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# Dynamic impact protective body armour: A comprehensive appraisal on panel engineering design and its prospective materials

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ABSTRACT

Personal body armour is one of the most important pieces of equipment to protect human beings from various critical and fatal injuries. In today's modern world, various organizations including law enforcement and security service have made it mandatory for their personnel to wear personal protection system while on field duty. However, the systems should comprise an improved ballistic performance, light-weighted, flexible as well as comfortable panel not only to be accepted with a wider range but also for effective performances of the consumer. Generally, the overall performances of the protective body armour could be affected by various parameters including armour design techniques, type of materials used and finishing of the panels. The current paper aims to critically review state-of-art for armour panel design techniques and the different perspective body armour materials. The paper starts by discussing the different body armour and its category. Later, the different states of technology for armour panel design (mostly for women), its problems and the possible solutions will be cited. Later, the commonly used different polymeric fibrous and the future possible advanced materials including carbon nanotube (CNT), Graphene CNT and shear thickening fluids (STFs) treated materials for developing the reinforced body armour panel will be discussed. The authors believe that this paper will enlighten useful guidelines and procedures about the different panel design techniques and current and promising future materials for researchers, designers, engineers and manufacturers working on the impact resistance body armour field.



## 1. Introduction

In general, ballistic and sharp weapon protecting clothing also called personal armour can be worn by law reinforcement police, military and other civilian such as journalist, security guards to protect themselves from ballistic, spike, knife and stab threats etc. [1]. Its developmental history is as old as the evolution of mankind and evolved from time to time to protect different parts of the body. It includes the torso (body armour), the cranium (helmets), and the face & eye (visors, glasses, goggles and pelvic & neck protection garments [2]. In today's scenario, many law enforcement agencies have made it mandatory for their officers to wear ballistic protective vests while on duty. Even though various countries make the ballistic vest an obligatory outwears for their officers, however, many personnel did not feel comfortable to wear the vests while on duty. This is because most of the developed vests are made with either heavy or/and rigid materials to achieve better ballistic impact protections for higher threat level (NIJ Level III and IV). Unless it is designed with lightweight, flexible, well-fitted along with good ballistic resistance performances, wearing heavy and inflexible body armour for an extended period could generate excessive heat and bring less mobility [3–5]. For the last many decades, various materials from felt to metal, fabric to composite, nanomaterials and further bioinspired materials in its biomimetic conditions were exploited for the developments of body armour systems [6]. Currently, various researchers and body armour developers have involved and continuously working intensively on the new generation and innovative different ballistic fibres, ballistic fabrics, panel layers parameters and body armour design techniques not only to improve the overall performance but also to

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**Nomenclature**

| | |
|---|---|
| FLG | Few-Layer Graphene reinforced |
| FGRP | Fiber Glass Reinforced Plastic |
| AP | Armour-Piercing |
| FMJ | Full Metal Jacket projectile |
| S & W | Smith & Wesson |
| RN | Round Nose |
| SJHP | Semi Jacketed Hollow Point |
| JSP | Jacketed Soft Point |
| BAS | Body Armor System |
| BFD | Back Face Deformation |
| V-50 | Velocity at which probability is 50% for perforation of an armour |
| UD | Unidimensional |
| 3D | Three-dimensional |
| PVEE | poly-vinyl-ester-epoxy |
| SEM | scanning electron microscope |
| PEG | polyethene glycol |
| TEM | Transmission electron microscopy |
| CNT | Carbon Nano Tube |
| SWCNT | single-walled carbon nanotube |
| MWCNT | multi-walled carbon nanotube |
| COD | Crack Opening Displacement |
| FSP | Fragment Simulating Projectile |
| HAP | Hard Armour Plate |
| UHMWPE | Ultra-High Molecular Weight Polyethylene |
| NIJ | National Institute of Justice (USA) |
| NATO | The North Atlantic Treaty Organization |
| BFS | Back Face Signature |
| SEA | Specific Energy Absorption |
| 2D | Two-dimensional |
| CAD | Computer-Aided Design |
| MLG | multilayer graphene |
| PVA | Polyvinyl alcohol |

realize the requirement of a modern military operation, technology-driven war tactics and current terror threats [7–9]. Meanwhile, the involvement and participation of women workforces have been also drastically increased for the last few decades in the field of law enforcement, privet security and military forces across the globe [10,11]. Even though the numbers of women personnel are significant, they were fitted with either unisex or smaller size of male-based body armour for so long. This fitting of male-based armour for women personnel's is not acceptable due to not only the physiological differences but also imposes the disproportionate on fitness, comfort, and worse ballistic protection causing functional sacrifices. Even, unlike the male, designing of women soft body armour encounter problems and need special attention due to its unique curvilinear body shape. Moreover, the effectiveness of the women soft body armour related to ballistic impact performance, fitness and comfort depend on the various factors including type of ballistic material, material finishing and garment designing techniques. Considering the above problems, various researchers and body armour manufacturer have been working on unique design techniques and appropriate materials to develop women soft body armour based on their morphological shape [3][ [12–20]]. However, most of such kinds of researches findings are funded either privately to improve the marketability of specific products or patented by intelligence security authorities or individuals. This makes those research output unreachable and secret for the wider audiences who are working and making research in the field. Moreover, despite various research studies on the field of ballistic material and design of body armour, it is also acknowledged that a detail and systematic review dealing with women soft body armour design, ballistic material and its testing methodologies have not been well investigated and documented. For this reason, it is very difficult to find the current situation and the specific gap in the field for further analyzing, investigations and improvement.

In general, the paper will try to discuss different types of body armour and their characteristics toward ballistic protections. Various materials and designing techniques (especially for women) for the developments of body armour have been also outlined. Specifically, a recent state of the technology used on design and developments of women body armour will be focused on. Moreover, recent and future possible material era for developing ballistic protective body armour will be mentioned. This review paper would give valuable information and hopefully help different researchers, body armour developers and armour manufacturers for future research and developments in the field of body armour by discussing and analyzing the different available resources related to designing techniques, a material used and its testing methods, standards and evaluations systems of body armour.

## 2. Personal body armour and its categories

### *2.1. A brief history of personal ballistic body armour*

Body armour is the most important piece of equipment to protect human beings from various critical and fatal injuries [4,21,22]. Among the different threats, impacting by the projectile is one of the most common threats. The ballistic impact is a very complex mechanical process where a very low-mass high-velocity projectile is propelled by a source onto a target and impacted which mainly effect near the location of impact. The absorption of energy before it gains access to the body and its energy distribution among the ballistic materials are very important aspects to understand the principle and effect of energy transfer from projectile [23]. Meanwhile, the demand by military and police personnel has drastically increased and the protection suits have been progressively improved by new constructions made from proper materials [24]. Besides, to be worn by the officer, the body armour generally not only constructed with the material having better resistance to projectile penetration but also designed in reasonably light in weight and flexible. Body armour was developed from different materials for the last many decades. Generally, the historical evolutions of body armour have a direct relationship with gun power improvement. For instance, the development of high-speed projectiles and explosive materials have reconstructed the dynamics of the battlefield, which further advocated the growth of the advanced ballistic protection system that is a low cost, damage-resistant, flexible, lightweight and comfortable to wear with efficient energy absorbing capacity [5].

Between the 1800s to World War I, various metallic materials were applied as ballistic protective materials to develop different levels of body armour [25]. For example, in 1879 the home-made suit weighed 44 kg body armour mainly made from metal scraps was developed in Australia to cover the upper torsos, upper arms and legs. Besides, the US has also developed various body armour with the hard plate to protect the chest and heads during World War I [26]. Besides, in the early stages of World War II, the US has also developed different body armour but found it very heavy, less mobile and uncomfortable. Later, the flexible body armour was developed with the help of different synthetic fibres like Nylon. Even though it was not successful, Nylon 6.6 was the first synthetic fibre used for ballistic systems in the form of a basket-weave flexible pad to cover the upper chest and shoulders and the plate for chest protections [27]. Later, around 1970, the DuPont company has introduced the new synthetic fibre (Kevlar) and later in1976 the first all-Kevlar based flexible ballistic body armour developed [28]. Later, several new fibres such as Dyneema by DSM's, GoldFlex by Honeywell's, Spectra and Twaron by Teijin, and Zylon by Toyobo's were introduced for flexible body armour development [29]. Unlike their higher cost, they were claimed as lighter in weight and possess much better ballistic protection than Kevlar. The first soft body armour has been invented in Korea around the 1860s with thirteen layers of cotton fabrics. Even though the developed soft body armour is hot to wear and easily burnt by fragment heat, it was considered at that time as effective regarding bullet protections. Silk was also introduced to develop the soft body armour using 18 to 30 layers of cloth to protect the wearers from arrow penetration [30]. The US has also designed and developed flak jackets made of nylon fabrics for aircraft crews to stop the flak and shrapnel but not bullets around the early stages of World War II [31]. Relatively lighter body armour but not successful to stop the bullet and fragments was developed using fibre-reinforced plastics by integrating with the nylon vests in 1951. However, the first soft body armour was designed to hold hard ceramic plates to successful stop 7 mm rifle rounds projectiles in 1967 [32]. Later, a quilted nylon faced with multiple steel plates was designed and developed by the American Body Armor and marketed to American law enforcement agencies under the trade name 'Barrier Vest.'

### 2.2. Categories of personal protective body armour

The higher demands of body armour by law enforcement agencies for their officers contributed not only to its huge demand but also to the improvement of body armour in terms of material and design aspects. A wide variety of body armour is nowadays available on the market with different threat and protection level. In general, those body armour could be classified as covert and overt based on their flexibility, wearing styles and wearing situations. Armour designed as thin as possible to be worn comfortably under standard uniforms or other garments is Covert body armour (Fig. 1(a)). It can be worn in a duty where less level of protection is required such as security operatives, cops, and close protection officers. Overt body armour is a usually bulkier design made from harder panels and wore over the garments (Fig. 1(b)). Such body armour styles are worn by officers, where they are under high-risk operation. However, all the mentioned body armour composed of three sections, namely carriers, panel cover and ballistic panels (Fig. 1(c)). The carrier is used to serve and secure the ballistic panels to the wearer's and usually made of typical garment fabrics such as nylon or cotton. The ballistic panels are usually constructed separately from the vest carrier of multiple layers of ballistic-resistant materials that help to provide ballistic protection. Whereas, the cover is mainly helping to protect the ballistic materials from the various environments. In general, the frontal and back ballistic panels are introduced into the front and back pockets of the vest carrier respectively. For better and easier cleaning, the ballistic panels could or could not be removed from the outer armour panel. Besides, depending on the level of firearm threats, modern body armour was worn by police, law enforcement agencies and the military categorized into two categories, namely, soft body armour and hard body armour [7].

#### *2.2.1. Hard (or rigid) body armour*

Hard (or rigid) armour is delicately designed when the textile-based soft body armour become ineffective against military rifle rounds. It mostly becomes standard in military use, corrections and other law enforcement to resist more than 500 m/s velocities. It is developed by integrating the textile-based soft body armour along with rigid materials such as metallic plates (steel or titanium), ceramic tiles, polyethene plate, silicon carbide, boron carbide plates or laminated (coated) composites, etc as shown in Fig. 2.

Besides, it is worn at a high risk of attack not only to stop the projectile against all handguns and a wide range of rifles but also fragments from explosions. The hard armour plate could weigh by itself up to 1.4 kg–3.0 kg. Ceramics such as alumina ($Al_2O_3$ and silicon carbide (SiC)) are commonly used armour plates for hard armour ballistic applications for the ballistic protection of NIJ standard level type III (rifle) and IV (armour-piercing rifle). It is also composed of ceramics parts combined with composite reinforcement with epoxy resin to obtain better flexibility, light-weight and ballistic performance as compared with pure ceramic tiles [34]. Nowadays, fibre-based textile laminated composite systems become the widely used armour panel materials in the market and get higher attention from researchers mainly due to their reduction of weight by maintaining the impact resistance. However, characterizing the composite material before the application will help to obtain an amour plate with better ballistic resistance and comfort. For example, a small amount of resin (20%) while impregnating the woven fabrics gives better energy absorption by maintaining flexibility than higher resin values through restricting yarns not to share the load effectively [35]. Incorporations of vinyl ester resins coated Dyneema® fabrics in the soft body amour (NIJ-level II) could also give a ballistic resistance up to NIJ standard level III. Moreover, various research studies have also intensively investigated and characterized the ballistic impact performances and flexibility

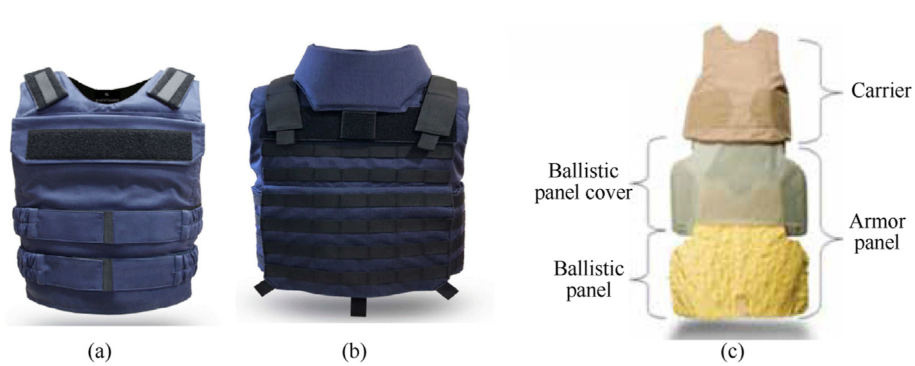


**Fig. 1.** (a) Compositions of typical body armour, (b) covert and (c) overt body armour [33].

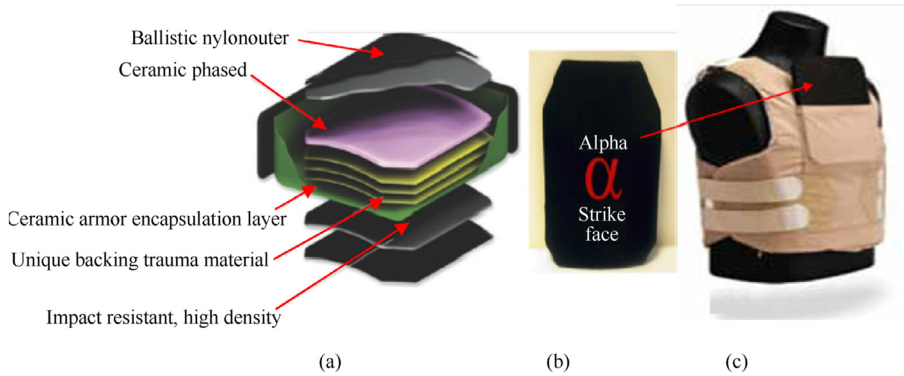


**Fig. 2.** Commercial hard ballistic armour (A) VestGuard, (B) Alpha™ (C) hard body armour with hard steel plates [33].

properties of the different fibre-based textile composite used as hard body armour [36–40].

