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respect to single-phase STFs. They also proposed that the STF in the STF-treated fabrics increased the inter-yarn friction and led to improvements in stab resistance. The weight percentage of the added STF was only 10 for all STF-treated fabrics in this study.[32] Feng *et al.* investigated the quasi-static stab resistance of STF-treated aramid fabrics and found that the aramid fabrics exhibited significant enhancements in quasi-static stab resistance after treatment with STF.[29] They also proposed that the enhancement in quasi-static stab resistance was due to increased friction between the yarns and filaments impregnated with STF. However, the quantity of absorbed STF in the aramid fabrics was not mentioned in this study.[29] Kang *et al.* reported that STF impregnation significantly improved the stab resistance of Kevlar fabric against spike threats. The role of the STF in the STF-treated fabrics was not mentioned, and the quantity of the absorbed STF in the fabrics was also ignored in this study.[33] Kalman *et al.* reported that stab resistance and ballistic resistance were enhanced for STF–Kevlar composites that absorbed 9 wt% to 14 wt% STF.[25,34] Majumdar found that the silica concentration, padding pressure and square of solvent ratio were the statistically significant terms influencing the impact energy absorption. The added STF in their composites was not more than 7 wt%.[26–28]

In summary, the role of STFs has been demonstrated and accepted in most studies, *i.e.*, the STF increases the friction between yarns and filaments and constrains the mobility of yarns and filaments in STF-treated fabrics. In this case, more yarns and filaments simultaneously sustain knife or spike threats instantaneously and impede their penetration. The friction between yarns and filaments should be related to the quantity of the absorbed STF between them; however, as stated above, all reports to date have ignored the relationship between the friction and the quantity of absorbed STF. The quantity of absorbed STF in STF-treated fabrics is no greater than 30 weight% and is usually a constant value in most existing reports. Moreover, the calculated volume porosity of Kevlar fabrics is between 40% and 70%, as stated in ref. 35. The density of the STF is much greater than that of the Kevlar fiber; hence, the theoretical quantity of absorbed STF in STF-treated fabrics is not less than 100 weight%. In other words, the quantity of absorbed STF in STF-treated fabrics is too low in most existing reports. In addition, the friction between yarns and filaments in STF-treated fabrics may be increased by increasing the quantity of absorbed STF, which may be favorable for improvements in stab resistance. Thus, it is significant to investigate STF-treated fabrics containing high quantities of STF.

In addition, STF-treated Kevlar fabrics as soft body armour materials will mostly experience quasi-static forces and rarely experience dynamic knife stab threats. Therefore, quasi-static properties, including tensile and tearing strength, are very important for STF-treated Kevlar fabrics in service life; moreover, related studies have not been reported, and it is necessary to investigate these properties.

In this study, a dispersion medium with low molecular weight, polyethylene glycol, was selected to prepare STF with silica microspheres. Both the dynamic and quasi-static knife-stabbing resistance and the quasi-static mechanical properties of the STF-treated Kevlar fabric composites with much greater quantities of added STF were investigated systemically for the first time. Moreover, yarn pull-out and tensile tests were performed to explore the inner mechanisms of the various STF-treated Kevlar fabrics, and bending length tests were performed to study their flexural rigidity. The detailed mechanisms of the STFs in the Kevlar fabrics were explored by combining the results of the dynamic and quasi-static tests.

2. Materials and methods

2.1 Materials

Tetraethoxysilane, absolute ethyl alcohol, polyethylene glycol with a molecular weight of 400 g mol^{-1} (PEG-400) and aqueous ammonia (weight% 28) were purchased from the Sinopharm Chemical Reagent Co., Ltd. Ultrapure water was used for all experiments. Plain woven Kevlar fabrics with K-29 were supplied by the Dupont Company; the area density was 240 g m^{-2}. Monodisperse silica microspheres with a diameter of 500 nm were prepared by a sol–gel method, and the products were centrifuged and washed with absolute ethyl alcohol at least three times.

