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Evaluation of Shear-Thickening-Fluid Kevlar for Large-Fragment-Containment Applications

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Application of a shear-thickening-fluid treatment to neat Kevlar has been reported to improve fabric ballistic performance for impacts of 0.22-caliber-fragment-simulating projectiles at velocities near 800 fps. In recent research, the authors have evaluated the ballistic performance of shear-thickening-fluid Kevlar in a series of impact experiments performed using larger projectiles and thicker targets at impact velocities near 1000 fps, including two different fabric boundary conditions. The experimental results indicate that, under these test conditions, the impact protection afforded by shear-thickening-fluid Kevlar is, at best, equivalent to that provided by neat Kevlar at the same areal density. In addition, the ballistic performance of shear-thickening-fluid Kevlar was found to be strongly dependent on fabric-target boundary conditions, with the best performance obtained in a friction-sensitive target configuration that is not representative of current body armor, orbital debris shielding, or fan-blade containment systems.

I. Introduction

SHEAR-THICKENING-FLUID (STF) treatments, developed by the University of Delaware and the Army Research Laboratory, have been proposed as a means for improving the ballistic performance of neat Kevlar fabric [1–3]. In impact experiments involving 0.22 caliber steel fragment-simulating projectiles, the developers reported an increase in the projectile kinetic energy absorbed, per unit target mass, by STF-treated fabric targets impacted at velocities near 800 fps. Motivated by these results, more recent experimental and computational work, performed at NASA Johnson Space Center and the University of Texas, has investigated the effectiveness of STF treatments on Kevlar shielding performance in the hypervelocity range [4–6]. The latter research, which involved 2.8–3.2-mm-diam aluminum projectiles and multilayer aluminum–Kevlar targets, concluded that STF treatment does not improve the shielding performance of fabrics at very high impact velocities, whether employed in a simple target stack or in a stuffed Whipple shield configuration. Note that the aforementioned work, motivated by either body armor or orbital debris shielding design problems, considered a wide range of velocities but only the rather small (mass of 1 g or less) projectiles that are a central focus of such applications.

The present paper describes the first systematic experimental investigation of STF Kevlar ballistic performance for large projectile impacts on fabric targets. The experiments were conducted at impact velocities near 1000 fps and included 1) two different (aluminum and steel) projectile materials, 2) two different fabric boundary conditions (clamped and free edges), 3) projectile masses as high as 56 g, 4) projectile dimensions as large as 1.5 in., and 5) target thicknesses as high as 24 fabric layers. Although the work described here represents a fundamental experimental investigation of the treated fabric's ballistic performance, the projectile size and impact velocity considered here are characteristic of a different class of engineering problems (e.g., fan-blade fragment-containment applications) than those considered in previously reported STF Kevlar research.

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II. Fragment-Containment Barriers

Published research has reported an average of 45 uncontained rotor failures per year in commercial, general, and rotorcraft aviation [7]. All such failures have the potential to produce fragments that may damage critical aircraft components. One method used to mitigate the damage resulting from such accidents is to introduce a fragment barrier, designed to prevent debris from penetrating the fuselage or damaging control lines, power units, or other engines. Barriers composed of multiple layers of high-strength fabrics can absorb significant fragment energy while minimizing the added weight associated with the fragment-containment system. Additionally, some fabric materials provide flame resistance, water absorption resistance, or thermal and acoustic insulation, and hence can serve more than one function [8,9].

Most regulatory organizations, including the Federal Aviation Administration, require that commercial jet engines be designed with a containment system that will prevent any single fan-blade failure from penetrating the engine case during flight operations. In general, this requires that manufacturers demonstrate that an engine fan blade can be contained within the engine when a blade is released with the engine running at full-rated thrust. There are two basic types of fan containment systems, referred to as hardwall and softwall systems. Hardwall systems are designed with sufficient strength to prevent penetration and sufficient stiffness to severely limit deflection of the hardwall system during fragment impacts. Softwall systems usually consist of a thin inner ring surrounded by multiple layers of neat fabric, most commonly Kevlar. A honeycomb structure is normally located between the inner ring and the fabric, providing stiffness to the case. Fan-blade failure in softwall systems usually results in large deformation of the fabric layer [10], which may consist of 30 or more Kevlar panels [11].

