Parametric optimisation of shear thickening fluid treatment for ultra-high molecular weight polyethylene woven fabric

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Abstract
The shear thickening fluid (STF) treatment enhances the low and high velocity impact resistance performances of para-aramid woven fabrics for soft armour application. This research investigates the effects of important parameters on the STF add on and impact energy absorption with the aim to develop a hybrid soft armour. The STF add-on on ultra-high molecular weight polyethylene (UHMWPE) woven fabrics was varied by altering the silica particle size, dilution ratio of STF and padding pressure. The results of the full factorial design of experiment showed that the energy absorption is independent of the add-on. Further, a soft armour panel (SAP) was made from the STF treated woven fabric. The ballistic performance of the panel was evaluated in terms of back face signature (BFS) against a $9 \times 19$ mm lead core bullet and was compared to that of a weight equivalent untreated panel. A hybrid SAP with unidirectional (UD) laminates of UHMWPE as strike face layers and STF treated woven fabrics as backing layers was prepared, and the BFS was found to be equivalent to that of a SAP containing 100\% UD laminates ($\sim 30$ mm). The

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results imply that a certain number of UD laminate layers can be replaced with STF treated flexible woven fabrics without compromising on the ballistic performance of SAP.

Keywords
Back face signature, shear thickening fluid, ultra-high molecular weight polyethylene, unidirectional laminates, woven fabric

Introduction
Soft armour panel (SAP) is a textile based flexible protective gear that provides protection against small arms like a revolver, pistol and handguns. At present, SAPs are made of multiple layers of woven fabrics or unidirectional (UD) laminates of para-aramid or ultra-high molecular weight polyethylene (UHMWPE) fibres. In recent years, UD laminates of UHMWPE have gained more attention due to its weight advantage and superior ballistic performance.

Over the last two decades, researchers have adopted several techniques to improve the bullet resistant jackets with respect to performance, weight and flexibility. Some of the noteworthy approaches include impregnation of high-performance fabrics with shear thickening fluid (STF), fabric surface treatment, growth of nanostructures on textile substrates, and hybridisation using different fibres and fabric structures. Among these, STF treatment and hybridisation, and a combination of both have been explored to a greater extent. For instance, Park et al. developed SAPs from different combinations of UD UHMWPE laminates and para-aramid fabrics, with and without STF treatment. It was concluded that the placement of STF impregnated fabrics as backing layers is beneficial in terms of ballistic performance and weight because the strategy offers enough time for the STF to trigger the thickening phenomenon. A similar observation was also reported by other researchers. It is hypothesised that the placement of stiff materials at the front layers helps in deforming the bullet and placement at the back layers, aids in restraining the backward deflection of the SAP. On similar grounds, hybridisation with stiff polycarbonate sheets and steel meshes have also been explored as sacrificial strike layers for V50 analysis. Further, logical sequencing and layering orientation have also been explored on different occasions with the sole intention of optimising the use of high-performance materials to prevent under or over designing of SAP with respect to the target performance. In this regard, UHMWPE is preferred to para-aramid due to lower density and higher speed of wave propagation in case of the former. Although the superiority of UHMWPE UD laminates is well documented in literature, however, its performance in combination with STF has not been explored thoroughly. An initial investigation was conducted by Mawkhlien and Majumdar using coarse and low-grade UHMWPE fabrics to study the effect of modulus. It was observed by Arora et al. in their low velocity impact experiment that there is a strong dependence of efficacy of STF on fabric structure, an interaction that was not taken into consideration in most of the studies.
Further, the enhancement in the performance of STF treated fabrics logically questions the level of STF add-on that is required to gain positive outcomes. In the literature, the add-on spans over a wide spectrum with values as low as 2%\(^34\)–\(^36\) to values as high as 237%.\(^37\) Since performance gain is observed at all the different levels of add-on, it is therefore important to understand if more add-on translates to even better impact resistance. From the available literature, it is observed that the efficacy of STF treated UHMWPE woven fabrics against high velocity impact has not been explored in isolation. Further, the strategic design of hybrid SAP employing STF treated UHMWPE fabrics deserves more attention.

Thus, in the present study, STF add-on optimisation was studied through a full factorial design of experiments. From the STF treated UHMWPE woven fabric, a panel was assembled and was compared to a weight equivalent panel constructed from 100% neat woven fabrics of UHMWPE in terms of BFS. Additionally, a hybrid panel with backing of STF treated fabrics was compared with a 100% UD panel to observe if STF treatment helps in maintaining or reducing the BFS.

