layer in the exterior and CF layer on the front side offers good ballistic impact resistance. The hybrid composite armour consisting of a CF layer in KF laminate acquires maximum impact resistance and is the best choice for the design compared to that of other studied combinations.

Similarly, the effects of hybrid on the composite made from plain weave E-glass/epoxy and satin weave (T300) carbon/epoxy against ballistic impact shows that ballistic limit velocity, V50 could be increased by placing E-glass layers on the top of T300 carbon layers as compared with either using the above in reverse sequence or only carbon composites materials considering similar laminate thickness [212]. The energy absorbing mechanisms and responses of hybrid composites containing various fibres under low-velocity impact loading reveals graphite fibre composites containing polyethylene (PE), Polyester (PET) and high-performance Nylon fibre were effective in both dissipating impact energy and resisting through penetration. Moreover, composites comprising PE or PET fibres shows good degree of flexural plastic deformation and some level of delamination, whereas as composite with Nylon fabric exhibit analogous behaviour with lower values. In general, the study has also concluded that the composite plastic deformation, delamination and the overall energy absorbing capability of the hybrid structure were critically influenced by the stacking sequence in hybrid laminates [301]**.** Besides 2D fabrics, hybridization of 3D fabric and its composite has also show great effect on the ballistic performances. The energy dissipated by 3D woven composites under low-velocity impact was around two times higher than that of the 2D counterparts, however this was not the case under ballistic impact where energy dissipation was not significantly improved by the presence of the z-yarns through the laminate thickness [302]. The different mechanical behaviours of hybrid 3D woven orthogonal composite with an asymmetric distribution of fibres while ballistic impact were studied both experimentally (impact tests) and numerically (X-ray computed tomography analysis of the failure mechanisms) [27]. As compared to 2D woven composites, since the damages were localized only around bullet path, its through-the-thickness z-yarns were not found significant to improve ballistic performance of the fabrics. Besides, the transverse impact behaviours of three-dimensional (3D) orthogonal hybrid woven fabric composites testing on a modified split Hopkinson pressure bar (SHPB) apparatus based on load–displacement curves shows that energy absorption of the composites increases with the impact velocity (i.e., strain rate). The failure modes under quasi-static transverse loading are tensile failure on backside and compressive failure on the front side, while those in transverse impact are matrix cracking, fibre breakage and fibre pull-out. The 3D orthogonal woven composites have the same failure mode in the warp and weft directions. There is no delamination for the 3D orthogonal woven composites under transverse impact as observed in laminated composites [303]. Besides, transverse impact behaviour of 3D orthogonal Twaron®/glass hybrid woven composite along warp and weft directions using modified Split Hopkinson Pressure Bar (SHPB) apparatus on energy absorptions and impact damage mechanisms under different impact velocities were analysed using load–displacement curves. Deformation and damage of the composites while impacted by a hemisphere-ended steel rod was also interpreted using a unit-cell model based on the microstructure of the 3D woven composite. Moreover, both elasto-plastic constitute equation of the 3D woven composite and the Critical Damage Area (CDA) failure theory of composites were used to determine Defined Material law (VUMAT) for ABAQUS/Explicit. According to simulation load–displacement curves result, both the impact deformations and damages were compared with experiment and result shows good agreements between the unit-cell model and user-defined subroutine VUMAT [304].

4.2.2 Ply arrangement, sequence and orientation in the ballistic target

Making good ballistic protective targets not only depends on materials which possesses both strong and low density fibres for better ballistic protection, but also it depends on both protective and lightweight. Therefore, other than developing an improved fibre, different approaches with the given materials will be also a solution for crafting more protective and lighter ballistic targets. Ply arrangement, continuity, sequence and orientations in the ballistic panels were some of the important parameters to improve the ballistic performance [117][305][306]. Beside experimental, virtual testing provides an efficient and inexpensive means of systematical study on the influence of various architectural and material parameters against ballistic impact behaviour of material before actual prototypes are designed and destructively tested [307]. In the hybrid ballistic panel development, arrangement of protective material in the face and back strike is very important. In one of the study, the laminating sequence was found an important parameter in improving the ballistic performance of STF impregnated fabric hybrid multilayer panels not only in terms of the BFS value but also the ballistic limit and bullet expansion [277]. Besides, at a fixed thickness of the hybrid composite armour, stacking sequence of hybridized layer shows significant effect on the ballistic performance [300]. The effects of layer stacking sequences on the behaviour of E-glass fibre reinforced composite hybridized with a layer of Kevlar 29 fibre under high velocity impact were studied by placing the Kevlar layer at four different locations. The results clearly reveal that hybridization improves the laminates performance under dynamic penetration. Another experimental followed by an analytical investigations to study the behaviour of E-glass fibre reinforced composite hybridized with a layer of Kevlar 29 fibre under high velocity impact were carried out. While experimental investigations, the Kevlar layer was placed at four different locations to verify the effects of the stacking sequence on the impact behaviour. Besides, three different projectile geometries, namely, flat-ended, hemispherical and conical were used. The experimental results reveal that hybridization improves the laminates performance under dynamic penetration [308]. One of the studies has also examined the effect of layering sequence of unidirectional (UD) and woven fabric hybrid panels on the perforation resistance (V50) and the blunt trauma resistance against a 5.56mm fragment-simulating projectile and .44 Magnum semi-jacketed hollow point projectile respectively [309]. The improved perforation resistance was achieved when a neat woven fabric was placed behind a larger in-plane constraint of either UD or STF-impregnated woven fabric layers due to the reduced out-of-plane constraint. In contrary if the neat woven fabric were placed in front of a larger in-plane constraint of either UD or STF-impregnated woven fabric layers an increase in blunt trauma resistance (i.e. smaller BFS) was observed due to its better coupling of yarn elongation in the frontal and rear layers. The effects of ply orientation on the deformation and energy absorption capabilities of multi-ply various woven fabric panels construction with angled plies as shown in **Fig. 27** (a) was numerically examined [310]. The model was simulated considering impact velocity, panel construction and the number of plies, and its numerical prediction revealed that the plies orientation and stacking sequence significantly affects the energy-absorbing capacity of the multi-ply fabric panels.

For example, the energy-absorbing capacity of multi-panels with more angle always shows better values compared to aligned panel as shown in **Fig. 27** (b) and (c). For example, depending on the number of plies, in the panel the angled panels shows as much as 20% than aligned panels. Concerning the effects of stacking sequence, there is an optimized sequence of plies for achieving maximum energy-absorbing capacity of the panel. As shown in **Fig. 27** (d), the numerical prediction was also validated by the experimental study. Moreover, ply orientation and layering sequence of plies with different laying angles against ballistic impact performance of the multi-ply fabric panels also shows that, angled multi-ply panel gives a significant improvement in energy-absorbing capacity over aligned panel. Specifically, depending on the number of plies, the angled fabric panels showed a 14% increase of impact energy absorption over the aligned counterpart and the optimized stacking sequence of the angled plies gives a 15% increase in impact energy absorption than the other sequences [224]. Another experimental study on the effect of number of plies against ballistic performance of Kevlar49/UHMW (ultra-high molecular weight polyethylene) layered-hybrid composite according to NIJ 0101.04 Level-III standards which were carried out. The study was explained in terms of trauma depth, energy absorption capacity and perforation display. According to the result, the critical number of ply for Kevlar49/ UHMW layered hybrid composite was 16 plies which consisting of 8 plies for each fabric type. Moreover, as plies number in the panel increases, trauma depth and energy absorption capability of the layered-composite has been also decreases and increased respectively [5]. The combined effects of both ply orientations and material properties on impact performance of multi-layered, non-stitched woven aramid fabrics using 2- and 4- sided clamping conditions were numerical simulated (LS-DYNA). The individual ply was oriented on 0, ±15, ±30, and ±45 and functionally graded progressively increases or decreases the yarn stiffness. While impacting each target with both non-penetrating and penetrating impact velocity, the 2-sided clamped targets and lower inter-yarn frictional levels generally resulted in better impact performance. Moreover, the graded targets showed either similar or inferior impact performance than the baseline fabric target configurations for the non-penetrating shots [307]. The FEA simulation of effects of both thickness and stacking sequence of GLARE 5 (2024-T3 aluminium alloy unidirectional S2-glass/epoxy) fibre–metal laminated (FML) plates subjected to ballistic impact shows that, for a given specimen thickness/stacking-sequence, by increasing the projectile incident velocity up to its V50 value, the maximum contact force increased. By further increasing the projectile velocity above its V50, the maximum contact force was relatively invariant with respect to an increase in the projectile incident velocity [311]. Besides, the effects of arrangement of protective material using UD aramid fabric, Polyethylene (PE) and laminated woven aramid fabric to develop flexible and comfortable hybrid protective materials were examined against work of rupture, young's modulus, bursting strength and penetration stroke at bursting of the materials in order to arrange the material in the face and back strike of the panel. The increasing of work of rupture enables energy absorbing mechanisms and the materials with high work of rupture enable to absorb energy to predict the arrangement of the layers before shooting [312]. In order to see the different angled ply-orientation effect on ballistic performances and failure mechanism of multi-ply UHMWPE fabric panels, 3-ply align-laid [0/0/0] and angle-laid [0/30/60] UHMWPE plain woven fabric panels were numerically examined by selecting the projectile energy loss, panel energy absorption, panel failure time, and the stress distributions. Based on the simulation result, the angle-laid panel is more energy absorbent than the align-laid until the impact velocity reaches a certain level. Moreover, critical velocity were found for 3-plies fabric panels, and under this velocity the enhanced inter-ply isotropy in the angle-laid panel contributes to the improved energy absorption, whereas above this critical velocity, the angle laid panel is found prone to initial stress concentration, leading to yarn premature damage on the rear ply of the panel and thus the disappearance of the advantages of the angle-laid panel [160]. The analytical model for the ballistic impact behaviour of 2D woven fabric composites with n number of layers without bonding and clamped boundary condition against flat-faced cylindrical projectiles based on conservation of momentum and wave theory shows that, the ballistic limit for constant number of layers, when increasing layer spacing would decrease but reduction will be stopped after a specific distance between layers. Besides, considering each to have plain weave with linear-elastic mechanical properties, further increases in the gaps between layers did not have any effect on the performance of the armour [25].

4.2.3 Effects of ballistic panel target layer bonding system

While ballistic impact, the energy absorbed by the ballistic materials would be propagated throughout or certain part of the target and the rest energy, which cannot be absorbed causes trauma at a certain depth to the material. However, both the energy propagated on the panel and formation of trauma is very complex phenomena to understand and influence with different parameters. As we discussed in last few sections, apart from material properties, fabric construction, fabric ply number etc., how the different layers are bonded together to create the target panels with different bonding systems also affect the ballistic performances of the final target? Even though there are inadequate reports, some researchers were studied the effects of different bonding systems on the ballistic performances of fabric systems (soft composites) and composites [313][314][315][316][317][318]. However, the bonding system in the formation of different panels affects not only their protective but also their comfort performance [319][320]. Besides, both moulding behaviour and other mechanical properties of multi-layered para-aramid panels were also affected by the stitching parameter used for bonding the different layers in the panels [240]. Different stitching types which affect the ballistic performance capabilities of plain woven aramid fabrics (Twaron CT 710) multi-layer panel were investigated according to NIJ standards [22]. For this study purpose, three kinds of stitches were used to join different number of layers to form the panel as shown in (**Fig. 28 (a)**). Based on the trauma values (depth and diameter), the energy absorbed by the panel and transmitted to the back of the panels after the ballistic test was significant affected by the stitch type applied in the panels. For example, significant differences were observed in the energy transmitted among stitching types specially, between type a and c as 11.5% and no significant difference in energy absorption between the different stitched panels (**Fig. 28 (b)**).

Even though the high stitch density used in type b and c panels brought the advantage of increasing panel strength but it also has the disadvantage of increasing the panel rigidity, which makes the panels difficult to use especially in the personal protective body armour. Moreover, as shown in **Fig. 28 (c)**, unlike trauma diameter, a reduction of 6.7% in trauma depth was found with type c stitching compared to the type a for the same fabric ply number. The effect of stitching pattern on ballistic limit performance was studied using different and alternately arranged 8-neat and 8-natural rubber (NR) coated layer panel systems as shown in **Fig. 29 (a)**. Certain stitching was found in enhancing the ballistic resistance of the fabric systems [321]**.** For example, the ballistic performance of unstitched fabric system shows lower value than 2-in. field diamond, diagonal, and perimeter stitched fabric systems but higher than 1-in. field diamond stitched fabric system. The 2-in. field diamond stitched system showed the highest ballistic limit than others. However, even 2-in. field diamond stitched panel showed some improvement in reducing the back face deformation from fabric systems (**Fig. 29 (b)**). Higher ballistic limit results indicate higher energy absorption by the fabric systems. Even though the stitched panel system gives better ballistic performances due to stiffer panels systems and better movement (shifting) of fabric layers while ballistic test, unstitched fabric systems offer better flexibility. The researcher even does not fully concluded but recommended further studies on effects of fabric stitching should be done to better understand with ballistic impact performance are needed.

The effects of through-the-thickness stitching on the impact damage resistance, impact damage tolerance, and inter-laminar fracture toughness of plain woven and uni-weave textile graphite/epoxy laminates were studied. The uni-weave textile was formed by weaving dry carbon-fibre tows with fibreglass fill tows (2.5% by weight), the plain-woven laminates were manufactured using resin infusion moulding, and uni-weave laminates through resin transfer moulding. Stitching was carried out using different yarn numbers of Kevlar and glass yarns. Static Indentation-Flexure, Compression-After-Impact, Double Cantilever Beam and End-Notched Flexure tests were conducted. According to the result, stitching did not have any effect on the onset of impact damage, but shows significant improvement (25-40%) in impact damage tolerance at impact damage area measured by CAI strength. Moreover, fracture toughness was found to increase by at least an order higher (15-30 times) than the unstitched laminates as characterized by critical strain energy release rate (GIC). Mode II fracture toughness (GIIC) increased by 5-15 times over the unstitched laminates [322].The Mechanical and energy absorption capability properties of S-2 Glass/Polyester, Kevlar/PVB-Phenol and Spectra/Vinyl ester woven laminate composites were improved at the optimum stitch density in the Z-axis compared to those of conventional unstitched one. The repeated impact on the stitched composite caused small damaged areas as compared to the unstitched laminate one. Moreover, the stitched composite showed about 10% improvement in ballistic efficiency over the conventional woven laminate composite at the optimum stitch design [313]. An experimental investigation of stitch density and stitch thread thickness effect against low-velocity impact response and damage behaviour of stitched composites was carried out on the test specimens with different laminate thicknesses, which are stitched with varying stitch densities, and stitch thread thicknesses. Based on the physical examination on damage surfaces, stitches were considered as crack initiators and crack arrestors. Longer and isolated cracks were observed in densely and moderately stitched composites respectively. The higher stitch density and thread thickness also showed more capable of impeding delamination growth through effectively bridging delamination cracks. Moreover, the load–time curves of the impact response showed that onset of delamination is independent of stitch density and thread thickness, but the maximum residual impact force is related to stitch parameters, which in fact related to the delamination size of the impacted laminates. Besides, the load–deflection graphs confirm that moderately stitched composite laminates are more flexible than densely stitched ones, mainly attributed to their overall larger delamination damage area. Finally, the energy absorption rate is also independent of stitch density and stitch thread thickness, but related to laminate thickness. However, densely-stitched and moderately-stitched composites consumed more energy for matrix cracks and delamination propagation respectively [316].

