Chapter 7
Shear Thickening Fluid–Based Protective Structures Against Low Velocity Impacts

Unsanhame Mawkhlieng, Mukesh Bajya, and Abhijit Majumdar

7.1 Introduction

The application of shear thickening fluid (STF) for protective structures has been researched extensively in the past couple of decades [1–5]. Specifically for textile structures intended for low velocity impact applications, STF has been found to be advantageous on many occasions [6, 7]. STF is a category of non-Newtonian fluid that hardens temporarily upon being impact. The opposite of quicksand, STF responses to sudden impact by forming a clustered mass that can resist and absorb the impact energy. This unique behavior of the fluid prompted researchers at the University of Delaware and the US Army Research Laboratory to explore its suitability for impact application [8, 9]. Since the use of STF with Kevlar® fabric revived in 2003 in the University of Delaware, many researchers have explored the possibility of a commercially feasible "liquid" armor [10]. Shear thickening is a triggered and reversible phenomenon, which means that under normal circumstances, STF does not affect the stiffness of the fabrics. STF has been studied extensively and a series of hypotheses have been proposed as an

U. Mawkhlieng
Department of Textile Design, National Institute of Fashion Technology Shillong, Shillong, India

Department of Textile and Fiber Engineering, Indian Institute of Technology Delhi, New Delhi, India

M. Bajya · A. Majumdar (✉)
Department of Textile and Fiber Engineering, Indian Institute of Technology Delhi, New Delhi, India
e-mail: majumdar@textile.iitd.ac.in

S. Gürgen (ed.), *Shear Thickening Fluid*,
https://doi.org/10.1007/978-3-031-25717-9_7

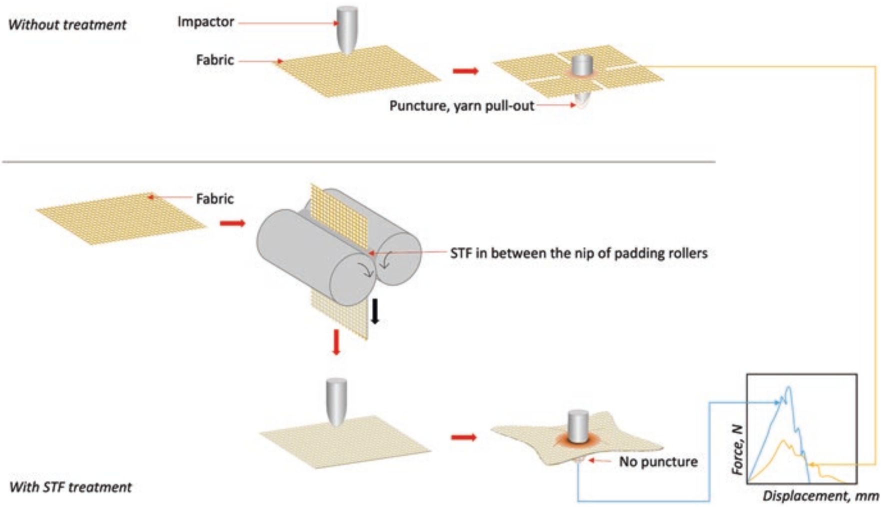

Fig. 7.1 A typical protocol adopted for impact test of (**a**) neat; (**b**) STF-treated fabrics

explanation to this reversible phenomenon of shear thickening. Several reviews [11–15] have been put forth to consolidate the works that have been carried out in the exploration of STF as a novel fluid as well as in its application for stab and impact resistances.

A quick overview explaining the common methodology of energy absorption assessment is presented here. Fabrics are treated with STF and then subjected to impact, the speed of which can vary significantly. The most followed protocol is depicted in Fig. 7.1. Most of the works report the behavior of STF-treated fabrics against low velocity impacts in the form of a drop tower test. In essence, an indenter or impactor in the shapes of knives, spikes, needles, blunt impactors, and flat impactors is made to fall from a certain height, carrying a certain amount of potential energy. The fabric that is placed at the bottom of the indenter absorbs much, if not all of its energy. The energy absorbed is then recorded. Sometimes, researchers present the values in terms of specific energy absorption which is a weight normalized figure. For higher velocity impact test by a projectile or bullet, the experimental setup is different. The target is usually placed at a certain distance away from the source of impact, usually separated by a velocity measuring system (VMS), say entry VMS. When energy absorption is considered, then another set of system, say exit VMS is placed after the target. On the other hand, when the behind armor blunt trauma (the indentation that occurs behind the armor if the bullet is stopped by the target) is assessed, then only the entry VMS is present. A representation of the test setups is shown in Fig. 7.2.

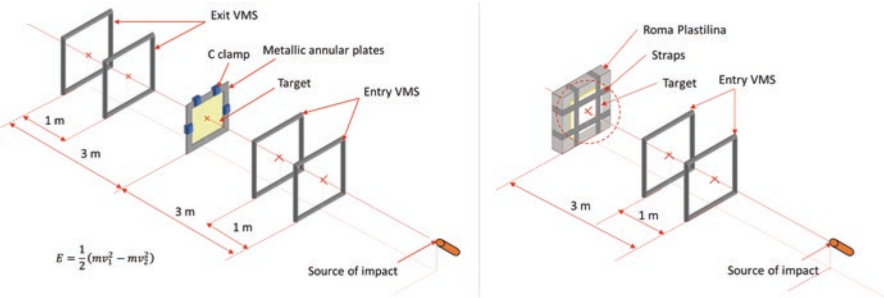

Fig. 7.2 A typical setup of a ballistic test for (**a**) exit velocity or energy absorption; (**b**) back face signature evaluation

7.2 Approaches to Improve the Energy Absorption of STF-Treated Structures

Researches have stretched in different directions with the sole purpose of improving the performance of STF-treated structures either in terms of energy absorption or reduction of weight and stiffness for a given level of performance. An extensive literature survey [16–21] reveals that the entire research is broadly concentrated in two different directions. Some works focus on improving the energy absorption capacity of the STF itself, while others, on enhancing the combined effect of STF and the structure in which it is integrated. Figure 7.3 depicts the different approaches that pertain to the use of STF-based protective structures against low velocity impacts.

In the first approach, some noteworthy steps that have been taken with the intent to tune the rheological behavior of the STF include the following:

1. Varying the contents of the fluid, either the dispersed phase (solid phase) or the dispersion medium (liquid phase). Here, either the contents are changed altogether, or the quantity of the content is altered.
2. Mixing two or more solid particles, either of the same material but with different sizes, or of completely different materials.
3. Introducing "foreign" additives in addition to the usual contents of the fluid to improve the "peak" viscosity. These foreign additives are either in the nano- or micro-scale.

In the second approach, the structure, mostly fabric, is modified to improve its overall energy absorption behavior after its treatment with STF. In this domain, several steps have been explored majorly aiming at optimizing the interaction of the fabric structure with the STF. Some of the approaches reported in literature include the following [22–24]:

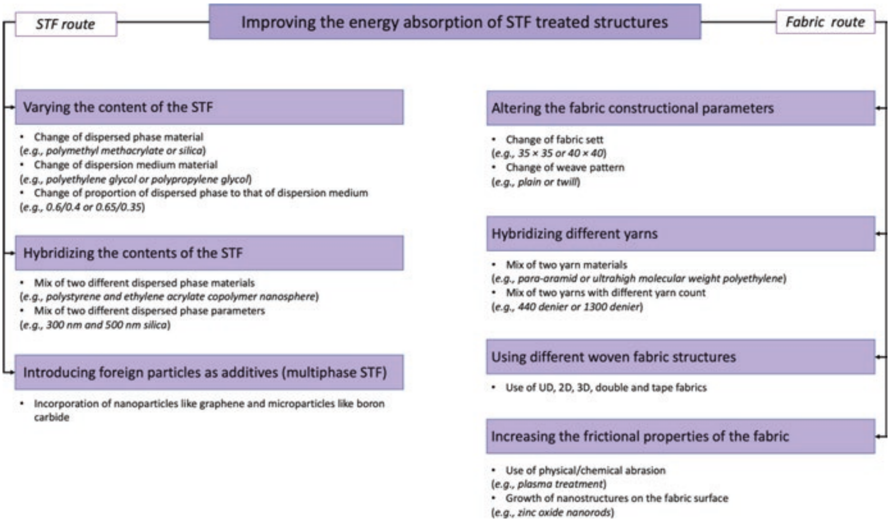

Fig. 7.3 Approaches to improve the energy absorption of STF-treated structures

1. Altering the fabric construction through parameters such as fabric sett (ends per inch and picks per inch) and weave pattern, which by extension, alters the areal density and the porosity of the structure.
2. Hybridizing different yarns, either of the same materials but with different parameters (mostly, yarn count) or of different materials altogether.
3. Exploring structure other than the conventional 2-dimensional (2D) fabric, such as unidirectional (UD), double, and 3-dimensional (3D) fabrics.
4. Increasing the internal friction of the fabric through physical and chemical roughening such as plasma treatment, or through the growth of nanostructures on the fabric surface.