**Materials and methods**

**Materials**

UHMWPE yarns having a linear density of 400 dtex and UD laminates of UHMWPE were used in the present study. From the yarns, a balanced woven UHMWPE fabric having thread density of 40 × 40 inch\(^{-2}\) was manufactured on a CCI sample loom. The areal density of the fabric was 150 ± 5 g.m\(^{-2}\). On the other hand, the UD laminates with an areal density of 216 ± 8 g.m\(^{-2}\) contained UHMWPE filament sheets layered orthogonally one above the other in (0°/90°)\(_3\) pattern and consolidated between two layers of low-density polyethylene films.

For the STF add-on optimisation experiment, three sizes of silica nanoparticles were used: 100 nm, 300 nm, and 500 nm. Polyethylene glycol (PEG Mw 200) was chosen as the carrier fluid. Silica nanoparticles were obtained from Nippon Shokubai, Japan, whereas PEG 200 was procured from Merck Specialities Pvt Ltd. Ethanol was used as a diluent for STF to facilitate easy mixing and proper impregnation.

**Fabric manufacturing**

Fabric manufacturing was carried out according to the standard weaving protocol: sizing (coating), warping (beam preparation) and weaving. Sizing of yarns was done on a single end sizing machine using polyvinyl alcohol (PVA) as a film-forming agent, and the sized yarns were dried at 80°C. Warping and weaving were carried out on a single end warping machine and single rapier loom, respectively. Fabric sett of 40 × 40 inch\(^{-2}\) was used as optimised by Arora et al.\(^33\) to obtain an areal density of 150 ± 5 g.m\(^{-2}\).
Preparation of shear thickening fluid

STF was prepared by dispersing a known amount of silica particles in PEG 200 such that the solid (silica) fraction was 0.65 by weight (w/w). The remaining 0.35 weight fraction was contributed by PEG 200. Three silica particle sizes were chosen: 100 nm, 300 nm and 500 nm and hence, three STFs were prepared- STF-100, STF-300 and STF-500. Prior to making the STF, the silica particles were oven dried for 2 h above 100°C to remove any volatile impurity or remnant moisture. The silica particles were initially dispersed in ethanol by using a high-speed homogeniser (17,400 rpm) and a probe sonicator sequentially for 5 min each. After the process, the ethanol dispersed silica was mixed with PEG 200 with the help of a homogeniser for 5 min and then with a probe sonicator for another 20 min. The prepared mixture of silica, PEG and ethanol was kept inside an oven at 120°C for 2 h to remove the ethanol. This resulted the STF that contains silica particles and PEG.

Impregnation of UHMWPE woven fabric with shear thickening fluid

To impregnate the UHMWPE woven fabric with STF, dilution of the highly viscous STF with ethanol was necessary. The PEG: Ethanol ratio was varied at three levels, namely 1:4, 1:6 and 1:8. A high-speed homogeniser was used to prevent agglomeration and to ensure the uniform dispersion of silica nanoparticles in the diluted suspension. Woven fabrics were impregnated with the diluted STF solution on a padding mangle keeping 3 m-min$^{-1}$ surface speed of padding rollers and at three different squeezing pressures (2 bar, 4 bar and 6 bar) to vary the amount of STF add-on. Figure 1 shows the schematic representation of the STF impregnation process. Each fabric was passed twice through the nip of padding rollers.
rollers and thereafter, the samples were kept in a hot air oven at 70°C for 30 min to evaporate the ethanol. Add-on (%) for each sample was calculated using equation (1).

\[
\text{Add-on} \% = \left( \frac{\text{Weight of fabric after STF treatment} - \text{weight of untreated fabric}}{\text{weight of untreated fabric}} \right) \times 100
\]  

(1)

**Preparation of soft armour panels**

For SAP preparation, the parameters optimised using a 3³ full factorial design were used for STF treatment. The chosen parameters were: 500 nm silica nanoparticles, STF dilution ratio of 1:8 and padding pressure of 6 bar. The nomenclatures, and specifications of different materials used for SAP are given in Table 1.

The SAP details are given in Table 2. In panel code, the numerical figure after the material code (W, S or U) denotes the number of layers used to make the SAP. The areal density of all the three panels was fixed at 4.5 kg.m⁻². The ballistic performance in terms of BFS of the panel composed of 100% STF treated UHMWPE woven fabrics (S25) was compared with that composed of neat UHMWPE woven fabrics (W30). The former had 25 layers whereas the latter had 30 layers of fabrics so that both SAPs had the same weight. Further, one additional hybrid panel was prepared with UHMWPE UD laminates placed at the front and STF treated UHMWPE woven fabric placed at the back (U11+S12). The panels were assembled on a JUKI LU 2810 sewing machine using a diamond stitch pattern for the woven fabric and an edge stitch pattern for the UD laminates, as shown in Figure 2. In the case of woven fabric, the stitch length and distance between the two parallel stitch lines were 5 mm and 50 mm, respectively. Shot locations were marked on the strike face of the panel following a particular pattern, as shown by numbers one to three in Figure 2. The minimum distance among the shot locations and between a shot location and the panel edge was kept at 51 mm as per IS 17,051: 2018.

