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Small-Scale Ballistic Impact Tests to Optimize Transport Airplane Rotor Burst Fragment Fabric Shielding Designs

October 2007

Final Report

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16. Abstract

Under the Federal Aviation Administration Airworthiness Assurance Center of Excellence and the Aircraft Catastrophic Failure Prevention Program, the University of California at Berkeley (UCB) teamed with The Boeing Company to investigate lightweight ballistic protection of commercial aircraft from engine fragments. UCB's role was to perform small-scale impact tests of barriers made from single and multilayer Zylon® fabric to assess different fabric shield concepts prior to full-scale aircraft fuselage demonstration. It should be noted that at the time of this study, Zylon fabric was found to have long-term environmental deterioration issues. However, for the purpose of this study, Zylon was used to leverage previous testing and analysis on this fabric. This report describes the test results, including the energy absorbed and postimpact condition of the fabric barriers.

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LIST OF ACRONYMS

AACE	Airworthiness Assurance Center of Excellence
FAA	Federal Aviation Administration
HP	Hewlett Packard
NAWC	Navel Air Warfare Center
SHCS	Socket head cap screw
UCB	University of California at Berkeley

EXECUTIVE SUMMARY

Uncontained turbine engine failures remain a predominant cause of commercial aircraft incidents and have led to catastrophic aircraft accidents. To mitigate the effect upon critical aircraft components from uncontained engine debris, the Federal Aviation Administration (FAA) under the Aircraft Catastrophic Failure Prevention Program has sponsored research to develop lightweight barrier systems for aircraft and to develop computational capability for designing these barriers.

The goal of this research project, carried out under the auspices of the FAA Airworthiness Assurance Center of Excellence, is to use the technical strengths and experience of The Boeing Company and the University of California at Berkeley (UCB) for developing prototype aircraft fuselage rotor burst fragment shielding and finite element modeling methodology. Boeing participated as a partner in this research. They were not funded by the FAA. This phase of the study concentrated on the various aircraft attachment designs, culminating in a full-scale aircraft fuselage demonstration test conducted at the Naval Air Warfare Center, China Lake.

UCB's role was to perform small-scale impact tests of barriers made from single and multilayer Zylon® fabric to assess different fabric shield concepts prior to full-scale aircraft fuselage demonstration. It should be noted that at the time of this study, Zylon fabric was found to have a long-term environmental deterioration issues. However, for the purpose of this study, Zylon was used to leverage previous testing and analysis on this fabric. The work presented in this report describes the test results, including the energy absorbed and postimpact condition of the fabric barriers.

1. INTRODUCTION.

A leading propulsion threat to commercial aircraft is the situation where a rotor disk on one of the main propulsion engines fails, usually due to fatigue failure, and passes through the engine containment structure showering the fuselage with engine fragments. While the loss of one engine itself is not enough to cause the complete failure of a commercial aircraft, if one or more of the fragments were to penetrate the fuselage and damage multiple critical components, such as the hydraulic or fuel lines, this could defeat design redundancy and result in the loss of control of the aircraft.

To help prevent such accidents from occurring, many lightweight materials, such as aluminum, titanium, high-strength fabrics, and other materials, are being considered to act as shields for critical aircraft systems. In developing a barrier for these fragments, it is necessary to characterize the ballistic performance of these materials and weigh their positive and negative attributes. This report examines the ballistic performance of Zylon® fabric under different test configurations as a possible material to be used in the shielding of critical aircraft systems.

Previous laboratory gun tests have shown that woven fabrics of high-polymers, particularly poly-benzbisoxazole, of which Zylon belongs, had very high energy absorption per unit weight in impact tests against fragment simulators [1].

Experiments were performed on samples of Zylon prepared at the University of California at Berkeley (UCB), and on samples provided by the Naval Air Warfare Center (NAWC), China Lake, to provide information about the ballistic limit of the material as well as energy absorption data. The targets were also examined postimpact to observe impact/failure characteristics. The goal of these experimental results was to provide information to determine whether Zylon is a suitable material to be used as a fragment barrier system and, if so, to aid in the design of a suitable barrier, helping to prevent accidents resulting from rotor burst failure.

1.1 BACKGROUND.

The Federal Aviation Administration (FAA), under the Aircraft Catastrophic Failure Prevention Program, has sponsored research to aid in the development of lightweight barrier systems for aircraft and related computational models of such systems. In May 2000, The Boeing Company (Boeing) expressed interest in Zylon's potential as a lightweight barrier system. SRI International (SRI) and Boeing began discussions of a program in this area and invited UCB, with its expertise in ballistic impacts and finite element analysis, to join in the discussions as well. UCB (teamed with SRI and Boeing) was awarded, by the FAA, an Airworthiness Assurance Center of Excellence grant to institute a computational and experimental program aimed at the industrial application of Zylon in a fabric barrier. According to the Center of Excellence legislation, FAA dollars were matched one for one by Boeing and UCB. Boeing participated as a partner in this effort. They were not funded by the FAA.

In 2002, Kelvin Kwong, under the advisement of Professor Werner Goldsmith at UCB, performed ballistic tests with Zylon, concentrating on the effects that different boundary conditions had on energy absorption. His results showed that plies of Zylon attached at four

corners provided the greatest potential for energy absorption. This report presents UCB's further investigation into the ballistic impact properties of Zylon beyond those described in Kelvin Kwong's report [2]. Since Zylon fabric was found to deteriorate with light and humidity, the fabric was covered and stored in an environmentally controlled building before the impact tests.

1.2 EXPERIMENTAL OBJECTIVES.

The primary objective of the experiments presented in this report was to provide insight into the effect of slack as well as other types of fastenings not previously tested. One ply of Zylon was the basis for testing and then was modified in the following ways: slack (more material in the same frame), pleats, fastenings (grommets and cords at the corners), overlap, and additional plies. Each feature was examined to get an idea of the energy absorption associated with said features and their effect on the ballistic limit. Finally, tests were completed on samples provided by NAWC China Lake, incorporating multiple design features being considered for the full-scale fuselage testing at NAWC China Lake.

2. EXPERIMENTAL SYSTEM AND PROCEDURE.

Most of the procedures used in these tests were identical to the procedures described by Sean Kelley of UCB in his thesis, so some pictures and descriptions were used with his permission [3]. A pneumatic gas gun was used to propel the projectiles into the Zylon test sheets. The gun system consisted of a blast shield, initial velocity laser timing circuit, target holder, target mount, residual velocity grids and timing circuit, catcher box, and a high-speed camera.

2.1 PNEUMATIC GUN SETUP.

2.1.1 Pneumatic Gas Gun.

The high-pressure pneumatic gas gun employed industrial grade compressed nitrogen gas up to a maximum pressure of 1500 psi with a maximum velocity of about 625 ft/s for the 0.5″ diameter by 1.5″ height right cylinders used in testing. The pneumatic gas gun is shown in figures 1 and 2, and a schematic of the setup is shown in figure 3.

The 52″ long barrel of the pneumatic gas gun had a 0.5″ nominal diameter. Thirty-nine inches from the start of the nozzle (in the direction of fire) there were slits in the barrel that relieved some of the pressure behind the projectile. A regulator on the nitrogen tank controlled the pressure of the gas used in each test. Providing the tank was full, the pressure in the regulator could be set by the user anywhere between 25 and 1500 psi. Once the pressure was set, an electronic control box opened solenoid valve 1 that released the gas at the specified pressure from the tank into the breech pressure chamber. After pressurizing the breech, solenoid valve 1 was closed. For safety reasons, solenoid valve 2 (between the breech and the gun barrel) was controlled by a trigger outside of the laboratory. This trigger released the gas from the breech pressure chamber and allowed it to flow into the barrel of the gun, accelerating the projectile through the barrel. A diagram of the gas flow can be seen in figure 4.

Figure 1. Angled View of the Pneumatic Gas Gun Setup Used for Testing

Figure 2. A Straight-on View of the Nitrogen Gas Gun Setup

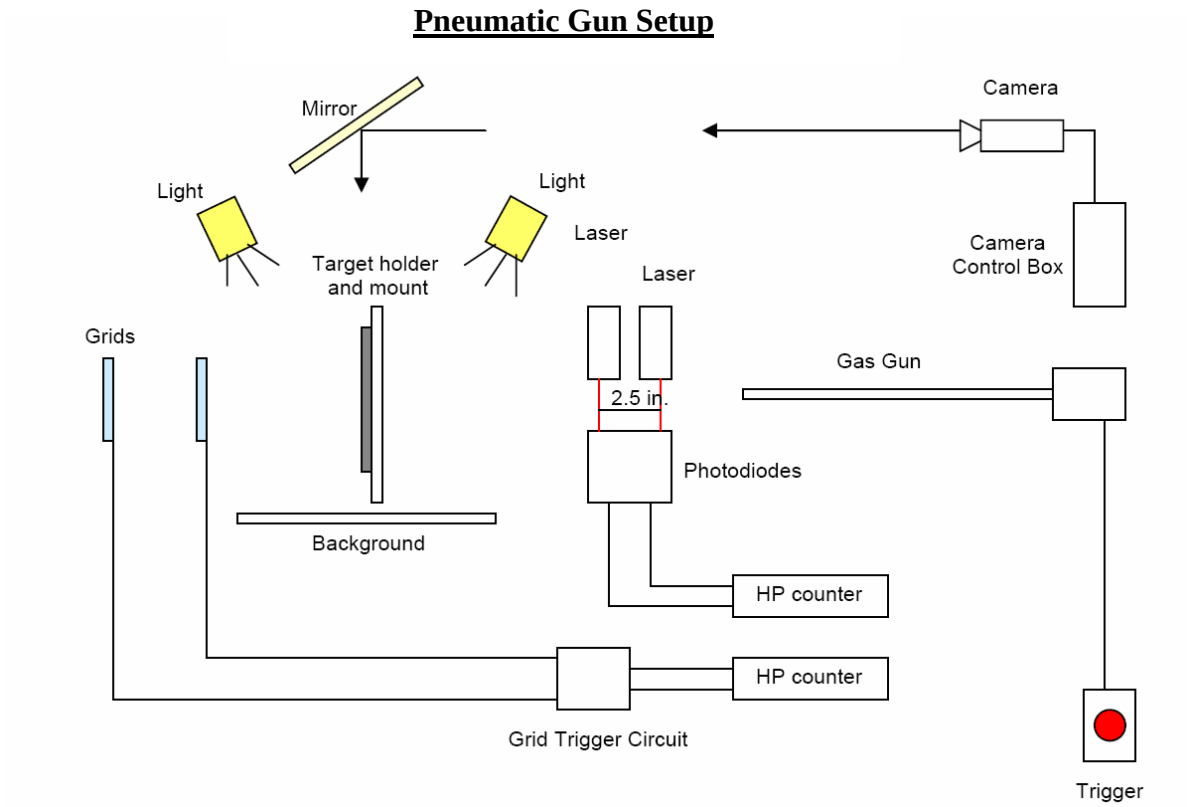


Figure 3. A Schematic of the Pneumatic Gas Gun

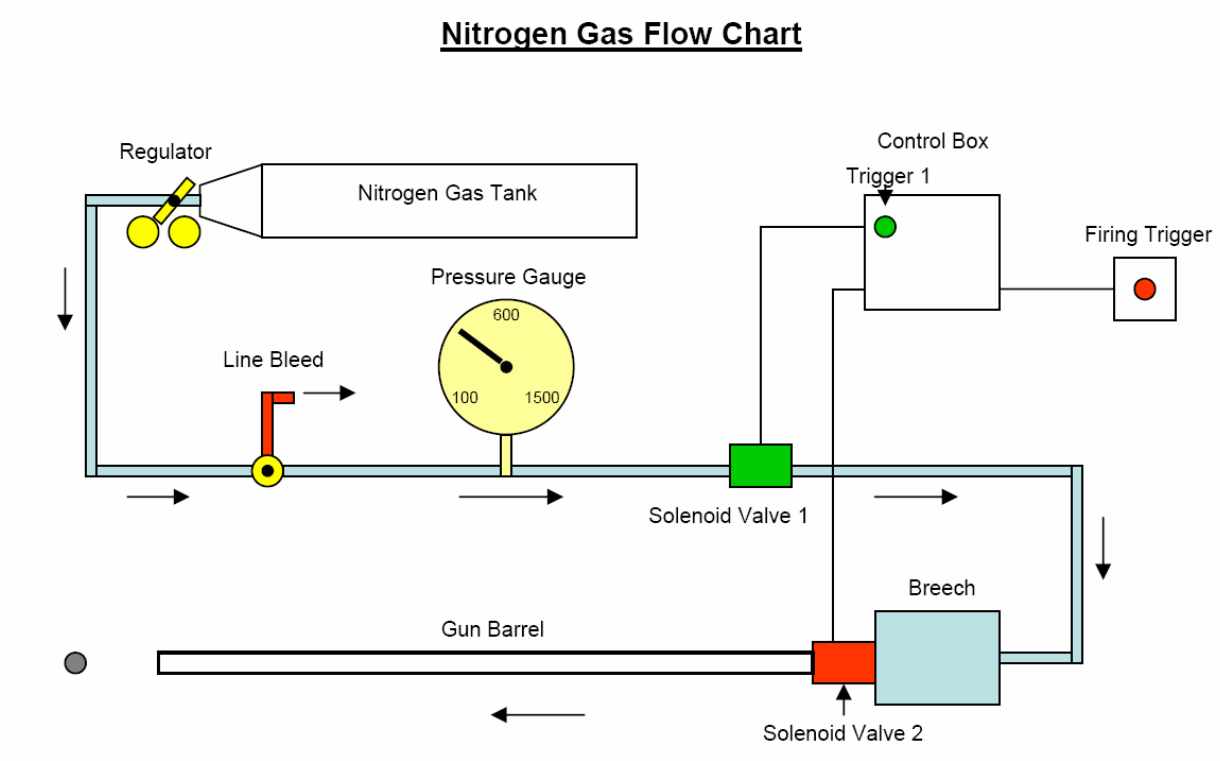


Figure 4. Diagram of the Flow of the Nitrogen Gas Through the Pneumatic Controls

2.1.2 Initial Velocity Measurement System.

A laser/photodiode setup was used to find the initial velocity of the projectile when fired from the pneumatic gun shown in figure 5. Two Uniphase, helium-neon gas lasers were focused across the path of the projectile at two Sharp IS489 high-sensitivity light detectors measuring 2.5″ apart. When the projectile was fired out of the barrel of the gun, it cut through the path of each of the lasers causing its respective photodiode circuit to produce a voltage drop (fall time ~0.1 micro-seconds (μs)) that a Hewlett-Packard (HP) 53131A Universal Counter detected. That counter measured the time between the two voltage drops and together with the known distance between the beams of the lasers, a velocity could be calculated.

