

STAB PERFORMANCE OF SHEAR THICKENING FLUID (STF)–FABRIC COMPOSITES FOR BODY ARMOR APPLICATIONS

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ABSTRACT

Conventional body armor systems protect against ballistic threats but have relatively little resistance to stab threats. Consequently, a need exists to create body armor materials that provide both ballistic protection and stab resistance. Previous studies (Lee et al., 2002, 2003) have shown that high strength fabric such as Kevlar impregnated with colloidal shear thickening fluids (STFs) have improved ballistic properties compared to neat fabrics used in conventional body armor systems. In this study, the stab resistance (against cut and puncture threats) of STF-fabric composites is reported. Kevlar and Nylon fabrics are investigated, utilizing a drop tower stab test based on the National Institute of Justice (NIJ) Standard 0115.0. The performance of multi-layer STF-fabric targets is compared to neat fabric targets of similar areal densities. Both qualitative and quantitative results show that fabrics impregnated with STF have improved stab resistance. In particular, significant improvement in puncture resistance (spike threat) is observed for STF-fabric composites compared to their neat counterparts. Additional tests demonstrate that STF addition can improve the resistance of tightly woven fabrics to penetration by syringe needles.

KEY WORDS: Armor Technology, Materials - Fabric/Textile Reinforcement

1. INTRODUCTION

Body armors for U.S. Army personnel have traditionally been designed to provide protection from fragmentation and ballistic threats. However, the increasing relevance of close-quarters, urban conflict necessitates the development of protective, flexible armor systems with additional stab-resistant capabilities. Stab threats encountered by soldiers in the field include direct attacks from knives and sharpened instruments, as well as physical contact with debris, broken glass, and razor wire. The demand for improved stab protection has also been motivated by civilian police forces, particularly in Europe, where restrictions on gun ownership have led to an increase in the proportion of assaults which are committed with knives.

Stab threats can be classified into two categories: puncture and cut. Puncture refers to penetration by instruments with sharp tips but no cutting edge, such as ice picks or awls. These threats are of primary concern to correctional officers, since sharply-pointed objects are relatively easy to improvise. Cut refers to contact with knives with a continuous cutting edge. Knife threats are generally more difficult to stop than puncture, since the long cutting edge presents a continuous source of damage initiation during the stab event.

The development of high strength fibers such as aramid (Kevlar®) and ultrahigh molecular weight polyethylene (Spectra®) have resulted in significant improvements in the performance of body armors against ballistic threats (Cheeseman and Bogetti, 2003). Unfortunately, most ballistic fabrics produced using these high strength fibers provide little protection against stab threats. Commercially available, high yarn count aramid fabrics (Kevlar Correctional™, DuPont Company) have been specifically developed to provide stab (puncture) resistance. However, these high yarn count fabrics are expensive to manufacture, and typically result in a decrease in the ballistic efficiency of the fabric. In order to improve the stab resistance of ballistic fabrics, thermal-sprayed hard ceramic coatings have been applied directly to aramid fabrics (Gadow and Niessen, 2003). These materials have demonstrated increased energy absorption during quasistatic stab testing, but also add significantly to fabric weight. Flambard and Polo (2004) report on knitted fiber constructions for enhanced cut resistance.

Commercially, a number of non-ballistic stab-resistant materials are available. Chain mails are frequently used for cut protection in commercial applications such as meat packing, and have been incorporated into some stab-resistant vests. These mails, however, do not provide puncture resistance. Other commercial designs utilize layers of titanium foil, which offer both cut and puncture resistance. However, both the foil and mail solutions are relatively heavy, and offer little ballistic resistance. Other designs utilize rigid metal, ceramic, or composite plates. These rigid armors can offer excellent stab protection, but are bulky and inflexible, making them uncomfortable to wear and difficult to conceal.

Shear thickening is a non-Newtonian flow behavior observed as an increase in viscosity with increasing shear rate or applied stress (Barnes, 1989; Maranzano and Wagner, 2001; Lee and Wagner, 2003). Concentrated colloidal suspensions consisting of solid particles dispersed in a liquid medium have been shown to exhibit reversible shear thickening resulting in large, sometimes discontinuous increases in viscosity above a critical shear rate. This transition from a flowing liquid to a solid-like material is due to the formation and percolation of shear induced transient aggregates, or “hydroclusters,” that dramatically increase the viscosity of the fluid. Support for this hydrocluster mechanism has been demonstrated experimentally through rheological, rheo-optics and flow-SANS experiments (Bender and Wagner, 1995; Maranzano and Wagner, 2002), as well as computer simulation (Bossis and Brady, 1989; Catherall et al., 2000)

In previous studies (Lee et al., 2002, 2003) we have investigated the ballistic properties of woven aramid fabrics impregnated with a colloidal, discontinuous shear thickening fluid (STF). These investigations have shown that, under some conditions, this STF-fabric composite offers ballistic properties which are superior to neat (non-impregnated) fabrics. Additionally, the addition of STF was shown to cause little or no increase in the thickness or stiffness of the fabric.