**Rheological analysis of shear thickening fluids**

The STFs were evaluated for their flow behaviour using Anton Paar Physica MCR 51 stress-controlled rheometer using a parallel plate geometry with 0.3 mm gap. The diameters of the upper and lower plates were 25 mm and 50 mm, respectively. The test was conducted at three different temperatures, i.e. 15°C, 25°C and 35°C, and the shear rate varied from 1 s⁻¹ to 1000 s⁻¹.
Scanning electron microscopy

ZEISS EVO 15 Scanning Electron Microscope (SEM) was used to analyse the morphology of fibre surface, the cross-sections of woven fabrics and UD laminates as well as to determine the failure modes during ballistic impact. For failure mode analysis, small samples were cut from the striking point on the SAPs. For cross-sectional view, small samples were cut by using a sharp surgical blade and were mounted vertically on a stub with the help of silver tape.

Full factorial design for optimisation of shear thickening fluid add-on

The three factors which were considered for optimisation were particle size, dilution ratio and padding pressure. The levels for each of these parameters are as shown in Table 3. Each sample was coded using three digit number such that the first represented the particle size; the second, the padding pressure; and the third, the dilution ratio, i.e. the volume of ethanol (mL) used for 1 mL of PEG 200. Hence, sample 546 represented the fabric that

| Panel code | Fabric mass (kg.m⁻²) | STF mass (kg.m⁻²) | Thickness (mm) | Total areal density (kg.m⁻²) |
|------------|----------------------|-------------------|----------------|----------------------------|
| W30        | 4.50                 | —                 | 8.30           | 4.50                       |
| S25        | 3.75                 | 0.75              | 7.20           |                            |
| U11 + S12  | 4.18                 | 0.32              | 6.20           |                            |
was treated with STF of 500 nm silica particle size at padding pressure 4 bar, where the
dilution ratio was 6:1. Fabric samples having dimensions of 150 mm × 150 mm were cut
from the manufactured UHMWPE woven fabric to form one set of untreated fabrics and
27 sets of STF treated fabrics.

**Tensile testing**

The tensile testing of woven fabrics and UD laminates was conducted on a universal
testing machine (Tinius Olsen) following ASTM D 5035. The specimens were cut in
rectangular strips having 250 mm length and 25 mm width and were clamped between
two serrated jaws at 75 mm gauge length. The test was conducted at a rate of extension of
300 mm·min⁻¹. Five specimens were tested for each sample in standard atmospheric
conditions for tropical region (25 ± 2°C temperature and 65 ± 4% relative humidity).

**Dynamic impact testing**

The dynamic impact testing was conducted for both neat and STF impregnated fabrics on
a falling dart type impact tester (CEAST, Model: FRACTOVIS PLUS). An indenter of
12.7 mm diameter that was attached to a mass of 20 kg was made to fall freely on the
samples with an impact velocity of 4.5 m·s⁻¹, releasing impact energy of 200 J. Five
specimens, each of 150 mm × 150 mm were tested for each set using ASTM D3763. The
specimens were placed between the two circular annular jaws having a knurled surface
that gripped the sample with a clamping force of 7000 N. The test set-up is shown in
Figure 3.

**Ballistic testing**

*Ballistic testing set up.* The ballistic testing was conducted according to NIJ
0101.06 standard, as shown in Figure 4. The distance between the universal mounting

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**Table 3.** Full factorial design and sample codes.

| Padding pressure (bar) | Dilution ratio | Particle size (nm) |
|------------------------|---------------|--------------------|
|                        |               | 100                |
|                        |               | 300                |
|                        |               | 500                |
| 2                      | 4             | 124                |
| 2                      | 6             | 126                |
| 2                      | 8             | 128                |
| 4                      | 4             | 144                |
| 4                      | 6             | 146                |
| 4                      | 8             | 148                |
| 6                      | 4             | 164                |
| 6                      | 6             | 166                |
| 6                      | 8             | 168                |

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barrel and the target was kept at 5 m to ensure maximum bullet stability with a minimal air drag effect. Furthermore, the optical velocity measurement system was kept in the mid position (2.5 m) of the barrel and target. A submachine carbine (SMC) gun was used to propel the bullets (7.5 g, 9 mm diameter) at a velocity of $430 \text{ ms}^{-1}$. Roma Plastilina #1® Grey moulding clay was used as the backing against which the SAPs were strapped using hook and loop fasteners in accordance to NIJ 0101.06. The hardness of moulding clay was calibrated before each test by ensuring that the depth of the indentation, when a steel sphere (1.043 kg weight and 63.5 mm diameter) was dropped on the clay, fell within the prescribed limit of $19 \pm 2 \text{ mm}$.