### 2.2.2. Soft body armour

The soft body armour is normally developed with various layers (20–50) of ballistic resistance flexible textile materials made of yarns of high-performance fibres and weighing (below 4.5 kg) in a different form as shown in Fig. 3 (a) and (b). Normally the different flexible ballistic layers are assembled in different forms to develop the final ballistic vest panel. In general, soft body armour could suffice to perform against low to medium level firearm threats. According to the National Institute of Justice (NIJ) standards, soft body armour includes type IIA (9 mm FMJ RN bullets, 8.0 g, the velocity of 373 ± 9.1 m/s and with 0.40 S&W FMJ bullets, 11.7 g and a velocity of 352 m/s ± 9.1 m/s), Level II (9 mm FMJ RN bullets, 8.0 g and a velocity of 398 m/s ± 9.1 m/s and with 0.357 Magnum JSP bullets, 10.2 g and a velocity of 436 m/s ± 9.1 m/s and Level IIIA (0.357 SIG FMJ FN bullets, 8.1 g and a velocity of 448 m/s ± 9.1 m/s and with 0.44 Magnum SJHP bullets, 15.6 g and a velocity of 436 m/s ± 9.1 m/s). It offers significant contributions to ballistic protection from small arms fire (handgun bullets) and tailored to conform very well to the body contour to provide good levels of comfort. Unidirectional (UD) and 2D woven fabrics are commonly used textile fabric structure used to develop soft body armour systems in terms of higher protection without sacrificing mobility and comfort [41]. However, the fabric type, all the different multi-scale structural hierarchy of soft body armour determines not only the ballistic impact performances but also can cause a probabilistic penetration response as shown in Fig. 3(c).

On contrary, the higher number of layer involved make it heavy, bulky, and inflexible, interfering which affects the mobility and comfort of the wearer [41,42]. This becomes challenges for researchers and armour development to device appropriate methods and materials for achieving lightweight, flexible, and comfortable armour panels [43].

## 3. State of technology – body armour panel design

The body armour panel is comprised of various layers of materials depending on the threat level to protect the wearer's upper torso [43,44]. Such multiple layers were arranged and joined together differently to create the two body armour panels, the front and back panels. The women body armour panel, especially the frontal panels, should comprise a non-planar panel to optimize its protection and comfort performance [45]. However, due to the lower involvement of women in security such as military professions, they were fitted with men's body armour for the last many years which causes poor ballistic protection, non-comfort, and negative psychological effect [46,47]. However, in the last few decades, women participation in military, law enforcement, security offices etc. have been become considerably increased. For example, in 2008, 16.7% of police officers in the EU were women. In the recent year of 2016, among the total of 324 police officers per 100 000 people in the EU, women police officers' percentages were increased to 21%. This indicates that one in five polices officers was a woman [48]. Similarly, the entire UK police forces were also male at the start of the 20th century and even their numbers were very small since the 1970s. However, according to the study, in March 2016, 28.6% of police officers in England and Wales were women. This was an increase from 23.3% in 2007 [49]. Besides, in March 2017, the percentage of female officers even increased to 29.1% in England and Wales, 29% in Scotland and 28.5% in Northern Ireland [49–51]. The women were made up of a 61% majority of non-sworn police staff and 45% of Police Community Support Officers. Women

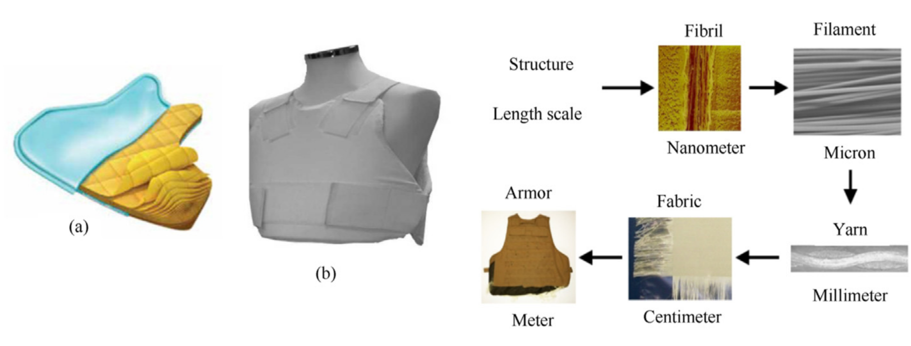


**Fig. 3.** (a) Panels, (b) soft body armour, (c) structural scales in Kevlar fabric armour.

became eligible to apply for all roles in the British forces in 2018 [52]. Moreover, the percentage of women was 5.0% in 1980 and 9.8% in 1995 for the police force in the United States [51,53]. This number even grew further and recorded 11.2% in 2005 and 11.9% in 2014 [54,55]. In the French Army, the number of women participant was evolved around 1987 with around 18000 which is about 7% and increased to 44500 women (12, 7%) in 2003 and even after a year in 2004 it was recorded about 18% [11]. In the Canadian Armed Forces (CAF), women participation made up 11.4% by 2001. By 2018, 15.3% in CAF personnel, 4.3% in combat personnel, and 17.9% in all CAF officers were women. Besides, out of 14 434 women, 7408 were in the Army, 2856 in the Royal Canadian Navy, and 4160 in the Royal Canadian Air Force [56]. Such increments of women participation in the field officer make it mandatory to design body armour based on their unique physique to achieve better protection and comfort. However, considering the women body armor design challenge, a dedicated design and manufacturing of female soft body armour based on their unique morphological differences for better protection and comfort are in great demand. The following section discussed on the different techniques to design women soft body armour.

### 3.1. Women body armour designing techniques

Nowadays due to the various ballistic threat levels and types, the demand for body armour for ballistic protection has been increased [1]. Similarly, apart from its ballistic protection, the body armour is essential to provide fit and comfort for personnel's who engage in military, police, personal security, reporter, and prison work. However, according to the study, the thermal comfort, fit and mobility of the body armour among the male and female personnel's are different due to their upper torso differences [57]. Such problems might be solved during women designing through the involvement of filler materials including foams and pads in the body armour panel system [58–60]. Moreover, the designing technique of the final soft body armour played a great role in the overall performances of the body armour. For example, at the time of the ballistic impact, the impacted body part should be properly fitted or the multi-layer panels should be designed to properly lie on the specific body to provide good protection. This well-fitted body armour will give the wearer all the time not only comfort but also secure and enhanced protection while instant impacting [61,62]. On the contrary, if the body armour is not developed considering proper material and appropriate design, the personnel's might be neither protected nor obtained comfort while performing their job outdoors [63]. It is also very challenging to improve both protective performance and comfort at the same time while developing body armour. On the other hand, unlike men, the above problem even became worse while manufacturing women body armour [52] due to the panel has to properly accommodate their upper curvaceous body shape. Moreover, not only the variability of the women's upper body shape but also the stiffness behaviours of the ballistic materials with its large number of layers make it very difficult to achieve the required performance. Nowadays, various women body armour designing techniques were proposed to minimize the above problems [64] [3] [13–15] [17–20]. Cut-and-sew, overlapping, folding, moulding methods is widely known techniques for designing women body armour [9,53–55]. This sub-section will try to discuss the different methods in details.

#### 3.1.1. Traditional cut-and-sew technique

For the last many years, cut-and-sew methods were commonly used design methods in the industry to develop women's body armour. Various researcher and armour developers have designed and developed women's soft body armour by involving different kinds of dart designs in different forms to accommodate the women's body bust area (cut-and-stitch approaches). However, such design methods bring lower ballistic protection at weakness points of the stitches (dart seams line) against projectile during impact. Moreover, the accumulated material at darts areas also cinches the body near-certain positions of the bust and creating uncomfortable when worn by the wearer [46] [19]. Research studies even further studied to optimize the ballistic performance and the comforts of women body armour design designed by the cut-and-stitch methods. For example, concealable soft body armour was designed using a plurality of layers of ballistic material, where the different layers of the material include a series of folded pleats arranged at selected angles and intervals along with the layer and sewn along their length [3]. Another woman's body armour having dual cups has been also designed for accommodating, protecting and supporting the breasts [15]. Body armour with contoured front panel, all-fabric, lightweight panel composed of a plurality of superposed layers of protective plies of fabric made of aramid polymer yarns has been also developed. This panel was contoured using overlapping seams joining two side sections to a central section of the panel to the curvature of the bust of a female wearer to convey good ballistic protection and comfort [13]. A ballistic vest with front and rear ballistic panel which also has elongated side portion to provide ballistic protection for the side of a female wearer's breast conformed to the body of a wearer by a stretchable outer garment located over the ballistic panels has been also developed [16]. Another study also optimizes the protection zones for tailor-made bullet-proof vest using a virtual body given by the body scanner for more comfort and to accelerate the sizing process through improving the measurement process [65] as shown in Fig. 4.

The study replaces the traditional design method with a three-dimensional design process using darts rotation techniques for better fitness based on the different female morphology.

Another approach with the new geometric definition of the vest by introducing different body parameters (Fig. 5) was proposed. The 3D virtual body was generated using Body Scanner to makes the tailor-made bullet-proof vest more comfortable and improve the measurement process during sizing. The optimization of the different protection zones by materials distribution based on the vulnerability of the body toward the impact was designed as shown in Fig. 5(a) and (b) [66]. The correct pattern was generated and draped on the attained virtual 3D female dummy using Design Concept (Fig. 5 (c)) and its various protection zone was delimited with the help of various darts positions (Fig. 5 (d)).

#### 3.1.2. Folding and overlapping

Fabric folding and overlapping are barely used designing techniques to develop the women's body armour [67] [3]. The folding technique is mainly used to shape the materials into a three-dimensional form by folding the materials and stitched at the side in a certain shift. This also revealed the limitation of ballistic performance due to material discontinuities and weak stitching area around folded material. One of the women's body armour with multiple layers of penetration-resistant material was designed using a series of V-shaped darts in successive layers to shape and fit the bust of women [67]. The V-shaped material was then folded on itself to form a pleat and is angularly offset from one another in directions so that the added thickness is distributed substantially evenly, thereby avoiding bulges or stiffness and improving the wearing comfort. However, folding techniques could also create many folded fabrics at the side with sharp edges create thicker panels while folding which causes itching, less personal mobility, and discomfort. Superposing methods have also used the layers of

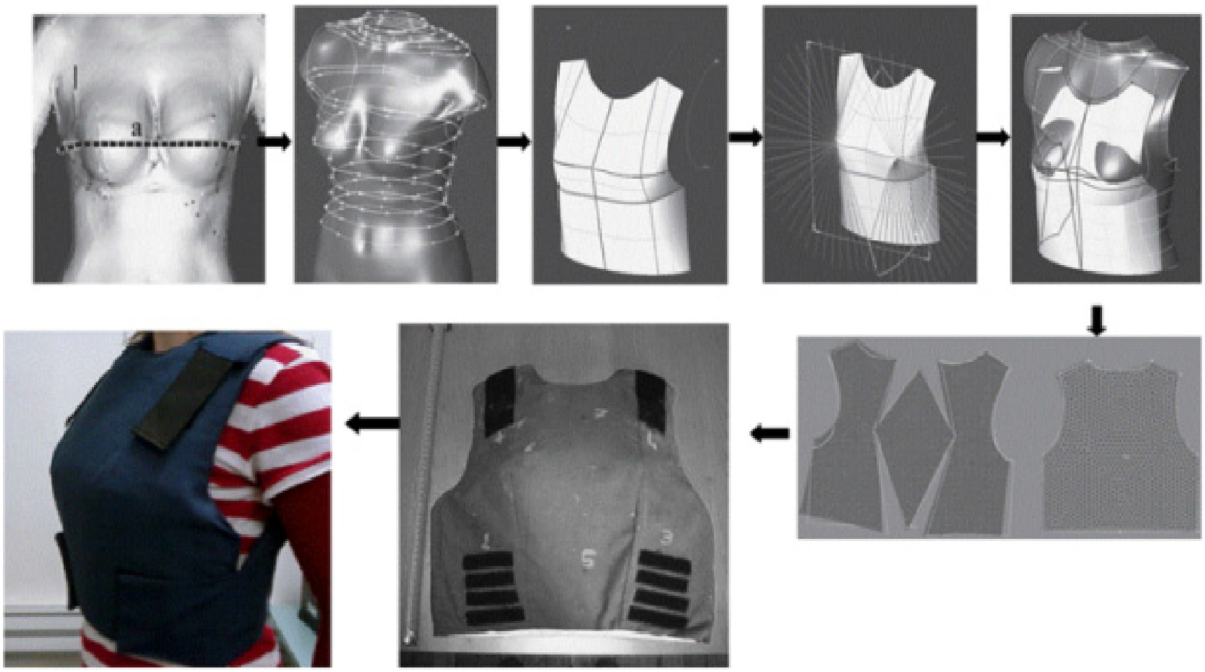


**Fig. 4.** Production process of women ballistic vest with dart rotation methods (a) 3D virtual model, (b) Mesh creation on the different body areas, (c) Dart formation and (d) Garment draping [65].