4.3 Ballistic testing parameters

4.3.1 Effect of projectile parameters on material ballistic performance

The ballistic performances measurement such as energy absorption, trauma values, failure mechanism and ballistic limit velocity of the materials are also affected by the projectile conditions including projectile mass and size [150][323], projectile impact trajectory [324], projectile shape and geometry [325][103][326][232], projectile nose angle [158] [147][327], projectile velocity [328] etc. The study on the effects of projectile nose geometries, such as high-carbon steel razor blade, 0.30 calibre rounded head and 0.30 calibre chisel nosed fragment simulation projectile (FSP)) used to better understand the local yarn failure of three types of yarn (Kevlar® KM2, Dyneema® SK76, and AuTx®) against transverse impact [327]. All the three yarn types were affected by the projectile head geometry, where razor blade impact revealed the lowest critical velocity for all yarns. Other than AuTx® yarn, both Kevlar®KM2 and Dyneema® SK76 showed a slight decrease in critical velocity from the round head when impact the FSP geometry. AuTx® and Kevlar®KM2 yarns exhibit a cutting fracture surface when impacted with the razor blade geometry. In addition, AuTx® and Kevlar® KM2 exhibited a high degree of fibrillation when impacted with both the FSP and round projectile heads and Kevlar® KM2 demonstrated a correlation between impact velocity and rupture surface geometry. Although Dyneema®SK76 exhibited cutting when impacted with the razor blade projectiles, and exposed a high degree of melting at all impact velocities when impact with both FSP and round projectiles. Studies on effect of 50-calibre projectile geometries with various shapes (hemispherical, conical, fragment simulating and flat tip) on the perforation mechanism, ballistic limit and damage evolution of satin weave carbon/epoxy laminates reveal that, conical shaped projectile gives highest ballistic limit, followed by the flat, hemispherical and the fragment simulating for both 3.2 and 6.5 mm laminate thickness [329]. Plugging and fibre separation failure mechanism were observed in the carbon/epoxy laminates during high velocity impact of different shaped projectiles as shown in **Fig. 30** (a) and **(b).** The studies were considered by the analytical predictions of the influence of projectile shape in the VARTM carbon/epoxy laminates under high velocity impact[330][331]. The panel thickness has also even shown a significant effect on the ballistic limit of panels impacted by different shaped projectiles as shown in Fig. 23 (c). Thin carbon/epoxy panels bend easily to absorb a majority of the projectiles energy and thick carbon/epoxy panels face different failure mechanisms for different ballistic limits [329]. The effects of projectile characteristics on the probabilistic impact response of fully-clamped single-layer flexible woven fabrics is numerically studied using a yarn-level fabric model with a statistical implementation of yarn strengths. While impacting with six small and large sized spherical, cylindrical, and conical projectiles of the same mass, the probabilistic fabric impact response is observed to be strongly dependent on the shape of the projectile's impact face and the manner of projectile–yarn interactions at the impact site [150]. Probabilistic velocity response curves, which describe the probability of fabric penetration as a function of projectile impact velocity, are generated for each projectile type through a series of forty impact simulations at varying impact velocities.

Another FE simulation model on high strength fabrics (Twaron®) at yarn level was generated with eight node solid elements to study the effects of projectile nose angle during impacting. The yarns are set as transversely isotropic and erosion algorithm was added to the yarn material for allowing yarn fracture.

Eleven different models were built with nose angle of the projectile ranging from 30° to 180° with the difference of 15° as shown in **Fig. 31 (a)**. The energy absorption trends were sectioned in four regions by which failure mechanisms and its ballistic resistance are recorded differently in each region (**Fig. 31 (b)**). However, among the different projectile nose angle, projectile with nose angle 60° generate the maximum efficiency to make the maximum damage to the fabric [147]. Obliquity of projectile is also another projectile condition, which affects the overall ballistic performance and mechanisms of the materials. However, unlike the normal impact effect on the ballistic performances of material, the report regarding oblique impact was very limited **(Fig. 32).** One study focused on a change in obliquity of the projectile using wave theory and energy balance analytical model based on the material behaviour just after impact and its surface condition during the ballistic impact. During the study, the researcher considered different energy absorbing mechanisms such as compression in the region surrounding the impacted zone, compression of the target directly below the projectile, tension in the layers, compression in the lateral direction, shear plugging, friction, matrix cracking and delamination **(Fig. 33)**. Based on the prediction, shear plugging was observed to more energy-absorbed mechanism followed by friction between the moving projectile and the target. Moreover, while increasing initial obliquity of impact, the ballistic limit velocity shows increased, decreased and then increased for 4 mm thick specimens, but straight increase for 19 mm thick specimens. As the initial obliquity of impact increased, the number of layers failing due to shear plugging has been decreased [332]. Another researcher has also studied focusing on the effect of an oblique impact on the ballistic resistance behaviour of basket 2-2 fabric aramid laminates composite materials. While impact test, obliquity can be created in two ways as shown in **Fig. 34 (a) and (b)**. The basket aramid laminates show greater ricochet angle (>75°) than metallic ballistic plate (60°) and possibly lower than plain weave aramid lamination. The projectile routs of inside the aramid laminates was found not linear and away from the cardinal line compared to metallic laminate due to the effect of shape of the projectile, target material properties, and resistance force toward the projectile [333]. The ballistic limits, energy absorption behaviour and perforation mechanisms of plain-woven single-ply high strength fabrics (Twaron® CT 716) were affected by the projectile shape during impact. Different projectile head shapes (flat, hemispherical, ogival and conical head) as shown in **Fig. 35 (a)** have been experimentally applied on the above-mentioned fabrics to access its effects. For all projectile shapes, the energy absorbed by the fabrics were explained in terms of strain energy and kinetic energy after impact and was found different quantitatively but show similar trends of energy absorption values which increased until critical impact velocity and then start to decrease (**Fig. 35 (b)**) [282]. Beside energy absorption, different projectiles shapes were also bring different failure mechanisms such as yarn rupture, fibrillation, failure by friction, and bowing while perforations (**Fig. 36**). It can be seen from **Fig. 36 (a),** the broken yarns ends shown as messy and disorderly for all projectile types other than flat projectiles. Due to head-on impact, hemispherical projectile causes disruptive yarn pull-out, whereas both conical and ogival projectile shown least yarn pull-out due to their slipping ability through the fabric. The bowing effect also appears most during hemispherical head and non-exist at flat-head projectile impact depending on their penetration ability by shearing and cross-section of the projectile respectively (**Fig. 36 (b)**). Moreover, round and blunt profile creates bowing by emerging more stresses on the fabric before yarn breakage due to their weakness to push neighbour yarn while passing in small perforations, whereas, ogival and conical-head projectiles develop bowing by pushing aside of yarns while penetration than by creating stresses on the fabrics due to their narrower and sharper profiles. It is also noticed that, for all projectile profiles, bowing becomes more localized at higher velocity and significantly reduced for the blunt projectiles due to more yarns breakage. Different occurrence of fibre flattening while projectiles press directly onto the fibres is shown in **Fig. 36 (c).** Based on the SEM observation, it was very severe and less severe for hemispherical-head projectile and conical-head projectile respectively due to the fact that conical-head projectile possesses more fibrillation at the angled edge adjoining the cone to the shank of the projectiles scrapes against the fibres. Based on the previous studies [282], the study were extended to investigate effects of projectile nose shape on energy absorption and failure mechanism on double-ply fabric (Twaron CT 716) systems.

Even though impact energy absorption and perforation mechanisms between single-ply and double-ply systems share similarity, but when the number of plies changed from single to double ply its energy do not necessarily double whereas its ratio also affected by impact velocity and projectile geometry as shown in **Fig. 37.** At points corresponding to maximum energy absorption, the ratio for all projectile types scatters about an average of 2.1 (**Fig. 37 (b)**) [325].

Besides, the failure mechanisms of a double-ply system are similar to those of a single-ply system, but the degree of damage of the impact and distal plies differs. The different failures of the doubly-ply fabrics both in the back and front sides while impacting by different nose shape projectile are shown in **Fig. 38.**

Based on these observations, except few yarn breakages, back ply shows lesser failure by yarn rupture and friction, whereas more broken yarns near perforation areas were appeared in front ply due to frictional effects. In contrary, bowing effects were also observed more at the back ply while it tried to absorb the impact energy. Unlike single-ply system, flat head projectiles impact create bowing significantly in the double-ply impact system and bowing present clearly apparent in the front ply than back ply as shown in **Fig. 39.**

Another oblique ballistic impact responses of two types of square shape fabrics (plain-woven (Twaron® CT 716) and pliable Spectra Shield® laminate) mounting at their top and bottom edges with various angle inclination were investigated [334]. Through high-speed photography deformation, failure and post-perforation projectile velocity were measured to analyse the influence of impact obliquity on the ballistic limit and energy absorbed. An increase in obliquity of Twaron® specimen shows an initial decrease followed by a slight increase in the ballistic limit due to asymmetric deformation of weft yarns and sliding of the projectile against the target. Whereas, as increase in obliquity of Spectra Shield® specimen the ballistic limit first increases then decreases due to competition between the weakening effect of asymmetric deformation and strengthening via sliding of the projectile against the fabric, and pulling out of horizontal yarns. Moreover, the influence of impact obliquity on energy absorbed generally diminishes with an increase in impact velocity, and finally vanishes when the impact velocity is sufficiently high for both samples. Another study on ballistic performances of Kevlar woven fabric against different projectile geometrical shape, weight, and impact velocity were carried out. The result revealed that, more pointed projectile decelerated highly at lower velocities and smaller at higher velocity compared to blunt projectile. This is due to the fact that with lower velocity the pointed bullets struck the fabric at an angle and more impact energy was extracted than expected [82]. Besides, more trauma depth and diameter were also recorded in projectile bluntness than the corresponding pointed bullets due to its energy propagation and absorption were carried out by more fabric mass which can reduced the degree of out-of-plane deformation. Even the penetrating energy based on projectile shape was also observed negligible as ply number increases. Another study also revealed that among the different projectile geometry, spherical and chisel shaped exhibited relatively similar ballistic capability as they both could push yarns away during the penetration process [250]. The effect of Flat and Saddle Nosed Projectiles on the ballistic impact performances of UHMWPE yarns (Dyneema® SK76) with 1760 dTex, 40 turns/m twist and 29 to 2200 MPa initial tension stresses impacted with velocities ranging from 150 to 555 m/s were investigated both numerically and experimentally. The yarn young's modulus was found varied from 133 to 208 GPa at minimal initial and highest initial tensions respectively, but shows negligible difference while varying the projectile velocity. However, unlike classical Cole-Smith 1D yarn impact model, yarn failure for the mentioned two types of projectile various significantly at the critical velocity. For example, the flat-faced projectile providing lower (18%) values compared to saddle-nosed projectile (25%) of yarn strength. Besides, an agreement between experiment and model predictions was outstanding across a wide range of initial yarn tensions [335]. A yarn-level FE model were also develop to study the effects of projectile characteristics (six projectiles of spherical, cylindrical, and conical shapes with varying sizes but same mass) against the impact response of fully clamped flexible woven fabric in terms of yarn tensile strengths and inter-yarn friction as shown in **Fig. 40 (a), (b) and (c)** [336]. The fabric impact response was measured in terms of residual projectile velocities **Fig. 40 (d) and (e)**, fabric energy dissipations **Fig. 40 (f) and (g)** and number of failed yarns considering single impact velocity and two impact locations (at a yarn cross-over and at the gap in between the yarns).

In general, the projectile size and shape characteristics affect largely the fabric impact response. Large cylinder and smaller cone gives lowest to highest residual projectile velocity during impact performance. The projectile velocity and energy dissipation for large spherical and small cylindrical projectiles were almost identical in spite of their different shape and size. Impacts on yarn crossover possess lower residual velocity than projectile impacts at the gap in between the yarns. The conical projectiles have also demonstrated the slowest decelerations by the fabric. The effects of various projectile geometry (flat-ended, hemispherical, ogival and conical) on ballistic impact perforation of flexible laminates of Spectra Shields comprising (0°/90°) extended chain polyethylene filaments embedded in a thermoplastic resin were studied [337]. According to the result, flat-ended projectiles cut the laminate through a shearing action, effectively punching a circular hole in the laminate whereas hemispherical projectiles perforate the laminates by stretching the Spectra filaments to failure resulting in a rectangular hole in the laminates. Hemispherical projectiles and flat-ended projectiles also results penetration as a circular hole through stretching of fibres and cut as a rectangular hole on the laminate through a shearing action respectively. Even though both projectile perforate differently, they show similarities in terms of formation of a generator strip, delamination extent, laminate creasing, laminate tearing at the edges, etc. On the other hand, ogival and conical projectiles perforate with minimal delamination and tearing of the specimens. Finally, the impacted region of the flexible laminates become higher in size instead of small localized at higher impact velocity, which makes it more effective in dissipating energy than woven fabric in the application of flexible armour. Moreover another experimental and numerical based study on effect of different projectile nose shapes (ogival, conical, spherical and blunt), incidence velocities, incidence angle and laminate thickness on the perforation behaviour of unidirectional (UD) glass fibre reinforced cross ply laminate against pneumatic gun with 52 g mass and 19 mm diameter steel projectile at incidence velocity up to 300 m/s revealed different outcomes [338]. The unidirectional (UD) sample (140 mm × 140 mm) with orientation (0°/90°/90°/0°) having 3.3 mm thickness and (0°/90°/90°/0°) with 6.6 mm were used for study. For all projectile nose shape, thick composite shows more damage zone than thinner target plate while ballistic impact. Besides, more damages occur when the projectile nose changes from conical to blunt followed by ogival and spherical. Whereas, as the projectile changes from conical to blunt for all target thickness, the projectile ballistic limit increases. As the projectile incidence angle increases, the amount of damage in the target plate also becomes more important. Matrix failure delamination by the tensile stress along the thickness direction and delamination by inter laminar stress were found a common failure in non-inclined and inclined impact respectively. Moreover, incidence velocity 500 m/s were reduced to 484 m/s and 495 m/s of residual velocity for blunt and ogival-nosed projectile respectively while incidence angle changed from 0˚ to 60˚. This shows that more energy and perforation resistance was achieved by inclined impact than normal impact. Moreover, for all projectile nose shape, as the impact incidence angle increases, the ballistic limit of projectile will be also increased. The projectile mass also shows its effect on the ballistic performances of the materials. For example, the influence of the projectile mass upon the impact response and subsequent load-bearing capability of a CFRP laminates composite structure against a series of low and high velocity impact tests resorted using C-scans and optical micrographs shows that, for a given impact energy, decreasing the impactor mass resulted in greater levels of incurred damage and, therefore, poorer post-impact properties [339].

4.3.2 Target impact situations and boundary conditions

Different target impact situation such as impact position point (yarn impact or gap impact), target conditioning (wet or dry), environmental conditions, target dimension and target boundary conditions of the ballistic targets including target clamping condition, clamping size, clamping shape, clamping pressure, frame type, target size, target shape while ballistic impact testing are another important parameters which can affect the ballistic performance of the materials and also useful to consider while assessing and comparing different impact performances of various ballistic materials [340][341][342][343][344][24].

In general, different standards have different armor target mounting procedures for the ballistic Testing. For example, according to NIJ standards the armor panel will be located on the backing material such that the point of impact, which is projected through the armor onto the surface of the backing material, is no closer than 106 mm (4.2 in) from the edge of the backing material fixture. Besides, the target panels should be firmly held in contact with the clay material and mounted using mounting strap. Basically, the mounting straps in this standard could be achieved by either using a 51 mm width elastic straps held together by hook-and-loop fasteners (Fig. 41 (a) and (b)) or using an integral strap which is constructed along the armour panel (**Fig. 41 (c)).** If the testing procedure applies the first strap type, two vertical and three horizontal straps without interfacing the impact points will be used for the panels smaller than the backing material as shown in **Fig. 41 (a).** However, in case the armour panel is larger than the backing material, an extension of fixture will be mounted on both sides for proper fixations as shown **in Fig. 41 (b)** [112].

A numerical study on the effects of target boundary conditions (first target was fixed on the two sides of warp direction and second target were fixed only at two edges of weft direction) were applied to analyses the 3D interlock woven fabric failure mechanism at 49.8 µs with a ballistic impact velocity of 200 m/s as shown in **Fig. 42**. The observation shown that, yarns at the free edge do not fail rather slip on other yarns and pulled out of the fabric by the projectile. However, this effect created damage zones at corresponding two free edges as shown in zoomed part. In contrary, fixed yarns at the two ends (either weft or warp directions) are ruptured around the impact area due to tension and friction with the projectile [345].

Longer deformational pyramid were also appeared in the direction where yarns were fixed. This evolution of deformational pyramid values is more described in **Fig. 43 (a) and (b)** for warp and weft yarn fixation respectively. Both the numeric and visual result revealed that only larger deformational pyramid dimensions were occurred in the direction where the yarns are fixed. Therefore, the effect of boundary conditions is more important than yarn undulation on the global behaviour of the tested 3D fabric. Moreover, as shown in **Fig. 43 (c),** the result also shows that projectile velocity decreases more strongly and reaction force increases greatly in the direction of fixed yarns than un-fixed one.

Another numerical simulation were modelled to study the effect of frame size, frame type, and clamping pressure against 3D deformations of a 10-layers woven Kevlar body armour while impacted by a 9 mm FMJ (full metal jacket), 124 grain projectile at normal incidence angle. Considering the target was firmly bonded on each edge, when smaller frame size is used, the residual speed and kinetic energy of the projectile found to be increase and vice-versa. Besides, for armour target which was clamped at both two and four-bar frames, the speed of the residual projectile will increase when pressure applied to the bars to firm the target increases. The armour fixed in the two-bar frame also exhibits higher impact resistance than that was held in the four-bar frame [346]. Another study also assessed the effect of different clamping design (4-sided, 2-sided, circular, diamond and corner-clamped frames as shown in **Fig. 44 (a)**) on the ballistic impact response of soft body armour panels impacted at yarn and between the yarn gaps. In general, clamping design while impacting the targets shows a significant effect on different ballistic performances of the target including fabric deformation, failure, energy dissipation, and V50 velocity [340]. In specific, the circular frame showed highest V50 velocity with no sensitivity of projectile impact location, followed by diamond clamped fabric. During impact test, the four corner plates and four corner points clamped design revealed tearing at the corners and distinct deformational failure mechanisms respectively for different impact velocity.