III. Projectile and Target Materials

The present work describes an experimental evaluation of STF Kevlar ballistic performance as a large-fragment-containment barrier. The projectiles used in the impact experiments described here were aluminum cylinders and steel disks. The cylindrical projectile was aluminum 6061-T6, 2.54 cm in length and 1.27 cm in diameter, with a mass of 8.69 g. The disk projectile was 4340 steel, 3.81 cm in diameter and 0.635 cm thick, with a mass of 56.7 g. The Kevlar fabric used in all targets was plain-weave Hexcel Schwebel style 706 (Kevlar KM-2 fiber, 600 denier yarns, 34 yarns per inch), commonly employed for ballistic protection applications. STF was applied to the neat fabric by the Army Research Laboratory and was composed of silica particles (Nissan Chemicals MP4540) [12,13] suspended in

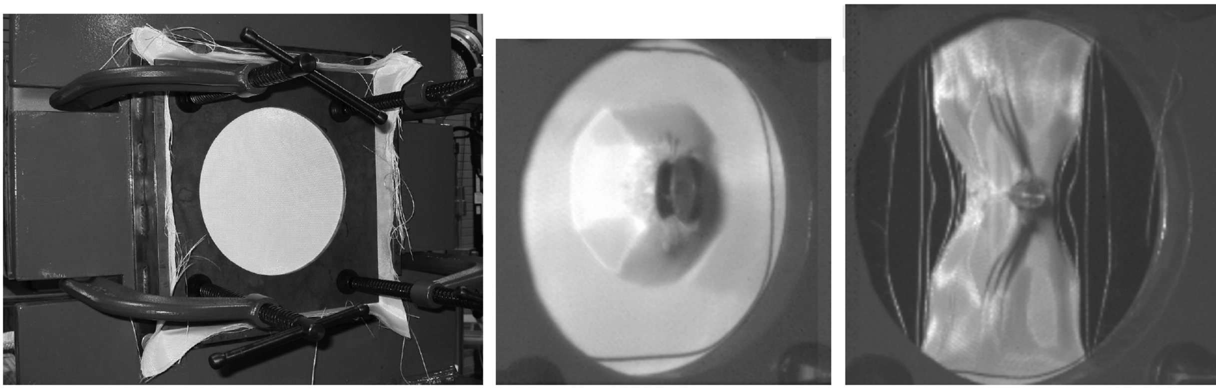

Fig. 1 Clamped fabric target, disk impact experiment (all target edges clamped), and cylinder impact experiment (two target edges clamped and two target edges free).

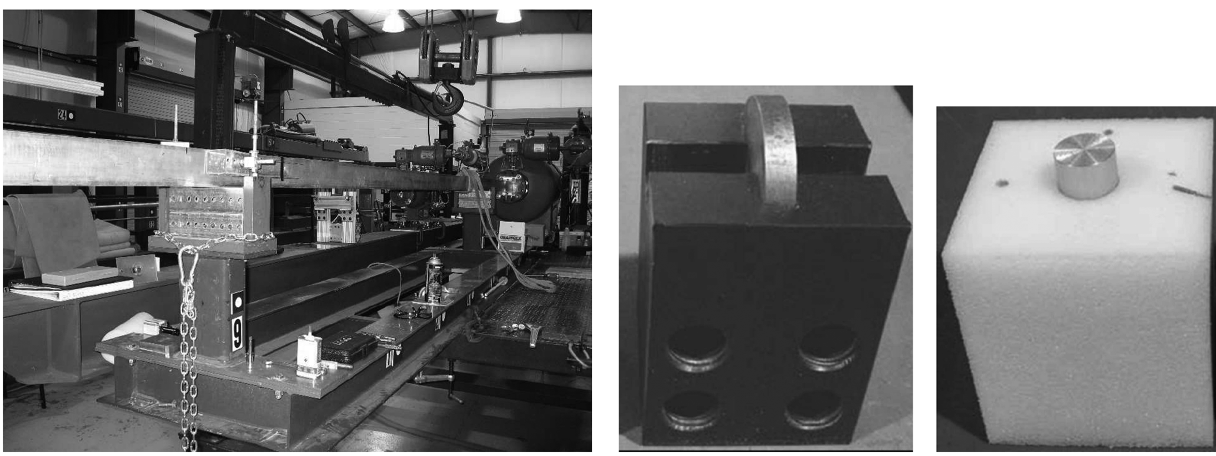

Fig. 2 Compressed gas gun, steel disk projectile with sabot, and aluminum cylinder projectile with sabot.