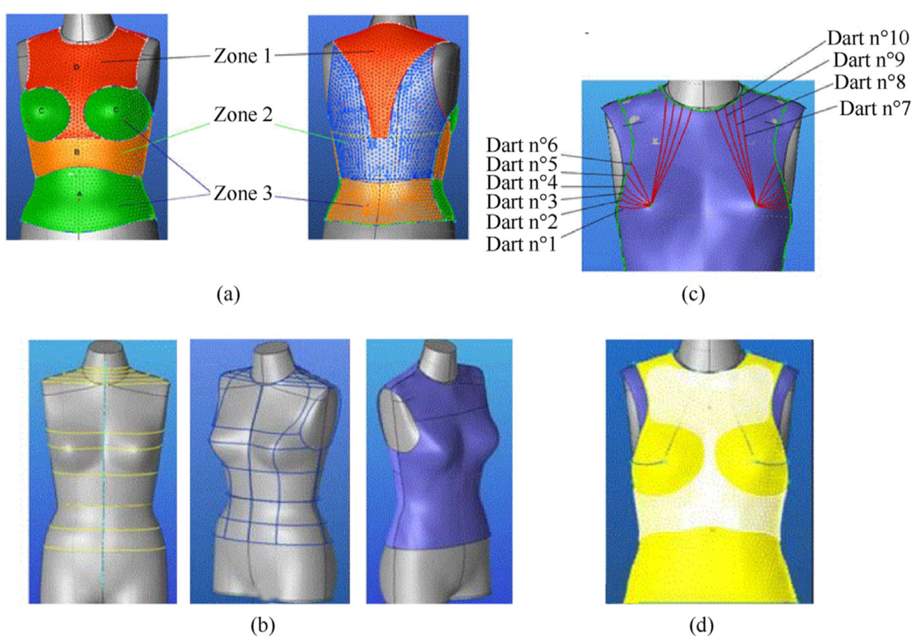


**Fig. 5.** Design processes of a ballistic vest with various protection zone (a) protection zones on front and back of the virtual body, (b) measurement values, fit and final fitting, (c) distribution of darts (d) Set of layers (12th) while alternation of darts [66].

ballistic material to develop contoured surfaces to accommodate the frontal women part called overlapping. It also applied overlapping seams to join the different superimposed layers. However, In this method, the small ballistic missiles still can penetrate by severing the loop of threads among the seams [68] [13]. One patent work tried to develop a light-weight, all-fabric and contoured body armour panel to protect the torso of a woman against small arms missiles using overlapping methods [13] as shown in Fig. 6. The frontal panels were contoured to the curvature of the women bust using overlapping seams while joining the two-side section to the centre section of the panel as shown. The multiple layers which were superimposed were comprised of ballistic-resistant fabric made of aramid polymer yarns.

### *3.1.3. Moulding methods*

Various researches have tried to develop women's body amour using the different traditional method to accommodate the bust area [66] [15] [16]. However, the above commonly used design system gives a weakness at the seams against projectile impact and low comfort performance. Besides, the above-methods also face difficulty to obtain accurate surface data for women's breasts due to the borderline of the breast is ambiguous at the skin surface which led to less fitted body armour. Considering all problems, additional designing techniques would be required to design the frontal women body armour panels to properly accommodate the bust shape with better for better impact performance, comfort and fitness. Different work has been done to come up with the solution to improve the problem and properly accommodating the curvy region[ [69,70]]. Normally, the more the ballistic vest resembles the required shape of the body; the better fitness and efficient protection will be obtained. Therefore, developing women's body armour which properly accommodates the bust area and fitting of the different curvilinear areas with the required dome-shape will improve not only the fit and comfort but also its ballistic protections for different women morphology [71]. Moulding becomes good technology to create the required dome-shape through the forming process without applying any kind of cutting and stitching but seamless frontal body armour by mimicking the bust area. However, the methods need both advanced designing techniques and proper materials to accommodate the required shape [19,20,72].

Teijin Aramid in collaboration with Triumph International claims the concept of manufacturing the women's body armour through the moulding process as shown in Fig. 7. The moulding process was carried out using pressure and heat on the 2D woven p-aramid (CT709) fabric to create the moulded panels [73]. Each moulded layer was then kept one over the top of the other to obtain a garment part and, joined by a base seam, e.g., in the middle of the panel as shown in Fig. 7 (b) and close look of the panel at the bust area in Fig. 7 (c). Another women's body armour using a 3D melded multilayer laminated woven structure was also developed with better retaining and conforms of the female torso [14]. Other researchers have also used a 3D pattern for the frontal panels of women's body armour. For example, parametric design methods for generating human body models of varying sizes according to different anthropometric measurements in the 3D domain and 3D presentation were used to develop warp-knitted seamless garments [74]. A new design approach has been also proposed for developing women's body armour by introducing the different personal parameters of the body inside the new geometric definition of the vest using real 3D body measurement to optimize the assembly process and projection zone [66]. Other three-dimensional seamless women body armour were also designed combining CAD software and knitting technology [70]. Some researchers have also used 3D warp interlock fabric to accommodate their women's body armour design due to its good moulding ability. A moulding process applied on the base functional materials of multi-layer woven laminated to substantially conform the women's frontal body morphology was invented (Fig. 8) [14]. The thermoplastic material was applied during the moulding process to fuse the fibres within the 3D woven material for better lamination and improved ballistic impact performances. The material forming on upper and lower panel shape Fig. 8 (a)) was designed based on the women's frontal shape. Such design was claimed for its capability of retaining the moulded shape for better comfort and ease of movement (Fig. 8 (b) & (c)).

A contoured, form-fitting and flexible panel through the moulding process using three-dimensional woven material was also invented (Fig. 9). The required number of layer fabric is placed jointly and substantially parallel with each other and moulded to adapt to the women's torso. Each layer of the fabric was made of weft and warp yarns with a long float weave in one or more directions. The Adhesive resin can be used for the impregnations of yarn in each sheet. As shown in Fig. 9 (a) the multiple woven ballistic fabric layers are placed on the preformed mould between the upper and lower portion to conform to the desired body contour. Then, the fabric sheets with applied adhesive will be compressed between the two portions and subsequently the long floats of the fabric weave help to conform to the required shape of the mould [75].

Another research presented the mathematical modelling for pattern developments of seamless women armour frontal panel considering body size and bra size [46] and combining the bust-cup and no bust-cup areas (block projection) using classic coat block pattern by omitting the dart. According to the study, three different models (Fig. 10(a–c)) to accommodate the bust-cup areas were developed.

Unlike the first two, the last model (Fig. 10 (c)) was likely appropriate since it is developed considering the shape of frontal mannequins and bust area, and dividing it into seven different geometrical shapes (Fig. 10 (d)). Finally, the mathematical model based on half of the female body armour front panel was computed based on a size 12 standard mannequin (Fig. 10 (e)) and a simple pattern for the first layer of the panel was generated for the frontal part (Fig. 10 (f)). Later, the pattern was transferred to a 3D warp angle-interlock fabric (Fig. 11 (a)) to validate the model through by moulding process. Later, a pattern for various panel layers was also developed (Fig. 11(b)) [69] and used 3D warp interlock fabric to shape the frontal women's body armour as shown in Fig. 11(c).

Another study [76] also used CAD knowledge to evolve women adaptive bust in the virtual manikin for body armour development (Fig. 12(a)). Such an adaptive bust was introduced into a 3D design process (Fig. 12 (b)) to create a well fitted 3D bra pattern (Fig. 12 (c)). An efficient reverse engineering approach (2D-3D-2D) was carried

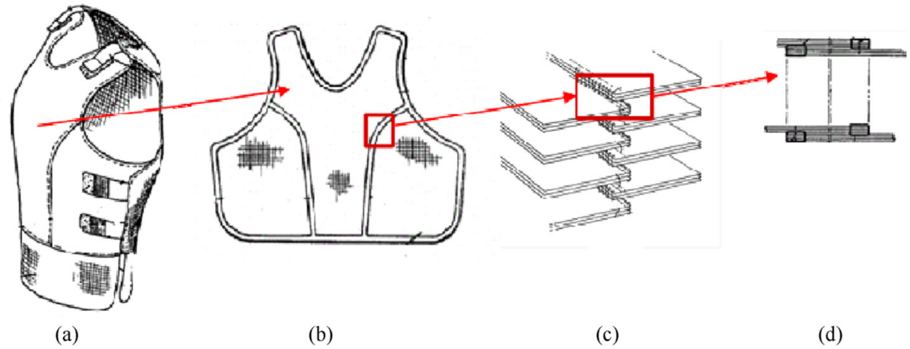


**Fig. 6.** Women body armour with overlapping seams, (a) Perspective view (b) plan view (c) exploded perspective view of different ply joined with overlapping and (d) a vertical section through the overlapping seams [13].

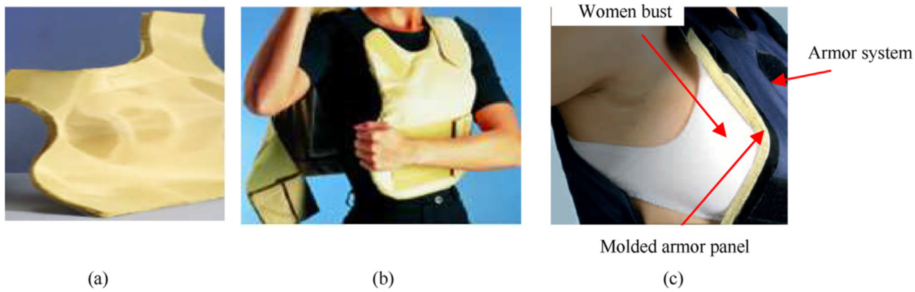


**Fig. 7.** Female body armour through the moulding process [73].

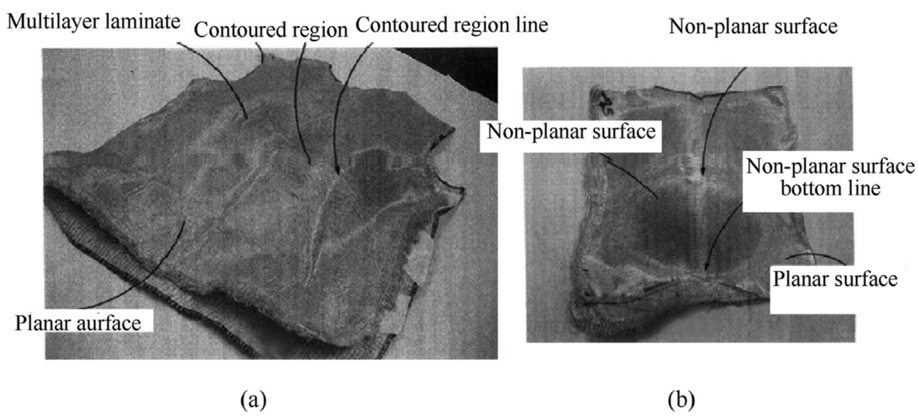


**Fig. 8.** (a) Multilayer laminate for ballistic protective wear in the vest form constructed to conform to the natural curvature of a female torso, (b) and (c) it's the front sectional component and fitting form [14].

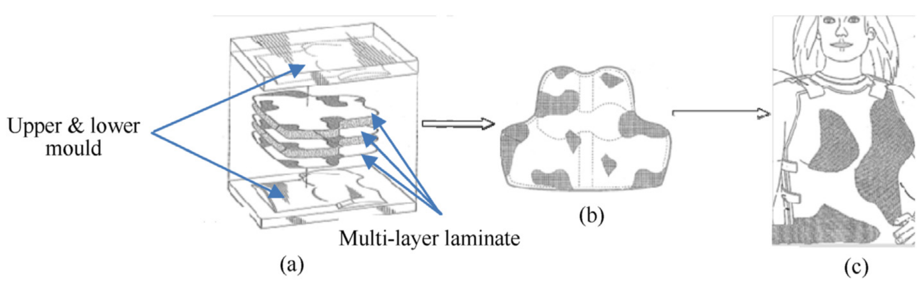


**Fig. 9.** Moulding process for developing flexible women body armour with 3D woven material [75].

out to design 2D patterns for female soft body armour seamless front panel design based on the developed adaptive mannequin (Fig. 12 (d) (e) (f) (g) [71].

Such methods mainly help to attain the required bust volume in the pattern generation process for eliminating the darts design element. The new frontal flattened pattern gives a better shape to accommodate the deformation with low distortion throughout the fabric surface while flattening. Later, a novel systematic 3D design approach was applied to generate a pattern for successive panel layer based on the first layer pattern [47] as shown in Fig. 13.

The design processes used the thickness of each layer in the 3D design database with appropriate coordinates. The armour system later developed using the developed pattern and 3D warp interlock. The moulding technique also used to develop composite riot helmet shells with reinforcing fibre continuity for better protection [77–81]. In the moulding process, the textile material possesses and considered different moulding characteristics such as surface shear angle, material thickness variation, drawing-in values and its corresponding mechanical damages [ [20]] [ [82–84]]. Still, an improvement is required in panel design and ballistic material with better moulding property.