Moreover, circular or diamond clamp configurations show more uniform and gradually-varying spatial distribution of fabric deformation and loading, as well as reduced fabric creasing than 4-sided, 2-sided, and corner clamp configurations (**Fig. 44 (b)).** Moreover it is observed that, the greater the extent of free edges in a fabric, the greater the occurrence of yarn pull-out exist which have also significant source of energy dissipation but at least two sides or sufficient areas at the four corners must be clamped to generate sufficient inter-yarn normal contact forces, which in turn results in greater force required to pull the yarns out of fabric weave. Otherwise, like corner point clamped fabric, it will face energy dissipation.

The fabric orientations on different clamping design have also show an effect on the ballistic performances of the target, especially for partially clamped fabric configurations. For example, fabric orientation makes no difference in a circular clamp due to its symmetry about the vertical axis whereas, a 4-sided clamp with a 0/90° orientation is the same as a diamond clamp with a ±45° orientation, and vice versa for a square exposed fabric shape. Finally, the dimensions of the fabric target, the projectile size relative to yarn width and span and extra length of yarn available due to de-crimping were also found another important consideration that could affect the fabric failure modes. Another study on the effect of target dimensions on its ballistic performance was also been studied in numerical modelling which could be used for armour dimensions optimization. For large targets where the transverse and the longitudinal waves do not reach the boundaries quickly, target dimensions do not show any effect on the ballistic performance [25]. The effects of target shape and size (between 5 cm^2 and 525 cm^2), impact location (yarn-based and impact-based), clamp design (4-sided, circular, and diamond clamped) were investigated against V_{50} ballistic impact response of non-backed woven aramid fabrics [341]. Based on the study, for all mentioned clamping configurations the target shows an initial very sharp rise in V_{50} velocity which then plateaus out as cross-areas of the target areas increase. This indicated that, for each clamped fabric shape impact velocities around the V_{50} velocity, there is a critical fabric size beyond which the projectile residual kinetic energy shows a sharp jump in magnitude, which continues to grow with increasing fabric sizes. Therefore, smaller fabric size targets led to faster projectile decelerations but higher residual velocities than larger fabric size. Regardless of fabric size, all impacts also show sensitivity to the precise projectile impact location with yarn-based impacts generally resulting in greater energy dissipations than gap-based impacts. Over the range of considered target sizes, the V_{50} velocities of the circular and diamond, clamped fabrics were very similar to each other and higher than the 4-sided clamped fabric targets. Moreover, both circular and diamond shaped clamped fabrics showed similar V_{50} velocities over the range of fabric target sizes studied at 4-sided clamped fabric. Another modelling were formulated to study the ballistic performances of plain-woven fabric targets (Twaron® CT716) clamped at three different boundary conditions (two-clamped-edges, 0° four-clamped-edges and 45° four-clamped-edges), as shown in **Fig. 45,** against 12 mm spherical projectiles weighing 7 g with striking velocities ranged from the ballistic limit $V50$ up to 500 m/s [144]**.** In general, the boundary conditions and yarn orientation were found sensitive factors toward ballistic resistance of such systems. However, the unclamped targets on the two edges can absorb more impact energy than those with all four sides clamped with different angles. However, the energy absorption of the clamped target can also be significantly improved by orienting the yarns at 45° (**Fig. 45 (c)).**

Moreover, based on the high-speed photographic images observations (**Fig. 46), w**hen the fabric ends are clamped with the yarns parallel to the edges, the primary yarns (those in contact with the projectile) face higher stresses which lead rapid impact point failure and less energy absorptions (**Fig. 46 (b)**). However, it is also possible to facilitate the energy dissipation of the four edges clamped fabrics by arranging the yarns 45° to the clamping edges and could increase the energy absorption of the fabric targets by allowing slippage at clamped edges.

The effect of conditioning of ballistic materials panels (wet or dry) and fabric ply number has also shown their own effect on trauma depth and ballistic properties of aramid fabrics during ballistic impacts [22]. For example, only 3.6% difference in trauma depth was measured between the dry and wet panels and a very small decreased value recorded in ballistic performance of aramid fabrics due to wetting so long as a good water-repellent treatment is applied. Moreover, only around 5.0% increase in the energy transmitted and no significant change in absorbed energy was observed in wet panels compared to dry panels (**Fig. 47**).

In another scenario, the energy absorption capacity of panel's increases and the amount of energy transmitted to the back of panels decreases with an increase in the number of fabric ply. According to the study, around 59.8% reduction in the transmitted energy and 4.4% increase in the absorbed energy occurred when the fabric ply number increased from 20 to 32 (**Fig. 48**).

Another numeric model were used to study the influences of three different boundary conditions (clamped-corners, clamped-edges and free boundary condition) on flat panels made of Ultra-High-Molecular-Weight-Polyethylene (UHMWPE) composite material using Tiebreak contacts methods for delamination. The approach revealed a good agreement along experimental result for clamped-corners and free boundary condition cases for the peak back face deformation (BFD), remaining thickness of the composite and the delamination behaviour. The model is useful to assess the size-effects and boundary proximity effects under blunt impact scenarios [342]. Another experimental analysis used two types of fabric constructions with square targets, two target sizes and four boundary conditions to assessed the effect of boundary conditions (BCs) against V_{50} and zone of mixed results (ZMR) against Remington 9mm 124 grain bullets. Based on the recovered bullet examination by capturing the selected shots with high-speed movies, boundary conditions showed a significant influence on V50 and ZMR and the strongest edge constraint and clay backing showed the most stable results. For example, Higher V50 values were obtained by higher edge constraint. Moreover, an increasing target size gave lower V_{50} and higher variability for most edge conditions [344]. Another study applying different clamping configurations (4-sided, 2-sided, circular, diamond, and corner-clamped frames) to study their effect on the V_{50} impact performance of non-backed aramid fabrics used in soft body armour. Based on the study, at similar fabric size, both V_{50} velocity and impact response was found sensitive to not only fabric shape and clamping configuration but to projectile impact location (impacts on a yarn and at the inter-yarn gap). For example, tearing at the sharp corners was found in corner-plate clamped fabrics whereas distinct fabric deformation and failure mechanisms occurred in corner-point clamped fabrics at various projectile velocities. In addition, among all the three considered shapes, as the target size increased, the 4-sided clamped fabrics shows inferior relative V50 impact performance than diamond and circular clamped fabrics [24].

5. Conclusions

Ballistic impact is an event normally created when a low mass and high velocity projectile hits a material caused at a propelling source. However, while impacting the ballistic material, it passes in to a very complex ballistic penetration mechanisms, which really need a complete and quantitative analysis for better understanding. For the effective understanding, the materials, the methods and different affecting factors should be also clearly understood. This paper has tried to outlined, reviewed and discussed both the intrinsic system parameters such as ballistic material properties including fabric property (weave design, fabric density, fabric type), fibre and yarn properties and fabric finishing properties and the topic of extrinsic parameters such as ballistic impact methodology, ballistic target compositions and arrangement, ballistic target conditions, projectile conditions etc. which affects the ballistic impact behaviours of ballistic textile and its corresponding composites. Apart from experimental investigation, nowadays ballistic impact mechanism on the ballistic impact performance of the different ballistic material has been studied using various technical approaches, which are less time consuming, accurate, scientific and less costly. This paper has also outlined with an example, the different methods used including theoretical, experimental, analytical, and numerical or combinations of two or more approaches to investigate, analyses, understand and even predict the ballistic impact mechanisms of the materials. The paper has also tried to outline and incorporate various research works, which studies the different material, used in the ballistic impact mechanism for different applications including body armour and armoured vehicles. According to the reviews, it is also very important to note that almost all of the parameters that affect the ballistic penetration resistance of materials are interrelated; thus, studies that attempt to single out an individual effect cannot yield conclusive results unless all of the other parameters are explicitly presented. The combinations of various parameters are incorporated into the study before a fixed rule can be ascertained. Moreover, different reviewed works under this paper, which are focusing on ballistic materials approaches, and ballistic impact performance along its influencing parameters would certainly help to the field scientists and researchers to considerate while assessing, analysing and applying the ballistic impact performance of various ballistic armours and textile composites. Even though the paper gives a tip-off to understand and considerate the different influential parameters during ballistic target preparation and impacting process, still a combined, detail and high level of research approach needs to be done and it is very crucial for better understanding of the vibrant deformation and failure mechanisms of ballistic materials.

6. Compliance with ethical standard

We declare there is no any financial or/and relevant interest that will influence the study. The study also consents for any involvement in the study.

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Figures and its Captions

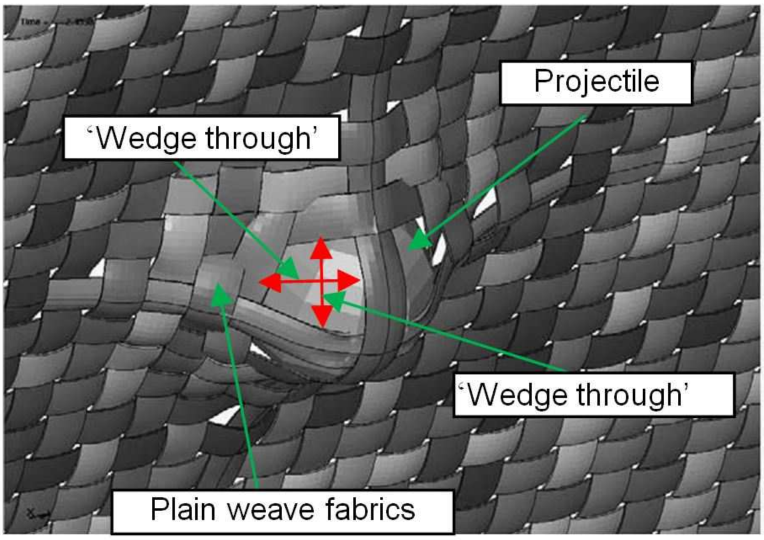


***Figure 1** Trapping of ballistic projectile by the plain weave fabrics and ''wedge through'' creation during ballistic impact [30]*

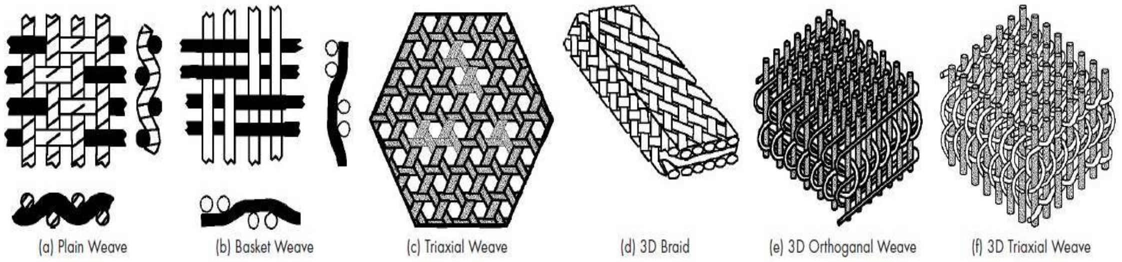


***Figure 2**. Different 2D and 3D fabric structures*

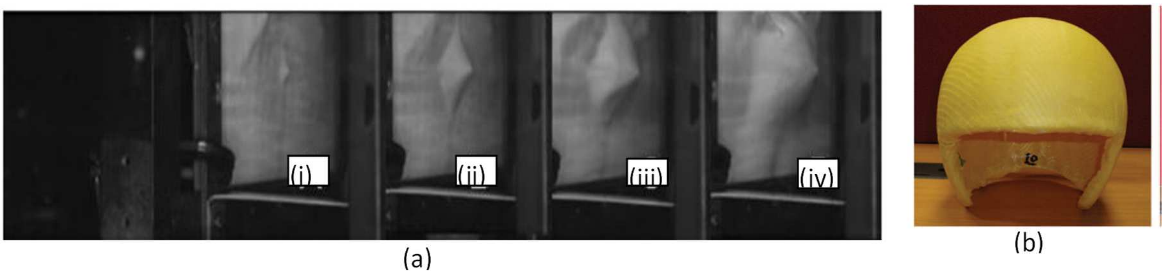


Figure 3.(a) Photographs of successive deformations of thermoplastic–aramid panels [94] and, (b) Single-piece textile reinforced riot helmet shell developed using vacuum bagging [95].

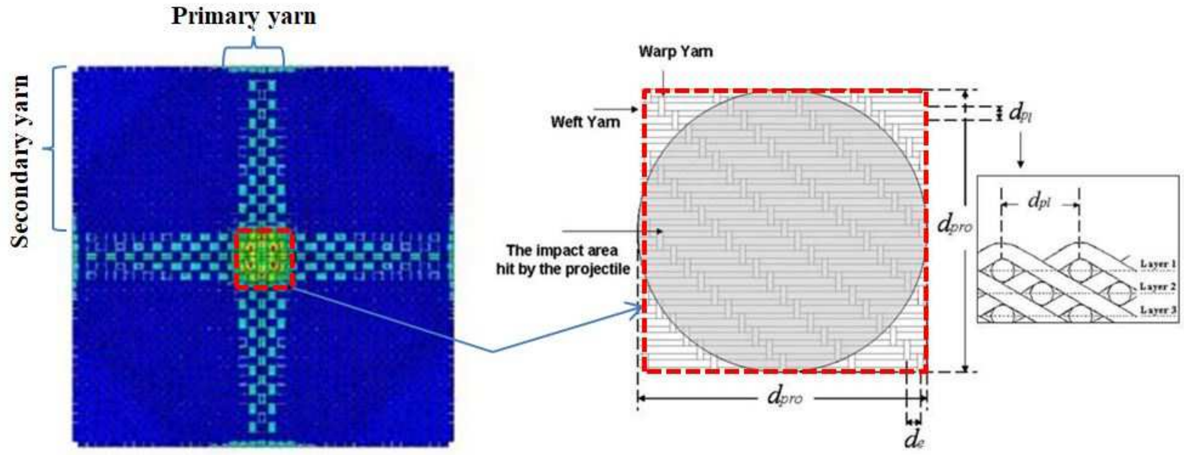


***Figure 4.** The fabric impact area hit by the projectile* [113] [191]

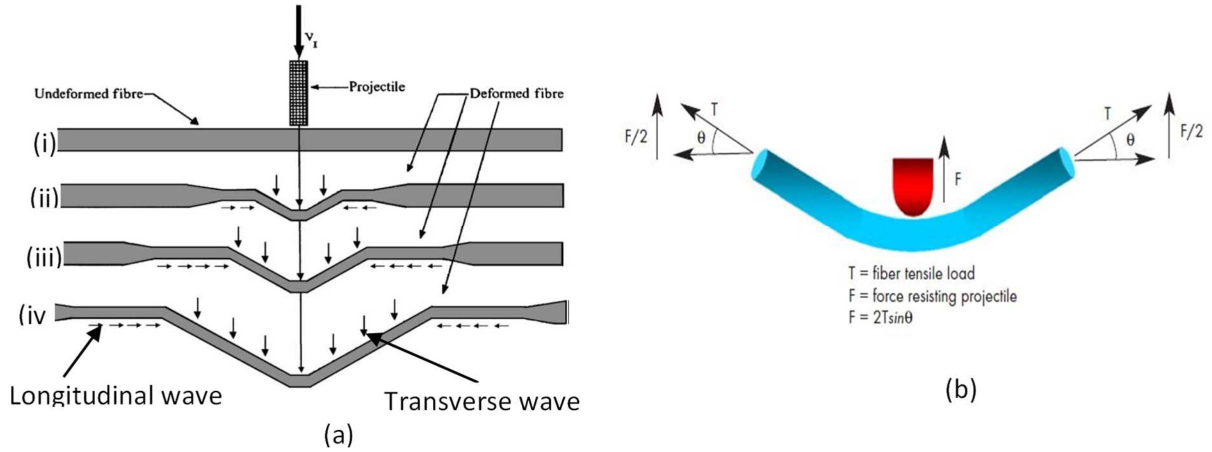


Figure 5.*Configuration of a yarn before (i) and after transverse impact (ii)(iii)(iv)* [101]*, and (b) energy absorbing mechanism for a single fibre* [347]

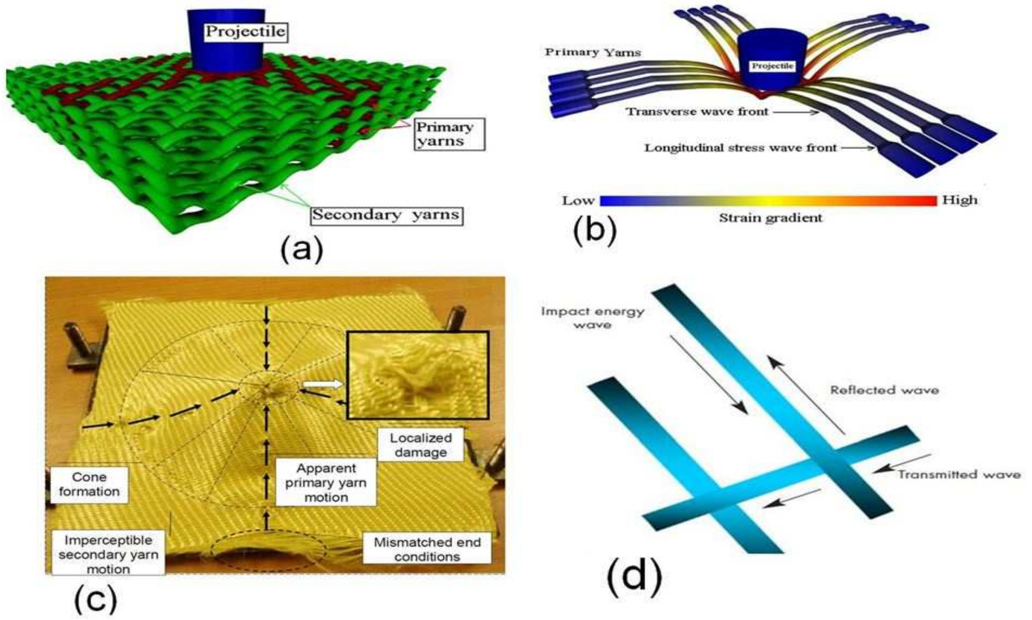


Figure 6. Illustration of ballistic impact on (a) multi-layered fabric panel by a cylindrical projectile (b) reaction of the primary yarns in one layer of fabric in multi-layer textile based body armour [131], (c) Impacted fabrics [191] and, (d) energy absorbing mechanism for Woven fabrics [347].