7.2.1 STF Route

7.2.1.1 Varying the Content of the STF

Rheological properties of STF can be modified by changing the constituent parameters of the dispersed phase or dispersion medium or by varying the ratio of the two [25–27].

Rheological properties of STF are modified by changing the dispersed phase of the STF or the parameters thereof. Researchers have explored various materials such as silica (SiO_2), polymethylmethacrylate (PMMA), and polystyrene-ethyl acrylate nanoparticles as dispersed phase. Each particle type is expected to cause a different response in the flow behavior of the fluid due to the change in the interaction between the two phases in the STF. In fact, several research works show that when a fabric is treated with different STFs, their response to low velocity impact is different. In general, the low velocity impact response depends on two factors: (1) types of particles and (2) types of low velocity impact. As far as particle type is concerned, the major deciding factor is particle hardness [28, 29]. Several review articles [12, 13, 30] have briefed about this aspect. However, the role of particle hardness seems to be relevant when the impact velocity is low and when the type of impact is knife-stab, involving severing of the structure. This is seen in the work of Gong et al. [31, 32], who found that for puncture type of impact involving major yarn pull-out, the fabrics treated with harder SiO_2-based STF did not perform better than those treated with softer polystyrene-ethyl acrylate based STF. Here, the role of fabric friction comes to play, and it is observed that those fabrics with the most internal friction, as estimated through tests such as yarn pull-out, tend to absorb higher puncture energy [31].

Shear thickening has also been tuned by changing the dispersion medium, keeping the dispersed phase constant. This aspect has been concisely reviewed by Gürgen et al. [12] and Mawkhlieng and Majumdar [11] in their respective progresses. A general understanding that emerges from the conclusion of different studies is that the dispersion medium not only "carries" the dispersed phase, but also has an interactive effect on the rheological behavior of the STF. In general, the study of Gong et al. [31] shows that a low viscous, low molecular weight medium is preferred to form the STF. This is probably because with the lower molecular weight medium, the trigger time for the STF to shear thicken is longer which is compatible with low velocity impacts. Additionally, the distribution of the dispersed phase is uniform and the level of penetration of the fluid inside the fabric structure during treatment through the process of padding is expected to be enhanced when the viscosity of the carrier fluid is least. However, a balance between low viscosity for ease of handling and high viscosity for better shear thickening must be maintained. Hence, the result from this study suggests the use of ethylene glycol instead of polyethylene glycol of higher molecular weights, at least for knife and stab impact conditions comparable to their work.

The proportions of dispersed phase and medium are changed by altering the solid fraction, the effect of which on the rheological behavior of STF is well grounded and documented. Hence, this aspect is not discussed in this chapter. However, a different but crucial perspective to note here is that the major contributing factor is the "volume fraction" and not "weight fraction." Since the same level of STF viscosity is achieved with much lower solid fraction (<20%) when fumed nanoparticles SiO_2 are used than when solid SiO_2 submicron particles (~65%) are used supports this logic.

7.2.1.2 Hybridizing the Content of STF

Hybridization of different dispersed phases is not readily available in literature. This is probably an extension of the knowledge gained from varying the properties of the same dispersed phase within the same STF. When the same dispersed phase, say SiO_2 is varied in terms of size, for instance, and mixed to form an STF, the shear thickening propensity reduces. In fact, when the difference between the particles is largely varied, shear thickening almost ceases to occur altogether. Hence, the exploration of combining two types of dispersed phases is of little interest to the research fraternity working in the domain of increasing low velocity impact resistance of structures through STF treatment. However, there are a few reported papers working in this area. For instance, in a unique approach, a different form of hybridization of the dispersed phase is explored by Son et al. [33] who prepared a special spherical particle of polystyrene surrounded by a poly (2-hydroyethyl methacrylate) shell. It is also claimed that this STF with polystyrene to poly (2-hydroyethyl methacrylate) ratio of 4:1 produces higher viscosity than equivalent polymer-based STFs. Such an STF ought to be researched further to check its applicability in real-life impact resistance applications. However, as of the day, the application of this STF has not been reported. The same authors have also developed an STF from the colloidal suspension of polystyrene-poly (acrylamide) and polystyrene-poly (2-hydroyethyl methacrylate) particles dispersed in ethylene glycol. Synthesized by emulsion polymerization method, this STF is again reported to exhibit enhanced shear thickening due to the presence of abundant hydrogen bond donor groups of polystyrene-poly(acrylamide) [34]. Chen et al. [35] also explored this approach of hybridizing two different dispersed phases using polystyrene and ethylene acrylate copolymer nanosphere in a suspension of ethylene glycol. Unfortunately, in both the works, the prepared STFs were not yet explored as energy-absorbing supplements in high performance fabrics for impact or stab resistance applications.

Hybridizing two variants of the same dispersed phase was explored by Mawkhlieng and Majumdar [36] who mixed two different sizes of SiO_2 in polyethylene glycol. As reported by Alince and Lepoutre in 1983 [37] also, the authors found that the mixture of widely different particles works against the purpose of achieving a high peak viscosity STF. Although the STFs prepared glaringly displayed weak shear thickening, the authors extended their study to observe the applications of such STFs through a drop tower experiment. As expected, the study revealed that those with only one type of dispersed phase in them suit the application better.

7.2.1.3 Introducing Foreign Particles as Additives

Hybridization by adding an extra foreign constituent to a “regular” STF has been explored thoroughly, if not systematically. Several additives, mostly nanoparticles and nano and micro fibers such as halloysite nanotubes, graphene, graphene oxides, graphene nanoplatelets, and carbon nanotubes, and microparticles such as boron carbide, silicon carbide, and aluminum oxide have been reported [38–42]. Such STFs are frequently referred to as multi-phase STFs. However, the flow behavior of multi-phase STFs varies based on the additives, a trend that is not understood to this day. This is probably due to the lack of a thorough and systematic experimental investigation. However, a few pioneering works surfacing the last 5 years or so are worth mentioning. For instance, Gürgen et al. [39, 43] studied the effect of carbide microparticles on the rheological behavior of STF. The results follow a similar logic of hybridizing two variants of the same dispersed phase, probably because the interparticle interaction in the STF is predominantly physical and not chemical. Hence, when the amount of carbide microparticles and particle size are increased, shear thickening reduces or almost ceases to appear. It is important to remember that the overall viscosity may be amplified when the amount is increased due to the general upsurge in solid content; however, when the viscosity versus shear rate curve is studied, it is seen that the sudden "jump" in viscosity or the characteristic discontinuous shear thickening rapidly diminishes. Gürgen et al. [39] describe this intensity of viscosity rise as thickening ratio, defined as the peak viscosity divided by the viscosity at critical shear rate. Gürgen and Kuşhan [44] furthered the experiment to investigate if such STFs would be practical for impact applications. The results show that the performance of STF-treated fabrics improves since the depth of penetration of knife and spike reduces with the presence of silicon carbide additives. While the outcome of the study shows improvement in performance, the scarcity of research suggests that this approach is yet to gain acceptance and popularity. The present authors anticipate the imbalance between increased performance and cost as one of the major causes that limits the research in this direction. However, more in-depth studies are important to arrive at any tangible conclusion.

The additives in the nanoscopic range have been explored more elaborately; however, the results vary widely. Largely, there is a lack of understanding on how these additives supplement the STF. It is understood that the rheological response of the fluid is influenced by many other factors other than the mere presence of the nanoparticles itself. The major factors that are often not accounted for are the inevitable increased in solid content, the effect of particle shape and size, and the interaction with the STF itself. Since it is complex to isolate the effect of each parameter, therefore, the increased in viscosity of STF upon inclusion of nanoparticles cannot be fully attributed only to the increased surface area of interaction, although this may be one of the major contributors. Further, the study of such STFs is often limited to their flow behavior although a few have explored beyond. Laha and Majumdar [45] studied the flow behavior of halloysite-reinforced STFs and the application thereof against low velocity drop tower impact. The results favored the use of the novel multi-phase STFs as expected since the STFs compounded with halloysite exhibited higher viscosity. The authors also hypothesized that the presence of the halloysites shorten the distance needed to be travelled by the particles to cluster and shear thicken. Similarly, Mawkhlieng and Majumdar [46] conducted an experiment exploring the use of graphene nanoplatelets, while keeping the overall solid fraction of the STF constant. As the amount of graphene nanoplatelets increased, the amount of SiO_2 originally present in the neat STF was adjusted accordingly. It is reported that the viscosity increased substantially when the nanoparticles were present and that the fabrics treated with more "viscous" STFs showed better energy absorption. In fact, when the panels were made and subjected to a bullet impact of higher impact speed (~165 m/s), the panels treated with the multi-phase STFs outperformed those that were not. As discussed in Sect. 7.2.1.1, the volume fraction played a major role here since the bulk density of graphene nanoplatelets is relatively lower. A simplistic representation of different types of STFs is shown in Fig. 7.4.