2.2 Preparation of STFs

Silica microspheres were dried at 100 °C for 12 h to remove water and then dispersed in PEG-400 by ultrasonication for not less than 2 h. The obtained samples were dried under vacuum at 80 °C for 24 h. Five STFs with different concentrations, 55 wt%, 60 wt%, 65 wt%, 68 wt% and 70 wt%, were prepared.

2.3 Preparation of composite and PEG-treated Kevlar fabrics

Various diluted STFs were obtained by adding 300 ml, 250 ml, 200 ml or 150 ml ethyl alcohol to different beakers containing 100 g STF. Then, different groups of neat Kevlar fabric were impregnated in the diluted STFs for 30 min. The impregnated fabrics were dried at 60 °C for 24 h and then dried in a vacuum oven at 80 °C for no less than 24 h to eliminate ethyl alcohol and water. The amount of added STF or PEG-400 was calculated by eqn (1). Four groups of composites with 13.4 wt%, 36.23 wt%, 65.21 wt% and 103.79 wt% added STF were prepared. The PEG-treated fabrics were prepared by impregnating Kevlar fabrics in PEG-400; then, surplus PEG-400 was removed with a pressure of about 2 bar. All samples were sealed with membranes.

$$\text{Added-on STF} = \frac{\text{weight of STF-treated fabric} - \text{weight of neat fabric}}{\text{weight of neat fabric}} \times 100\% \quad (1)$$

2.4 Measurements

All rheological experiments were performed with a stress controlled rheometer (Anton Paar MCR 302) at 30 °C. According to the principles of NIJ Standard-0115.00, the dynamic knife-stabbing tests were performed with a simple self-made

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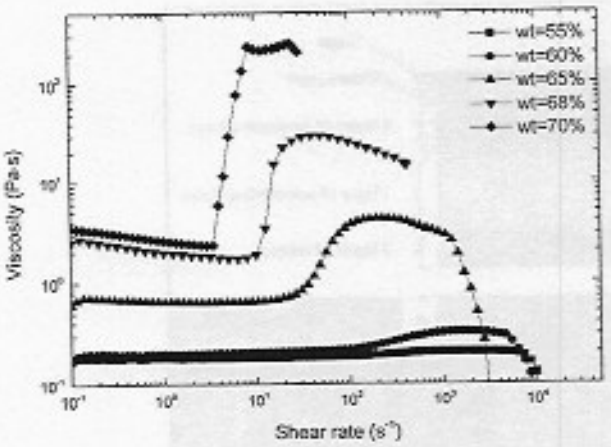


Fig. 2 Shear rate dependencies of the viscosity of STFs with different concentrations.

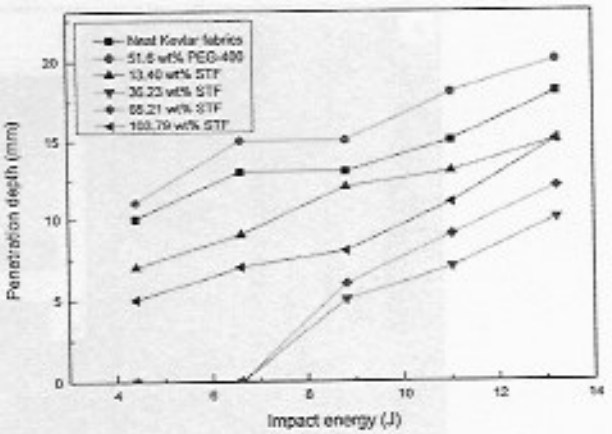


Fig. 3 Impact energy dependencies of the knife penetration depth for targets containing different quantities of STF and 51.6 wt% PEG.

layers. Although the targets of the composites were thinner than the other targets, their stabbing penetration was less than those of the neat and PEG-treated Kevlar fabrics. Both the untreated and PEG-treated targets with twelve layers were penetrated easily. Moreover, the areal density of the target with 13.40 wt% added STF was lower than that of the neat Kevlar fabric target, while its stabbing penetration was also lower. The knife-stabbing resistances of the targets for the composites containing 36.23 wt% and 65.21 wt% STF are prominent. The knife could not penetrate the target and was bounced back in some dynamic knife-stabbing tests. However, the knife-stabbing resistance became low and the area density was very high for the target containing excessive STF (103.79 wt% added). It is clear that the optimal amount of added STF is between 36.23 wt% and 65.21 wt% for dynamic stab resistance.