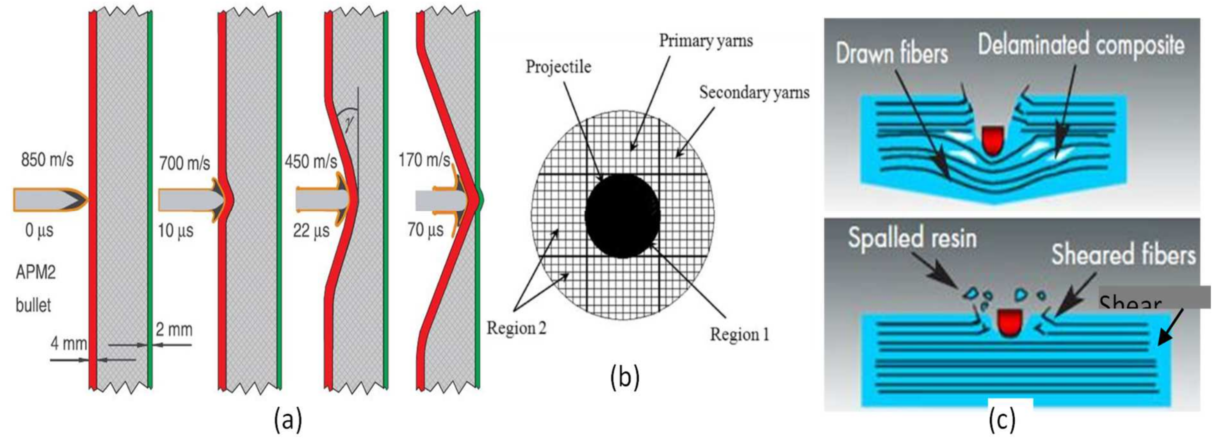


Figure 7. Schematic of a layered fibrous structure envisioned arrangement of a typical 2D woven fabric composite target (a) side view to stop armour piercing APM2 bullets [348], (b) different impact regions and yarns in front view [181], and (c) Energy Absorption Mechanisms [347].

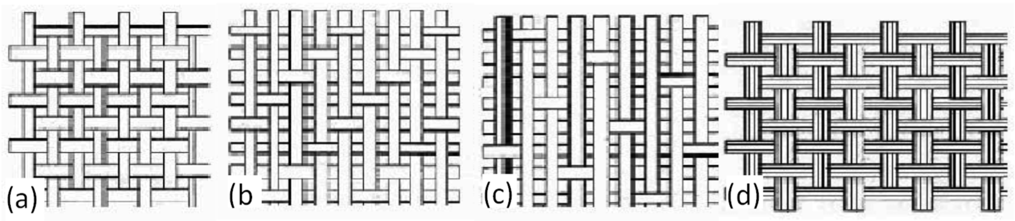


Figure 8 Various weave structure; (a)) Plain weave, B) 3/1Twill weave, (c) 8-end Satin weave and (d) 2 X 2 Basket weave [248].

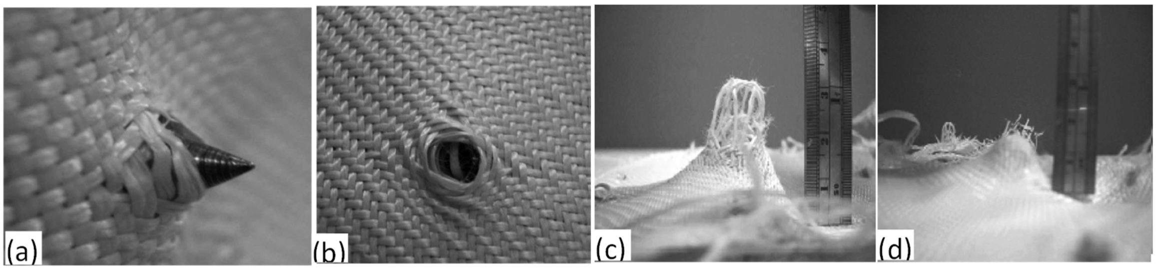


Figure 9 Fabrics after impact: (a) Steel-cored bullet test of 2x2 Basket weave fabrics, (b) Twill fabrics with a steel-cored bullet removed, (c) General view of Satin weave fabric damaged with fibres drawn out and (d) General view of Plain weave fabric damaged with torn fibres [248].

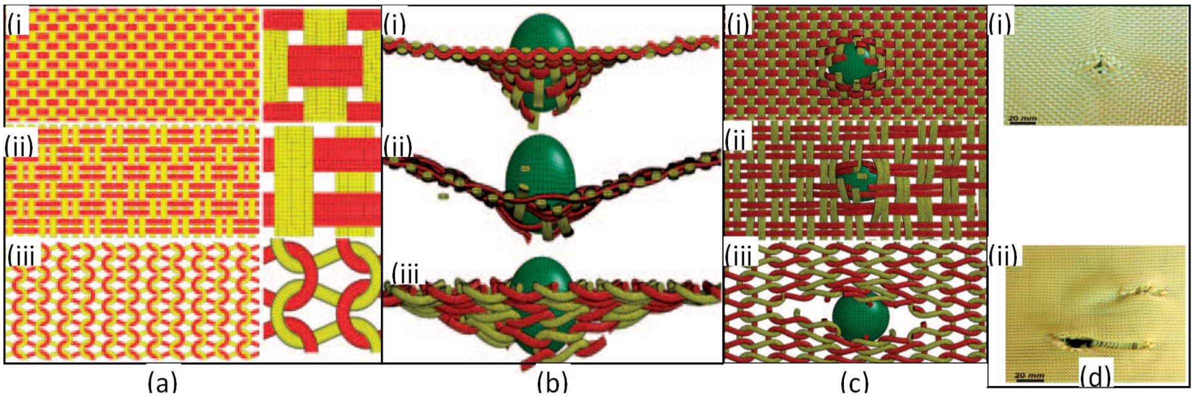


Figure 10 Ballistic mechanisms of different composite textile materials (a) different textile fabrics (i) plain weave (ii) basket weave and (iii) knitted fabric, (b) Side view of projectiles penetrating fabrics (i) plain weave (ii) basket weave and (iii) knitted fabric at time=0.4ms), (c) Bottom view of projectiles penetrating the fabrics (i) plain weave, (ii) basket weave and (iii) knitted fabric (at time 0.4m/s) and (d) Experimental results of (i) woven and (ii) knitted Twaron fabrics subjected to ballistic impacts [190].

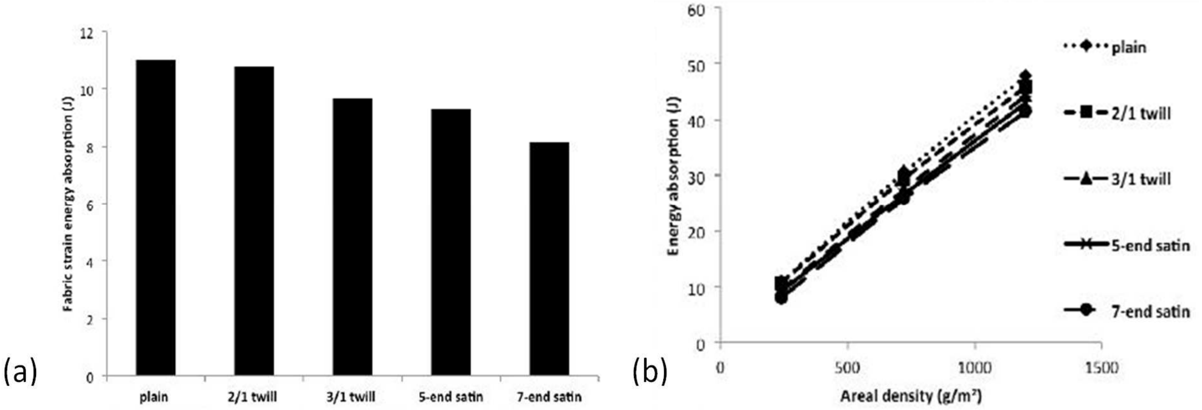


Figure 11 Fabric energy absorption (a) Single-ply and (b) Multi-ply fabric models [251].

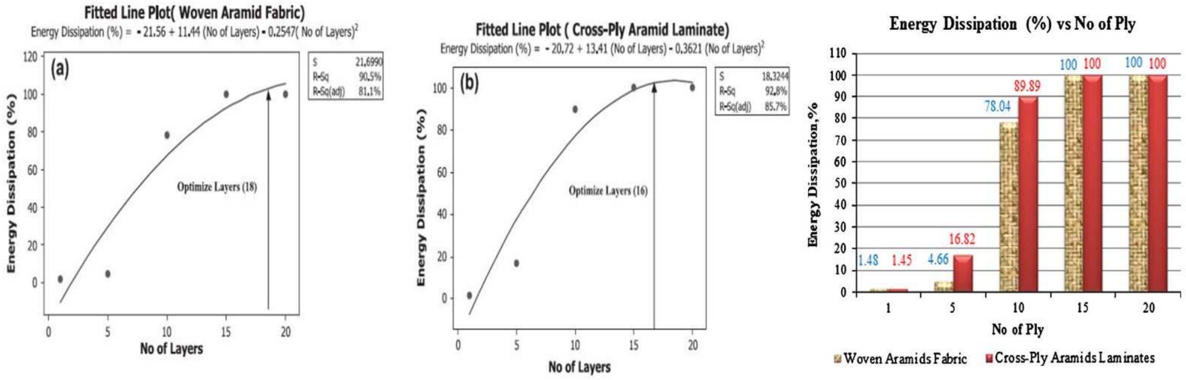


Figure 12 *Depth of depression and energy transferred to backing material* [177].

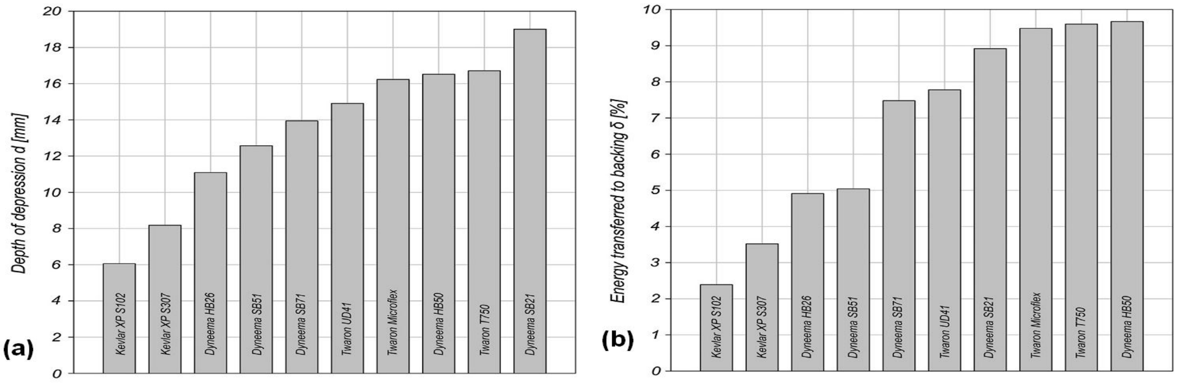


Figure 13 Ballistic performances of cross-laminated vs. woven aramid fabrics, the curved regression lines for (a) woven aramid (b) cross-ply aramid, and (c) Energy dissipation comparison vs. number of ply for both fabrics [73].

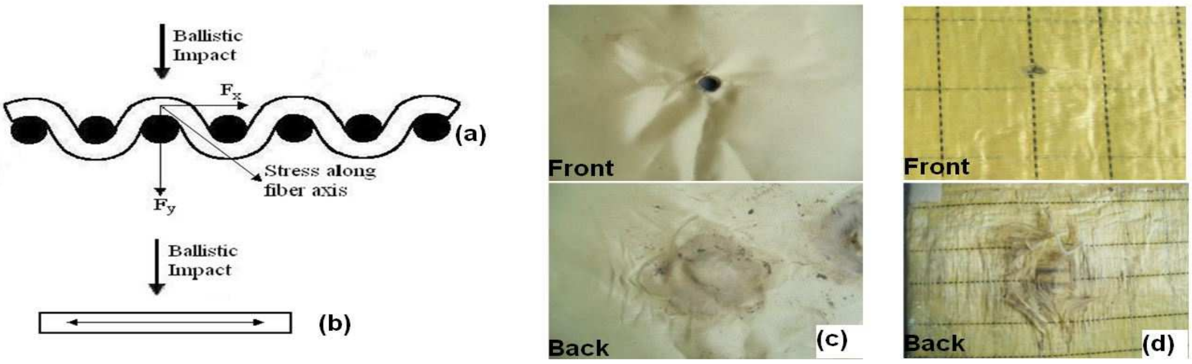


Figure 14 *Different fabric structure while ballistic impact (a) woven fabric and (b) UD nonwoven fabric, shape of deformation created after shooting on the front and back side of (c) woven Twaron and (d) K-Flex fabric panels on shooting points* [252].

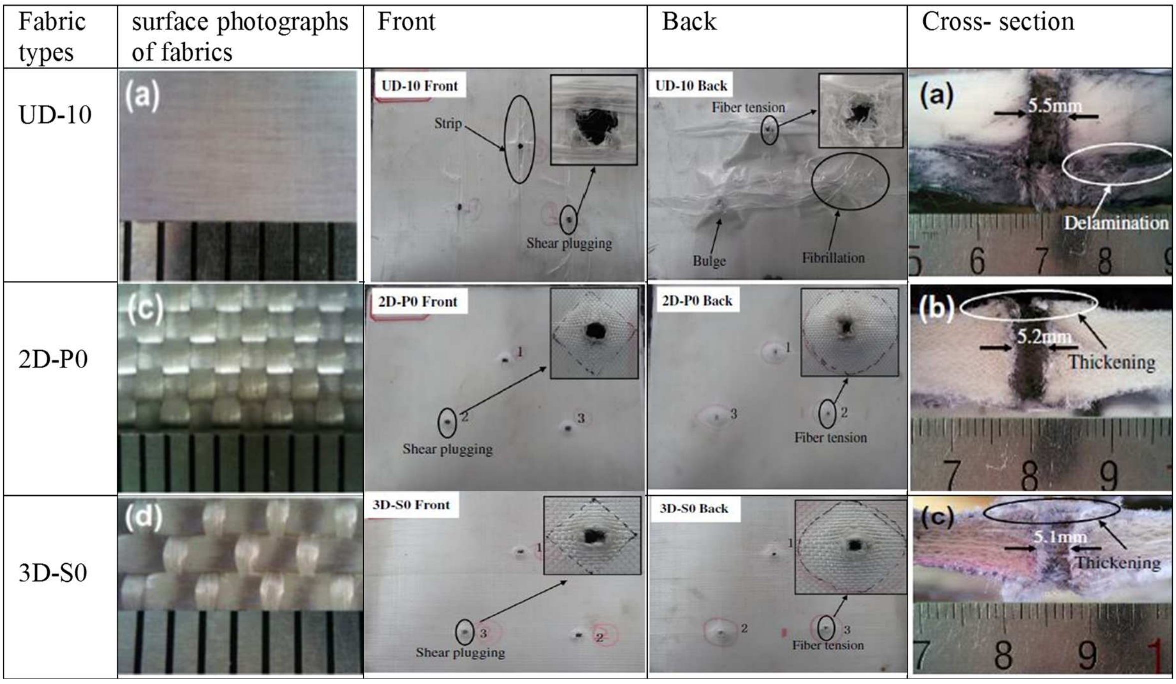


***Figure 15** The surface photographs and Ballistic failure modes of both the front and back surfaces of various fabrics* [202].

