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Low Velocity Ballistic Properties of Shear Thickening Fluid (STF)–Fabric Composites

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Previous studies have shown that the ballistic and stab properties of fabrics can be improved through the addition of shear thickening fluids (STFs). In this paper, ballistic testing is performed on unbacked STF-Kevlar composites using hard spherical projectiles at low velocities, for combined fixed-free boundary conditions and finite fabric dimensions. In general, the addition of STF causes a dramatic increase in the V_{50} performance of the fabric. This increase in ballistic performance is related to increases in yarn pull-out resistance, which is also measured and reported. Additional experiments on fabrics impregnated with Newtonian fluids and non-discontinuously shear thickening fluids show that full, discontinuous shear thickening properties are most effective for improving fabric properties.

INTRODUCTION

Woven ballistic fabrics respond to impact through a combination of mechanisms, including yarn rotation, lateral sliding, uncrimping, translation, plastic deformation, and fracture [1-4]. Yarn pull-out, including both uncrimping and translation, is particularly important under conditions of low impact velocity, impact near a free edge, and loosely woven fabrics. Yarn plastic deformation and fracture are most relevant for conditions of high impact velocity and tightly woven fabrics. Yarn rotation and lateral sliding have not been studied extensively but are likely to be relevant under conditions of low impact velocity and loosely woven fabrics.

A number of studies [5-8] have shown that the ballistic and stab properties of woven fabrics can be improved through the addition of discontinuous shear thickening fluids (STFs). Discontinuous STFs are materials that undergo a sharp transition from flowable to solid-like behavior when subjected to stresses above a critical value [9, 10]. Most of the studies demonstrating favorable properties for STF-fabric composites utilize impact conditions which favor low-velocity fabric mechanisms such as yarn pull-out, rotation, and lateral sliding. In particular, ballistic studies on small (5.08 cm × 5.08 cm) samples at low velocities (800 fps) indicated that STF addition appeared to repress yarn pull-out [6-8]. Puncture studies using a spike penetrator, at both low velocity impact and quasistatic conditions, indicated that STF addition repressed yarn rotation, lateral sliding, and yarn pull-out [5].

In this paper, we systematically study the effect of STF addition on both the ballistic properties and yarn pull-out properties of Kevlar fabrics. Previous ballistic experiments utilized fully free edge boundary conditions and clay backing, with results reported in terms of penetration depth into the clay under fixed velocity conditions. In contrast, the ballistic studies in this report utilize fabric samples with two free edges and two clamped edges. The fabrics are unbacked, and a range of impact velocities are used in order to characterize V_{50} performance.

Additional results are reported for a range of fabric treatments: untreated, treated with Newtonian fluid (neat polyethylene glycol, PEG), treated with a nominally shear thickening silica-PEG suspension (PEG with a moderate loading of stabilized silica), and treated with a discontinuously shear thickening fluid (PEG with a high loading of

Material	Silica vol% in fluid	Wt% addition to Kevlar	Target areal density (g/cm^2)
Neat	N/A	0.0	0.0180
PEG	0.0	23.7	0.0222
SPS	20.0	23.6	0.0220
STF	52.0	23.0	0.0219

(a)

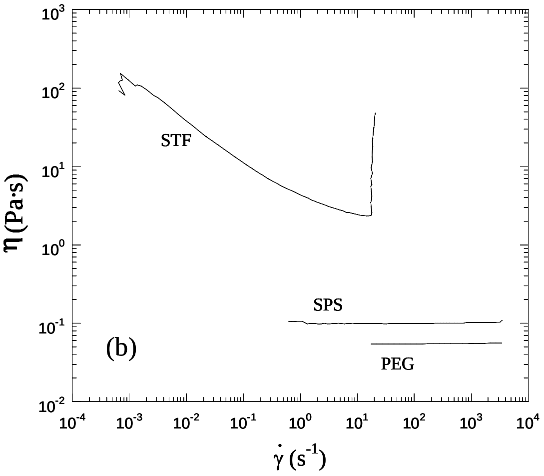


Figure 1. (a) Table of areal densities of Kevlar fabrics tested. (b) Rheological properties of PEG, SPS, and STF.

stabilized silica). These treatments should provide a systematic increase in the suppression of yarn-yarn mobility. To quantify this effect, the quasistatic yarn pull-out behavior of these treated fabrics is measured according to the method of Kirkwood et al. [11]. These yarn pull-out results are then correlated with the ballistic results, and oobservations are made regarding the overall role of yarn mobility under our ballistic conditions.

