STAB RESISTANCE OF SHEAR THICKENING FLUID (STF)–KEVLAR COMPOSITES FOR BODY ARMOR APPLICATIONS

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ABSTRACT

The stab resistance of shear thickening fluid (STF)-Kevlar and STF-Nylon fabric composites are investigated and found to exhibit significant improvements over neat fabric targets of equivalent areal density. Specifically, dramatic improvements in puncture resistance (spike threat) are observed under high and low speed loading conditions, while slight increases in cut protection are also observed. These results, combined with improvements in ballistic properties reported in earlier studies (Lee et al., 2002, Lee et al. 2003), indicate that these novel materials could be used to fabricate flexible body armors which provide improved protection against both stab and ballistic threats.

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 decreases 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

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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

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 are performed using a drop tower equipped with knife and spike impactors, based on the National Institute of Justice (NIJ) standard for stab protective armors. Additional results are included for quasistatic stab loading of fabrics.

2. EXPERIMENTAL

2.1 Materials

STFs were generated by dispersing commercially available, surface functionalized colloidal silica particles (500 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.

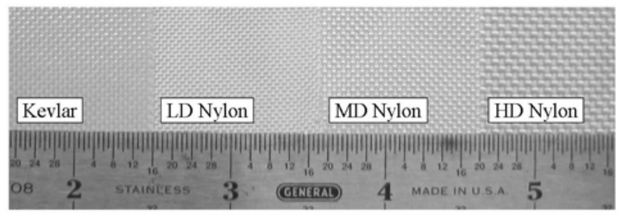


Figure 1: Kevlar and Nylon fabrics tested.

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. 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.

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.,

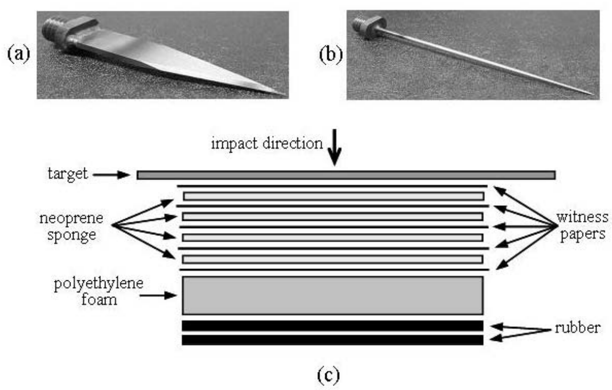


Figure 2: (a) Knife impactor. (b) Spike impactor. (c) Foam backing.

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			Spike	Knife
2.33	2.34	0.1	1.40	2.29	2.29
2.74	2.75	0.1	1.40	2.68	2.69
3.14	3.15	0.1	1.40	3.08	3.09
3.60	3.61	0.1	1.40	3.53	3.54
4.01	4.01	0.1	1.40	3.93	3.94
4.67	4.68	0.1	1.40	4.58	4.59
2.33	2.34	0.25	2.21	5.72	5.74
2.33	2.34	0.5	3.13	11.43	11.47
2.33	2.34	0.75	3.84	17.15	17.21

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.

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.

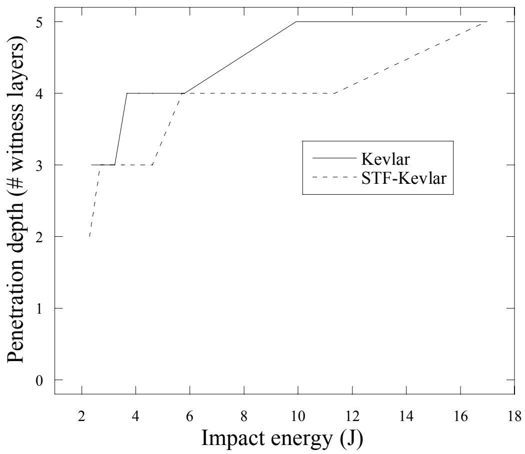
2.3 Quasistatic testing

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 than pushed into the target at a rate of 5 mm/min to a total depth of 30 mm. Load versus displacement data was recorded.

3. RESULTS

2.1 Drop tower testing

Figure 3a shows the drop tower stab performance of the Kevlar and STF-Kevlar targets against the knife



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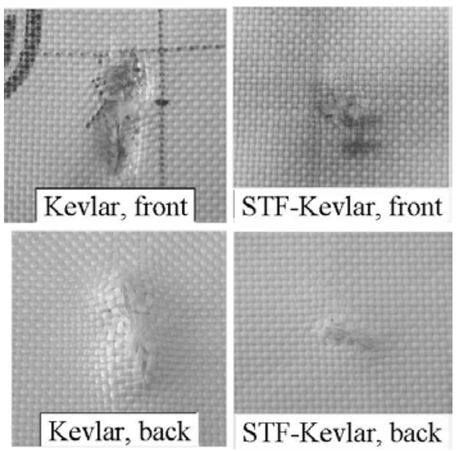

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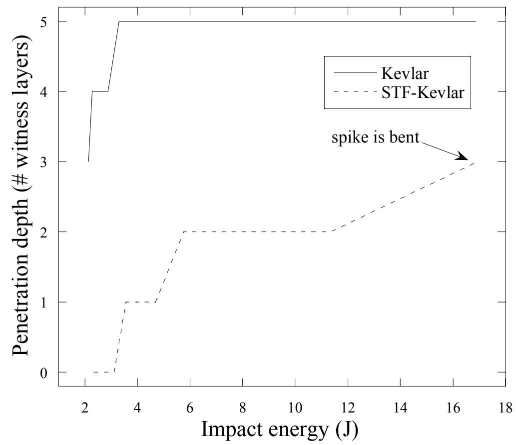
Figure 3: (a) Knife drop tower results for Kevlar and STF-Kevlar fabrics. (b) Photographs of fabric damage at m=2.34 kg and h=0.75 m.