In this paper, the stab resistance of STF-fabric composites is reported. Kevlar and Nylon fabrics are tested, with variations in Nylon fabric yarn denier and yarn count explored in order to determine the importance of fabric architecture on STF-fabric performance. Tests based on the National Institute of Justice (NIJ) standard for stab protective armors are performed using a drop tower equipped with knife and spike impactors. Additional results are included for quasistatic stab loading of fabrics, including loading using a conventional syringe needle. These needle experiments are especially relevant for applications in medical protective clothing and storage.

Table 1: Stab test targets.

Label	Yarn material	Yarn denier	Yarn count (yarns/in)	STF wt%	Single layer areal density (g/cm ²)	Number of layers in target	Target areal density (g/cm ²)
Kevlar	KM-2 Kevlar	600	34×34	0.0	0.0180	15	0.270
STF-Kevlar				25.1	0.0225	12	0.271
LD Nylon	Heat set Nylon	525	41×42	0.0	0.0204	13	0.265
STF-LD Nylon				27.7	0.0261	10	0.261
MD Nylon	Heat set Nylon	840	31×32	0.0	0.0257	10	0.257
STF-MD Nylon				19.6	0.0308	9	0.277
HD Nylon	Heat set Nylon	1050	23×21	0.0	0.0440	6	0.264
STF-HD Nylon				19.5	0.0526	5	0.263

2. EXPERIMENTAL

2.1 Materials STF's were generated by dispersing surface-functionalized colloidal silica particles (450 nm) in 200 MW polyethylene glycol at a volume fraction of approximately 52%. Rheological characterization of this STF confirmed discontinuous shear thickening at a shear rate of approximately 20 s⁻¹.

One type of Kevlar fabric, Hexcel-Schwebel (Anderson, SC) Style 706, and three types of Nylon fabric, from Performance Textiles (Greensboro, NC), were tested. The yarn deniers, yarn counts, and areal densities for the fabrics are given in Table 1, and a photograph is shown in Figure 1. All fabrics are plain woven. We will use the abbreviations LD, MD, and HD to refer to the Nylon fabrics composed of low denier (525), medium denier (840), and high denier (1050) yarns, respectively.

To fabricate the STF-fabric composites, the STF was first diluted in ethanol at a 3:1 volume ratio of ethanol:STF. Individual fabric layers, each measuring 38.1 cm × 38.1 cm, were then soaked in the solution for one minute, squeezed to remove excess fluid, and dried at 60°C for 30 minutes. This drying process removes the ethanol co-solvent, and leaves behind STF in the fabric. The STF weight additions reported for each target represent an average value over all of the target layers. STF addition is greatest, at 27.7%, for the highest yarn count fabric (LD Nylon), and is lowest, at 19.5%, for the lowest yarn count fabric (HD Nylon). These STF-fabrics were then arranged into multilayer targets, as shown in Table 1. The number of fabric layers for each target was selected to match overall target areal densities as closely as possible. Within each multi-layer target the amount of STF in each layer varies somewhat, resulting in layer-to-layer areal density standard deviations of 1-4%. For consistency, the fabric layers in these targets are ordered in increasing areal density, with the impact face being the lowest areal density layer.

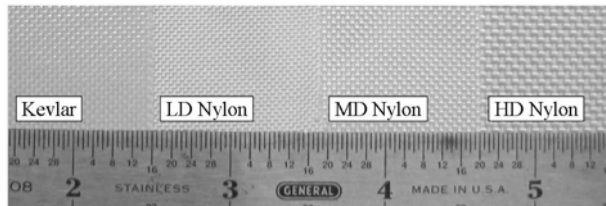


Figure 1: Kevlar and Nylon fabrics tested.

Additional targets were prepared for needle testing based on Hexcel-Schwebel Style 779, also known as DuPont Correctional[®] Kevlar (CK). This fabric has a 70×70 yarns per inch, plain woven structure, using 200 denier Kevlar 159 yarns, with an areal density of 0.0132 g/cm². The very tight weave of the CK fabric provides higher puncture resistance than conventional woven fabrics. STF-CK fabrics were prepared using the same process used to prepare the other STF fabrics, resulting in an average weight gain of 23.5%wt. Six-layer targets were constructed out of both neat CK and STF-CK fabrics. Note that the layer count, rather than areal densities, are matched for these targets. This comparison was chosen because, for needle protection applications such as gloves and soft containers, fabric thickness and flexibility are more relevant than weight.

2.2 Drop tower testing The stab tests performed are based on the NIJ Standard 0115.0 for stab resistance of body armor. Two NIJ-specified impactors are used: the "S1" knife, and the "spike" (Figures 2a and 2b). The impactors are rigidly mounted to a crosshead in a conventional rail-guided drop tower. The stab targets are placed on a multi-layer foam backing (Figure 2c), as specified by the NIJ standard. This backing consists of four layers of 5.8-mm-thick neoprene sponge, followed by one layer of 31-mm-thick polyethylene foam, backed by two 6.4-mm-thick layers of rubber (all backing materials from PCF Foam Corp., Cincinnati, OH). Synthetic polymer-based Polyart[™] witness papers (Arjobex Corp., Charlotte, NC) were placed between the target and foam backing, and behind each layer of neoprene sponge.