## 4. The new possible future era materials in impact armour panel development

For the last many decade's body armour was developed using heavy and rigid materials including ceramics and steels. So, attaining better and improved ballistic performance was in the scarifications of the weight and comforts of wearers. Nowadays, introducing high-performance fibre in body armour system make it possible to achieve both soft and light weighted along with sufficient protection performance. However, the continuous changing of threat type, level and environments make it difficult to predict the future capabilities of the body armour. This phenomenon engaged the researchers to work further and developed new materials and appropriate designs [27]. Therefore, applications of various

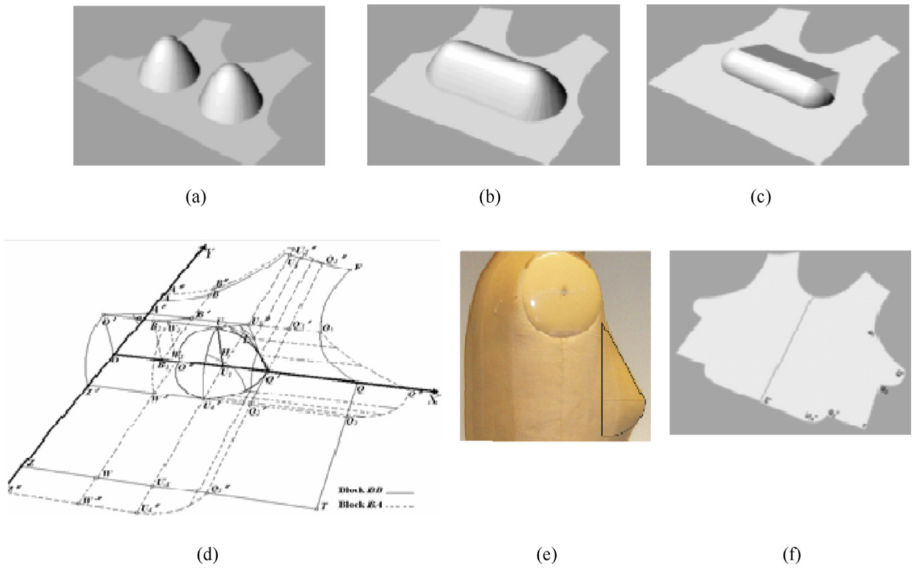

**Fig. 10.** (a), (b) and (c) different geometrically models to represent the bust area, (d) mathematical model of half front panel of the women body armour, (e) size 12 standard mannequin and (f) the developed pattern [46].

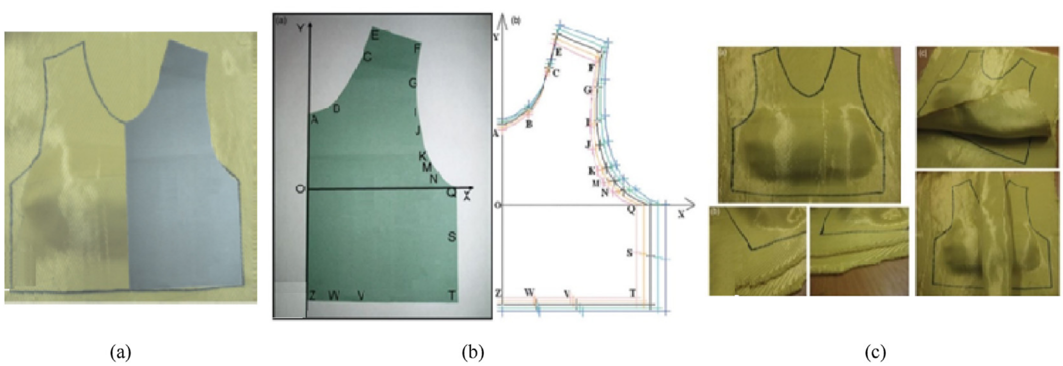

**Fig. 11.** (a) Single-layer validations (b) pattern development process for multiple layers and (c) experimental validation for multiple layers of the front panel of the female body armour using 3D warp angle interlock fabrics [69].

methods and materials including chemical treatment for surface modifications and new material development would be interesting to enhance the body armour performance at a lower weight [85–92]. The following section will discuss the different latest and promising materials which could drive the next armour milestone.

### *4.1. Applications of carbon nanotube (CNTs)*

Applications of Nanomaterials in the area of textiles are drastically growing to improve performance and create unparalleled textile functions. Nanotechnology is the process of developing and applying material, device and mechanisms to enhance significantly the physical, chemical and biological properties at their nanoscale size (0.1–100 nm) [93]. It usually provides either enhancement on the existing properties or adds new functionalities to textiles. Due to the advancements of Nanomaterials manufacturing, newly developed materials such as; Carbon Nanotube (CNTs) and Graphene CNT has been discovered and used for protection. The Carbon nanotubes (CNTs) material generally revealed unique mechanical properties, particularly in improving tensile strength and provides stronger, tougher and stiffer than synthetic fibres [94]. It also possesses high ballistic resistance, high energy absorbing capability and multi-hit resistance to develop an enhanced making ballistic armour [95]. Mostly, fabrics and composite which is reinforced by nano material depend on the surface area, volume ratio and nano reinforcement interphase characteristics. The particles might be silica, organic and inorganic, and the layered material includes graphite, whereas the fibrous material mainly involves nano-fibres and nano-tubes [6]. Carbon nanotubes (CNTs) (which is rolled as hexagonal carbon network and covered by pentagonal carbon ring) are one of the nano additives which are increasingly used with unique but supreme properties in terms of mechanical, chemical, electronic and magnetic as compared to other categories [96]. In general, such kinds of CNTs could be also come with a category of multi-walled carbon nanotube (MWCNT) and single-walled carbon nanotube (SWCNT). They are mainly produced through arc discharge, pyrolysis of hydrocarbons over metal particles, laser vaporization of graphite target, solar carbon vaporization, electrolysis of carbon electrodes in molten ionic salts etc. Various researchers have also studied the CNTs as reinforcement for body armour applications [97–101]. One of the researchers investigated the impact and bouncing-back processes performances of elastic carbon nanotubes with large radii as anti-ballistic materials. It shows better performance in projectile halting, rebounding the force instead of spreading throughout the panel and able to repel the projectile with minimum or no damage to the wearer of a

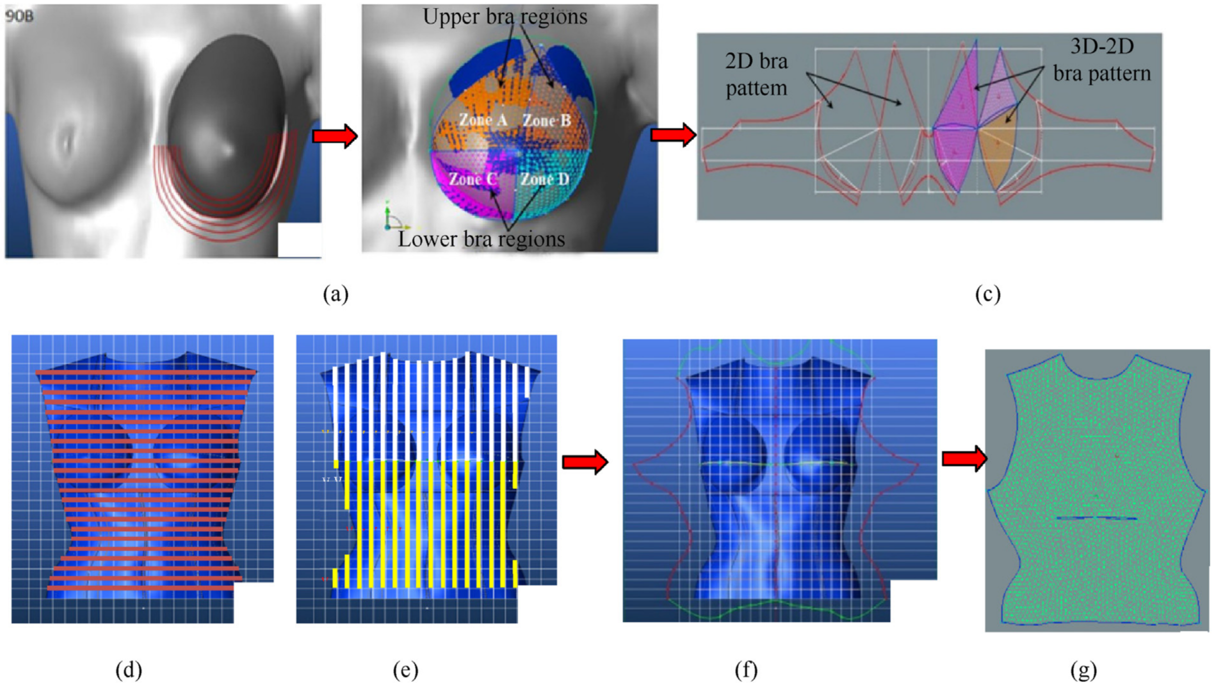


**Fig. 12.** Developing first seamless women body armour panel layer pattern (a) adaptive bust on a virtual mannequin, (b) Mesh creation on the adaptive bust for bra design, (c) well-fitted bra pattern flattening through the 3D design process (CAD Knowledge) [76], Reveres engineering pattern developing a system for generating the 1st layer of seamless female frontal soft body armour panel from the adaptive bust, (d) horizontal (e) vertical projection line, (f) projections of 3D body measurement on the horizontal and vertical projection line and (g) Flattened pattern for first layers of seamless women body armour [71].

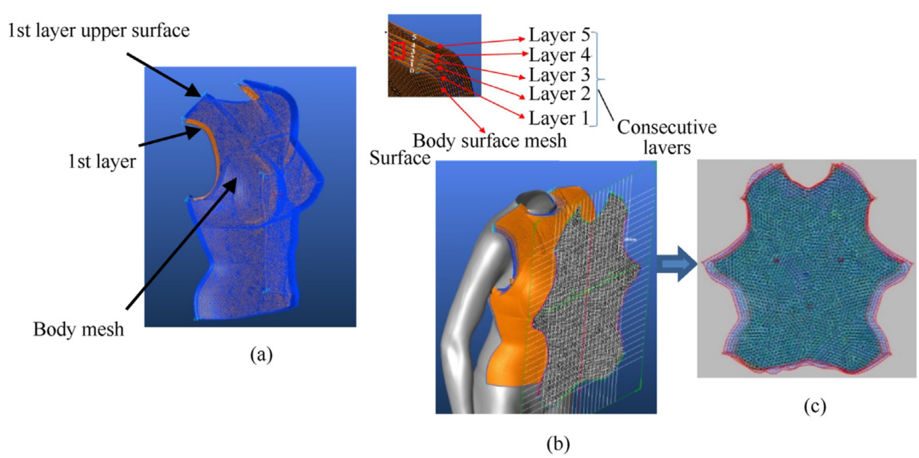


**Fig. 13.** Multilayer seamless armour pattern development (a) 3D body mesh creation on frontal virtual adaptive women body and its multi-layer panels with zoomed views of corresponding mesh (5 layers), (b) pattern block projection to projection grid for multi-layer through flattening (c) Flattened multi-layer soft body armour panel pattern [47].

bulletproof vest [102]. Another study has also developed, tested against 9 mm Full Metal Jacket projectile to investigate the influence of multi-walled carbon nanotube (MWCNT) inclusion with different weight percentage (0%, 0.1%, 0.55% and 1.0 wt %) on the energy absorption capabilities of ballistic composite panels. The composite with compositions of MWCNT greatly improves the impact energy absorption value of the panel and proportional with the epoxy/MWCNT matrix's fracture toughness properties [103]. Furthermore, the mechanical behaviour against the ballistic impact (V50) tests of E-glass fabric composite reinforced with multi-walled carbon nanotubes (CNTs) showed a higher V50 value by 11.1% and promised for the applications of blast protection due to their reduced weight and energy dissipation behaviours compare with composites without CNTs [104]. Another study has also studied the performances of CNTs in various armour composite panels with Kevlar®29 woven fabrics in an epoxy matrix against V50 test for 44 calibre soft-point rounds and 30 calibres FSP (fragment simulated projectile). The armor composite panel with 1.65 wt % carbon nanotubes and 1.65 wt % milled fibres revealed a 6.5% improvement in the V50 test results [105]. The research study also designs polymer matrix composite armour with E-glass continuous fibre poly-vinyl-ester-epoxy matrix composite laminas interlaced with multi-walled carbon nanotube (MWCNT) reinforced composite mats. Different armour panels were then designed by varying the different location and thickness of the carbon nanotube reinforced composite mats to test against FSP) for their ballistic impact performance. Based on the result, at the specified armor thickness, the position as well as the carbon nanotube reinforced composite mats thickness greatly influences the ballistic performance of the armor. For example, armor panel composites with thicker CNTs reinforced composite mats at the armor frontal face (projectile strike side) revealed best ballistic performances [106]. Similarly, the role of multi-walled carbon-nanotube (MWCNT) reinforcements in improving the ballistic-protection performance of polyvinyl-ester-epoxy matrix (PVEE)/E-glass fiber matrix reinforced laminate armor was investigated through model development approach and transient non-linear dynamics simulations of the projectile/armor interactions. In this study a hybrid armor with 100 μm-thick high MWCNT-content PVEE-matrix MWCNT-reinforced lamina sandwiched between two PVEE-matrix/E-glass mat reinforced laminas and monolithic E-glass mat reinforced composite laminate with a low MWCNT-content MWCNT-doped PVEE-matrix were investigated. According to the V50 results of projectile/armor interaction simulation, both armor systems yield a minimal (6%) increase in the ballistic protection [107].