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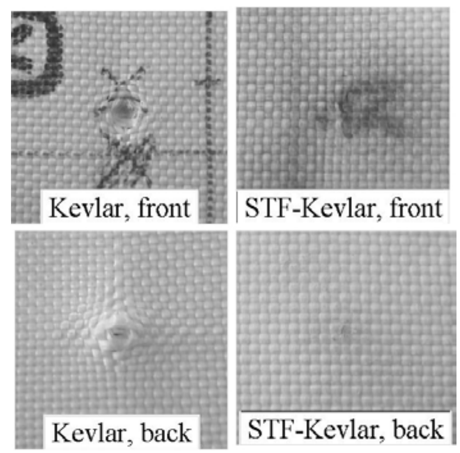


(b)

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.

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 ~ 15° 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.

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 6 shows the drop tower stab performance of the Nylon and STF-Nylon targets against the knife impactor.

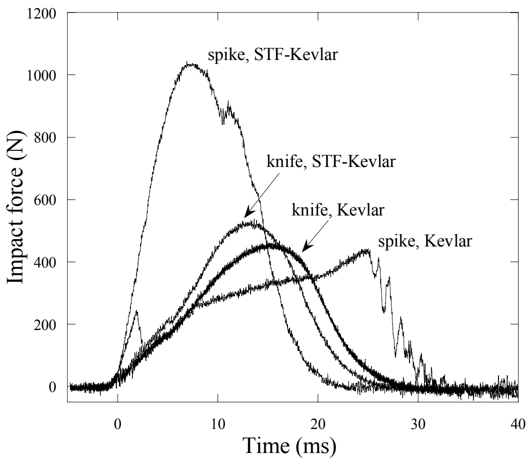


Figure 5: Load versus time curves for Kevlar and STF-Kevlar targets under knife (m=0.1 kg, h=0.25 m) and spike (m=0.1 kg, h=0.75 m) drop tower loading.

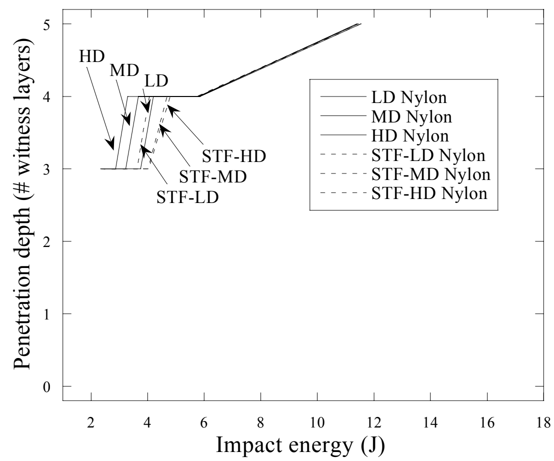


Figure 6: Knife drop tower results for Nylon and STF-Nylon fabrics.

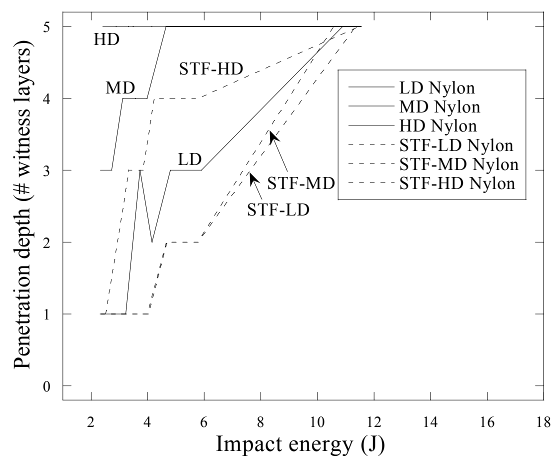


Figure 7: Spike drop tower results for Nylon and STF-Nylon fabrics.

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.

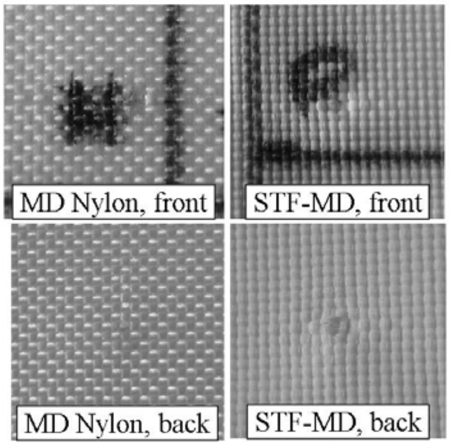
Figure 7 shows the drop tower stab performance of the Nylon and STF-Nylon targets against the spike impactor. As impact energy increases, depth of penetration into the backing material increases. The STF-Nylon targets exhibit moderately better stab resistance as compared with the Nylon targets, for all 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 8. 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.

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).

2.2 Quasistatic testing

Figure 9a 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 9b, which shows significantly less damage in the STF-Kevlar target, as compared with the neat Kevlar target. However, for



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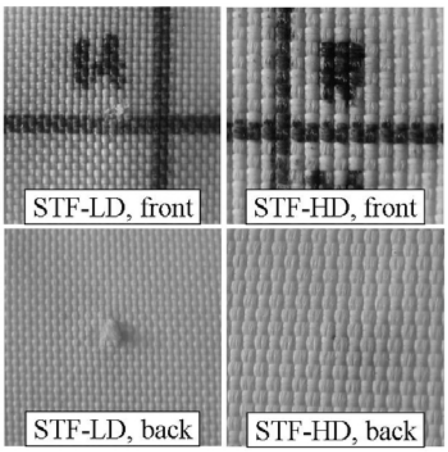
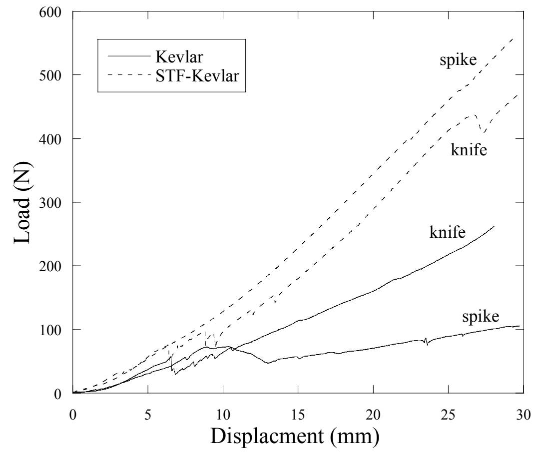


(b)

Figure 8: 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.