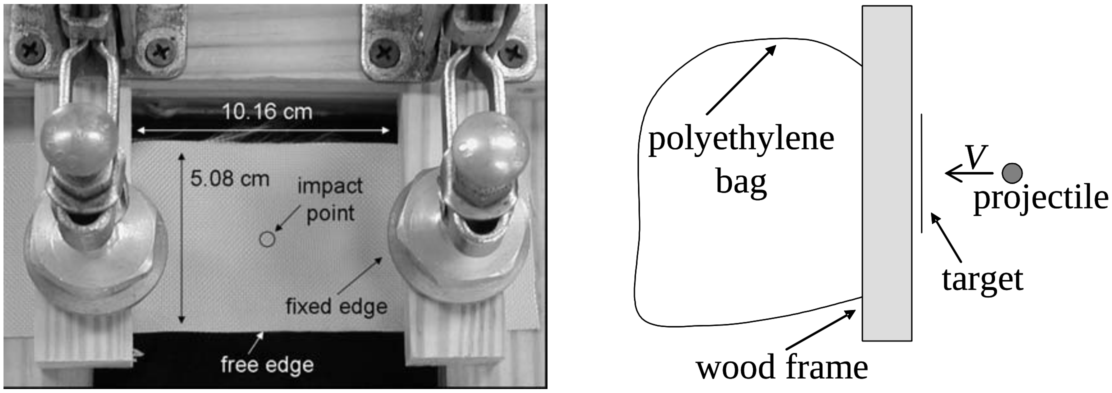
Previous studies [12] have demonstrated or hypothesized linkages between frictional treatments and fabric ballistic properties. For STF systems, we have previously shown relationships between rheology, yarn pull-out, and ballistic performance [6,7]. More recently, Tan et al. [13] have demonstrated both increased yarn pull-out resistance and ballistic properties for Twaron fabrics treated with silica-water suspensions. The simulations of Duan et al. [14] also show that yarn-yarn frictional properties play an important role in determining the penetration resistance of woven fabrics at low velocities. This paper is one part of an ongoing effort to comprehensively characterize the effect of STF addition on various yarn mobility mechanisms and to determine the role of these mechanisms in the response of woven fabrics to ballistic impact.

EXPERIMENTAL

Materials

The Kevlar fabrics used in this study are Hexcel Schwebel Style 706 (600d KM-2, 34×34 yarns per inch, plain weave). The details of STF preparation and fabric treatment can be found elsewhere [5-8] and are only summarized here. PEG (M_n=200), ethanol, and 450 nm colloidal silica are combined to produce a dilute solution. The Kevlar fabric is dipped in the bath, pressed between rollers to remove excess fluid, and then dried at 66°C to remove the ethanol and leave behind PEG and silica. This fabrication approach results in a uniformly and fully impregnated fabric, with PEG and silica infused between yarns and between filaments.

Three PEG-to-silica ratios were investigated, in order to produce three different fabric treatments: neat PEG, 20%vol silica in PEG, and 52%vol silica in PEG. The amount of ethanol used in each bath was tailored so that the final weight addition to the Kevlar



(a) (b)

Figure 2. (a) Photograph and (b) schematic of ballistic target mounting apparatus.