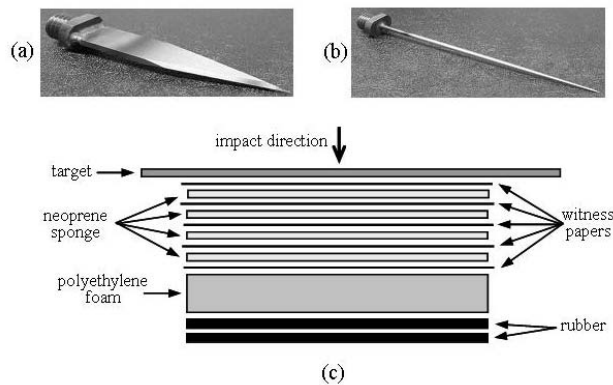


Figure 2: (a) Knife impactor. (b) Spike impactor. (c) Foam backing.

Table 2: Conditions for drop tower stab testing.

Drop mass (kg)	Drop height (m)	Theoretical impact velocity (m/s)	Theoretical impact energy (J)	
			Spike	Knife
2.33	2.34	0.1	2.29	2.29
2.74	2.75	0.1	2.68	2.69
3.14	3.15	0.1	3.08	3.09
3.60	3.61	0.1	3.53	3.54
4.01	4.01	0.1	3.93	3.94
4.67	4.68	0.1	4.58	4.59
2.33	2.34	0.25	5.72	5.74
2.33	2.34	0.5	11.43	11.47
2.33	2.34	0.75	17.15	17.21

To perform a stab test, the impactor is mounted to the crosshead, which is then loaded with weights to a specific mass. The crosshead is dropped from a fixed height to impact the target. The velocity of the crosshead at impact is measured using fixed flags and sensors attached to the frame. Impact loads are measured using a load cell mounted to the impactor. The depth of penetration into the target is quantified in terms of the number of witness paper layers penetrated by the impactor. Note that there are 5 layers of witness paper, so the maximum reported depth of penetration is 5 layers.

Two sets of experiments were performed for each target. For the first set, the drop mass (m) was fixed (2.34 kg for the knife impactor, 2.33 kg for the spike impactor) and the drop height (h) was varied from 0.1 to 0.75 m. For the second set of experiments, the drop height was fixed at 0.1 m (velocity of ~ 1.4 m/s) and the drop mass was varied from 2.34 kg to 4.68 kg for the knife, and from 2.33 kg to 4.67 kg for the spike. The full set of testing conditions are given in Table 2. The Nylon and STF-Nylon targets were fully defeated (through 5 witness layers) at energy levels of 11.5 J, so experiments at the highest energy level (17.2 J) were not performed on these materials. Variations in the actual impact velocities result in some deviation (~ 1 -10%) of the actual impact energies relative to the theoretical values. All plotted data reports the actual measured impact energies.

Tests were performed on both the neat fabric and STF-fabric targets. The same targets were used for all tests, with each impact point spaced at least 5.28 mm from the target edge and from previous impact locations. The targets were held in place during testing using nylon straps. The sharpness of the impactors was monitored between tests by using a modified hardness tester (as described by the NIJ standard), and did not vary systematically during the experiments.

The stab testing procedure used in this study differs from the NIJ study in two important ways. First, the NIJ standard uses a two-mass, damped impactor. This damping more closely represents realistic stabbing dynamics than our rigidly-mounted impactor. This damped configuration is also much easier to defeat than our rigid fixture. Therefore, our energy values cannot be directly compared to NIJ-based energy values, but we expect superior performance for our materials in the NIJ standard tests of similar energy. Secondly, our configuration uses multiple witness paper layers to measure depth of penetration. The NIJ standard calls for inferring depth of penetration based on measuring the final location of the blade in the backing material. However, this approach is very inaccurate, time-consuming, and does not account for spring-back of the impactor out of the backing. In contrast, our witness paper approach is objective, rapid, and simple to implement.

Note that the allowable depth of penetration for the NIJ standard, for which injury would be unlikely, is 7 mm. Since the thin foam witness layers are 5.8 mm thick, and the first layer of witness paper is on top of the foam backing, tests in which only 1 or 2 witness layers are penetrated correspond to adequate protection.

2.3 Quasistatic testing To complement the drop tower tests, quasistatic stab tests were also performed. The knife and spike impactors were mounted to the upper grip of an MTS Synergie universal tester, with the target placed below the impactor and on top of the same multi-layered backing as used in the drop tower tests. The impactor was then pushed into the target at a rate of 5 mm/min to a total depth of 30 mm. Load versus displacement data was recorded.