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 9c 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 10 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



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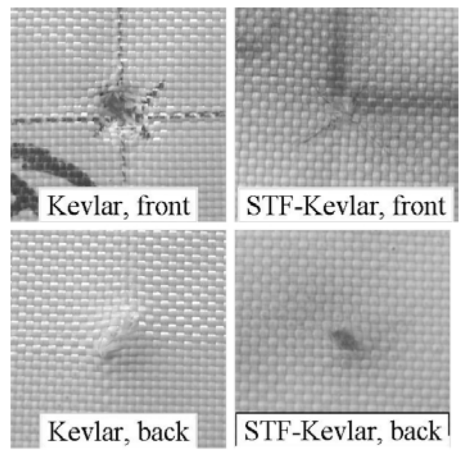

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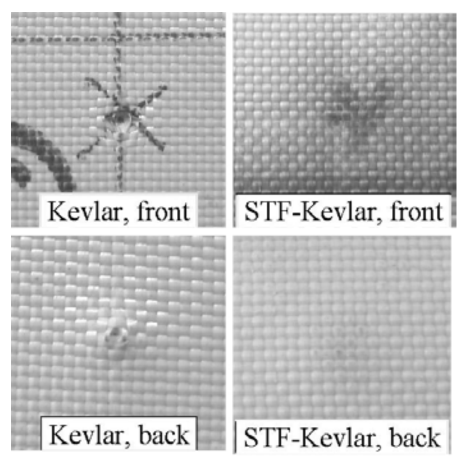

(c)

Figure 9: (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.

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.

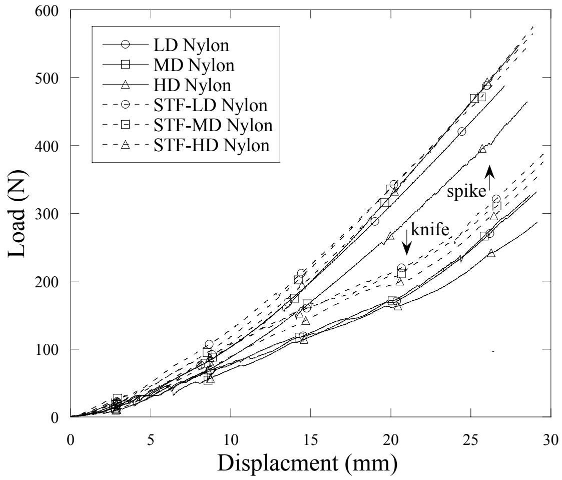

Figure 10: Load-displacement curves for quasistatic loading of Nylon and STF-Nylon targets, against both spike and knife impactors.

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. Secondarily, 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.

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.

ACKNOWLEDGEMENTS

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Stab Resistance of Shear Thickening Fluid (STF)– Kevlar Composites for Body Armor Applications

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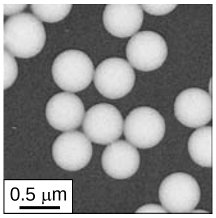
Orlando, FL
2 December 2004

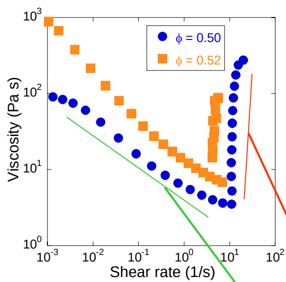
Outline

- **Background**
  - **Shear thickening fluids (STFs)**
  - **STF-fabric composites**
- **Materials**
  - **STF components and preparation**
  - **Fabric and STF impregnation**
- **Testing**
  - **Stab testing**
    - **Drop tower**
      - **Spike**
      - **Knife**
    - **Quasistatic**
  - **Archery testing**
- **Fieldability**
- **Conclusions**

Shear Thickening Fluid (STF)

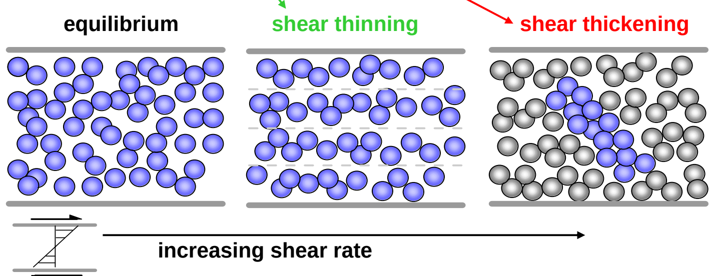


colloidal silica particles




shear-thickening fluid

- Liquid phase highly filled with rigid, colloidal particles
- At high shear rates, hydro-dynamic forces overcome repulsive interparticles forces, and hydroclusters form
- Particles collide, material becomes macroscopically rigid