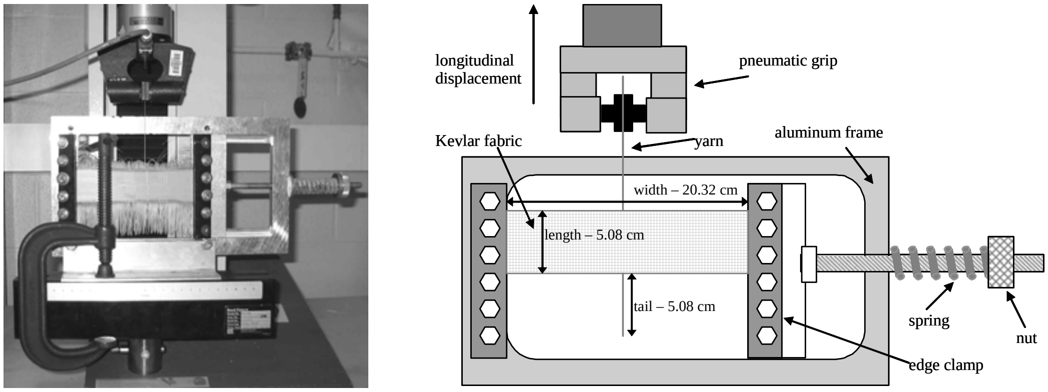
fabric was between 23 and 24% for each treatment. Figure 1a shows the weight addition and average areal densities for the fabrics studied.

Figure 1b shows the rheological properties of PEG, 20%vol silica in PEG, and 52%vol silica in PEG, measured using an SR 5000 stress control rheometer (Rheometric Scientific Corp.) with a 40mm, 0.04 radian cone at 25ºC. PEG is Newtonian over the measured range as expected. The 20%vol silica-PEG shows slight shear thinning at low shear rates, and slight shear thickening at higher shear rates. The 52%vol silica in PEG shows strong shear thinning and discontinuous shear thickening above a critical shear rate. We will refer to these three treatments as PEG, silica-PEG suspension (SPS), and shear thickening fluid (STF).

Ballistic Testing

V_{50} ballistic tests were performed using a smooth-bore helium gas gun operated at room temperature. A 0.22 caliber (0.56 cm diameter) spherical, steel projectile with an average mass of 0.62 grams (9.6 grains) was used in testing. A single-layer fabric target was mounted to a wood frame using staples and clamps, resulting in a 5.08×10.16 cm target area. The long edges of the fabric are unconstrained, while the short edges are fixed rigidly to the frame. A small amount of pretension (less than 10 N) was manually applied to the fabric prior to clamping to eliminate fabric slack. A photograph and schematic of this setup is shown in Figure 2.

The impact velocity of each projectile was measured with a light chronograph positioned immediately in front of the target. Impact velocity was varied to produce a range of complete penetrations (projectile travels through fabric) and partial penetrations (projectile does not travel through fabric). To determine if an impact was complete or partial, a polyethylene bag was attached to the back of the target frame. A complete target penetration resulted in a hole in the bag, or the projectile trapped within the bag. This method of penetration witness was used instead of traditional metal foil or paper witness, because the low residual velocities in our experiments were sometimes insufficient to penetrate traditional witness layers. The V_{50} of each sample (velocity at which the probability of penetration is 50%) was determined from the average impact velocity of ten targets: five partial and five complete penetrations.



(a) (b)

Figure 3. (a) Photograph and (b) schematic of the yarn pull-out apparatus.

Yarn Pull-Out Testing

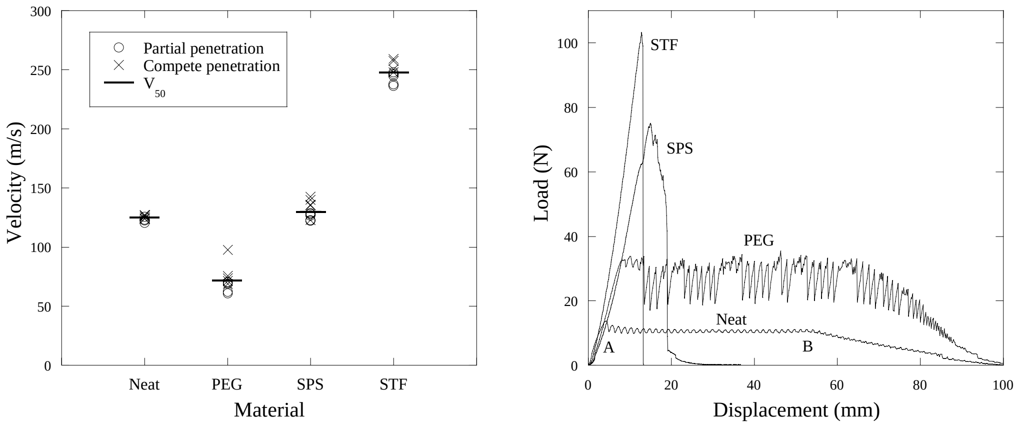
All fabric samples were 20.32 cm long × 25.40 cm wide. Prior to testing, transverse yarns were manually removed from the sample to expose 10.16 cm and 5.08 cm of longitudinal yarns at the top and bottom of the sample, respectively. The remaining 5.08 cm length of intact woven fabric (dimension L from [11]) was mounted in an edge-clamped holding fixture as shown in Figures 3a and b, as adapted from Shockey et al. [15] and Kirkwood et al. [11]. The width of fabric, defined as the distance between the transverse clamps, for all experiments was 20.32 cm.