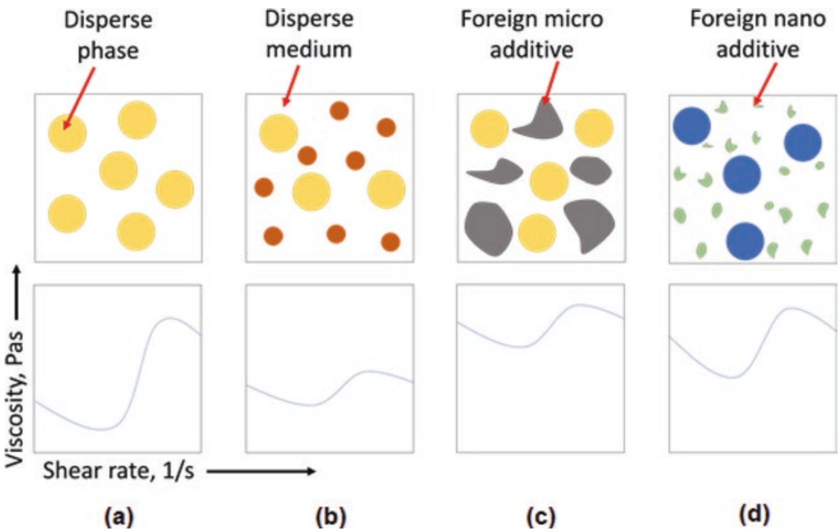

Fig. 7.4 Varying and hybridizing the solid content of STF. (**a**) Mono dispersed phase; (**b**) two variants of the same dispersed phase; (**c**) microscopic additives; (**d**) nanoscopic additives. Below each representation is the corresponding typical rheological behavior

However, the major question that is left unanswered is whether this positive response of multi-phase STF-treated fabrics is a mere consequence of the rise in viscosity or does the presence of the nanoparticles physically contribute to anything. A study in this direction is important as it will justify the use of nanoparticles which are generally expensive and toxic.

7.2.2 *Fabric Route*

7.2.2.1 Changing the Parameters of the Fabric

Altering the structure of the fabric by varying the fabric sett and weave are the common approaches that researchers have resorted to in order to maximize the energy absorption. Much work has been dedicated to fabric structure in isolation as well as its effect with STF. A detailed analysis of fabric sett was done by Arora et al. [22] experimenting on ultra-high molecular weight polyethylene (UHMWPE) fabrics. From this study, an important conclusion is drawn highlighting the interactive effect of STF and fabric structure. It is then understood that STF treatment on a high performance fabric is beneficial only when the fabric conditions are favorable. Until that time, the general practice for researchers is to procure commercially available *p*-aramid fabrics and then treat them with STF. However, Arora et al. [22] showed that STF depicts positive effect when the sett is such that the fabric is neither too tight nor too loose. In fact, Laha and Majumdar [47] had shown prior to this that

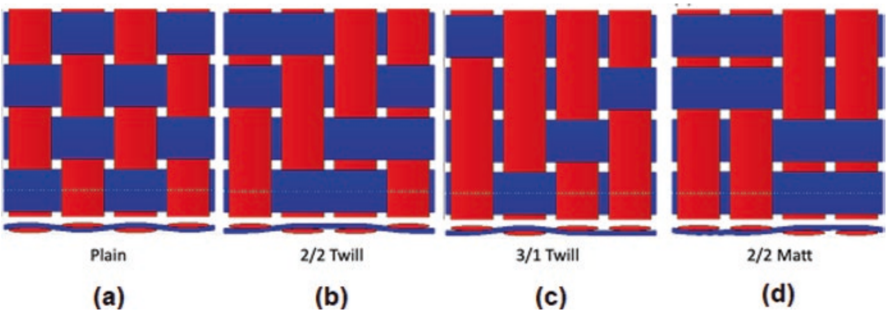

Fig. 7.5 Fabrics with: (**a**) plain; (**b**) 2/2 twill; (**c**) 3/1 twill; (**d**) matt weaves

STFs lose their effectiveness when the fabric structure is jammed. Similarly, in the works of Mawkhlieng et al. [36] and Bajya et al. [48], two grades of Kevlar® fabrics are often explored: one low sett Kevlar® 802F and the other high sett Kevlar® 363. It is often observed that the percentage increment in energy absorption from untreated fabric to STF-treated fabric is substantially large in the case of Kevlar® 802F.

The effect of weave is also expected to be significant since fabric weave alters the openness or looseness of the structure (Fig. 7.5), even when the fabric sett is constant. The effect of weave has been discussed by Mawkhlieng and Majumdar [11] in detail in their textile progress. Various studies reveal that plain weave generally outperforms other weaves due to an optimized balance between the isotropic nature and firmness of the structure. However, from the works of Laha and Majumdar [45, 47, 49], Chu and Chen [50], and Shimek and Fahrenthold [51], the effect of fabric structure is seen to also depend on the type of impact, the yarn count, and number of layers in the panel. An oversimplified generalization is to have a tight plain-woven structure for low velocity puncture type of impact to resist the incoming impacting object from windowing through the structure (Fig. 7.6). However, for a panel of many layers against higher velocity impact, a balance between tight weaves and low yarn crimp has to be met. While the former ensures structural integrity, the latter ensures rapid wave propagation from the impact point. This is probably why Shimek and Fahrenthold [51] observed a harness satin four weave to be superior to the plain weave. Noting that the testing conditions in various studies differ from each other, it is evident to conclude that the impact resistance of a fabric is highly dependent on structure. The complexity of structural effect only increases when STF is added.

Structural integrity of a fabric is a term that is used often in literature to qualitatively assess the firmness of the structure [23, 52]. In the first, Mawkhlieng et al. [23] attemptted to add a numerical figure to this term in their work on STF-treated fabrics against low velocity impact. However, the approach was addressed toward 3D-woven fabrics only. For 2D structures, the authors considered the number of binding points per repeat unit as the major factor contributing to integrity. The integrity factor, as they call it, relates to the energy absorption of the different structure. However, the calculation did not consider the effect of STF add-on, an important

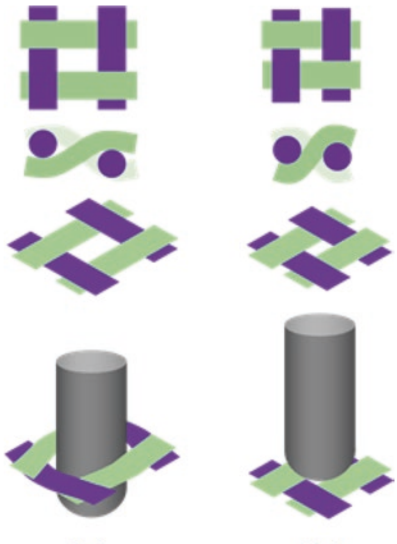

Fig. 7.6 Structure dependent low velocity impact for: (**a**) low fabric sett (windowing effect); (**b**) high fabric sett

aspect since STF treatment "consolidates" or "binds" the structure. Further research along this line is therefore crucial and worthwhile [53].

7.2.2.2 Using Different Woven Structures

The suitability of UD, 2D, and 3D fabric structures for impact resistance has all been explored, if not to the same degree. The structure difference among the three is simplified in Fig. 7.7. UD fabrics outperform any other structure [54–61]. However, such fabrics are often stiff and inflexible. They are mainly advised to be used against high velocity impact in an assembled panel especially at the front and back. At the front, the monolithic nature of the structure helps to deform the bullet by blocking it and rapidly propagating the massive stress waves through the structure, which is effective due to lack of crimp. At the back, the UD laminates restrict the outward deflection of the panel thus, minimizing the behind armor blunt trauma. One of the reasons for the superiority of UD fabrics is the absence of interlacement which causes: (1) maximum accommodation of fibers or filaments in a given area and (2) elimination of interstices that can work as weak spots. While this property is beneficial in many ways, however, this type of void-free structure limits the application of STF, which is probably why research in this area is almost nonexistent. As per the knowledge of the presenting authors, there is only one trial that has been reported recently. Mishra et al. [62] investigated the treatment of STF on UD UHMWPE fabric against the high velocity projectile. Figure 7.8 clearly shows that UD fabric exhibits improved ballistic performance in terms of energy absorption

