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LIGHTWEIGHT FRAGMENT BARRIERS FOR COMMERCIAL AIRCRAFT

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The ballistic resistance of woven high-strength polymer fabrics to aircraft engine fragments was evaluated. Gas gun tests were performed to determine the relative effectiveness of Kevlar, Spectra, and Zylon and the effect on ballistic performance of fragment sharpness, fabric gripping conditions, and fabric areal density. A computational fabric model was constructed based on yarn geometry and properties and weave configuration. The model was implemented in LS-DYNA3D to simulate impact tests and elucidate the effect of yarn density and fabric gripping conditions. In its detailed form, the model will be useful to yarn and fabric designers; in its simplified shell-element form, the model will be useful for designing fragment barriers. Full-scale tests on an aircraft fuselage section showed that a few plies of Zylon fabric glued to the insulation package within the fuselage wall successfully stops a typical engine-burst fragment at areal densities of only about 0.06 g/cm^2.

INTRODUCTION

On rare occasions a rotor disk of a main propulsion engine on a commercial aircraft fails and defeats the containment structure in the nacelle, showering a section of the fuselage with engine fragments [1]. The loss of an engine on a multi-engine aircraft is not necessarily disastrous, because the plane can fly with one engine. However, fragments may penetrate the fuselage and damage critical systems such as control lines or fuel lines, compromising the pilot's ability to safely land the aircraft. Thus, fragment barrier systems are being considered for implementation at strategic locations on an aircraft to prevent penetration of engine fragments and protect critical aircraft systems [2]. Such barriers must be lightweight, inexpensive, and easy to install and remove for inspection. This work examined the ballistic performance of high-strength fabrics and evaluated barriers designed from these fabrics [3].

BALLISTIC SCREENING TESTS

Small-scale impact tests were performed to evaluate the ballistic effectiveness of candidate barrier materials. As shown in Figure 1, a 25-gram titanium alloy fragment simulator was mounted on the front of an aluminum sabot, which was accelerated down the evacuated barrel of a 100-mm-diameter-bore gas gun to a velocity of 80 m/s. The sabot was slowed and then stopped by a momentum trap and by rings of crushable aluminum honeycomb located at the end of the barrel, while the fragment simulator continued to travel toward the target. Achieved velocities were within 3% of prescribed. The targets were clamped tightly around their peripheries, leaving a free region of 13.3-cm-square for the 15.2-cm-square target configuration.

A high-speed camera with framing rates of about 20,000 frames per second was focused on the regions in front of and in back of the target to record both the initial velocity and orientation of the fragment before impact as well as the residual velocity and orientation of the fragment after target penetration. The energy absorbed by a target was computed from the difference between initial and residual fragment velocity. Because weight is a critical concern for aircraft fragment barriers, the Specific Energy Absorbed (SEA), defined as the energy absorbed by a barrier divided by its areal density, was taken as the merit parameter.

Initial experiments measured the energy absorbed by 1-mm-thick 2024-T3 aluminum fuselage skin. Later experiments evaluated fabrics woven from three high-strength polymers: an aramid (Kevlar), a polyethylene (Spectra), and a polybenzobisoxazole (Zylon). Yarn densities (900 denier) and mesh densities (30 x 30 yarns/inch) for the three fabrics were as close as possible to one another to obtain a direct comparison of their ballistic response.

The results in Figure 2 show that, on an areal density basis, the fabrics outperformed monolithic aluminum alloy by a substantial amount. The specific energy absorption of Kevlar and Spectra exceeded that of aluminum alloy by a factor of 6 and 7, respectively. Zylon, however, absorbed more than 12 times the energy absorbed by an equal areal density of aluminum. These impressive results encouraged us to concentrate on high-strength polymer fabrics in seeking engine fragment barriers and to direct particular attention to Zylon.

PARAMETRIC IMPACT STUDIES WITH ZYLON

Further ballistic tests examined the influence of mesh density, boundary conditions (how the fabric is gripped), and fragment sharpness. Tests on more tightly woven fabrics and multiple fabric ply targets showed that SEA increased nearly linearly with areal density. Sharp-edged fragments resembling a compressor blade penetrated with much less energy than equivalent blunt-edged fragments. Multiple layers of fabric reduced the ability of sharp fragments to perforate (cut through) the target.