**Figure 3.** Dynamic impact testing set-up.
Results and discussion

Tensile properties

Figure 5 shows the stress-strain behaviour of UHMWPE woven fabric (W) and UD laminate (U). It is observed that the former exhibits lower initial slope of strain-strain curve, lower ultimate stress (0.64 N-tex\(^{-1}\)) and higher strain at break (18%) as compared to the latter (stress of 0.86 N-tex\(^{-1}\), strain of 4.6%). Lower ultimate stress and higher strain at break in case of woven fabrics are due to the presence of undulation or crimp in the yarn which is completely absent in case of UD laminate. However, the toughness of woven fabric is higher than that of UD laminate because of the higher strain in the woven fabric arising from the removal of yarn crimp during tensile testing.

Rheological analysis

Figure 6 depicts the rheological flow behaviour of the STFs. All three STFs show discontinuous shear thickening behaviour. It is also observed that for given particle size, the viscosity drops with increasing temperature, a trend that is well documented in the literature. Additionally, among the different STFs, the critical shear rate reduces with increasing particle size. An interesting phenomenon which is presently termed as “span” (shear thickening plateau) is seen to be prominent in STFs with larger particle sizes of silica. It is generally observed that the span increases with increasing particle size and that it decreases with increasing temperature. At present, the significance of this zone is not
Figure 5. Stress-strain curve of UHMWPE UD laminate and woven fabrics.

Figure 6. Flow curves of STF-100, STF-300, and STF-500.
fully understood. However, it is envisaged that as shear thickening spans over a range of shear rates, the benefit of high viscosity may be more exploitable for impact applications.

**Optimisation of shear thickening fluid treatment parameters**

Tables 4 and 5 show the ANOVA to explain the dependency of two responses: add-on and energy absorption on the three input parameters. Figure 7(a)–(c) and Figure 7(d)–(f) show the contour plot of add-on and energy absorption as a function of silica particle size, STF dilution ratio and padding pressure, respectively. It is seen from Table 4 that the overall effect of particle size, dilution ratio and padding pressure on add-on is statistically significant ($p$-value < 0.05), although the least significant among the three being the particle size. On the other hand, the most significant parameter is the dilution ratio ($p$-value ~0.000). Moreover, the interactive effect of these three input parameters is also significant ($p$-value < 0.01). Figure 7(a)–(c) shows that with low padding pressure and low dilution ratio, the add-on increases irrespective of particle size of silica. For 100 nm and 300 nm silica particles, the add-on is the least when both the padding pressure and dilution ratio are at their respective maximum values. For 500 nm, the add-on is observed to be the least when the padding pressure is low and the dilution ratio is high.

Table 5 reveals that the model considering the effect of the three considered parameters on impact energy absorption is statistically insignificant ($p$-value = 0.217). However, akin to the effect on add-on, dilution ratio seems to be statistically significant and the most effective parameter ($p$-value = 0.031). The effect of particle size is found to be statistically insignificant which may be attributed to the opposing effect of particle size on surface coverage and dilatancy both of which have role in influencing impact energy absorption. While looking at the energy absorption values at three different pressures, it is noted that the range of energy absorption varies from 41 J to 51 J at low pressure (2 bar), 39 J–49 J at medium pressure (4 bar) and 41 J–52 J at high pressure (6 bar). Therefore, it is observed that padding pressure is not playing any significant role on energy absorption. This may be due to the fact that low pressure induces surface

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**Table 4. ANOVA for shear thickening fluid add-on.**

| Sources of variation | Sum of squares | df | Mean square | $F$-value | $p$-value |
|----------------------|---------------|----|-------------|-----------|-----------|
| Model                | 769.33        | 18 | 42.741      | 18.32     | 0.000     |
| A-particle size      | 43.56         | 2  | 21.78       | 9.33      | 0.008     |
| B-dilution ratio     | 480.89        | 2  | 240.44      | 103.05    | 0.000     |
| C-pressure           | 157.56        | 2  | 78.78       | 33.76     | 0.000     |
| AB                   | 29.56         | 4  | 7.389       | 3.17      | 0.077     |
| AC                   | 30.22         | 4  | 7.556       | 3.24      | 0.074     |
| BC                   | 27.56         | 4  | 6.889       | 2.95      | 0.090     |
| Residual             | 18.67         | 8  | 2.333       |           |           |
| Total                | 788.00        | 26 |             |           |           |
coating of fibre and yarn by STF but low penetration inside the yarn and fabric structure. On the other hand, high pressure facilitates deeper penetration but less surface coating by STF.