Another recent research has also studied the effects of depositions of various micro and nano-fillers to the fibre on its ballistic impact performances and energy absorption of the hybrid laminates consisting of woven Kevlar fibre fabric, epoxy, and AA 5086-H32 aluminium sheets against NATO standards by calibre 270 Winchester rifle. The result shows that hybrid composite laminates with micro and nano-fillers deposition into the surface of the Kevlar fibres fabrics revealed an enhanced ballistic impact resistance and impact energy absorption capabilities than its counterpart laminate containing no nano-filler impregnation. Specifically, laminates deposited by aluminium powder nano-fillers gives the highest impact energy absorption capacity followed by colloidal silica and silicon carbide powder. Gamma alumina powder and potato flour addition on the laminate revealed minimum impact energy absorption capability enhancements. The researcher claims additions of micro-and nano-fillers coating on Kevlar fabrics using PEG-400 is a promising method for strengthening interfacial bonding between the matrix and fibres in hybrid composite laminates [108]. Another study also tried to use two kinds of multi-walled carbon nanotubes (MWCNTs), namely pristine MWCNT and Carboxylic acid-functionalized MWCNTs to demonstrate their effect on the ballistic behaviour of MWCNT/epoxy nanocomposites. The dynamic behaviours of the MWCNT reinforced nanocomposite such as the damping ratio showed a decreased value with the increasing of the MWCNT addition, whereas the natural frequency enhanced as MWCNT addition increased. Specifically, functionalized MWCNTs faces reductions in energy dissipation ability but increments of stiffness due to an improved interfacial bonding between the nanotubes and epoxy resin [109]. A 3.5 mm thick tiles made of hybrid multi-scale material by integrating several layers of Kevlar fabric and carbon fibre plies within a polymeric matrix reinforced by carbon nanotubes were also tested against metallic bullets fired at about 400 m/s and 1000 m/s. The results show that a thin and light tile of the designed composite material can absorb high energy impacts with local delamination of the layered structure [110]. Another study was also numerically investigated to study the ballistic resistance of the carbon nanotube (CNT) fibres reinforced composites based on the reinforcement characteristics (single fibre geometrical, fibres volume (mass) concentration and distribution). Both the finite element simulations and it's sharp nose projectile impact experimental investigation shows that the involvements of the carbon nanotube fibres in the matrix composites show a great impact on its final ballistic performances [111]. Unlike the addition of nano-reinforcements to plastics and fibres, another study investigated the effect of nano-reinforcements infusion into an epoxy layer on the ballistic performances of bi-layer armour system. Thus, one of the researchers has investigated the bi-layer panel which comprises an alumina layer and a nano-infused epoxy layer against Fragment Simulating Projectile (FSP) at V50 of 400 m/s [112]. A 0 to 1 wt% loading range of Silica nanoparticles and MWCNT were applied, and Nano-silica infused composite armour shows better ballistic properties up to 0.5 wt% loading beyond which the MWCNT infused one has better ballistic properties. As shown in Fig. 14 (a) & (b), the nano-silica infused epoxy/ceramic armour under the high-velocity impact, the maximum enhancement in the energy absorption and the ballistic limit respectively occurred with 0.5 wt % nano-silica infusion.

At this percentage, the enhancements in energy absorption and ballistic limit were observed as 67.48% and 28.7% respectively compared to neat epoxy armour. Besides, as shown in Fig. 14 (c), the MWCNT infused epoxy/ceramic armour also revealed the maximum enhancement in the energy absorption and ballistic limit at 1 wt % MWCNT infusion. At this percentage, the enhancements in energy absorption and ballistic limits were 45.8% and 19.74% respectively than neat epoxy ceramic armour.

From the different perspectives, the collective dynamics behaviours of CNT fibres were compared directly against Nylon, Kevlar, and aluminium monofilament fibres under the same supersonic impact conditions. The result shows that the kinetic energy absorption characteristics of the CNT fibres dominate all other fibres (Fig. 15 (a) - (f)). Thus, the strain-rate-dependent strengthening mechanics of an ensemble of nanomaterials is also a promising insight for the development of high-performance fibres used in body armour including its exceptional stability in various harsh environments [113].

### *4.2. Applications of shear thickening fluids (STFs) on body armour*

Shear thickening fluid (STF) is a non-Newtonian fluid, and its behaviour is usually shown by concentrated colloidal dispersions comprising of solid particles (silica, calcium carbonate, silicon carbide, etc.) in a dispersion liquid (water, polyethylene glycol, ethylene glycol, silicone oil, etc.). This helps to exhibit a sudden increase in viscosity above a critical shear rate, which transforms a liquid dispersion into a material with solid-like properties [114]. The mixture of such flowable and hard components at a particular composition results in a material with remarkable properties [115]. Thus, various studies have hypothesized and discussed the interactions of the different mechanisms of the above particle media in developing the STF systems to increase their shear rate [116] [117] [118] [119]. It also comprised concentrated stabilized dispersions of rigid sub-micrometre particles in a carrier fluid [120]. Such shear thickening fluids (STF) mechanism allows for further enhancement of ballistic resistance without hindering flexibility by the fabric impregnation process. Among the different theories, the hydro-clustering mechanism [114] [117], considered as one of the substantial and acceptable method systems to the explication of the STF mechanism and even further supported by different techniques including neutron scattering and shear rheology [119]. As shown in Fig. 16, at the equilibrium conditions, the particles were found at the state of continuous Brownian motion while and staying at random positions but persistent particle-to-particle repulsive forces. While applying an external shear force on the system, the particles have moved and align themselves along with that shear force and create some kind of ordered structure to lower its viscosity.

The shear thickening behaviour and its performance will be affected by different factors. Various researchers have studied and intensively discussed the relationship between the different parameters and their performances [42] [122] [121]. The particle size distribution, solid volume fraction, particle size, particle shape and

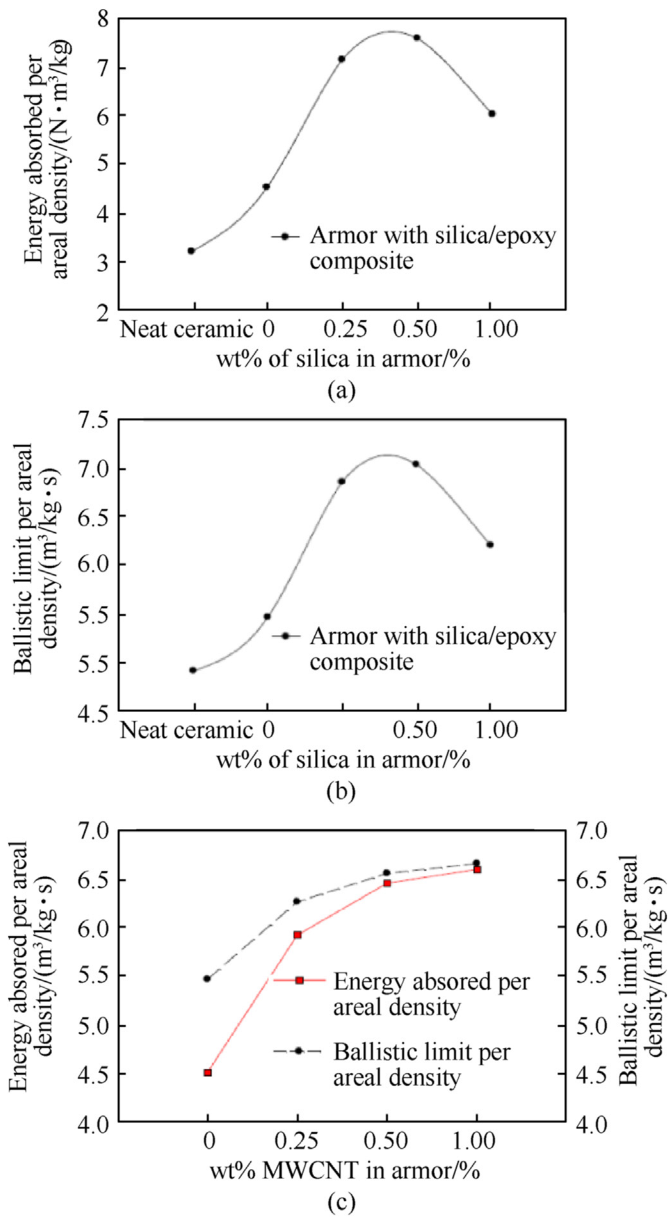


**Fig. 14.** (a) The Energy absorption and Ballistic limit per areal density for neat ceramic and Nano silica-phased epoxy composite armour, (b) Ballistic limit per areal density for neat ceramic and Nano silica-phased epoxy composite armour and (c) Absorbed Energy/Ballistic limit per areal density for MWCNT-phased epoxy composite armour [112].

particle size distribution are among the different parameters which affect the final shear-thickening performances (as shown in Fig. 17). In general, the higher solid volume fraction, lower particle size and higher aspect ratio in shape brought the shear thickening to perform at lower shear rates [122].

Considering the different remarkable property of shear-thickening fluids (STFs), it was extensively used in different applications. Nowadays, a significant performance improvement of soft body armour has been attained with the help of different advanced mechanisms including STFs. The applications of shear thickening fluid (STF) has brought a new horizon and become one of the recent mechanism used to enhance the ballistic impact resistance of soft body armour materials [123] [124]. Such an application in impact body armour has led to the development of the concept of liquid body armour [86] [125]. However, the energy absorption mechanism of STF treated textile structure still needs further investigation and quantitative verification to better understand. Various researchers in the scientific world have worked hard to apply, investigate and analyses the effect of STFs on the final performances of the body armour on different forms.

#### *4.2.1. Applications of shear thickening fluids (STFs) on material for impact performances*

Various research has investigated the application of shear thickening fluid (STF) with different viscosity on Kevlar fabrics. Most of the result shows an improvement of the overall impact energy absorption capability of the soft impact panels and composites as the viscosity of the former increases during impact [126] [127] [128] [129] [130]. For example, one of the studies has recently investigated the deformation and energy absorption modes of shear thickening fluid (STF) treated and untreated Kevlar woven fabrics against impact. The analysis revealed that, unlike treated fabrics, untreated fabrics have only involved primary yarns in impact load sharing and energy absorption as shown in Fig. 18 [131]. Thus, limited yarns involvements ultimately bring lower energy absorption as compared to STF treated fabrics, where STF has transformed the fabric into a solid-like material (for entire fabric involvement in load-bearing and energy absorption) [131].

The same researcher has also investigated the effect of process parameter (padding pressure and silica concentration) in STFs applying on the impact performances of Kevlar–STF soft composite. Table 1 shows the results of the Kevlar–STF composites impact energy absorption capability for different padding pressure (bar) and silica concentration (%). Based on the result, the impact energy absorption capabilities of Kevlar–STF soft composite were enhanced by higher STF concentration. Meanwhile, increasing the padding pressure on the STFs reduces its add-on % on the fabrics and further helps to make the final composite lighter and higher impact energy absorption of the Kevlar–STF composite. This is due to the better and uniform distribution of STF within the fabric and yarn structures. For example, an increase of 150% and 400% of impact energy-absorbing by Kevlar–STF soft composite was achieved depending on optimum process conditions and the type of Kevlar fabric [132].

Similarly, another study has examined the effects of silica concentration, padding pressure and diluent (STF ratio) on impact energy absorption capability of Kevlar (para-aramid) fabrics treated with silica nanoparticle based shear thickening fluid (STF) to achieve an optimal design of soft body armour materials. The result shows that the impact of energy absorption was significantly affected by silica concentration, padding pressure and the square of solvent ratio. Moreover, with the higher padding pressure, the improved impact energy absorption of STF treated Kevlar fabric was achieved [124]. The energy absorption capabilities under high-velocity impact between STF pre-impregnated aramid fabric and neat STF target soaked in STF in different add-on wt. % (20, 30, and 40) nano-size fumed silica particles used in polyethene glycol and ethylene glycol was also assessed [133]. Based on the investigations, even though higher fabric weave density and multi-layered target play a great role to optimize the SFT impregnated targets performance, STF pre-impregnated aramid fabric revealed higher energy absorption than dry fabric. However, the neat STF had also shown good energy absorption at velocities near STF critical shear rate. Unlike textile structure, the energy absorption and high-velocity impact performance of Poly-aramid Twaron fabric and open-cell flexible foam which is impregnated with a shear thickening fluid (STF) with a different form of friction were quantitatively studied [134]. Different wt. % (35, 40 and 45) of Silica oxide Aerosil 0X50 were employed as a suspending material and

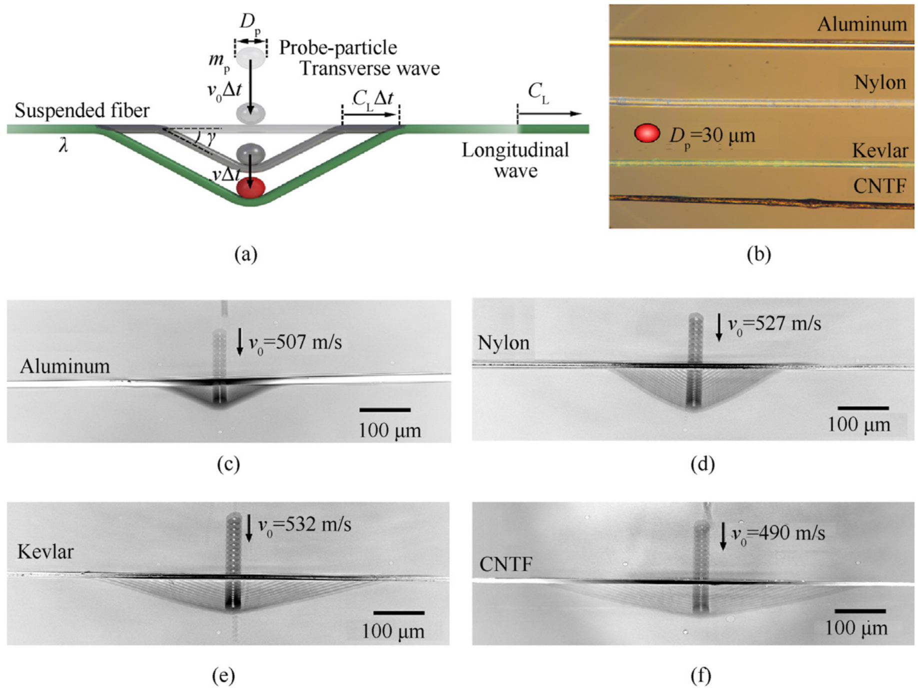


**Fig. 15.** Ultrafast stroboscopic imaging of individual fibres subjected to the supersonic transverse impact of a probe-particle. (a) Schematic of sequential deformation shapes of a fibre under a probe-particle impact. (b) Optical image of four fibres suspended in the air. The typical size of a probe particle is depicted. Femtosecond multi-exposure micrographs of (c) aluminium, (d) nylon, (e) Kevlar, and (f) CNTF showing real-time deformation of the fibres [113].