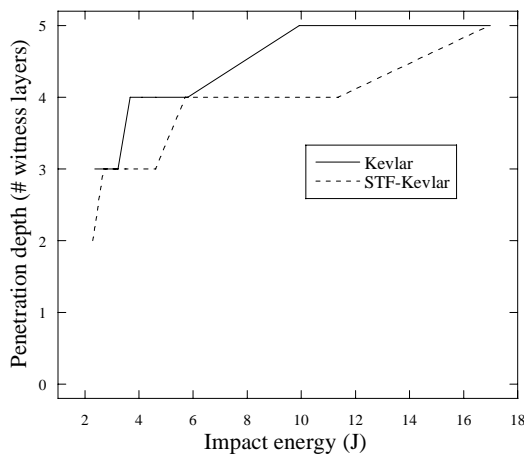
2.4 Quasistatic needle testing Additional quasistatic tests were performed by pushing an 18 gauge (1.27 mm nominal diameter) disposable syringe needle (Becton-Dickinson Precisionglide, from Aldrich), instead of a spike or knife impactor, into fabric targets. These tests utilized the same MTS

Synergie universal tester, witness papers, and foam backing used for the spike and knife quasistatic tests. Only the CK and STF-CK fabric targets were tested for needle puncture resistance.

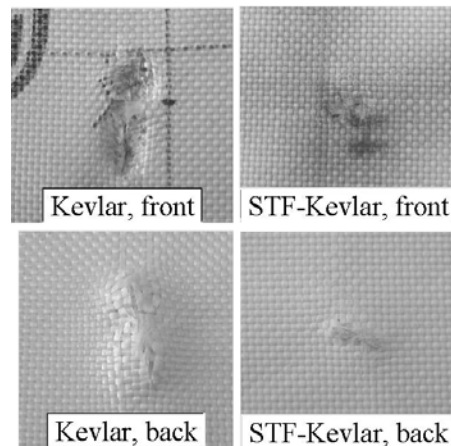
3. RESULTS

3.1 Drop tower testing Figure 3a shows the drop tower stab performance of the Kevlar and STF-Kevlar targets against the knife impactor. As impact energy increases, depth of penetration into the backing material increases. In general, the STF-Kevlar target exhibits slightly less penetration depth as compared with the Kevlar target. At higher energy levels, both targets reach the maximum penetration depth, 5 witness layers. Figure 3b shows the fabric targets after testing, at $m=2.34$ kg and $h=0.75$ m. Note that extensive yarn cutting occurs in both targets, although the extent of damage is clearly less for the STF-Kevlar target.

Figure 4a shows the drop tower stab performance of the Kevlar and STF-Kevlar targets against the spike impactor. As impact energy increases, depth of penetration into the backing material increases. The STF-Kevlar target exhibits significantly better stab resistance as compared with the Kevlar target. The Kevlar target exhibits maximum penetration, 5 witness layers, at an energy of ~ 4 J. In contrast, even at the highest energy level of ~ 17 J, the STF-Kevlar target is only penetrated through 3 witness layers. Furthermore, at this highest energy level against the STF-Kevlar target, the spike impactor was plastically bent. The bend occurred at a distance of ~ 3 cm from the tip of the spike, to an angle of $\sim 15^\circ$ from center. Figure 4b shows the fabric targets after testing, at $m=2.33$ kg and $h=0.75$ m. The Kevlar target shows significant puncture damage, while there is little obvious damage to the STF-Kevlar target. Note that, in the Kevlar target, there is no significant fiber fracture. Instead, the spike defeats the fabric by parting Kevlar filaments, both within yarns and between yarns.



(a)



(b)

Figure 3: (a) Knife drop tower results for Kevlar and STF-Kevlar fabrics. (b) Photographs of fabric damage at $m=2.34$ kg and $h=0.75$ m.

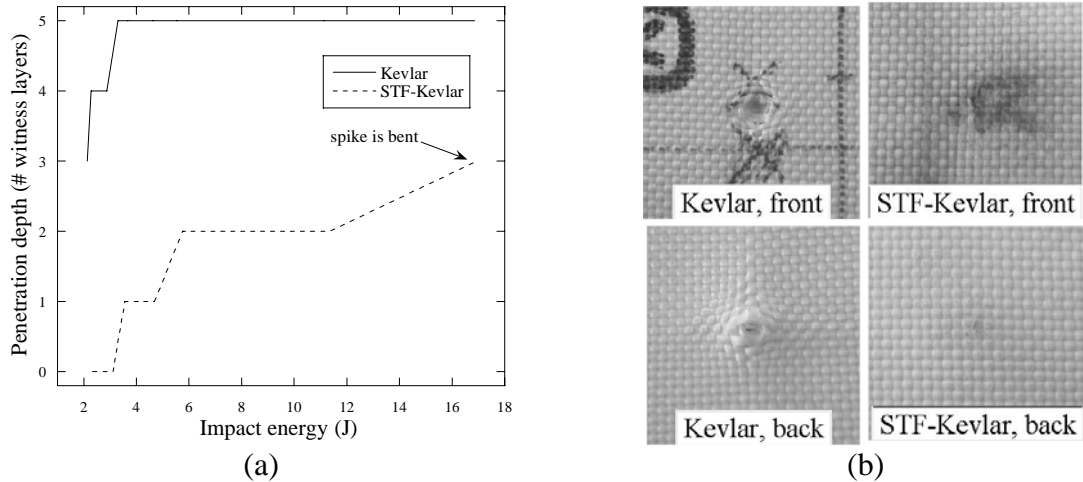


Figure 4: (a) Spike drop tower results for Kevlar and STF-Kevlar fabrics. (b) Photographs of fabric damage at $m=2.33$ kg and $h=0.75$ m.