polyethylene glycol (PEG 200) [14,15]; the silica-to-PEG mass ratio was 2:1. The mass fraction of the STF in the STF Kevlar composite was 20%, so that the areal density of the STF Kevlar panels was 25% higher than that of the corresponding neat Kevlar panels. Based on published rheological measurements for the STF [13] and the impact velocities employed in these and previously reported tests [1], the STF shear rate under impact was well above the transition rate for shear thickening. Details of the STF application process for Kevlar fabric are available in the published literature [15,16]. The STF Kevlar target panels used in the current work were fabricated with the following constituent mass fractions: 0.8000 for Kevlar, 0.1333 for silica, and 0.0667 for PEG 200. Care was taken to minimize exposure of the target panels to the environment by storing the panels in Ziploc bags until testing.

IV. Impact Testing Procedures

The neat and STF Kevlar impact experiments were performed by Southwest Research Institute [17,18]. All impacts were at normal obliquity, with flat-end impacts for the aluminum cylinders and edge impacts for the steel disks. The target frame was constructed of steel backing and cover plates, each with a 20.32 cm circular aperture (Fig. 1). To minimize fabric slip at the clamped edges of the target, cover plates were fabricated to accommodate various target thicknesses. Two different boundary conditions were employed in the testing. For the tests conducted with four clamped edges, the Kevlar was cut into square panels 38.1 cm on a side and mounted between the steel plates, hand stretching the panels to minimize any slack without applying significant tensile loads. For the tests conducted with two edges clamped and two edges free, the Kevlar was cut into strips with dimensions 10.16×38.1 cm and mounted between the steel plates; the strips were oriented vertically and centered in the aperture. The strips were again hand stretched to minimize slack without applying significant tensile loads.

The impact tests were performed using a compressed gas gun, with helium as the driving gas (Fig. 2). The gun consisted of a gas chamber and a 20-ft-long barrel with a 2 by 2 in. bore size. A sabot trap was located at the muzzle, to avoid sabot debris impact on the target. The sabot materials were polystyrene for the aluminum cylinder and Noryl[‡] for the steel disk. All tests were performed at room temperature. A laser was used to confirm target obliquity and align the barrel with the desired impact location. Three Vision Research Phantom V7 monochrome cameras recorded the impact event at 40,000 frames per second and a resolution of 192×192 pixels. The first camera measured the impact velocity, using a calibration bar to determine projectile position. A second camera provided a side view of the target and measured the residual velocity of the projectile after it penetrated the target. The third camera provided an oblique view of the rear of the target, recording target deflection and projectile perforation. Additional details on the experimental procedures are provided by Rabb [19].

V. Impact Testing Results

In each of the three series of experiments, targets consisting of the same number of layers of neat or STF fabric were tested, for the same boundary conditions and projectile types, at a nominal impact velocity of 1000 fps. The precise impact velocity and residual velocity of each projectile were measured in order to evaluate the relative ballistic performance of the neat and STF Kevlar for the impact conditions investigated. The first test series employed steel

[‡]Data available at http://www.plasticsintl.com/datasheets/419943590 Noryl.pdf [retrieved 1 August 2007].

disk projectiles and targets clamped on all edges, with target thickness varying from 3 to 24 fabric layers. The second test series employed aluminum cylinder projectiles and targets clamped on all edges, with target thickness varying from one to five fabric layers. The third test series was a repeat of the second test series, except that the targets were fabric strips clamped on two edges and free on two edges.

Figure 3 plots the results of the steel disk impact experiments and includes a set of high-speed video images that depict a steel disk impact at 294 m/s on three layers of STF Kevlar. The test results are plotted as the ratio of residual velocity to impact velocity versus normalized target areal density, where the reference areal density is that for one layer of neat Kevlar. Since the measured impact velocities varied less than 1% from a median velocity for the test series, normalization of the residual velocities by the impact velocities provides an appropriate measure of relative ballistic performance. Note that the projectile failed to penetrate the target in each of the 24 layer tests, so that the residual velocity for both of those tests is zero. Comparison of the data for the neat and STF targets indicates that the STF treatment did not improve Kevlar ballistic performance. The number of data points is limited, so that the estimation of error bars is difficult; however, taken as a whole, the data clearly suggest that no advantage is gained from the STF treatment.