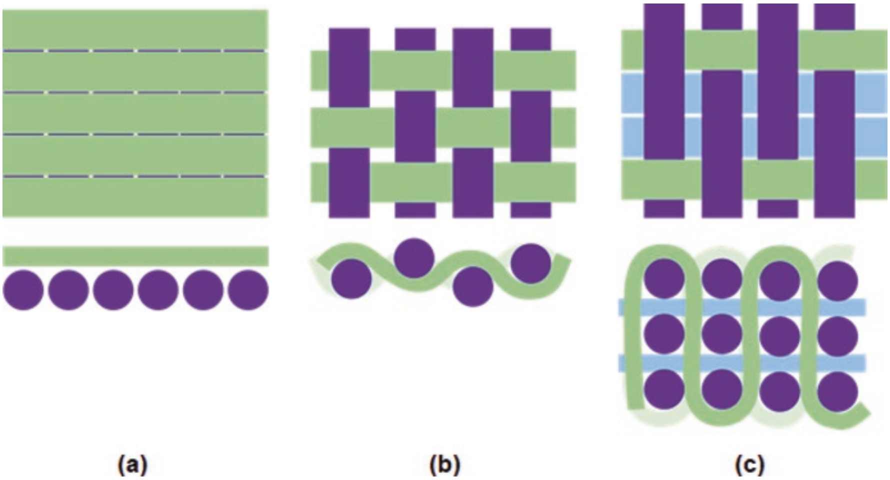

Fig. 7.7 Structural difference among: (**a**) 2 ply UD laminate; (**b**) 2D plain-woven fabric; (**c**) 3-layered orthogonal 3D-woven fabric. Here, green represents the lengthwise yarns (warp in 2D or binder in 3D), purple represents the widthwise yarns (weft), and blue represent the stuffer yarns in 3D

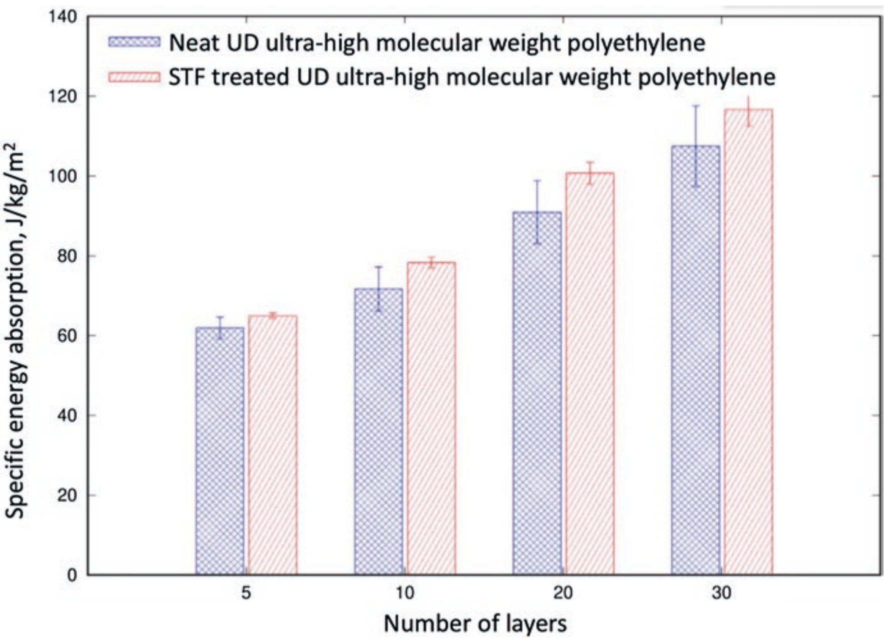

Fig. 7.8 Ballistic performance of neat and STF-treated UD UHMWPE fabrics in terms of specific energy absorption [62]. Reprinted by permission from Elsevier

(13%) and ballistic limit (5%) at varying number of UD laminates when STF is added. The percentage increase in energy absorption is however nowhere close what is commonly observed in the case of 2D woven fabrics.

For STF treatment, 2D- and 3D-woven fabrics dominate. 2D fabrics have been explored extensively, contributing to much of the work reported. The exploration of double fabrics and 3D structures have also begun to surface. The advantage of woven structures is the presence of the interlacements that enables the STF to act as a friction enhancer as one its role. The deposition of STF on the interstices and surface of the fabric helps achieve a certain level of firmness and generates friction when the yarns of the fabrics are pulled. The mechanism is illustrated in Fig. 7.9. Hence, it is not wrong to conclude that in a condition where there is no yarn pull-out, STF is anticipated to help merely through shear thickening.

From the work of Mawkhlieng et al. [23], it is seen that a judiciously designed double fabric can perform better than 2D fabric at least in neat form, if not in the STF-treated state. However, a preliminary study like this and probably the first paper that reported on double fabrics for impact applications can only be a guiding step for future and advanced work. Hence, unless a detailed study is conducted, the potential suitability of double fabrics cannot be undermined. 3D fabrics in general have been seen to underperform 2D counterparts of comparable areal density on multiple occasions at least against low velocity impact. This is because 3D fabrics cannot be woven as tightly as 2D fabrics because of the interlacement nature of three sets of yarns, implying that yarns can be pulled out with ease during impact. However, with STF addition, the performance enhances substantially. Although 3D fabrics are not as attractive for these applications as are 2D fabrics, there is an added advantage of these architectures, particularly the angle interlocks. Their moldability has been explored successfully for designing female body armor [63–65].

Knit structures have also been explored as suitable candidates although to a much lesser extent than woven structures. This is due to the openness of the

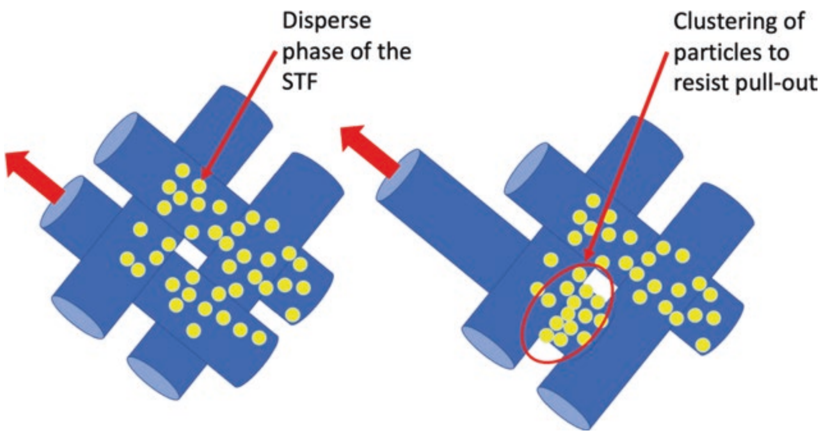

Fig. 7.9 STF treatment enhances fabric friction during yarn pull-out

structure, restricting its applicability in impact resistance applications. Nonetheless, it can potentially be used as a backing material in a hybrid panel. For instance, Lu et al. [66] studied the compressive behavior of neat and STF-filled warp-knitted spacer fabrics when subjected to quasi-static compression and low velocity impact. The STF-filled warp-knitted spacer fabric shows higher energy absorption and a lower peak load as compared to neat fabric. However, further research in this direction is almost missing.

7.2.2.3 Hybridizing Different Yarns

Hybrid fabrics consisting of different yarns have gained the attention of the research fraternity. The yarns can vary either in material or in terms of yarn parameters. Again, this aspect has been dealt in a number of reviews [11, 13, 67–69]. The purpose of hybridization is to synergistically combine the strong features of different materials or different variants of the same material, often driven by cost reduction without compromising on the performance. If some portion of an excellent expensive material can be safely replaced with a lower grade cost-effective alternative, then the manufacturing cost can be reduced. Alternately, the performance of a certain inferior material can be significantly improved by incorporating another superior alternative with it. For example, when lower grade UHMWPE is hybridized with superior *p*-aramid yarns in the same fabric, substantial improvement is expected [23]. Sometimes, hybridization is carried out to achieve a certain objective as in the case of Chitrangad [70] who suggested the use of warps and wefts with different failure strain so that both can break together at the time of impact. In the case of 3D fabrics, different yarns play varying roles. Stuffer and weft yarns are expected to absorb energy whereas binder yarns majorly consolidate the structure. Because of the path they take which is in the Z-direction along the height, the use of finer yarns for binders is suggested [23].

7.2.2.4 Increasing the Fabric Friction

Treatment with STF increases friction as supported by yarn pull-out test results. Friction has also been increased through other techniques such as plasma treatment and growth of nanostructures [71–77]. These approaches have not been reported as successful as STF treatment. This may confirm that STF plays dual roles. Combining both STF treatment and growth of nanostructures has also been explored. Dixit et al. [78] found that fabric treated with both exhibited superior resistance to low velocity impact. Again, progressive work has not been reported in this area.

7.3 STF Treatment of High Performance Fabrics

STF-treated structures have been tested for their impact resistance at varying speeds from impactor drops to low velocity bullet shots. There is a consistent and strong evidence to support that STF structures are resistible against such impacts. Since the revival of the inception of liquid armor in 2003, STF has proven to be an effective alternative to augment the energy absorption capacity of high performance fabrics. However, the use of STF is limited due to a number of reasons, which means that a "liquid armor" in its true sense is far from reality. An initial attempt was to have the fluid stored in pouches that were inserted either before, after, or in between layers of Kevlar® as shown in Fig. 7.10. However, the most successful combination was obtained when the fabric was immersed or impregnated with the fluid. From Fig. 7.10, it is also clear that the presence of fabric layers at the front or strike face is crucial for the success of the invention.