Figure 5. A Top View of the Initial Velocity Measurement System Including the Lasers, Photodiodes, and Their Accompanying Circuit House Within the Grey Box

2.1.3 Target Fabric—Zylon.

With the exception of the Zylon samples from NAWC China Lake or unless otherwise noted, the tests were performed on Zylon cut from a 20″ wide bolt of fabric. All the woven fabric was supplied by Lincoln Fabrics Ltd., Ontario, Canada. Serrated scissors were used to cut the Zylon from the bolt, and cuts were generally sized in width to make 20″ x 20″ targets after all other testing configuration details were secured. Zylon is known to deteriorate in light, and for the purpose of testing, the bolt was stored in a special black plastic bag when not in use.

2.1.4 Target Frame.

All targets were held by a square 0.5″ thick steel frame, 10″ square on the inside and 14″ square on the outside. In the few cases that a side clamping method of attaching the fabric were needed, a hexagonal tongue and groove clamping configuration was used. In all other tests, the Zylon was secured by four pegs, one at each corner, spaced approximately 10.75″ apart. The holes

accommodated 3/8-16 socket head cap screw (SHCS) alloy steel bolts. The frame is shown in figure 6. Clamp-up force was controlled by tightening the SHCSs with a torque wrench.

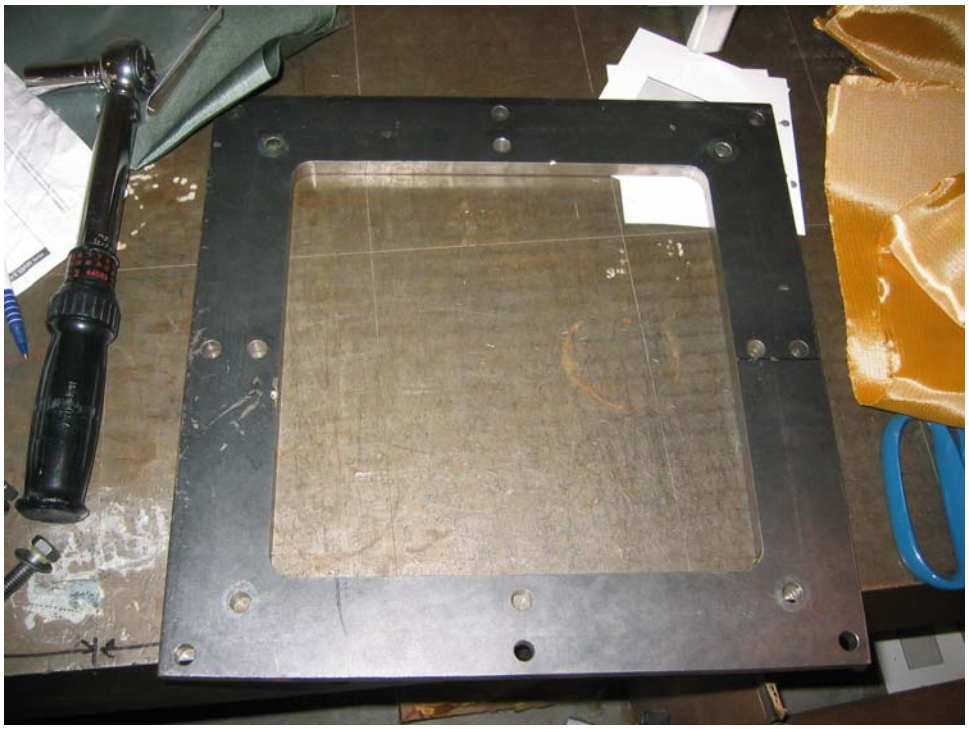


Figure 6. A Top View of the Frame Used to Hold the Zylon for Testing

2.1.5 Target Mount.

The target frame was held in place, in the path of the projectile, by a large steel angle mount manufactured for this specific purpose. The mount was made so that the frame could be moved and the target could be impacted at nearly all of its 10″ square area, although for the purpose of this project, all shots were fired at the center of the fabric square. The target mount was firmly attached to the steel table on which the gun rested to prevent any motion upon impact. The frame was attached to the mount by four C-clamps, one at each corner, as shown in figure 7. Two aluminum spacers kept the Zylon fabric normal to the path of the projectile.

Figure 7. The Target Frame Attached to the Target Mount

2.1.6 Residual Velocity Measurement System.

2.1.6.1 Grids.

The primary method used to measure the residual (or postimpact) velocity of the projectile consisted of two paper grids, each consisting of two sets of interdigitated, conducting silver ink lines, as shown in figures 7 and 8. An alligator clip was attached to each set of lines by way of a large lead at the bottom of the grids. The alligator clips were then attached to a circuit that produced a small output voltage and to an HP 53131A universal counter. When the conducting projectile came into contact with the grids, it completed the circuit and sent a positive voltage gain to the counter. Two grids were held 7.25″ apart behind the target frame. The universal counter recorded the time between the two successive signals and that time was used to calculate the residual velocity.

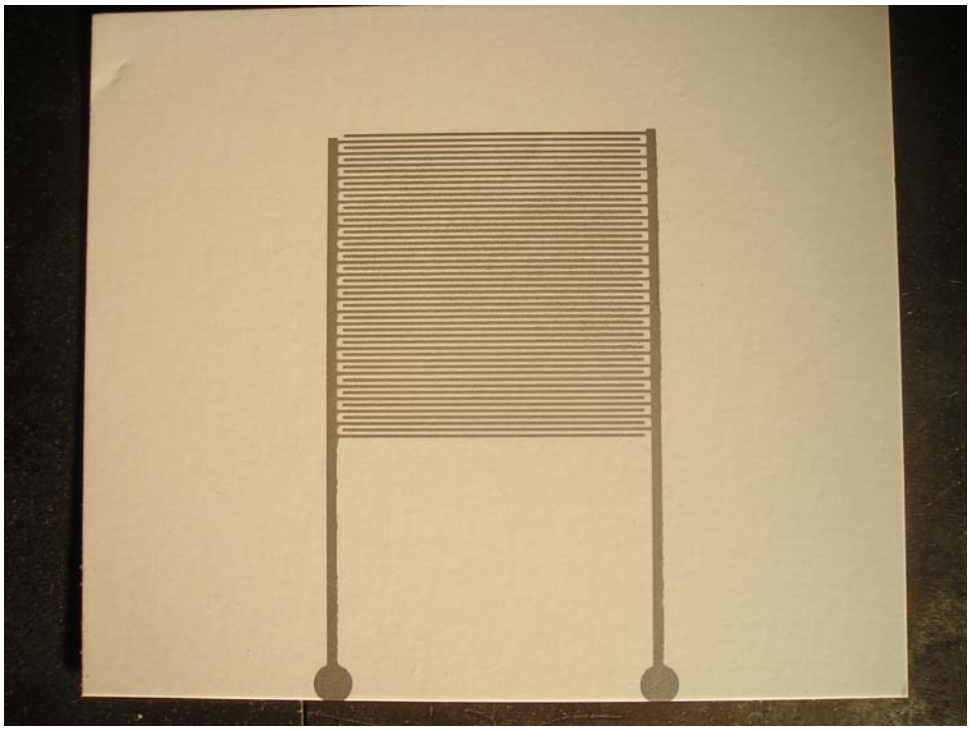


Figure 8. A Single Grid Used to Calculate the Residual Velocity of a Projectile

2.1.6.2 High-Speed Camera.

In case the grids failed, which they were prone to do from time to time, a Photron Fastcam high-speed camera controller with a Kodak Motion Corder Analyzer, Series SR camera was used as a secondary method to calculate residual velocity. Using a recording speed of 10,000 frames per second, the projectile's path was recorded just before and just after impact. To minimize position error in the frames, the maximum shutter speed of 1/20,000 seconds was used and required a great deal of light. The light was provided by two high-intensity 650-watt lamps that were turned on during filming only. Due to restrictions on space within the laboratory, the camera had to be moved often, but it was usually set up so that the wide-angle lens could capture close to 2″ before impact and 8″ after impact. After calibrating the camera, the recorded files could be analyzed to obtain a residual velocity for the projectile. This was done by measuring the distance the projectile traveled in pixels and converting that to a real distance using a ratio of pixels to inches found during calibration and dividing that by the time it took the projectile to travel said distance. This method of obtaining residual velocity was less accurate and more subject to user error than were the grids, but it was also much more reliable. Pictures of the camera and controller can be seen in figures 9 and 10.

The high-speed camera recordings also provided valuable observations of target and projectile behavior during testing. Files were examined and archived as .avi files so that the characteristics of the fabric and projectile could be seen in greater detail.

Figure 9. The High-Speed Kodak Camera

Figure 10. The Photron Fastcam Camera Controller

2.1.7 Catcher Box.

The purpose of the catcher box was to stop the projectile after each test without causing damage to the laboratory and also to prevent the projectile from ricocheting. As shown in figure 11, the catcher box was simply a wooden box open to the projectile's flight path filled with old Zylon sheets and a large 0.5″ thick steel plate secured to the back.

Figure 11. The Catcher Box on the End of the Table With the Pneumatic Gun

2.1.8 Projectiles.

A right circular cylindrical projectile was used in these tests, as shown in figure 12. The projectile was machined from a drill rod and heat treated to a Rockwell Hardness of 60 and then copper plated to reduce barrel wear. (Although consistently referred to in this report as a 0.5″ diameter projectile, the actual diameter did not exceed 0.496″ so as to fit into the barrel of the pneumatic gun.) The height of the cylindrical projectile was nominally 1.5″ and had a mass of 0.082 lb (37.1 gm).

For the last two ballistic tests using a powder gun, high-density tungsten material projectiles were used. These projectiles were the same diameter as the steel projectiles but were approximately 2″ long and had masses of between 0.231 and 0.249 lb (105 and 113 gm).

Figure 12. One of the Steel Right Cylindrical Projectiles Used in the Tests

2.2 POWDER GUN SETUP.

The powder gun was not used except for two tests in this project, but a detailed description of the gun and its related components can be found in reference 3. It was used twice because of the need for higher energy shots.

2.3 TESTING PROCEDURE.

2.3.1 Zylon Preparation.

- The Zylon was cut from either a 20″ or 13″ wide fabric bolt using serrated scissors. The fixed dimension of the Zylon was used as the height dimension for testing. (This means the fill direction of the yarn was vertical and the warp direction horizontal.)

- Using a straight edge, the points at which the Zylon would be attached were marked using a black permanent marker while taking into consideration any configurations that called for extra slack in the fabric. These marks were judged by eye to try and be as close to centered as possible.

- A special arrowhead cutter, provided by SRI and shown in figure 13, was used to cut the Zylon at the marked locations into the shape of an X. The arrowhead cutter was not particularly sharp, so often cutting consisted of pushing the fiber threads apart and away in the shape of the X. The holes were made as small as possible while still allowing a bolt to pass through.

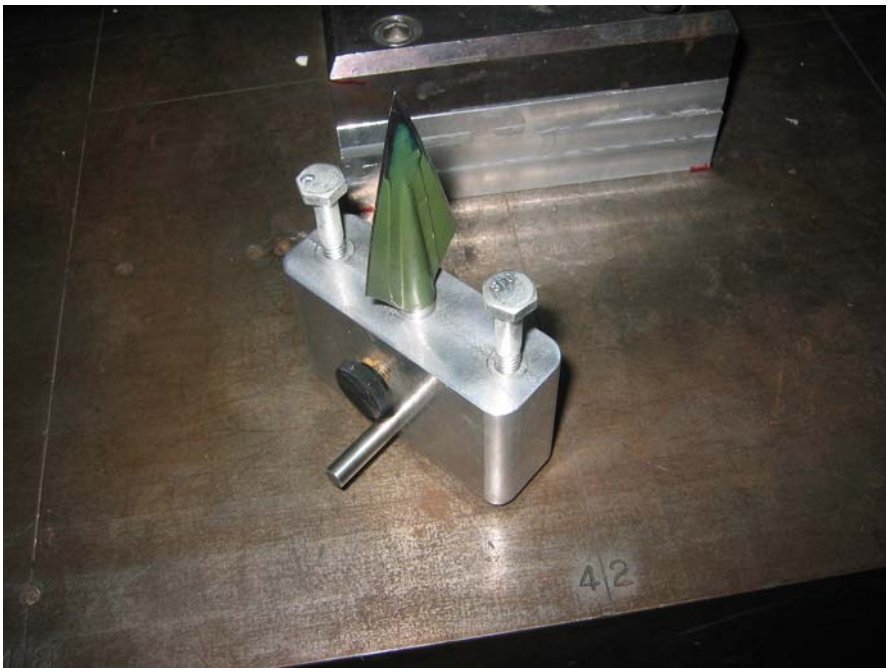


Figure 13. The Arrowhead Cutter Provided by SRI

Four 3/8″ grade eight bolts were pushed through the fabric and frame and fastened with nuts. Eight 2″ fender washers were used to hold it to the frame securely. They were torqued to 40 foot pounds. (Note: Test samples not fabricated at UCB were received in completed form from NAWC China Lake and were not prepared in this manner.)

2.3.2 Pneumatic Gun Tests.

- The target frame was placed on the target mount so that the center of the fabric was aligned with the path of the projectile. As mentioned in section 2.1.5, aluminum spacers were placed on the sides of the frame to keep the fabric normal to the path of the projectile. The target frame was then clamped to the mount at each of the four corners using C-clamps.

- The initial and residual velocity measurement systems were prepared and tested. The paper grids were placed behind the target and out of the range of the camera's field of vision. The grids were tested numerous times to ensure proper function. Errors in the grid sometimes led to the grids having to be replaced. The laser/photodiode system was also tested to ensure successful measurement. (Although the laser system was much more reliable in general, if photodiodes were exposed to too much light from the high-intensity lamps, they would sometimes not register the projectile passing through the lasers' path.)