Figure 5 shows the dynamic loads on the knife and spike impactors during impact of the Kevlar and STF-Kevlar targets. Against the knife threat, the Kevlar and STF-Kevlar exhibit comparable load histories, with slightly higher loads in the STF-Kevlar case. Against the spike threat, the loads during STF-Kevlar impact are much higher than the loads during neat Kevlar impact. The peak and drop in load for the neat Kevlar specimen at ~ 2 ms is characteristic of fabric break-through.

Figure 6a shows the drop tower stab performance of the Nylon and STF-Nylon targets against the knife impactor. As impact energy increases, depth of penetration into the backing material increases. The STF-Nylon targets exhibit slightly less penetration depth than the neat Nylon targets. For the neat fabrics, fabric performance increases slightly as yarn denier decreases. In contrast, for the STF-Nylon targets, fabric performance increases slightly as yarn denier increases. All of the Nylon and STF-Nylon fabrics perform comparably to the neat Kevlar target against the knife impactor.

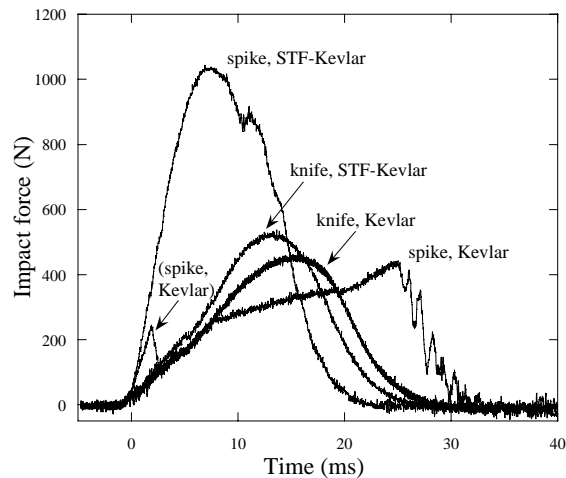


Figure 5: Load versus time curves for Kevlar and STF-Kevlar targets under knife ($m=0.1$ kg, $h=0.25$ m) and spike ($m=0.1$ kg, $h=0.75$ m) drop tower loading.

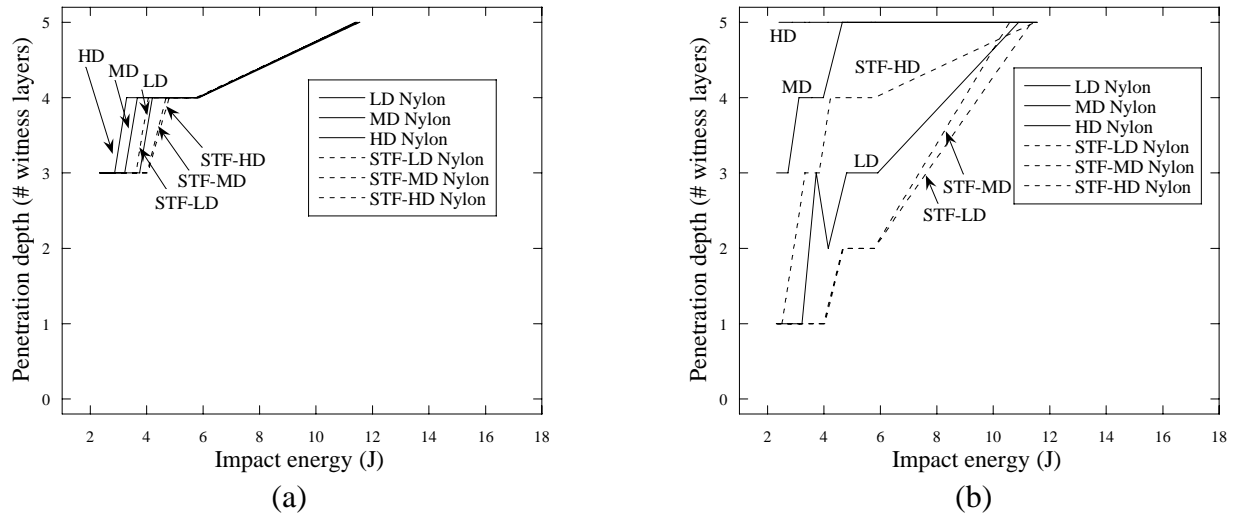


Figure 6: (a) Knife and (b) spike drop tower results for Nylon and STF-Nylon fabrics.