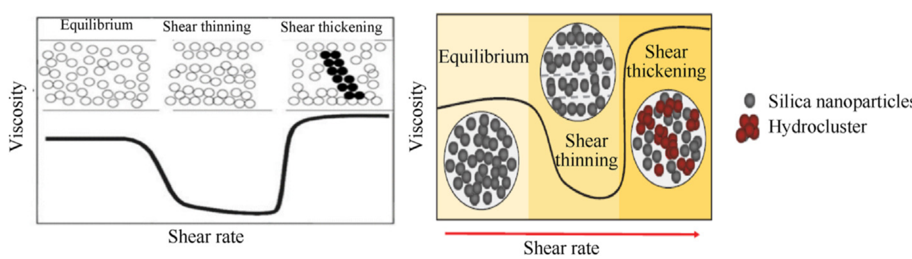


**Fig. 16.** The basic hydro cluster mechanism and its schematic representation of shear-thinning and shear-thickening forming behaviours of particle suspensions [42] [121].

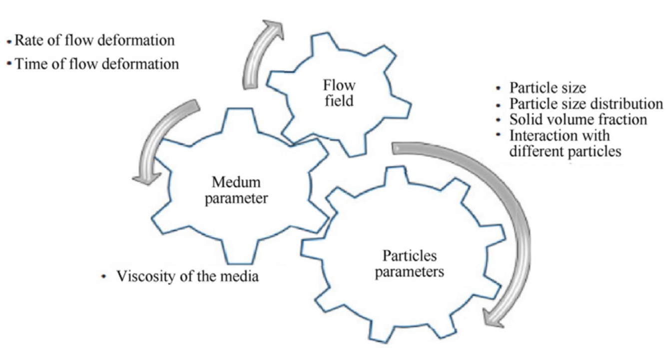


**Fig. 17.** Parameters affecting the rheological performance of STF [42].

spread-out using polyethylene glycol. Twaron fabric impregnated with STF with 45 wt % composition shows the highest shear thickening at the lower shear rate and produces a significant frictional force effect at fibre–fibre level. This helps to attain higher values for impact tests conducted at a higher rate of loading. The particle size and concentration of colloidal silica are also other parameters that could affect the final performances of STF. A research study has thoroughly investigated the influences of the STF rheological parameters of particle size and concentration of colloidal silica considering a range from 100 to 750 nm on the ballistic performance of STF as shown in Fig. 19.

According to the study result, the STF with 600 nm–67% provides improved ballistic performances by slowing down the projectile speed as shown in Table 2. However, increments of silica nanoparticles mass loading in STF beyond the limit could adversely affect its final ballistic performance [135]. Unlike applying solely for ballistic application, textile fabric (Kevlar) impregnated with shear thickening fluid (STF) using sphere silica and fumed silica particles dispersed in ethylene glycol and polyethene glycol (PEG 200) also significantly improved both stab and ballistic resistance of the fabric over the net fabrics [136]. Fig. 20 shows the photographs of neat Kevlar fabric and STF treated Kevlar fabric after ballistic resistance testing. Similarly, the ballistic responses, energy absorption and ballistic limit of a woven Kevlar fabric reinforced composite material were significantly enhanced when impregnated with colloidal shear thickening fluid (STF) made of dispersing silica nanoparticles with different wt. % loading in polyethylene glycol [137].

As shown in Fig. 21, increasing the nano-silica loading (from 15

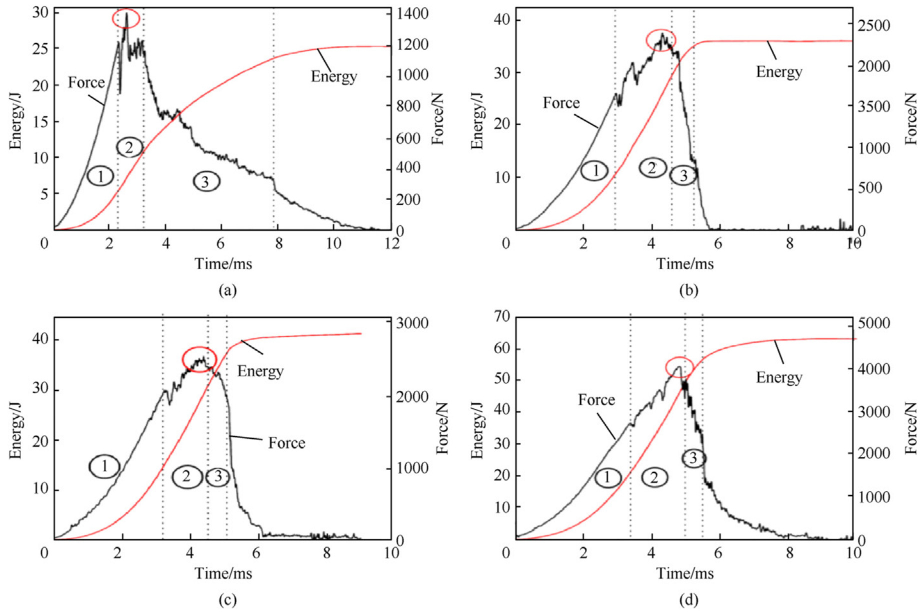


**Fig. 18.** Force generation and energy absorption graphs of untreated Kevlar fabric, and Force generation and energy absorption graphs of STF treated Kevlar fabric at (b) (50%, 2.0 bar), (c) 60%, 2.0 bar and (d) 70%, 2.0 bar [131].

**Table 1**
The ballistic impact energy absorption by Kevlar–STF composites with different padding pressure(bar) and silica concentration (%) in dynamic impact test [132].

| Padding pressure/bar | Silica concentration/% | Impact Energy/J | % increase in impact energy | Impact energy/J | % increase in impact energy |
|---|---|---|---|---|---|
| | | 200 g·m$^{-2}$ fabrics | | 465 g·m$^{-2}$ fabrics | |
| Untreated | – | 25.3 | – | 41.4 | – |
| 0.5 | 50 | 27.7 | 9.3 | 97.6 | 136.0 |
| | 60 | 31.4 | 24.2 | 112.0 | 195.0 |
| | 70 | 53.2 | 11.0 | 124.3 | 200.5 |
| 1.0 | 50 | 29.8 | 17.6 | 107.5 | 159.9 |
| | 60 | 37.1 | 46.5 | 127.3 | 207.8 |
| | 70 | 57.9 | 128.8 | 172.0 | 315.9 |
| 2.0 | 50 | 35.4 | 40.0 | 119.1 | 188.0 |
| | 60 | 40.6 | 60.3 | 140.9 | 240.7 |
| | 70 | 62.6 | 147.3 | 208.2 | 403.4 |

to 45 wt %) revealed an increment in the energy absorption capabilities of composites.

Besides, the specific energy absorption (SEA) based on the normalized areal density of the neat and impregnated fabrics revealed the SEA of 15 wt % nano-silica loading is lower compared to the neat fabric. However, 35 wt % STF/Kevlar composites show the highest and 2.3 times larger SEA than those of the neat fabric.

Unlike other researchers, one of the studies has revealed that the Shear thickening fluid (STF) impregnated fabrics brought an improved ballistic performance against impacts but its effect was not obvious at high impact velocity (e.g., 300 m/s). The study utilizes the single-ply and 10-ply neat and STF-impregnated aramid fabric panels and tested against high impact velocities (500 m/s).

Based on the investigations, the specific energy absorption (SEA) of the single-ply and 10-ply STF impregnated fabric panels was found 44.8% and 64.1% lower than that of their corresponding neat fabrics respectively as shown in Fig. 22 (a) and (b). Based on the morphological mechanisms' analysis Fig. 22(c), (d) (e) and (f)), due to the total movement constraint of the primary yarns in the STF impregnation, the bullet velocities were reduced while perforating the fabrics. Such a mechanism helps to change only from tensile to shear dominant but also increases the possibility of earlier damage and failure of the primary yarns, and reduces the pull outdistance, causing a decrease in the energy absorption [138]. Apart from 2D woven fabric structure, nowadays 3D woven fabrics impregnated with shear thickening fluid has been also involved and investigated for developing higher performance body armour [139].

For example, one of the researches has engineered five different structures of 3D woven orthogonal aramid fabrics based on binding and stuffer warp yarn ratios and treated with shear thickening fluid (STF) for soft body armour [140]. The STF treated 3D woven fabric and its corresponding net fabric were tested against the energy absorption and back face signature (BFS). Even though STF impregnation generally improved the impact of energy absorption and BFS depth as shown in Fig. 23**.** Moreover, STF treated 3D woven aramid fabrics with higher stuffer to binding yarns (revealed much better impact energy absorption and bullet resistance due to its good synergy effects of the fabric with STF. For example, STF impregnated 3D fabrics with 4:1 and stuffer to binder ratio performed the best in ballistic evaluations.

Besides the different STF parameter, the fabric count and shot location are also other factors which affect the ballistic performances of shear thickening fluid (STF) treated p-aramid fabrics. One of the studies tested fabric panels made of different counts against 9 mm bullets at 436 m/s for body armour application. Based on the result, soft body armour panel made of higher fabric count

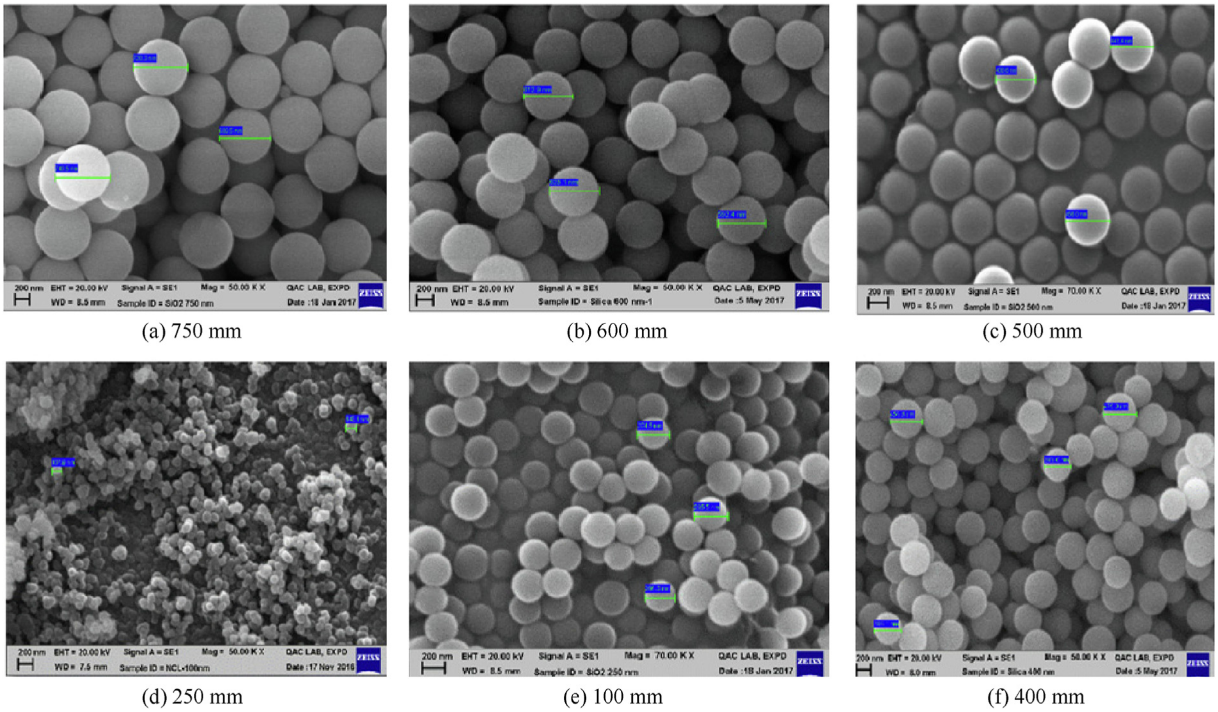


**Fig. 19.** SEM analysis of silica nanoparticles of different sizes [135].

**Table 2**
Data of the ballistic samples ([135]).

| S. No. | Sample Code | Impact Velocity /($m \cdot s^{-1}$) | Residue Velocity /($m \cdot s^{-1}$) |
|---|---|---|---|
| 1 | STF-100 nm-65% | 181.4 | 92.1 |
| 2 | STF-250 nm-67% | 182.0 | 81.3 |
| 3 | STF-400 nm-67% | 183.0 | 73.2 |
| 4 | STF-500 nm-67% | 175.0 | 68.2 |
| 5 | STF-750 nm-67% | 178.1 | 59.1 |
| 6 | STF-600 nm-67% | 169.9 | 63.2 |
| 7 | STF-600 nm-69% | 176.1 | 57.1 |
| 8 | STF-600 nm-70% | 177.1 | 53.2 |
| 9 | STF-100 nm-71% | 178.2 | 50.1 |
| | STF-100 nm-72% | 179.0 | 47.1 |
| 10 | PEG-200 | 181.1 | 160.1 |

lower speeds (<700 m/s). However, one of the researchers tried to understand the impact energy absorption characteristics of neat fabric and STF impregnated Kevlar fabric specimens at higher speeds (>700 m/s). Based on the high-speed test, STF impregnation provides substantial energy absorption enhancement in terms of volume, areal density, and fabrication material cost. For example, a 5-layer STF impregnated Kevlar configuration revealed similar specific energy absorption (SEA) as that of 8-layer neat Kevlar at a normalized level in terms of areal density and thickness. This means that STF impregnated Kevlar provides an approximately 70% enhanced SEA over neat Kevlar [142]. Besides, the above high-velocity impact experiment conducted studies have been also