- The pressure to the gun was set using a regulator valve attached to the nitrogen tank. The desired pressure was set according to the pressure versus speed calibration for the

projectile. The desired speed was determined based on results from previous tests for a specific projectile and fabric attachment to test the ballistic limit for each configuration. A calibration curve is shown in figure 14.

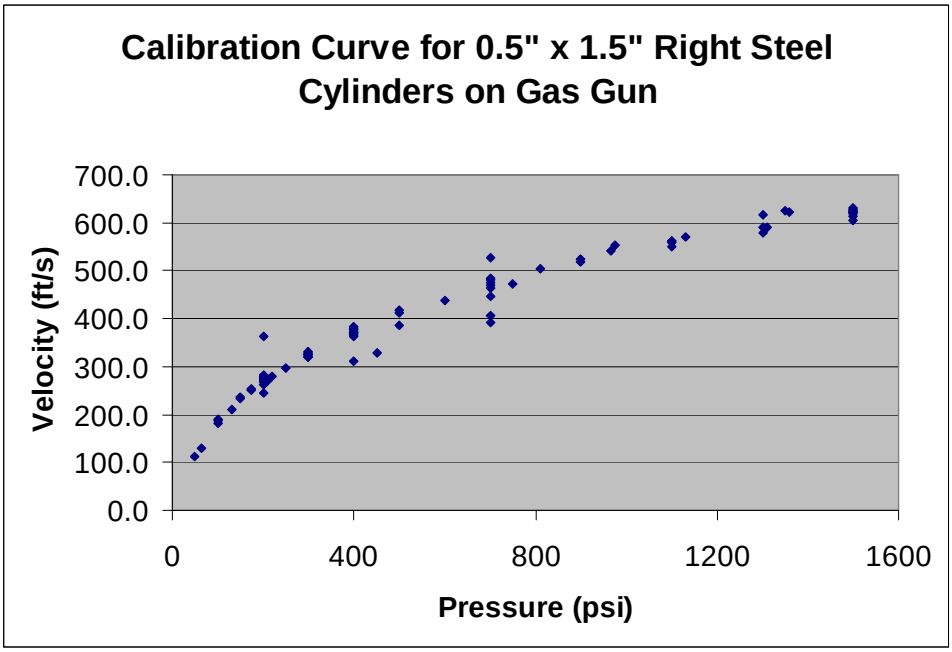


Figure 14. The Calibration Curve for 0.5″ x 1.5″ Right Steel Cylinders on the Pneumatic Gas Gun

- The breech of the gun was slid back on its support rails and the projectile was placed into the barrel of the gun just in front of the pressure chamber. Then the breech was slid forward and reattached to the barrel of the gun. This process is shown in figure 15.

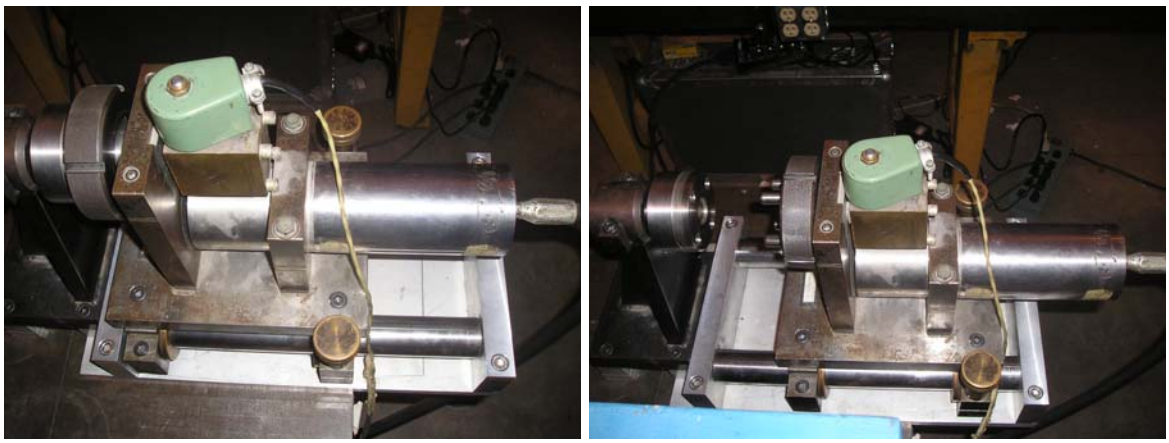


Figure 15. A View of the Pressure Chamber and Breech Attached to the Barrel of the Pneumatic Gas Gun (left) and Slid Back to Allow the Loading Projectile Into the Barrel (right)

- The high-speed camera was aligned and set to record 10,000 frames per second to prepare for the shot. The high-intensity lamps were turned on to provide enough light, and again, the camera was checked for alignment by observing the video output of the camera. From this point until the actual firing of the projectile, there was, at most, 5 minutes until the camera would shutdown to prevent overheating.

- The gas was released at the specified pressure into the pressure chamber of the breech. The firing trigger was connected to the electronic control box and the counters were reset.

- The room was evacuated and the camera control box was brought outside the laboratory through a small side door. Recording was started on the camera control box, the trigger was fired, and the recording was stopped, all within a second of each other.

- Returning into in the laboratory, all measurements were recorded and the video file of the test was analyzed and saved. If possible, the projectile was recovered. The target was taken down and observations concerning the failure pattern and other notable characteristics were recorded. The Zylon was removed from the frame, labeled, and stored for future reference.

3. RESULTS AND DISCUSSION.

3.1 PROJECTILES.

In most tests, the projectiles used at UCB were 0.5″ diameter by 1.5″ length, copper-plated steel right cylinders. It was thought that spherical projectiles would be more likely to push through the Zylon fibers without breaking them and the cylindrical projectiles that were used would give us more consistent results. The copper-plated steel projectiles did not suffer any permanent deformation in the tests that were performed. In the last two tests, 0.5″ diameter, 2″ long copper-plated tungsten projectiles were used in an attempt to match conditions of larger-scale testing at NAWC China Lake.

3.2 ACCURACY OF RESULTS.

There were a number of factors that could have influenced the accuracy of the tests performed at UCB that need to be addressed. All of the UCB fabricated Zylon sheets were prepared by hand, as described in section 2.3.1. While the same general procedure was used each time, one cannot expect the conditions between tests to be as uniform as they would be had a machine prepared the samples. Some of the more important variables that could have been different were amount of slack, amount of material used in testing, fastening consistency, and gun power. A timing circuit (described in reference 3) connected to two lasers was used to measure the time that it took the projectile to pass between the two independent laser beams. Any error in the measurement of the laser placement, as well as any intrinsic errors associated with the circuit, would be propagated throughout the initial velocity calculations. In a similar manner, the grids and timing circuit used to calculate the residual velocity carried with them similar sources of error. In the event that either the lasers or the timing grids did not activate correctly, the video camera was used to calculate the associated velocities. Using the camera presented a whole new set of variables that affected the accuracy of results. At the beginning of each set of tests, the

velocity of a projectile was calculated using the lasers (the most consistently accurate method available) and then that data was used to calibrate the camera. The camera display consisted of 128 pixels in the horizontal direction and captured images with a time step of 0.0001 seconds. Using the velocity calculated from the laser setup, it was possible to work backwards and, counting the number of pixels on the camera's display through which the projectile passed, determine the number of pixels per inch on the display. These calibration tests were usually performed at a relatively slow projectile speed so that a larger time span was used in relating the measurement to a distance on the display, thus reducing the error as much as possible. When actual tests were performed, conditions were not always as ideal as they were during the calibration test. The fabric sometimes caused the projectile to tumble, resulting in blurring of the images. Also, sometimes shadows and other lighting conditions would make the projectiles position on the camera hard to determine with the amount of accuracy that one would have liked. Errors from all these aspects of testing made the camera the least accurate of the velocity measuring devices, but at times, it was the only working speed measuring component available.

Professor Tarek Zohdi's computational analysis suggested that the introduction of slack might result in more absorbed energy in the Zylon [4]. Though Kelvin Kwong's earlier work with different boundary conditions [2] did not deal directly with the idea of slack, it did introduce the idea that more tension in the fibers due to boundary restraints resulted in lower energy absorption. It was decided to investigate whether or not less tension (i.e., more slack) in the Zylon would have the opposite effect—more absorbed energy. While slack introduced on the macroscopic level (i.e., more material/area of testing) did not appear to result in a larger amount of absorbed energy, it did introduce a greater amount of variability in the results. Those results are discussed in greater detail in section 3.3 as well as the result that in some cases, the amount of fabric material surrounding the fastenings played a role in the amount of energy absorbed.

3.3 INVESTIGATION OF DIFFERENT CONFIGURATIONS.

3.3.1 Four-Corner, Single-Ply Test.

The most basic test configuration consisted of a single ply of Zylon attached to the frame by four corner pegs. This setup was the same as Kelvin Kwong's "four pegs/Center shot" test without the multiple plies [2]. Figure 16 shows that while there was some variance in the results of the test, the ballistic limit can be estimated to be approximately 285 ft/s.

The amount of energy absorbed can also be seen in figure 17. Using the amount of energy absorbed and the assumption that a constant amount of energy (141.3 J from the average measurement) was absorbed when the projectile penetrated the fabric, a trend line was produced to which one can compare the results of future tests with alternative test configurations. This trend line is hereafter referred to as the "baseline curve."

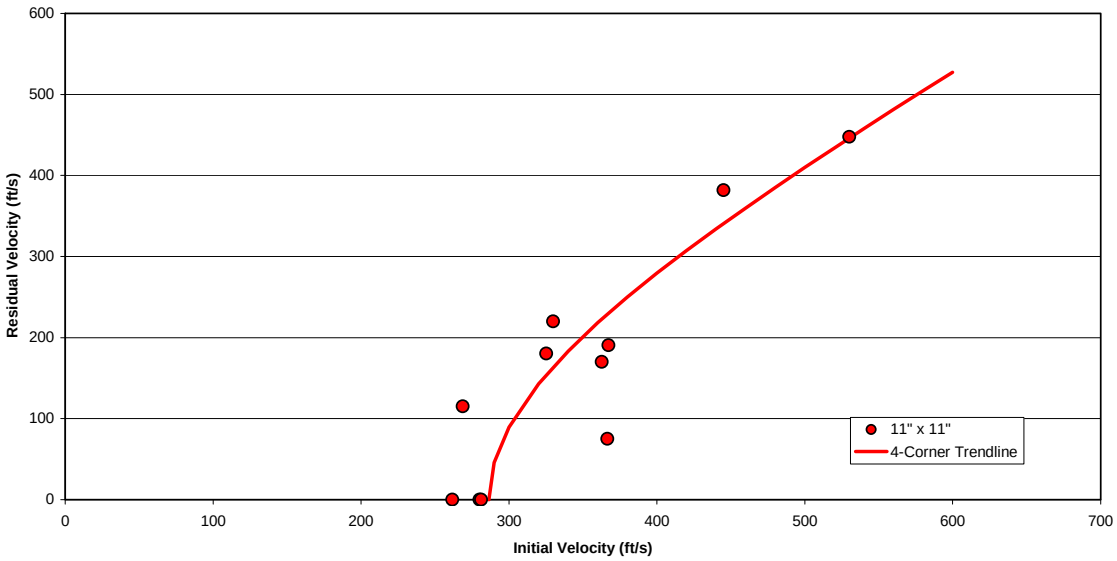


Figure 16. Projectile Initial Velocity vs Residual Velocity for Four-Corner Tests With Trend Line

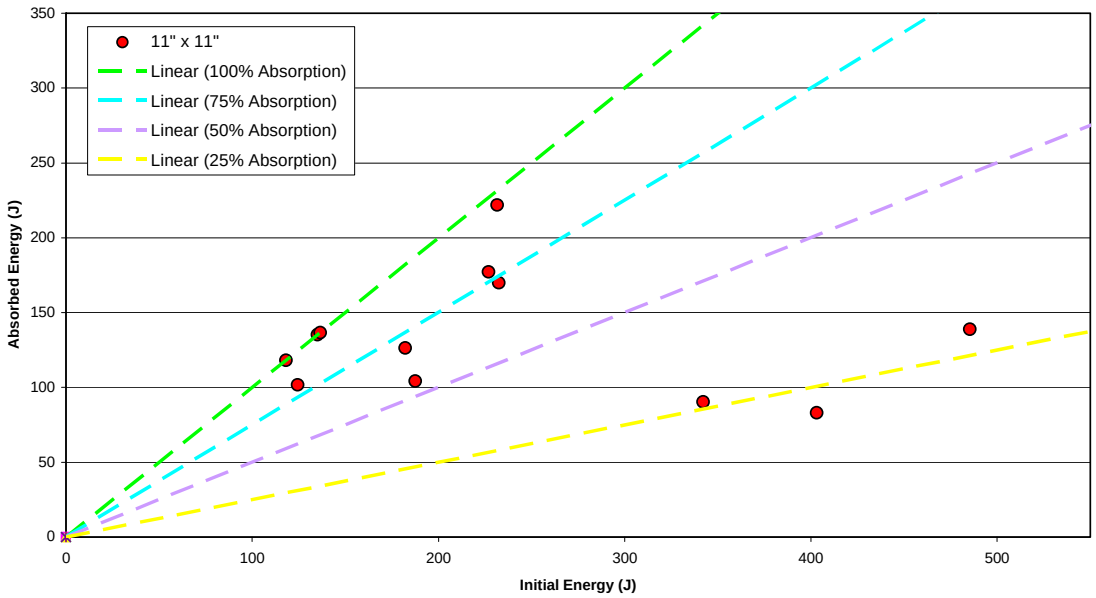


Figure 17. Projectile Initial Energy vs Absorbed Energy for Four-Corner Tests

In some cases, tumbling introduced upon the projectile's impact on the Zylon caused a greater amount of energy to be absorbed, although in this configuration, much of the tumbling was minimal. For clarity's sake, unless otherwise noted, the tumbling effect is assumed to be a part of the normal variance associated with the tests. The main purpose of these tests was to establish a baseline measurement, shown on plots as "four-corner trend line," since other tests would be variations on this configuration.

3.3.2 Four-Corner (1″ Slack), Single-Ply Test.

The most basic alteration to the four-corner test scheme involved adding more material to the test configuration. The thought was that introducing more material within the clamped area of the test frame would provide greater energy dissipation since the Zylon would have more give to it. One inch of additional Zylon material was added to the length and width in each of these tests so that a 12″ x 12″ sheet of Zylon was attached to the test frame at the corners of dimension 11″ by 11″ leaving 1″ of slack in each direction. The results can be seen in figures 18 and 19 along with the baseline curve for comparison.