Figure 6b shows the drop tower stab performance of the Nylon and STF-Nylon targets against the spike impactor. As impact energy increases, depth of penetration into the backing material increases. The STF-Nylon targets exhibit moderately better stab resistance as compared with the Nylon targets, for all yarn deniers. For both neat and STF-impregnated Nylons, stab resistance increases as yarn denier decreases. Note that all STF-Nylon targets, and neat LD Nylon target, exhibit better spike protection than the neat Kevlar target. The STF-Kevlar target, however, performed significantly better than any of the Nylon or STF-Nylon targets.

Photographs of some of the Nylon and STF-Nylon targets, after spike testing, are shown in Figure 7. Comparing the MD Nylon and STF-MD Nylon targets, significantly more damage is evident in the STF-MD target. Comparing the STF-LD Nylon and STF-HD Nylon, there is significantly more damage in the STF-LD target. In fact, there is little evidence of damage in the STF-HD target, even though the spike penetrated through all 5 layers of witness paper. The damage on the back face of the STF-LD target includes significant fiber fracture.

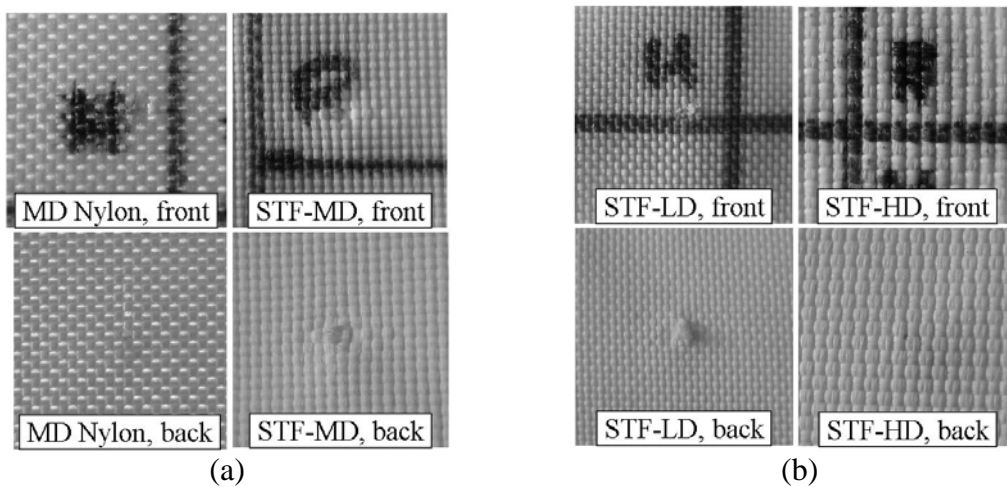
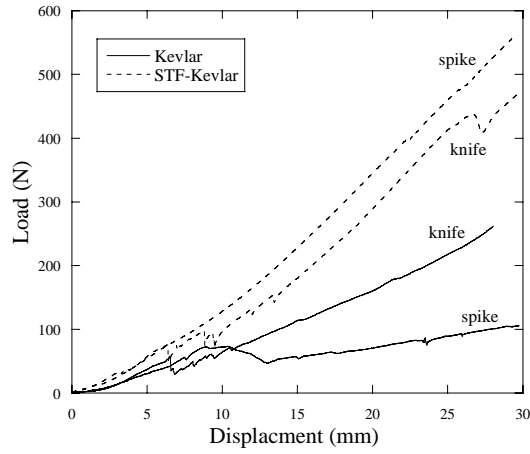
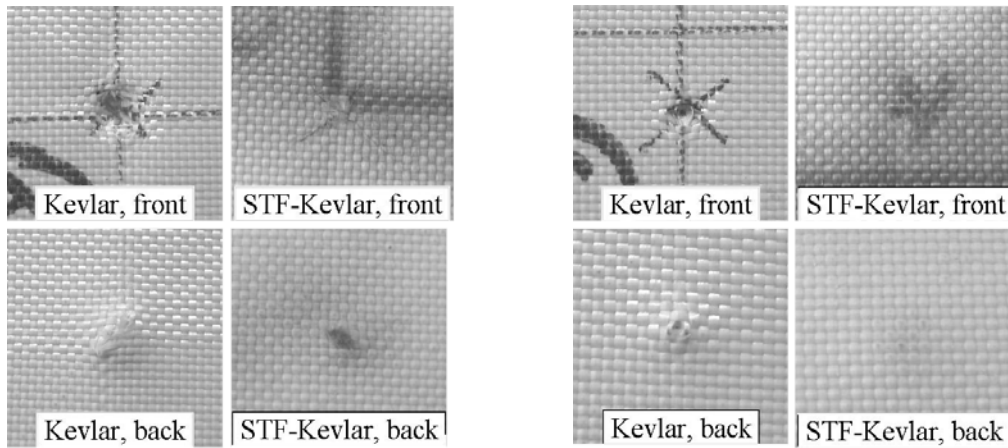


Figure 7: Photographs of fabric damage at $m=2.33$ kg and $h=0.5$ m, for spike impactor. (a) MD Nylon and STF-MD Nylon. (b) STF-LD Nylon and STF-HD Nylon.