Furthermore, to investigate the microscopic mechanism, microscopic pictures of the damaged targets were investigated by photographic and SEM images, as shown in Fig. 4. For the neat Kevlar fabric, a crossed trace arises for the slippage of yarns around the cutting hole, as shown in the red rectangle in Fig. 4a. The broken cross-section is irregular, and the filaments are frayed and disordered, as shown in Fig. 4d and g. Some fibrils are dragged out, as shown in Fig. 4j. For the STF-prepared composites, as shown in Fig. 4b and c, the crossed trace does not exist around the cutting hole, implying that the friction in the yarns is increased. The damaged cross-section of yarns is more regular than that of the neat Kevlar fabric, as shown in Fig. 4e, f, h, i, k and l; this indicates that the mobility of the yarns declines, which can be attributed to the increase of friction between yarns. Moreover, it is clear that the STF is coated perfectly on the filaments in the composites, as shown in Fig. 4k. There is a large quantity of surplus STF on the surface of the target with 103.79 wt% STF, and its cutting hole is significantly larger than that of the target with 36.23 wt% STF.

Fig. 5 presents the generated force and absorbed energy against displacement as the knife quasi-statically punctured the neat Kevlar fabric, PEG-treated fabric and STF-prepared composites. Both the maximum generated force and the maximum absorbed energy in the composites are two or three times that of the neat or PEG-treated Kevlar fabrics, respectively. The maximum generated force in the neat or PEG-treated Kevlar fabrics was obtained at a displacement of about 55 mm, as shown in Fig. 5a and b, while the generated force in the composites reached a higher value at a relatively small displacement, as shown in Fig. 5c–f. Moreover, except for a few yarns or filaments, most of these slipped around the punctured hole in the neat or PEG-treated Kevlar fabrics (as shown in Fig. S3a in the ESI†), and the generated force increased steadily with increasing puncture displacement, as shown in Fig. 5a and b. However, the primary yarns are cut off one by one around the punctured hole in the composites (as shown in Fig. S3b in the ESI†); this may cause the generated

Table 2 Dynamic knife stab testing sample parameters

Label	Dimensions: length (cm) by width (cm)	STF absorbing capacity (wt%)	PEG-400 absorbing capacity (wt%)	Number of layers in target	Areal density ($g\ m^{-2}$)
Neat Kevlar fabric	15 × 15	0.00	0.00	12	2880
PEG-400/Kevlar fabric	15 × 15	0.00	51.60	12	4366
STF/Kevlar fabrics	15 × 15	13.40	4.02	9	2449
	15 × 15	36.23	5.28	9	2942
	15 × 15	65.21	9.51	9	3568
	15 × 15	103.79	15.13	9	4401