To investigate the effect of boundary conditions on ballistic performance, we performed gas gun tests in which the fabric targets were held firmly at only two sides (uniaxially) with the lateral sides ungripped. The energies absorbed were

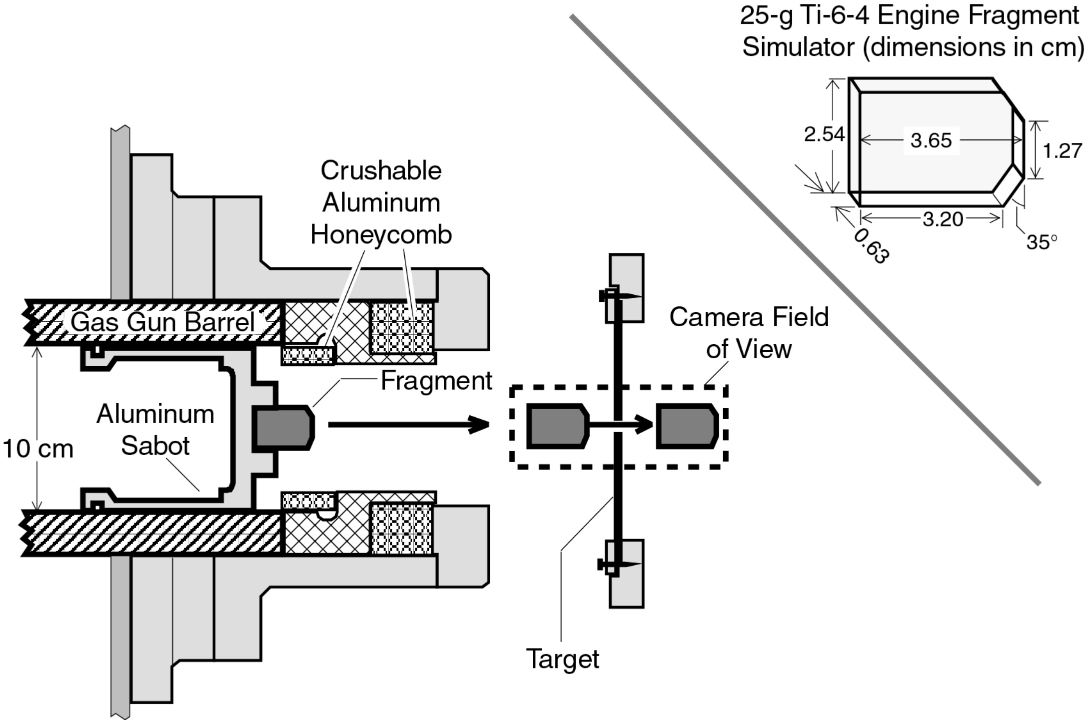


Figure 1. Experimental setup for evaluating fragment penetration resistance.