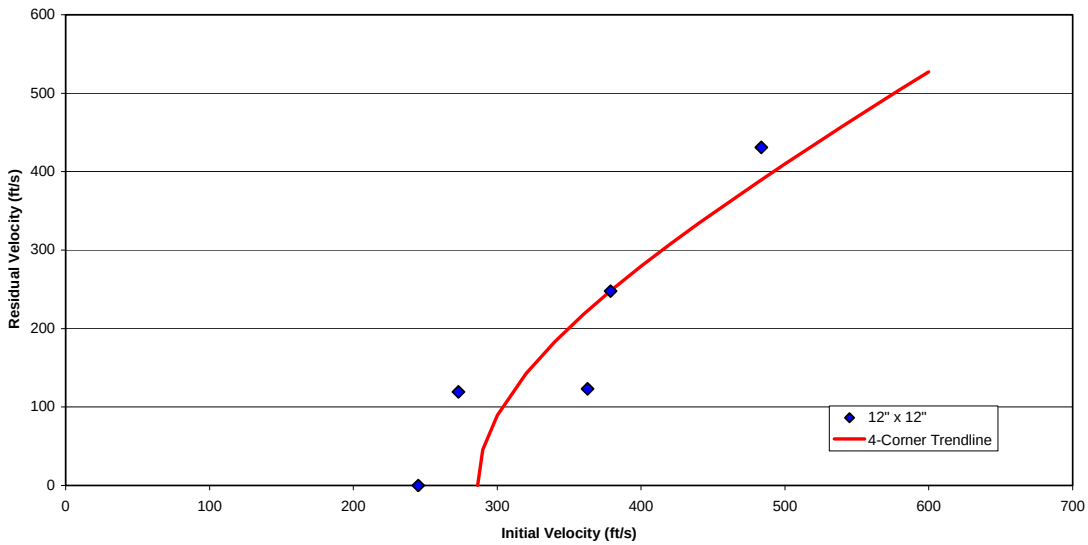


Figure 18. Projectile Initial Velocity vs Residual Velocity for Four-Corner Tests With Slack

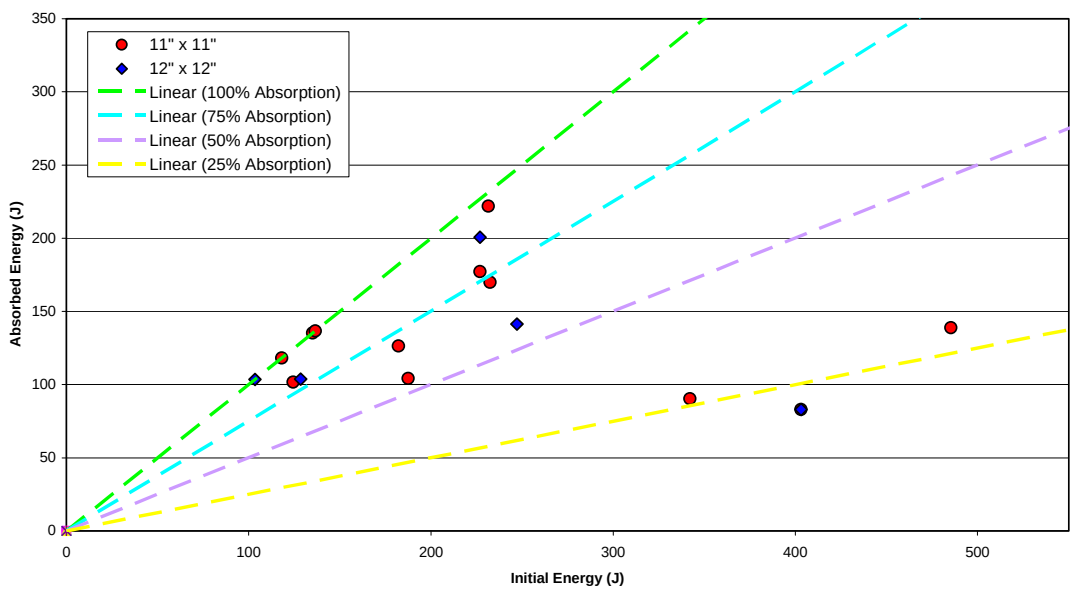


Figure 19. Projectile Initial Energy vs Absorbed Energy for Four-Corner Tests With Slack

The results show that the additional Zylon material did not have a noticeable effect on the ballistic properties of the single-ply targets. At velocities both below and above the ballistic limit, the test results fall along the same general ballistic curve as the tests without any slack, only with a noticeably increased amount of variance. Note that the slack introduced in these tests was on a macroscopic scale, meaning that the individual yarns making up the Zylon sheets had the same amount of tension as the yarns making up the sheets of Zylon in the previous four-corner tests, there was only more sheeted Zylon within the testing frame. This type of macroscopic slack will be referred to as "sheet-level" slack, while tension in the individual yarns will be referred to as "yarn-level" slack. It appears that sheet-level slack did not have much effect on the ballistic limit of Zylon during these single-ply tests.

3.3.3 Two-Sided Clamped (With and Without Slack), Single-Ply Test.

Before examining the other alterations to the four-corner test configuration, tests were run with the two sides of the sheets of Zylon clamped into the frame as in Kelvin Kwong's "two clamping edges" tests [2] to further examine the effects of slack—this time on the yarn level. Having two sides clamped into the frame left the same area exposed to the projectile, but the horizontal yarns were restrained by the clamping, increasing the tension upon impact over the four-corner tests. Tests were also run that introduced 1″ of sheet-level slack in the direction running between the two clamped sides. Figure 20 shows the results of these tests with and without the fabric slack along with the baseline curve for comparison.

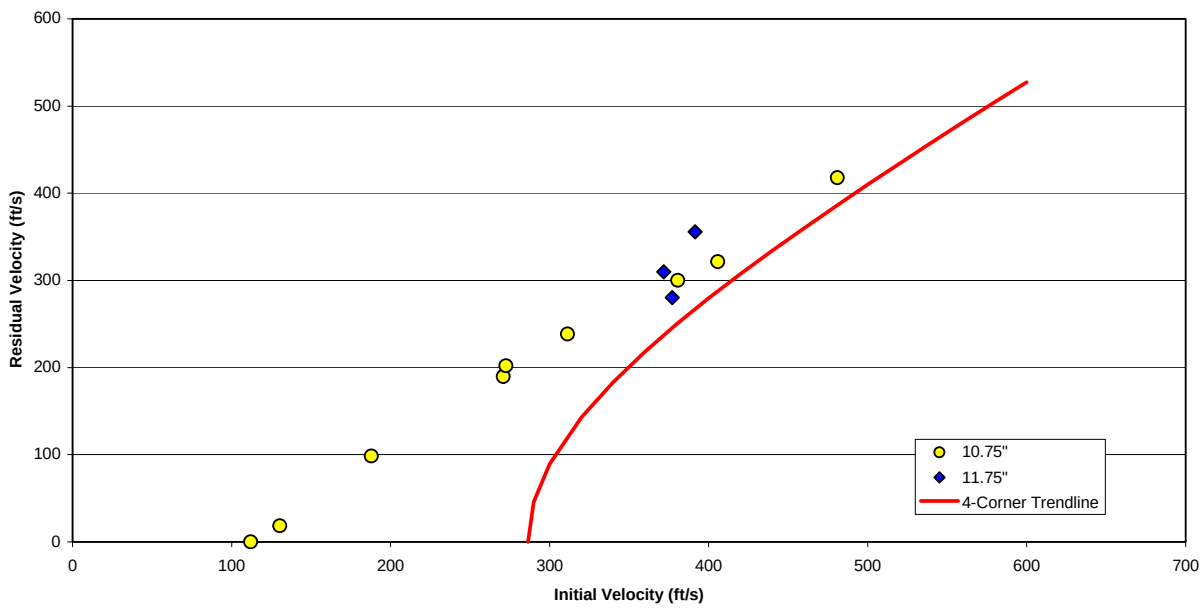


Figure 20. Projectile Initial Velocity vs Residual Velocity for Two-Sided Clamped Tests

The results from this test were more consistent and showed the ballistic limit to be about 110 ft/s, which was almost 40% less than the ballistic limit determined from the four-corner test. Also, the energy absorption graph, shown in figure 21, revealed that while the amount of energy absorbed does increase with an increasing initial velocity, it would appear that it reaches a limit of about 100 J. Again, the presence of sheet-level slack introduced some variance, but does not appear to fall significantly outside the results of tests without slack. These results coupled with Tarek Zohdi's computational models of the effect of fiber-level slack [4] suggest that possibly the yarn-level slack might influence the ballistic limit to a much greater extent than sheet-level slack. The scope of the project did not allow testing of such a hypothesis, but future consideration on the topic might prove insightful. It should also be noted that the total amount of deflection in the fabric was much less in the two-sided clamped versus the four-corner attachment whether it had slack or not.

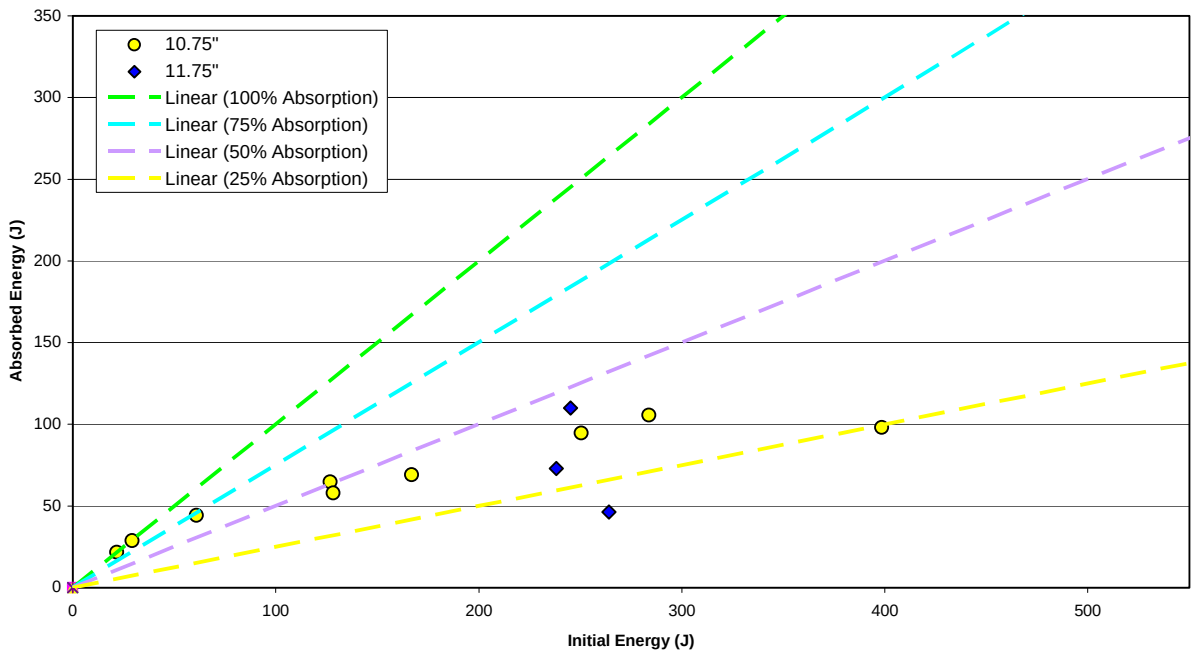


Figure 21. Projectile Initial Energy vs Absorbed Energy for Two-Sided Clamped Tests

3.3.4 Free Boundaries, Single-Ply Test.

Going to the other extreme of slack on the yarn level, tests without any boundary restrictions were conducted. A single ply of Zylon was loosely attached to the frame by a piece of tape before the projectile was fired into it. Because the Zylon often wrapped around the projectile, the grids normally used to determine the residual velocity were ineffective. Also, because the Zylon and projectile traveled together for a distance not even considered in the previous tests, the video setup was unable to capture any conclusive video about when projectile penetration took place, if it did at all. However, by examining the Zylon and projectile position in the catcher box after each test, one could give a good guess as to whether or not penetration occurred. But, even if penetration did occur, it was never known if the event occurred before or after the Zylon and projectile combination came into contact with the catcher box imposing more friction, etc. In any case, at speeds of even 504.5 ft/s, no penetration occurred, which was significantly higher

than the ballistic limit of even the four-corner test case. However, the projectile was finally stopped by the catcher box material, not by the attachment as in previous tests. Additional results for these tests can be found in appendix A.

3.3.5 Grommets, Single-Ply Test.

The Systems Vulnerability Branch at NAWC China Lake provided single ply sheets of Zylon to test in the four-corner configuration with one important modification—grommets at the corners. To attach the grommets, ends of the Zylon sheet were folded back upon each other and sewn down. This may also have had a small effect on the ballistic limit since the fibers would be more constrained than they were in the four-corner baseline tests shown in figure 22. Figure 23 shows the energy plot results of the test with the grommets and the data from the baseline four-corner 11″ x 11″ tests.