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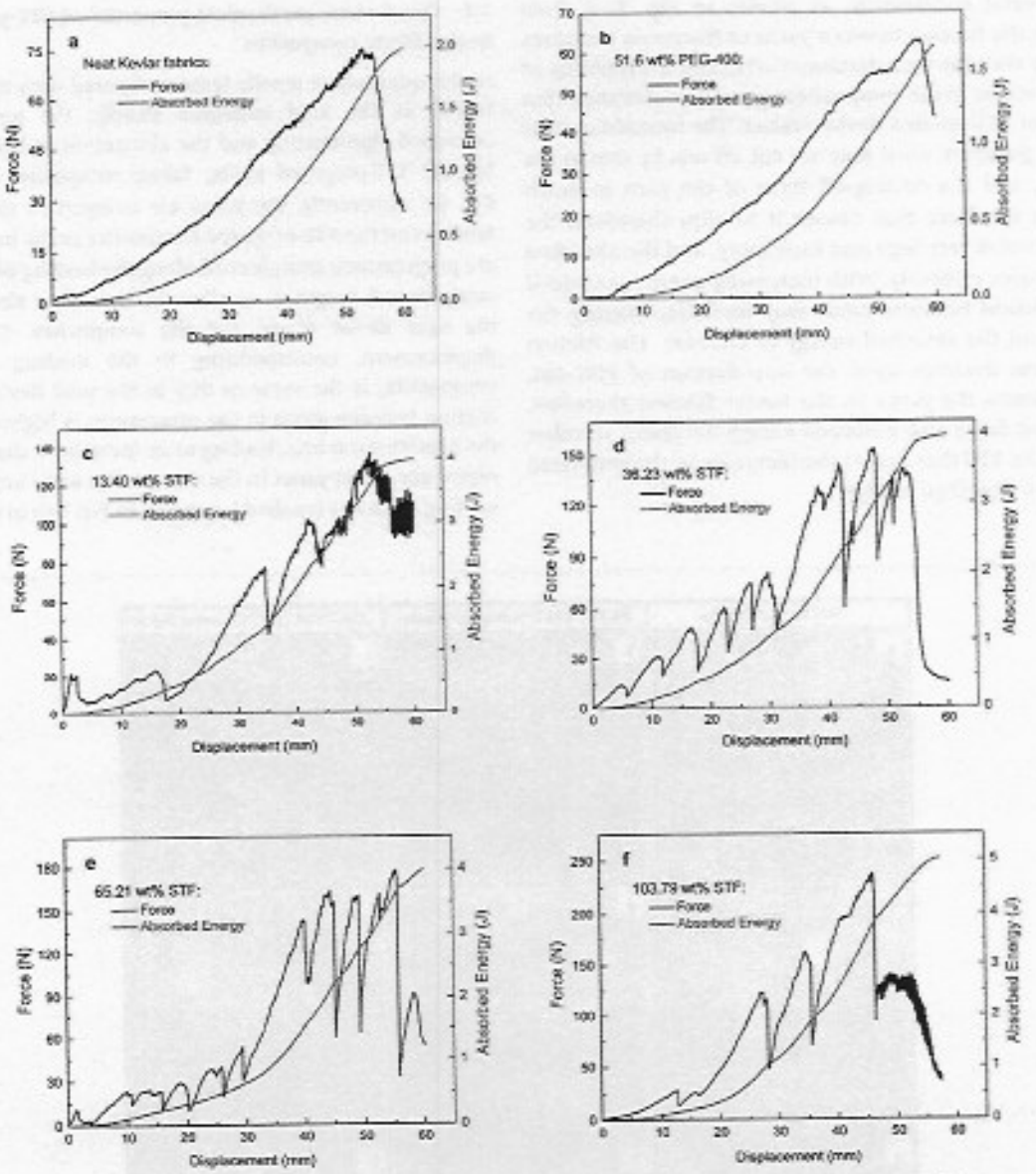


Fig. 5 Force generation and energy absorption *vs.* displacement during a quasi-static knife stab at a rate of 10 mm min^{-1} for (a) neat Kevlar fabric, (b) PEG-treated Kevlar fabric, and (c–f) the STF-prepared composites.