Yarn pull-out testing was conducting by clamping an individual yarn in the upper, rubberized grips. The upper grip was a pneumatic grip at 90 psi attached to a MTS testing machine and 5 kN load cell. The individual yarn was held in the upper grips and pulled through the fabric at a constant crosshead speed of 50 mm/min. Transverse tension was applied to the fabric through a spring-mounted side-edge clamp. The precise tension was set by compressing the spring to a given distance through a fine-thread nut. All reported tensions refer to the entire transverse load on the fabric and not the per-yarn tension. Note that, unlike in [11], these experiments utilize a 5.08 cm–long "tail" on the yarns extending past the bottom edge of the intact fabric. This yarn tail results in a finite yarn translation distance with nearly constant yarn pull-out force, which may provide an additional characteristic fabric property in addition to peak force (F_p from [11]).

RESULTS

Ballistic Testing

Figure 4 shows the ballistic performance of the neat, PEG-treated, SPS-treated, and STF-treated Kevlar targets. Note that the complete and partial penetration velocities are very close and show only slight overlap, indicating high fidelity V_{50} determination. The results show that adding PEG to the Kevlar fabric decreases the V_{50} significantly, from 125 m/s to 71.9 m/s. The SPS sample, in contrast, showed only a marginal difference in V_{50} performance, 131 m/s, relative to the neat Kevlar. The STF-Kevlar target showed a remarkably higher V_{50} of 248 m/s.



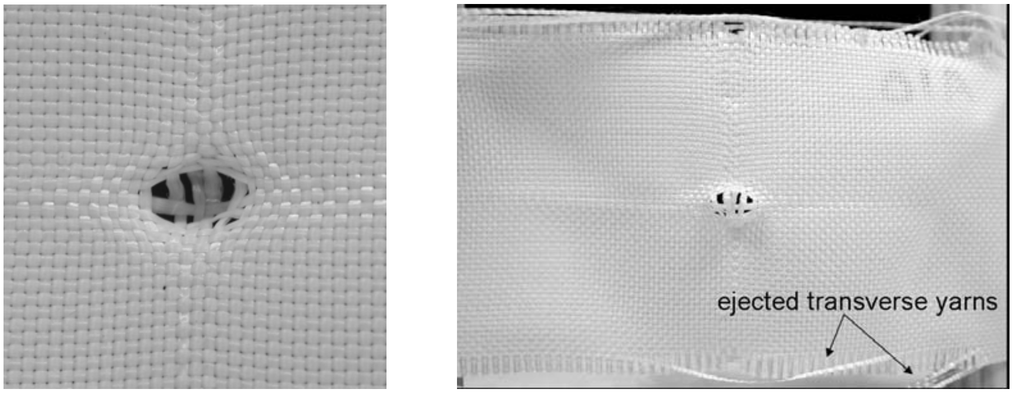
(a) (b)

Figure 4. (a) Comparison of the ballistic penetration resistance of the neat, PEG-treated, SPS-treated, and STF-treated Kevlar fabrics. (b) Yarn pull-out loading curves for neat, PEG-treated, SPS-treated, and STF-treated fabrics, for a transverse tension of 100 N.