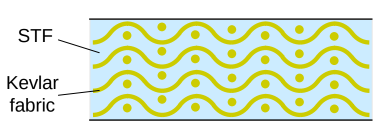


Objective

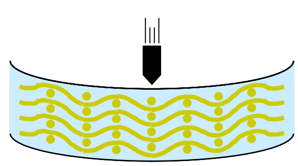
- Impregnate STF into fabric to improve its protective properties
  - STF should be flowable and deformable during low speed, low deformation events
    - STF-fabric should be drapable, flexible like ordinary fabrics
  - STF should be rigid during high speed, high deformation events
    - STF may enhance the ability of the fabric to protect against threats such as projectiles and sharp objects
- U.S. Army applications
  - Improve flexbility, reduce weight and thickness of vest materials
  - Enable flexible, low thickness extremities protection


PASGT Vest
Kevlar® 29


Interceptor Vest
Kevlar® KM2

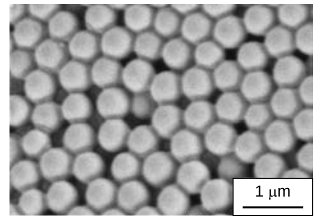


before impact

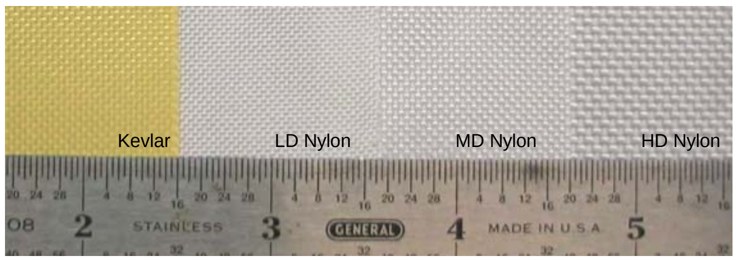

during impact

Materials

- STF
  - 450 nm silica particles
  - Polyethylene glycol carrier fluid
  - Silica particles added at 0.52 volume fraction, mixed to achieve high dispersion
- Fabrics → all fabric plain woven
  - Kevlar → Hexcel-Schwebel Style 706
    - 600 denier KM-2, 34x34 yarns per inch (ypi), 0.0369 lbm/ft² (psf)
  - Nylon → Performance Textiles, Inc.
    - Low denier (LD): 525 denier, 41x42 ypi, 0.0418 psf
    - Medium denier (MD): 840 denier, 31x32 ypi, 0.0527 psf
    - High denier (HD): 1050 denier, 23x21 ypi, 0.0901 psf

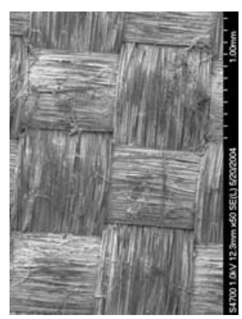


450 nm colloidal silica



Fabric Impregnation

- Processing route
  - STF diluted in ethanol
  - Fabric dipped into solution
  - Fabric squeezed in roller to remove excess
  - Fabric dried for 30 minutes at 150ºF to remove ethanol
- Impregnate fabrics at ~20%wt STF
  - Control STF wt% by ethanol:STF ratio in dip bath
  - All fabric targets have comparable areal density



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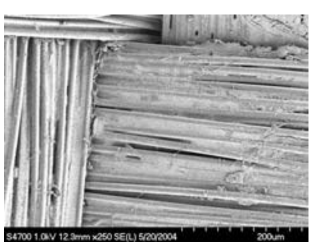
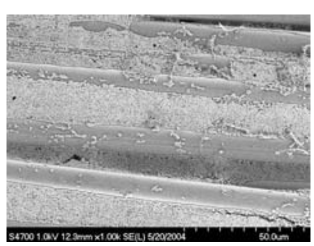
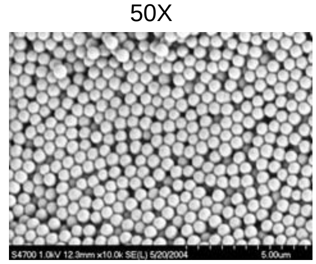


250X



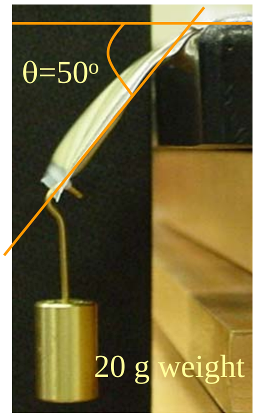
1000X



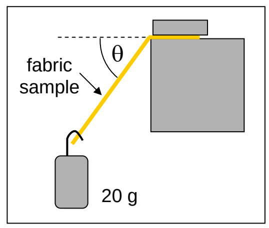
10,000X

Flexibility / Thickness of STF-Impregnated Kevlar

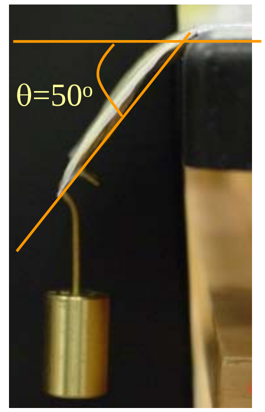
- Adding **STF** to Kevlar fabric **does not change** its **flexibility or thickness**
  - STF fabrics can be draped and flexed like normal fabrics



4-layer Kevlar:
Thickness: 1.4 mm
Weight: 1.9 g



4-layer STF-Kevlar:
Thickness: 1.4 mm
Weight: 2.3 g

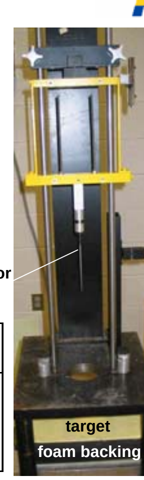


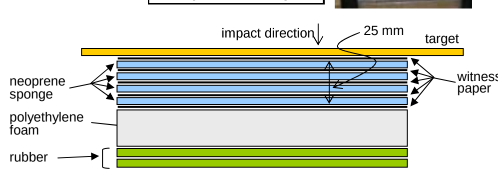
Stab Resistance Testing

- Testing method based on **NIJ Standard 115.00** (2000)
  - Drop tower with two types of impactors
    - **Knife blade** (NIJ "knife blade S1")
    - **Ice pick** (NIJ "spike")