Further, the STF treatment process is crucial. When the fabrics are simply soaked in the fluid, handling and containing the fluid is naturally a challenge. Hence, excess STF has to be removed. The most common procedure reported in literature are as follows: (1) soaking the fabric in STF for a given time and then calendaring and (2) padding. In either case, it is understood that the application should be even to ensure uniformity in the properties of the treated fabrics in all

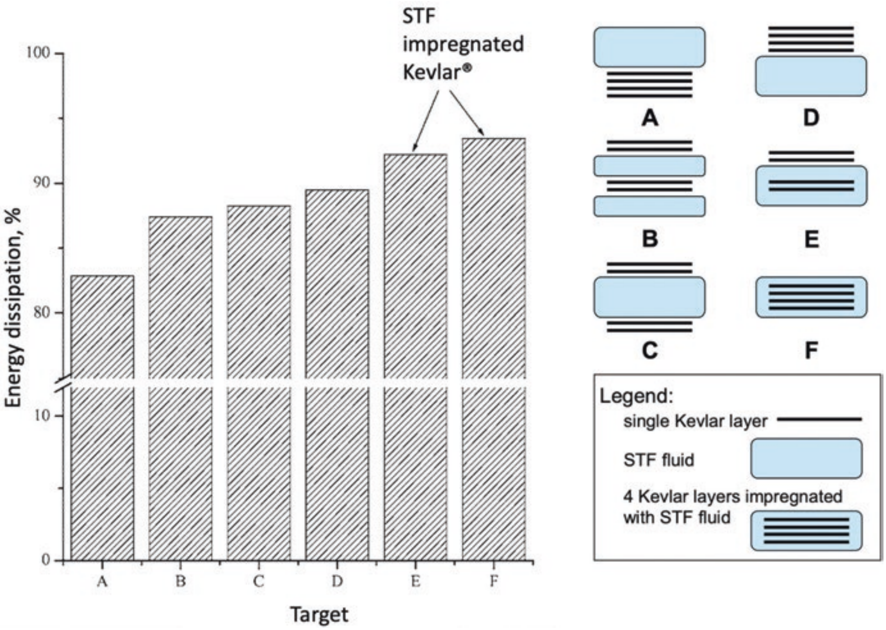

Fig. 7.10 Different combinations of STF and fabrics and their performance in the terms of penetration depth [79]. Reprinted by permission from Springer

directions. Also, the level of penetration, i.e., how deep the fluid impregnates the fabric is important as this decides the concentration of the fluid in the fabric—either at the surface or in the interstices. The implication of this aspect is not thoroughly researched, but it has been observed that the yarn pull-out results are often related to the distribution of the solid particles of the STF in the fabric. Consequently, Majumdar et al. [80] attempt to optimize STF-treated structures through a Box-Behnken design of experiment to obtain the best combination of SiO_2 concentration, padding pressure, and diluent to STF ratio to achieve maximum energy absorption for Kevlar® fabrics. The authors also proposed a two-step sequential padding to ensure the best results. A similar trial has been carried out by Bajya et al. [81] for UHMWPE fabrics. It is critical to note the conclusions of these two studies that more STF add-on does not translate to better energy absorption. The energy absorption evaluation in both these studies was through a drop tower dynamic impact experiment with an impact speed below 5 m/s. Based on these results, it can be extrapolated that the same independency is expected at higher speeds as well. Therefore, it is clear that although STF treatment is beneficial, its undue incorporation either in the form of the liquid itself inside pouches or in terms of excess add-on is not useful. On the contrary, the extra weight addition hinders the practical applicability of the treated structures.

After padding, the STF-treated fabrics are often dried before assembling into a panel. Thus, the fabrics are dry and do not differ in appearance to the untreated fabrics significantly. The only noticeable difference is the matt finish appearance that results from the deposition of the solid particles of the fluid. In fact, the handle of the fabric in terms of stiffness does not change [75]. The STF treatment process quickly changes the phase of STF from fluid form in the literal sense to a fine coating that is barely visible by the naked eye. Hence, this aspect enforces many to speculate if shear thickening plays a significant role as it is supposed to. Rather, its appearance in the fabric suggests that the solid particles' mere adherence to the surface of the fabric simply improves the friction. An "ideology" as such poses several questions to the successful works done before and to those that will be carried in the future as well. If STF merely enhances friction, then other methods of friction enhancement such as plasma treatment and in situ nanostructure growth should be equally efficacious. However, none of these are as successful a story as is the use of STF. Mawkhlieng and Majumdar [36] conducted an experiment to understand this aspect through an indirect approach by relating the rheological flow behavior, fabric friction, and energy absorption. It was found that the low velocity energy absorption relates to the fluid flow behavior and not to the fabric friction. The observation was valid for two sets of fabrics explored. Hence, it is conclusive that STF plays dual roles; while its does improve friction, shear thickening as a mechanism also helps.

7.4 STF-Treated Structures Against Low Velocity Impact

Before furthering the discussion of suitability of STF-treated structures for low velocity impact, it is important to define what low velocity covers. While the speed of "low velocity" impacts can be subjective and can vary based on contexts, this chapter considers impact speeds below 450 m/s as low. For armor applications, the National Institute of Justice (NIJ) is drafting a standard, NIJ 0101.07 that classifies armor types based on the level of protection they provide [82]. The new standard uses acronyms such as HG for handgun and RF for rifle to distinguish the type of weapon used to fire the bullet, a classification that automatically takes bullet speed into consideration also. This chapter covers all impact speeds that pertain up to those that are propelled from a handgun. Rifle shots (~847 m/s and above) can be classified as high velocity impact and are therefore, not included in this chapter.

For stab and spike impacts, STF-treated structures have been reported as successful. An excerpt of a pioneering work is reproduced here in Fig. 7.11a,b. For both knife and spike drop tower tests, the effect of STF is demonstrated through images of the fabric appearance with and without STF treatment post impact. Clearly, the addition of STF remarkably improves the resistance against both impactors. There is evidence in the case of knife impact that no yarns were severed after STF treatment (Fig. 7.11a). Similarly, in the case of spike impact, there was little to no yarn fracture after STF is incorporated. In both cases, after STF treatment, the affected area was much lower, and the damage was hardly visible from the rear side. In case of blunt impact, there was formation of a dome that resulted in substantial energy absorption as displayed in Fig. 7.12. The untreated fabric failed through windowing and yarn pull-out without the real involvement of the yarns whereas in the STF-treated fabrics, the yarns participated in failure by deformation and rupturing. The way STF binds the fabric is witnessed through the involvement of secondary yarns, those that are not directly contacted by the falling impactor.

For higher velocity impacts around 450 m/s, the response depends on the placement of the STF-treated structure in the panel. STF-treated fabrics when placed toward the rear provide better protection in terms of back face signature. It is hypothesized that this arrangement allows sufficient time for the bullet's speed to reduce from the front to the back of the panel so that the rear layers are subjected to a relatively low speed. When placed at the front, the results do not seem to differ than when untreated fabric layers serve as the strike face [48]. Similarly, in the case of hybrid panels, where different materials are used, it has been observed that the replacement of neat fabrics in the back layers with those that treated with STF has an added advantage in reducing the back face signature [65]. An important point to note here is that when the panels are compared on the basis of equivalent weight, the number of fabric layers can be reduced when STF-treated fabrics are used to replace the untreated counterparts. Treatment with STF involves cost, whereas reduction in the number of layers of high performance can reduce cost significantly particularly in bulk production. Hence, cost comparison must be considered, keeping in mind that the performance should be optimum. Consequently, a Memorandum of