Figure 8 depicts the scatter plot of STF add-on and energy absorption by UHMWPE woven fabrics. It is witnessed that while STF addition is beneficial for augmenting impact resistance, its undue add-on does not have any beneficial effect other than increasing the weight and cost. The independency is clearly highlighted in Figures 7(d)–(f) and 8 which show no distinct relationship between STF add-on and impact energy absorption. Therefore, the minimum add-on should be standardised to obtain the benefit of STF in terms of enhanced specific impact resistance, i.e. energy absorption as a ratio of areal density of STF treated fabric. Therefore, for the present study, 500 nm is chosen based on the shear thickening span as observed in the rheological analysis, whereas the highest level of dilution ratio (1:8) and padding pressure (6 bar) are chosen based on the result of the experiment design.

### Energy absorption and deformation behaviour

Figure 9(a)–(c) show the energy absorption by neat, STF-100, STF-300 and STF-500 impregnated fabrics. All STF impregnated fabrics show higher impact energy absorption compared to the neat fabric. The range of improvement in energy absorption for STF-100, STF-300 and STF-500 impregnated fabrics, compared to neat fabric, is found to be from 43% to 79%, from 35% to 66% and from 51% to 75%, respectively. STF-100 and STF-300 impregnated fabric indicate less within-sample variation which can be observed from the smaller error bar when compared to STF-500. Figure 9(d) depicts the force and deformation behaviour of neat and STFs impregnated fabrics (1:4 dilution ratio and 2 bar pressure). The peak force of neat fabric is much lower (~2000 N) than those of STFs impregnated fabrics. The impregnation of fabric with STF increases the inter-yarn friction. Besides, due to the dilatancy of STF, the entire

| Table 5. ANOVA for impact energy absorption. |
|---------------------------------------------|
| Sources of variation | Sum of squares | df | Mean square | F-value | p-value |
|----------------------|----------------|----|-------------|---------|---------|
| Model                | 225.344        | 18 | 12.519      | 1.73    | 0.217   |
| A-particle size      | 41.783         | 2  | 20.891      | 2.89    | 0.114   |
| B-dilution ratio     | 80.090         | 2  | 40.045      | 5.54    | 0.031   |
| C-pressure           | 2.032          | 2  | 1.016       | 0.14    | 0.871   |
| AB                   | 39.168         | 4  | 9.792       | 1.36    | 0.330   |
| AC                   | 31.386         | 4  | 7.846       | 1.09    | 0.425   |
| BC                   | 30.886         | 4  | 7.721       | 1.07    | 0.432   |
| Residual             | 57.810         | 8  | 7.226       |         |         |
| Total                | 283.154        | 26 |             |         |         |
fabric behaves coherently resisting the impacting force. Therefore, more force is needed to either break or push apart the yarns. It is conspicuous that the neat fabric has an elongated failure zone signifying the yarn pull-out whereas the failure of STF treated fabrics is more catastrophic.

Figure 7. Contour plot showing the effect of dilution ratio and padding pressure on add-on (LHS) and energy absorption (RHS): (a), (d) STF-100; (b), (e) STF-300; (c), (f) STF-500.
Scanning electron microscope analysis of shear thickening fluid impregnated UHMWPE

Figure 10 shows the scanning electron micrographs of neat and STF-100, STF-300, and STF-500 impregnated UHMWPE woven fabrics (1:4 dilution ratio and 2 bar pressure). It is seen that the nanoparticles are evenly distributed on the yarn surface and fabric interstices. It is noticed that the coverage of STF-100 on the yarn surface is better than that of STF-300 and STF-500. This can be attributed to the fact that even for the same add-on%, the total surface area is the maximum for 100 nm silica particle and the minimum for 500 nm silica particle. In case of STF-500, silica particles seem to cover the minimum area of filament surface.

Ballistic performance

Back face signature. Table 6 shows the individual BFS, average BFS in case of non-perforation and average impact velocities related to ballistic testing. Both homogeneous SAPs made from neat (W30) and STF impregnated woven fabric (S25) were unable to stop the bullet from piercing, as shown in Figure 11. From a previous work, it is observed that a SAP made from UD laminate of UHMWPE having equivalent areal density was able to stop the bullets with a BFS of ∼30 mm. The under-performance of SAPs made from woven fabrics in neat as well as STF impregnated conditions can be attributed to lower tenacity and modulus of fabrics, as explained in Section 3.1. Besides, too many interlacement points might have caused excessive
stress concentration deteriorating the ballistic performance. However, when STF treated fabrics are positioned at the back of UD laminates (U11 + S12), the bullets are stopped and the BFS recorded (30.3 mm) is similar to that obtained for the SAP containing 100% UD laminate as reported in the work by Bajya et al.3 Thus, the effectiveness of STF treated fabrics is observed to be position dependent as witnessed in other works as well.8,9,25,26 If STF treated fabrics are positioned at the rear side of SAP, then the STF gets more time to trigger and thus its effectiveness is realised. By placing a few layers of STF treated woven fabrics at the rear side of the panel, the number of UD laminates used can be significantly reduced thus reducing the cost and increasing the flexibility of the panel.