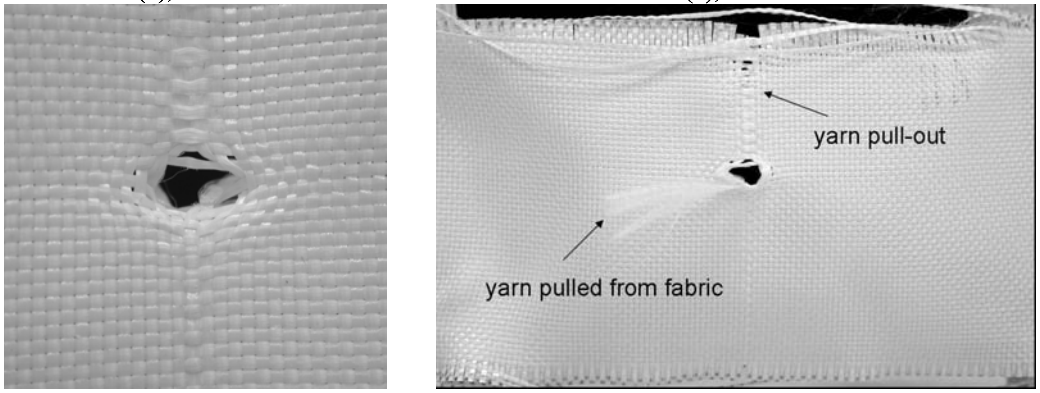
Figure 5 shows images of the neat Kevlar fabric, under conditions of partial penetration and complete penetration. Images are chosen from samples very near to the V_{50} velocity, to show the transitional behavior as penetration becomes more likely. The partial penetration targets show yarn pull-out and fabric "windowing", or yarn separation. The complete penetration photos show extensive yarn pull-out and windowing, with one half of a longitudinal yarn pulled completely out of the fabric. Note that, for the case of complete penetration, there is no sign of yarn fracture. Instead, the projectile is able to penetrate the target by pushing and pulling the yarns to create penetration space. Also note that yarn pull-out is most extensive in the longitudinal direction, where the yarn length is short and the edges are unconfined. The photographs also show that, for both cases, some transverse yarns at the top and bottom edges of the fabric are ejected from the fabric during impact.

The observed fabric damage for PEG-Kevlar and SPS-Kevlar targets impacted near their V_{50} is similar to the neat Kevlar samples, with no yarn breakage and extensive yarn pull-out and windowing. These fabrics are being penetrated by allowing the projectile to pass between yarns and by extracting yarns from the fabric, similar to the penetration mechanisms observed for the neat fabric. The very low V_{50} of the PEG target, however, could indicate that these mechanisms of yarn motion are facilitated by the presence of the PEG.

Figure 6 shows an STF-Kevlar target after a complete penetration near the V_{50}. Unlike the other fabrics, the STF-Kevlar samples shows extensive yarn fracture near the impact point, with moderate yarn pull-out. This behavior indicates that the projectile is able to efficiently load the yarns to their ultimate failure strength, and that penetration through yarn motion alone is not permitted. The change in failure mode, as compared to the neat fabric, suggests that the presence of the STF suppresses yarn mobility. It is also interesting to note that STF-Kevlar fabrics impacted at velocities significantly below the V_{50}, but above the V_{50} of neat Kevlar (e.g. up to 200 m/s), showed almost no sign of damage or distortion after projectile impact. This comparison is a striking illustration of the efficacy of the STF treatment for enhancing the penetration resistance of the Kevlar fabric, under these testing conditions.

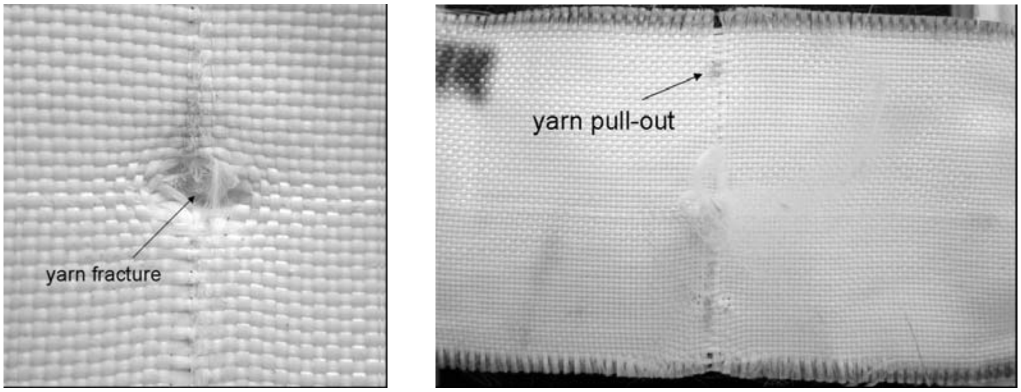


(a), Front (a), Rear



(b), Front (b), Rear

Figure 5. Photographs of neat Kevlar after ballistic impact, for (a) partial penetration and (b) complete penetration conditions.