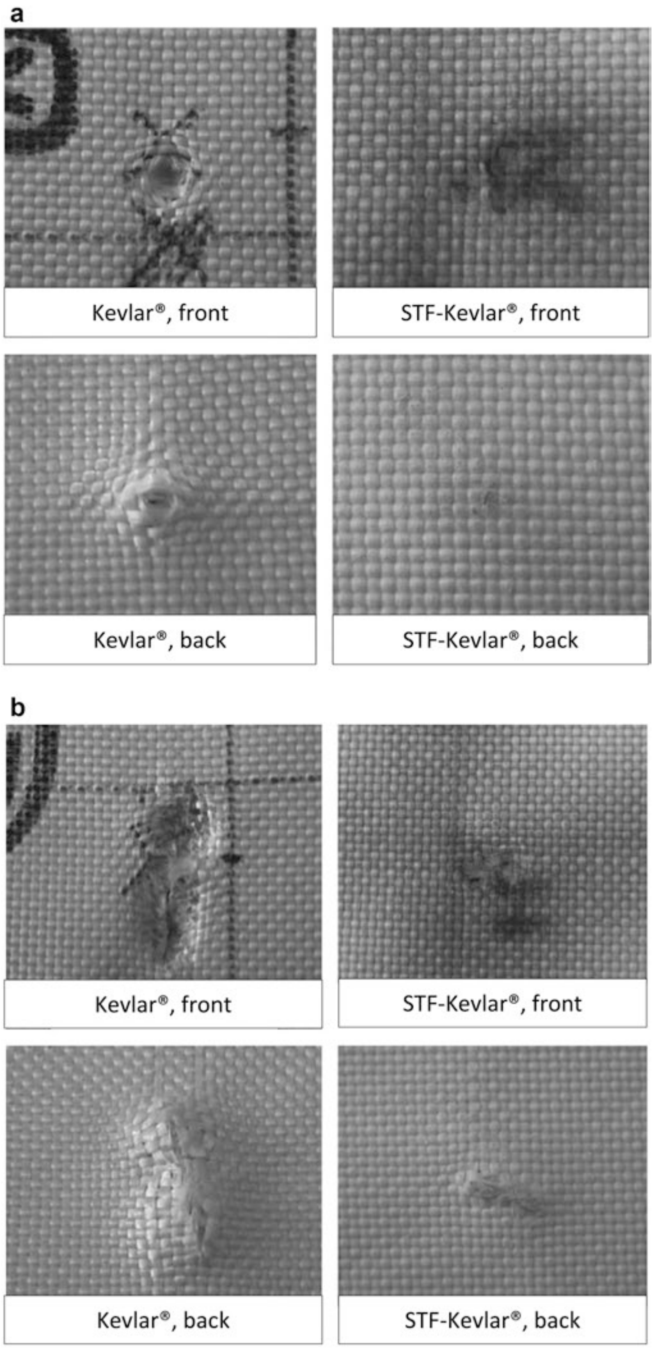

Fig. 7.11 Photographs of neat Kevlar® and STF-treated Kevlar® fabrics after: (**a**) knife; (**b**) spike drop tower test with mass 2.33 kg and height 0.75 m [83]. Reprinted by permission from Elsevier

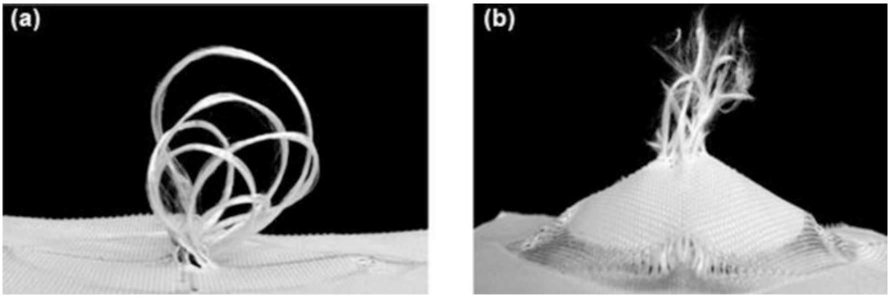

Fig. 7.12 Photographs of (**a**) neat Kevlar® and (**b**) STF-treated Kevlar® after impact [84]. Reprinted by permission from Elsevier

Understanding (MoU) was signed in 2017 between BAE Systems and Helios Global Technologies to commercialize this technology [85]. BAE Systems is an international defense, aerospace, and security company, whereas Helios Global Technologies is a designer, manufacturer, and distributor of technologies related to hazardous worker safety. This is the latest news concerning the "liquid armor" that is known to the day this chapter is written. It is not clear as of now if all the layers of the armor will be treated with STF or if only a portion of the STF-treated layers are to replace the neat layers. Researches show that for low velocity impact where the number of layers required is substantially low, replacing all the woven layers with STF-treated alternatives may be beneficial. This conclusion is drawn from the results of several research works that report on the effectiveness of STF on single layer fabrics. Further, the panels experimented by Mawkhlieng and Majumdar [46] against an impact velocity of ~165 m/s consisted of three layers, and the superior panel that was able to stop maximum number of bullets had all STF-treated layers. However, for higher velocity impact, the replacement of all layers is not required. Realistically, to maintain the panel weight, there is a balance between the replaceable number of layers and the corresponding reduction in the total number of layers. From the work of Bajya et al. [48], it can be extrapolated that for low velocity impact, a superior panel may be composed of neat high performance fabrics with a few layers at the back replaced with STF-treated substitutes without changing the panel weight. The exact number of layers depends on the type of impactor, the velocity of impact, and level of protection required, for which a trial must be conducted considering the findings of existing works. The design strategy of placing a layer of UD laminate or two behind the STF-treated layers may also be followed where reduction of back face signature is crucial [65]. Here, it is also important to mention the cost incurred in STF treatment, an aspect crucial from a commercial standpoint. Therefore, an optimized level of STF treatment in terms of the number of layers has to be considered. Several review papers [15, 86, 87] are dedicated specifically to stab and spike resistance of STF-based armor which can be read further.

Another important consideration is the packaging of STF-treated fabrics. STF when left exposed in atmospheric conditions for several days can absorb water, resulting in the reduction in the effective solid fraction and consequently, in viscosity. This effect when STF is added to fabrics is still unknown as there is no study at present that investigates this matter. A detailed and extended study on the effect of exposure of STF-treated fabrics in atmosphere for a given number of days will be helpful to throw light on the longevity of the effect of such treatment, if any. Although in practice, the fabric layers are sealed in a water-resistant nylon carriage fabric that are later used as armor panels, this study will suggest the number of days the STF-treated fabrics can be safely placed unpacked from the time of treatment to the time of assembling and sealing. In a number of unreported works by the present authors, it has been observed that when the panels are isolated in an airtight seal, then then effect of moisture can be eliminated. In fact, when the same sealed panels were tumbled under adverse humid conditions, a process called as accelerated ageing, the performance of panels dropped only slightly.

Furthermore, hybridization at the panel stage is also advised. A hybrid panel is an assemble of different layers of materials that can be judiciously designed so that the performance can be improved within the limitations of cost and weight. Such a panel may be represented by Fig. 7.13. The image is only representative and hence, does not reflect the actual number of layers or the exact sequence to be used.

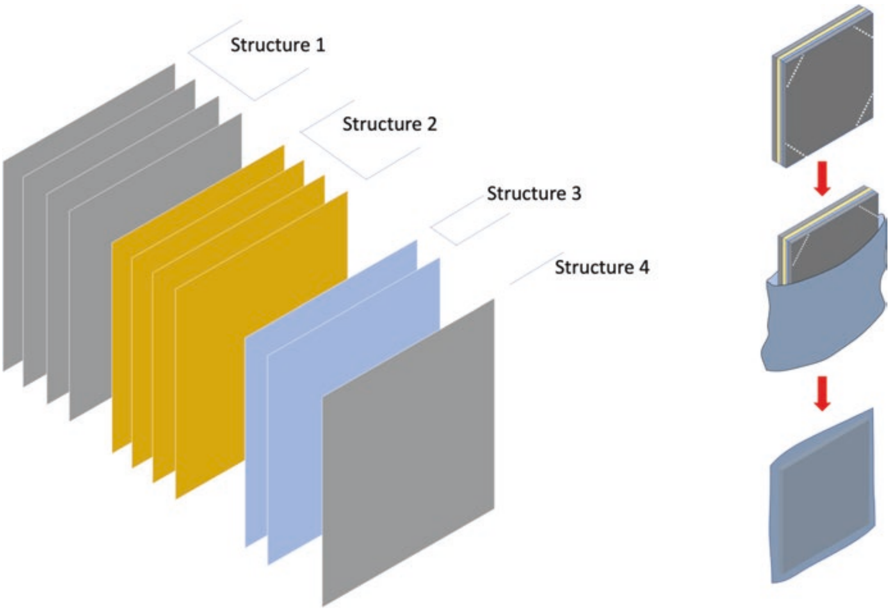

Fig. 7.13 Representative assembly of different materials strategically sequenced. Here, structure represents either UD laminates, 2D- or 3D- woven structures, either in neat or STF-treated conditions. Also, the panel is stitched and sealed in a water-resistant carriage

7.5 Summary

In this chapter, the important facets of various types of STF and protective structures have been summarized against low velocity impacts. The introduction section provides a concise summary of the measurement system for low and high velocity impacts. The methods of augmenting energy absorption are categorically routed through the improvement of shear thickening or viscosity of STF or through the thoughtful construction of fabric. The STF route briefly describes the methods to prepare an effective STF for protective application either by varying or hybridizing the contents, or by incorporating additives. The fabric route illustrates the approaches to alter the structure. This chapter focuses on the STF treatment of high performance 2D-, UD-, and 3D-woven fabric structures of aramid and UHMWPE and their performances against low velocity impact. The failure modes of STF-treated fabrics depend on the type of impactor and its speed (spike, knives, blunt indenter, or bullet). For bullet type of impact with high velocity, the arrangement of STF-treated layer in the panel is an important aspect to consider.