  - Stab target backed by multi-layer **foam support**
  - Measure **depth of penetration** of spike into backing
    - Witness papers between foam layers determine whether puncture occured
  - Vary **impact energy** by varying **drop height** (velocity) and **drop mass**

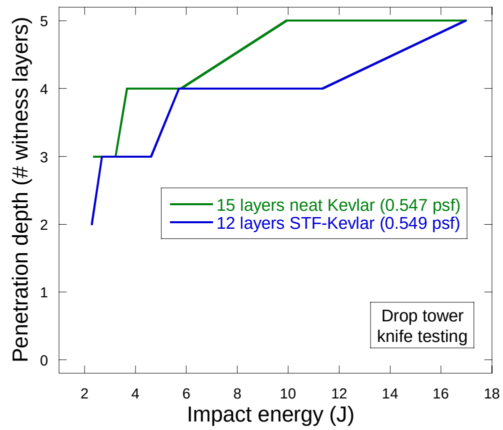
Number of paper layers penetrated	Penetration depth (mm)
0	0
1	0 - 5.8
2	5.8 - 11.6
3	11.6 - 17.4
4	17.4 - 23.2
5	> 23.2





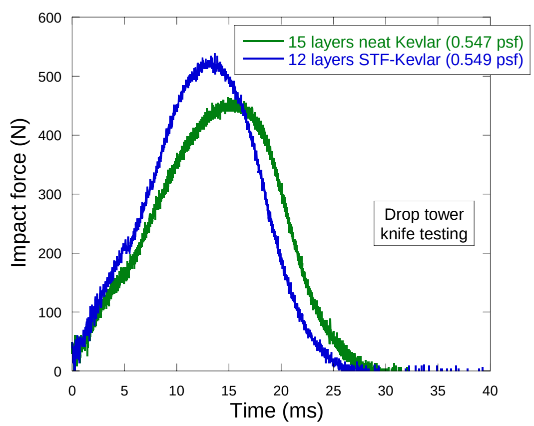
Knife Stab Results (1)

- STF-Kevlar shows slightly less penetration depth than neat Kevlar
  - Penetration observed for both targets at all energy levels
- Note that areal density of targets are comparable, but STF-Kevlar composite uses fewer total layers of Kevlar fabric

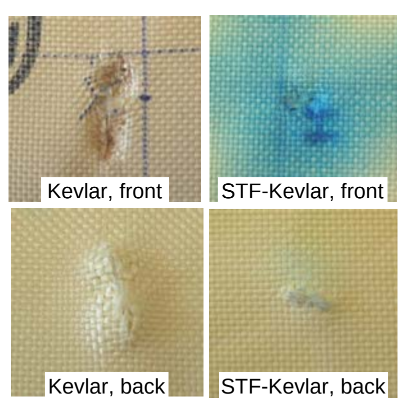


Knife Stab Results (2)

- STF-Kevlar shows slightly higher impact loads
  - Significantly less damage in STF-Kevlar target



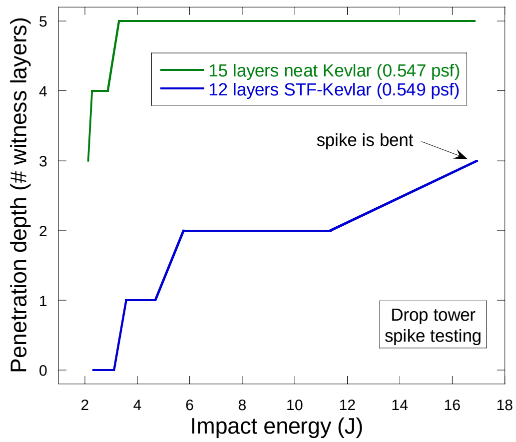
Load on knife during impact
(h = 0.25 m, m = 2.34 kg, E = ~ 6 J)



Photos of neat Kevlar and STF-Kevlar targets after knife impact
(h = 0.75 m, m = 2.34 kg, E = ~ 17 J)

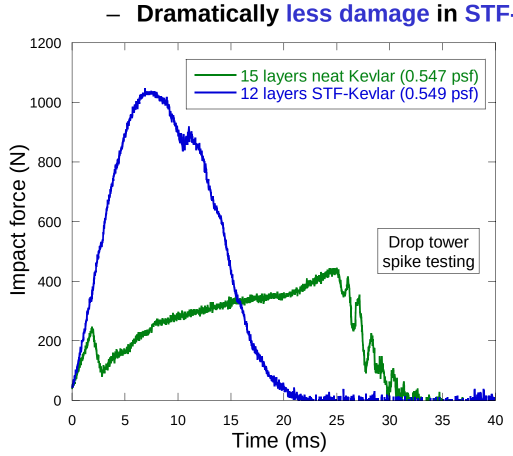
Spike Stab Results (1)

- **STF-Kevlar show dramatically less penetration depth than neat Kevlar**
  - **STF-Kevlar never penetrated → bends spike at highest energy level**
- **Note that areal density of targets are comparable, but STF-Kevlar target uses fewer total layers of Kevlar fabric**

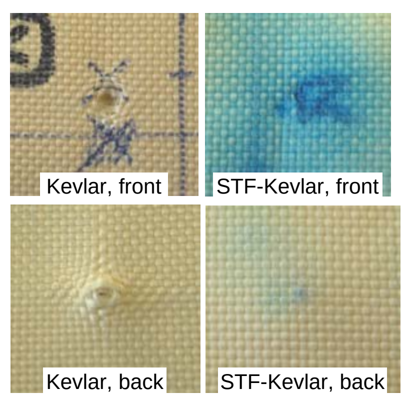


Spike Stab Results (2)