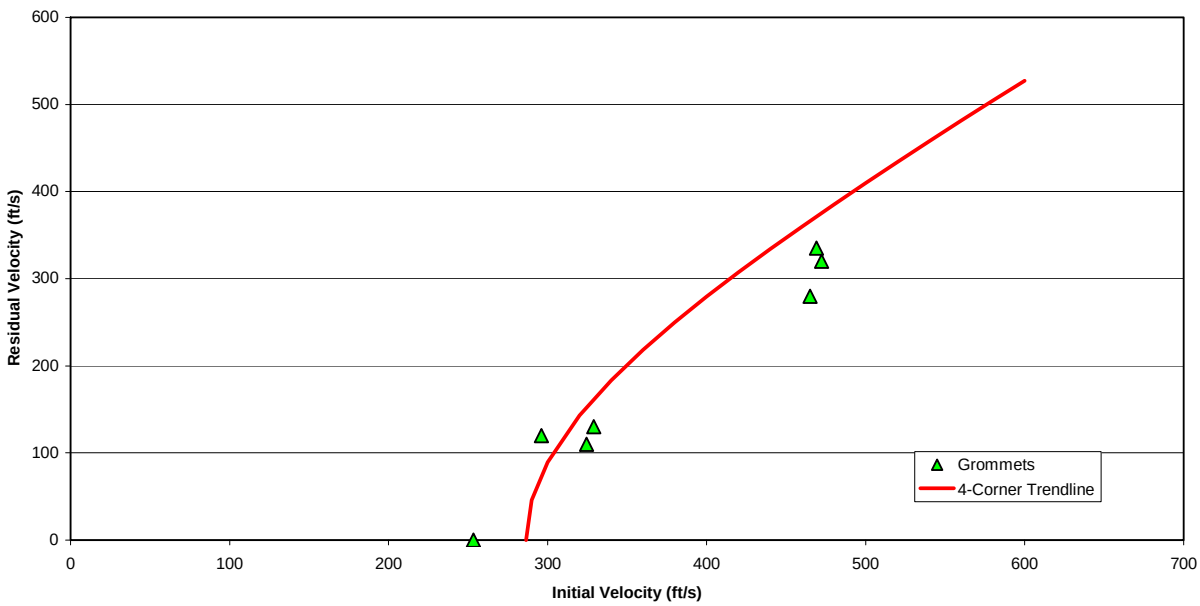


Figure 22. Projectile Initial Velocity vs Residual Velocity for Grommets

At the lower firing velocities, the results were almost identical to the original four-corner tests with similar damage patterns. However, at higher speeds, one can see particularly stretched fibers (in figure 24) stemming out both horizontally and vertically from the hole in the Zylon, which were not present in the four-corner tests. This might be attributed to the stitching in the sides of the test sheets, which did not allow the fibers of Zylon to move as freely as they did in the four-corner tests.

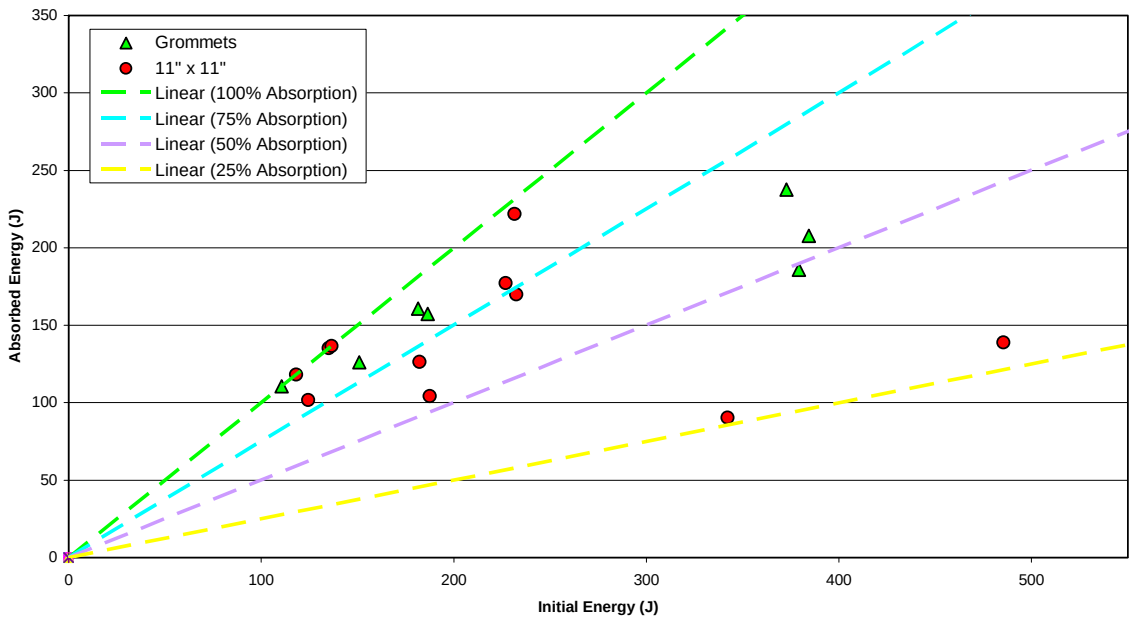


Figure 23. Projectile Initial Energy vs Absorbed Energy for Grommets

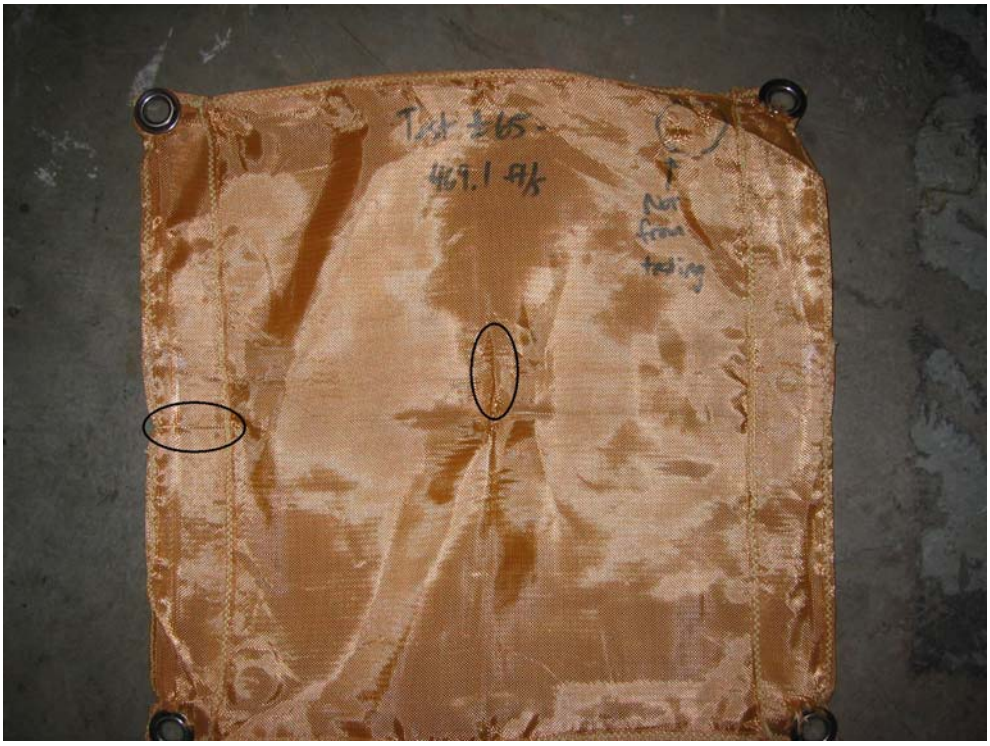
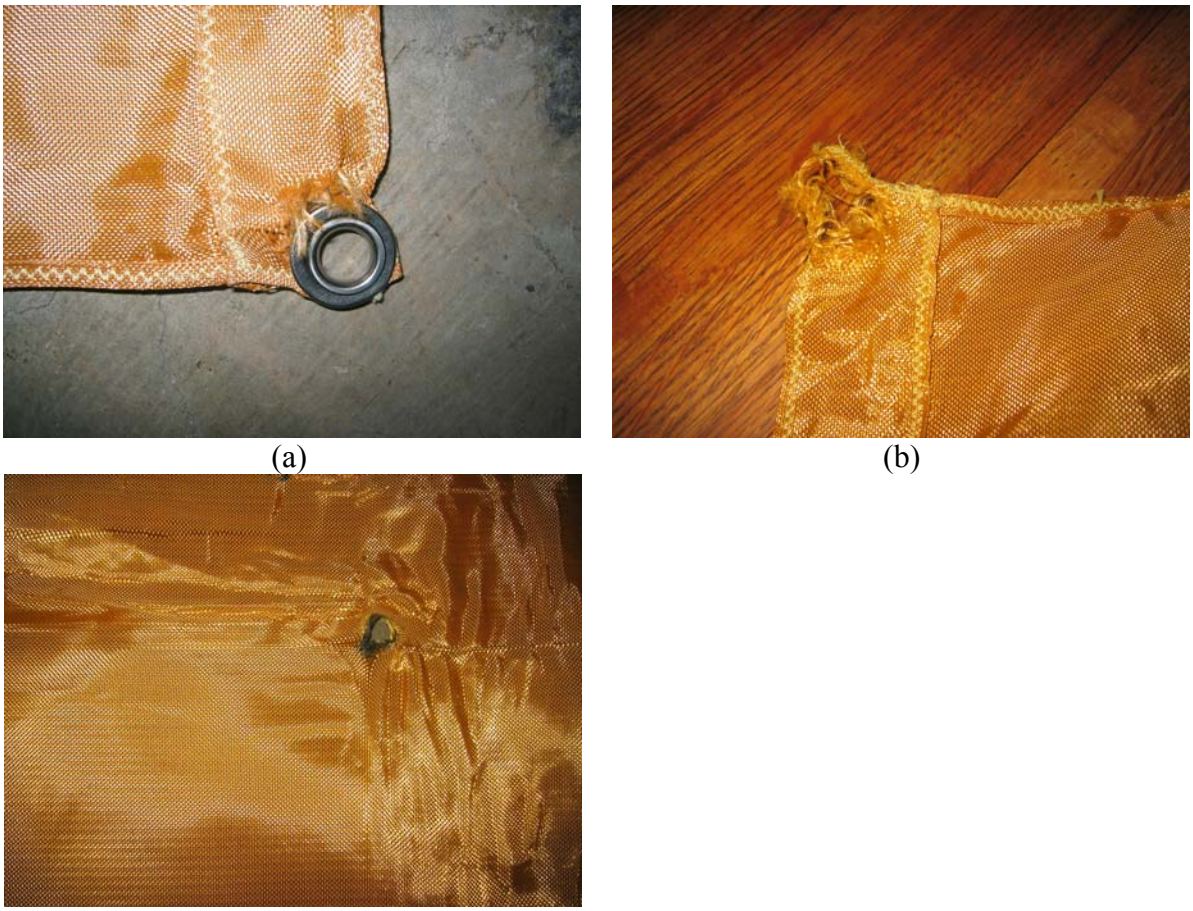


Figure 24. A High-Speed Test With Grommets and Particularly Strained Fibers are Highlighted

Looking at the energy plot, at the higher test speeds, even though the movement in the fibers was restricted, more energy was absorbed than in the four-corner counterparts. There had to be another form of energy dissipation, and it was found at the grommets themselves. More tearing at the corners was present than in the four-corner tests and is apparent in figure 25.



(a) (b)

(c)

Figure 25. (a) Great Amount of Tearing to the Area Surrounding the Grommet, (b) Corner Where the Grommet was Torn Away Completely, and (c) Relatively Small Amount of Tearing on a Standard Four-Corner Test

All three of the photographs were taken from three distinct tests with similar initial velocities of about 460 ft/s. This configuration, however, would be inadequate for multiple layers because the grommets were too close to the edge to take an additional load. Subsequent testing at NAWC China Lake had additional fabric around the grommets to prevent tearout.

3.3.6 Corded, Single-Ply Test.

The corded sheets of Zylon featured yet another way to attach the material to the test frame. Cords of nylon, 0.236″ in diameter, were run through hems of Kevlar® sewn into the sides of the fabric and looped over themselves at the corners to provide a method of fastening the sheet to the frame. Figure 26 shows a corded sample after testing.

Figure 26. Corded Zylon Sheet After Testing

Figure 27 shows that the ballistic limit is about 250 ft/s, which is about 35 ft/s lower than that of the original four-corner tests. The rest of the curve also seems flatter than the four-corner ballistic curve, suggesting that at higher speeds, the corded fastening performs better, but at lower speeds, slightly worse. Energy plots can be seen in figure 28.

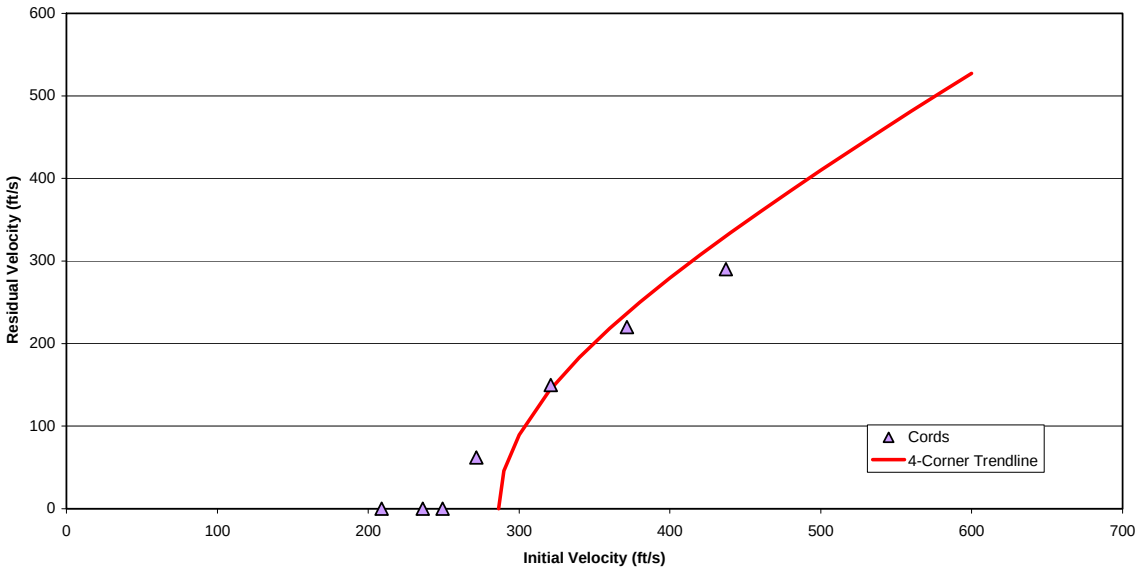


Figure 27. Projectile Initial Velocity vs Residual Velocity for Cord Tests

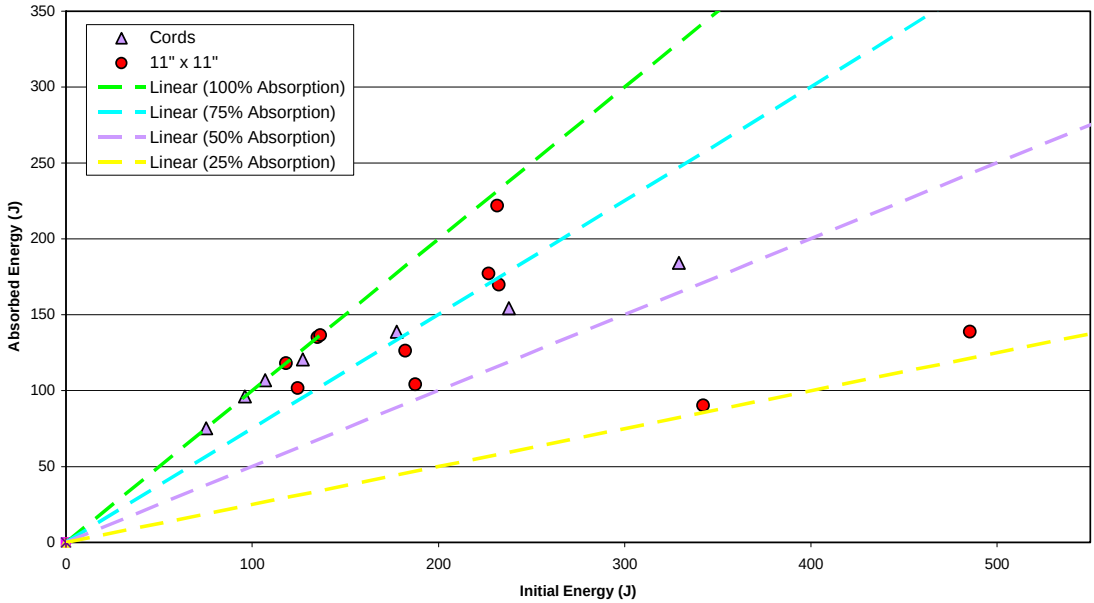


Figure 28. Projectile Initial Energy vs Absorbed Energy for Cord Tests

The tearing at the corner of the fabric in the tests with grommets (and to a lesser extent, the four-corner tests) was not present in the corded tests since there was no material to tear away. Therefore, it appears that the energy dissipation was focused to the sides of the sheets, pulling the fibers away from the seam directly along the perpendicular fibers of the impact region, as shown in figure 29.