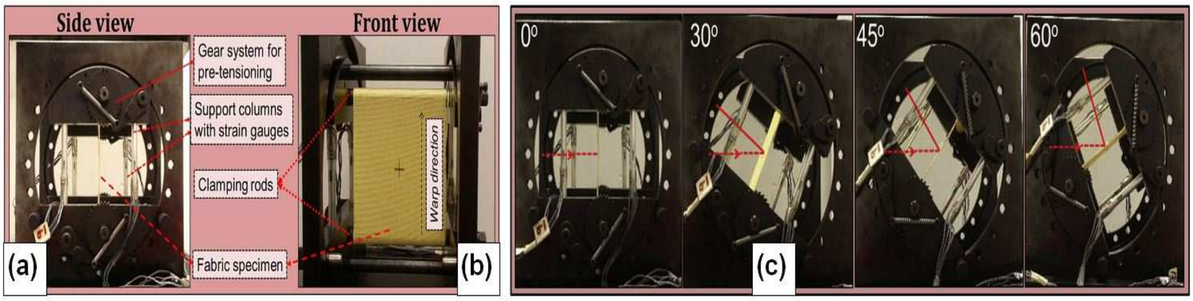


***Figure 16** The test fixture views in (a) side (b) front view and (c) different fabric position and projectile trajectory for different angles* [253].

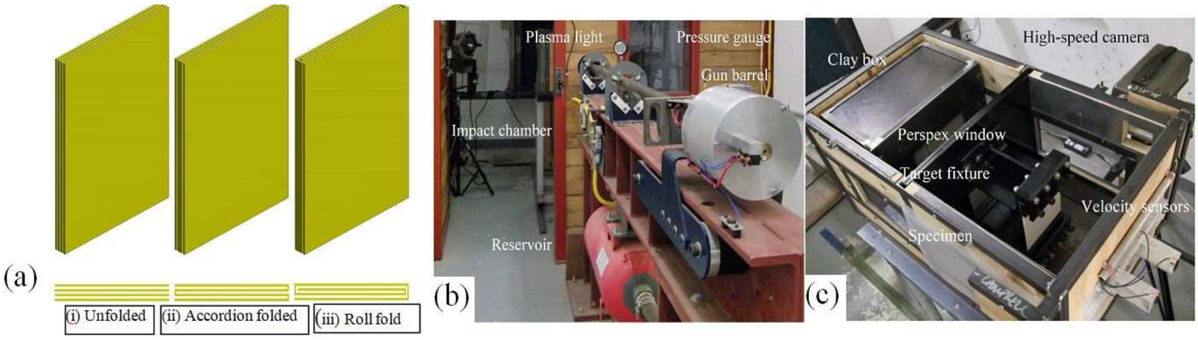


***Figure 17** Investigation effect of folding on ballistic impact (a) Schematic diagram of different folding systems of the fabric (b) a single-stage gas gun and (c) impact chamber* [258]

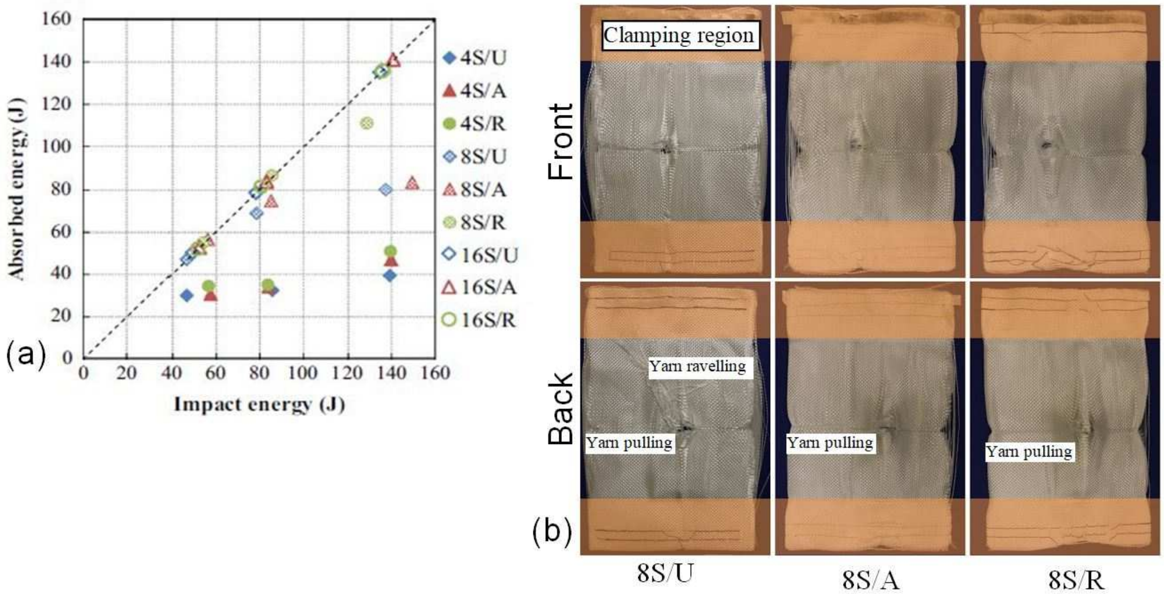


Figure 18 (a) Absorbed-impact energy of various layer with different folding pattern, (b) Front and back views of 8S/U, 8S/A, and 8S/R fabric specimens subjected to nominal impact of 83 J [258].*(the fabric samples were represented using a code 'NX/ Y', where 'N' indicates the number of layers, 'X' denotes the fabric material and 'Y' denotes the fold pattern type ('U' for Unfolded, 'A' for Accordion fold, and 'R' for Roll fold).*

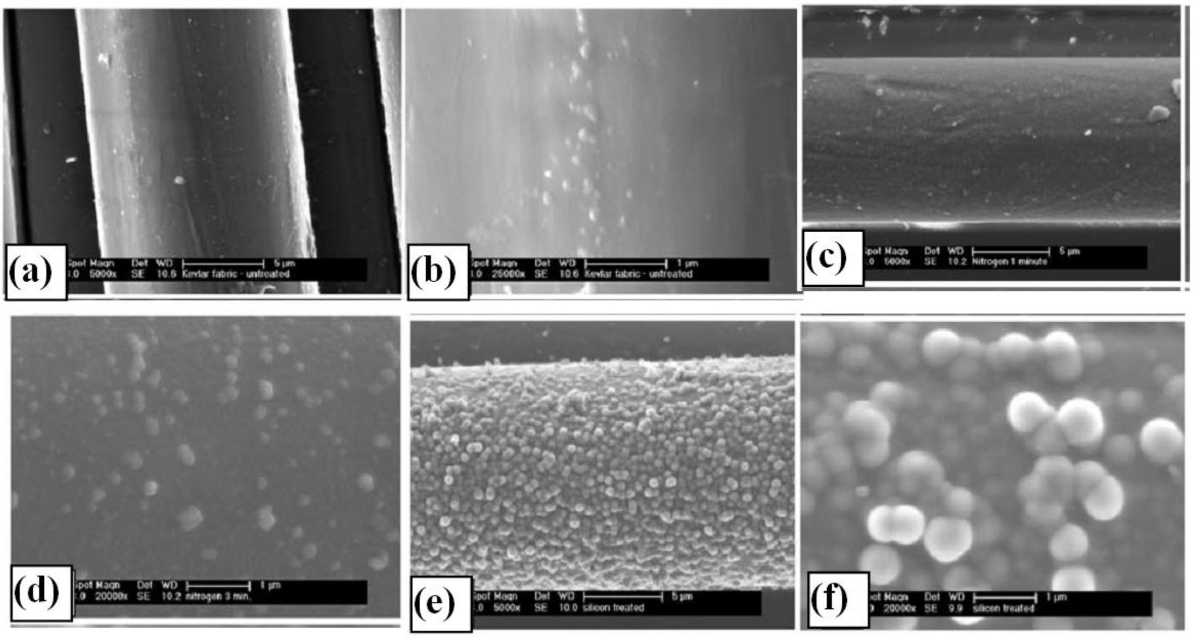


Figure 19. Scanning electron microscopy images of (a) and (b) untreated, (c) and (d) N2 plasma-treated, and (e) and (f) $(CH_3)_2Cl_2Si$ plasma-treated fibres [278].

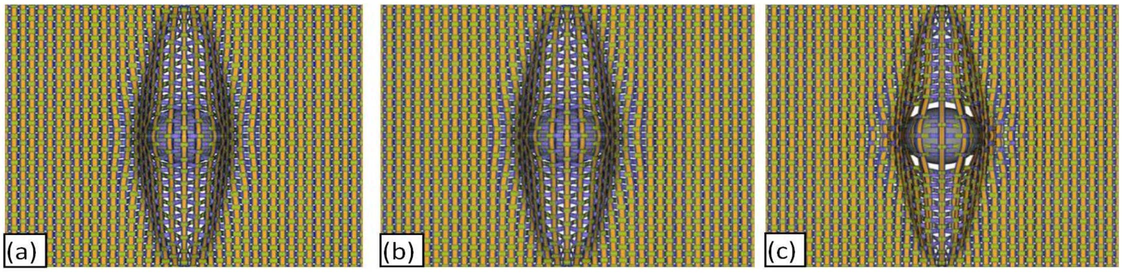


Figure 20 Configuration of the 3D fabric (a) at 10 μs in the case of friction used for both projectile/fabric and yarn/yarn contacts (b) at 10 μs in the case of friction used only for yarn/yarn contact and (c) at 10 μs in the case without friction

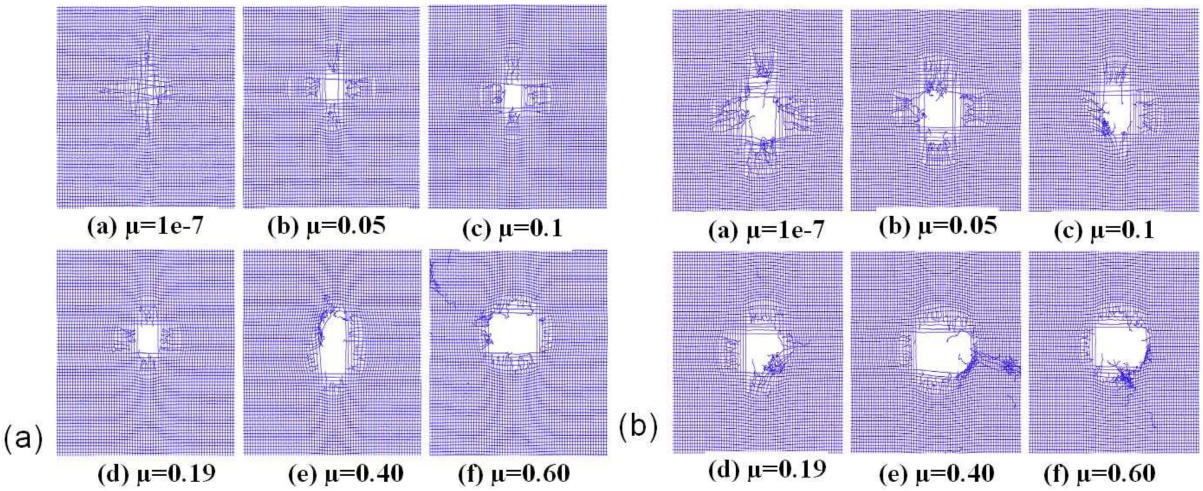


Figure 21 *Effect of friction on penetration and failure mechanism (a) round nose projectile (b) flat nose projectile (enlarged views at impact end; all edges of the fabric specimen are clamped)* [287].

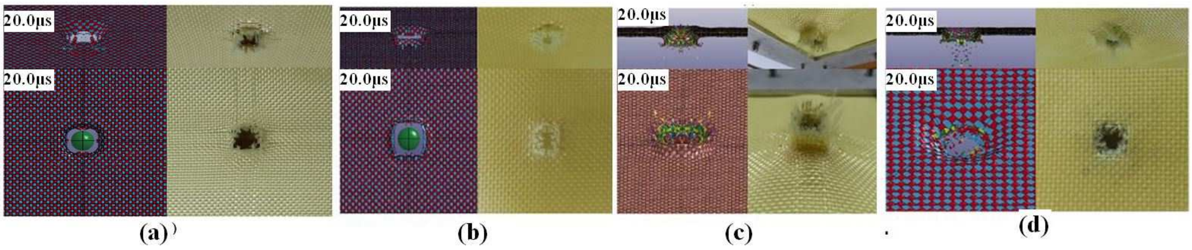


Figure 22 *Impact penetration hole formation comparison between the numerical and experimental results for (a) single layer neat Kevlar, (b) single layer STF impregnated Kevlar, (c) 8 layer neat Kevlar, (d) 5 layer STF impregnated Kevlar* [289]

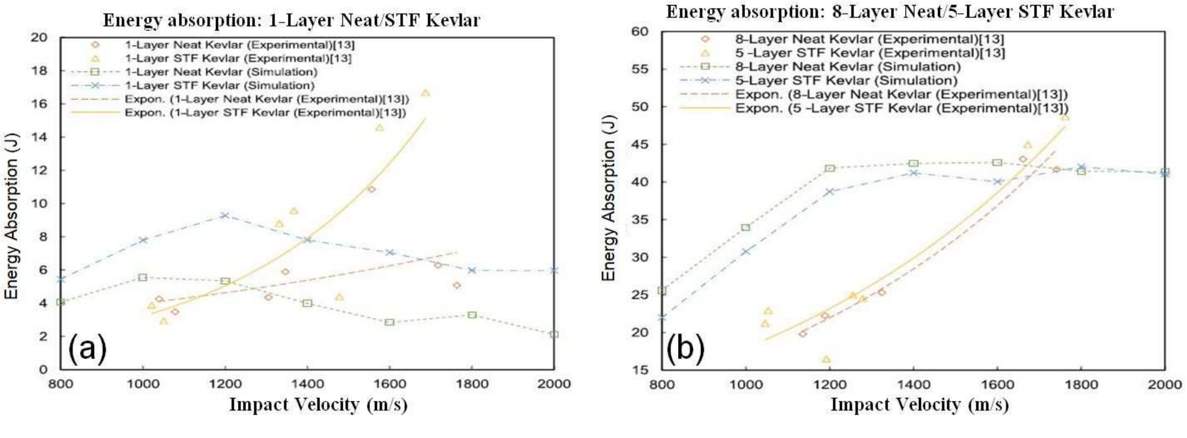


Figure 23 *Energy absorption for (a) single layer cases and (b) for multiple layer cases* [289]