(a)



(b)

(c)

Figure 8: (a) Load-displacement curves for quasistatic loading of Kevlar and STF-Kevlar targets, against both spike and knife impactors. Photographs of fabric damage after testing against the (b) knife and (c) spike impactors.

These results provide further insight into damage mechanisms in these fabrics. The neat MD Nylon and STF-HD Nylon likely allow the spike to penetrate between yarns and filaments. The high elongation to failure of Nylon (~15-20%), as compared with Kevlar (3-4%), enables the yarns to stretch during this penetration process, rather than pull-out from the weave (as is observed for Kevlar, Figure 4b). Upon removal of the spike, the yarns relax and little damage is evident. In contrast, the STF-LD and STF-MD have restricted yarn mobility, due both to the presence of STF and their high yarn count. The yarns are more constrained, and are therefore more highly loaded during penetration, increasing their probability of failure. As compared with the Kevlar, the Nylon fabrics are much more likely to fracture, due to their lower tenacity (~7 g/denier vs. ~ 28 g/denier for Nylon and Kevlar, respectively).

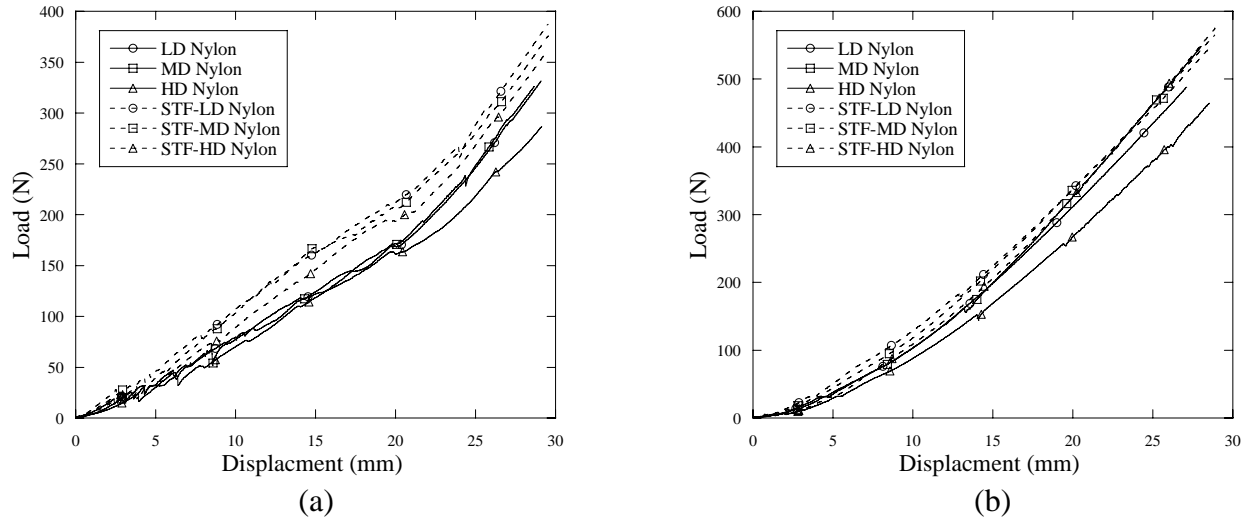


Figure 9: Load-displacement curves for quasistatic loading of Nylon and STF-Nylon targets, against both (a) knife and (b) spike impactors.

3.2 Quasistatic testing Figure 8a shows the quasistatic loading results for the Kevlar and STF-Kevlar targets against both the knife and spike impactors. Against the knife impactor, the STF-Kevlar target supports significantly higher loads than the neat Kevlar target. This behavior correlates with the appearance of the targets after testing, Figure 8b, which shows significantly less damage in the STF-Kevlar target as compared with the neat Kevlar target. However, for both Kevlar and STF-Kevlar targets, 4 witness paper layers were penetrated. Against the spike impactor, the differences in behavior are more dramatic. The neat Kevlar target supports very little load before allowing puncture, while the STF-Kevlar target supports high loads and is never punctured. Figure 8c shows these fabrics after testing. For the neat Kevlar target after spike loading, all 5 witness papers were penetrated while none of the witness papers were penetrated for the STF-Kevlar target.

Figure 9 shows the quasistatic loading results for the Nylon and STF-Nylon targets. In contrast to the Kevlar results, the STF-Nylon targets exhibit only slightly higher loading than the neat Nylon targets, with fabric loading increasing slightly as yarn denier decreases. It is also remarkable that the neat Nylon load levels are significantly higher than the loads supported by the neat Kevlar fabric. For all Nylon and STF-Nylon knife quasistatic experiments, 4 witness papers were penetrated. For the spike quasistatic experiments, 1 witness paper was penetrated for all STF-Nylon targets and the LD Nylon target, while the 4 and 3 witness layers were penetrated for the MD and HD Nylon targets, respectively.

3.3 Quasistatic needle testing Figure 10 shows the load versus displacement curves for six-layer CK and STF-CK targets against the 18 gauge needle. The curves show that the loads in the STF-CK target are roughly twice as high as those in the neat CK target, with peak loads of 45.7 and 24.0 N, respectively. Also shown in the plot is the loading curve for the foam backing alone, which remains significantly lower than the fabric curves and never rises above 10 N. These results show that STF addition can dramatically improve the puncture resistance of tightly woven fabrics against very small, sharp puncture threats.