**Failure mechanisms.** Figure 12 depicts the cross-section of woven and UD laminates, along with the schematic of failure mechanism of woven fabrics and UD laminates. In the case of the UHMWPE woven structure, the yarns are arranged in warp (0°) and weft (90°) directions. In other words, it can be postulated that woven fabrics are thick orthotropic membranes of UHMWPE yarn assemblies having crimp as seen in the SEM images. The schematic shows that the bullet impacting the woven fabric-based SAP deforms minimally as the resistance offered by the woven fabric is less. This is
Figure 10. Scanning electron micrographs of fabric impregnated with Neat, STF-100, STF-300 STF-500.

Table 6. Hybrid soft armour panels configuration details.

| Sl.no. | Panels configuration | Areal density (kgm$^{-2}$) | BFS (mm) | Average BFS (mm) | Average velocity (ms$^{-1}$) |
|--------|----------------------|----------------------------|----------|------------------|-----------------------------|
| 1      | W30                  | 4.5                        | 37.4, P, P | —                | 429.0                       |
| 2      | S25                  |                            |          | Perforated       | 429.2                       |
| 3      | U11+S12              | 30.8, 30, 30              | 30.3     |                  | 423.5                       |

Figure 11. Soft armour panels after ballistic evaluation.
because the bullet follows the path of least resistance (inter yarn spacing) and waviness (crimp) in the yarn. Contrary to this, UD laminate is an arrangement of straight crimp-less filaments laid parallel, one over the other orthogonally as seen from the SEM micrographs. In case of UD structure, the filament assembly creates a net like structure of very thin orthotropic membrane. From the schematic, it can be seen that the bullet impacting on the SAP made from UD laminates deforms more extensively, resulting in less stress concentration at the point of impact. Besides, the absence of crimp also facilitates the faster travel of the stress wave away from the impact point. Therefore, the bullet gets trapped after penetrating a few layers of UD laminate.

**Failure mode analysis.** Figure 13(a)–(c) show the electron micrographs of failure zones at the front layers of SAPs made from neat and STF treated UHMWPE woven fabrics and UD laminates. Figure 13(a) depicts the partial melting and fusing of multifilaments in the woven fabric due to the lower melting point (155°C) of UHWMPE fibres. Figure 13(b) shows the failure behaviour of STF impregnated woven fabric. It can be seen from the failure zone that the silica particles present on the STF impregnated woven fabric enhances the coefficient of friction between the yarns and filaments. Partial melting and fusing of filaments is also visible in this case. The failure mode of UHMWPE UD laminates depicted in Figure 13(c) reveals similar observations to that of the woven fabric with additional evidence of delamination of cross ply layers and bead formation due to
fusing. Similar types of failure modes of different grade of UD laminates have also been reported by other researchers. 3,39–42

**Conclusion**

Influence of process parameters (silica particle size, padding pressure and dilution ratio) for STF application on UHMWPE woven fabrics has been investigated in this research by using a full factorial experimental design plan. Contour plots were generated along with ANOVA to explain the role of these parameters on STF add-on and impact energy
absorption of UHMWPE woven fabric. It was found that the effects of silica particle size, padding pressure and dilution ratio were statistically significant on STF add on while only the effect of dilution ratio was statistically significant on impact energy absorption. Increasing both the padding pressure and dilution ratio resulted in the least amount of STF add on due to excess STF being squeezed out. Scatter plot of STF add-on and impact energy absorption showed no correlation within the range of add-on observed (16%–34%). All STF impregnated UHMWPE fabrics at low velocity impact tests showed significant improvement in energy absorption compared to neat fabric. Furthermore, the performance of neat and STF impregnated multi-layered SAPs were evaluated at higher impact velocity (430 ms\(^{-1}\)). It was found that similar to the neat panel, STF treated panel of UHMWPE was also unable to stop the bullet from perforating. However, when the STF treated fabric layers were strategically placed at the rear side of an assembly of UHMWPE UD laminates forming a hybrid panel, all the bullets were stopped. Moreover, BFS obtained (∼30 mm) was similar to that obtained in SAP with 100% UHMWPE UD panel. Outcome of this research will be useful to design hybrid SAPs using UD laminate and STF treated woven fabrics to ensure ballistic protection as well as flexibility of soft armour.