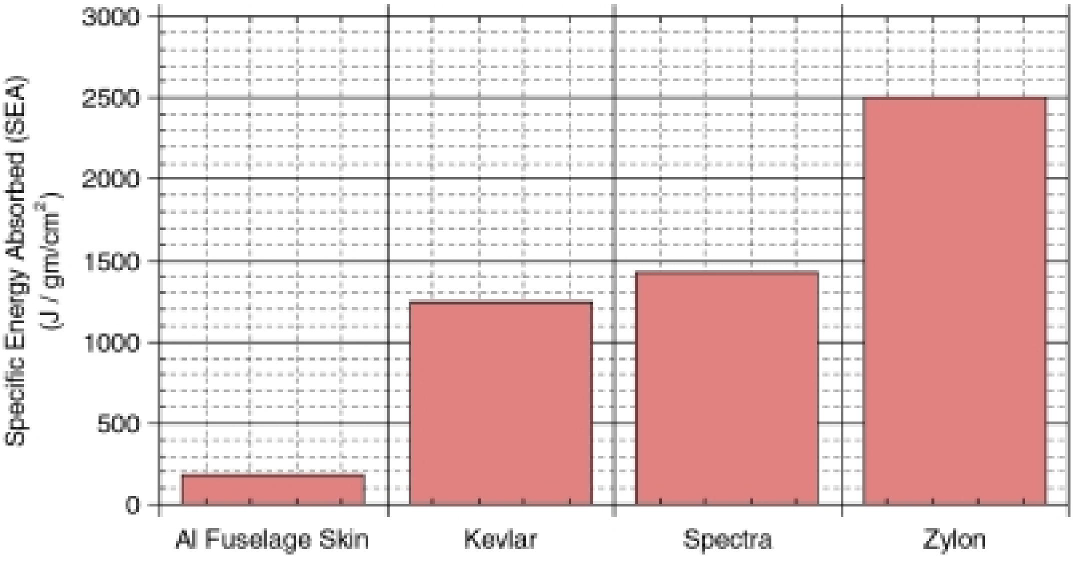


Figure 2. Ballistic efficiencies of aluminum fuselage skin and three high-strength polymer fabrics (as determined with a 25-g fragment simulator at 80 m/s into targets firmly gripped on four sides).

significantly higher (25%-60%) than obtained in the earlier tests where the fabric was gripped biaxially. Uniaxial gripping allows greater fabric deformation before failure.

FULL-SCALE TESTS

Several barrier designs and implementation schemes were evaluated at full scale using a 15-cm-bore gas gun to accelerate 160-gram fragments against a retired aircraft fuselage at velocities up to 250 m/s (Figure 3). The exploded view of the fuselage wall in Figure 4 shows the locations of the ballistic fabric with respect to the aluminum fuselage skin, the insulation packet, and the interior wall panel (IWP). The fabric was glued around its edges, either to the outboard side of the insulation or to the outboard side of the IWP, or both. In contrast to previous laboratory tests where the fabric was firmly gripped biaxially or uniaxially, the fabric in these tests was lightly held along its edges. Up to 3 fabric plies were attached to the insulation packet, and for some tests, an additional ply was attached to the IWP.

The Zylon fabric barriers enhanced the energy absorption of the fuselage wall enormously and were able to stop energetic fragments. Whereas the unfortified wall structure absorbed 482 J when struck by a 152-g fan blade fragment, the wall absorbed 1670 J when 2 layers of Zylon were attached to the insulation package, and 4700 J when 3 fabric layers plus a layer on the IWP were installed. This level of protection was obtained at a weight penalty of 0.063 g/cm^2, an order of magnitude less than would be required by increasing the thickness of aluminum skin.

The arrested fragment from a test near the ballistic limit of the wall showed another energy absorption mode. A fragment "capture" mechanism operates when the fabric resists cutting and can pull the insulation package along with it, adding considerable mass and drag to the fragment, especially as material is pulled through the hole in the interior wall panel. Multiple fabric layers improve the resistance to cutting and fragment punch-through.

COMPUTATIONAL MODEL FOR BALLISTIC FABRICS

To help understand the ballistic response of high strength fabrics and help design weight-efficient fragment barriers, we developed a computational capability for simulating the impact response of woven fabrics [3]. First we formulated a constitutive model for Zylon that describes yarn failure and includes orthotropic response, i.e., stiff under tension in the direction of the fibers and compliant in the other directions. This constitutive model was implemented into the three-dimensional finite element code LS-DYNA3D [4].

We then developed finite element models of single yarns and woven fabrics. The mesh for a single crimped yarn is shown in Figure 5a. The yarn cross section was based on measurements from micrographs of yarns in woven fabrics. We used 8 brick elements across the cross section of the yarn and 12 elements along a crimp

Figure 3. Test setup for full-scale evaluation of engine fragment barriers in the fuselage wall.