Figure 29. A Close-Up View of a Corded Sample and the Stretching of Fibers Near the Seam

While this alternative energy release mechanism did not appear to be as effective at lower speeds, using corded attachments to induce such a mechanism at higher speeds could prove slightly more useful.

3.3.7 Four-Corner, Double-Ply Test.

Having tested several different possible energy absorption features with one ply, testing moved on to two or more plies. Would the extra plies cause additional energy absorption linearly or otherwise? To get a baseline, tests were run with the original four-corner configuration but with two plies of Zylon. Figure 30 shows a substantial increase in the ballistic limit of nearly 95% to 550 ft/s.

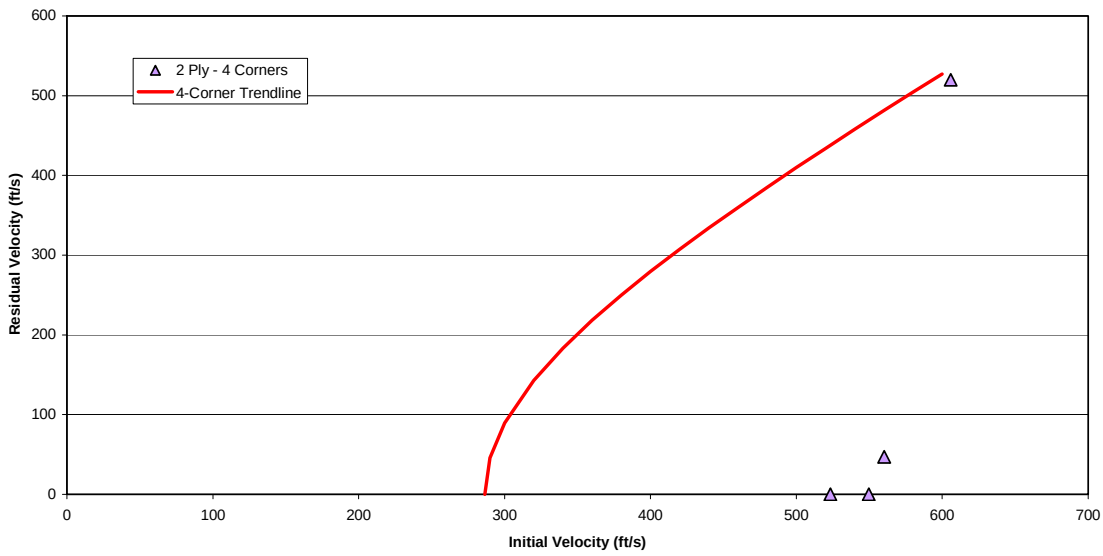


Figure 30. Projectile Initial Velocity vs Residual Velocity for Two-Ply Tests

Furthermore, the energy absorption graph, shown in figure 31, shows that the amount of energy dissipated in the two-ply test was nearly 4 times that of the single ply (at the ballistic limit). This implies that there was some other interaction between the two plies of Zylon and that they did not act independently of one another. Two possible reasons for this are

- the two layers strengthened the impact area enough to blunt the sharp edges of the projectile.
- the additional layer caused the projectile to tumble at impact, increasing the surface area contact.

One test did not show such marked improvement over the single-ply test configuration. That particular test was taken at the extreme limits of the test equipment and was not able to be repeated due to the restraints of this project. Video and notes of that one test are not significantly different (other than in the results) from the others and is considered a random outlier at this point in time. Further testing, perhaps, could show otherwise.

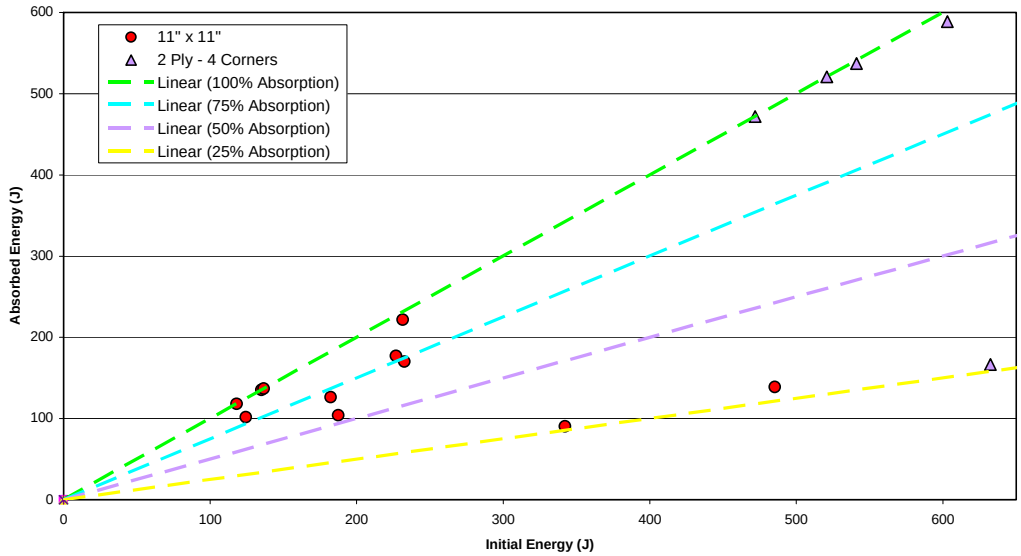


Figure 31. Projectile Initial Energy vs Absorbed Energy for Two-Ply Tests

3.3.8 Free and Four-Corner, Double-Ply Test.

Although the free boundary condition, single-ply test would not stop a projectile from its projected path effectively, it nonetheless had the highest ballistic limit. Tests with a free ply taped to the front face of a single four-corner attached ply (two plies total) were run in the hopes that it would combine the path restriction of the four-corner attached tests with the high ballistic limit of the free boundary condition test.

As shown in figure 32, while the two sheets (one free) interacting did increase the ballistic limit from that of the single four-corner configuration to about 450 ft/s, it was not as effective in slowing or stopping the projectile as the two-ply, four-corner configuration. The energy results in figure 33 also show the same trend. The results indicate that by attaching the second layer to the four pegs, more energy was removed from the projectile.

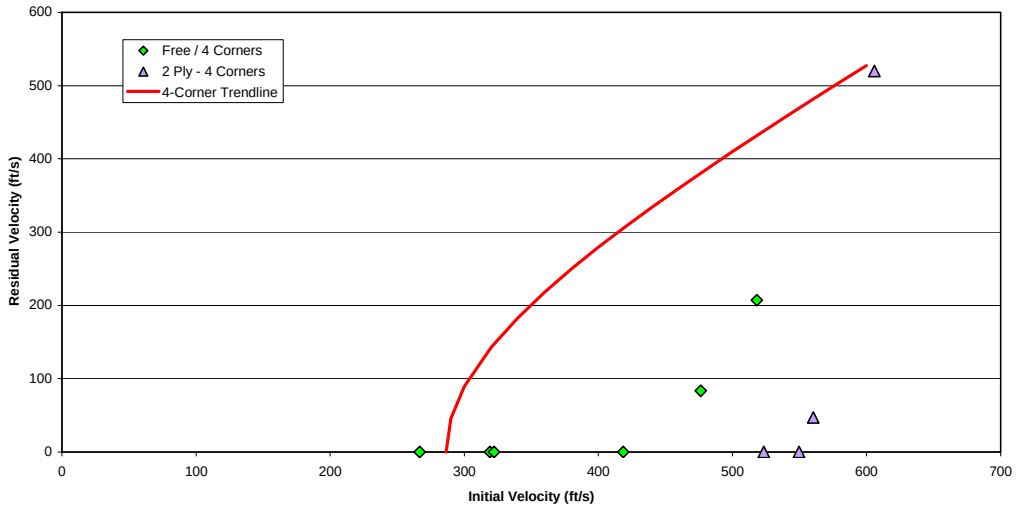


Figure 32. Projectile Initial Velocity vs Residual Velocity for Other Two-Ply Tests

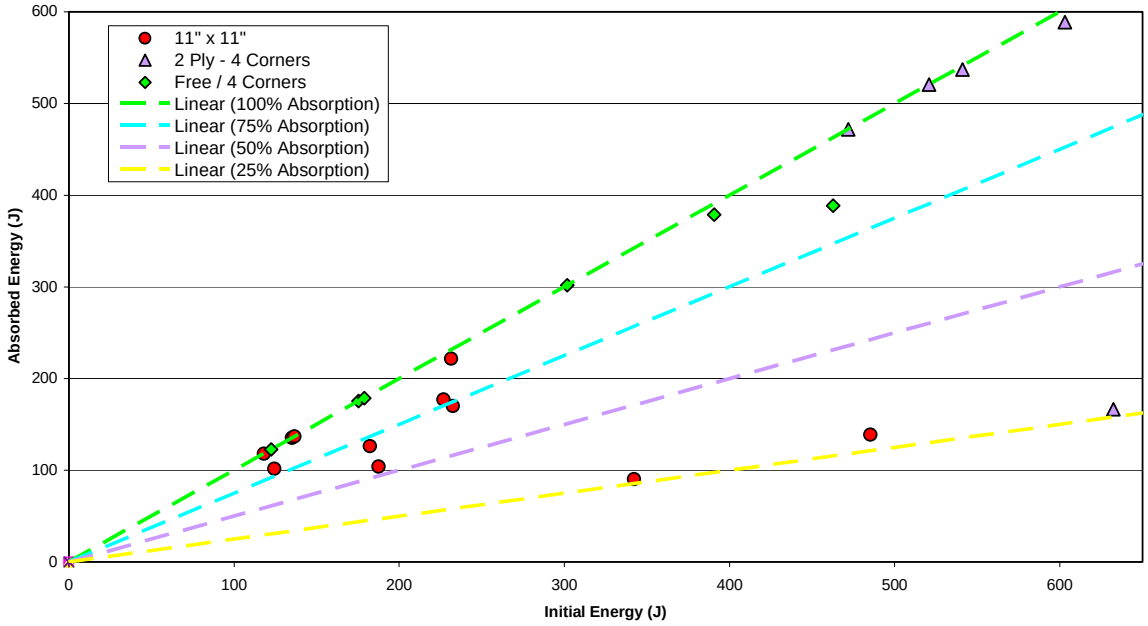


Figure 33. Projectile Initial Energy vs Absorbed Energy for Other Two-Ply Tests

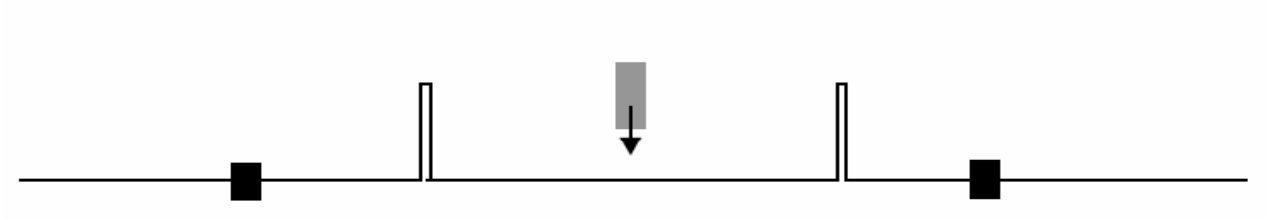
3.3.9 Four-Corner, Triple-Ply Test.

For completeness, four-corner tests with three plies of Zylon were also performed on the pneumatic gas gun, but with the equipment available, it was not possible to achieve an initial velocity high enough to perforate the Zylon. Even though the higher energy points were not completed, there was still an increase in strength over the double-ply experiments. A table containing the results from the triple-ply tests can be found in appendix A.

3.3.10 Pleats, Single-Ply Test.

The idea surfaced that perhaps it was possible to gain some of the benefits of multi-ply testing using just one sheet of Zylon by overlapping the fabric. Ideally, the projectile would have to pass through all of the overlapping sections and perhaps the relative movement of the overlapping fabric as it unfolded would impart a spin to the projectile further limiting its ability to penetrate the fabric sheet. In addition to overlapping fabric, pleats were also tested with thread and staple reinforcements. The three major configurations can be seen in figure 34.

(a) Overlapped pleats



(b) Double pleats

(c) Sewn pleats

Figure 34. (a) Overlapping Sheet of Zylon Without the Stitches, (b) Side View Diagram of the Zylon With the Two 0.5″ Pleats, and (c) Top View of the Sewn Pleated Sample Sent From NAWC at China Lake

The overlapping sheet of Zylon (made at UCB) was kept in place by both staples (as a preliminary method) and sewing (very light cotton thread) upon further testing. Unfortunately, a particularly small number of tests were run with the sewn overlapping configuration. The NAWC China Lake's samples had grommets at the corners and were sewn (with Kevlar or Zylon

thread) in a manner such that the projectile penetration would hopefully release energy through the tearing of the stitches holding the pleat in place. Though the stitches per inch varied between the tests, they are presented lumped together here since the difference between the stitching type was minimal. Results from the individual tests, as well as stitch per inch numbers, can be found in appendix A.