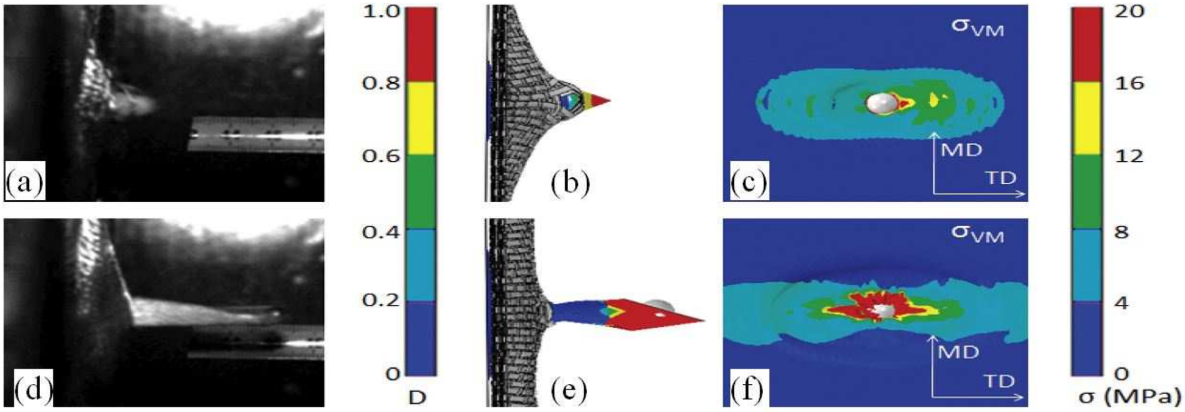
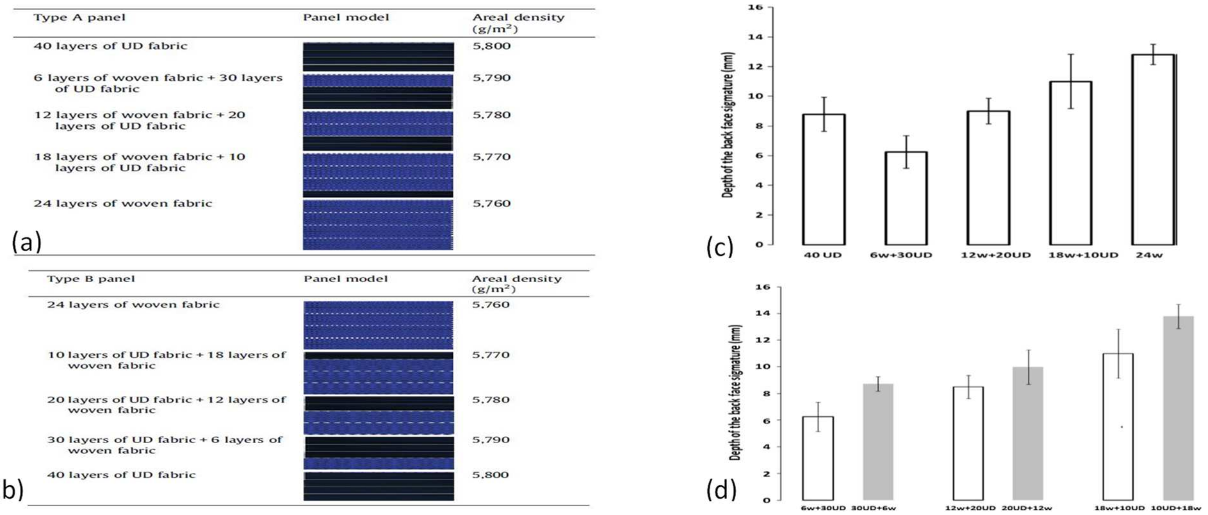


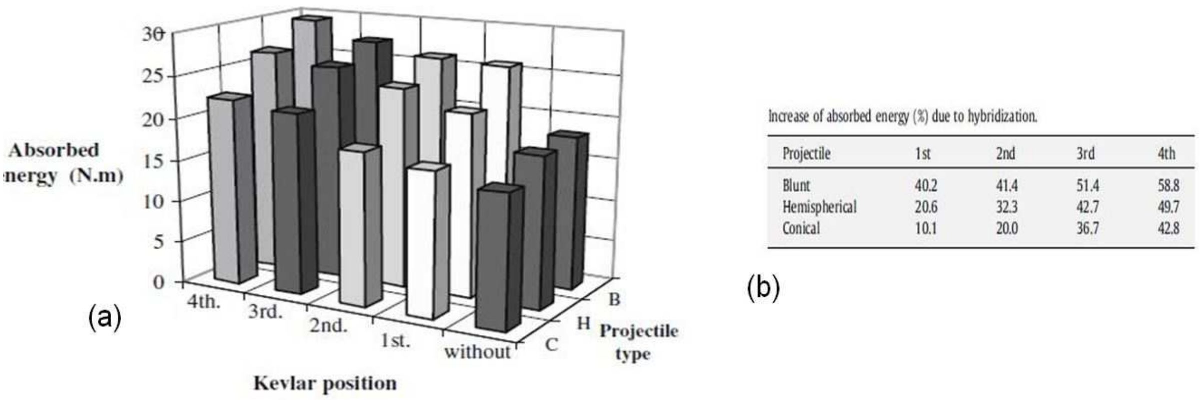
Figure 24 Deformation during impact at 380 m/s of the hybrid shield. (a) and (d) Experimental photographs obtained at t = 25 µs and 150 µs, respectively, (b) and (e) Contour plots of the damage variable D at t = 25 µs and t = 150 µs, respectively and (c) and (f) Contour plots of the Von Mises stress, σVM at t = 25 µs and 150 µs, respectively [298]*(The zones in red in the contour plots are representative of a fully disentangled fabric)*



Type A panel	Panel model	Areal density (g/m^2)
40 layers of UD fabric		5,800
6 layers of woven fabric + 30 layers of UD fabric		5,790
12 layers of woven fabric + 20 layers of UD fabric		5,780
18 layers of woven fabric + 10 layers of UD fabric		5,770
24 layers of woven fabric		5,760

Type B panel	Panel model	Areal density (g/m^2)
24 layers of woven fabric		5,760
10 layers of UD fabric + 18 layers of woven fabric		5,770
20 layers of UD fabric + 12 layers of woven fabric		5,780
30 layers of UD fabric + 6 layers of woven fabric		5,790
40 layers of UD fabric		5,800

***Figure 25** (a) Panel arrangement for panel A (b) Panel arrangement for panel B (c) Depth of the back face signature for Type A panels and (d) Depth of the back face signature comparison of Type A panels and Type B panels* [299].



Increase of absorbed energy (%) due to hybridization.

Projectile	1st	2nd	3rd	4th
Blunt	40.2	41.4	51.4	58.8
Hemispherical	20.6	32.3	42.7	49.7
Conical	10.1	20.0	36.7	42.8

***Figure 26** Energy absorbed by laminates with different Kevlar layer position impacted by three different projectile shapes (B, blunt; H, hemispherical; C, conical) and (B) Increase of absorbed energy (%) due to hybridization* [300].

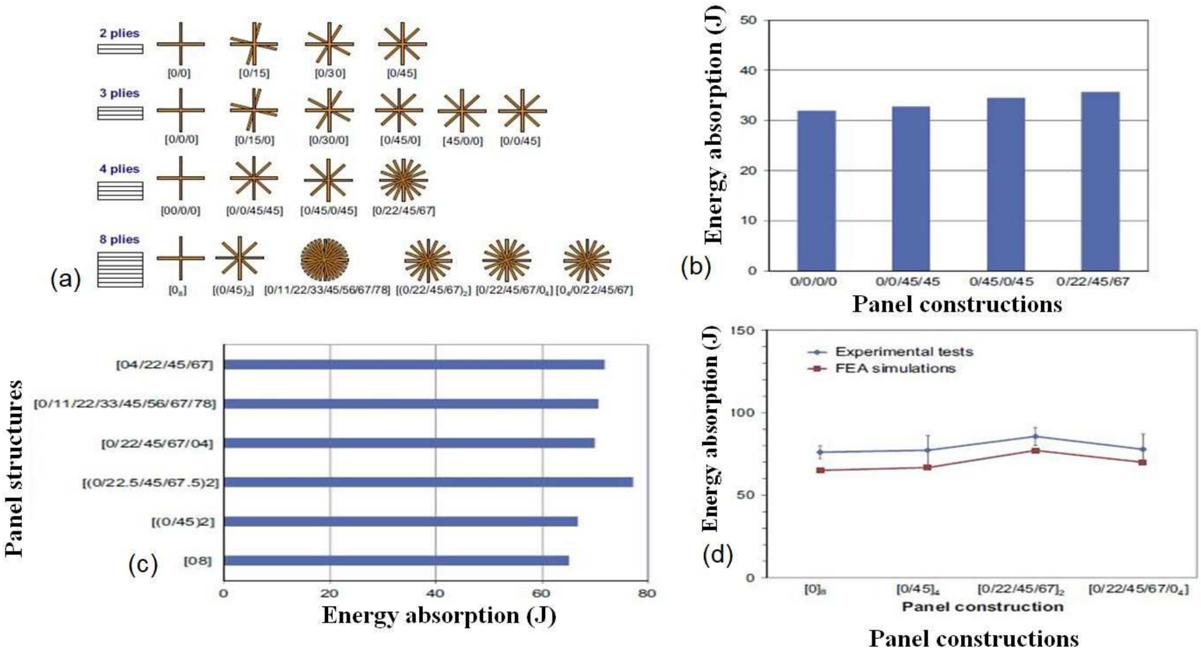


Figure 27 *(a) Schematic showing fabric structures used in FEA simulation (b) Energy absorption against panel structures for the four-ply panels, (c) Energy absorption of various panels for the eight-ply panels and (d) Plot of energy absorption in various fabric structures for 8-ply fabrics*[310]

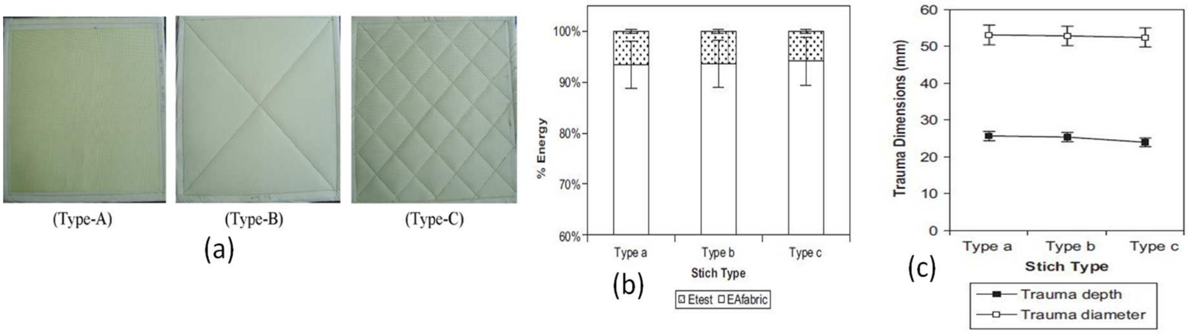


Figure 28 *Stitching types and its effect on ballistic performances of plain woven aramid fabrics panels (a) Types of stitching applied in the panels (Type A: sewn only 2.5 cm inside from the edges; type B: sewn 2.5 cm inside from the edges and in diamond shape; type C: sewn 2.5 cm inside from the edges and then with 5 cm intervals in bias type), (b) Effect of stitch type on energy absorption by the panels and transmitted energy to the backing material and (c) Effect of stitch type on trauma dimensions [22]*

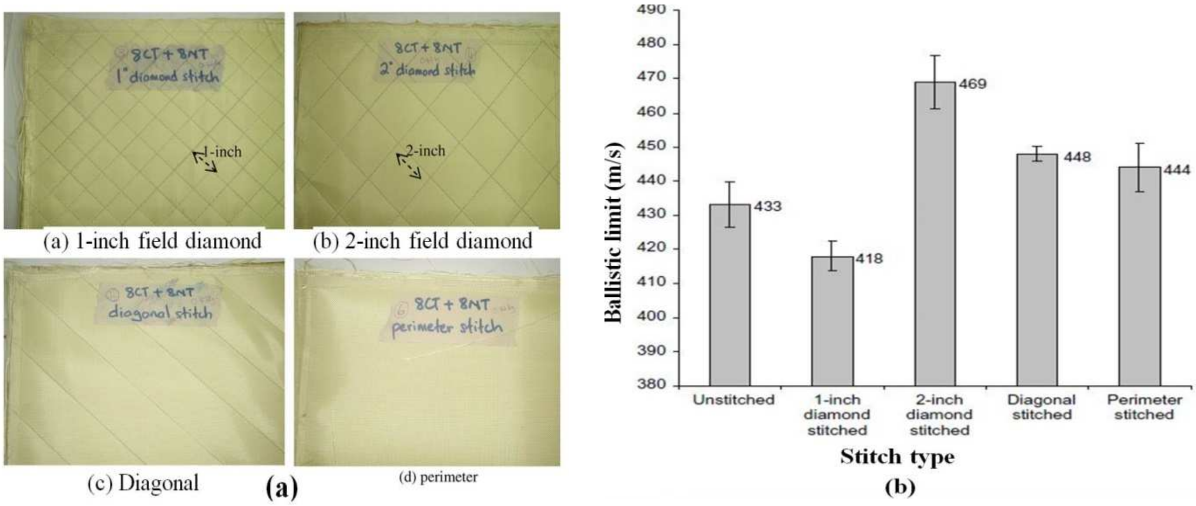


Figure 29 *Effect of fabric stitching on ballistic impact resistance of natural rubber coated fabric systems (A) Photographs showing the types of stitching pattern (1-in. field diamond, 2-in. field diamond, diagonal, and perimeter stitching patterns) on the fabric systems (B) Ballistic limit of fabric systems*[321]

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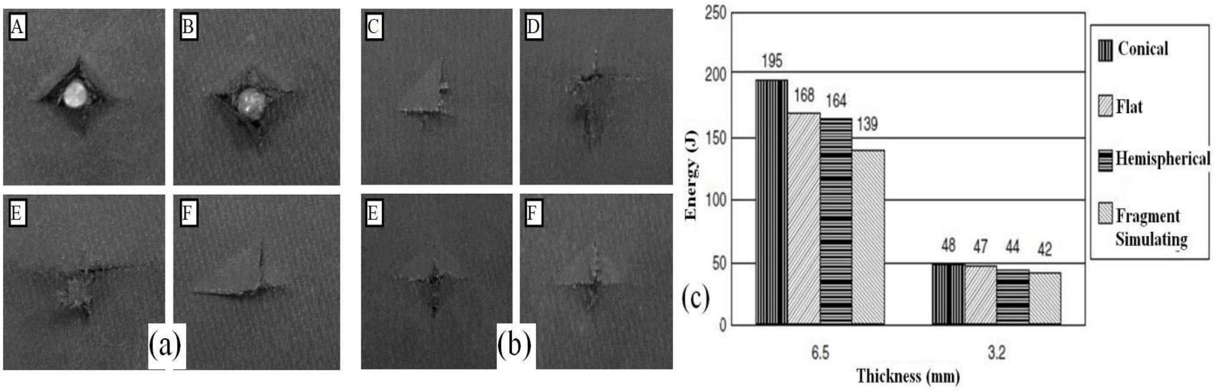


Figure 30 *(a) Back face damage of (A) fragment simulating, (B) hemispherical, (C) conical, (D) flat projectiles for 6.5 mm thick panels (b) Back face damage of (A) fragment simulating, (B) hemispherical, (C) conical, (D) flat projectiles for 3.2 mm thick panels (c) Energy absorbed at ballistic limit velocity for each specimen* [329]

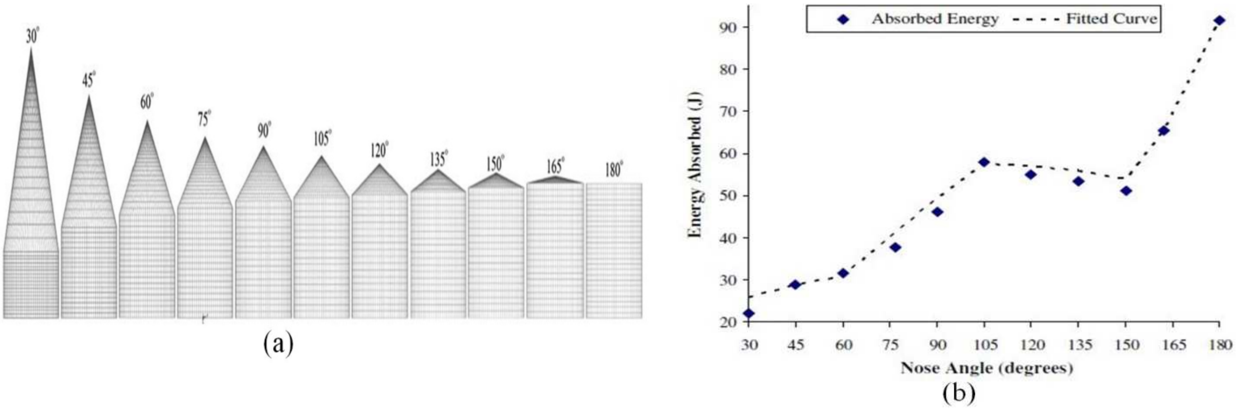


Figure 31 *(a) Front view of the conical projectiles with different nose angles and, (b) Energy absorption as a function of nose angle* [147].