**Declaration of conflicting interests**

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**References**

1. Mawkhlieng U and Majumdar A. Soft body armour. *Text Prog* 2020; 51: 139–224. DOI: 10.1080/00405167.2019.1692583.
2. Mawkhlieng U, Majumdar A and Laha A. A review of fibrous materials for soft body armour applications. *RSC Adv* 2020; 10: 1066–1086. DOI: 10.1039/c9ra06447h.
3. Bajya M, Majumdar A, Butola BS, et al. Ballistic performance and failure modes of woven and unidirectional fabric based soft armour panels. *Compos Struct* 2021; 255: 112941. DOI: 10.1016/j.compstruct.2020.112941.
4. Arora S, Majumdar A and Butola BS. Interplay of fabric structure and shear thickening fluid impregnation in moderating the impact response of high-performance woven fabrics. *J Compos Mater* 2020; 54: 4387–4395. DOI: 10.1177/0021998320932991.

5. Liu X, Li M, Li X, et al. Ballistic performance of UHMWPE fabrics/EAMS hybrid panel. *J Mater Sci* 2018; 53: 7357–7371. DOI: 10.1007/s10853-018-2055-4.

6. Lin CC, Lin JH and Chang CC. Fabrication of compound nonwoven materials for soft body armor. *J Forensic Sci* 2011; 56: 1150–1155. DOI: 10.1111/j.1556-4029.2011.01832.x.

7. Bilisik K. Ballistic and stabbing protection: a review. *Text Res* 2017; 87: 2275–2304. DOI: 10.1177/0040517516669075.

8. Mawkhlieng U and Majumdar A. Designing of hybrid soft body armour using high-performance unidirectional and woven fabrics impregnated with shear thickening fluid. *Compos Struct* 2020; 253: 112776. DOI: 10.1016/j.compstruct.2020.112776.

9. Bajya M, Majumdar A, Butola BS, et al. Design strategy for optimising weight and ballistic performance of soft body armour reinforced with shear thickening fluid. *Compos B* 2020; 183: 107721. DOI: 10.1016/j.compositesb.2019.107721.

10. Park JL, Chi YS and Kang TJ. Ballistic performance of hybrid panels composed of unidirectional/woven fabrics. *Text Res J* 2013; 83: 471–486. DOI: 10.1177/0040517512444337.

11. Park Y, Kim YH, Baluch AH, et al. Numerical simulation and empirical comparison of the high velocity impact of STF impregnated Kevlar fabric using friction effects. *Compos Struct* 2015; 125: 520–529. DOI: 10.1016/j.compstruct.2015.02.041.

12. Kim YH, Park Y, Cha JH, et al. Behavior of shear thickening fluid (STF) impregnated fabric composite rear wall under hypervelocity impact. *Compos Struct* 2018; 204: 52–62. DOI: 10.1016/j.compstruct.2018.07.064.

13. Chu Y. *Surface Modification to Aramid and UHMWPE Fabrics to Increase Inter-yarn Friction for Improved Ballistic Performance*. PhD thesis. University of Manchester, 2015.

14. Sun D and Chen X. Plasma modification of Kevlar fabrics for ballistic applications. *Text Res J* 2012; 82: 1928–1934. DOI: 10.1177/0040517512450765.

15. Chu Y, Chen X, Sheel DW, et al. Surface modification of aramid fibers by atmospheric pressure plasma-enhanced vapor deposition. *Text Res J* 2014; 84: 1288–1297. DOI: 10.1177/0040517513515311.

16. Chu Y, Chen X and Tian L. Modifying friction between ultra-high molecular weight polyethylene (UHMWPE) yarns with plasma enhanced chemical vapour deposition (PCVD). *Appl Surf Sci* 2017; 406: 77–83. DOI: 10.1016/j.apsusc.2017.02.109.

17. Hwang HS, Malakooti MH, Patterson BA, et al. Increased interyarn friction through ZnO nanowire arrays grown on aramid fabric. *Compos Sci Technol* 2015; 107: 75–81. DOI: 10.1016/j.compscitech.2014.12.001.

18. Dixit P, Ghosh A and Majumdar A. Hybrid approach for augmenting the impact resistance of p-aramid fabrics: grafting of ZnO nanorods and impregnation of shear thickening fluid. *J Mater Sci* 2019; 54: 13106–13117. DOI: 10.1007/s10853-019-03830-z.

19. Hazarika A, Deka BK, Kim DY, et al. Growth of aligned ZnO nanorods on woven Kevlar® fiber and its performance in woven Kevlar® fiber/polyester composites. *Compos A Appl Sci Manuf* 2015; 78: 284–293. DOI: 10.1016/j.compositesa.2015.08.022.
20. Arora S, Majumdar A and Butola BS. Deciphering the structure-induced impact response of ZnO nanorod grafted UHMWPE woven fabrics. *Thin-walled Struct* 2020; 156: 106991. DOI: 10.1016/j.tws.2020.106991.