While the pleated configuration did not show an appreciable increase in the ballistic limit (see figure 35), the 2″ overlap configuration showed some promise at higher test velocities. The sewn samples confirm this with a ballistic limit of 560 ft/s, which was similar to the two-ply, four-corner configuration. The energy plots are shown in figure 36.

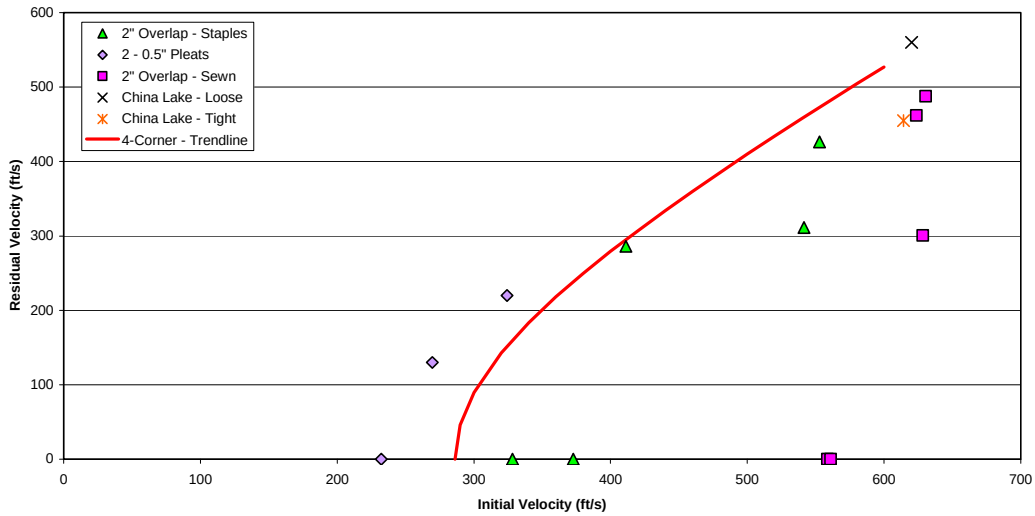


Figure 35. Projectile Initial Velocity vs Residual Velocity for Induced Slack Tests

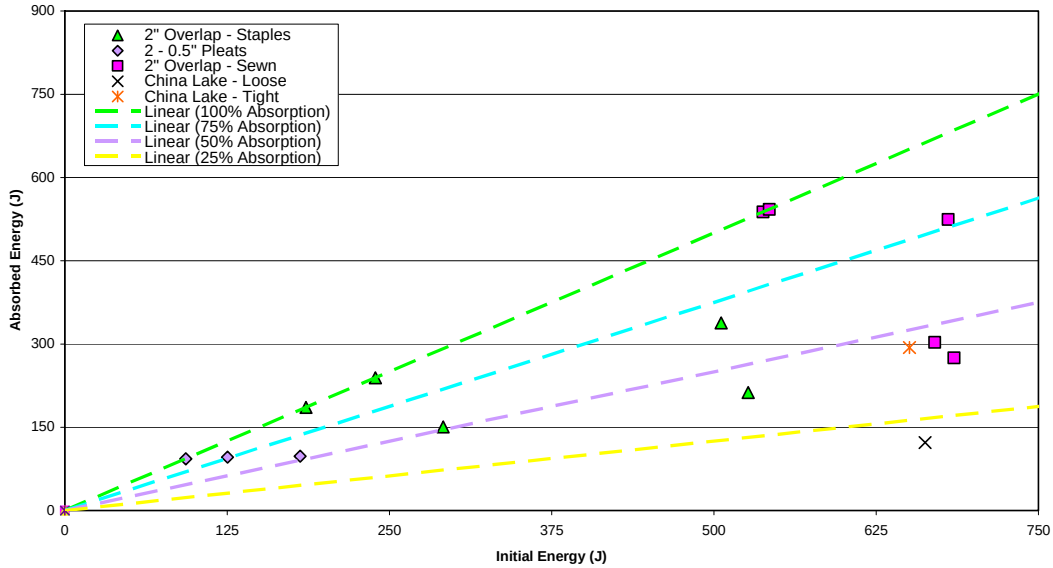


Figure 36. Projectile Initial Energy vs Absorbed Energy for Induced Slack Tests

It is tough to draw many conclusions from the NAWC China Lake samples given that there was only one sample of each to test. However, in general, the stitches and pleats did not tear away entirely as designed, but rather the projectile tore straight through the middle of the sheets indicating the stitching was too strong for just one ply of fabric. What little tearing there was occurred at the ends of the sheets, as can be seen in figure 37. There was virtually no tearing at the corners, suggesting that all energy dissipation went to the stitches at either end of the sheets.

Figure 37. Tearing on NAWC China Lake Pleated Zylon Sheet Near the Ends of the Stitching

While other tests had very localized damage, the UCB overlapping samples, sewn with the weaker cotton thread, showed a much more generally distributed load. Figure 38 shows both an extreme and moderate example of a sewn overlapped sheet of Zylon that the projectile penetrated after being fired at the highest velocity attainable by the pneumatic gun (~625 ft/s).

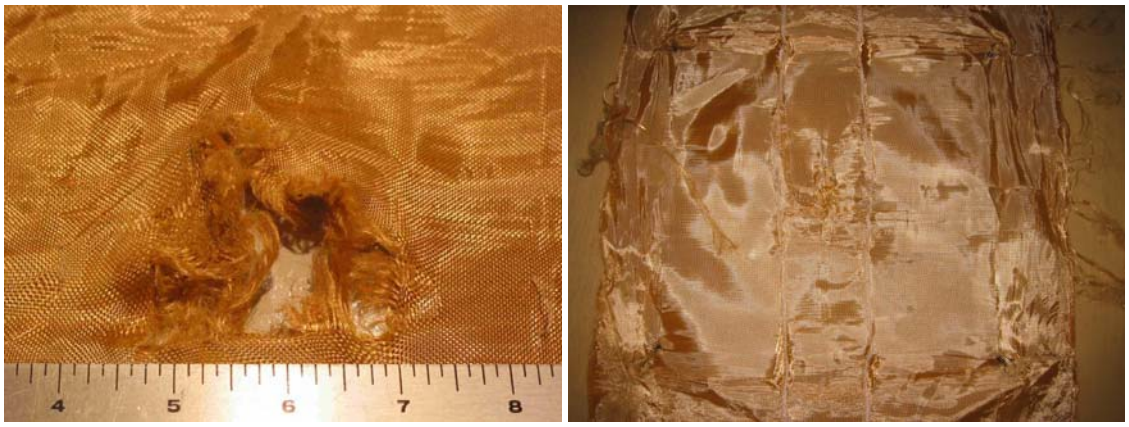


Figure 38. A Very Wide Hole Torn by the Projectile (Left) and Moderate Damage Done by Penetration (Right)

Even in tests where the projectile did not penetrate the overlapping sheet, the damage was spread to the outer edges along the sewn areas. Figure 39 shows, once again, an extreme and more moderate example of samples of Zylon that stopped projectiles fired at about 560 ft/s.

Figure 39. Stitching Almost Completely Torn While Stopping a Projectile (Left) and Minor Stitching Torn While Stopping a Projectile (Right)

Clearly, this delocalization of the damage was part of the reason for the higher ballistic limit and greater energy absorption.

3.4 VERIFICATION—NAWC CHINA LAKE BLANKETS.

The last two tests were a bit of a departure from the others. Instead of testing new configurations and examining their gain or loss of energy absorption, these tests combined many of the energy absorbing features that were already tested. Figure 40 shows the sample that contained elements of pleating, stitching, multiple plies (3), and grommets. The only difference between the two samples was the stitching used to hold the pleats together—one was stitched with a weaker thread (nylon) and one was stitched with a stronger thread (Kevlar). Although the grommets did not help in energy absorption, except at higher speeds, they would be necessary to hold a Zylon shield to the frame of an airplane, and for that reason, they are included.

To simulate the full-scale aircraft tests to be conducted at NAWC China Lake, a heavier projectile made out of tungsten was used, weighing ~0.25 lb (113.7 gm). The powder gun was used exclusively in these tests to obtain speeds high enough so that the kinetic energy of the projectile would be comparable to the kinetic energy in full-scale tests. Since the cross-sectional area of this projectile is much smaller than a blade fragment, a sheet of Zylon was folded into quarters and placed in front of the sample provided by NAWC China Lake. This helped distribute the load of the projectile in the impact zone to allow a better simulation of the grommet attachments to the actual aircraft barriers.

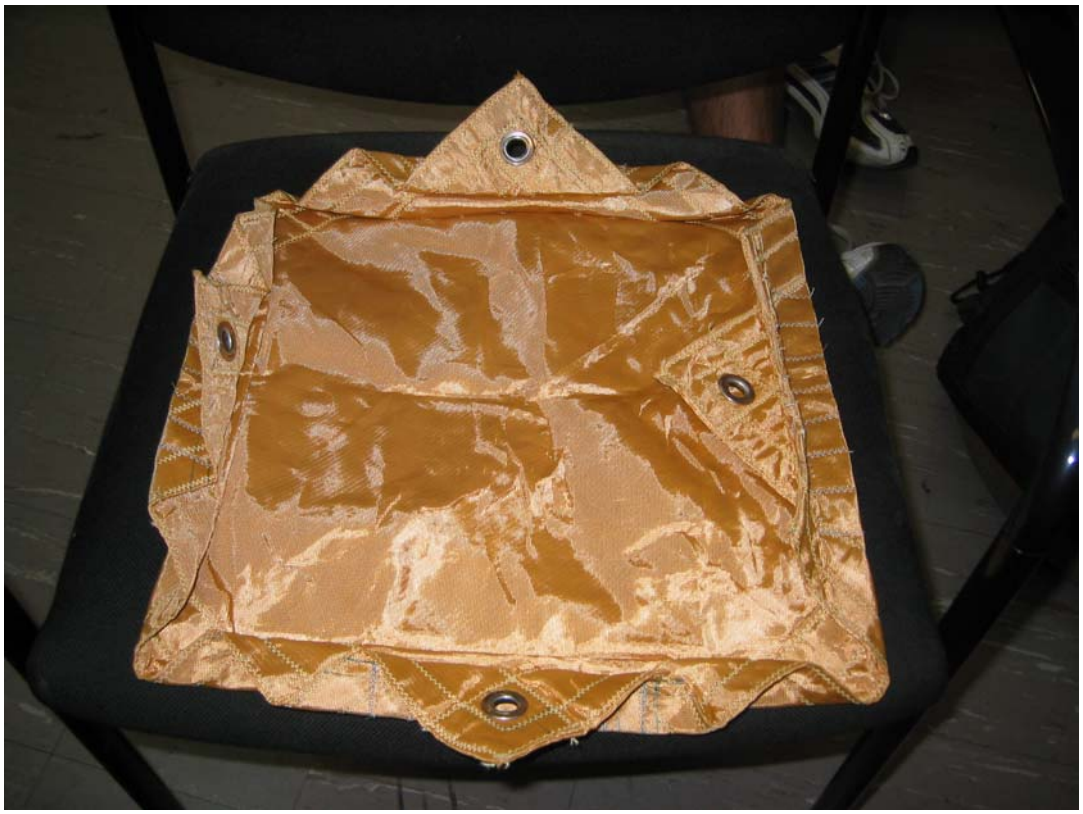


Figure 40. The Sample With Multiple Energy Absorbing Features Sent From NAWC China Lake

The residual velocity of the projectile in these tests could not be calculated because the extra slack in the blankets left no room for the grids when the slack was extended and the high-speed camera's field of vision was not wide enough to see the exit of the projectile. Instead, these tests were judged on the basis of whether they were successful in stopping the projectile or not.

Once the first Zylon blanket was attached to the frame, it was shot with the projectile at a speed of 597.0 ft/s. Though the projectile did penetrate the blanket with the weaker (nylon) threads, the fixed/free Zylon sheet interaction kept the projectile within the folds of the quarter piece of Zylon. A picture of the blanket after testing can be seen in figure 41. There was also noticeable deformation at the corners on the grommets (shown in figure 42). All threading was also torn.

The second sample was attached to the frame in the same way and shot at a velocity of 571.1 ft/s. For this sample with the stronger (Kevlar) threading, the Zylon was not penetrated and the projectile only left indentations in the fabric at the impact point (see figure 43). There was slight damage to the grommets, and all threads tore releasing the extra material that was originally folded and sewn down.

Figure 41. The Sample After Being Shot, as Viewed From the Side Opposite the Barrel of the Gun

Figure 42. Damage Done to the Grommets at the Corners

Figure 43. The Stronger Threaded Blanket After Testing With the Indentation From the Projectile Circled

Without video and more samples to test, not much more can be said, other than the first blanket was not successful in stopping the penetration of a projectile with ~1880 J of kinetic energy, while the second blanket with the stronger threads was able to stop the ~1600 J of kinetic energy provided by the projectile. In both cases, the threads tore as they were designed to, providing an energy release mechanism along with the deformation of the grommets at the corners. The testing of these last two NAWC China Lake configurations proved very valuable in providing a good starting point for the full-scale testing.

4. SUMMARY.

This test program covered many different test configurations without really going into depth on any one configuration. Because of the nature of the tests, results were of a more qualitative nature. While it was difficult to pinpoint quantities such as the ballistic limit for any given test configuration with a good statistical certainty, the tests did provide a good general idea of what to expect from a given characteristic.

Zylon, the fabric purchased for this fragment barrier study, was found to have long-term degradation of properties during this study [5]. The various attachment and energy absorbtion features studied here are applicable to other fabric barrier materials. The original idea of adding slack to sheets of Zylon to increase the amount of kinetic energy it would absorb did not work in these tests. Instead of increasing the amount of energy absorbed from the projectile, the slack

increased the amount of variance in the performance of the Zylon, but the average amount of energy absorbed by the slack configuration remained consistent with the tests without slack. It should be noted that for many layers of Zylon, slack appears to have a positive energy absorption effect due to the inertia of the fabric being accelerated [1]. It was, however, confirmed that the boundary conditions did play a more substantial role in the absorption of energy—the more constrained the boundaries of the Zylon, the lower the ballistic limit and the lower the amount of energy absorbed.