- **STF-Kevlar targets able to withstand much higher peak impact loads than neat Kevlar**
  - **Dramatically less damage in STF-Kevlar target**



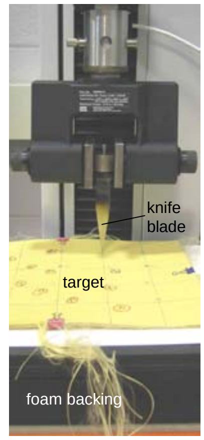
Load on spike during impact
(h = 0.75 m, m = 2.33 kg, E = ~ 17 J)

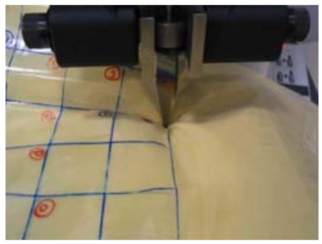


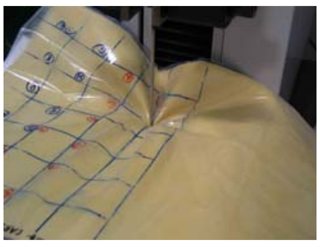
Photos of neat Kevlar and STF-Kevlar targets after spike impact
(h = 0.75 m, m = 2.33 kg, E = ~ 17 J)

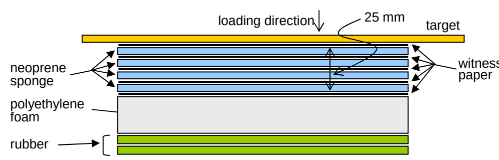
Quasistatic (QS) Stab Resistance Testing

- Use mechanical tester instead of drop tower
  - Slow (quasistatic) loading of end effector into target
    - Displacement rate ~ 5 mm/min
  - Use NIJ spike and knife blade (S1) end effectors
  - Use same foam backing stack as NIJ standard
- Measurements
  - Load vs. displacement
  - Number of witness paper layers perforated





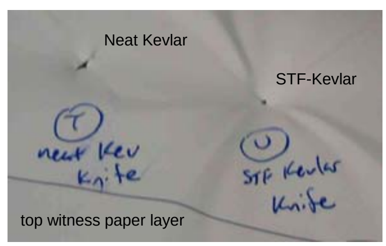


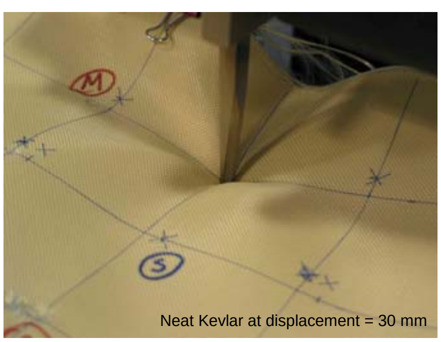


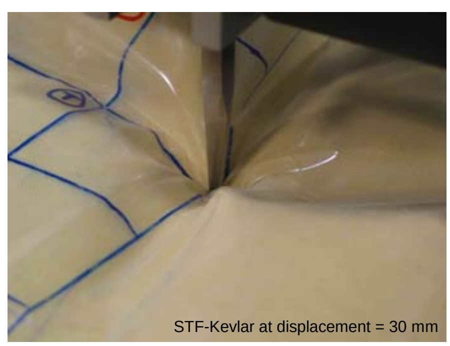
Knife QS Testing (1)

- Knife blade penetrates both targets
  - STF-Kevlar provides slightly more penetration resistance than neat Kevlar
    - Neat Kevlar: 4 witness papers penetrated
    - STF-Kevlar: 4 witness papers penetrated

    (both measurements at 30 mm crosshead displacement)

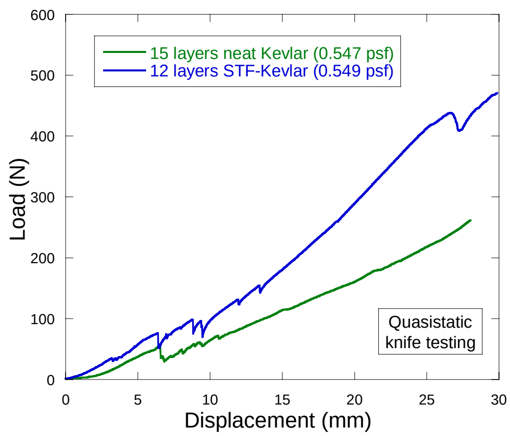


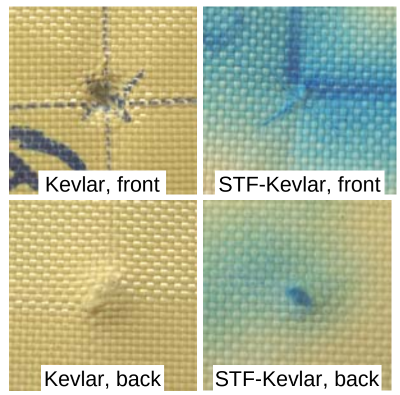

Neat Kevlar at displacement = 30 mm


STF-Kevlar at displacement = 30 mm

Knife QS Testing (2)

- **STF-Kevlar exhibits somewhat higher loading than neat Kevlar**
  - **Damage in STF-Kevlar appears significantly less than in neat Kevlar → Fewer cut yarns**