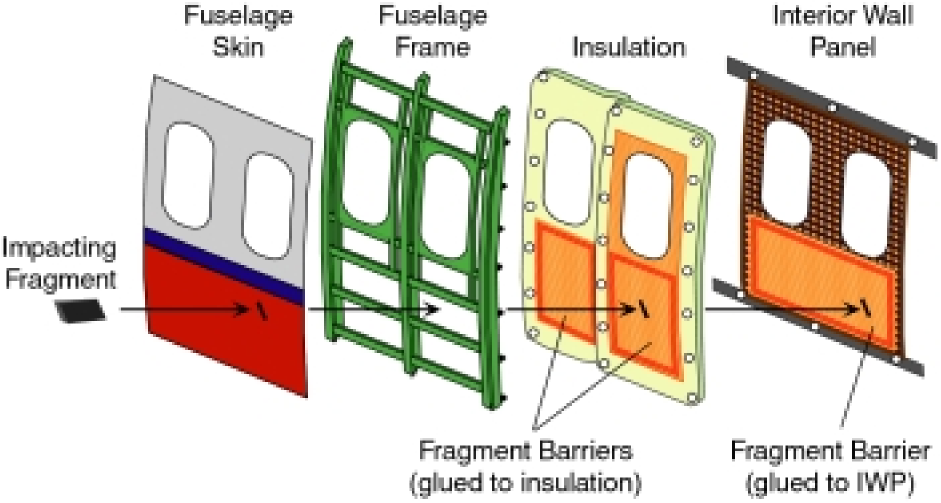
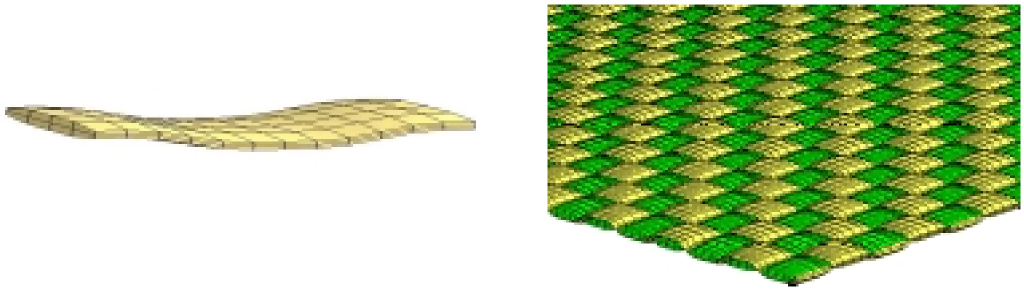


Figure 4. Exploded view of fuselage wall showing location of Zylon fragment barriers.



(a) Single crimped yarn (b) Woven fabric

Figure 5. Finite element meshes.

wavelength. The amount of crimp was also taken from measurements. Typically the amount of crimp in the fabric was greater for the warp yarns than for the fill yarns.

The property data for computational model development, calibration, and verification was provided by a variety of laboratory tests on the woven fabrics and on individual yarns removed from the fabrics. These tests included standard yarn tensile tests and transverse yarn load tests (in which the yarn is gripped on the ends and loaded transversely at the midpoint), to determine modulus, tensile strength, and strain-to-failure.

We simulated the response of crimped single yarns for simple tensile tests and transverse tensile tests. These simulations allowed us to set material parameters for Zylon. We then modeled a woven fabric by interweaving single yarns. The mesh for a section of woven fabric is shown in Figure 5b. The interfaces between the yarns are currently frictionless, but we plan to add friction when the results of the friction pull tests are available.

We used this model to simulate fragment impact scenarios and perform parametric studies on the fabrics. For example, Figure 6 shows simulation of a 1.7-mm rectangular titanium impactor hitting a square patch of woven Zylon at 120 m/s. The Zylon target is 25 yarns in each direction. Although the target and impactor are small (because of calculation time limitations), the simulations give useful insight into the fabric response. They show how the fabric responds, where the yarns break, and how the load is transferred when yarns fail.

Results from a parametric study of the effects of boundary conditions are shown in Figure 7. We simulated three cases of boundary conditions for the geometric configuration shown in Figure 6: (1) four sides firmly held, (2) two sides firmly held, and (3) no sides firmly held. Figure 7a shows the force on the impactor for the three cases. The peak force for four sides held is the greatest, but at 50 ms the yarns break in both directions and the impactor is free to penetrate. For the case held on two sides, the initial peak is less than for four sides held, but as held yarns break, the unheld yarns transfer the load to adjacent held yarns, resulting in a longer duration resisting force on the impactor. For the case with no sides held, the fabric still provides some resistance due to inertia.