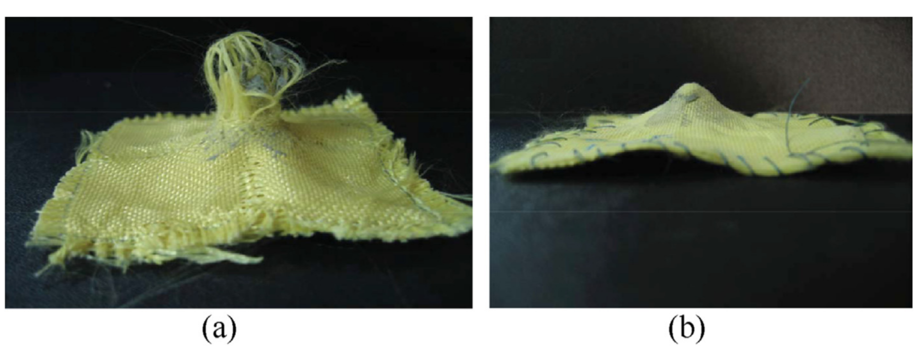


**Fig. 20.** Photographs of neat Kevlar fabric (a) and sphere silica/EG suspension treated Kevlar composite fabric (b) after ballistic resistance testing [136].

performed higher impact energy dissipation and lower BFS (back face signature). Besides, shots at the edge of the target face a higher ballistic limit value (V50), as well as the BFS value of the panels [141]. The most researcher has investigated the impact energy absorption characteristics of STF impregnated fabric specimens at the compared with the numerical result by using the commercial tool LS-DYNA [143]. Based on the experimental and numerical analysis, the friction between the impacting projectile, fabric, and yarns within the fabric during impact was found the major factor behind the energy absorption mechanism of the material. Similarly,

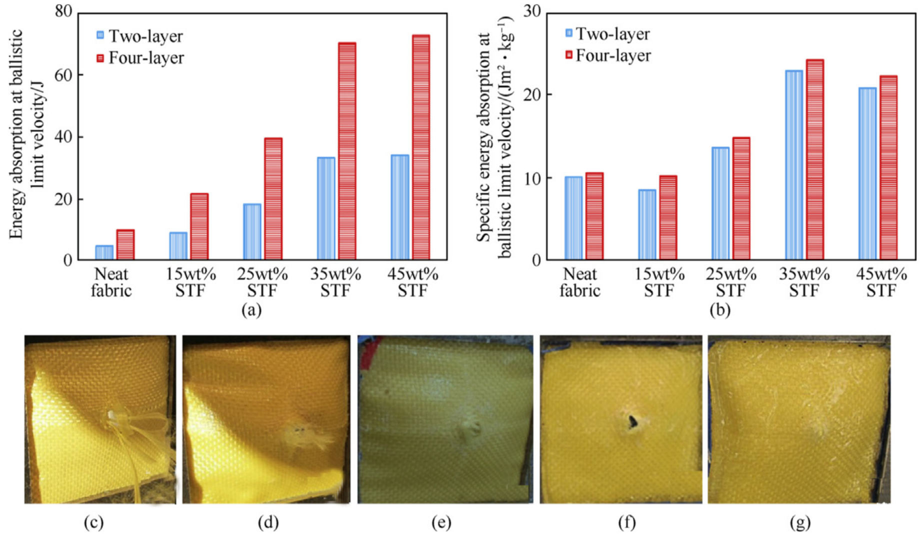


**Fig. 21.** (a) Energy absorption of two- and four-layer samples and (b) Specific energy absorption (SEA) of two- and four-layer samples, Panels in high velocity impact tests of (c) Neat fabric, (d) Impregnated fabric with (d) 15 wt % STF (e) 25 wt % STF (f) 35 wt % STF (g) 45 wt % STF [137].

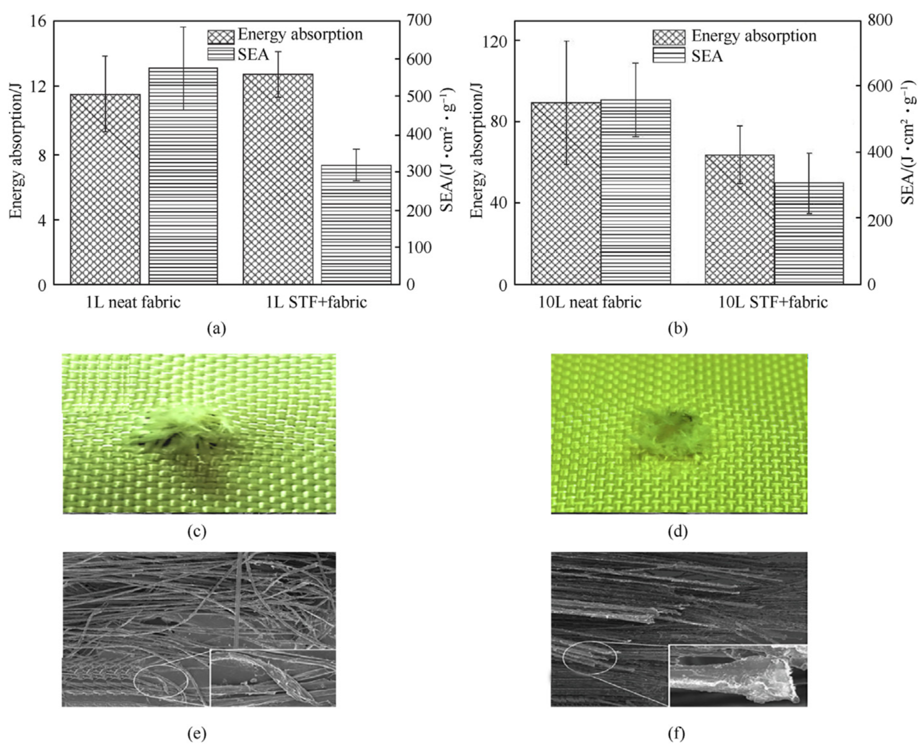


**Fig. 22.** Energy absorption and SEA at impact velocity (455–510 m/s) for (a) single-ply fabrics (b) 10-ply fabrics, and fiber damage after ballistic tests of (c) failed neat fabric, (d) failed fabric with STF impregnation, (e) and(f) are SEM images and zoomed image of the failed fibers respectively [138].

another study has also studied the effect of STF impregnation fabric with effective dispersing silica nanoparticles in a suspension, impregnating fabrics, and performing high-velocity impact experiments (>1 km/s) to compare the post-impact characteristics between neat and impregnated Kevlar fabrics. The high-velocity impact of STF-impregnated Kevlar fabric revealed differences in the post-impact rear formation compared to neat Kevlar [144]. On the other hand, the most researcher has extensively investigated the effects of Single-phase shear thickening fluids (STFs) for body protective applications. On the contrary, a study has fabricated and tested the ballistic impact performances of multi-phase STFs by adding different amount of silicon carbide (SiC) additives into silica and polyethylene glycol (PEG) based suspensions using lead-core bullets with an impact speed of ~330 m/s. The result shows that multi-phase STFs improve the ballistic performance of high-performance fabrics in comparison to single-phase STFs, however, the mass efficiency of fabrics has a loss of performance for high-velocity impact conditions [145]. Some research has also attempted to investigate numerically and computationally the potential of STF in ballistic application [146,147]. Some researcher has also

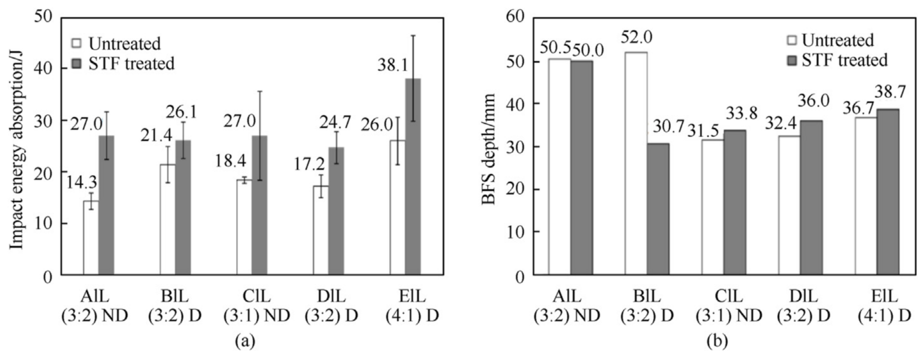


**Fig. 23.** (a) Impact energy absorption by single layer and (b) Back Face Signature for different 3D fabric panels [140].

applied STF to enhance the stab performances of the body armour panel composites [127] [148] [149]. One of the studies has prepared STF through ultrasound irradiation of silica nanoparticles dispersed in liquid polyethene glycol polymer to make STF/fabric composite (Kevlar and Nylon fabrics as reinforcement) against Knife threats and quasi-static penetration performances against both engineered spike and knife [115]. The results showed that STF impregnated fabrics have better penetration resistance as compared to neat fabrics without affecting the fabric flexibility and could be used for liquid body armour applications. Similar studies have also performed to study the stab resistance of shear thickening fluid (STF)-treated Kevlar® and Nylon fabrics [150]. With the same density, (STF)-treated Kevlar® and Nylon composites exhibit a significant improvement compared to neat fabric targets. Very recent works also presented the recent advances and future potentials of the SSG (Shear stiffening gel) and its derivatives to involve in practical applications of sensors, energy devices, damper controls, and body armors [151].

### 4.3. Applications of graphene on body armour development

Graphene, which is the basic form of all graphitic structure, is a two-dimensional (2D) crystal sheet of sp2-hybridized carbon atoms with a single layer mostly organized in a honeycomb matrix structure (Fig. 25 (a). It was first discovered around 2004 by the University of Manchester professors and presented their achievement in the science magazine [152]. It is a basic atomic monolayer building block for other kinds of graphitic materials having different geometries which can be wrapped into spherical structures (zero-dimensional fullerenes), rolled into one-dimensional (1-D) structures (carbon nanotubes, CNTs), or stacked into three-dimensional (3-D) layered structures (graphite) as shown in Fig. 24 (a) [153]. Graphene has also exceptionally high intrinsic strength and stiffness arising from the two-dimensional (2D) hexagonal lattice of covalently bonded carbon atoms.

It is considered the world's thinnest, strongest, and most conductive material in electricity and heat application. Its excellent behaviours in its thermal conductivity, physical-chemical properties, fast mobility of charge carriers, electrical conductivity, mechanical strength, lightweight behaviours, biocompatibility etc. show a great interest in various field of application [153–156]. Due to such outstanding behaviour, it has the potential to revolutionize entire industries in the field of nanoelectronics, energy generation, nanocomposites, nanomedicine and biomaterials [157–164]. Its introduction will discover new advanced materials, and many more future technologies will become realistic in the forthcoming years [154]. Recently, a great effort has been dedicated to assessing the potential applications of graphene and its oxide in the developments of body armour. Even though there is a limited study, this section will discuss the current state-of-the-art of graphene research for body armour applications. Research study has studied the ballistic tests of graphene with the steel ball (Fig. 25 (b)) and the result revealed that a layer of carbon one-atom thick can absorb blows and the pure graphene performs twice as the currently used fabrics in bulletproof vest applications. However, such high-speed projectile methods make it very difficult not only to assess and understand its toughness behaviour but also could not provide evidence of graphene's real strength.

To avoid such a problem, a group of researcher from Rice University & University of Massachusetts [165] has come with a new engineering method of miniaturized ballistics to test and describe the high–strain-rate behaviour of multilayer graphene over a range of thicknesses (10–100 nm). The study applied laser pulse to superheat gold filaments until they vaporized (as gunpowder) to fire such projectiles into 10 to 100 sheets of graphene at 3 km/s. Based on the results (as shown in Fig. 26), the single graphene sheets dissipate kinetic energy by tensile stretching of the membrane a cone shape followed by crystallographic directions at the impact point, and then by cracking outward radially. In meantime, the study suggested to use either multiple graphene layers or incorporating them into a composite structure to encounter the crack spreading. However, the penetration energy for multilayer graphene was found ~10 times more than literature values for macroscopic steel sheets at 600 m per second. Besides, the graphene quickly absorbs, and dissipate its energy effectively to halt the projectile due to its higher sound wave propagation performance, high strength, stiffness, and structural anisotropy than steel. This makes the MLG an extraordinary armour material revealing excellent impact energy delocalization under a supersonic penetration event which consumes kinetic energy from the μ-bullet while the MLG membrane sustains high dynamic tensile stress, the μ-bullet effectively experiences a higher areal density material. The thin graphene atom revealed excellent mechanical behaviours, but less performance in its hardness and transverse stiffness as compared to diamond. Besides, no research group has performed a practical demonstration regarding the transformation of multilayer graphene into diamond-like ultrahard structures. However, a group of researchers from the University of New York [166] has developed two-layer graphene (graphene foil) on SiC(0001) which exhibits higher transverse stiffness and hardness. The material is 1000 times thinner than a single hair but shows an excellent protective resistant toward perforation with diamond tips upon indentation.