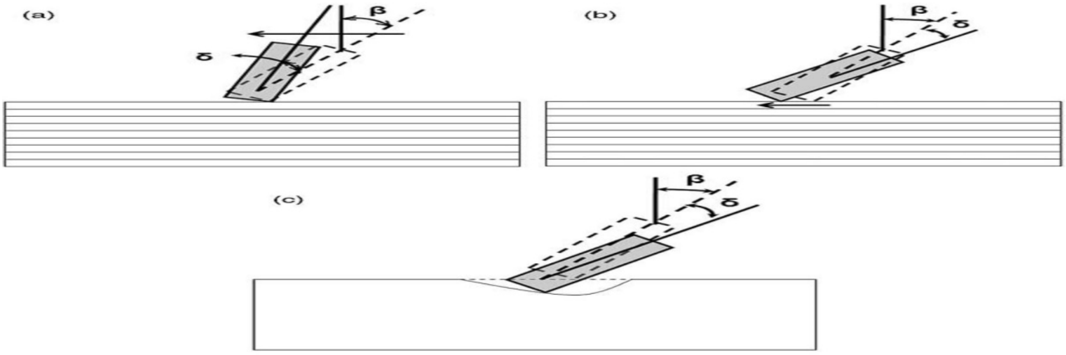


Figure 32 Change in projectile obliquity on ballistic impact: (a) target characterized by initial compression – rough surface; (b) target characterized by initial compression – smooth surface; and (c) target characterized by crater formation [332]

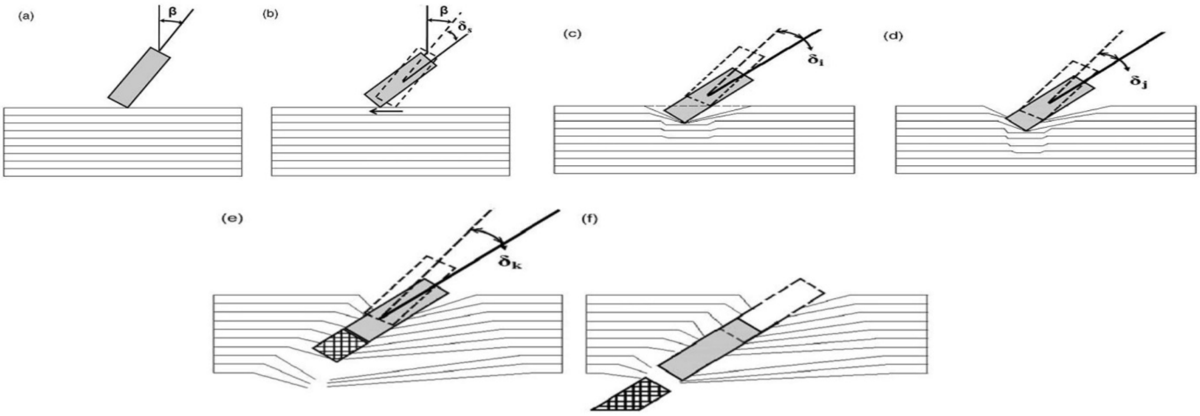


Figure 33 *Schematic of an oblique ballistic impact: (a) impact, (b) slipping, (c) compression, (d) penetration, (e) total failure and (f) perforation* [332]

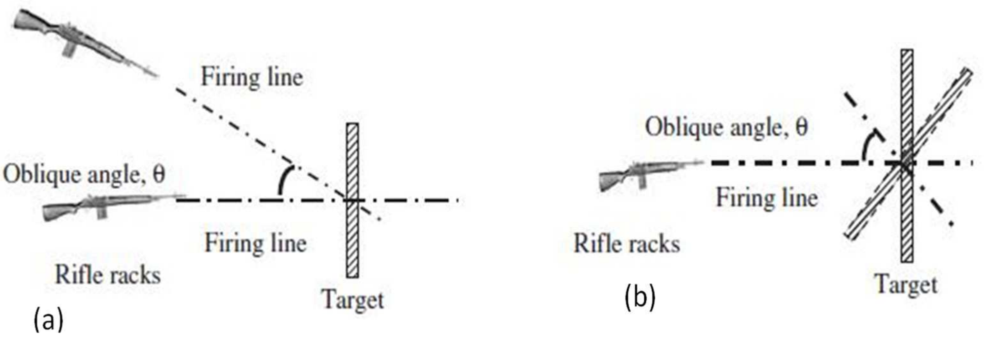


Figure 34 *Oblique developing methods (a) Change of firing line, and (b) changed angle of the impact surface* [333].

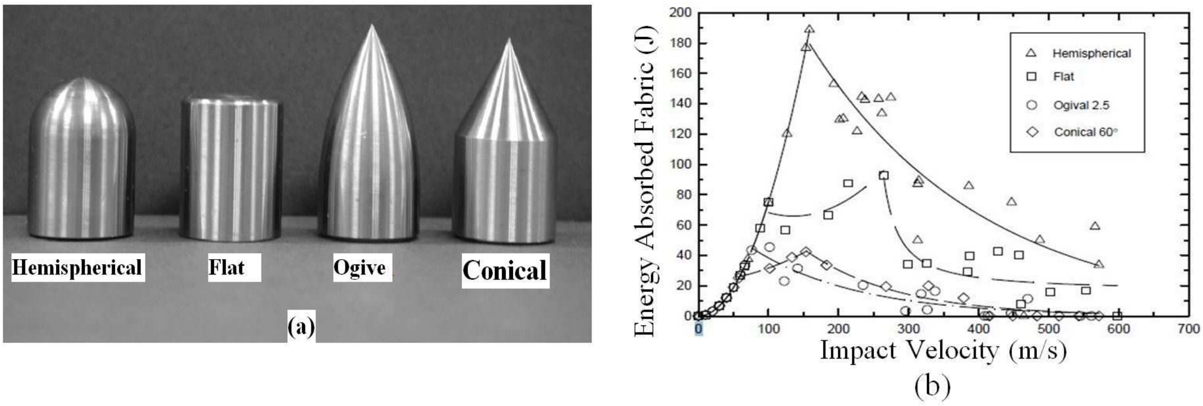


Figure 35 *(a) Types of projectiles used and (b) energy absorbed by fabric against impact velocity of projectiles* [282]

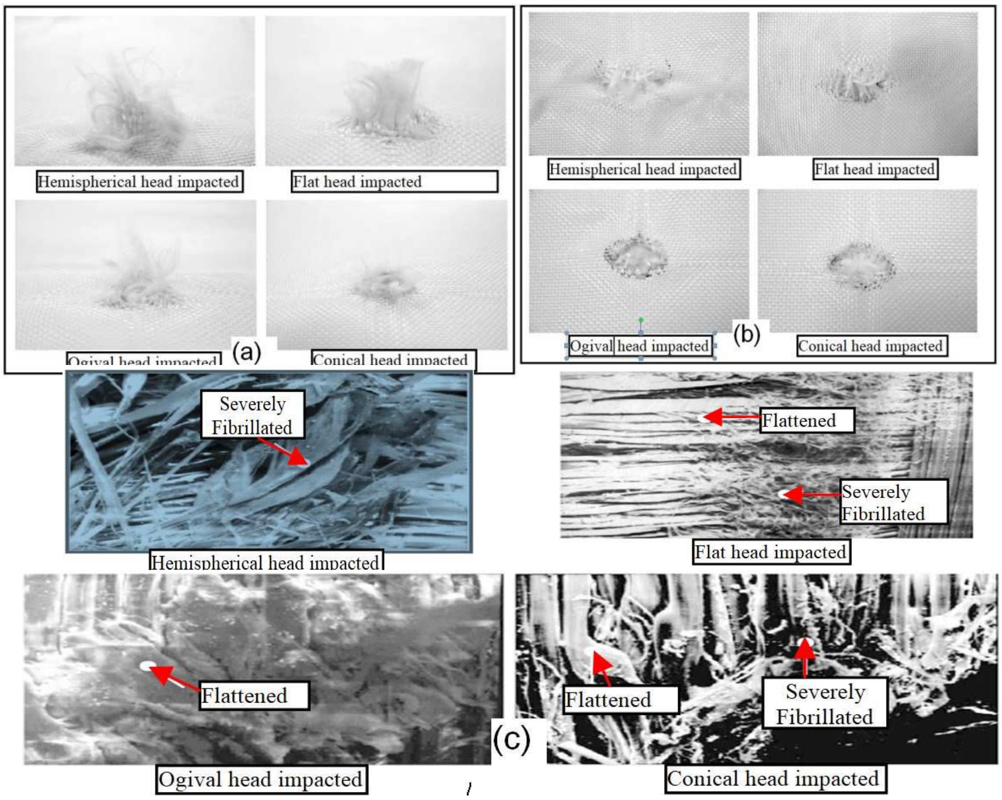
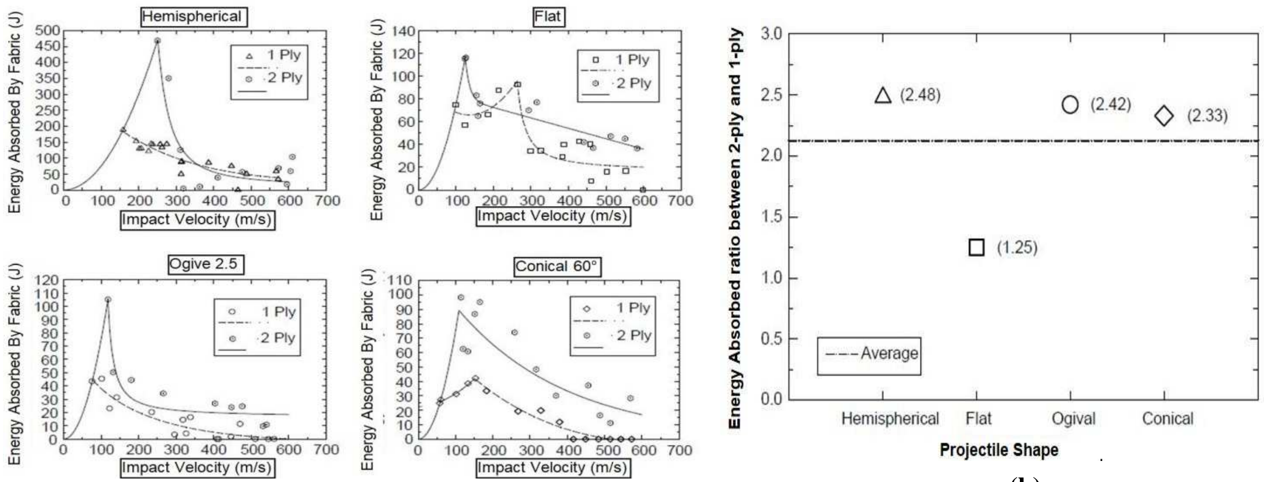
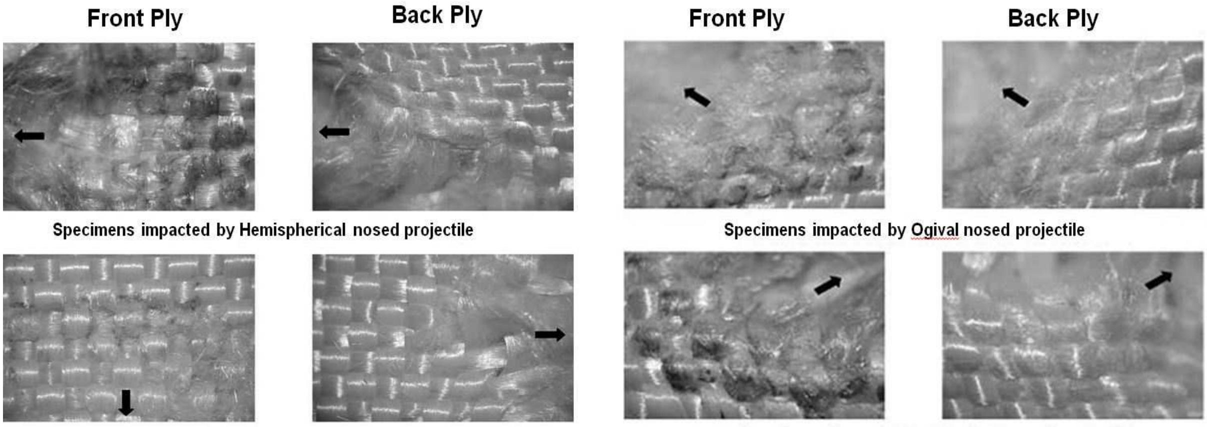


Figure 36 *Plain-woven single-ply fabric (Twaron® CT 716) failure mechanisms by different projectile shapes (a) Rupturing of yarns at back view of specimens perforated at about 200 m/s. (b) Bowing of yarns near the impacted point for impact velocity of 200 m/s, and (c) Scanning electron microscopy (SEM) images of failure of fibres by friction (include flattening of the fibres, fibrillation and rupture of fibres)* [282].



(a) **(b)**

Figure 37 *(a) Impact energy absorption curves for single and double-ply systems and, (b) Ratio of maximum impact energy absorbed in single- to double-ply system*[325]



Specimens impacted by Hemispherical nosed projectile

Specimens impacted by Ogival nosed projectile

Specimens impacted by Flat nosed projectile

Specimens impacted by Conical nosed projectile

Figure 38 *Difference in fibre breakage due to friction for front and back plies* [325]. *(Black arrow points towards location of perforation.)*

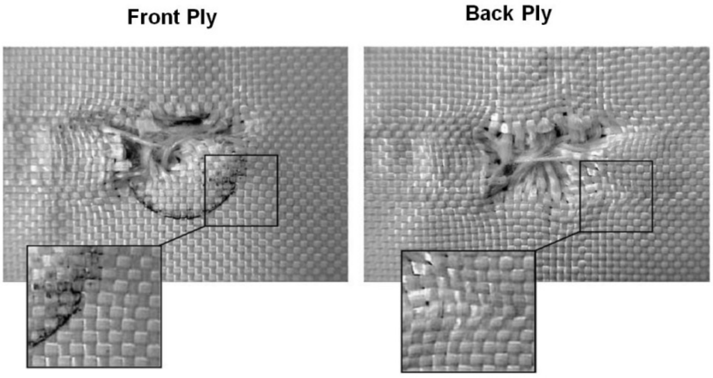


Figure 39 *Amplification of bowing in back ply of specimen impacted by a flat-nosed projectile* [325].

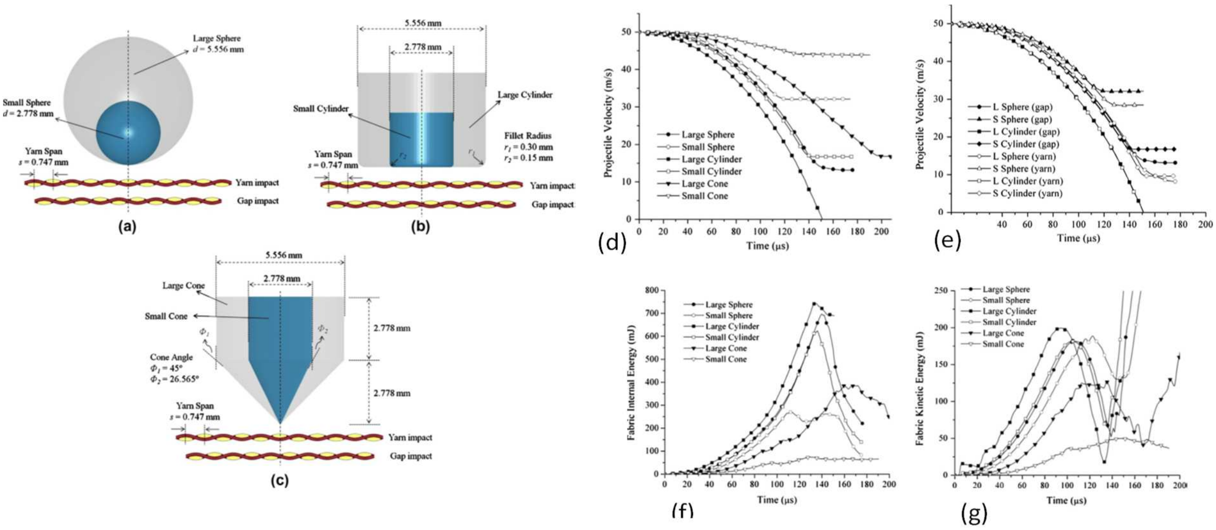


Figure 40 *Shapes and dimensions of the various projectiles used. (a) Spherical, (b) cylindrical, and (c) conical,(d) Comparison of projectile velocity histories for 'gap' impacts, (e) Comparison of projectile velocity histories for 'gap' and 'yarn' impacts, and Comparison of fabric energy histories for 'gap' impacts (f) Internal energy and (g) kinetic energy* [334]