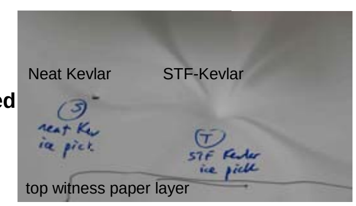


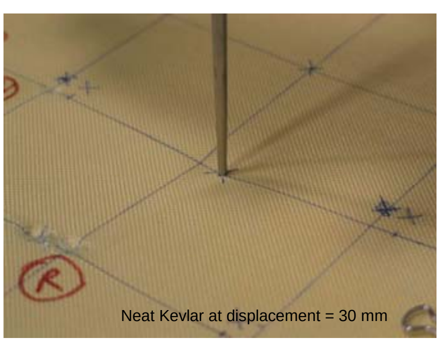
Photos of neat Kevlar and STF-Kevlar targets after quasistatic knife testing

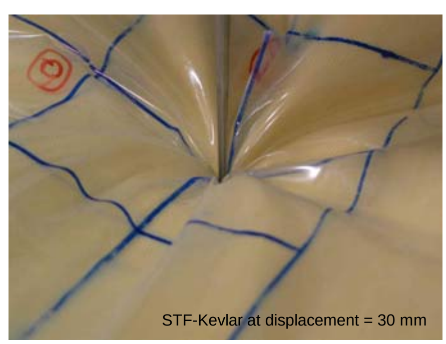
Spike QS Testing (1)

- **Spike only penetrates neat Kevlar**
  - **STF-Kevlar provides drastically higher penetration resistance than neat Kevlar**
    - **Neat Kevlar: 5 (all) witness papers penetrated**
    - **STF-Kevlar: 0 witness papers penetrated**

    (both measurements at 30 mm crosshead displacement)

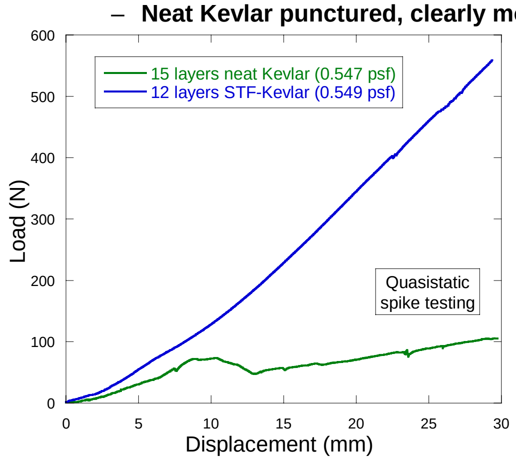


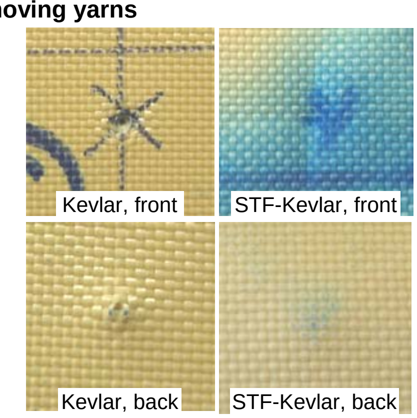




Spike QS Testing (2)

- **STF-Kevlar reaches significantly higher loads than neat Kevlar**
  - **Neat Kevlar fails at low displacements, and offers little further resistance to penetration**
- **STF-Kevlar exhibits little evidence of puncture, even on front face**
  - **Neat Kevlar punctured, clearly moving yarns**



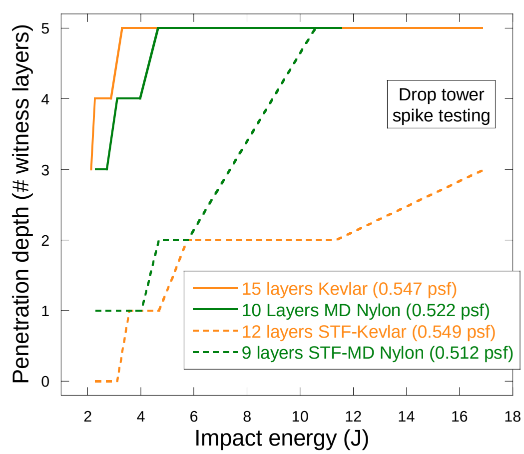


Photos of neat Kevlar and STF-Kevlar targets after quasistatic spike testing

Kevlar and MD Nylon

Drop Tower Spike Testing Results

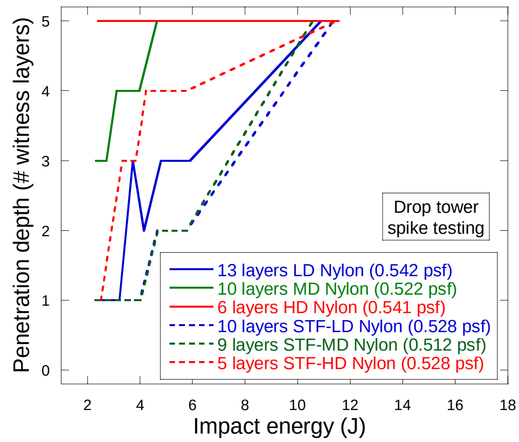
- **STF addition enhances performance of both Kevlar and Nylon fabrics**
  - **STF-Kevlar performs better than STF-Nylon**
  - **STF-Nylon performs better than neat Kevlar**



Effect of Nylon Denier / Yarn Count

Drop Tower Spike Testing Results

- **Increasing yarn count (decreasing denier) improves fabric performance**
- **Adding STF analogous to increasing fabric yarn count**
  - **Note that DuPont Correctional Kevlar® utilizes high yarn counts (200 denier yarns) for high spike resistance**