Grommets at the corners for fastening the Zylon to the frame also did not result in extra kinetic energy loss except at higher speeds when the corners tended to tear more than in the standard four-corner test configuration. Perhaps this was due to the fact that the sides of the Zylon with grommets attached were stitched upon each other and, therefore, did not provide the tearing of the fabric as seen in previous four-peg tests [2]. Given that if the Zylon were to be used as a ballistic shield on commercial jets, it would probably have to be attached to the frame by a method similar to the grommets. It was fortunate that results did not show any decrease in energy absorption performance around the ballistic limit.

The corded sheets of Zylon had performance characteristics somewhere in between the four-corner tests and two-sided clamped test. This is actually not surprising since the Zylon was only attached at the corners, but the cords running through the length of the Zylon acted more like a flexible version of the side clamps.

Testing of two ply versus one ply tripled the ballistic limit (~185 ft/s to ~550 ft/s) and nearly quadrupled the energy absorption. Intuition would say that placing two plies attached in the same manner in a row should double the amount of energy absorbed. Clearly, there is some other interaction between the plies of Zylon that increases its ability to absorb the projectile's kinetic energy. It is interesting to note that the single-ply Zylon energy absorption numbers match Kelvin Kwong's numbers [2] for energy absorption rather well, while the results from the two-ply tests exceeded them. Future testing to determine the exact relationship between the number of plies and amount of energy absorbed per ply might be in order.

Of all the overlapping and pleating configurations, the UCB cotton thread sewn, overlapping sheets of Zylon showed the biggest performance increase over the original four-corner tests. The increase in absorbed energy was on par with the two-ply tests. Some of the performance increase might have been that the closeness of the stitches imparted a spin to the projectile, in effect, blunting the leading-edge impact with the fabric. This would be consistent with the posttest damage pattern seen in those tests. Again, with so few tests run on each configuration, it is difficult to know for sure, therefore, further testing is suggested.

The three-ply pleated samples sent to UCB from the NAWC China Lake showed promise. Adding enough of the energy damping properties and blunting the impact zone optimized the three plies of fabric. Only three plies with pleats and a free ply in front to distribute the load were able to absorb 1600 J of kinetic energy of one projectile and nearly absorbed all of another 1880 J of kinetic energy of another. A key to success is preventing penetration at the impact zone.

This study has shown that overlap or pleats with multiple plies was the most promising configuration. However, further investigation is needed.

Reusability is an issue for multiple fragment strikes since in many cases some of the energy absorbing properties (such as overlap) are "used up" even when the projectile does not penetrate the material. Perhaps tests with a first shot fired below the ballistic limit and then another fired above it would reveal how adversely the Zylon is affected by nonpenetrating shots.

Finally, it is suggested that if further testing were to take place at UCB, the laboratory equipment should be updated. The grid system for measure residual velocity was often rendered ineffective and the high-speed camera cannot adapt as easily to certain conditions due to space and lighting constraints. The power supply in the laboratory was also inadequate and caused instruments such as the digital balance to fail. A computer connected to the Internet or other university network would also help in the transfer and analysis of results.

5. REFERENCES.

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APPENDIX A—ZYLON TEST RESULTS

Test	Gun Press. (psi)	Initial Vel. (ft/s)	Final Vel. (ft/s)	Mass (g)	Initial Vel. (m/s)	Final Vel. (m/s)	Mass (kg)	Initial Energy (J)	Absorbed Energy (J)	Energy Absorbed (%)	Fabric Penetration
1 Ply Zylon—4 Corners											
1	200	278.4	0.0	37.1	84.86	0.00	0.0371	133.57	133.57	100.00	
2	400	367.3	190.5	37.1	111.95	58.06	0.0371	232.50	169.96	73.10	
3	700	445.4	381.8	37.2	135.76	116.37	0.0372	342.80	90.91	26.52	
4	700	528.0	447.8	37.2	160.93	136.49	0.0372	481.74	135.23	28.07	
5	200	281.2	0.0	37.2	85.71	0.00	0.0372	136.64	136.64	100.00	
86	300	329.9	220	37.1	100.55	67.06	0.0371	187.56	104.15	55.53	
87	300	325.2	180	37.1	99.12	54.86	0.0371	182.25	126.42	69.36	
88	400	362.9	170	37.1	110.61	51.82	0.0371	226.96	177.15	78.06	
89	400	366.5	75	37.1	111.71	22.86	0.0371	231.48	221.79	95.81	
90	200	268.8	115	37.1	81.93	35.05	0.0371	124.52	101.73	81.70	
91	200	261.8	0.0	37.1	79.80	0.00	0.0371	118.12	118.12	100.00	
1 Ply Zylon—4 Corners (1″slack)											
6	200	362.9	123.4	37.1	110.61	37.61	0.0371	226.96	200.72	88.44	
7	200	245.1	0.0	37.1	74.71	0.00	0.0371	103.53	103.53	100.00	
8	210	273.0	119.5	37.1	83.21	36.42	0.0371	128.44	103.83	80.84	
9	400	378.7	247.8	37.1	115.43	75.53	0.0371	247.15	141.33	57.18	
10	700	483.6	431.0	37.1	147.40	131.37	0.0371	403.04	82.91	20.57	
1 Ply Zylon—2 Sides-10.75″											
11	200	270.9	189.4	37.2	82.57	57.73	0.0372	126.81	64.82	51.12	
12	200	272.5	201.9	37.2	83.06	61.54	0.0372	128.31	57.88	45.10	
13	400	no data	225.4	37.2	no data	68.70	0.0372				
14	400	380.7	300.2	37.2	116.04	91.50	0.0372	250.44	94.72	37.82	
15	400	311.3	238.4	37.1	94.88	72.66	0.0371	167.01	69.06	41.35	
16	700	480.9	417.6	37.1	146.58	127.28	0.0371	398.55	98.02	24.59	
17	700	405.8	321.5	37.1	123.69	97.99	0.0371	283.79	105.66	37.23	
30	100	188.0	98.4	37.1	57.30	29.99	0.0371	60.91	44.22	72.60	
31	50	112.2	0.0	37.1	34.20	0.00	0.0371	21.69	21.69	100.00	
32	65	130.5	18.6	37.1	39.78	5.67	0.0371	29.35	28.75	97.97	
1 Ply Zylon—2 Sides-11.75″											
18	400	377.2	280.2	37.1	114.97	85.40	0.0371	245.20	109.89	44.82	
19	400	371.8	309.7	37.1	113.32	94.40	0.0371	238.23	72.93	30.62	
20	700	391.5	355.6	37.1	119.33	108.39	0.0371	264.14	46.22	17.5	
2 Plys Zylon—2 Sides-10.75″ + Adhesive											
21	220	278.1	0.0	37.1	84.76	0.00	0.0371	133.28	133.82	100.00	
22	200	276.4	no data	37.1	84.25	no data	0.0371	131.66			
1 Ply Zylon—Free											
23	400	382.5	no data	37.1	116.59	no data	0.0371	252.14			No
24	810	504.5	464.9	37.1	153.77	141.70	0.0371	438.63	66.16	15.08	No
25	Error	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
26	1300	615.4	no data	37.1	187.57	no data	0.0371	652.66			Yes
27	1360	623.0	no data	37.1	189.89	no data	0.0371	668.88			Yes
28	1350	623.7	no data	37.1	190.10	no data	0.0371	670.39			Yes
29	1310	589.1	no data	37.1	179.56	no data	0.0371	598.07			Yes
33	1130	570.9	no data	37.1	174.01	no data	0.0371	561.69			Yes
34	1120	no data	no data	37.1	no data	no data	0.0371				Yes
2 Plys Zylon—Free/2 Sides											
35	100	181.6	0.0	37.1	55.35	0.00	0.0371	56.83	56.83	100.00	
36	100	188.8	0.0	37.1	57.55	0.00	0.0371	61.43	61.43	100.00	
37	500	387.0	247.6	37.1	117.96	75.47	0.0371	258.10	152.45	59.07	
38	300	330.0	145.4	37.1	100.58	44.32	0.0371	187.67	151.24	80.59	
39	200	276.1	105.1	37.1	84.16	32.03	0.0371	131.37	112.34	85.51	

Test	Gun Press. (psi)	Initial Vel. (ft/s)	Final Vel. (ft/s)	Mass (g)	Initial Vel. (m/s)	Final Vel. (m/s)	Mass (kg)	Initial Energy (J)	Absorbed Energy (J)	Energy Absorbed (%)	Fabric Penetration
2 Plys Zylon—Free/4 Corners											
40	200	266.7	0.0	37.1	81.29	0.00	0.0371	122.58	122.58	100.00	
41	300	319.0	0.0	37.1	97.23	0.00	0.0371	175.37	175.37	100.00	
42	300	322.1	0.0	37.1	98.18	0.00	0.0371	178.79	178.79	100.00	
43	500	418.5	0.0	37.1	127.56	0.00	0.0371	301.83	301.83	100.00	
44	700	476.2	83.6	37.1	145.15	25.48	0.0371	390.80	378.75	96.92	
45	900	518.1	207.3	37.1	157.92	63.19	0.0371	462.60	388.54	83.99	
1 Ply Zylon—4 Corners-Pleated											
46	975	552.7	426.5	37.1	168.46	130.00	0.0371	526.44	212.96	40.45	
47	965	541.6	311.5	37.1	165.08	94.95	0.0371	505.51	338.29	66.92	
48	500	411.2	286.1	37.1	125.33	87.20	0.0371	291.39	150.33	51.59	
49	300	328.3	0.0	37.1	100.07	0.00	0.0371	185.74	185.74	100.00	
50	400	372.6	0.0	37.1	113.57	0.00	0.0371	239.25	239.25	100.00	
3 Plys Zylon—4 Corners											
51	1500	626.5	no data	37.1	190.96	no data	0.0371	676.42			
52	1500	622.7	0.0	37.1	189.80	0.00	0.0371	668.24	668.24	100.00	
1 Ply Zylon—Pleated/Sewed											
53	500 (loose)	628.4	300.7	37.1	191.54	91.65	0.0371	680.53	524.70	77.10	
54	1500 (tight)	622.5	no data	37.1	189.74	no data	0.0371	667.81			
						Corners tore away letting the projectile pass					
55	500 (12 spi)	630.4	487.7	37.1	192.15	148.65	0.0371	684.87	274.97	40.15	
56	500 (10 spi)	623.6	461.7	37.1	190.07	140.73	0.0371	670.17	302.81	45.18	
57	100 (12 spi)	558.7	0.0	37.1	170.29	0.00	0.0371	537.94	537.94	100.00	
						Projectile may have rebounded (i.e., it was not found)					
58	100 (10 spi)	561.1	0.0	37.1	171.02	0.00	0.0371	542.57	542.57	100.00	
spi = stitch per inch						Projectile came to a near dead stop					
2 Plys Zylon—4 Corners											
59	900	523.3	0.0	37.1	159.50	0.00	0.0371	471.93	471.93	100.00	
60	1100	560.3	47	37.1	170.78	14.33	0.0371	541.02	537.22	99.30	
61	1300	591.5	-91	37.1	180.29	-27.74	0.0371	602.95	588.68	97.63	
62	1300	579.8	-25.0	37.1	176.72	-7.62	0.0371	579.34	578.26	99.81	
63	1100	549.7	0.0	37.1	167.55	0.00	0.0371	520.75	520.75	100.00	
64	1500	605.8	520	37.1	184.65	158.50	0.0371	632.46	166.46	26.32	
1 Ply Zylon—4 Corners w/Grommet											
65	700	469.1	335	37.1	142.98	102.11	0.0371	379.23	185.83	49.00	
66	750	472.2	320	37.1	143.93	97.54	0.0371	384.26	207.79	54.08	
79	175	253.4	0.0	37.1	77.24	0.00	0.0371	110.66	110.66	100.00	
80	300	324.6	110	37.1	98.94	33.53	0.0371	181.58	160.73	88.52	
81	700	465.1	280	37.1	141.76	85.34	0.0371	372.79	237.68	63.76	
82	250	296.0	120	37.1	90.22	36.58	0.0371	150.99	126.18	83.56	
83	450	328.9	130	37.1	100.25	39.62	0.0371	186.42	157.30	84.38	
1 Ply Zylon—w/Grommet and Pleated											
67	500 (loose)	620.1	560	37.1	189.01	170.69	0.0371	662.67	122.23	18.44	
68	1500 (tight)	614.4	455	37.1	187.27	138.68	0.0371	650.54	293.77	45.16	
1 Ply Zylon—4 Corners-2 - 0.5″ Pleats											
69	300	324.3	220	37.1	98.85	67.06	0.0371	181.25	97.84	53.98	
70	200	269.5	130	37.1	82.14	39.62	0.0371	125.17	96.04	76.73	
71	150	232.3	0.0	37.1	70.81	0.00	0.0371	93.00	93.00	100.00	

Test	Gun Press. (psi)	Initial Vel. (ft/s)	Final Vel. (ft/s)	Mass (g)	Initial Vel. (m/s)	Final Vel. (m/s)	Mass (kg)	Initial Energy (J)	Absorbed Energy (J)	Energy Absorbed (%)	Fabric Penetration
1 Ply Zylon—w/Cords											
72	210	271.7	62	37.1	82.81	18.90	0.0371	127.22	120.59	94.79	
73	150	236.2	0.0	37.1	71.99	0.00	0.0371	96.15	96.15	100.00	
74	300	321.0	150	37.1	97.84	45.72	0.0371	177.58	138.80	78.16	
75	600	437.0	290	37.1	133.20	88.39	0.0371	329.11	184.17	55.96	
76	400	371.5	220	37.1	113.23	67.06	0.0371	237.84	154.43	64.93	
77	130	208.9	0.0	37.1	63.67	0.00	0.0371	75.21	75.21	100.00	
78	175	249.2	0.0	37.1	75.96	0.00	0.0371	107.02	107.02	100.00	
1 Ply Zylon—w/Cords (Big Brown)											
84	200	771.2	0.0	37.1	235.06	0.00	0.0371	1024.96	1024.96	100.00	
								Projectile rebounded			
1 Ply Zylon—w/Cords (Green)											
85	200	267.9	-90	37.1	81.66	-27.43	0.0371	123.69	109.73	88.71	