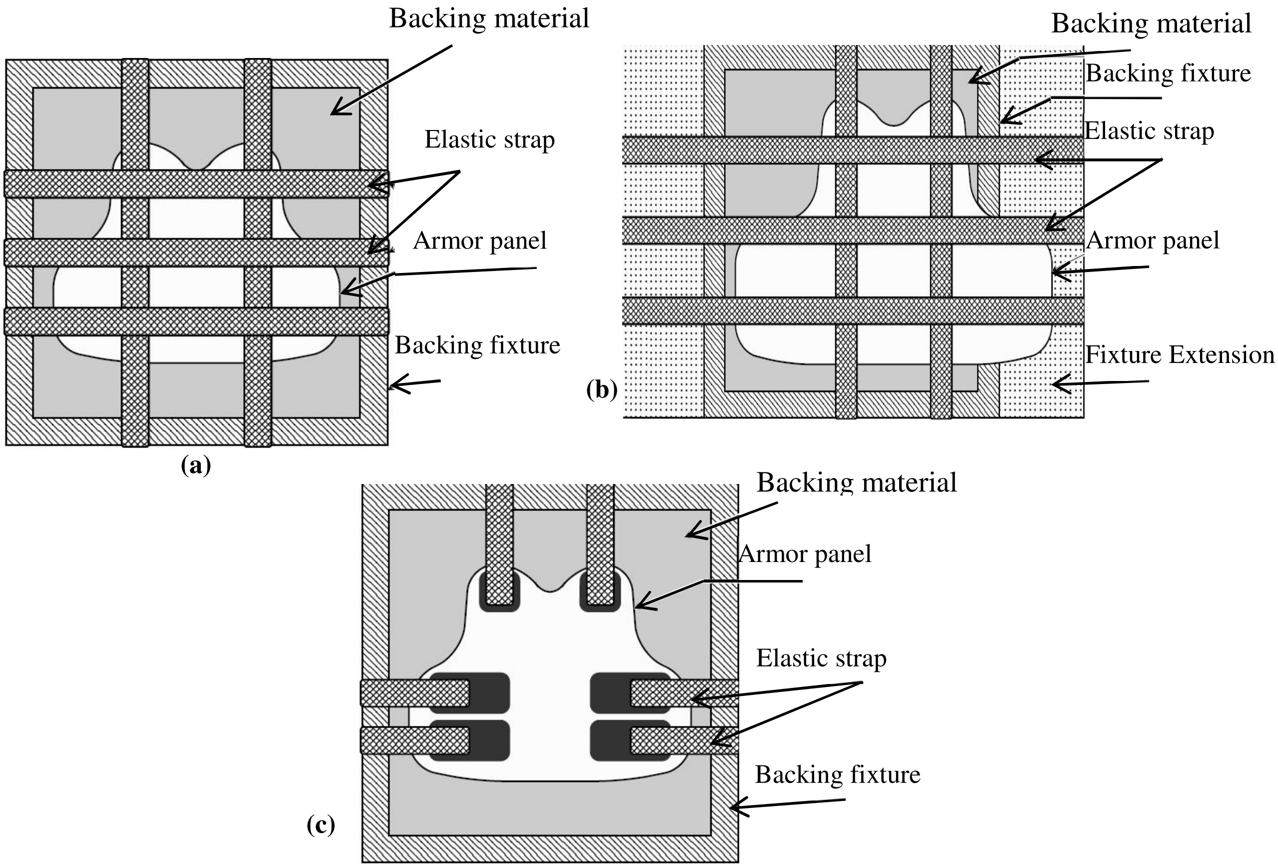


Figure 41 *Standard strapping techniques of the sample against NIJ standard ballistic test for (a) Smaller samples (b) Larger samples and (c) Special strapping arrangement with inbuilt attachments* [112].

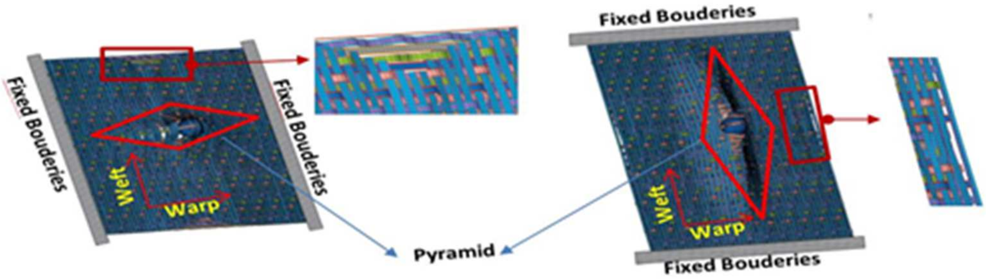


Figure 42 *Configurations of 3D fabric at 49.8 μs of 200 m/s impact both global view and its corresponding damage at free edges (a) Boundary fixation in only warp yarns direction and (b) Boundary fixation in only weft yarns direction* [345]

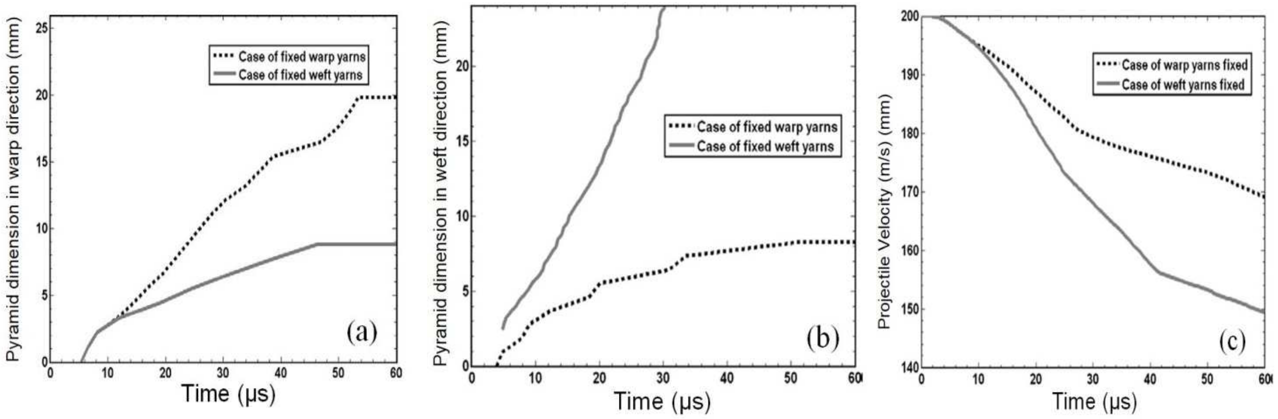


Figure 43 *Evolution of different parameters for two different boundary conditions at 200 m/s (a) Deformational pyramid dimension in warp direction (b) Deformational pyramid dimension in weft direction, and (c) Evolution of projectile velocity in two conditions* [345]

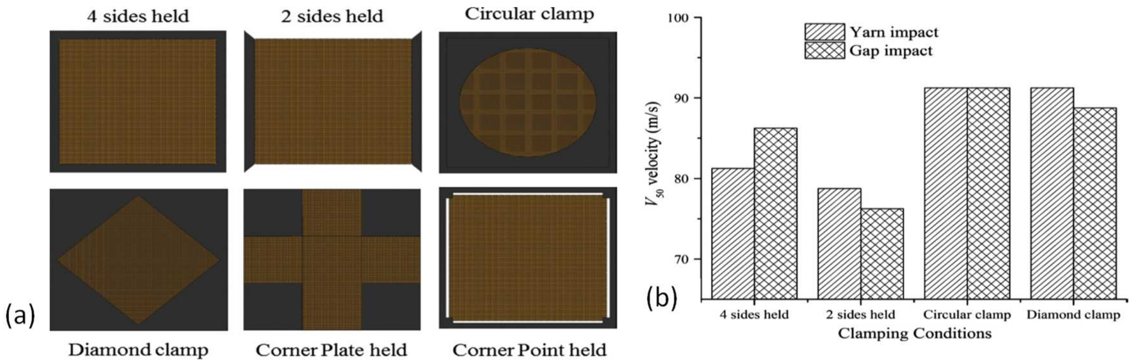


Figure 44 *(a) clamping configurations for the fabric impact testing and (b) Effect of precise impact location on V50 velocities* [346].

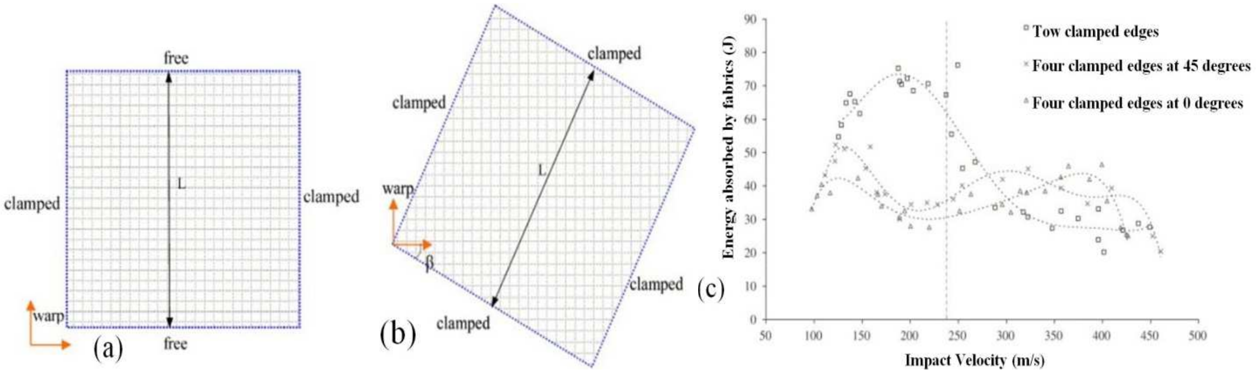


Figure 45 *Schematic diagram of fabric systems studied: (a) two-clamped-edges (b) four-clamped-edges at angle β and (c) Experimental results on energy absorption characteristics for fabric targets with different boundary conditions*[144]

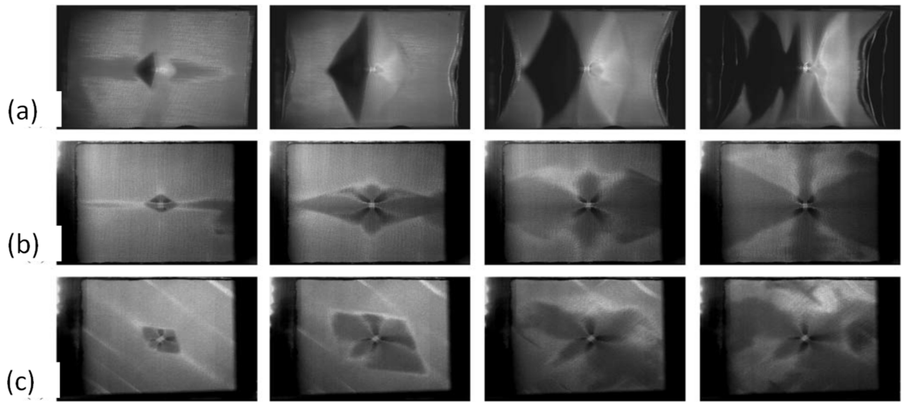


Figure 46 *High-speed images of development of fabric deformation for selected impact velocities: (a) two-clamped-edges, 122 m/s, (b) 0° four-clamped-edges, 110 m/s, (c) 45° four-clamped-edges, 103 m/s* [144].

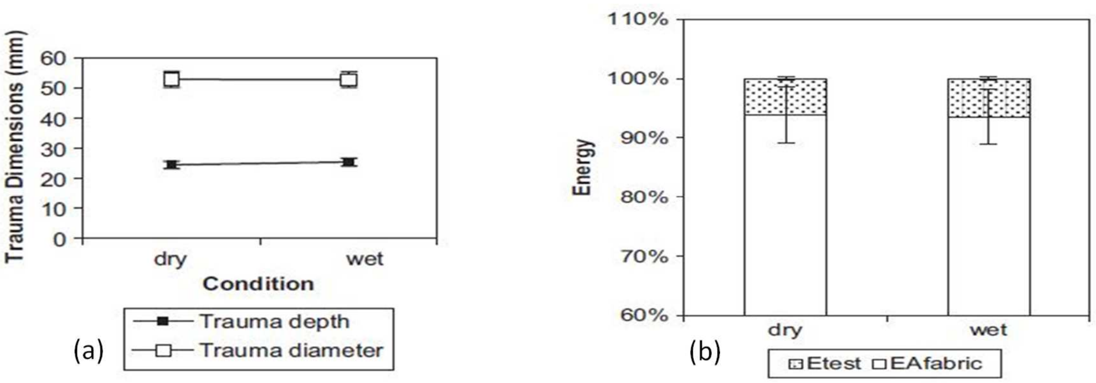


Figure 47 *Panel conditioning (wet and dry) effect on ballistic performances of panels made of plain woven aramid fabrics, Twaron CT 710. (a) Effect of Panel conditioning (wet and dry) on trauma dimensions (b) Effect of Panel conditioning (wet and dry) on energy absorption by the panels and transmitted (%) to the backing material [22].*

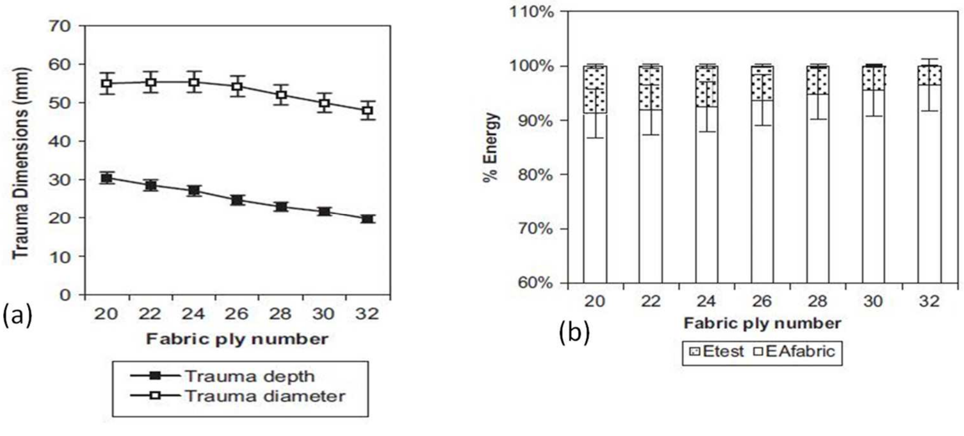


Figure 48 *Effect of fabric ply number in the panel on ballistic performances of panels made of plain-woven aramid fabrics, Twaron CT 710. (a) Effect of fabric ply number in the panel on trauma dimensions (b) Effect of fabric ply number in the panel on energy absorption by the panels and transmitted (%) to the backing material [22].*

Tables

Table 1. The specifications of some basic high-strength/modulus fibres [349]*[35]*[70].

Fibre Types	Fibre categories	Density (g/cm3)	Elastic modulus (Gpa)	Tensile strength (Mpa)	Strain to Failure (%)
Glass	S-Glass [10]	2.48	90	4400	5.7
	E-Glass	2.63	68.5	3500	4
Ceramic Fibres	Alumina (Nextel, 3M)	250	152	1720	2.0
	Silicon Carbide	280	420	4000	0.6
Carbon Fibre	Standard	1.77	33.5	3651	1.5
	Celion	1.8	230	4000	1.8
	Aksaca	1.78	240	4200	1.8
Para-Aramid	Technora, Teijin	1.39	70	3000	4.4
	Twaron, Teijin	1.45	121	3100	2.0
	Kevlar 29, DuPont	1.44	70	2965	4.2
	Kevlar 129,DuPont	1.44	96	3390	3.5
	Kevlar 49, DuPont	1.44	113	2965	2.6
	Kevlar KM2, DuPont	1.44	70	3300	4.0
HMWPE	Spectra 900, Honeywell	0.97	73	2400	2.8
	Spectra 1000,Honeywell	0.97	103	2830	2.8
	Spectra 2000, Honeywell	0.97	124	3340	3.0
	Dyneema, Toyoba/DSM	0.97	87	2600	3.5
Aromatic polyester	Vectran	1.47	91	3200	3.0
	Zylon AS	1.54	180	5800	3.5
	Zylon HM	1.56	270	5800	2.5
	M5 (2001 sample) [21]	1.70	271	3960	1.4
	M5		450	9500	2.5

***Table 2**. Glass fibre designations and their characteristics* [52][53].

Letter Designations	Product property Description
E, Electrical	Low electrical conductivity
S, Strength	High strength
C, Chemical	High chemical durability
M, Modulus	High stiffness
A, Alkali	High alkali or soda lime glass
D, Dielectric	Low dielectric constant

***Table 3.** The density and Hugoniot Elastic limits (HEL) of the commonly used ceramic fibres*

Materials	Density (g/cm3)	Hugoniot Elastic limits (HEL)
Al2O3	3.93	11.2
B4C	2.50	15.0
BeO	2.84	8.5
MgO	3.57	8.9