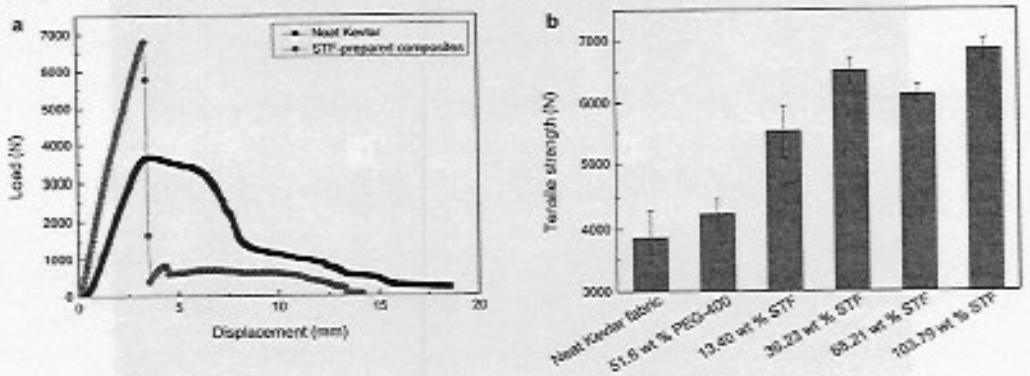


Fig. 6 (a) Tensile load *versus* displacement and (b) tensile strength for Kevlar fabrics treated by different methods at a constant rate of 100 mm min^{-1}.

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from about 12 J to 30 J with increasing amount of added STF, as shown in Fig. 7c–f. Most of the yarns and filaments slip out in the tearing tests for high tensile strength of the Kevlar filament.[34] This implies that the introduction of STF causes the friction between yarns to increase. For the neat and PEG-treated Kevlar fabrics, the tearing force increases progressively, and all yarns finally slip out. The tearing strength of the PEG-treated fabric is slightly lower than that of the neat Kevlar fabric because the inter-yarn friction decreases due to the lubrication of PEG-400. For the STF-prepared composites, the tearing force increases steeply at the initial displacements for the de-crimp and slippage of yarns. Some yarns are squeezed together at the point of the tearing gap with increasing displacement, which severely increases the friction between yarns; therefore, the tearing force is enhanced significantly. Moreover, the tearing force increases with increasing STF, also indicating that the friction between yarns or filaments is enhanced due to the introduction of the STF. The friction oscillates as soon as the yarns slip from one displacement to another, as shown in Fig. 7c–f; therefore, the tearing force is oscillatory. The tearing force decreases and its amplitude declines as the yarn progressively slips out of the fabrics.

Moreover, compared with the neat Kevlar yarn, the tensile strengths of a single yarn for the composites with different amounts of added STF and the PEG-treated fabric are increased by about 12%, as shown in Fig. 8. The friction between the filaments in the yarns may also be enhanced due to the introduction of the STF, which is beneficial for the delivery of stress between different filaments. More filaments uniformly load the tensile stress, leading to increases in the tensile strengths of single yarns of the composites. Furthermore, the bending lengths of the composites and PEG-treated Kevlar fabric are shorter than that of the neat Kevlar fabric and decrease with increasing amount of added STF, as shown in Fig. 9. In other words, the flexural rigidity of the composites is better than that of the neat Kevlar fabric. Finally, the STF can be diluted and separated easily from the composites with ethyl alcohol and then recycled by volatilizing the ethyl alcohol.