Front Rear

Figure 6. Photographs of STF-Kevlar after ballistic impact, for complete penetration.

Yarn Pull-Out Testing

Figure 4b shows typical yarn pull-out curves for the neat, PEG-treated, SPS-treated, and STF-treated fabrics at 100 N. The neat Kevlar curve shows behavior similar to previously published measurements for neat Kevlar [11]. Up to the peak load point (labeled "A" in Figure 7), the yarn is uncrimping, with no bulk yarn translation. From point A to point B the yarn is translating through the fabric, resulting in a long, steady force value with small, regular oscillations. Each period of these oscillations corresponds to the motion of the longitudinal yarn past two transverse yarns, as its as-received kinks are pulled in-phase and out-of-phase with the transverse yarns. At point B, the end of the yarn tail reaches the bottom of the fabric, and the load decays as the length of yarn within the fabric decreases.

The PEG-treated Kevlar shows qualitatively similar behavior to that of the neat Kevlar. However, it shows a higher peak force value than the neat fabric. The result is surprising, given its significantly lower ballistic performance. The amplitude of its oscillations is also substantially higher than the amplitude observed for the neat Kevlar.

The SPS-treated Kevlar samples show higher peak loads than the PEG-treated or neat Kevlar samples. The SPS sample also does not show a constant translation force value, instead showing a relatively rapid and staggered dropoff in pull-out force. This force dropoff is due to degradation and fracture of the yarn, typically very near to the top of the fabric (slightly below the highest transverse yarn). The failed yarn typically shows extensive fibrillation.

The STF-treated Kevlar samples show the highest peak loads, followed by sudden and complete yarn failure. Yarn failure again occurs near the top of the fabric, and results in extensive fibrillation.

Note that the measured peak loads, for the case of yarn fracture, approach ~ 100 N. This value is slightly lower than the theoretical strength of a 600d KM-2 yarn, 170 N (based on a tenacity of 3.7 GPa). This result may indicate that the yarn is being weakened due to crimping effects, or some form of transverse loading. It is also possible that the silica particles physically abrade the yarn, reducing its ultimate strength.

DISCUSSION AND CONCLUSIONS

The ballistic results clearly show that STF addition substantially improves the V_{50} performance of Kevlar fabric, under our particular ballistic conditions and target configuration. The ballistic results also show that adding a Newtonian fluid, PEG, to Kevlar fabric can dramatically reduce its ballistic efficiency. It is not surprising that the slightly shear thickening, SPS-treated fabric shows ballistic performance intermediate between the PEG and STF materials.

Analysis of the ballistic results indicates that the increase in penetration resistance exhibited by STF-treated fabric is due to a repression of yarn pull-out, translation, and windowing behaviors. This hypothesis is confirmed by the quasistatic yarn pull-out experiments, which show significantly higher pull-out resistance for the STF-treated fabric as compared with the neat fabric. In fact, yarns fail before significant pull-out is achieved.

PEG-treated Kevlar exhibited poorer ballistic performance than neat Kevlar yet, surprisingly, the PEG-treated samples show higher yarn pull-out resistance as compared with the neat fabric. The pull-out velocities are much higher during ballistic impact and the transverse tensions induced by ballistic impact are unknown, and so, the lack of correspondence between tests may be a consequence of these differences. Nonetheless, both materials exhibited poorer ballistic performance and much lower pull-out tensions than the STF– and SPS-treated fabrics.

Continuing work is needed to fully characterize these mechanisms, including the effects of multiple fabric layers, decreasing STF weight addition, and increasing fabric longitudinal dimensions. The exact role of specific STF rheological properties on enhanced ballistic performance is a topic of ongoing research.

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