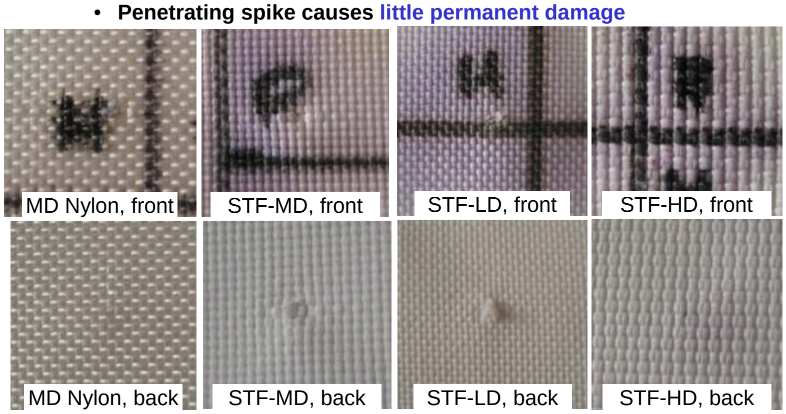


Nylon Stab Results (2)

Drop Tower Spike Testing Results

- **Damage mechanism depends on yarn mobility**
  - **Low yarn mobility → LD, STF-LD, STF-MD**
    - **Spike causes yarn fracture and irreversible yarn motion**
  - **High yarn mobility → MD, STF-HD**
    - **Spike causes reversible yarn motion and elastic deformation**
    - **Penetrating spike causes little permanent damage**

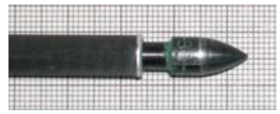
Elongation to failure:
Kevlar (KM-2): 3-4%
Nylon (heat set): 15-20%



Photos of neat Nylon and STF-Nylon targets after spike impact (h = 0.5 m, m = 2.33 kg, E = ~ 11 J)

Archery Testing

- Projectile
  - Carbon Express - Terminator 4560 arrow with sharp point
    - Shaft diameter: 0.296 in
    - Tip diameter: 0.278 in
    - Mass: 23.83 g

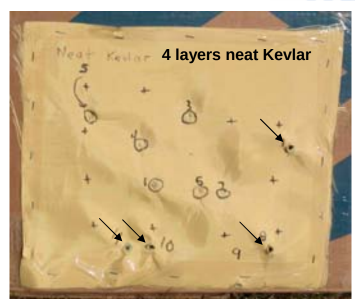


  - Velocity: 169 fps (standard deviation: 6 fps)
- Backing
  - Target taped and stapled to 6 layers of heavy cardboard
  - Cardboard backed by "Black Hole" archery target
- Targets
  - Hexcel Style 706 (600 denier KM-2 34x34) Kevlar fabric
  - PEG-based STF (450 nm silica) at 20 wt% in fabric

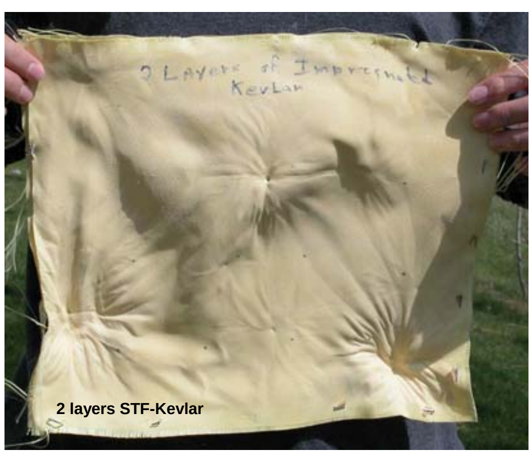
arrow vs. 4 layers of neat Kevlar

Archery Results

- STF-Kevlar more resistant to penetration than neat Kevlar
  - 4 layers neat Kevlar: penetrated 4/4 shots
    - Yarns mostly "pushed aside" to enable penetration
  - 4 layers STF-Kevlar: no penetration 3/3 shots
  - 2 layers STF-Kevlar: no penetration 3/3 shots



4 layers neat Kevlar



2 layers STF-Kevlar

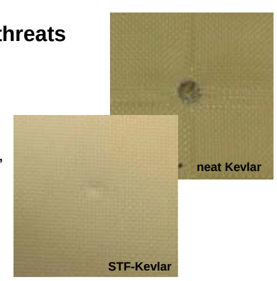
4 layers STF-Kevlar

Fieldability

- Manufacturability
  - Dip process for STF fabrication should be scalable
  - Base materials for STF (silica, PEG) are commodity materials
- Environmental resistance
  - STF can be further engineered to achieve high levels of thermal and moisture resistance
- Health
  - STF components are benign and non-toxic
    - Some care required in handling dry colloidal silica, which aerosolizes easily, during processing

Conclusions

- STF addition significantly improves puncture resistance of Kevlar fabrics
  - At same areal density, STF-Kevlar has dramatically higher spike protection than neat Kevlar
  - At same areal density, STF-Kevlar and neat Kevlar offer comparable knife protection
    - However, STF-Kevlar has significantly fewer fabric layers than neat Kevlar → STF-Kevlar thinner, more flexible than neat fabric
- At higher speeds (archery tests), STF-Kevlar offers significantly more puncture resistance than neat Kevlar
  - Mechanisms of STF performance apply to multiple threats
- Other work
  - Ballistic properties
    - Y.S. Lee, E.D. Wetzel, and N.J. Wagner. "The ballistic impact characteristics of Kevlar woven fabrics impregnated with a colloidal shear thickening fluid." J. Mat. Sci. v38 n13 p2825-2833. 2003.
    - Other ballistic properties available upon request
  - Non-Kevlar fabrics
    - More complete data available on STF-Nylon studies
  - Other engineered STFs
    - Vary constituent chemistries, particle size, particle shape
  - Vary STF content (wt%) in fabric



Comparison of neat Kevlar and STF-Kevlar after ballistic impact