3.4 Mechanism of STF in Kevlar fabric composites

In order to demonstrate the working mechanism of the STF in fabrics, the effect of the STF on the friction in yarns was investigated in detail by single yarn pull-out tests, as shown in Fig. 10. In the first stage, the pull-out load increases rapidly, reaching the maximum value as soon as the straightening of the yarn has progressed past the final bottom transverse yarn. In the second stage, the pull-out force exhibits a fluctuant state as the residual crimp in the yarn moves alternately over and under transverse yarns. Moreover, it declines monotonically overall as the residual crimp and the length of the yarn in the fabric decreases progressively and engages with increasingly fewer transverse yarns. As shown in Fig. 10a, the pull-out forces of the different composites are much higher than those of the neat and PEG-treated Kevlar fabrics and increase with increasing amount of added STF. In contrast, the yarn pull-out force in the PEG-treated fabric is small and slightly less than that of the neat fabric due to the lubrication of PEG. In other words, the friction between yarns is significantly enhanced by the introduction of STF. As shown in Fig. 10b, the pull-out force of the composites with 65.21 wt% STF is small and similar to that in the neat fabric at lower testing rates, such as 0.1 mm min^{-1}, 1 mm min^{-1} and 10 mm min^{-1}. It increases prominently when the rate reaches 100 mm min^{-1}, which is the same as the rates the of tensile and tearing tests. Moreover, with increasing rate of the pull-out tests, for 200 mm min^{-1} and 300 mm min^{-1}, the yarn pull-out force increases slightly. However, the pull-out force changes slightly as the pull-out rate changes from low to high values for the neat Kevlar fabric, as shown in Fig. 10c. These results clearly demonstrate that the shear thickening of the STF between yarns is triggered as the relative rate of yarns exceeds 100 mm min^{-1} and the friction between yarns is enhanced.

The working mechanism of STF in the composites can be explained as follows. At first, the STF combines uniformly with the Kevlar fabric, as shown in Fig. 11a. The gap (y) between adjacent filaments can be assumed to be 10 μm, which is larger

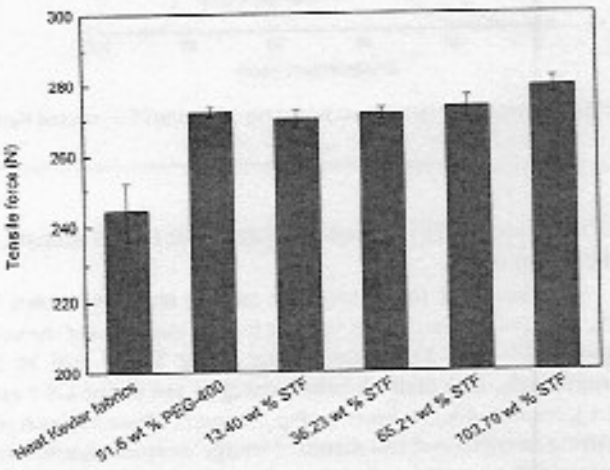


Fig. 8 Tensile strengths of single yarns of Kevlar fabrics treated by different methods at a constant rate of 100 mm min^{-1}.

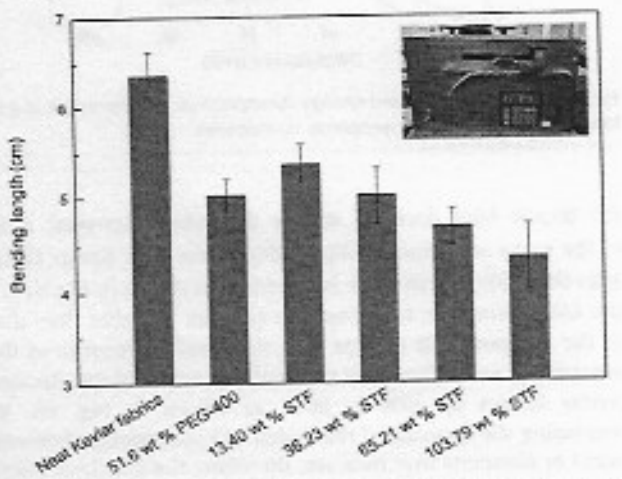


Fig. 9 Bending lengths of Kevlar fabrics treated by different methods.