References

1. A. Laha, A. Majumdar, Shear thickening fluids using silica-halloysite nanotubes to improve the impact resistance of p-aramid fabrics. Appl. Clay Sci. **132–133**, 468–474 (2016)
2. S. Gürgen, M.C. Kuşhan, The ballistic performance of aramid based fabrics impregnated with multi-phase shear thickening fluids. Polym. Test. **64**, 296–306 (2017)
3. H. Liu, H. Zhu, K. Fu, et al., High-impact resistant hybrid sandwich panel filled with shear thickening fluid. Compos. Struct. **284**, 115208 (2022)
4. A. Ghosh, A. Majumdar, B.S. Butola, Modulating the rheological response of shear thickening fluids by variation in molecular weight of carrier fluid and its correlation with impact resistance of treated p-aramid fabrics. Polym. Test. **91**, 106830 (2020)
5. Y. Ma, Z. Lei, G. Huang, et al., Energy absorption analysis of STF/Kevlar composite fabric based on 3D morphology of impact basin under low-speed impact. Compos. Struct. **283**, 115152 (2022). https://doi.org/10.1016/j.compstruct.2021.115152
6. A. Majumdar, A. Laha, Effects of fabric construction and shear thickening fluid on yarn pull-out from high-performance fabrics. Text. Res. J. **86**, 2056–2066 (2016)
7. S. Gürgen, T. Yıldız, Stab resistance of smart polymer coated textiles reinforced with particle additives. Compos. Struct. **235**, 111812 (2020). https://doi.org/10.1016/j.compstruct.2019.111812
8. R.G. Egres Jr., Y.S. Lee, J.E. Kirkwood, et al., "liquid armor": Protective fabrics utilizing shear thickening fluids. 4th International Conference on Safety and Protective Fabrics, 1–8 (2004)
9. Y.S. Lee, E.D. Wetzel, R.G. Egres Jr., NJW, Advanced body armor utilizing shear thickening fluids. J. Chem. Inf. Model, 1689–1699 (2013)
10. N. Wagner, ED. Wetzel, Advanced body armor utilizing shear thickening fluids. US 7.498,276 B2, US, (2009)
11. U. Mawkhlieng, A. Majumdar, Soft body Armour. Text. Prog. **51**, 139–224 (2020)
12. S. Gürgen, M.C. Kuşhan, W. Li, Shear thickening fluids in protective applications: A review. Prog. Polym. Sci. **75**, 48–72 (2017)
13. U. Mawkhlieng, A. Majumdar, A. Laha, A review of fibrous materials for soft body Armour applications. RSC Adv. **10**, 1066–1086 (2020)

14. K. Patel, S.H. Chikkali, S. Sivaram, Ultrahigh molecular weight polyethylene: Catalysis, structure, properties, processing and applications. Prog. Polym. Sci. **109**, 101290 (2020). https://doi.org/10.1016/j.progpolymsci.2020.101290
15. K. Bilisik, Ballistic and stabbing protection: A review. Text Res. **87**, 2275–2304 (2017)
16. V.B.C. Tan, T.E. Tay, W.K. Teo, Strengthening fabric Armour with silica colloidal suspensions. Int. J. Solids Struct. **42**, 1561–1576 (2005)
17. B.-W.W. Lee, I.-J.J. Kim, C.-G.G. Kim, The influence of the particle size of silica on the ballistic performance of fabrics impregnated with silica colloidal suspension. J. Compos. Mater. **43**, 2679–2698 (2009)
18. C. Fischer, S.A. Braun, P.E. Bourban, et al., Dynamic properties of sandwich structures with integrated shear-thickening fluids. Smart Mater. Struct. **15**, 1467–1475 (2006)
19. M. Hasanzadeh, V. Mottaghitalab, M. Rezaei, et al., Numerical and experimental investigations into the response of STF-treated fabric composites undergoing ballistic impact. Thin-Walled Struct. **119**, 700–706 (2017)
20. L. Lam, W. Chen, H. Hao, et al., Numerical study of bio-inspired energy-absorbing device using shear thickening fluid (STF). Int. J. Impact Eng. **162**, 104158 (2022)
21. H. Mahfuz, F. Clements, V. Rangari, et al., Enhanced stab resistance of armor composites with functionalized silica nanoparticles. J. Appl. Phys. **105**, 3086431 (2009). https://doi.org/10.1063/1.3086431
22. S. Arora, A. Majumdar, B.S. Butola, Structure induced effectiveness of shear thickening fluid for modulating impact resistance of UHMWPE fabrics. Compos. Struct. **210**, 41–48 (2018)
23. U. Mawkhlieng, M. Gupta, A. Majumdar, An exposition of shear thickening fluid treated double and 3D woven fabrics with a new integrity factor for enhanced impact resistance. Compos. Struct. **270**, 114086 (2021)
24. Q. Hu, G. Lu, N. Hameed, et al., Dynamic compressive behaviour of shear thickening fluid-filled honeycomb. Int. J. Mech. Sci. **229**, 107493 (2022)
25. A. Khodadadi, G. Liaghat, A. Taherzadeh-Fard, et al., Impact characteristics of soft composites using shear thickening fluid and natural rubber–a review of current status. Compos. Struct. **271**, 114092 (2021)
26. T.A. Strivens, The shear thickening effect in concentrated dispersion systems. J. Colloid Interface Sci. **57**, 476–487 (1976)
27. A. Srivastava, A. Majumdar, B.S. Butola, Improving the impact resistance performance of Kevlar fabrics using silica based shear thickening fluid. Mater. Sci. Eng. A **529**, 224–229 (2011)
28. D.P. Kalman, R.L. Merrill, N.J. Wagner, et al., Effect of particle hardness on the penetration behavior of fabrics intercalated with dry particles and concentrated particle-fluid suspensions. ACS Appl. Mater. Interfaces **1**, 2602–2612 (2009)
29. D.P. Kalman, J.B. Schein, J.M. Houghton, et al., Polymer dispersion based shear thickening fluid-fabrics for protective applications. Int. SAMPE Symp Exhib. **52**, 1–9 (2007)
30. J. Ding, P. Tracey, W. Li, et al., Review on shear thickening fluids and applications. Text. Light Ind. Sci. Technol. **2**, 161–173 (2013)
31. X. Gong, Y. Xu, W. Zhu, et al., Study of the knife stab and puncture-resistant performance for shear thickening fluid enhanced fabric. J. Compos. Mater. **48**, 641–657 (2014)
32. Y.L. Xua, X.L. Gong, C. Peng, et al., Shear thickening fluids based on additives with different concentrations and molecular chain lengths. Chinese J. Chem. Phys. **23**, 342–346 (2010)
33. H.S. Son, K.H. Kim, J.H. Kim, et al., High-performance shear thickening of polystyrene particles with poly(HEMA). Colloid Polym. Sci. **296**, 1591–1598 (2018)
34. H.S. Son, K.H. Kim, J.H. Song, et al., Enhanced shear thickening of polystyrene-poly(acrylamide) and polystyrene-poly(HEMA) particles. Colloid Polym. Sci. **297**, 95–105 (2019)
35. Q. Chen, W. Zhu, F. Ye, et al., PH effects on shear thickening behaviors of polystyrene-ethylacrylate colloidal dispersions. Mater. Res. Express **1**, 015303 (2014). https://doi.org/10.1088/2053-1591/1/1/015303