Figure 4 plots the results of the second test series involving aluminum cylinder impacts on fabric clamped on all edges and includes a set of high-speed video images that depict an aluminum cylinder impact at 335 m/s on two layers of neat Kevlar. The test results are again plotted as the ratio of residual velocity to impact velocity versus normalized target areal density, where the reference areal density is again that for one layer of neat Kevlar. In this case, the measured impact velocities varied less than 10% from a median velocity for the test series, so that normalization of the residual velocities by the corresponding impact velocities provided an approximate measure of relative ballistic performance. Note that the projectile failed to penetrate the neat fabric target in the five-layer test, so that the residual velocity for this test is zero. Although the number of data points is limited, comparison of the data for the neat and STF targets again indicate that the STF treatment did not improve Kevlar ballistic performance.

The performance of the STF Kevlar in the first two test series was unexpectedly poor, since previous work had reported improved ballistic performance for smaller (0.22 caliber) projectiles at a similar impact velocity [1]. Since the last cited experiments differed not only in projectile size but also in target boundary conditions, it was decided to directly investigate the effect of target boundary conditions on STF Kevlar performance by performing a third series

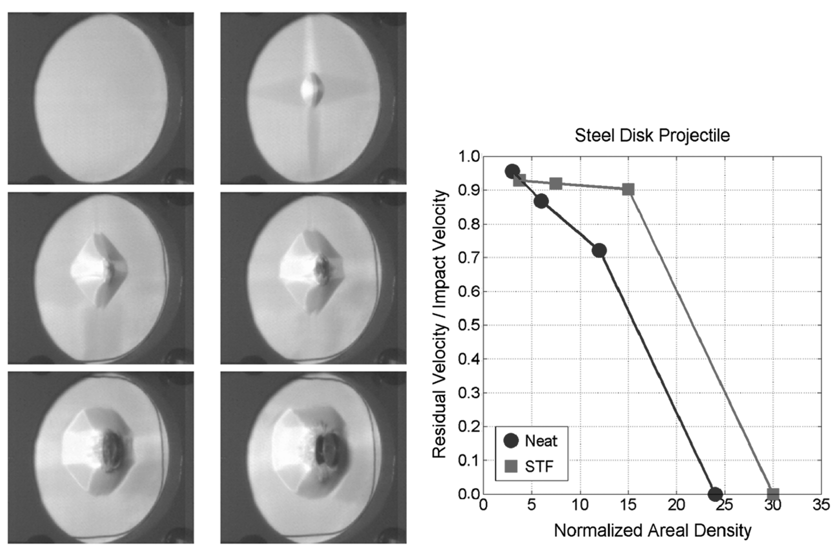

Fig. 3 High-speed video images of a steel-disk impact test and a plot of the test results.

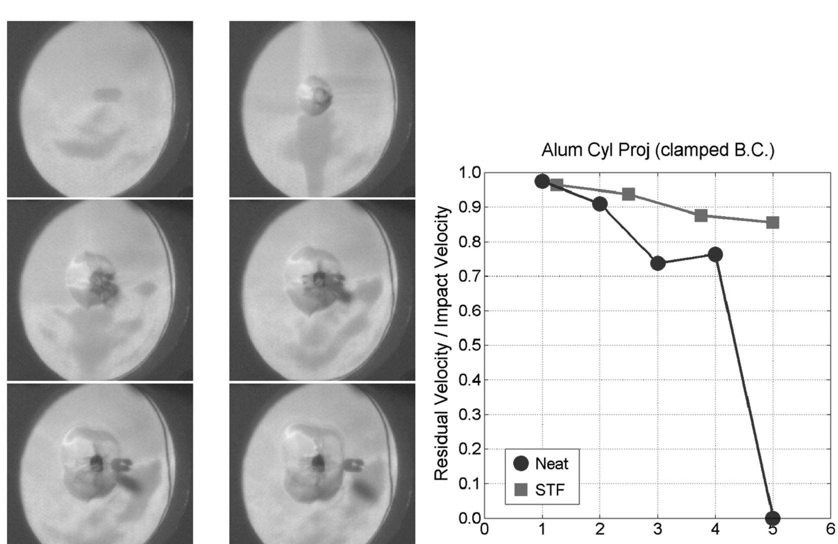

Fig. 4 High-speed video images of an aluminum cylinder impact test and a plot of the test results (B.C. denotes boundary conditions).