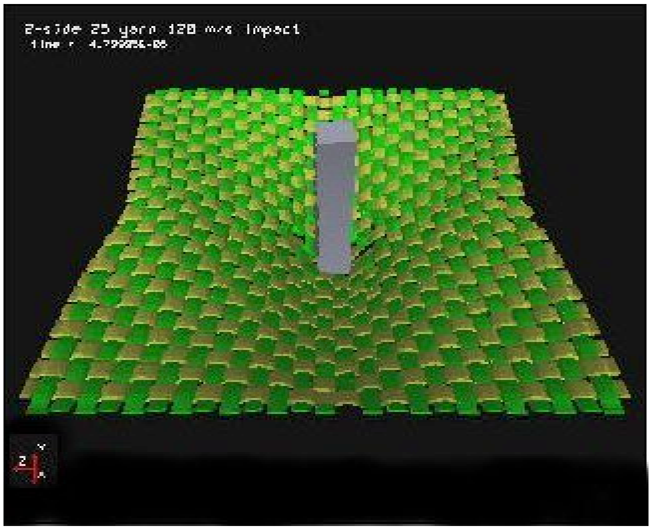
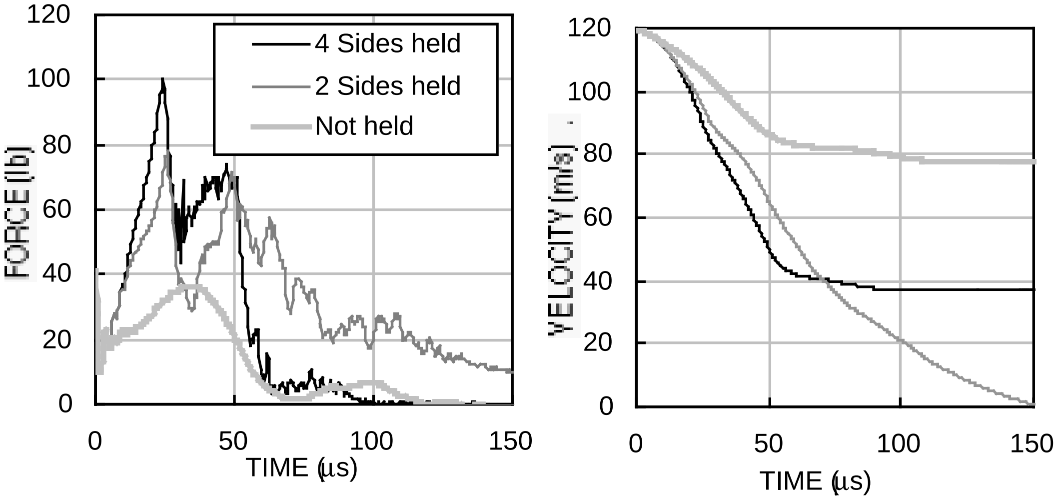


Figure 6. Impact simulation with 2 sides held.



(a) Resisting force

(b) Impactor velocity

Figure 7. Simulation results for parametric study on boundary conditions.

The calculated velocity history of the impactor is shown in Figure 7b. For the case with no sides held, the impactor slows from 120 to about 80 m/s. This result is consistent with conservation of momentum for a simple inelastic collision. For four sides held, the velocity is reduced from 120 to about 38 m/s, and for two sides held, the velocity of the impactor is reduced to zero. The result that holding on two sides is more effective than holding on four sides agrees with the experimental results described above and helps explain that result. The result for no sides held shows that, if the impactor is prevented from cutting through the fabric, significant energy can be absorbed by inertial effects.

The model can now be used to study ways to improve the efficiency of the fabric for barriers. We plan to investigate the effect of varying parameters such as yarn density, stiffness, strength, and interyarn friction on barrier efficiency.

Using the information we have gained from computer simulations, we plan to develop a less detailed model for use by aeronautical engineers in computationally designing fabric barrier structures. This simplified model will use shell elements to model layers of fabric. The deformation and failure response of the shell model will be consistent with the results of the laboratory experiments and the detailed model simulations.

CONCLUSIONS

High strength polymer fabrics provide a lightweight solution for mitigating the effects of turbine engine fragments on commercial aircraft. Fabric fragment barriers are ballistically efficient, can be unobtrusively positioned with the fuselage wall, and, if combined with the insulation package, can be easily installed and removed to allow required periodic inspection of the fuselage structure.

In its brick element form, the computational fabric model can assist in material development. In its shell element form, the model will be a useful fragment barrier design tool.

The results reported here will find application in other areas such as body armor and bulletproof cars.

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