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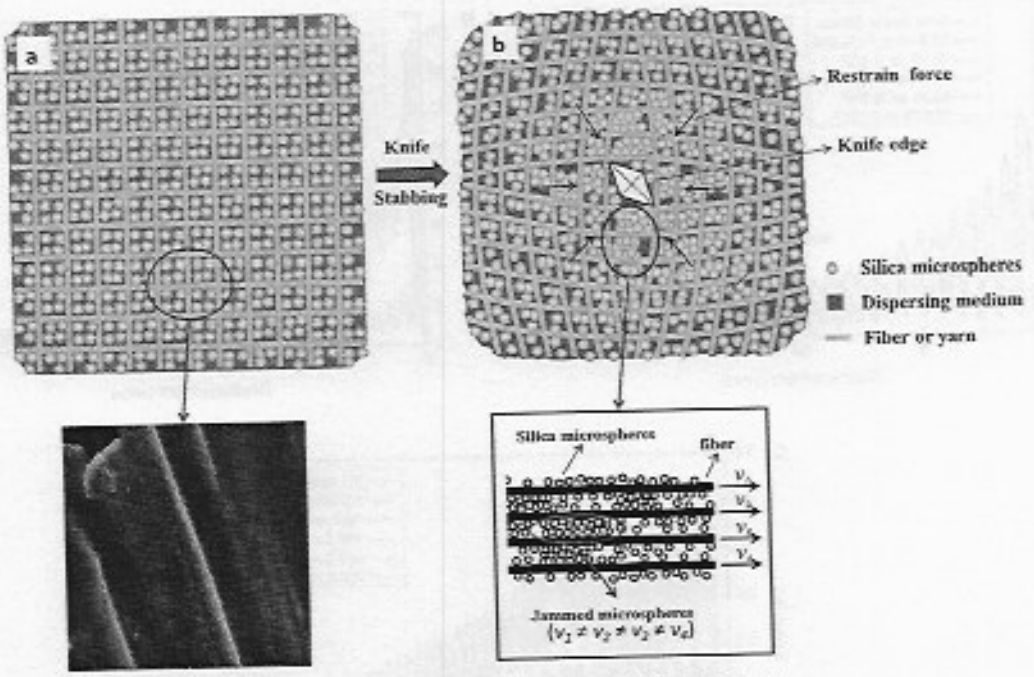


Fig. 11 Schematic of the dynamic knife-stabbing resistance of the STF-prepared fabric composites.

4. Conclusions

Both the dynamic and quasi-static knife-stabbing resistance and the quasi-static mechanical properties of STF-prepared Kevlar fabric composites are significantly improved compared to those of neat Kevlar fabric. The optimal dynamic knife-stabbing resistance is obtained when the added STF is between 36.23 wt% and 65.21 wt%. In this case, the composites are much lighter, thinner and more flexible than the neat Kevlar fabric and cannot even be penetrated by a knife. However, the dynamic stab resistance declines when the fabric contains excessive amounts of STF. The generated forces and the absorbed energies of the composites are much higher than that of the neat Kevlar fabric in the quasi-static knife-stab, and they increase with increasing amount of added STF. The quasi-static mechanical properties of STF-treated Kevlar fabric composites were studied for the first time. Both their tensile strengths and tearing strengths were enhanced significantly compared with those of neat Kevlar fabric. Their tensile strength is increased by 40% to 80%, and their tearing strength is increased by as much as nearly eight times as the amount of added STF increases. Moreover, the flexural rigidities of the composites were superior to that of the neat Kevlar fabric.

The critical velocity of the shear thickening for STF in the composites is very low, and a series of yarn pull-out tests suggests that the increased friction between yarns or filaments is attributed to the shear thickening of the STF. More yarns or filaments will participate in bearing external forces with increased friction, leading to improvement in the dynamic and quasi-static properties of the STF-prepared composites. Regarding the dynamic knife-stabbing resistance, it is detrimental when the composite contains excessive STF. The optimal amount of added STF for the composites to resist dynamic knife impacts is between 36.23 wt% and 65.21 wt%. These composites have good adaptability for both high and low speeds, including dynamic and quasi-static conditions, and are suitable for use as soft body armour materials. Moreover, the STF can be separated easily from the composites and recycled due to its chemical properties.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors are grateful for the financial support provided by the National Science Foundation of China (No. 51303149) and the Foundation for the Fundamental Research Funds for Central Universities (3102014JC01095).

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