36. U. Mawkhlieng, A. Majumdar, Deconstructing the role of shear thickening fluid in enhancing the impact resistance of high-performance fabrics. Compos. Part B Eng. **175**, 107167 (2019)
37. B. Alince, P. Lepoutre, Viscosity, packing density and optical properties of pigment blends. Colloids Surf. **6**, 155–165 (1983)
38. A. Ghosh, A. Majumdar, B.S. Butola, Role of surface chemistry of fibres additives on rheological behavior of ceramic particle based shear thickening fluids. Ceram. Int. **44**, 21514–21524 (2018)
39. S. Gürgen, W. Li, M.C. Kuşhan, The rheology of shear thickening fluids with various ceramic particle additives. Mater. Des. **104**, 312–319 (2016)
40. M. Zojaji, A. Hydarinasab, S.H. Hashemabadi, et al., Rheological behaviour of shear thickening fluid of graphene oxide and SiO2 polyethylene glycol 400-based fluid with molecular dynamic simulation. Mol. Simul. **47**, 317–325 (2021)
41. L. Liu, M. Cai, X. Liu, et al., Ballistic impact performance of multi-phase STF-impregnated Kevlar fabrics in aero-engine containment. Thin-Walled Struct. **157**, 107103 (2020)
42. M. Hasanzadeh, V. Mottaghitalab, Tuning of the rheological properties of concentrated silica suspensions using carbon nanotubes. Rheol. Acta **55**, 759–766 (2016)
43. S. Gürgen, M.C. Kuşhan, W. Li, The effect of carbide particle additives on rheology of shear thickening fluids. Korea Aust. Rheol. J. **28**, 121–128 (2016)
44. S. Gürgen, M.C. Kuşhan, The stab resistance of fabrics impregnated with shear thickening fluids including various particle size of additives. Compos. Part A Appl. Sci. Manuf. **94**, 50–60 (2017)
45. A. Laha, A. Majumdar, Shear thickening fluids using silica-halloysite nanotubes to improve the impact resistance of p-aramid fabrics. Appl. Clay Sci. **132–133**, 468–474 (2017)
46. U. Mawkhlieng, A. Majumdar, D. Bhattacharjee, Graphene reinforced multiphase shear thickening fluid for augmenting low velocity ballistic resistance. Fibers Polym. **22**, 213–221 (2021)
47. A. Laha, A. Majumdar, Interactive effects of p -aramid fabric structure and shear thickening fl uid on impact resistance performance of soft armor materials. Mater. Des **89**, 286–293 (2016)
48. M. Bajya, A. Majumdar, B.S. Butola, et al., Design strategy for optimising weight and ballistic performance of soft body Armour reinforced with shear thickening fluid. Compos. Part B **183**, 107721 (2020)
49. A. Laha, A. Majumdar, I. Biswas, et al., Role of fabric geometry in ballistic performance of flexible Armour panels. Procedia Eng. **173**, 747–754 (2017)
50. C.K. Chu, Y.L. Chen, Ballistic-proof effects of various woven constructions. Fibres Text. East. Eur **83**, 63–67 (2010)
51. M. Shimek, E. Fahrenthold. Effects of weave type on ballistic performance for aramid, UHMWPE, and hybrid fabrics. In: 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA. Reston, Virigina: American Institute of Aeronautics and Astronautics, 1–12
52. F. Boussu, I. Cristian, S. Nauman, General definition of 3D warp interlock fabric architecture. Compos. Part B Eng. **81**, 171–188 (2015)
53. S. Arora, A. Majumdar, B.B. Singh, Interplay of fabric structure and shear thickening fluid impregnation in moderating the impact response of high-performance woven fabrics. J. Compos. Mater. **54**, 4387–4395 (2020)
54. Y.Yang, Study on ballistic performance of hybrid soft Body armour. Ph.D. Thesis. University of Manchester, (2015). https://www.research.manchester.ac.uk/portal/files/61848779/FULL_TEXT.PDF
55. J.L. Park, B.I. Yoon, J.G. Paik, et al., Ballistic performance of p -aramid fabrics impregnated with shear thickening fluid; Part I–Effect of laminating sequence. Text. Res. J. **82**, 527–541 (2012)
56. J.L. Park, Y.S. Chi, T.J. Kang, Ballistic performance of hybrid panels composed of unidirectional/woven fabrics. Text. Res. J. **83**, 471–486 (2013)

57. M. Bajya, A. Majumdar, B.S. Butola, et al., Mitigating the blunt trauma of soft Armour panels using polycarbonate sheets: A cost-effective solution. Appl. Compos. Mater. **28**, 1089–1109 (2021)
58. M. Bajya, A. Majumdar, B.S. Butola, et al., Efficacy of various structural forms of disentangled polyethylene laminates against low velocity impact. J. Thermoplast. Compos. Mater. (2022). https://doi.org/10.1177/08927057221145573
59. M. Karahan, A. Jabbar, N. Karahan, Ballistic impact behavior of the aramid and ultra-high molecular weight polyethylene composites. J. Reinf. Plast. Compos. **34**, 37–48 (2015)
60. F. Boussu, T. Kanit, D. Crepin, et al., Behaviour of a warp interlock fabric subjected to ballistic impact : Experimental analysis. 12th World Text Conf. AUTEX, 1–7 (2012)
61. X. Chen, D. Sun, Y. Wang, et al., 2D/3D woven fabrics for ballistic protection. 4th World Conf. 3D Fabr. Their Appl., 1–12 (2012)
62. V.D. Mishra, A. Mishra, A. Singh, et al., Ballistic impact performance of UHMWP fabric impregnated with shear thickening fluid nanocomposite. Compos. Struct. **281**, 114991 (2022)
63. F. Boussu, I. Cristian, S. Nauman, et al., Effect of 3D-weave architecture on strength transfer from tow to textile composite. 2nd World Conf 3D Fabr. their Appl., 2–8 (2009)
64. M.A. Abtew, F. Boussu, P. Bruniaux, et al., Engineering of 3D warp interlock p-aramid fabric structure and its energy absorption capabilities against ballistic impact for body Armour applications. Compos. Struct. **225**, 111179 (2019)
65. U. Mawkhlieng, A. Majumdar, Designing of hybrid soft body Armour using high-performance unidirectional and woven fabrics impregnated with shear thickening fluid. Compos. Struct. **253**, 112776 (2020)
66. Z. Lu, X. Jing, B. Sun, et al., Compressive behaviors of warp-knitted spacer fabrics impregnated with shear thickening fluid. Compos. Sci. Technol. **88**, 184–189 (2013)
67. A. Srivastava, A. Majumdar, B.S. Butola, Improving the impact resistance of textile structures by using shear thickening fluids: A review. Crit. Rev. Solid State Mater. Sci. **37**, 115–129 (2012)
68. G. Nilakantan, J.W. Gillespie, Yarn pull-out behavior of plain woven Kevlar fabrics: Effect of yarn sizing, pullout rate, and fabric pre-tension. Compos. Struct. **101**, 215–224 (2013)
69. M. Bajya, A. Majumdar, B.S. Butola, Criticality of inter-yarn friction in high-performance fabrics for the design of soft body Armour. Compos. Commun. **29**, 100984 (2022)
70. M V, Chitrangad, Nelson PEA. Hybrid ballisitc fabric. US5187003A, US, (1993)
71. Y. Chu, *Surface Modification to Aramid and UHMWPE Fabrics to Increase Inter-Yarn Friction for Improved Ballistic Performance.PhD Thesis* (University of Manchester, 2015). https://www.escholar.manchester.ac.uk/uk-ac-man-scw:264414
72. Y. Chu, X. Chen, L. Tian, Modifying friction between ultra-high molecular weight polyethylene (UHMWPE) yarns with plasma enhanced chemical vapour deposition (PCVD). Appl. Surf. Sci. **406**, 77–83 (2017)
73. H.S. Hwang, M.H. Malakooti, B.A. Patterson, et al., Increased interyarn friction through ZnO nanowire arrays grown on aramid fabric. Compos. Sci. Technol. **107**, 75–81 (2015)
74. S. Arora, A. Majumdar, B.S. Butola, Deciphering the structure-induced impact response of ZnO nanorod grafted UHMWPE woven fabrics. Thin-Walled Struct. **156**, 106991 (2020)
75. D. Sun, X. Chen, Plasma modification of Kevlar fabrics for ballistic applications. Text. Res. J. **82**, 1928–1934 (2012)
76. Y. Chu, X. Chen, D.W. Sheel, et al., Surface modification of aramid fibers by atmospheric pressure plasma-enhanced vapor deposition. Text. Res. J. **84**, 1288–1297 (2014)
77. A. Hazarika, B.K. Deka, D.Y. Kim, et al., Growth of aligned ZnO nanorods on woven Kevlar® fiber and its performance in woven Kevlar® fiber/polyester composites. Compos. Part A Appl. Sci. Manuf. **78**, 284–293 (2015)
78. P. Dixit, A. Ghosh, A. Majumdar, Hybrid approach for augmenting the impact resistance of p-aramid fabrics: Grafting of ZnO nanorods and impregnation of shear thickening fluid. J Mater Sci. **54**, 13106–13117 (2019). https://doi.org/10.1007/s10853-019-03830-z
79. Y.S. Lee, E.D. Wetzel, N.J. Wagner, The ballistic impact characteristics of Kevlar® woven fabrics impregnated with a colloidal shear thickening fluid. J. Mater. Sci. **38**, 2825–2833 (2003)

80. A. Majumdar, B.S. Butola, A. Laha, et al., Improving the impact resistance of p-aramid fabrics by sequential impregnation with shear thickening fluid. Fibers Polym. **17**, 0–6 (2016)
81. M. Bajya, A. Majumdar, B.S. Butola, et al., Parametric optimisation of shear thickening fluid treatment for ultra-high molecular weight polyethylene woven fabric. J. Ind. Text. **52**, 152808372211267 (2022)
82. Ballistic Resistance of Body Armor, NIJ standard-0101.07.2018
83. M.J.J. Decker, C.J. Halbach, C.H. Nam, et al., Stab resistance of shear thickening fluid (STF)-treated fabrics. Compos. Sci. Technol. **67**, 565–578 (2006)
84. A. Majumdar, B.S. Butola, A. Srivastava, An analysis of deformation and energy absorption modes of shear thickening fluid treated Kevlar fabrics as soft body Armour materials. Mater. Des. **51**, 148–153 (2013)
85. https://www.baesystems.com/en-ca/article/liquid-armour-to-become-a-future-choice-for-protecting-soldiers
86. M. Wei, K. Lin, L. Sun, Shear thickening fluids and their applications. Mater. Des. **216**, 110570 (2022)
87. R. Nayak, I. Crouch, S. Kanesalingam, et al., Body armor for stab and spike protection, part 1: Scientific literature review. Text. Res. J. **88**, 812–832 (2018)