Moreover, the two-layer graphene film even converts into a diamond-like film upon compression to produce a change in both elastic deformations and sp2 to sp3 chemical. However, the researcher also discovered that both experiments and theoretical calculations, exhibits such reversible phase change did not work for

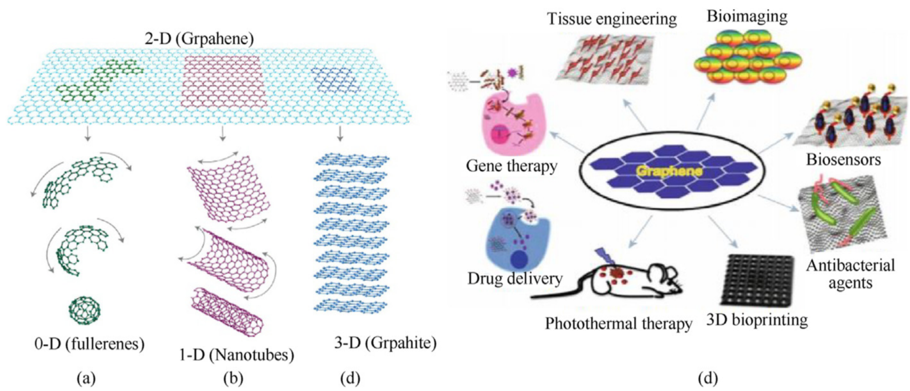


**Fig. 24.** Mother of all graphitic forms, Graphene is a 2D building material for carbon materials of all other dimensionalities with (a) wrapping up into 0D buckyballs, (b) rolled into 1D nanotubes or (c) stacked into 3D graphite [153] and (d) Graphene application on Biomedical field [154].

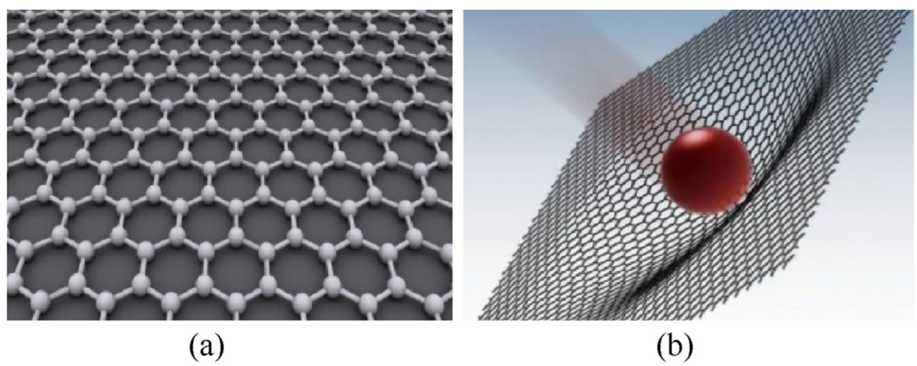


**Fig. 25.** (a) Graphene structure and (b) miniature ballistic tests by firing tiny silica spheres at sheets of graphene [165].

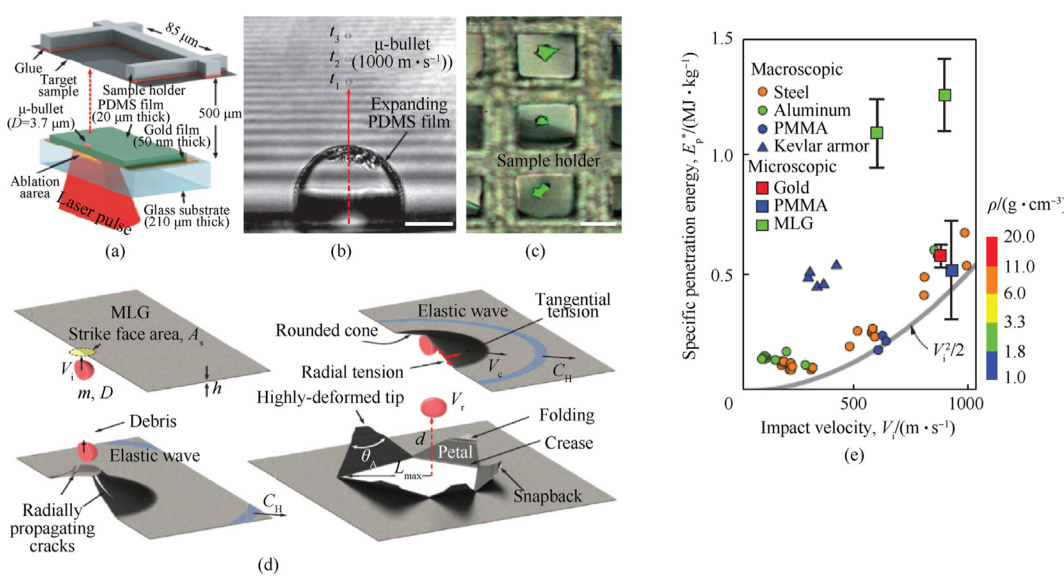


**Fig. 26.** The micro ballistic experiment. (A) Scheme of the experiment. (B) Side-view image of a moving μ-bullet taken by triple exposure at time steps $t_1$ to $t_3$. (C) MLG membrane on a sample holder after a-LIPIT with 3 separate impact test regions (green backlight). (D) Schematic illustration of penetration steps: (i) pre-penetration stage; (ii) conic deformation stage; (iii) fracture stage; and (iv) post penetration stage (film morphology) after penetration and relaxation. (E) Specific penetration energy of MLG, PMMA, and gold membranes compared with macroscopic materials at various impact velocities [165].

either thicker graphene films (three to five layers) or a single SiC buffer layer due to higher thickness deters the phase transformation as shown in Fig. 27.

The research also proposes the two-layer graphene film could as a flexible protective coating placed on top of body armour for enhancing its strength. Recently, researchers become more interested and greatly involved to further investigate and understand the extraordinary properties of graphene against ballistic impacts.

One study has tried to predict the penetration resistance of multilayer graphene membranes under uniaxial tension based on analytical *ab initio* density functional theory calculations. Their prediction confirms that continuous graphene membranes perform extraordinary performance on penetration at masses up to 100x lighter than existing state-of-the-art barrier materials [167]. Another study also investigated the quasi-static and dynamic loading responses of multilayer graphene/polyvinyl alcohol (MLG/PVA) and compared them with pure PVA and aluminium (having equal areal mass). The MLG/PVA was produced with 10 μ m thick films, reinforced by 35 vol % MLG and 85 $mm^2$ through graphene liquid exfoliation followed by filtration of the MLG/PVA dispersion. The MLG/PVA films revealed a 50% higher ballistic limit and twice Young's modulus than Aluminum films and pure PVA respectively. On contrary, MLG/PVA shows lower tensile strength and higher load carrying capacity compared to Aluminum films [168]. Another study has also proposed a multi-layered graphene–polyethylene nanocomposite as a lightweight and energy-absorbing material [169]. To strengthen the current investigations values of graphene under impact operations, a recent study has suggested a combined numerical and analytical modelling system. The study involves reactive molecular dynamics for ballistic tests on single, double, and triple-layered graphene sheets at experimental velocity values in their numerical modelling. Thus, both simulations and experiments agree that as the layer number (N) increases (from ~15 MJ/kg for N = 1 to ~0.9 MJ/kg for N = 350), then the specific penetration energy decreases [170]. Another study has also fabricated graphene-based nanocomposites with polyester resin matrix doped in pristine few-layer graphene (FLG) and reinforced with glass fibre fabric (FGRP) with 0.25% and 1% w/w doping percentages range. The impact test against 7.62 × 51 mm NATO Ball ammunition & $V_0$ (NATO STANAG 2920 standard) shows that an increment of doping percentage graphene raises its Vo values (reach 266.4 m/s at 1% w/w), which is 72.2% improvement as compared with non-doped FRGP laminate. Besides, the graphene doped samples (graphene-based nanocomposites) revealed better tensile and impact properties and claimed to be a promising research area for developing a new generation of body armour systems with better protection levels in terms of ballistic performance and comfort [171]. Researchers have also involved derivatives of such materials with the existing body armour to enhance its performances. The effect of graphene nanoplatelets (GnPs) with different wt. % (0%, 0.25%, 0.50%) on the ballistic performance of Kevlar/Cocos nucifera sheath-reinforced epoxy composites was investigated. Nine- and 12-layered laminates were fabricated with different numbers of Kevlar and Cocos nucifera sheath plies. Based on the result, the addition of GnPs improved the energy absorption by 8.5% (nine plies) and 12.88% (12 plies) and the ballistic limit by 4.28% (nine plies) and 6.17% (12 plies), respectively at 0.25 wt %. However, hybrid Kevlar/Cocos nucifera sheath/epoxy/GnP composites and Cocos nucifera sheath/epoxy/GnP laminated composites decreased the energy absorption and ballistic limit after the addition of GnPs due to GnPs addition improved the interfacial interactions between the fibre and GnP modified epoxy matrix, which is inappropriate to absorb and dissipate the kinetic energy of the projectile [172]. Another research also used graphene oxide (GO) reinforced Twaron® fabric to improve the ballistic properties of the material. The results show a better resistive force of the two filtrations GO coated fabric, up to 50%, when compared to the plain as-received fabric while subjected to ballistic tests with 9 mm ammunition [173].

## 5. Conclusions

It is very challenging to improve simultaneously protection and comfort while developing body armour. Either the comfort or weight of body armour will be sacrificed to maintain better protection or vice-versa. Many researchers, engineers, armour developers and manufacturers have worked very hard to challenge such problems and bring innovative solutions based on various parameters. The current paper critically reviews and gives a detail discussion to understand the various armour panel designs, specifically for women, and the present and future era armour materials.

The different researcher has proposed various armour design techniques specifically used for women body, such as cut-and-stitch, folding and overlapping, moulding etc. All the designing techniques shows their advantages and disadvantageous in the final performances. For example, cut-and-stitch brought the weakest point on the stitch line and discomfort around the dart due to accumulations of fabrics. Fabric folding and overlapping also revealed some limitations on performance due to material discontinuity and weak stitching area around the folded materials. On contrary, moulding techniques gives produces the required

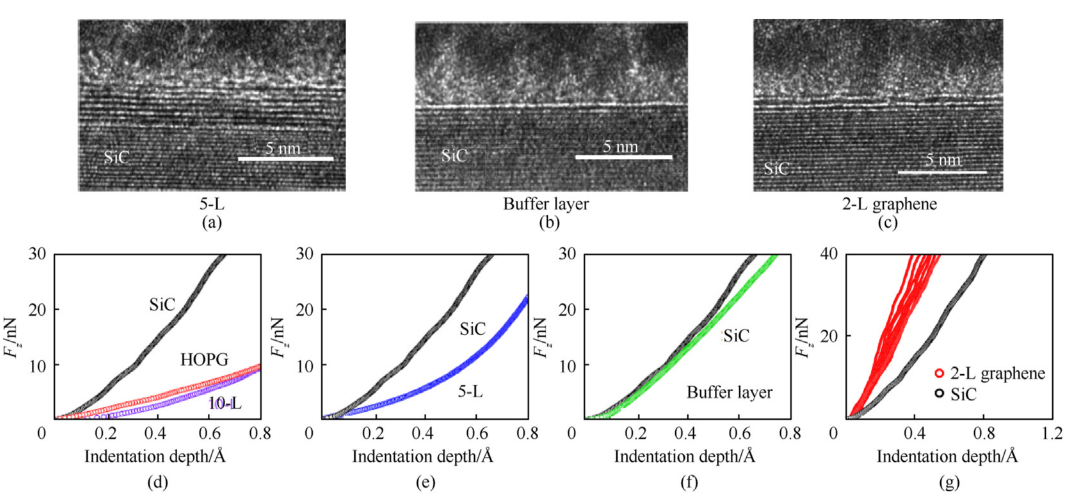


**Fig. 27.** TEM images of (a) 5-L graphene on SiC (0001) (b) the buffer layer on SiC (0001), (c) 2-L epitaxial graphene on SiC. Scale bar, 5 nm, and Indentation curves of (d) SiC, HOPG and 10-L graphene on SiC (000−1), (e) 5-L graphene on SiC (0001), (f) the buffer layer on SiC (0001) and (g) 2-L epitaxial graphene (red) and SiC (black). For 2-L graphene, curves were acquired at different positions on different samples [166].

frontal dome to accommodate frontal body shape without involving other designing techniques, such as dart. However, the method needs both unique designing techniques and proper materials with better performance and moulding ability to accommodate the shape. In general, the impacted body part should be properly fitted, or panels should be designed to lie on the specific body to provide good protection. Thus, well-fitted body armour will give the wearer not only comfort and fit but also secure and enhanced protection while instant impacting.

Apart from proper armour design, developing and using appropriate material which is strong and lightweight is also another critical parameter for body armour protection and comfort. Researchers have invented different materials and finishing methods to obtain enhanced protection without compromising comfort. For example, high-performance fabrics development has advanced body armour technology and improved ballistic performance while maintaining flexibility. Furthermore, recent research studies have agreed that impregnation of shear thickening fluid (STF) with different parameters (nanoparticle characteristics and rheological properties) on the traditional ballistic fabric further enhanced the stab, puncture and ballistic performance without hindering flexibility of the fabric. For example, fabric treated with STF revealed better involvements of primary yarns in impact load sharing and energy absorption's during the impact process compared with non-treated fabrics. However, the degree of its effects influenced by the padding pressure, STF rheological parameters (concentration, solvent ratio, particle size. The involvements of carbon nanotube (CNT) fibres reinforced composites based on different reinforcement characteristics on the ballistic protection was discussed. Both the numerical and experimental investigations show that the involvements of the carbon nanotube fibres in the matrix composites show higher ballistic resistance, high energy absorbing capability and multi-hit resistance which makes it a suitable material for making ballistic armour. The CNTs possesses such performances not only by halting the projectile but also by rebounding the force instead of spreading throughout the panels. The involvements of CNTs with different weight percentage (%), thickness, positions etc. of greatly influences the ballistic performances of the armour panel. Apart from its wide application, recent experimental and computational investigations on the behaviour of graphene under impact conditions have been exploited. The graphene quickly absorbs and dissipate its energy effectively to halt the projectile due to its higher sound wave propagation performance, high strength, stiffness, and structural anisotropy. Based on the investigations, the Graphene-based nanocomposites was found as rising star materials which greatly opens a promising research field in the design of a new generation body armour systems with not only excellent ballistic resistant but also lightweight and comfort for law enforcement, security and military defence forces personnel.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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