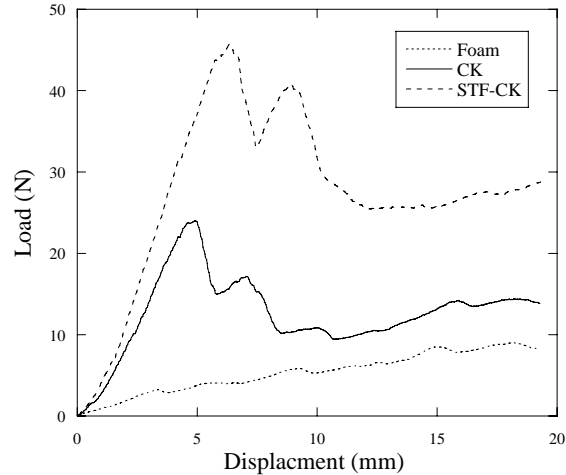


Figure 10: Load-displacement curves for quasistatic needle loading of six-layer CK and STF-CK targets, and needle loading of the backing foam alone.

4. DISCUSSION AND CONCLUSIONS

The drop tower results demonstrate that the addition of STF to Kevlar fabric can slightly improve its resistance to knife threats. However, it is important to note that the Kevlar and STF-Kevlar targets were compared at equal areal densities. The fabric layers for the two targets were significantly different, with the 12-layer STF-Kevlar target providing better protection than the 15 layer neat Kevlar target. Since the addition of STF to fabrics has been shown to cause little measurable increase in fabric thickness or flexibility (Lee et al., 2003), these results show that STF-Kevlar protective fabrics could offer knife protection with thinner, more flexible armors than simple neat Kevlar designs. The quasistatic knife testing results show that, at slow loading rates, the presence of STF greatly improves the cut resistance of the Kevlar fabric. The differences between the high speed (impact) and low speed (quasistatic) defeat mechanisms require further study.

The drop tower and quasistatic spike tests show that STF addition significantly improves the puncture resistance of Kevlar fabrics. Again, note that the STF-Kevlar target exceeded the performance of the neat Kevlar target even though the STF-Kevlar target had 20% fewer fabric layers. The mechanism for this enhancement is most likely a decrease in yarn mobility within the fabric, in agreement with previous yarn pull-out and ballistic studies (Egres et al., 2003). The STF acts to restrict motion of the filaments and yarns, preventing the sharp tip of the spike from pushing aside yarns and filaments and penetrating between them. This mechanistic hypothesis is also supported by the knife drop tower results. Since the knife threat primarily defeats fabrics by cutting filaments, decreases in yarn mobility would have much less influence on global cut resistance of the fabric.

The Nylon studies show that fabric architecture (yarn denier and yarn count) have very little influence on cut performance. In contrast, puncture resistance increases measurably as yarn denier decreases (yarn count increases). Two independent mechanisms are likely responsible for this trend. Most importantly, higher yarn count fabrics have more restricted yarn mobility, analogous to the effects of adding STF to neat fabrics. Secondly, since the low denier fabrics have lower areal densities, the number of plies in targets of fixed areal density increases as yarn denier decreases (the LD Nylon target had 13 layers, while the HD Nylon target had 6 layers). This increased layer count introduces increased inter-ply interfaces, which could enhance the ability of the target to defeat the impactor.

Comparing Nylon and Kevlar performance, the Nylon fabrics are more likely to stretch and contract. This behavior results in little evidence of fabric damage, even in cases where the fabric is completely penetrated. This behavior could also explain why both the Nylon fabrics showed little dependence on yarn count or STF content during quasistatic testing. The high elongation of the fabrics, combined with the slow loading rates, may have allowed the fabrics to stretch rather than cut or puncture. The Nylon fabrics are also more likely to exhibit yarn fracture, as compared with the Kevlar fabrics, due to their lower tenacity.

The Nylon studies also demonstrate, for the first time, that the beneficial effects of STF addition are not restricted to aramid (Kevlar) fabrics. This result presents new opportunities to exploit STF addition with other high performance fabrics such as ultrahigh molecular weight polyethylene (Spectra[®]) or PBO (Zylon[®]). The low cost and high availability of Nylon fabrics may also enable unique protective applications such as shelters, vehicle armors, and sporting goods.

The needle studies demonstrate that the protective benefits observed for spike impact into conventional woven fabrics also scales to much smaller size scale penetrators and fabric architectures. These results indicate that a wide range of threats can be addressed through STF modification of fabrics.

Finally, these results show that ballistic fabrics can be modified to provide enhanced stab resistance. Previous studies have indicated that these STF-based modifications may also improve fabric ballistic properties. Therefore, these results demonstrate that it may be possible to engineer a single fabric material which is capable of providing meaningful levels of both ballistic and stab protection, properties which are often engineered independently with conventional materials.

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