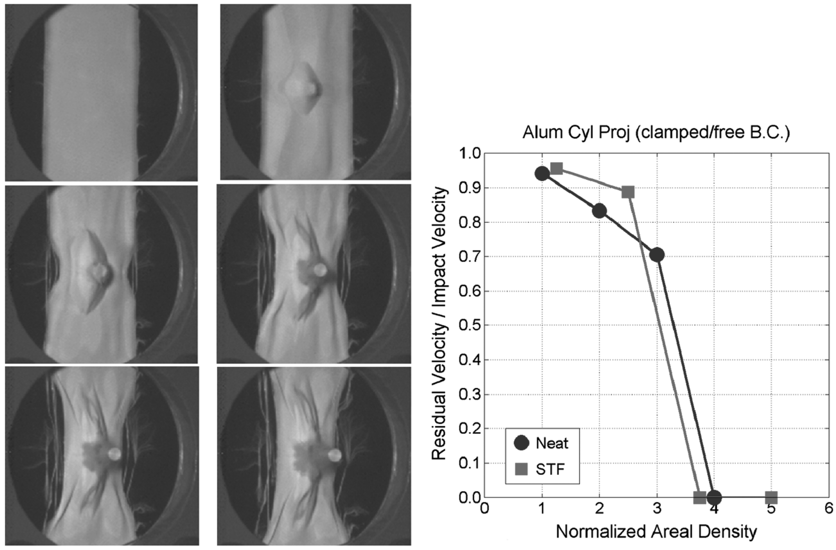

Fig. 5 High-speed video images of an aluminum cylinder impact test and a plot of the test results.

of impact tests. These tests differed from the second test series by employing a rectangular fabric target with two edges clamped and two edges free. Figure 5 plots the results of the third test series and includes a set of high-speed video images that depict an aluminum cylinder impact at 298 m/s on one layer of STF Kevlar. In this set of experiments, the measured impact velocities varied less than 2% from a median velocity for the test series. The test results show that, for fabric targets configured with two target edges free, the neat and STF Kevlar exhibit very similar ballistic performance.

A comparison of the results of the two series of cylinder impact tests suggests that the ballistic performance of STF Kevlar is sensitive to fabric-target boundary conditions. A likely explanation for this sensitivity is as follows. In the third test series, the horizontal yarns were held in place by friction only. The effect of the STF treatment was to increase frictional loads on the horizontal yarns, making displacement of these yarns, and hence perforation of the fabric panels, more difficult. Although the number of data points is limited, the test results clearly suggest that, in this friction-sensitive target configuration, the beneficial effects of STF treatment on frictional energy dissipation neatly compensate for the negative effects of STF treatment on fragment barrier areal density.

VI. Conclusions

This paper describes the first systematic investigation of STF Kevlar ballistic performance in large-fragment-containment applications. The research results indicate that STF treatment is not an effective means for improving Kevlar ballistic performance in such applications, for impact velocities near 1000 fps. In addition, the impact test data suggest that the ballistic performance of the treated fabric is a strong function of target boundary conditions. For fabric barriers configured with clamped, woven, or otherwise constrained edges, which restrict yarn motion, STF treatment is not expected to improve upon the ballistic performance of neat Kevlar. In the case of friction-sensitive target configurations, in which the cut yarns are unconstrained at target edges, the increased frictional energy dissipation associated with the STF treatment does exert a favorable effect. This benefit is, however, negated by the increase in fabric panel areal density associated with the STF treatment in applications where ballistic performance is evaluated on a mass specific basis. Since most fabric armor and fabric barrier designs are weight constrained and do not incorporate free-running yarns, opportunities for practical exploitation of the enhanced frictional dissipation properties of STF Kevlar appear to be limited.

The focus of published research on this material appears to be shifting away from ballistic applications and toward the development of improved stab-resistant fabrics [20,21].

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