21. Chen X, Lo W and Tayyar AE. Mouldability angle-interlock applications. *Text Res J* 2002; 72: 195–200.

22. Luo Y, Lv L, Sun B, et al. Transverse impact behavior and energy absorption of three-dimensional orthogonal hybrid woven composites. *Compos Struct* 2007; 81: 202–209. DOI: 10.1016/j.compstruct.2006.08.011.

23. Zhou F, Zhang C, Chen X, et al. An experimental comparison of different carbon and glass laminates for ballistic protection. 18th Int Conf Compos Mater, 2011; 1–5.

24. Bandaru AK, Chavan V V., Ahmad S, et al. Low velocity impact response of 2D and 3D Kevlar/polypropylene composites. *Int J Impact Eng* 2016; 93: 136–143. DOI: 10.1016/j.ijimpeng.2016.02.016.

25. Majumdar A, Laha A, Bhattacharjee D, et al. Tuning the structure of 3D woven aramid fabrics reinforced with shear thickening fluid for developing soft body armour. *Compos Struct* 2017; 178: 415–425. DOI: 10.1016/j.compstruct.2017.07.018.

26. Park JL, Yoon B il, Paik JG, et al. Ballistic performance of p -aramid fabrics impregnated with shear thickening fluid; Part I – Effect of laminating sequence. *Text Res J* 2012; 82: 527–541. DOI: 10.1177/0040517511420753.

27. Guo Z, Chen W and Zheng J. Effect of replacement strike-face material on the ballistic performance of multi-ply soft armor targets. *Text Res J* 2019; 89: 711–725. DOI: 10.1177/0040517517753641.

28. Chen L, Cao M and Fang Q. Ballistic performance of ultra-high molecular weight polyethylene laminate with different thickness. *Int J Impact Eng* 2021; 156: 103931. DOI: 10.1016/j.ijimpeng.2021.103931.

29. Yang Y and Chen X. Investigation of energy absorption mechanisms in a soft armor panel under ballistic impact. *Text Res J* 2017; 87: 2475–2486. DOI: 10.1177/0040517516671129.

30. Yang Y and Chen X. Influence of fabric architecture on energy absorption efficiency of soft armour panel under ballistic impact. *Compos Struct* 2019; 224: 111015. DOI: 10.1016/J.COMPSTRUCT.2019.111015.

31. Bajaj P and Sriram. Ballistic protective clothing: an overview. *Indian J Fibre Text Res* 1997; 22: 274–291.

32. Crouch IG. Body armour-New materials, new systems. *Def Technol* 2019; 15: 241–253. DOI: 10.1016/j.dt.2019.02.002.

33. Arora S, Majumdar A and Butola BS. Structure induced effectiveness of shear thickening fluid for modulating impact resistance of UHMWPE fabrics. *Compos Struct* 2018; 210: 41–48. DOI: 10.1016/j.compstruct.2018.11.028.

34. Majumdar A, Butola BS, Laha A, et al. Improving the impact resistance of p-aramid fabrics by sequential impregnation with shear thickening fluid. *Fibers Polym* 2016; 17: 6. DOI: 10.1007/s12221-016-5839-7.

35. Srivastava A, Majumdar A and Butola BS. Improving the impact resistance performance of Kevlar fabrics using silica based shear thickening fluid. *Mater Sci Eng A* 2011; 529: 224–229. DOI: 10.1016/j.msea.2011.09.021.
36. Caglayan C, Osken I, Ataalp A, et al. Impact response of shear thickening fluid filled polyurethane foam core sandwich composites. *Compos Struct* 2020; 243: 112171. DOI: 10.1016/j.compstruct.2020.112171.

37. Khodadadi A, Liaghat G, Vahid S, et al. Ballistic performance of Kevlar fabric impregnated with nanosilica/PEG shear thickening fluid. *Compos B Eng* 2019; 162: 643–652. DOI: 10.1016/j.compositesb.2018.12.121.

38. Textiles-Bullet resistant jackets-Performance requirements, IS standard-17051. 2018.

39. Yang Y and Chen X. Determination of materials for hybrid design of 3D soft body armour panels. *Appl Compos Mater* 2018; 25: 861–875. DOI: 10.1007/s10443-018-9716-y.

40. Yang Y. *Study on Ballistic Performance of Hybrid Soft Body Armour*. PhD thesis. University of Manchester, 2015.

41. Zhang D, Sun Y, Chen L, et al. Influence of fabric structure and thickness on the ballistic impact behavior of Ultrahigh molecular weight polyethylene composite laminate. *Mater Des* 2014; 54: 315–322. DOI: 10.1016/j.matdes.2013.08.074.

42. Zhang TG, Satapathy SS, Vargas-Gonzalez LR, et al. Ballistic impact response of ultra-high-molecular-weight polyethylene (UHMWPE). *Compos Struct* 2015; 133: 191–201. DOI: 10.1016/j.compstruct.2015.06.081.